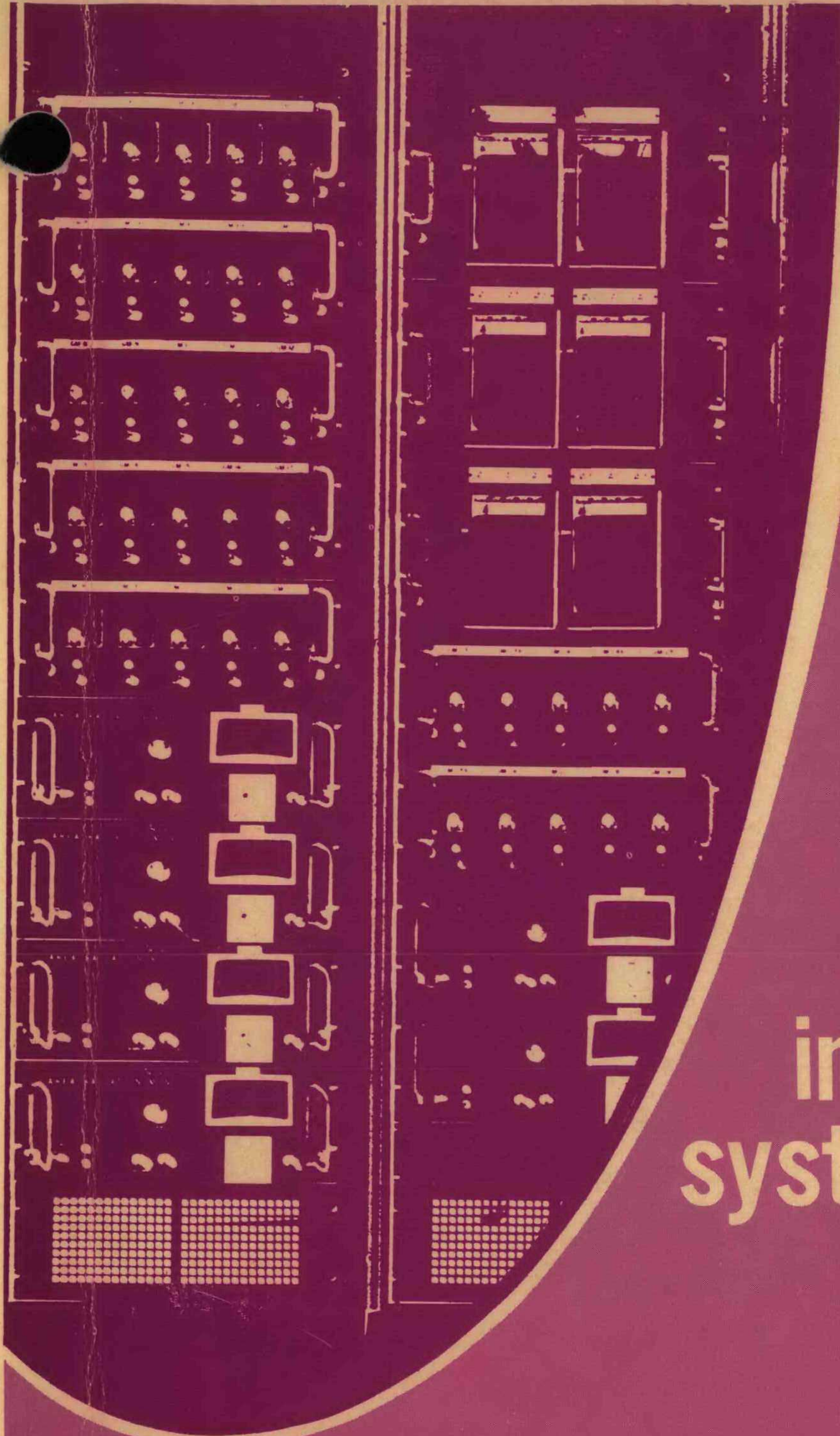

nuclear power reactor instrumentation systems handbook

Joseph M. Harrer and James G. Beckerley

VOLUME 1

Office of Information Services U. S. Atomic Energy Commission

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TID-25952-P1

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Prepared for the Division of Reactor Development and Technology
U. S. Atomic Energy Commission

VOLUME 1

1973

Published by the Office of Information Services
U. S. Atomic Energy Commission

Available as TID 25952-P1 for $7 60 from

National Technical Information Service
U S Department of Commerce
Springfield, Virginia 22151

International Standard Book Number 0-87079-005-6
Library of Congress Catalog Card Number 72-600355
AEC Distribution Category UC-80

Printed in the United States of America
USAEC Technical Information Center Oak Ridge Tennessee

May 1973

Preface

Nuclear power technology has reached the stage where there are "accepted practices" in many aspects of reactor design and construction The systems of instrumentation used in reactors of a specific type have more common features than differences Changes are gradual and evolutionary What is accepted practice today will be recognized as good practice for some years to come This does not mean that there will be no major changes in nuclear power technology in the future, it simply means that the rate of change will not be so rapid that what is learned today will have to be forgotten tomorrow

The instrumentation systems of today's power reactors—including those on the drawing boards—are described in this book The performance and characteristics of the major components of power-reactor instrumentation systems are presented but with a minimum discussion of component design For example, in the chapters concerned with nuclear radiation sensors, sensor construction and performance are described in detail, but the data required by one who wishes to design a nuclear radiation sensor are not given This is in keeping with the basic intent to emphasize the systems aspect of power-reactor instrumentation

The book is intended for the designers and operators of power-reactor instrumentation systems, i e , those concerned with the applications, not with the invention, of devices All systems aspects are discussed, including the problems associated with integrating individual components into subsystems and systems, the so-called "interface" problems The requirements (or design bases) to be satisfied by each system and subsystem are given, and current practices are outlined and evaluated

As the title indicates, systems associated with the nuclear power reactor are considered Systems associated with the electric power generated and with generator operation are not discussed In a sense the book is concerned with steam generation by nuclear reactors, although the fact that a turbogenerator is being driven by the steam does become involved in some of the instrumentation systems discussed

The book is organized into 18 chapters, divided into two volumes After an introductory chapter that summarizes basic definitions, reactor kinetics, and reactor types, Volume 1 continues with three chapters concerned with sensors The next chapter is concerned with the important electronics associated with neutron sensors Systems for determining the dynamic properties of nuclear reactors are then described Because control-rod drives and control-rod-position indicators have such a unique relation to the operation of nuclear power reactors and are so closely coupled to the neutron and position sensors of protection systems, these are briefly described in a chapter

The next four chapters are concerned with topics that are relevant to all reactor systems The increasing use of computers in data handling and process control in power reactors is described Systems for monitoring nuclear radiations and radioactive materials in nuclear plants are discussed Since power supplies are essential to the operation of instrumentation systems, a chapter on the subject is included Many problems are the result of improper installation of the components of instrumentation systems, a chapter is devoted to this topic In the same manner, a chapter on quality assurance and reliability provides basic information needed by all reactor-instrumentation-systems designers and users

Volume 2 takes up the application of the material developed in Volume 1

The importance of reactor protection systems is such that one chapter is devoted to outlining the bases for their design and to describing current designs And a chapter describing radiation monitoring is included

A chapter summarizing the status of standards and codes on nuclear reactor instrumentation systems is then followed by the "big four " These final four chapters summarize the current state of the art in instrumentation systems for the four major reactor types pressurized-water reactors, boiling-water reactors, sodium-cooled reactors, and gas-cooled reactors

Volume 2 concludes with one appendix a summary of in-core sensors in present-day reactors.

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Fundamental Considerations

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1-1 NUCLEAR AND FOSSIL FUELS

Many instrumentation systems are required to monitor, control, and regulate the nuclear and chemical processes of an operating nuclear power plant Although some of the systems are identical to those used in fossil-fueled power plants, many are entirely different

Perhaps the most important reason for differences between the instrumentation systems of conventional (fossil-fueled) and nuclear power plants is that conventional plants operate with continuous fuel feed and nuclear plants operate with stored feed In a conventional plant fuel is fed continuously to the combustion chamber, in present-day nuclear plants all the nuclear fuel necessary for many months of operation is in the reactor all that time Because of the large fuel inventory, an increasing nuclear reaction rate caused by equipment failure or malfunction will not be stopped by exhaustion of fuel Perhaps in future nuclear plants (e.g , those using fluid fuels), the inventory of fuel in the reacting region can be reduced and the associated hazard thereby diminished. In the meantime nuclear power plant instrumentation must be dependable to prevent damage.

Another reason for instrumentation differences is the concentration of heat energy in the two types of fuel About 40 billion Btu of heat is released in the fissioning of 1 lb of pure nuclear fuel On the other hand, about 14 thousand Btu is released in the burning of 1 lb of coal Since nuclear fuels are such concentrated heat sources, the heat flux from a nuclear fuel can exceed the capabilities of the coolant to remove heat Consequently, the details of nuclear-fuel performance must be measured The development of instrumentation systems for monitoring fuel performance has been a major effort in nuclear power technology.

The heat energy of a nuclear fuel comes almost entirely from the fission fragments At the time of their formation, the fragments have kinetic energies that correspond to particle temperatures of about 10^{12} °C In present-day solid fuels, the fission-fragment energies are immediately shared with the surrounding approximately 10^{22} atoms/cm^3 of the fuel (usually uranium metal or oxide or carbide), and the average temperature of the nuclear fuel is many orders of magnitude less than the initial fission-fragment temperature. In fact, the rate of coolant flow is regulated to keep the interior temperature of the nuclear fuel in the same general range (a few thousand degrees centigrade) as typical fossil-fuel temperatures Should coolant flow be impeded, however, the nuclear fuel temperature could become much higher. One of the primary purposes of nuclear power reactor instrumentation is to prevent this

Another difference between nuclear and conventional power plants that affects instrumentation is the presence of strong nuclear radiation fields in certain regions of a nuclear reactor The interaction of these fields with sensors and with electrical components can cause a deterioration in signal and system performance Because of this, the materials and techniques used in nuclear power plant

instrumentation often differ from those used in fossil-fueled power plants

1-2 DEFINITIONS

Nuclear power plants are based on concepts that require careful definition In subsequent chapters many definitions of specialized terms are presented whenever relevant to the discussion In this section definitions of a number of fundamental terms basic to an understanding of nuclear power plant operation are given The definitions are listed by concept rather than alphabetically Most of the definitions are taken verbatim from the *American National Standard Glossary of Terms in Nuclear Science and Technology* [1]

1-2.1 Nuclear Terms

Nuclide A species of atom characterized by its mass number (number of neutrons and protons in nucleus), atomic number (number of electrons in the neutral atom), and energy state of the nucleus, provided that the mean life in that state is long enough to be observable

Neutron An elementary particle, electrically neutral, whose mass is approximately equal to that of a hydrogen atom which with a half-life of about 11 7 min, decays, in the free state, into a proton and an electron

Thermal neutrons Neutrons essentially in thermal equilibrium with the medium in which they exist

Fast neutrons Neutrons of kinetic energy greater than some specified value In reactor physics the value is frequently chosen to be 0 1 MeV

Beta particle An electron, of either positive charge (β^+) or negative charge (β^-), which has been emitted by an atomic nucleus or neutron in the process of a transformation

Radioactive decay A spontaneous nuclear transformation in which the nucleus emits particles or gamma radiation, or undergoes spontaneous fission, or in which the atom emits x-radiation or Auger electrons following orbital electron capture or internal conversion

Decay constant (or *disintegration constant*) For a radioactive nuclide (radionuclide), the probability per unit time for the spontaneous radioactive decay of a nucleus It is given by

$$\lambda = -\frac{1}{N}\frac{dN}{dt}$$

in which N is the number of nuclei of concern existing at time t

Curie The special unit of activity (nuclear disintegration rate) One Curie equals 3.7×10^{10} disintegrations per second, exactly "Curie" is abbreviated as Ci

Half life (radioactive half life) For a single radioactive decay process, the time required for the activity (dN/dt or λN) to decrease to half its value by that process The half-life is related to the decay constant $T_{1/2} = (\log_e 2)/\lambda = 0.69315/\lambda$

Cross section A measure of the probability of a specified interaction between an incident radiation and a target particle or system of particles It is the reaction rate per target particle for a specified process divided by the particle-flux density of the incident radiation *(microscopic cross section)* In reactor physics the term is sometimes applied to a specified group of target particles, e g , those per unit volume *(macroscopic cross section)* or per unit mass, or those in a specified body [*Note* Unless otherwise qualified the term "cross section" means "microscopic cross section"]

Macroscopic cross section The cross section per unit volume of a given material for a specified process It has the dimension of reciprocal length. For a pure nuclide, it is the product of the microscopic cross section and the number of target nuclei per unit volume, for a mixture of nuclides, it is the sum of such products

Microscopic cross section The cross section per target nucleus, atom, or molecule It has the dimension of area and may be visualized as the area normal to the direction of an incident particle which has to be attributed to the target particle to account geometrically for the interaction with the incident particle Microscopic cross sections are often expressed in *barns*, where 1 barn = 10^{-24} cm^2

Particle flux density At a given point in space, the number of particles or photons incident per unit time on a small sphere centered at that point divided by the cross-sectional area of that sphere It is identical with the product of the particle density and the average particle speed The term is commonly called *flux*

Neutron flux density Particle-flux density for neutrons Also commonly called *neutron flux* Often denoted by nv or ϕ

Particle fluence At a given point in space, the number of particles or photons incident during a given time interval on a small sphere centered at that point divided by the cross-sectional area of that sphere. It is identical with the time integral of the particle-flux density Often denoted by nvt

Particle density At a given point in space, the number of particles or photons per unit volume in a small sphere centered at that point

Ionizing radiation. Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, by interaction with matter

Indirectly ionizing particles Uncharged particles or photons which can liberate directly ionizing particles or can initiate a nuclear transformation

Directly ionizing particles. Charged particles having sufficient kinetic energy to produce ionization by collision.

Exposure. A measure of the ionization produced in air by x or gamma radiation. It is the sum of the electrical charges on all of the ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in the air, divided by the mass of the air in the volume element. The special unit of exposure is the roentgen.

Roentgen. The special unit of exposure. One roentgen = 1 R = 2.58×10^{-4} coulomb per kilogram of air.

Dose. A general term denoting the quantity of radiation or energy absorbed in a specified mass. For special purposes, its meaning should be appropriately stated, e.g., absorbed dose.

Absorbed dose. The energy imparted to matter in a volume element by ionizing radiation divided by the mass of irradiated material in that volume element. The special unit of absorbed dose is the rad. (Absorbed dose is often called dose.)

Rad. The special unit of absorbed dose. One rad equals 100 ergs/gram.

Dose equivalent (radiation protection). The product of absorbed dose, quality factor, dose distribution factor, and other modifying factors necessary to express on a common scale, for all ionizing radiations, the irradiation incurred by exposed persons. The special unit of dose equivalent is the rem.

Rem. The dose equivalent in rems is numerically equal to the absorbed dose in rads multiplied by the quality factor, the distribution factor, and any other necessary modifying factors.

Quality factor (radiation protection). A linear-energy-transfer-dependent factor by which absorbed doses are to be multiplied to obtain the dose equivalent. (*Note:* The term "RBE" should be used only in the field of radiobiology.)

Linear energy transfer (LET). The average energy locally imparted to a medium by a charged particle of specified energy per unit distance traversed. [*Notes:* (1) The term "locally imparted" may refer either to a maximum distance from the track or to a maximum value of discrete energy loss by the particle beyond which losses are no longer considered as local. In either case, the limits chosen should be specified. (2) The concept of LET is different from that of stopping power. The former refers to energy imparted within a limited volume, the latter to loss of energy from the particle regardless of where this energy is absorbed.]

Dose distribution factor (radiation protection). A factor used in computing dose equivalent to account for the nonuniform distribution of internally deposited radionuclides.

Maximum permissible dose equivalent (MPD) (radiation protection). The largest dose equivalent received within a specified period which is permitted by a regulatory agency or other authoritative group on the assumption that receipt of such dose equivalent creates no appreciable somatic or genetic injury. Different levels of MPD may be set for different groups within a population. (By popular usage, "maximum permissible dose" is an accepted synonym.)

Kerma (kinetic energy released in material). The ratio of the sum of the initial kinetic energies of all the charged particles liberated by indirectly ionizing particles in a volume element to the mass of the matter in the volume element.

1-2.2 Fission-Process Terms

Nuclear fission. The division of a heavy nucleus into two (or, rarely, more) parts with masses of equal order of magnitude; usually accompanied by the emission of neutrons, gamma rays, and, rarely, small charged nuclear fragments.

Fast fission. Fission caused by fast neutrons.

Thermal fission. Fission caused by thermal neutrons.

Spontaneous fission. Fission which occurs without the addition of particles or energy to the nucleus.

Fissionable. Of a nuclide, capable of undergoing fission by any process.

Fissile. Of a nuclide, capable of undergoing fission by interaction with slow neutrons. (In reactor physics, slow neutrons are frequently defined as those of kinetic energy less than 1 eV.)

Fertile. Of a nuclide, capable of being transformed, directly or indirectly, into a fissile nuclide by neutron capture. Of a material, containing one or more fertile nuclides.

Fission fragments. The nuclei resulting from fission and possessing kinetic energy acquired from that fission.

Fission products. The nuclides produced either by fission or by the subsequent radioactive decay of the nuclides thus formed.

Fission yield. The fraction of fissions leading to fission products of a given type.

Prompt gamma radiation. Gamma radiation accompanying the fission process without measurable delay.

Prompt neutrons. Neutrons accompanying the fission process without measurable delay.

Delayed neutrons. Neutrons emitted by nuclei in excited states which have been formed in the process of beta decay. (The neutron emission itself is prompt, so that the observed delay is that of the preceding beta emission or emissions.)

1-2.3 Nuclear-Reactor Terms

Nuclear chain reaction. A series of nuclear reactions in which one of the agents necessary to the series is itself produced by the reactions so as to cause similar reactions. Depending on whether the number of reactions so caused directly by one reaction is on the average less than, equal to, or greater than unity, the

reaction is convergent (*subcritical*) self-sustained (*critical*), or divergent (*supercritical*)

Nuclear reactor A device in which a self-sustaining nuclear fission chain reaction can be maintained and controlled (fission reactor). The term is commonly called "reactor" or "pile "

Fast reactor A reactor in which fission is induced predominantly by fast neutrons (Also called fast-neutron reactor.)

Thermal reactor A reactor in which fission is induced predominantly by thermal neutrons.

Multiplication factor The ratio of the total number of neutrons produced during a time interval (excluding neutrons produced by sources whose strengths are not a function of fission rate) to the total number of neutrons lost by absorption and leakage during the same interval When the quantity is evaluated for an infinite medium or for an infinitely repeating lattice, it is referred to as the *infinite multiplication factor* (k_∞) When the quantity is evaluated for a finite medium, it is referred to as the *effective multiplication factor* (k_{eff}) (The term is also called *multiplication constant*.)

Critical Fulfilling the condition that a medium capable of sustaining a nuclear chain reaction has an effective multiplication factor equal to unity (A nuclear reactor is critical when the rate of neutron production, excluding neutron sources whose strengths are not a function of fission rate, is equal to the rate of neutron loss)

Delayed critical Identical with critical, the term is used to emphasize that the delayed neutrons are necessary to achieve the critical state

Prompt critical Fulfilling the condition that a nuclear chain-reacting medium is critical utilizing prompt neutrons only.

Prompt neutron fraction. The ratio of the mean number of prompt neutrons per fission to the mean total number of neutrons (prompt plus delayed) per fission.

Delayed-neutron fraction. The ratio of the mean number of delayed neutrons per fission to the mean total number of neutrons (prompt plus delayed) per fission.

Effective delayed neutron fraction. The ratio of the mean number of fissions caused by delayed neutrons to the mean total number of fissions caused by delayed plus prompt neutrons. (*Note* The effective delayed-neutron fraction is generally larger than the actual delayed-neutron fraction)

Reactivity. A parameter, ρ, giving the deviation from criticality of a nuclear chain-reacting medium such that positive values correspond to a supercritical state and negative values to a subcritical state Quantitatively, $\rho = 1 - (1/k_{eff})$, where k_{eff} is the effective multiplication factor.

Excess reactivity. The maximum reactivity attainable at any time by adjustment of the control members.

Built-in reactivity The reactivity of a system as a function of design excluding the experimental and control inserts of the system.

Reactor control The intentional variation of the reaction rate in a reactor or adjustment of reactivity to maintain a desired state of operation.

Reactivity coefficient. The change in reactivity caused by inserting a small amount of a substance in a reactor The reactivity coefficient of a substance may depend upon the amount and distribution of the substance inserted, but is usually quoted as the reactivity change per unit mass of the substance at specific positions in the reactor or as a uniform distribution.

Void coefficient The partial derivative of reactivity with respect to a void (i.e , the removal of the material) at a specified location within a reactor. It is equal to the reactivity coefficient of the material removed.

Isothermal temperature coefficient of reactivity. The change of reactivity caused by a one-degree increase in the uniform temperature of a reactor at zero power

Power coefficient of reactivity The change of reactivity per unit change of reactor thermal power when other variables are not independently changed

1-3 NUCLEAR-REACTOR KINETICS

The design of instrumentation systems for a nuclear power plant must take into account the specific properties of the reactor for that plant. Of particular importance is the kinetic behavior of the reactor Many textbooks and monographs have been written on nuclear reactor kinetics, the reader is referred, for example, to Refs. 2 through 6 for details The following paragraphs summarize basic material particularly relevant to instrumentation systems in nuclear power reactors.

1-3.1 Point Kinetics Without Delayed Neutrons

The symbol n (neutrons/cm^3) is used to designate the neutron density at a given position in a nuclear fission chain reactor. If the reactor is just critical, the effective multiplication factor, k, is exactly 1 and the neutron density, n, is constant. If the effective multiplication factor is increased by $\delta k = k - 1$ (with $\delta k > 0$), then n increases with time.

The rate of increase of n, dn/dt, is the number of extra neutrons in the next generation, n δk, divided by the time between generations l

$$\frac{dn}{dt} = \frac{n\,\delta k}{l} = \frac{n(k-1)}{l} \qquad (1\ 1)$$

Integrated, this is

$$n = n_0 e^{(\delta k/l)t} \qquad (1\ 2)$$

where n_0 is the neutron density at t = 0 The reciprocal of the first factor, $\delta k/l$, in the exponential has the dimensions of time and is known as the reactor period

$$n = n_0 e^{t/T} \qquad T = l/\delta k \tag{1 3}$$

These equations have been developed on the assumption that there is a single characteristic time between generations in a nuclear fission chain reaction This is the same as assuming that only prompt neutrons participate in the chain reaction

To introduce the effect of delayed neutrons on the nuclear chain reaction, we consider the effective multiplication factor to be the sum of two terms

$$\begin{aligned} k &= \text{(multiplication factor for prompt neutrons)} \\ &\quad + \text{(multiplication factor for delayed neutrons)} \\ &= k(1 - \beta) + k\beta \end{aligned} \tag{1 4}$$

where β is the delayed neutron fraction, or the number of delayed neutrons per fission divided by the total prompt and delayed neutrons per fission The delayed-neutron fraction can be expressed as the sum of the delayed-neutron fractions for each group of the delayed neutron emitters

Table 1.1—Delayed-Neutron Half-Lives and Yields in Thermal-Neutron Fission[7]

Isotope	Delayed neutrons/fission	Group index (i)	Half-life ($T_{1/2}$), sec	Decay constant* (λ), sec^{-1}	Relative abundance (a)	Absolute group yield, %
^{233}U	0 0066 ± 0 0003	1	55 00 ± 0 54	0 0126 ± 0 0002	0 086 ± 0 003	0 057 ± 0 003
		2	20 57 ± 0 38	0 0337 ± 0 0006	0 299 ± 0 004	0 197 ± 0 009
		3	5 00 ± 0 21	0 139 ± 0 006	0 252 ± 0 040	0 166 ± 0 027
		4	2 13 ± 0 20	0 325 ± 0 030	0 278 ± 0 020	0 184 ± 0 016
		5	0 615 ± 0 242	1 13 ± 0 40	0 051 ± 0 024	0 034 ± 0 016
		6	0 277 ± 0 047	2 50 ± 0 42	0 034 ± 0 014	0 022 ± 0 009
^{235}U	0 0158 ± 0 0005	1	55 72 ± 1 28	0 0124 ± 0 0003	0 033 ± 0 003	0 052 ± 0 005
		2	22 72 ± 0 71	0 0305 ± 0 0010	0 219 ± 0 009	0 346 ± 0 018
		3	6 22 ± 0 23	0 111 ± 0 004	0 196 ± 0 022	0 310 ± 0 036
		4	2 30 ± 0 09	0 301 ± 0 012	0 395 ± 0 011	0 624 ± 0 026
		5	0 61 ± 0 083	1 13 ± 0 15	0 115 ± 0 009	0 182 ± 0 015
		6	0 23 ± 0 025	3 00 ± 0 33	0 042 ± 0 008	0 066 ± 0 008
^{239}Pu	0 0061 ± 0 0003	1	54 28 ± 2 34	0 0128 ± 0 0005	0 035 ± 0 009	0 021 ± 0 006
		2	23 04 ± 1 67	0 0301 ± 0 0022	0 298 ± 0 035	0 182 ± 0 023
		3	5 60 ± 0 40	0 124 ± 0 009	0 211 ± 0 048	0 129 ± 0 030
		4	2 13 ± 0 24	0 325 ± 0 036	0 326 ± 0 033	0 199 ± 0 022
		5	0 618 ± 0 213	1 12 ± 0 39	0 086 ± 0 029	0 052 ± 0 018
		6	0 257 ± 0 045	2 69 ± 0 47	0 044 ± 0 016	0 027 ± 0 010

*The decay constants are related to the half-lives by the equation $\lambda = (\ln 2)/T_{1/2} = 0\ 693/T_{1/2}$

1-3.2 Point Kinetics with Delayed Neutrons

Some of the neutrons participating in the chain reaction are emitted at various times after the fission event When certain fission product nuclides decay by emitting beta particles, the resultant nuclides are unstable, and each of the nuclides emits a neutron immediately after the beta decay The rate of neutron emission therefore is the same as the rate of beta decay of these "precursor" nuclides, i e , a rate that decreases exponentially with time

Tables 1 1 and 1 2 list the half lives and decay constants $[\lambda = (\ln 2)/T_{1/2} = 0\ 693/T_{1/2}]$ of the delayed neutron emitters resulting from the fissioning of ^{233}U, ^{235}U, and ^{239}Pu by thermal neutrons and by fast neutrons, respectively The tables also list the absolute yields of delayed neutrons (number of delayed neutrons per fission emitted by each precursor type) and the relative abundances of the delayed neutrons (number of delayed neutrons emitted by each precursor type divided by the total number of delayed neutrons emitted in a fission process)

$$\beta = \sum_{i=1}^{m} \beta_i \tag{1 5}$$

where m is the number of delayed-neutron groups Table 1 3 lists the values of β_i for the fission of ^{233}U, ^{235}U, and ^{239}Pu by thermal and fast neutrons The table also lists ν, the number of prompt neutrons per fission Values of β_i are obtained by multiplying the relative abundance values in Tables 1 1 and 1 2 by the values of β in Table 1 3

The average energy of the delayed neutrons is not the same as the average energy of the prompt neutrons Thus, in any chain-reacting system, the effectiveness of the delayed neutrons in propagating the nuclear fission chain reaction differs from that of the prompt neutrons The factor β used in Eq. 1 4 does not take this into account

since β is a simple ratio of numbers of neutrons. To take the neutron energies into account, replace β with

$\gamma\beta$ = effective delayed neutron fraction

= (number of fissions caused by delayed neutrons)/ (number of fissions caused by delayed plus prompt neutrons) (1.6)

where γ is the delayed-neutron effectiveness. The value of γ depends on the chain-reacting system and is generally slightly greater than 1. For the power reactors discussed in this book, it is a good approximation to assume $\gamma = 1$. Likewise, the delayed-neutron effectiveness for the individual delayed-neutron groups can be assumed to be 1, i.e., $\gamma = \gamma_i = 1$.

The basic kinetic equations for a nuclear fission chain reaction in which delayed neutrons are taken into account are obtained by writing the rate of change of the neutron density (n = neutrons/cm^3) as a sum of two terms

$$\frac{dn}{dt} = \text{(rate of change of prompt-neutron density)} + \text{(rate of change of delayed neutron density)}$$

$$= \frac{n}{l}[k(1-\beta) - 1] + \sum_{i=1}^{m} \lambda_i C_i \qquad (1.7)$$

where C_i is the density (number/cm^3) of delayed-neutron emitters of the *ith* group and λ_i is the decay constant (fraction decaying/sec) of the *ith* delayed-neutron emitter group. The number of groups, m, is 6 (see Tables 1.1 and 1.2). The first term of Eq. 1.7 is obtained by substituting the multiplication factor for prompt neutrons (Eq. 1.4) for k in Eq. 1.1.

The density of each of the delayed neutron-emitting groups, C_i, is obtained from the equation

$$\frac{dC_i}{dt} = \text{(rate of production of } ith \text{ group of delayed-neutron emitters)} - \text{(rate of decay of } ith \text{ group of delayed-neutron emitters)}$$

$$= \frac{k\beta_i n}{l} - \lambda_i C_i \qquad (1.8)$$

The first term is the multiplication factor for delayed neutrons (Eq. 1.4) divided by the time interval between generations, or the prompt-neutron lifetime, l. If there is a source of neutrons present other than the fissionable isotopes and the fission products that emit neutrons, then a source term must be added to the right-hand side of Eq. 1.8.

Equations 1.7 and 1.8 are the basic neutron kinetics equations. They are important in the design of the instrumentation and control systems for nuclear power reactors. In Chap. 6 the equations are used to show how transfer-function measurements can yield useful information on power-reactor behavior. In Chap. 7 the equations are shown to be basic to the design of reactor control systems.

1-3.3 Reactivity

When a nuclear power-reactor plant is generating electrical energy at a steady or constant rate, the reactor is in a steady state in which the neutron density is fixed, the temperatures at various positions in the reactor are constant, etc. Equations 1.7 and 1.8 show that, since $dn/dt = dC_i/dt = 0$ in this steady state, the effective multiplication factor is just 1. If the effective multiplication factor increases above 1, n will increase with time. Similarly, when $k < 1$, n decreases with time.

As k is increased above 1, it reaches a value where the first term of Eq. 1.7 becomes zero; then, for higher values of k, the term becomes positive. When $k(1-\beta) - 1$ is positive, the neutron density increases with time at a rate depending on the ratio of the prompt-neutron lifetime, l, to $k(1-\beta) - 1$. Under these conditions the reactor is prompt critical, and, because l is so small ($l \lesssim 10^{-4}$ sec for a thermal reactor, $l \lesssim 10^{-7}$ sec for a fast reactor), n increases very rapidly with time for any appreciable positive value of $k(1-\beta) - 1$. The value of the effective multiplication factor when the reactor is just prompt critical is $1/(1-\beta)$. Since power reactors are always kept below prompt criticality, the practical range of the effective multiplication factor is between 1 and $1/(1-\beta)$ when the reactor is operating and between 0 and 1 when the reactor is being started up or shut down.

In place of the effective multiplication factor it is more convenient to refer to the reactivity, or the fractional deviation of the effective multiplication factor from unity, $(k-1)/k$,

$$\text{Reactivity} = \rho = \frac{k-1}{k} = \frac{\delta k}{k} \qquad (1.9)$$

When the effective multiplication factor varies from 1 to $1/(1-\beta)$, the reactivity varies from 0 to β. In other words, the reactivity increases by β as the reactor goes from delayed critical to prompt critical. It is convenient to designate this change of reactivity as "one dollar" = \$1 = unit of reactivity equal to the reactivity difference between the prompt critical ($k = 1/1 - \beta$) and the delayed critical ($k = 1$) conditions of a reactor. The dollar is further subdivided into 100 cents; a change in reactivity of 1¢, for example, is $\Delta\rho = 0.01\beta$. From the values of β in Table 1.3, it follows that a 1¢ reactivity increment is 0.000064 for a ^{235}U-fueled reactor.

Frequently the terms "excess k," "$\delta k/k$," and "reactivity" are used interchangeably. As Eq. 1.9 shows, the second and third terms are exactly equivalent. The use of "excess k" or "δk" as equivalent to reactivity is approximately correct, since $\rho = \delta k/k = \delta k/(1+\delta k) = \delta k - (\delta k)^2$, etc., and $\delta k \ll 1$ in all practical cases.

Table 1.2—Delayed-Neutron Half-Lives and Yields in Fast Fission*[7]

Isotope	Delayed neutrons/fission	Group index (i)	Half-life ($T_{1/2}$), sec	Decay constant (λ), sec^{-1}	Relative abundance (a)	Absolute group yield, %
^{233}U	0.0070 ± 0.0004	1	55.11 ± 1.86	0.0126 ± 0.0004	0.086 ± 0.003	0.06 ± 0.003
		2	20.74 ± 0.86	0.0334 ± 0.0014	0.274 ± 0.005	0.192 ± 0.009
		3	5.30 ± 0.19	0.131 ± 0.005	0.227 ± 0.035	0.159 ± 0.025
		4	2.29 ± 0.18	0.302 ± 0.024	0.317 ± 0.011	0.222 ± 0.012
		5	0.546 ± 0.108	1.27 ± 0.266	0.073 ± 0.014	0.051 ± 0.010
		6	0.221 ± 0.042	3.13 ± 0.675	0.023 ± 0.007	0.016 ± 0.005
^{235}U	0.0165 ± 0.0005	1	54.51 ± 0.94	0.0127 ± 0.0002	0.038 ± 0.003	0.063 ± 0.005
		2	21.84 ± 0.54	0.0317 ± 0.0008	0.213 ± 0.005	0.351 ± 0.011
		3	6.00 ± 0.17	0.115 ± 0.003	0.188 ± 0.016	0.310 ± 0.028
		4	2.23 ± 0.06	0.311 ± 0.008	0.407 ± 0.007	0.672 ± 0.023
		5	0.496 ± 0.029	1.40 ± 0.081	0.128 ± 0.008	0.211 ± 0.015
		6	0.179 ± 0.017	3.87 ± 0.369	0.026 ± 0.003	0.043 ± 0.005
^{238}U	0.0412 ± 0.0017	1	52.38 ± 1.29	0.0132 ± 0.0003	0.013 ± 0.001	0.054 ± 0.005
		2	21.58 ± 0.39	0.0321 ± 0.0006	0.137 ± 0.002	0.564 ± 0.025
		3	5.00 ± 0.19	0.139 ± 0.005	0.162 ± 0.020	0.667 ± 0.087
		4	1.93 ± 0.07	0.358 ± 0.014	0.388 ± 0.012	1.599 ± 0.081
		5	0.49 ± 0.023	1.41 ± 0.067	0.225 ± 0.013	0.927 ± 0.060
		6	0.172 ± 0.009	4.02 ± 0.214	0.075 ± 0.005	0.309 ± 0.024
^{239}Pu	0.0063 ± 0.0003	1	53.75 ± 0.95	0.0129 ± 0.0002	0.038 ± 0.003	0.024 ± 0.002
		2	22.29 ± 0.36	0.0311 ± 0.0005	0.280 ± 0.004	0.176 ± 0.009
		3	5.19 ± 0.12	0.134 ± 0.003	0.216 ± 0.018	0.136 ± 0.013
		4	2.09 ± 0.08	0.331 ± 0.012	0.328 ± 0.010	0.207 ± 0.012
		5	0.549 ± 0.049	1.26 ± 0.115	0.103 ± 0.009	0.065 ± 0.007
		6	0.216 ± 0.017	3.21 ± 0.255	0.035 ± 0.005	0.022 ± 0.003
^{240}Pu	0.0088 ± 0.0006	1	53.56 ± 1.21	0.0129 ± 0.0004	0.028 ± 0.003	0.022 ± 0.003
		2	22.14 ± 0.38	0.0313 ± 0.0005	0.273 ± 0.004	0.238 ± 0.016
		3	5.14 ± 0.42	0.135 ± 0.011	0.192 ± 0.053	0.162 ± 0.044
		4	2.08 ± 0.19	0.333 ± 0.031	0.350 ± 0.020	0.315 ± 0.027
		5	0.511 ± 0.077	1.36 ± 0.205	0.128 ± 0.018	0.119 ± 0.018
		6	0.172 ± 0.033	4.04 ± 0.782	0.029 ± 0.006	0.024 ± 0.005
^{232}Th	0.0496 ± 0.0020	1	56.03 ± 0.95	0.0124 ± 0.0002	0.034 ± 0.002	0.169 ± 0.012
		2	20.75 ± 0.66	0.0334 ± 0.0011	0.150 ± 0.005	0.744 ± 0.037
		3	5.74 ± 0.24	0.121 ± 0.005	0.155 ± 0.021	0.769 ± 0.108
		4	2.16 ± 0.08	0.321 ± 0.011	0.446 ± 0.015	2.212 ± 0.110
		5	0.571 ± 0.042	1.21 ± 0.090	0.172 ± 0.013	0.853 ± 0.073
		6	0.211 ± 0.019	3.29 ± 0.297	0.043 ± 0.006	0.213 ± 0.031

* Fast fission is defined as fission induced by a continuous neutron spectrum similar to a prompt fission neutron spectrum.

Table 1.3—Delayed-Neutron Fractions and Yields*†

Fission nuclide	Fast fission (E_{eff} ~ fission spectrum)			Thermal neutron induced fission		
	n/F	ν	β	n/F	ν	β
^{239}Pu	0.0063 ± 0.0003	3.08 ± 0.04	$0.0020_4 \pm 0.0001_1$	0.0061 ± 0.0003	$2.82_6 \pm 0.02_1$	0.0021[illegible] ± 0.0001_1
^{233}U	0.0070 ± 0.0004	2.61 ± 0.03	$0.0026_8 \pm 0.0001_6$	0.0066 ± 0.0003	$2.46_9 \pm 0.02_0$	$0.0026_7 \pm 0.0001_2$
^{240}Pu	0.0088 ± 0.0006	3.3 ± 0.2	$0.0026_6 \pm 0.0002_4$			
^{241}Pu				0.0154 ± 0.0015	3.14 ± 0.06	0.0049 ± 0.0005
^{235}U	0.0165 ± 0.0005	2.59 ± 0.03	$0.0063_7 \pm 0.0002_2$	0.0158 ± 0.0005	$2.43_0 \pm 0.001$	$0.0065_0 \pm 0.0002_1$
^{238}U	0.0412 ± 0.001	2.80 ± 0.13	0.0147 ± 0.0009			
^{232}Th	0.0496 ± 0.0020	2.42 ± 0.20	0.0205 ± 0.0019			

*From H. C. Paxton and G. R. Keepin, *The Technology of Nuclear Reactor Safety*, Vol. 1, p. 267, The M.I.T. Press, Cambridge, Mass., 1964.

†Symbols: n/F = delayed neutrons per fission; ν = average total neutrons per fission; β = n/Fν = fraction of total neutrons that are delayed.

1-3.4 The Inhour Equation

The basic kinetic equations, Eqs. 1.7 and 1.8, can be solved for constant k (e.g., following a step change in reactivity). The neutron density as a function of time is:

$$n = \sum_{j=1}^{m+1} A_j e^{\omega_j t} \qquad (1.10)$$

where the values of A_j are determined by the initial values (at $t = 0$) n_0 and C_{i0}, and where the values of ω_j are the m + 1 roots of the equation:

$$\rho = \frac{l\omega}{k} + \sum_{i=1}^{m} \frac{\omega\beta_i}{\omega + \lambda_i} \qquad (1.11)$$

The β_i and λ_i are the delayed neutron fractions and decay constants for the m groups of delayed-neutron emitters.

The roots of ω in Eq. 1.11 have the following properties: For ρ = constant > 0, m roots are negative and 1 is positive. The m negative roots are approximately $-\lambda_1$, $-\lambda_2, \ldots, -\lambda_m$, the decay constants of the delayed-neutron emitters. For ρ = constant < 0, all m + 1 roots are negative.

Thus, for constant positive values of the reactivity, the neutron density is the sum of one positive exponential and m negative exponentials. After an interval of time large compared to the delayed-neutron periods, the positive exponential remains

$$n = n_0 e^{\omega_0 t} = n_0 e^{t/T} \qquad (1.12)$$

The quantity T (= $1/\omega_0$) is the stable reactor period or asymptotic period, and $1/\omega_1$, $1/\omega_2$, ..., $1/\omega_m$ are the transient periods. Figure 1.1 shows the stable and transient periods vs. reactivity for ^{235}U with the prompt-neutron lifetime as a parameter. Note that for δk small and positive the stable period is independent of l (for $l \leqslant 10^{-3}$ sec); in fact, T is approximately $\bar{l}/\delta k$ where $\bar{l} = l + \tau_{av}$ and τ_{av} is the average decay period of the delayed-neutron emitters, $\tau_{av} = (1/\beta)\Sigma(\beta_i/\lambda_i)$. The quantity $\bar{l}$ is the effective neutron lifetime. Figure 1.1 also shows that for large δk the stable period is approximately $l/\delta k$.

The relation between the reactivity and the stable reactor period is obtained by substituting 1/T for ω_0 in Eq. 1.11,

$$\rho = \frac{l}{Tk} + \sum_{i=1}^{m} \frac{\beta_i}{1 + T\lambda_i} \qquad (1.13)$$

This is the inhour equation. Reactivity can be expressed in "inverse hours" or "inhours," where 1 inhour is defined as the amount of reactivity that makes the stable reactor period equal to 1 hr. Substituting T = 3600 sec and the values of β_i and λ_i from Table 1.1 and noting that $l/T \lessapprox 3 \times 10^{-6}$, we find the following:

1 inhour $\approx 2.4 \times 10^{-5}$ for a ^{235}U-fueled thermal reactor
$\approx 1 \times 10^{-5}$ for a ^{239}Pu-fueled thermal reactor
$\approx 1.4 \times 10^{-5}$ for a ^{233}U-fueled thermal reactor.

The inhour equation is shown graphically in Figs. 1.2, 1.3 and 1.4, where the reactivity is plotted against the stable period for various values of l and for various isotopes of uranium and plutonium.

1-3.5 Effects of Reactivity Insertions*

When a power reactor is operating in a steady state (constant coolant flow, constant temperatures, etc.), the effective multiplication factor is 1 and the reactivity is zero. If any of the basic parameters, such as coolant flow or temperature, are changed (e.g., to increase or decrease the power level or to compensate for changes in fuel reactivity), then reactivity must be added or subtracted. The most common situations are those in which the reactivity is inserted at a steady rate or as a step function.

Equations 1.7 and 1.8 can be solved for the case where the reactor is taken from delayed critical ($\rho = \delta k/k = 0$) to prompt critical ($\rho = \delta k/k = \beta$) by inserting reactivity at a constant rate (ramp insertion). Figure 1.5 shows how the relative neutron density, $n/n_0 = n(t)/n(0)$, increases with time for several reactivity insertion rates and for several values of the neutron lifetime. Table 1.4 presents similar data in tabular form.

In Fig. 1.6 the effect of inserting a step change in k is shown. The reactor is at delayed critical at t = 0.

1-3.6 Reactivity Changes

For curves, tables, and equations presented in the preceding sections, we assumed that the reactivity was only being altered by some control mechanism that "inserts reactivity." There are other ways that reactivity is altered in an operating power reactor. The most important are: (1) variation of fission-product concentrations, (2) burnup or depletion of fuel, and (3) variations in reactor temperatures, pressures, and densities.

An increase in the concentration of fission products reduces reactivity because the fission products absorb some of the neutrons that carry on the chain reaction. The

*The terminology "reactivity insertion," adding or subtracting reactivity, is used here because it is commonly considered proper language of the trade. More exactly, reactivity can be negative, positive, or zero at any operating instant, and adding reactivity could mean, for example, decreasing the negative reactivity toward zero as in startup or in going critical. If, during reactor operation, power is falling and we do not want it to, we say that we add reactivity. If the power is steady but low and we want to increase it, we again say that we add reactivity. If the power is high and we want to lower it, we say that we decrease reactivity, which more exactly means inserting negative reactivity to cause the power to fall. To level the power at a lower point, however, we again say that we add reactivity to compensate or return to a condition of zero reactivity.

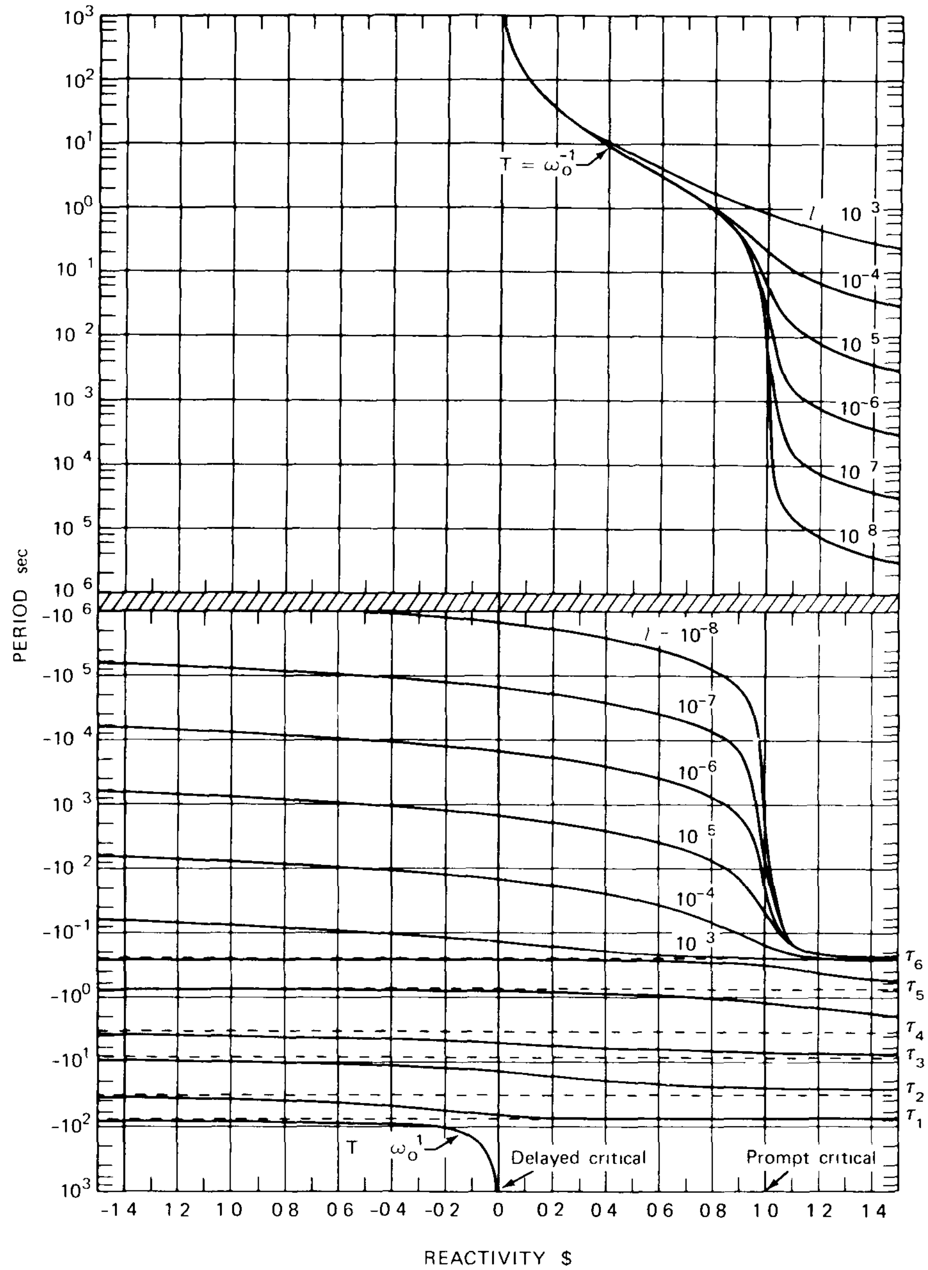

Fig 1.1—Reactor stable and transient periods vs reactivity for ^{235}U The broken lines are drawn at the delayed neutron mean lives ($\tau_1 = 1/\lambda_1, \tau_2, \ldots, \tau_6$) for ^{235}U The parameter l is the prompt neutron lifetime in seconds (From H C Paxton and G R Keepin, *The Technology of Nuclear Reactor Safety,* Vol 1, p 262, The M I T Press, Cambridge, Mass , 1964)

products of fission comprise a large variety of radioactive and stable nuclei whose relative concentrations in a reactor vary with time, power level, and prior operating history Two thermal-neutron absorbing fission products have strong effects on the reactivity of thermal reactors (the pressurized water reactors, the boiling-water reactors, and the gas-cooled reactors of Chaps 15, 16, and 18, respectively), namely, ^{135}Xe (a 9 2 hr beta emitter) and ^{149}Sm (a stable nuclide) Because both these nuclides are strong absorbers of thermal neutrons, they are referred to as fission-product poisons or simply poisons The absorption of thermal neutrons by ^{135}Xe is about 5000 times more probable, on an atom-for-atom basis, than the absorption of thermal neutrons by ^{235}U Similarly, ^{149}Sm absorbs thermal neutrons nearly 90 times as easily as ^{235}U In almost all present-day power reactors, the chain reaction is propagated almost entirely by thermal-neutron fission processes Consequently, the presence of thermal-neutron

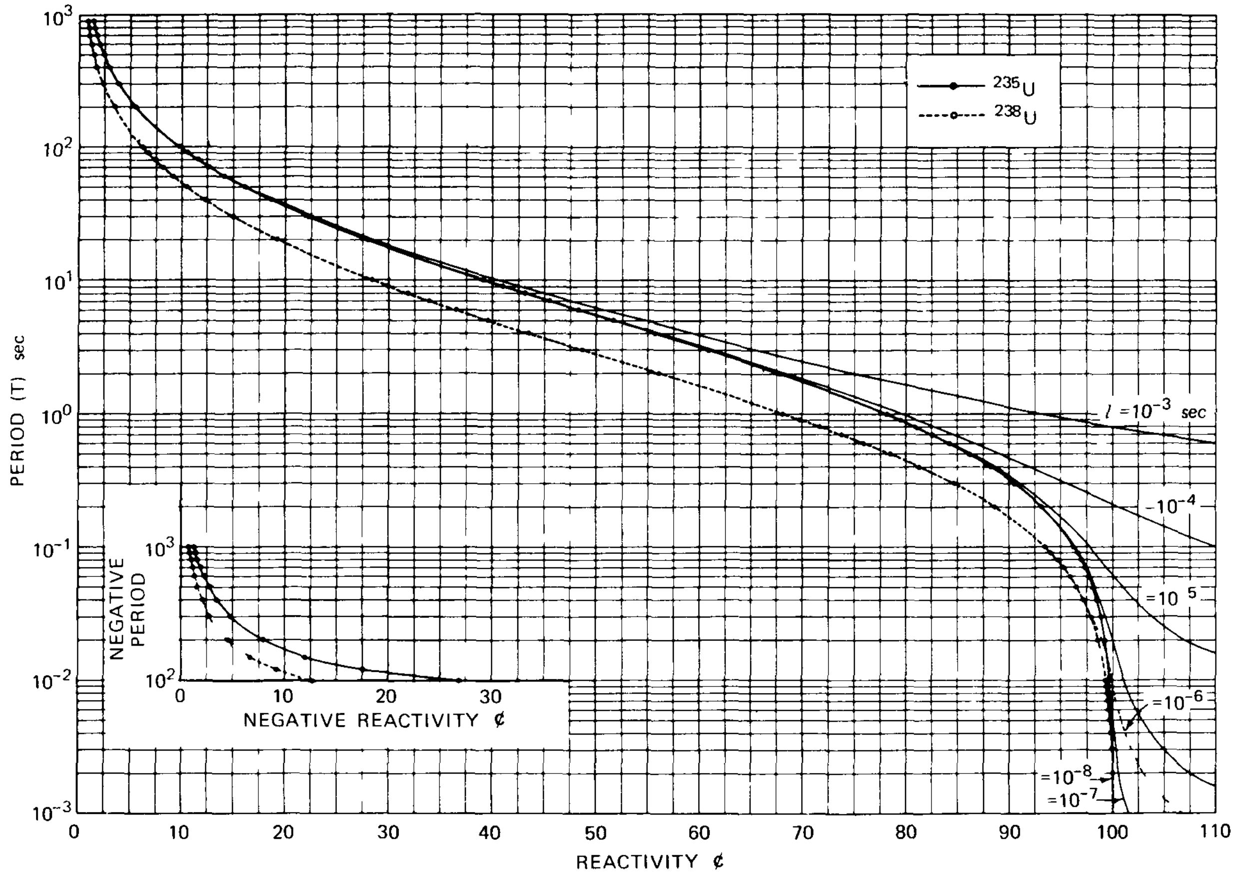

Fig. 1.2—Stable (asymptotic) period vs. reactivity for ^{235}U and ^{238}U. The parameter l is prompt neutron lifetime. Heavy curves are calculated from Laplace-transformed prompt burst decay data; corresponding points are calculated from delayed neutron periods and abundances. (From H. C. Paxton and G. R. Keepin, *The Technology of Nuclear Reactor Safety*, Vol. 1, p. 263, The M.I.T. Press, Cambridge, Mass., 1964.)

absorbers in the fuel reduces the reactivity of these reactors by absorbing neutrons that otherwise would be available to carry on the chain reaction.

In the following paragraphs the basic effects of these two fission products are briefly summarized. For details see Refs. 3, 5, and 7.

(a) Xenon-135.* In 6.1% of the fissions of ^{235}U (or 5.1% of ^{233}U fissions, or 5.5% of ^{239}Pu fissions), one of the fission fragments has a mass number of 135. It decays to stable ^{135}Ba in the following chain:

$$\text{Fission} \rightarrow {}^{135}\text{Te}(0.5\ \text{min}) \xrightarrow{\beta} {}^{135}\text{I}(6.7\ \text{hr})$$
$$\xrightarrow[0.3]{\beta} {}^{135}\text{Xe}(15.3\ \text{min})$$
$$\xrightarrow[\beta]{0.7} {}^{135}\text{Xe}(9.2\ \text{hr}) \xrightarrow{\beta} {}^{135}\text{Cs}(2.6 \times 10^{6}\ \text{yr})$$
$$\xrightarrow{\beta} {}^{135}\text{Ba(stable)}$$

Because of the short half life of ^{135}Te, the above decay scheme can be simplified for most purposes to

$$\text{Fission} \rightarrow {}^{135}\text{I}(6.7\ \text{hr}) \xrightarrow{\beta} {}^{135}\text{Xe}(9.2\ \text{hr}) \xrightarrow{\beta} {}^{135}\text{Cs}$$

In addition to being produced via the above chain, ^{135}Xe is produced directly in 0.3% of the fissions of ^{235}U.

The rate of change in the concentration of ^{135}Xe is the difference between its production rate (per cm^3) and its loss (per cm^3). It is produced from the decay of ^{135}I and directly from the fission process. It is lost by decay to ^{135}Cs and by neutron absorption to ^{136}Xe(stable). The equation is thus

$$\frac{dX}{dt} = (\lambda_I I + Y_X \Sigma_f \phi) - \lambda_X X - \sigma_X X \phi \qquad (1.14)$$

where X = ^{135}Xe concentration (nuclei/cm^3)

I = ^{135}I concentration (nuclei/cm^3)

λ_X = ^{135}Xe decay constant (fractional change in concentration attributable to beta decay) = $0.693/9.2\ \text{hr} = 2.1 \times 10^{-5}$/sec

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*Numerical values used in this section are from Ref. 7.

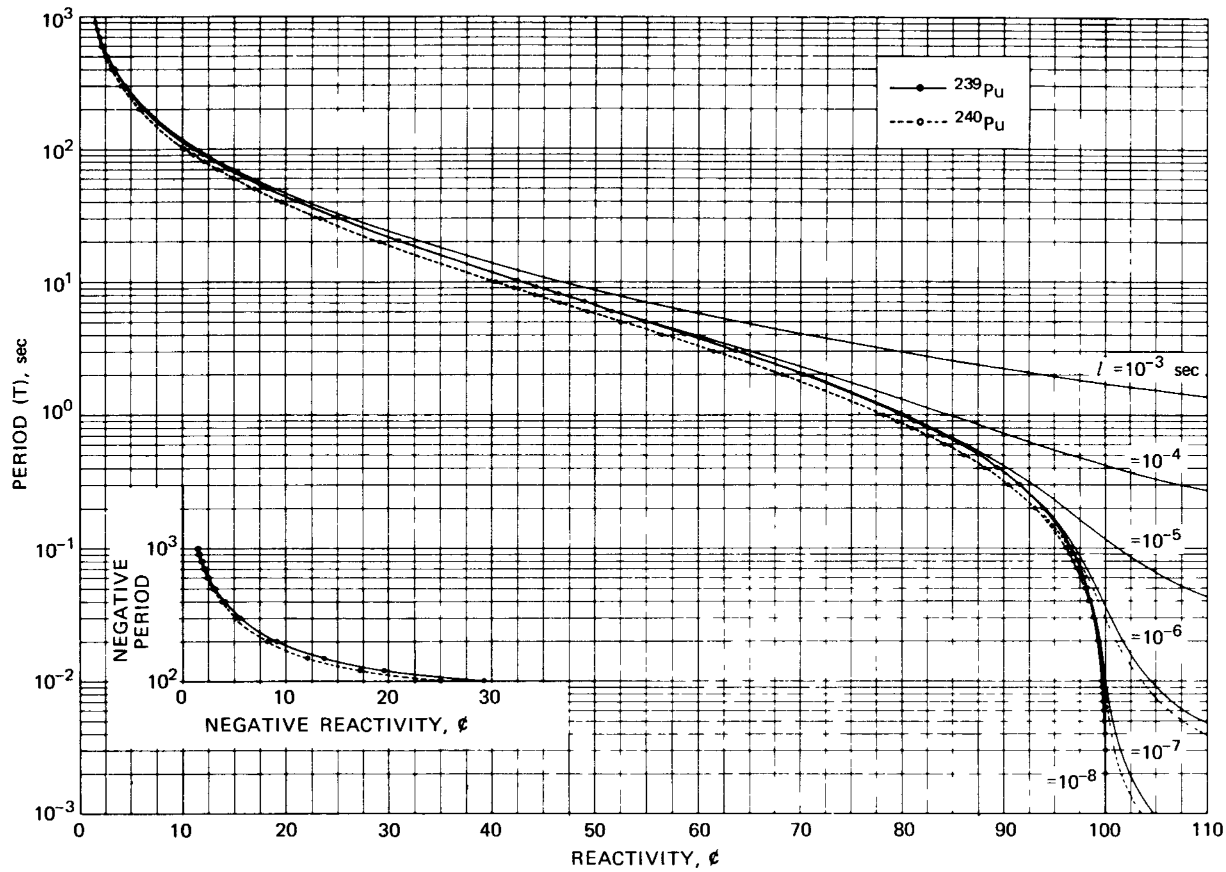

Fig. 1.3—Stable (asymptotic) period vs. reactivity for ^{239}Pu and ^{240}Pu. See caption for Fig. 1.2. (From H. C. Paxton and G. R. Keepin, *The Technology of Nuclear Reactor Safety*, Vol. 1, p. 264, The M.I.T. Press, Cambridge, Mass., 1964.)

λ_I = ^{135}I decay constant (fractional change in concentration attributable to beta decay) = 0.693/6.7 hr = 2.9×10^{-5}/sec

ϕ = thermal-neutron flux (neutrons cm^{-2} sec^{-1})

σ_X = microscopic thermal-neutron-capture cross section of ^{135}Xe = 3.5×10^{-18} cm^2

Σ_f = macroscopic thermal-neutron-fission cross section of fuel = concentration of fuel (nuclei/cm^3) times the microscopic thermal-neutron-fission cross section

Y_X = fractional yield of ^{135}Xe directly from fission

The quantity $\lambda_I I$ can be determined by considering the rate of change in the ^{135}I concentration. The ^{135}I is produced from the decay of ^{135}Te, which, in turn, is produced directly from the fission process. Since the ^{135}Te is so short-lived, it is valid to consider the ^{135}I as produced directly from fission. In this case the equation for the ^{135}I concentration is

$$\frac{dI}{dt} = Y_{Te}\Sigma_f\phi - \lambda_I I - \sigma_I I \phi \qquad (1.15)$$

where Y_{Te} is the yield of ^{135}Te (6.1% for ^{235}U fission, etc.). The final term is the loss of ^{135}I because of neutron capture ($\sigma_I \ll \sigma_X$).

Equations 1.14 and 1.15 can be solved for various initial (t = 0) conditions and for various values of the thermal-neutron flux. One important solution is the equilibrium concentration of ^{135}Xe. The last term of Eq. 1.15 can be neglected; so $\lambda_I I \cong Y_{Te}\Sigma_f\phi$ at equilibrium conditions, and

$$\frac{dX}{dt} = 0 = Y_{Te}\Sigma_f\phi + Y_X\Sigma_f\phi - \lambda_X X - \sigma_X X\phi$$

Solving for X yields

$$X_{eq} = \frac{Y\Sigma_f\phi}{\lambda_X + \sigma_X\phi} \qquad (1.16)$$

where Y is $Y_X + Y_{Te}$, the total fractional yield of ^{135}Xe per fission (i.e., the yield via the ^{135}Te chain and the direct yield). Equation 1.16 shows that, as the thermal-neutron flux is reduced, the equilibrium concentration of ^{135}Xe becomes proportional to the flux; for high thermal-neu-

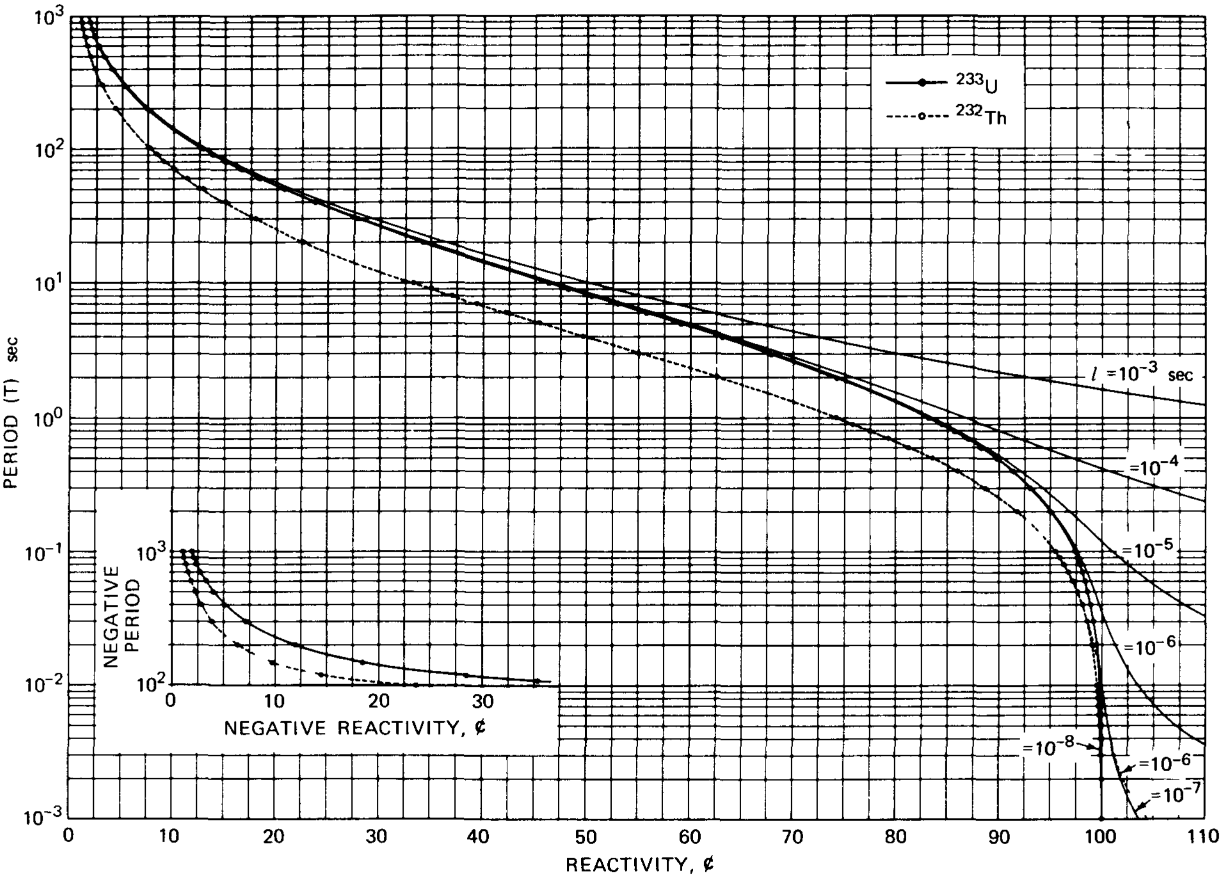

Fig. 1.4—Stable (asymptotic) period vs reactivity for ^{233}U and ^{232}Th See caption for Fig 1 2 (From H C Paxton and G R Keepin *The Technology of Nuclear Reactor Safety* Vol 1, p 265, The M I T Press, Cambridge, Mass , 1964)

tron-flux values, the equilibrium concentration of ^{135}Xe becomes independent of the flux

$$X_{eq} \approx Y\Sigma_f/\sigma_X \qquad (\text{for } \phi \gg \lambda_X/\sigma_X)$$

$$X_{eq} \approx (Y\Sigma_f/\lambda_X)\phi \qquad (\text{for } \phi \ll \lambda_X/\sigma_X) \qquad (1\ 17)$$

The effect of the ^{135}Xe concentration on the control and operation of a nuclear power reactor is determined by how large the absorption of neutrons by ^{135}Xe is relative to the absorption of neutrons by the nuclear fuel This determines the degree that the ^{135}Xe interferes with the chain reaction The ratio of macroscopic thermal neutron-absorption cross sections is defined

$$\text{Poisoning} = P(t) = \frac{\text{macroscopic neut abs cross section of } ^{135}\text{Xe}}{\text{macroscopic neut abs cross section of the fuel}} = \frac{X\sigma_X}{N_u\sigma_a} \qquad (1\ 18)$$

where N_u is the number of fuel nuclei/cm^3 and σ_a is the thermal-neutron-absorption cross section for the fuel The poisoning, when the ^{135}Xe concentration is the equilibrium concentration, is obtained by substituting Eq 1 16 into Eq 1 18 and noting that $\Sigma_f/N_u\sigma_a = N_u\sigma_f/N_u\sigma_a$ = the ratio of the fission to absorption cross sections for the fuel

$$P(t_{eq}) = \frac{Y(\sigma_f/\sigma_a)\phi}{\lambda_X + \sigma_X\phi} \qquad (1\ 19)$$

Equation 1 19 is plotted in Fig 1.7 for ^{235}U fuel Values of λ_X and σ_X are given following Eq 1.14. The total yield is Y = 0 064 and σ_f/σ_a = 580 barns/685 barns = 0 85 The figure shows the equilibrium poisoning to be linear with the neutron flux when $\phi \lesssim 10^{12}$ neutrons cm^{-2} sec^{-1} (see Eq 1 17) and to approach a constant for high flux values

It can be shown (e g , Ref 3, p 334) that the poisoning defined in Eq 1 18 is approximately equal to the reduction in reactivity in a thermal reactor attributable to fission-product poisoning

$$\text{Change in reactivity} = \delta k/k \approx -P(t) \qquad (1.20)$$

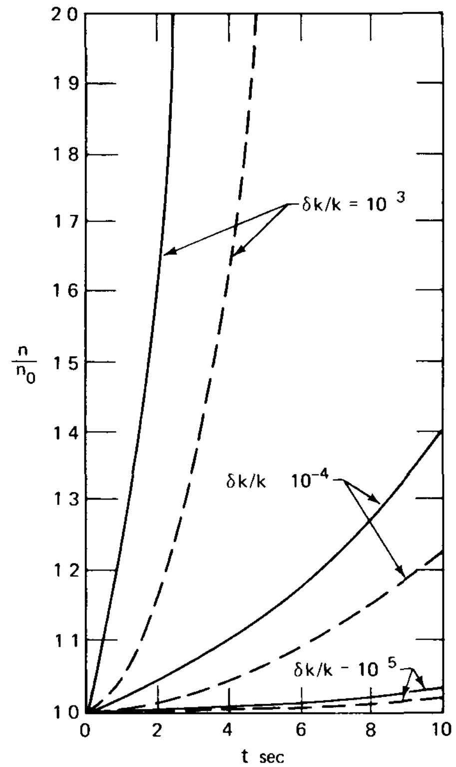

Fig. 1.5—Relative neutron density n/n_0, vs time for reactivity insertion rates of 10 3, 10 4 and 10 5 δk/k per second for ^{235}U Solid curve is for neutron lifetime of 10 6 sec, broken curve is for 10 2 sec (From J M Harrer, *Nuclear Reactor Control Engineering,* p 92, D Van Nostrand Company, Inc , Princeton, N J 1963)

To keep a reactor operating at steady state (k = 1), sufficient reactivity must be added, e g , by withdrawing control rods, to compensate for (or override) the reduction in reactivity caused by the fission products in the fuel Thus, for example, in a ^{235}U-fueled thermal power reactor that is operating at k = 1 with a thermal-neutron flux at the fuel position of 5×10^{13} neutrons cm^{-2} sec^{-1}, the reactivity that must be added to compensate for the effect of the equilibrium concentration of ^{135}Xe is about σk/k = 0 049 (see Fig 1 7)

The effect of ^{135}Xe poisoning is most pronounced when a reactor is shut down after it has been operating at full power for a time sufficiently long that the equilibrium concentration of ^{135}Xe (Eq 1 16) is present In this case the xenon concentration increases considerably above its equilibrium value since it is no longer being removed by thermal neutron capture The ^{135}Xe is being produced by the decay of the equilibrium concentration of ^{135}I (6 3 hr) and being lost by its own 9 2 hr beta decay The net result is shown in Fig 1 8, where the poisoning is plotted as a function of time after shutdown from equilibrium for several values of the thermal neutron flux The t = 0 values of Fig 1 8 are obtained from the equilibrium curve shown in Fig 1 7 The ^{135}Xe poisoning builds up to a maximum after shutdown For low values of the flux, the time to reach maximum poisoning is only a few hours For the higher flux values normally encountered in power-reactor operation, the poisoning reaches a maximum about 10 hr after shutdown The value of the poisoning does not return to its preshutdown value until 30 or 40 hr after shutdown

Table 1 4—Relative Neutron Density (n/n_0) as a Function of Time During Ramp Insertions of 10 3, 10 4, and 10 5 δk/k Per Second*

Time, sec	(δk/k)/sec ramp	^{233}U		^{235}U		^{239}Pu	
		l = 10 2	*l* = 10 6	*l* = 10 2	*l* = 10 6	*l* = 10 2	*l* = 10 6
0 5	A = 10 3	1 012	1 254	1 011	1 092	1 012	~1 35
	10 4	1 001	1 021	1 001	1 009	1 001	1 026
	10 5	1 0001	1 002	1 0001	1 0009	1 0001	1 003
1 0	A = 10 3	1 047	1 723	1 042	1 218	1 048	2 112
	10 4	1 005	1 045	1 004	1 018	1 005	1 057
	10 5	1 0005	1 004	1 0004	1 002	1 0005	1 005
							(1 4 = 3 84)
1 5	A = 10 3	1 106	2 768	1 090	1 388	1 108	(1 6 = 6 16)
	10 4	1 010	1 071	1 009	1 029	1 010	1 093
	10 5	1 001	1 007	1 0009	1 003	1 001	1 009
2 0	A = 10 3	1 189	6 350	1 156	1 626	1 195	62 5
	10 4	1 017	1 101	1 014	1 041	1 018	1 133
	10 5	1 002	1 009	1 001	1 004	1 002	1 012
5 0	A = 10 3	2 644	3 0 sec = 3 7 x 10^{37}	2 069	15 9	2 792	2 5 sec = 7 7 x 10^{37}
	10 4	1 096	1 358	1 069	1 137	1 103	1 517
	10 5	1 009	1 028	1 007	1 012	1 010	1 037
10 0	A = 10 3	46 5	∞	15 7	6 8 sec = 1 4 x 10^{18}	59 0	∞
	10 4	1 366	2 401	1 229	1 406	1 411	3 675
	10 5	1 031	1 069	1 020	1 031	1 034	1 094

*From J M Harrer, *Nuclear Reactor Control Engineering* p 91, D Van Nostrand Company, Inc , Princeton, N J 1963

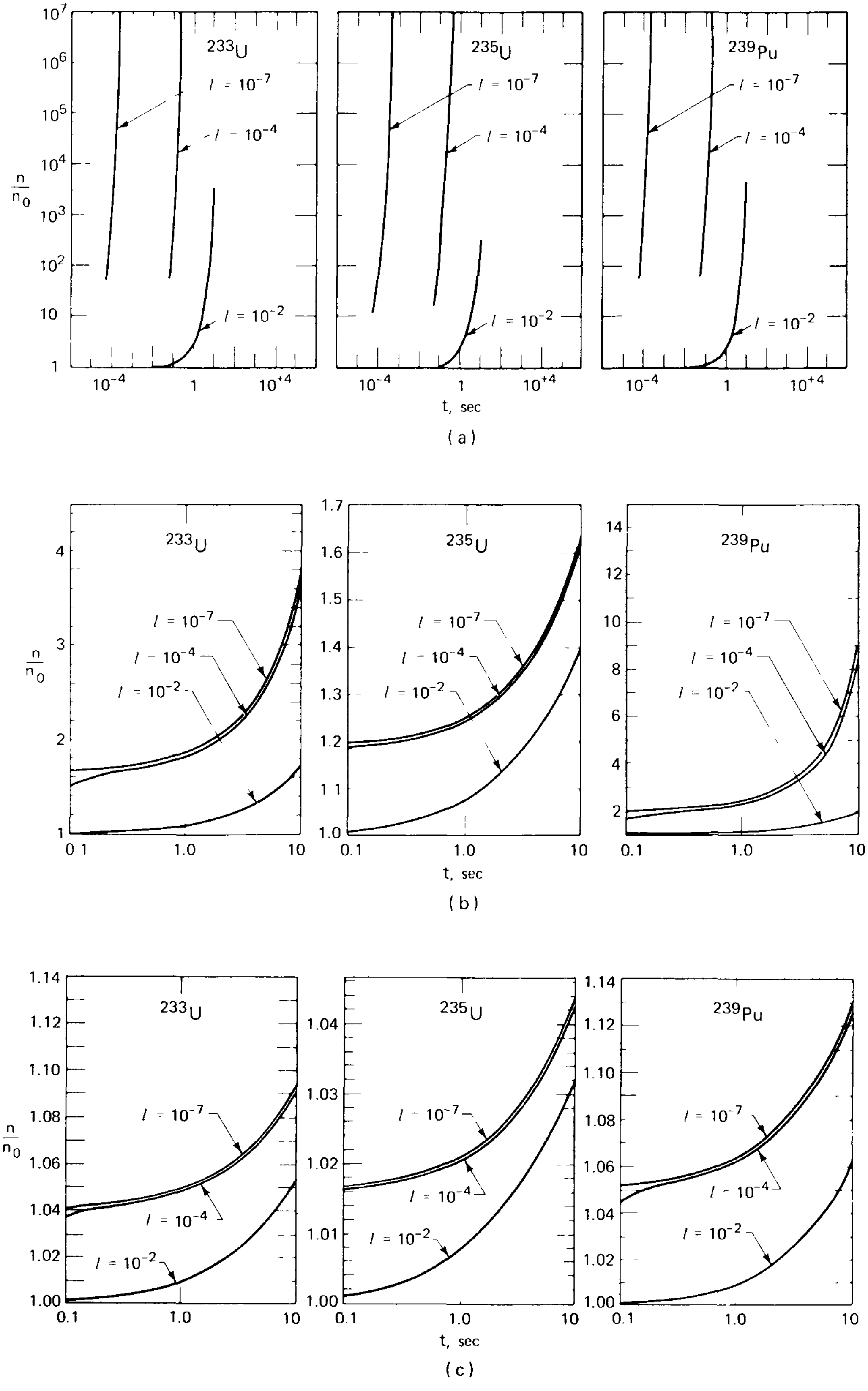

Fig. 1.6—Relative neutron density, n/n_0, vs. time for step insertions of (a) 10^{-2} $\delta k/k$; (b) 10^{-3} $\delta k/k$; and (c) 10^{-4} $\delta k/k$ starting at delayed critical in ^{233}U, ^{235}U, and ^{239}Pu. (From J. M. Harrer, *Nuclear Reactor Control Engineering*, pp. 88 and 89, D. Van Nostrand Company, Inc., Princeton, N. J., 1963.)

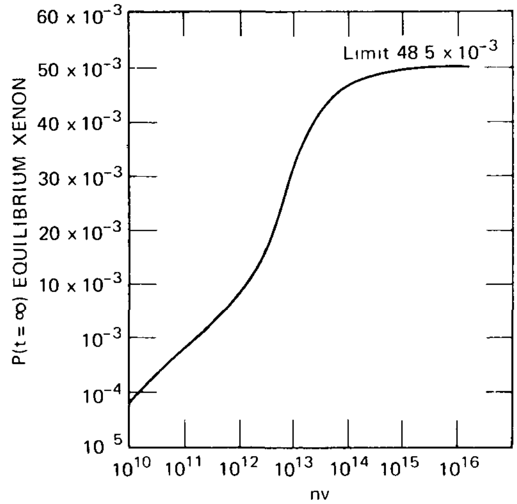

Fig. 1.7—Poisoning P(t), vs thermal neutron flux for equilibrium ^{135}Xe concentration in ^{235}U (From J M Harrer *Nuclear Reactor Control Engineering* p 393, D Van Nostrand Company, Inc, Princeton, N J, 1963)

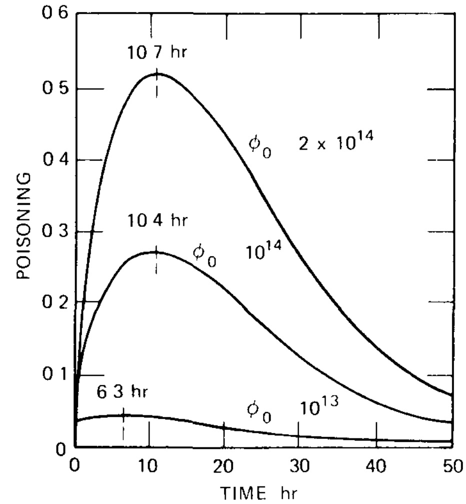

Fig. 1 8—Poisoning vs time for various thermal neutron flux values, assuming equilibrium concentration of ^{135}Xe at t = 0 (From J M Harrer, *Nuclear Reactor Control Engineering* p 394, D Van Nostrand Company, Inc Princeton, N J 1963)

As Fig 1 8 shows, the value of the poisoning at maximum can be many times the equilibrium (before shutdown) value The excess reactivity required to overcome the maximum poisoning may be more than is available in power reactor, particularly if the fuel has been depleted by prior operation If this is the case, then the reactor shutdown time has to be limited to less than a few hours or more than 30 or 40 hr must be allowed

The full shutdown from equilibrium shown in Fig 1 8 is not the only situation of practical interest Often the power level is cut back or increased by some fraction of full power Initially the ^{135}Xe concentration has a value corresponding to the initial power level, after the change in power level, the ^{135}Xe concentration changes until it reaches a new equilibrium value corresponding to the final power level Figures 1 9 and 1 10 show the time to reach the maximum poisoning following a step decrease or a step increase of the thermal-neutron flux (which is directly proportional to the reactor power level) Figure 1 9 shows, for example, that a 50% cutback from 4×10^{13} neutrons cm^{-2} sec^{-1} creates a maximum ^{135}Xe poisoning about 23,000 sec (6 4 hr) after the cutback In the reverse process, Fig 1 10 shows that when the flux level is doubled from 2×10^{13} neutrons cm^{-2} sec^{-1}, the maximum ^{135}Xe poisoning effect occurs about 11,600 sec (3 2 hr) after the increase From the initial values of the neutron flux, the initial equilibrium concentration of ^{135}Xe and ^{135}I, and the value at the time the maximum effect occurs, the maximum poisoning or maximum reduction in $\delta k/k$ can be calculated

(b) Samarium-149 * In 1 13% of the fissions of ^{235}U (or 0 66% of ^{233}U fissions, or 1 9% of ^{239}Pu fissions), one of the fission fragments has a mass number 149 Some of the fissions form ^{149}Pm and others form ^{149}Nd

$$\text{Fission} \rightarrow {}^{149}\text{Pm}(54\text{ hr}) \xrightarrow{\beta} {}^{149}\text{Sm(stable)}$$

$$\text{Fission} \rightarrow {}^{149}\text{Nd}(2\text{ hr}) \xrightarrow{\beta} {}^{149}\text{Pm}(54\text{ hr})\ {}^{149}\text{Sm(stable)}$$

Because the ^{149}Nd half-life is small compared to the ^{149}Pm half life, the first chain above is a good approximation for both chains As noted earlier, ^{149}Sm strongly absorbs thermal neutrons The other nuclides in the chain are not anomalous in this respect

The rate of change of the ^{149}Sm concentration is just equal to its production rate from ^{149}Pm decay minus its rate of loss from thermal neutron capture (which converts it to stable ^{150}Sm)

$$\frac{d(Sm)}{dt} = \lambda_{Pm}\ (Pm) - (Sm)\sigma_{Sm}\phi \qquad (1\ 21)$$

where (Pm) and (Sm) are the concentrations of ^{149}Pm and ^{149}Sm, respectively, λ_{Pm} is the decay constant of $^{149}Pm = 3\ 56 \times 10^{-6}$/sec, σ_{Sm} is the thermal-neutron-capture cross section of ^{149}Sm = 50,000 barns = 5×10^{-20} cm^2, and ϕ is the thermal neutron flux (neutrons cm^{-2} sec^{-1}) Note that, unlike ^{135}Xe, the ^{149}Sm is removed only when it captures thermal neutrons The rate of change of ^{149}Pm is its production rate from fission (neglecting the intermediate ^{149}Nd) minus its loss by beta decay (loss by neutron capture is negligible)

$$\frac{d(Pm)}{dt} = Y_{Pm}\phi\Sigma_f - \lambda_{Pm}\ (Pm) \qquad (1\ 22)$$

where (Pm) is the concentration (atoms/cm^3) of ^{149}Pm, Y_{Pm} is the yield of ^{149}Pm in fission, and Σ_f is the macroscopic thermal-neutron-fission cross section of the nuclear fuel

*Numerical data used in this section are from Ref 7

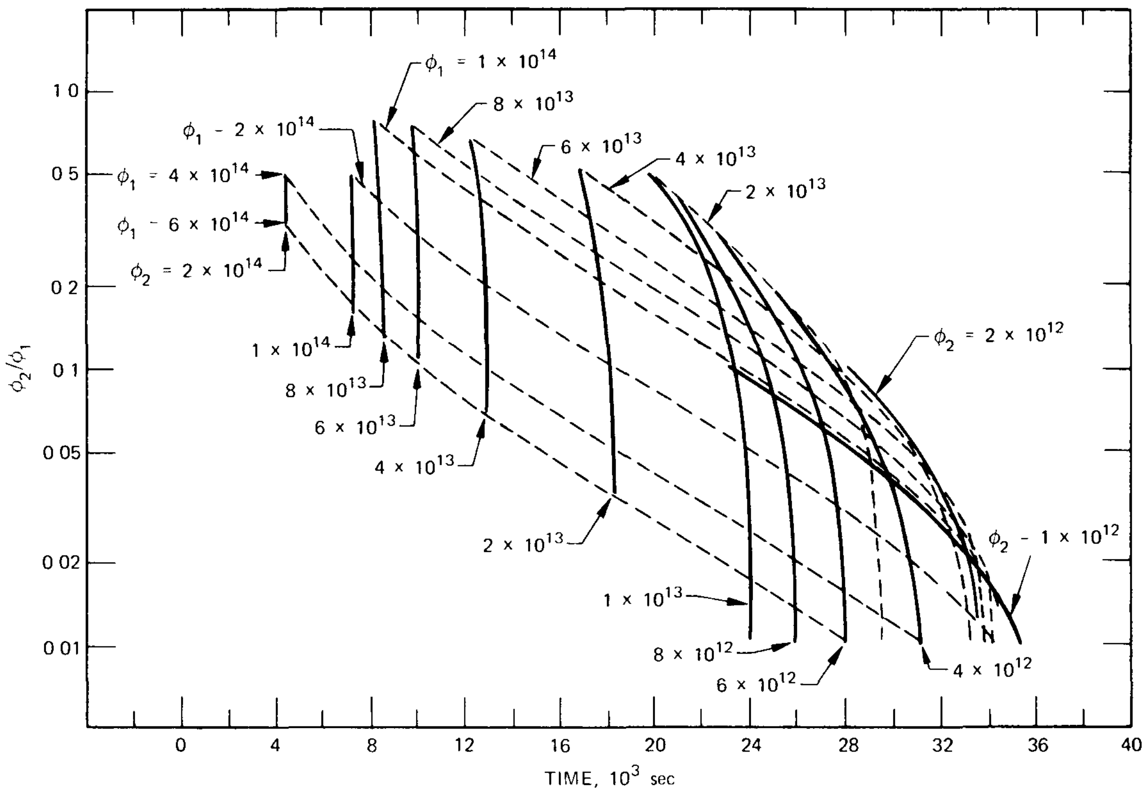

Fig. 1.9—Time to reach maximum xenon poisoning after a decrease of thermal-neutron flux from ϕ_1 to ϕ_2.[7]

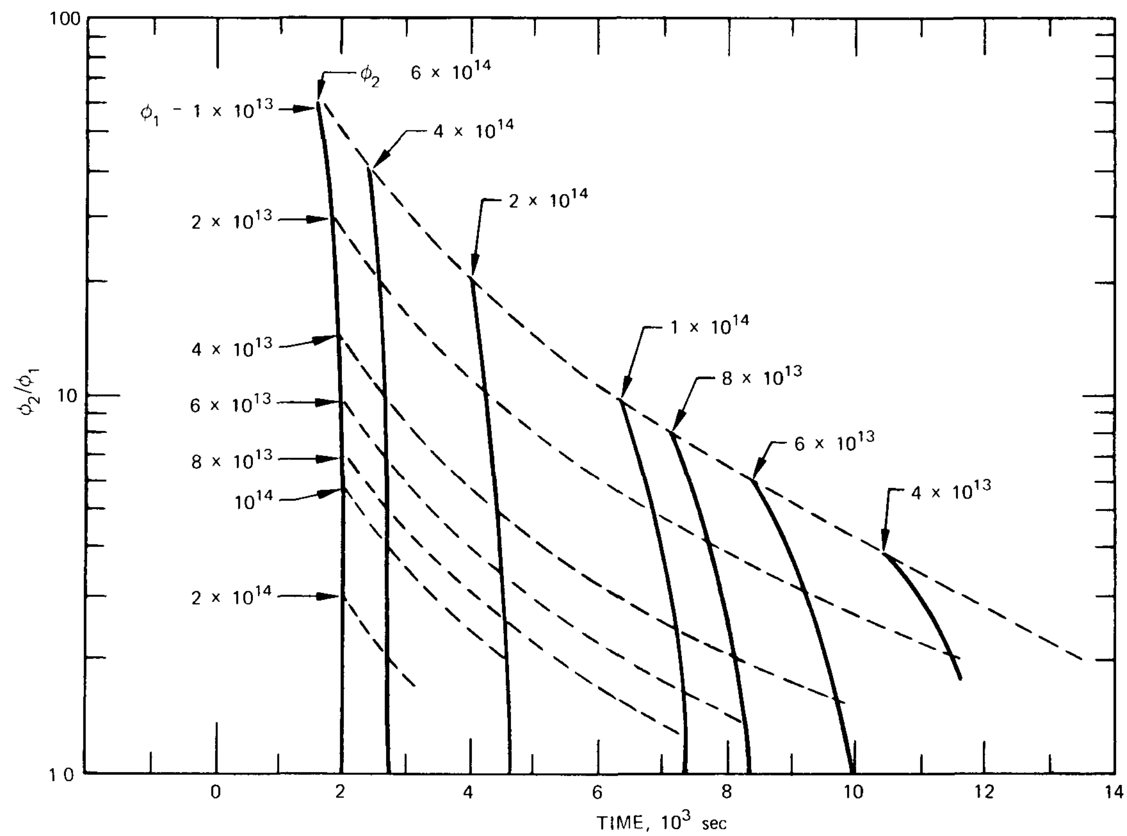

Fig. 1.10—Time to reach maximum xenon poisoning after an increase of thermal-neutron flux from ϕ_1 to ϕ_2.[7]

When a power reactor has been operating at a steady state ($k = 1$) for many hours, the equilibrium concentrations of ^{149}Pm and ^{149}Sm (from Eqs. 1.21 and 1.22) are

$$(Pm)_{eq} = \frac{Y_{Pm}\phi\Sigma_f}{\lambda_{Pm}}$$

$$(Sm)_{eq} = \frac{\lambda_{Pm}(Pm)_{eq}}{\sigma_{Sm}\phi} = \frac{Y_{Pm}\Sigma_f}{\sigma_{Sm}} \qquad (1\ 23)$$

Note that the equilibrium concentration of ^{149}Pm is proportional to the thermal-neutron flux, ϕ, while the equilibrium concentration of ^{149}Sm is independent of the flux.

The equilibrium ^{149}Sm poisoning (Eq 1.18) is

$P(t_{eq})$ = poisoning of ^{149}Sm at equilibrium concentration

$$= \frac{(Sm)_{eq}\sigma_{Sm}}{N_u\sigma_a} = \frac{Y_{Pm}\Sigma_f\sigma_{Sm}}{N_u\sigma_a\sigma_{Sm}} = Y_{Pm}\left(\frac{\sigma_f}{\sigma_a}\right) \qquad (1\ 24)$$

which is also independent of the thermal-neutron flux Substituting into Eq. 1.24 the values of the yields and the fission/absorption cross section ratios gives

	^{235}U	^{233}U	^{239}Pu
Y_{Pm}	0.0113	0.0066	0.019
σ_f/σ_a	580/685	524/593	860/1220
$P(t_{eq})$ for ^{149}Sm	0.0096	0.0058	0.077

These correspond approximately to $\delta k/k$ values of -0.96% for ^{235}U, $-0\ 58\%$ for ^{233}U, and -7.7% for ^{239}Pu Comparison of the equilibrium value of ^{149}Sm poisoning in ^{235}U-fueled reactors with the equilibrium values of ^{135}Xe poisoning (Fig. 1.7) shows the former to be only about one-fourth of the latter.

When a power reactor that has been operating at steady state ($k = 1$) for some hours is shut down, the concentration of ^{149}Sm increases from its initial ($t = 0$) value by the creation of ^{149}Sm from ^{149}Pm decay

^{149}Sm conc. after shutdown

$$= {}^{149}Sm \text{ conc. at shutdown} + (1 - e^{-\lambda_{Pm}t}) \times {}^{149}Pm \text{ conc. at shutdown} \qquad (1\ 25)$$

Since the half-life of ^{149}Pm is 54 hr, the ^{149}Sm concentration is increased by one-half the ^{149}Pm shutdown concentration during the first 54 hr after shutdown After a few hundred hours the ^{149}Sm concentration is equal to the sum of the ^{149}Sm concentration at shutdown and the ^{149}Pm concentration at shutdown.

When a power reactor has been operating at a steady state ($k = 1$) and at constant flux for a few hundred hours, both the ^{149}Pm and ^{149}Sm concentrations have their equilibrium values (Eq 1.23). If the reactor is then (at $t = 0$) shut down, the ^{149}Sm concentration builds up according to Eq. 1.25. Substitution of the equilibrium concentrations into Eq. 1.25 gives

^{149}Sm conc. after shutdown from equilibrium

$$= (Sm)_{eq}\ [1 + (\phi\sigma_{Sm}/\lambda_{Pm})(1 - e^{-\lambda_{Pm}t})]$$

$$= (Sm)_{eq}\ [1 + 1.40 \times 10^{-14}\phi \times (1 - e^{-\lambda_{Pm}t})] \qquad (1.26)$$

where ϕ is the thermal-neutron flux in neutrons $cm^{-2}\ sec^{-1}$ and λ_{Pm} is the disintegration constant of ^{149}Pm ($= 3\ 56 \times 10^{-6}$/sec $= 0.693/54$ hr). It is apparent that the poisoning effect of ^{149}Sm becomes quite important in high flux operation A shutdown from operation at a flux of 10^{14} can increase the poisoning effect by a factor of $1 + 1.40$, or 2 40 times the equilibrium poisoning (Eq. 1.24), if the shutdown continues for a few hundred hours. Sufficient excess $\delta k/k$ must be available to compensate for this poisoning when the reactor is started up.

(c) Fuel Burnup. During the operation of a nuclear power reactor, fuel (^{235}U, ^{233}U, or ^{239}Pu) is continually being burned up (i e., fissioned) so the remaining fuel becomes depleted in the fissionable nuclide. The effect of this burnup, or depletion, is to reduce the reactivity available to compensate for fission-product poisoning or for other reactivity-reducing effects Eventually the depletion becomes intolerable, and the reactor has to be refueled

At a point in the reactor fuel where the thermal-neutron flux is ϕ, the absorption of neutrons decreases the concentration of fissile material (^{235}U, ^{233}U, or ^{239}Pu) exponentially with time

Fuel conc at time t

$$= (\text{Fuel conc at } t = 0) \exp\left(-\sigma_a \int_0^t \phi\, dt\right) \qquad (1\ 27)$$

where σ_a is the neutron absorption cross section of the fissile material The neutron flux is assumed to vary with time (For convenience the integral can be written as $\phi_{av}\, t$, where ϕ_{av} is the average flux during the time from $t = 0$ to $t = t$)

The fractional burnup is defined as the change in fuel concentration divided by the initial concentration. From Eq 1.27 it follows that

$$\text{Fractional burnup} = F = 1 - e^{-\sigma_a\phi_{av}t} \qquad (1\ 28)$$

As an example, the fractional burnup of ^{235}U in three months (7.8×10^6 sec) in a power reactor with an average thermal-neutron flux at the fuel of 5×10^{13} neutrons $cm^{-2}\ sec^{-1}$ is $1 - \exp\ [(-685\ \text{barns})(5 \times 10^{13})(7\ 8 \times 10^6\ cm^{-2})] = 1 - \exp\ (-0\ 267)$, or 0 234, i.e , a fractional burnup of 23.4%.

Figure 1-11 shows the relation between the fractional burnup of fuel and the resulting loss in reactivity $\delta k/k$. For a 23.4% burnup, the loss in reactivity is about 2.7%. This is to be compared with the reactivity loss of 4.9% (see discussion after Eq. 1-20) attributable to equilibrium xenon poisoning at the same average neutron flux and the 1% (see discussion after Eq. 1-24) loss in reactivity from samarium poisoning.

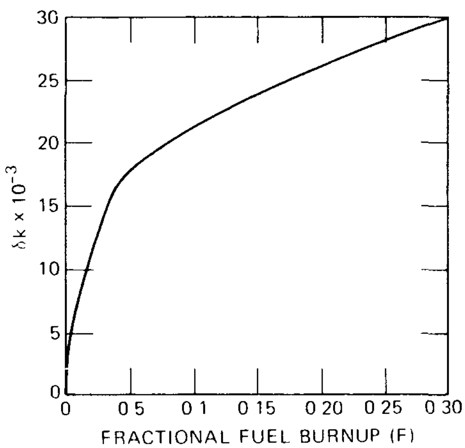

Fig. 1-11 — Poisoning as function of fractional fuel burnup. (From J. M. Harrer, *Nuclear Reactor Control Engineering*, p. 399, D. Van Nostrand Company, Inc., Princeton, N. J., 1963.)

In any actual power reactor, calculations of burnup must take into account many factors not considered in the foregoing. These include the presence of fertile material (^{238}U or ^{232}Th) in the fuel, the energy and spatial distributions of neutron flux, the geometry and composition of the fuel elements, and the operating history of the reactor. The data presented here are intended to provide a semi-quantitative indication of the effect of fuel depletion on the reactivity that is needed for instrumentation system design.

1-3.7 Three-Dimensional Kinetics

The reactor kinetics equations derived in Section 1-3.2 are labeled "point" kinetics since the neutron density, n, was considered only as a function of time. Actually, n should be written as n(x,y,z,t) to emphasize its spatial dependence. Similarly, the density of delayed-neutron emitters should be written $C_i(x,y,z,t)$, and each of the fission-product concentrations should be written as functions of x,y,z,t. The spatial dependence of the neutron flux depends on many factors, such as fuel loading, primary-coolant-system structure, and reactor-vessel penetrations. It also depends on the past history of the individual fuel elements.

Since the neutron flux in the fuel determines the heat generated, it follows that knowledge of the spatial distribution of the flux is necessary if the reactor is to be used safely and efficiently as a heat source. Instrumentation systems must be included to provide this knowledge to the operator.

If the neutron flux is not constant throughout the reactor, then the kinetics of the chain reaction is not the same in all parts of the reactor. The preceding section shows that many reactivity effects are flux-dependent. For example, if a reactor is operating with the neutron flux less in one region of the reactor than in another region, then the equilibrium concentrations of the fission-product poisons in the two regions will not be the same, nor (if the reactor has run this way for any length of time) will the fuel burnup be the same in the two regions.

Nonuniform spatial distribution of neutron flux can lead to self-induced oscillations of the flux level, the so-called xenon instability or flux tilt. The oscillations result from the fact that regions with different neutron-flux levels have different equilibrium ^{135}Xe concentrations (Eq. 1-16). If the flux is increased in a region where it has been low, then the increased flux reduces the ^{135}Xe concentration (since more is removed by neutron capture) and, thereby, the poisoning. The reduction in ^{135}Xe is not offset immediately by ^{135}I decay since the ^{135}I concentration has been set by the previous (lower) flux level. The net result is that the flux tends to keep on increasing. On the other hand, in regions where the flux has been high, a decrease in flux tends to increase the ^{135}Xe (fewer are removed by neutron capture), again with no immediate compensation by decreased ^{135}I. The tendency of the increasing flux to keep on increasing and the decreasing flux to keep on decreasing is eventually reversed by the ^{135}I decay—the peaking of the xenon poisoning shown in Fig. 1-8. The net result is an oscillation in ^{135}Xe poisoning between the regions of the reactor with a period given by

$$\text{Period of xenon oscillation} = \frac{2\pi}{[\lambda_I(\lambda_X + \sigma_X\phi)]^{1/2}} \qquad (1\text{-}29)$$

where λ_I = disintegration constant of ^{135}I (2.9×10^{-5}/sec)

λ_X = disintegration constant of ^{135}Xe (2.1×10^{-5}/sec)

σ_X = microscopic thermal-neutron cross section of ^{135}Xe

ϕ = thermal-neutron flux

If the flux is 5×10^{13} neutrons cm^{-2} sec^{-1}, the period of the oscillation is 23 hr, somewhat longer than either the ^{135}I half-life (6.7 hr) or the ^{135}Xe half-life (9.2 hr). As the flux is lowered, the period of the xenon oscillation

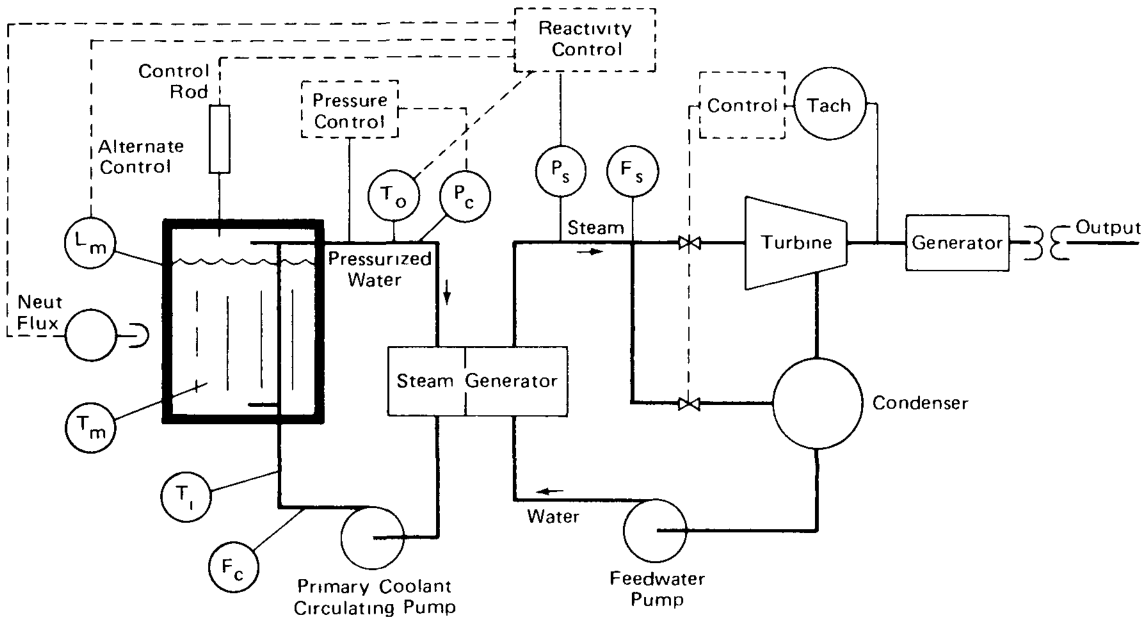

Fig. 1.12—Pressurized water reactor (From A. Pearson and C.G. Lennox, *The Technology of Nuclear Reactor Safety*, Vol 1, p 288, The M.I.T. Press, Cambridge, Mass, 1964.)

approaches 70 hr, at 10^{14} neutrons cm^{-2} sec^{-1}, it is about 17 hr.

The possibility of such flux oscillations must be taken into account in designing the reactor control system. The possibility of high and low regions of heat generation can introduce potential hazards if there is a natural mechanism that makes the high higher and the low lower. Instrumentation must be provided to sense the onset of any such oscillations.

1-4 NUCLEAR POWER PLANTS

1-4.1 Types of Plants

Nuclear power plants are categorized according to the type of nuclear reactor that is the primary heat source. In this book, reactor types are identified by the coolant used to extract heat from the nuclear fuel.*

Pressurized-water reactors: reactors cooled by water in the liquid state

Boiling-water reactors: reactors cooled by water in the liquid and gaseous states

Sodium-cooled reactors: reactors cooled by liquid sodium

Gas-cooled reactors: reactors cooled by gas (helium in the United States)

Every nuclear power plant presently in operation in the United States derives its heat from a reactor in one of these four categories.

Classification of nuclear power plants according to the primary reactor coolant is particularly appropriate to a consideration of power-reactor instrumentation systems since the coolant properties determine many aspects of instrumentation design. This is not surprising since the basic function of the nuclear reactor in a power plant is to generate the heat and to transfer it to a coolant that can then transfer heat to the steam that drives a turbogenerator. The coolant that extracts the heat from the nuclear fuel is the key link in the sequence of operations that converts nuclear energy to electrical energy. Moreover, because material constraints are critically important in any heat engine, the properties of the coolant have a strong influence on the plant design.

Figures 1.12 through 1.15 illustrate the basic configurations of the four categories of nuclear power plants. It must be emphasized that the figures do not purport to show any actual plant configuration (see Chaps. 15 through 18) but rather show those features of each reactor type which are relevant to the design of the principal instrumentation systems.

1-4.2 Sensed Variables

The nuclear chain reaction produces heat (primarily from the dissipation of the kinetic energy of the fission fragments) and nuclear radiations. Consequently, nuclear-power-reactor instrumentation depends primarily on thermal sensors and nuclear-radiation sensors. The former

*Reactors can also be classified in other ways: according to the energy spectrum of the neutron population (thermal, intermediate, and fast), according to use (research, development, test, plutonium production, and power), according to fuel arrangement (homogeneous or heterogeneous), or according to whether the fuel fissioned is less than or greater than the fuel generated (breeder, nonbreeder, and converter).

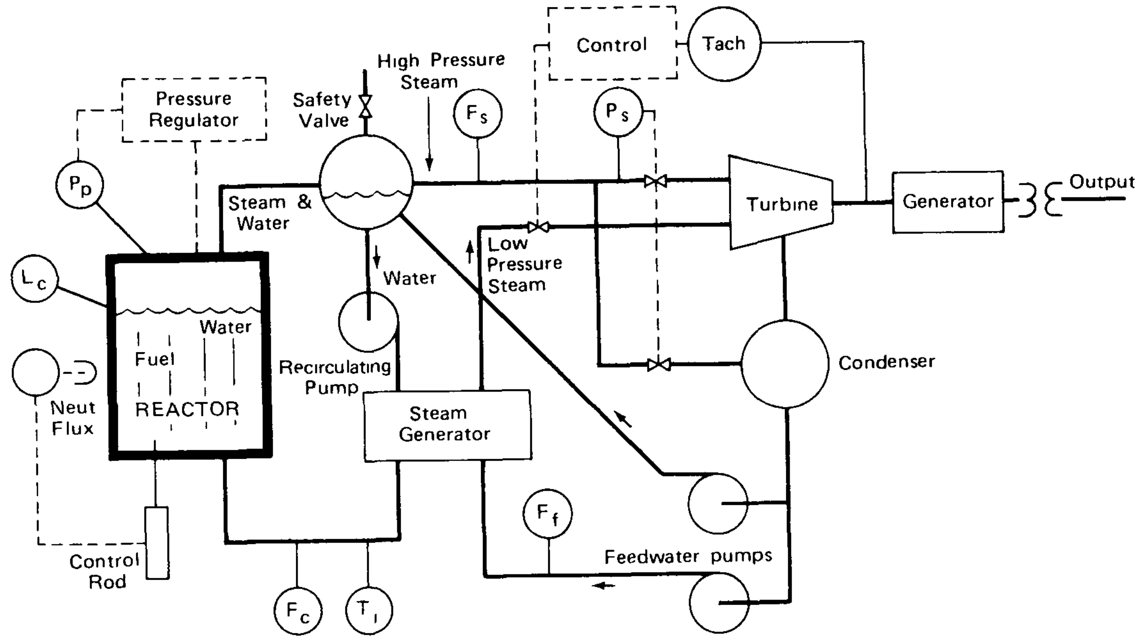

Fig 1 13—Boiling-water reactor. (From A Pearson and C. G. Lennox, *The Technology of Nuclear Reactor Safety*, Vol 1, p 288, The M I T. Press, Cambridge, Mass , 1964.)

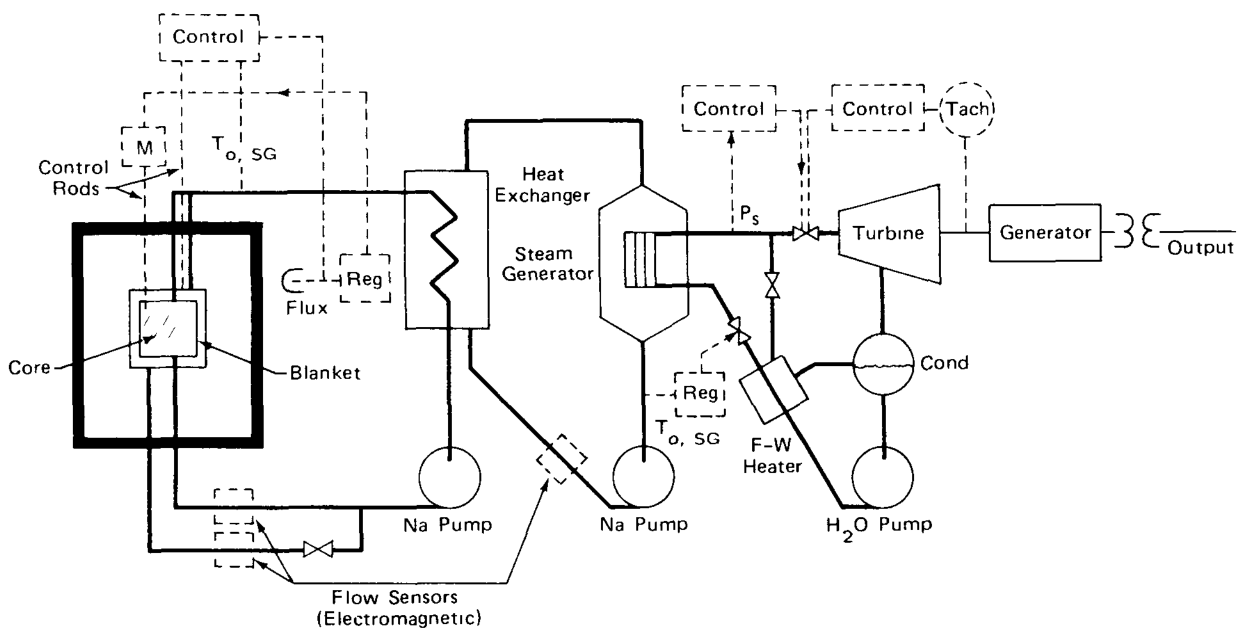

Fig. 1.14—Sodium-cooled reactor. (From A. Pearson and C. G. Lennox, *The Technology of Nuclear Reactor Safety*, Vol 1, p. 289, The M I.T. Press, Cambridge, Mass., 1964.)

(thermocouples and resistance thermometers) are discussed in Chap 4 and the latter in Chaps. 2 and 3. Although a number of nuclear radiations are associated with the fission process, only neutrons can be unambiguously related to the occurrence of fissions, because of this, neutron sensors are the most important of the nuclear-radiation sensors. The neutron sensors are used to determine the rate of fissions, the time derivative of the fission rate, and the fission rate as a function of position in the reactor. (The circuits required to convert the signals from neutron sensors into outputs that are directly related to nuclear reactor performance are described in Chap. 5)

The primary coolant that transfers heat from the nuclear fuel to the turbogenerator (or to a heat exchanger coupled to the turbogenerator) must be examined by suitable sensors to determine such important parameters as

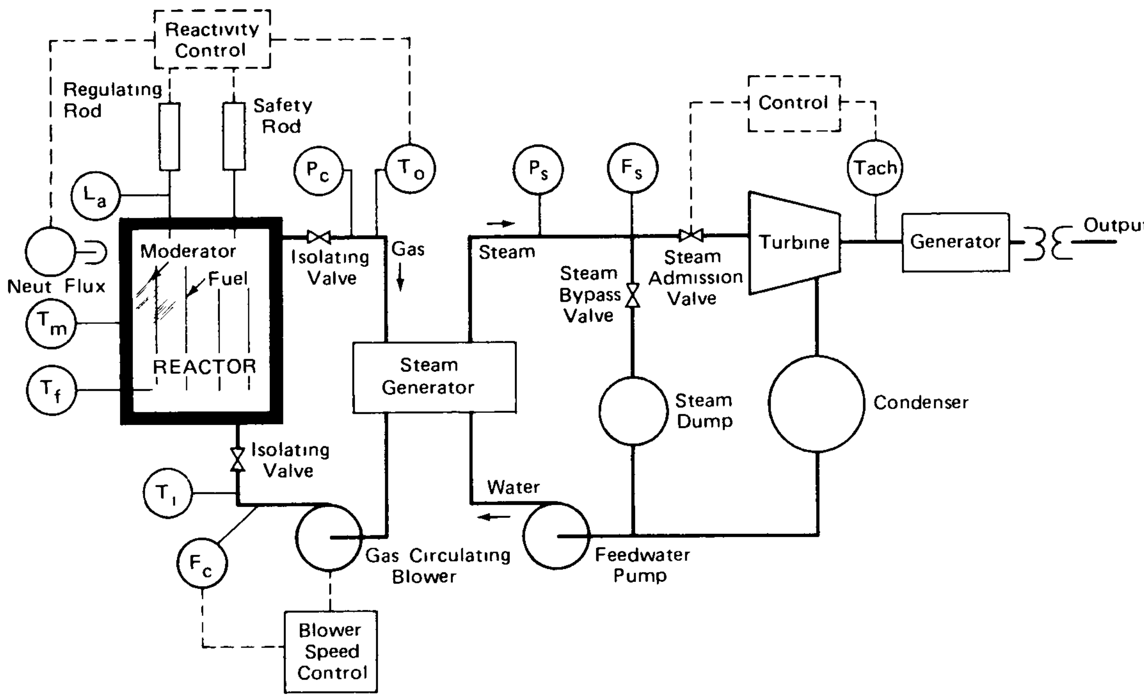

Fig. 1.15—Gas cooled reactor (From A Pearson and C G. Lennox, *The Technology of Nuclear Reactor Safety*, Vol. 1, p. 287, The M.I.T. Press, Cambridge, Mass., 1964)

(1) the temperature of the coolant entering the reactor (T_i in Figs. 1.12 through 1 15), (2) the temperature of the coolant leaving the reactor (T_0 in the figures), (3) the temperature of the coolant at other positions in the reactor, (4) the rate of flow of coolant into and out of the reactor (F_c in the figures), (5) the rate of flow of coolant in various coolant channels in the reactor, (6) the radioactivity of the coolant after leaving reactor, (7) the purity of the coolant, and (8) the presence of water vapor in the coolant when the coolant is a gas To sense these parameters, there must be temperature sensors, flowmeters, humidity detectors, nuclear-radiation (gamma in this case) sensors, etc

Reactor operation itself involves a number of parameters, including (1) the position of the control rods (L_a in Fig. 1.15), (2) the water level of the moderator (L_m in Fig. 1.12), (3) the water level in the reactor (L_c in Fig. 1 13), (4) the pressure in the primary system (P_p in Fig. 1.13), (5) the pressure at the coolant outlet (P_c in Figs. 1.12 and 1.15), and (6) the temperature of the moderator (T_m in Fig. 1.15) Temperature sensors, position indicators, pressure transducers, etc., are required to take data on these parameters.

The steam system is characterized by such parameters as steam flow rate (F_s in the figures), steam pressures (P_s in the figures), steam quality, and feedwater flow (F_f in Fig. 1.13). Thermal sensors, pressure and differential-pressure transducers, flowmeters, water-level indicators, and other sensors (Chap. 4, Sec. 4-6), must be used

In addition, there will be sensors associated with the important components of the plant. Thus, for example, tachometers to sense turbine rotation, meters to sense electrical generator output, thermal and mechanical devices to sense the performance of primary-coolant-pump drive motors, etc., must be installed

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Chapter 2

Nuclear Radiation Sensors — Out-Of-Core

Joseph F Mech

2-1 INTRODUCTION

CHAPTER CONTENTS

2-1.1 Reactor-Power Measurement

Since a nuclear power plant generates power from the heat produced by nuclear fissions, the power level is commonly measured by observing the "radiations" directly associated with the fission process Energetic fission fragments, neutrons, photons, and other particles are produced at the time each fission occurs [1,2] The number of these radiations, or components of these radiations, is proportional to the number of fissions The rate of appearance of these radiations is proportional to the fission rate and, thus, to the reactor power level

Most fission fragments are radioactive and continue to emit betas and gammas long after the fission events in which they were created * In addition, the fission neutrons and some of the more energetic photons can induce radioactivity This induced radioactivity also persists long after the creating process The radiations from the total residual radioactivity, variously called afterglow, decay heat, or fission-product activity, contribute up to 5% of the reactor heat However, the decay heat is not an indicator of reactor power but is related to the history of operation of the reactor

The most desirable way to make any measurement is to use the most direct method Reactor power therefore should be measured by detecting the prompt fission radiations The fission fragments and beta radiations are short range and are stopped in the reactor fuel However, the neutrons and gamma rays accompanying fission are sufficiently penetrating to be detected at some distance The technology for reactor power measurement is based on the detection of neutrons or gammas or both.

*Less than 1% of the fission fragments emit neutrons Most neutrons are emitted in the first few seconds after the fission event that created the fragments See Chap 1, Sec 1 3 2

2-1.2 Interactions with Matter

Fission gammas and neutrons interact with surrounding material in many ways Three interaction processes are of special interest in reactor power measurement, nuclear reactions, recoils or collisions, and ionization The interaction of any single gamma photon or neutron may involve more than one of these three basic processes (For details on these interactions, see Refs 3 and 4)

A nuclear reaction results from sufficiently energetic collisions of a specific radiation with the nuclei of a specific material The consequence of a nuclear reaction is a nuclear excitation or transmutation or the formation of a new

material The reaction may be described symbolically as A(*a b*)C where A is the *target* nucleus, the first symbol, *a* within the parentheses denotes the radiation causing the reaction, the second symbol, *b*, within the parentheses denotes the effect or secondary radiation, and C is the nucleus that remains after the secondary radiation, *b* has been emitted An example of this symbolism is the nuclear reaction $^{103}Rh(n,\gamma)^{104}Rh$, in this reaction ^{103}Rh has been converted to ^{104}Rh by the capture of a neutron, *n* and the emission of a capture gamma, γ

If the principal interest lies not in ^{104}Rh but in its decay product, the expression may be expanded to $^{103}Rh(n,\gamma)^{104}Rh \xrightarrow{\beta} {}^{104}Pd$ Here the arrow with β superposed indicates radioactive decay by beta particle emission to ^{104}Pd

Usually there are other radiations associated with the nuclear reaction, but the symbolism is restricted to the principal reaction or the reaction of interest Reactions of interest in nuclear instrumentation are neutron induced and result in the emission of fission fragments and of alpha particles, namely, (n,f) and (n,α) reactions

Most fission-neutron interactions with the nuclei of material in and around a nuclear reactor core are capture reactions [(n,γ) reactions] and elastic collisions [(n,n) reactions] Some interactions are transmutations of the $(n\ p)$ type, and some are inelastic collisions [$(n\ n')$ reactions] The products of these interactions, i e , the neutrons, gammas, and protons, also interact with the nuclei of material in and around the reactor core

Fission gammas and the gammas produced in neutron capture or -scattering reactions interact with the electrons in surrounding material, usually creating energetic electrons (Compton or photo effect)

Energetic particulate radiations (protons or nuclei recoiling after a nuclear reaction), if not stopped in nuclear reactions or nuclear collisions, ultimately lose their energy by ionizing atoms Ionization results in a "cloud" of free electrons and positive ions The cloud or track of ionization is sharply defined by the trajectory of the initiating particle and usually has a definite length, or range, that depends on the particle energy and the density of the medium A heavy, highly charged particle, such as a fission fragment has a short, densely ionized range An electron, or beta, has a longer range with less dense ionization

The neutral radiations (neutrons and gamma rays) associated with fission travel much farther than the charged particles and have poorly defined ranges They can penetrate thick layers of matter Neutrons usually terminate in some nuclear reaction, gamma rays produce secondary electrons, which, in turn, are stopped by ionizing other atoms The difference in the penetrating power of neutron and gamma rays makes possible a partially selective detection process in monitoring nuclear reactors

All the interactions of the radiations accompanying fission produce heat Thus the heat generated is a direct measure of the power of a nuclear reactor (It is also a nuisance in instruments used to detect radiation) Unfortunately, heat is a very slow indicator (because of thermal inertia) In the steady state, the reactor heat or thermal power can be accurately measured and used in calibrating the nuclear instrumentation

2-1 3 Accepted Detection Principles

In principle, any fission neutron or gamma interaction with matter which produces measurable effects can be used for reactor-power measurements Practical considerations, however, limit the choice to a few The commonly used detectors have evolved through a selection process based on considerations of signal strength, response time, and tolerance of interfering radiations

The radiation detector produces an electrical signal that overrides typical electronic-circuit noise levels If the detector is to be used in reactor protection systems, its signal must be reliable and its response time should be short In event of a reactor accident or major component failure, the detector may have to respond rapidly to initiate a shutdown before damage can occur The time constants of signal conditioning circuits are longer than detector response and normally are limiting for protection system considerations In addition, a strong gamma background can obscure the neutron signal Fission product gamma radiation is always a large contributor to the background gammas in power reactors

Despite considerable research and development on other types most operating detectors depend on gas ionization Generally, gas ionization detectors[5] can be made to have sufficient sensitivity without excessive size and to have a wide operating range, a fast response time, and adequate radiation selectivity

Most neutron sensors utilize gas ionization caused by charged particles emitted in neutron-induced fission reactions in ^{235}U or in $(n\ \alpha)$ reactions in boron Gamma sensors detect the ionization caused by Compton electrons

2-1 4 "Out-of-Core" Defined

Figure 2 1 shows a typical location for an out of core neutron sensor In this example, the sensor is also outside the reactor vessel The figure also shows the magnitude of the neutron flux, the gamma exposure rate, and the temperature in the out of core location typical of a boiling-water or pressurized-water reactor during operation at rated power

In today's power reactors the neutron flux inside the core boundary is always greater than 10^{11} neutrons cm^{-2} sec^{-1} Consequently, it is current practice to define an out of-core sensor as one that is not exposed to a neutron flux greater than 10^{11} neutrons cm^{-2} sec^{-1} The temperature and gamma exposure rate are not involved in this definition Both the temperature and the gamma exposure rate in Fig 2 1 are at least an order of magnitude less in out of core locations than they would be within the core

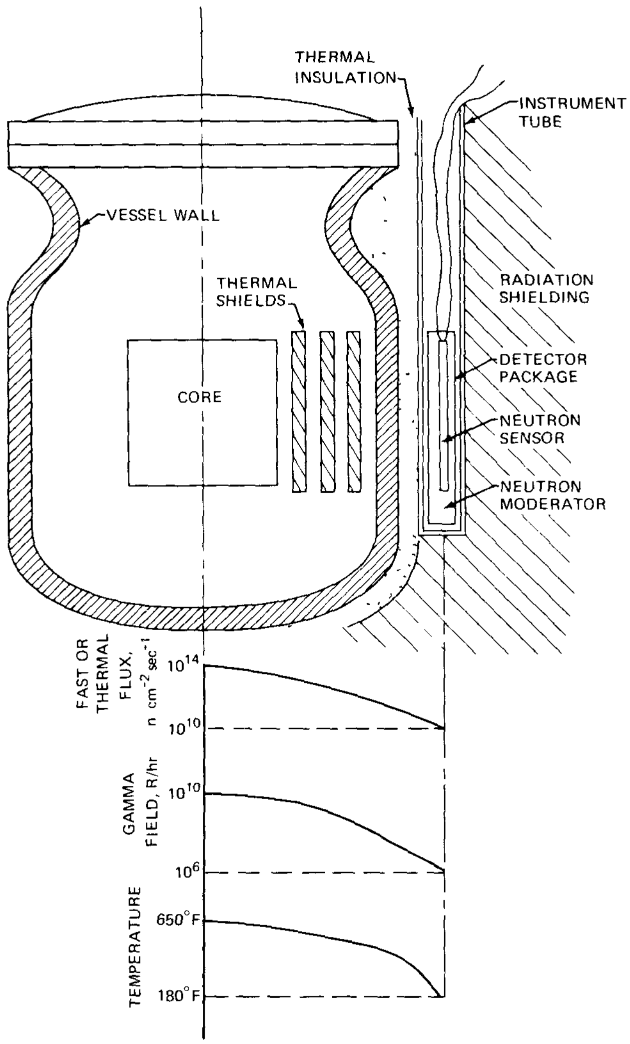

Fig. 2.1—Typical environmental profile for neutron sensors in a pressurized-water reactor at full power. (*Courtesy M. A. Schultz, Pennsylvania State University.*)

boundary. An out-of-core sensor, however, can be located inside the reactor pressure vessel, e.g., in the region of the thermal shield, provided the neutron flux does not exceed 10^{11} neutrons cm^{-2} sec^{-1}.

2-1.5 Use of Out-of-Core Sensors in Reactors

The application of nuclear instrumentation demands an understanding of the behavior of a reactor. Because power density varies with position in the reactor, an average power measurement is needed. Out-of-core detectors are considered to be spatially averaging and are discussed here from this viewpoint. Detectors for measuring spatial variations in nuclear fluxes are discussed in Chap. 3. Out-of-core detectors are reasonably good averaging devices for most reactors if their installation is properly designed, especially in regard to shadowing by movable objects in or around the reactor.

To a limited extent, nuclear instrumentation influences reactor design. For example, it may be necessary to adjust the location of control elements to avoid shadowing effects on radiation sensors. It may be desirable to introduce a window to cause streaming that will ensure an adequate level of radiation for reliable instrumentation response. Although it is always desirable to avoid reactor-vessel penetrations, penetrations are sometimes necessary to ensure an adequate signal. The minimum reactor power level must be determined to ensure measurements at all reactor levels. If the minimum is too low or uncertain, a neutron source must be provided to maintain the minimum level at a measurable value. There must be provisions for renewing or replacing the source.

All these requirements stem from the mandate that the state of the reactor must always be known. In other words, the reactor level and the rate at which the reactor level is changing must always be known and must always be under control. To ensure this knowledge, redundancy is always used to some degree (see Chap. 12). A common mode of redundancy is to make measurements with three separate detectors or channels, each with independent circuitry. The shutdown signal from any one channel must be in coincidence with another signal (i.e., a two-out-of-three coincidence) before shutdown is allowed.

Radiation detectors sample radiation intensity. Initially, the relationship between reactor power level and the sampled radiation intensity is based on design calculations alone. At power levels near full-power operation, the detectors must be calibrated. This is best accomplished by making heat-balance measurements. Subsequent calculations, using the calibration, then relate the detector response to the reactor power level. Periodic recalibration is required to take into account changing radiation patterns and spectra, fuel burnup, and changes in detector sensitivity.

The great range in reactor power (from watts to hundreds of megawatts) makes it impossible to use one set of detectors and circuits, despite the wide range of the detectors. Research has produced detector and circuit arrangements capable of measuring over a range of 10 decades. Signal-conditioning circuits are the key to success (see Chap. 5).

A single set of detectors can be used to measure only a part of the reactor range and must be complemented by additional sets of detectors. For safety and reliability, a part of the range of the detectors is sacrificed by having them duplicate the measurements of a part of the range of other detectors. This duplication, or overlapping, is needed for a smooth transfer of control and safety functions from one detector set to another. The amount of overlap is typically one to two decades.

The most common way of dividing the power-level range is to use three ranges: source, intermediate, and power ranges.[6] This nomenclature is used in commercial

practice. Figure 2.2 shows a typical selection of neutron detectors to cover these ranges.

Each range has peculiarities that depend on the radiation levels corresponding to that range and on whether or not a reactor has been operated. Special features, sometimes temporary, must be incorporated into the instrumentation design to ensure reliable performance during the initial period of a reactor when it is "clean and cold." The same instrumentation must operate when the reactor has accumulated its full burden of radioactivity and at every condition in between.

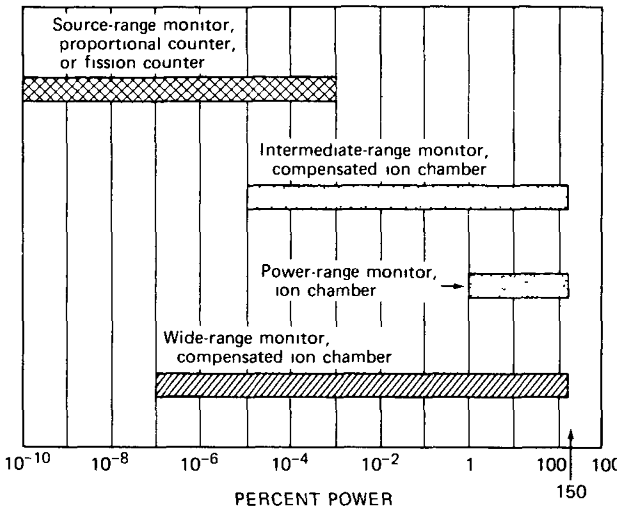

Fig. 2.2—Typical detectors used in out-of-core systems to cover the source, intermediate, and power ranges. (*Courtesy General Electric Co.*)

In the source and intermediate ranges, the reactivity of the reactor is limited by controlling or limiting the rate (period) at which the power can be increased. In the power range, instrumentation must prevent the reactor from exceeding its rated or licensed operating limit.

In the fully shutdown condition, the neutron density to which the detectors are exposed is frequently quite low, in fact, so low that individual neutrons are counted in order to gain information about the reactor status. Counting is also the only way to detect neutrons in the relatively high gamma fields that may be present.

The limits of the source range (or counting range) are determined by permissible counting rates, expressed in counts per second. The low end of the source range is determined by the counting rate needed to achieve a safe condition, as specified in the safety review (see Chap. 12). This minimum counting rate is normally from 1 to 10 counts/sec. The counting rate is established during the preliminary design and is fixed by consideration of the statistical nature of the neutron population and the time interval needed to achieve a measurement of prescribed accuracy. The counter must be located where the flux density is sufficiently large to ensure that this counting rate is achieved. The magnitude of the neutron source is selected to attain (at the detector location) a neutron flux that results in at least the minimum counting rate at all times. The maximum or high end of the source range is determined by the ability of the counter and the associated electronic circuits to resolve the individual counts. If the counting rate is too high, the resolution loss produces a serious error in the signal. Typical maximum counting rates are 0.5 to 1 $\times$ 10^6 counts/sec, and the allowable resolution loss is less than 10%.

The source range presents an adverse situation for the detection of neutrons. The detector used must be carefully selected for its sensitivity to neutrons in the presence of a large gamma background. The condition of few neutrons and many gammas exists immediately following a scram from full power.

The intermediate range overlaps the source range, and its gamma background is not as severe. However, since the neutron flux is high, individual neutrons are no longer resolved, and the signal takes on a direct-current aspect, becoming indistinguishable from the gamma background (also a d-c signal). Here again, it is essential to know the gamma level at the low end of the intermediate range. Through sensor design the gamma contribution at the low end is normally kept below 10% of the neutron signal. Again, the worst condition exists during a start-up immediately following full-power scram. The intermediate range usually extends into and completely overlaps the power range.

The power range covers from 1 to 150% of full power to provide some allowance for small power excursions. In the power range there is normally no great difficulty with interfering radiation. Neutron detectors that are not gamma compensated are satisfactory, but gamma-compensated sensors may be used for uniformity. These are similar to those used in the intermediate range.

2-2 PRINCIPLES OF GAS IONIZATION SENSORS

Most detectors in common use in nuclear power reactors are ionization chambers.[5,7] Since the principles of the ionization chamber apply broadly to gas-filled detectors, only ionization chambers are considered in this section. Specific characteristics of other types of gas-filled detectors are discussed in Sec. 2-4.

2-2.1 Ionization Chambers

Ionization chambers are used to collect and measure the electric charge of ions and electrons that result from the interaction of incident radiation and secondary radiation from the chamber structure with the fixed, known volume of gas in the chamber. The quantity of collected charge is a measure of the incident radiation.

The sensitivity of ionization chambers can be increased by incorporating materials[8] into their structure which interact with the incident reactor radiation to create energetic ions or electrons These materials can be coated as a thin film on the electrodes of the chamber or they can be included in the chamber as a gas For the detection of thermal neutrons, ^{235}U and ^{10}B in various degrees of isotopic enrichment are used Other materials can be used if it is desired to increase the chamber sensitivity to fast neutrons Table 2 1 is a partial listing of materials that can

Table 2 1—Threshold Energies of Materials for Fast-Neutron Detection

Thermal	<1 MeV	>1 MeV
^{233}U	^{234}U	^{232}Th
^{235}U	^{237}Np	^{238}U
^{239}Pu		

be used in fast neutron detectors Of the isotopes listed, ^{238}U is available commercially in a limited number of chamber configurations ^{239}Pu and ^{237}Np can be obtained by special order

Many isotopes of the heavy elements are of potential value in fast neutron detection Of these, the most likely candidates are ^{236}U, ^{241}Am, ^{240}Pu, and ^{241}Pu The list is limited by the availability of accurate fission cross section data, by interfering alpha radiation, and, in some instances, by spontaneous fission

Fast neutron measurements must be interpreted with caution Some of the above isotopes are available only by separation from thermally fissionable isotopes For example, ^{236}U and ^{240}Pu may have traces of ^{235}U and ^{239}Pu, respectively These traces may cause errors A second reason for caution is that these isotopes are sensitive to the entire neutron spectrum above the fission threshold Thus, information about the entire neutron spectrum is contained in the signal

Basically, an ionization chamber consists of at least two insulated electrodes sealed within a metallic case or enclosure Connections are made through electrical seals designed for minimum charge leakage Typical resistance between electrodes and case is high, of the order of 10^{12} ohms or greater A guarded structure can be used for the seals if very low signal levels are anticipated Such a structure consists of insulated conducting guard rings or cylinders surrounding each lead The guard rings are maintained at the potential applied to the corresponding electrode Figure 2 3 shows the structure of a fission chamber

The electrodes must be designed and placed so there is a uniform electric field within the sensitive volume of the chamber Auxiliary electrodes can be used to help attain field uniformity, which is particularly important when the sensitive volume of the chamber must be well defined and when uniform ion collection rates are needed In practical detector designs for reactor service, electrode spacing is small compared to the electrode dimensions As a consequence, the fringing electric field at the edges of the electrodes does not seriously compromise performance Possible errors are usually small compared to other uncertainties in reactor flux measurements Because of this, auxiliary electrodes for field shaping are not used in normal commercial practice

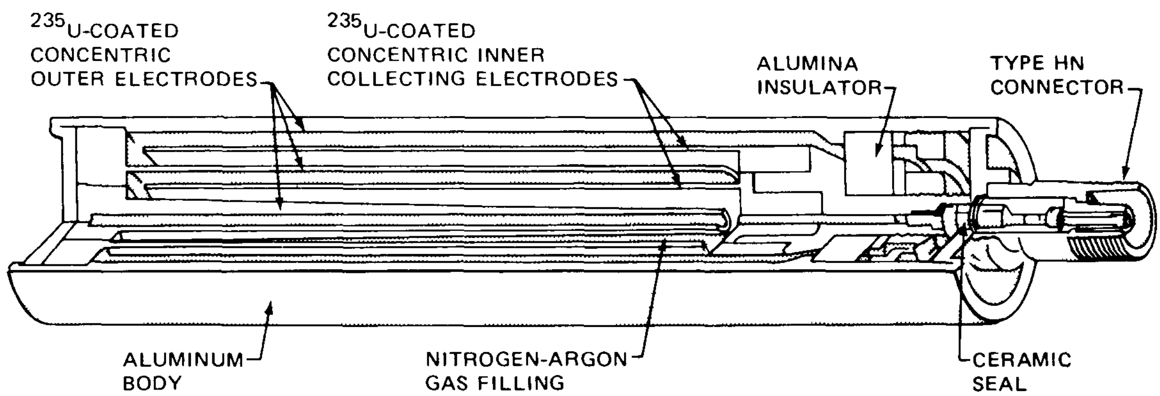

Fig 2.3—Fission ionization chamber (*Courtesy Westinghouse Electric Corp*)

High voltage, the magnitude depending on the chamber design and application, is applied to one of the electrodes, and the other electrode is operated close to ground potential This high voltage may be quite low for a chamber of small physical dimensions and low gas pressure (<100 volts) For good performance, the minimum voltage on a large chamber with high gas pressure may be many hundreds of volts Since the gas pressure is fixed to optimize performance (Fig 2 4), the high-voltage limits are also fixed The maximum voltage is limited by the danger of breakdown The applied voltage is usually negative for counters since the collection of electrons is desired at the

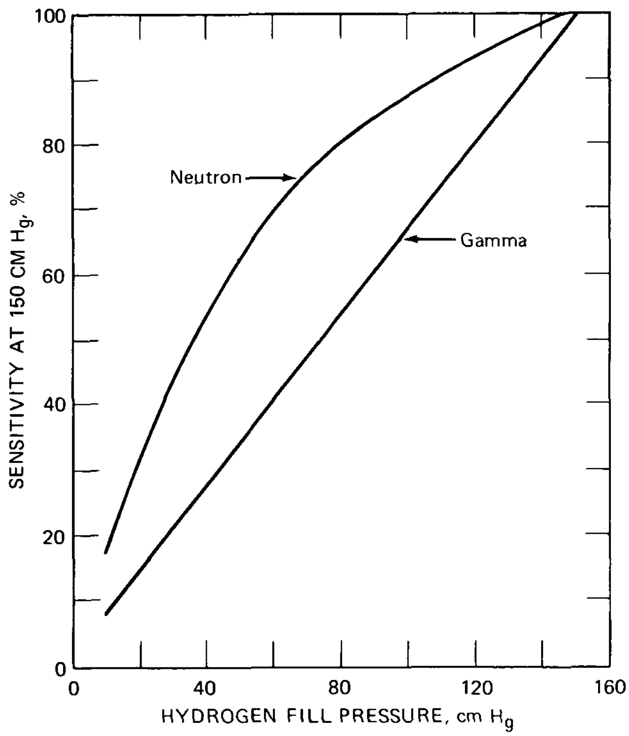

Fig. 2.4—Variation of neutron and gamma sensitivity with pressure for boron-coated electrodes spaced 0 25 in apart [From W Abson and F Wade, Nuclear Reactor Control Ionization Chambers *Proc Inst Elec Eng (London)*, **103B**(22) 590 (1956)]

low-voltage electrode For other types, the voltage may be positive or negative The value of the applied voltage depends on the plateau of the chamber

Free electrons and positive ions are produced in the gas fill of the chamber Because ions are much heavier than electrons and not as mobile, electrons are normally collected faster [9] However, in some gases there is a tendency for the free electrons to associate with the molecules of the gas, producing negative ions These negative ions are also relatively immobile The gas fill of the chamber is therefore commonly selected from one of the electron-free gases, such as the inert gases helium and argon Nitrogen also has good properties and is frequently used A number of gas mixtures promote electron mobility to an extent much greater than possible with any pure gas and have found great favor in ionization chambers [10]

In general, gases whose chemical activity is enhanced by radiation are avoided since they may be gettered by the metals of the electrodes and the chamber enclosure Gases that are chemical compounds may be dissociated in a high radiation field, recombination is not spontaneous in most of these gases, and their use is avoided A BF_3 counter or chamber, for example, may have a short life [11]

When a voltage is applied to an ionization chamber and the resulting current is measured in a constant radiation field, the current is found to vary with the voltage A graph of pulse amplitude vs voltage (Fig 2 5) shows the pulse amplitude increasing with voltage in a very characteristic

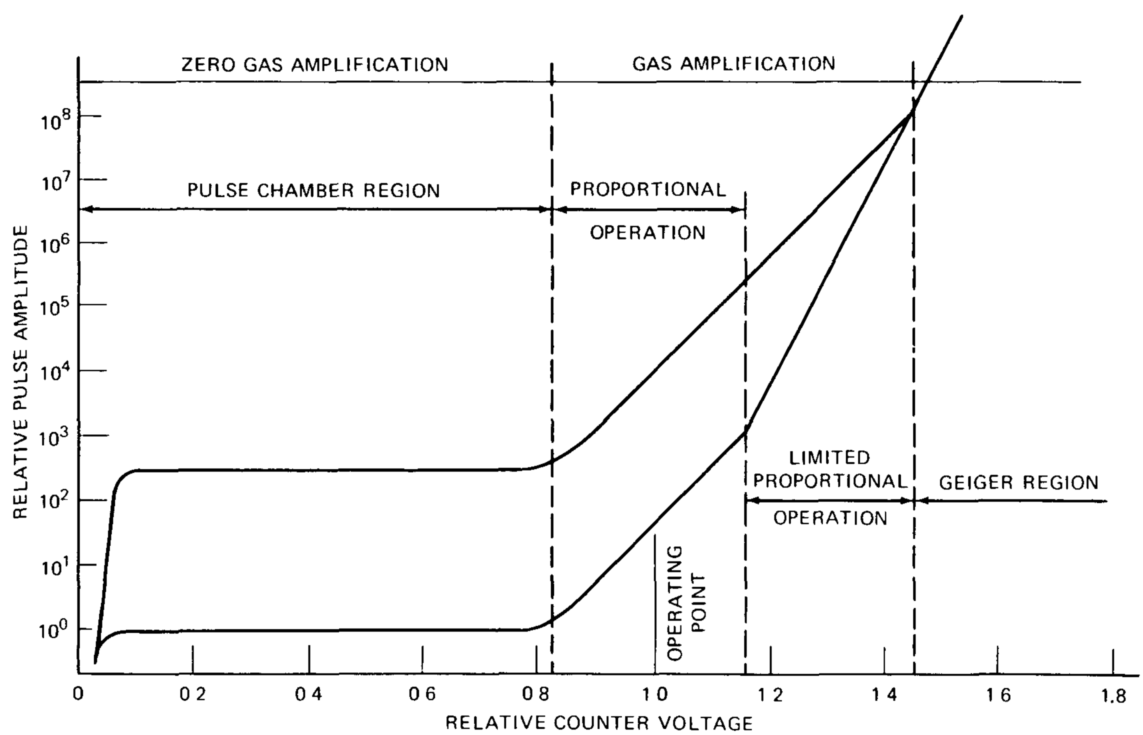

Fig 2.5—Counter pulse height vs supply voltage [From H Etherington (Ed), *Nuclear Engineering Handbook* p 8-54, McGraw-Hill Book Company, Inc , New York, 1958]

fashion * At low voltages competing gas processes hold the current down As voltage is increased, the current increases rapidly, and, then, as the voltage is increased further, the current remains nearly constant, increasing only slightly The flat region of nearly constant current is known as the plateau, and the region where the current begins to flatten is called the knee of the plateau The voltage just above the knee is the minimum operating voltage Normally, the operating voltage is selected, somewhat arbitrarily, to be considerably above the minimum

As the chamber voltage is increased along the plateau, assuming that voltage breakdown does not occur, a point is reached where the current again begins to increase Voltages above this point cause gas multiplication This voltage or the breakdown voltage, whichever is smaller, determines the maximum voltage In turn, the maximum rated voltage must normally be considerably below the breakdown voltage for reliable operation, again a somewhat arbitrary choice Since the reactor radiation field tends to promote voltage breakdown, operation at minimum voltage is preferred

If the voltage plateau for a given chamber[12] is determined for a number of radiation-field values, it is found that the voltage at the knee increases with radiation intensity, as shown in Fig 2 6 This is caused by recombination and space-charge effects, which increase rapidly with radiation intensity It is important to recognize this fact and to select an operating voltage that is on a plateau at the maximum radiation intensity experienced during operation At this voltage, again somewhat arbitrary, the magnitude of the chamber current is a faithful indicator of radiation intensity

Radiation emitted by neutron-induced radioactivity within the chamber may, under some circumstances, increase the background and limit the range of usefulness of the chamber [13] Figure 2 7 shows the residual current due to the induced activity in the fission chamber

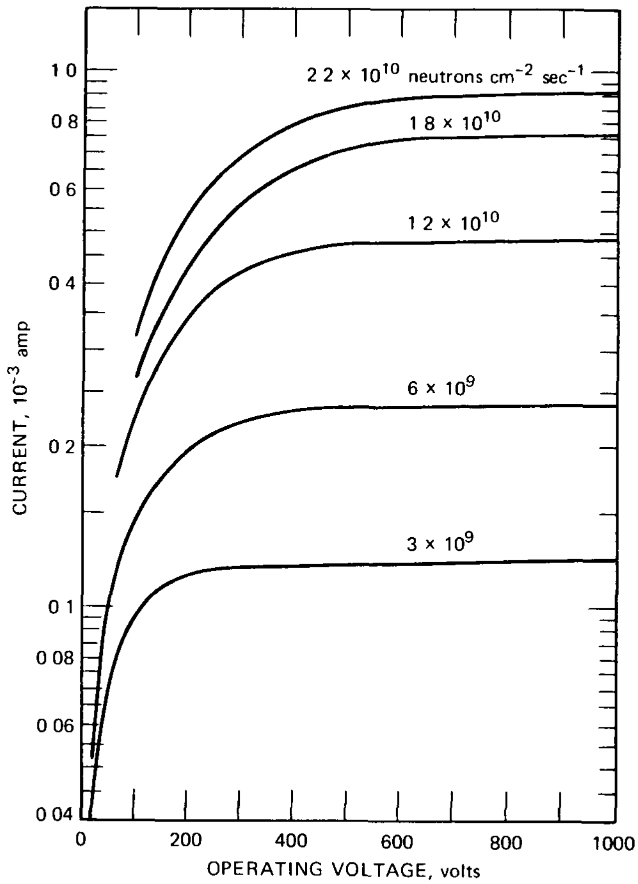

Fig. 2.6—Typical neutron saturation curves, illustrating the change in plateau with increasing current (*Courtesy Westinghouse Electric Corp*)

2-2.2 Compensated Ionization Chambers

One of the problems with ionization chambers is that the detector is indiscriminate and will detect any ionizing radiation If, for example, neutrons are to be detected in the presence of a strong gamma field and the neutron flux is to be related to the average current, then it is necessary to take into account the component of the current that is due to the gamma field

Part of the gamma-induced current is due to prompt gammas and is proportional to the neutron induced current This part is indicative of reactor power and is not detrimental However, the remainder of the gamma-induced current is relatively unchanging and creates a spurious signal, i e , a signal not indicative of the reactor power level

This, in turn, is not a problem at high power levels when the neutron field is much more intense than the background gammas At low power levels, the gamma contribution to the chamber current may be a large fraction of the chamber current and might exceed the neutron-induced current Thus the range of reactor power in which an ionization chamber can be used to measure the power level may be severely reduced

Two ionization chambers can be used to decrease the effect of the gamma background If an ionization chamber sensitive to gamma radiation only is installed near an ionization chamber that is primarily sensitive to neutrons, the signal from the gamma chamber may be used to cancel the gamma contribution to the neutron-chamber signal In practice, the chambers must be carefully matched and their relative positions must be properly fixed Chamber pairs for this purpose are commercially available

A common way of neutralizing or compensating for the effect of gamma radiation is to combine the two ionization chambers into a single unit called a compensated ionization chamber,[14,15] frequently abbreviated CIC A typical CIC is shown in Fig 2 8

A compensated ion chamber is essentially two ionization chambers in a single case One chamber collects the

*A plot of current would vary in a similar way, except that it would not be possible to indicate clearly gas amplification with a steady current

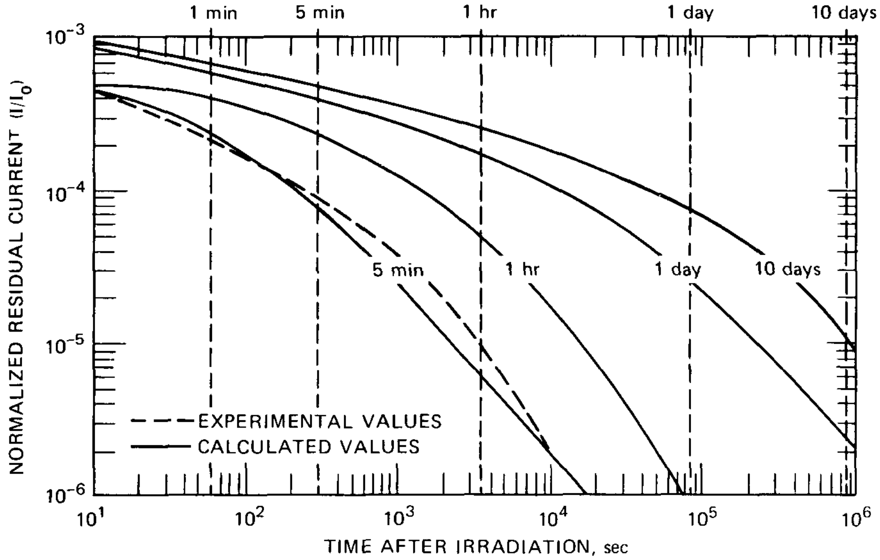

Fig. 2.7—Calculated and experimental fission-chamber residual currents due to fission-product activity as a function of the time after irradiation.[13] Parametric curves are for different irradiation times.

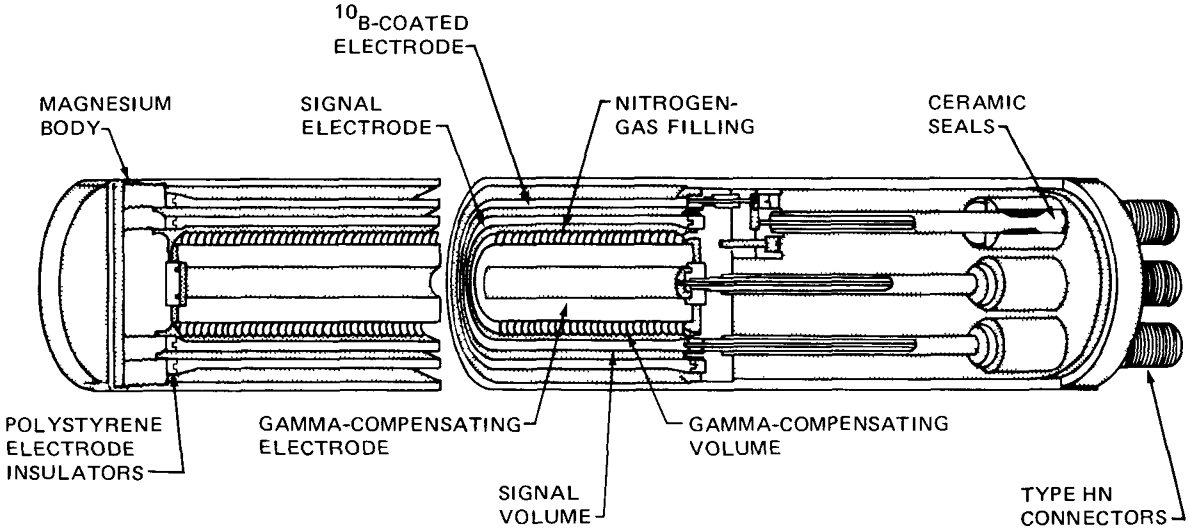

Fig. 2.8—Compensated ionization chamber. (*Courtesy Westinghouse Electric Corp.*)

total current due to both neutrons and gammas. The other chamber is identical to the first in sensitive volume but lacks the neutron-sensitive materials. If electrons are collected in one chamber and positive ions in the other and if the resulting currents are summed, the gamma-induced currents are cancelled. In practice, it is normally immaterial whether the signal is obtained by collecting electrons or positive ions.

Theoretically, the cancellation could be complete. In practice, cancellation can be made complete at a given reactor power level. However, over the range of reactor power levels, most of the gamma effects can be nulled but a residual should be expected. The residual may be less than 1% of the signal or as great as 10% and depends on the specific detector and the effort made to achieve good compensation. A reasonable state-of-the-art number is 2 to 3%, i.e., 97 to 98% compensation.

It is also possible to overcompensate. Figure 2.9 illustrates the manner in which compensation varies as a function of operating voltage. Because of this voltage-sensitive feature, it is possible to use variable compensation.[16] The variable-compensation feature has been commercially used.

Figure 2.10 shows one way in which compensation might vary over a portion of the reactor range. With fixed voltages, compensation is exact at only one point. Figure 2.11 is an illustration of the improvement gained from using a compensated ionization chamber. The figure

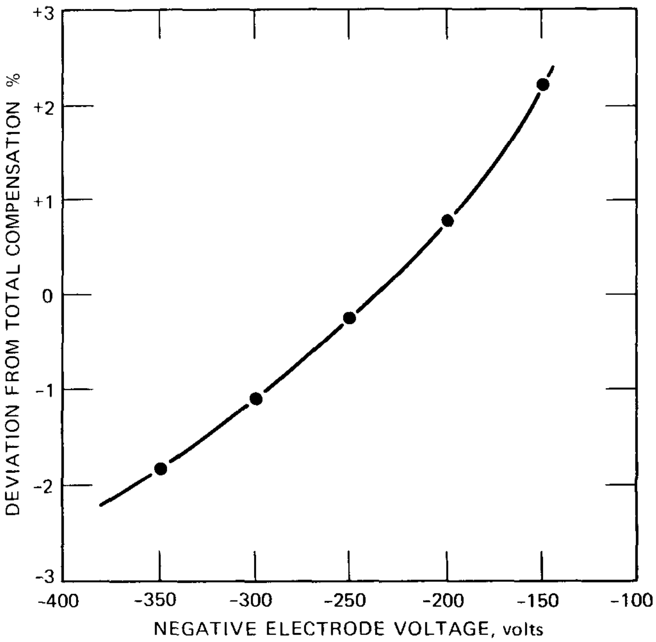

Fig 2 9—Gamma compensation as a function of electrode voltages Measurements were made in a hot cell with a ^{60}Co source[13] Fixed positive electrode voltage 300 volts Basic compensation 1 2%

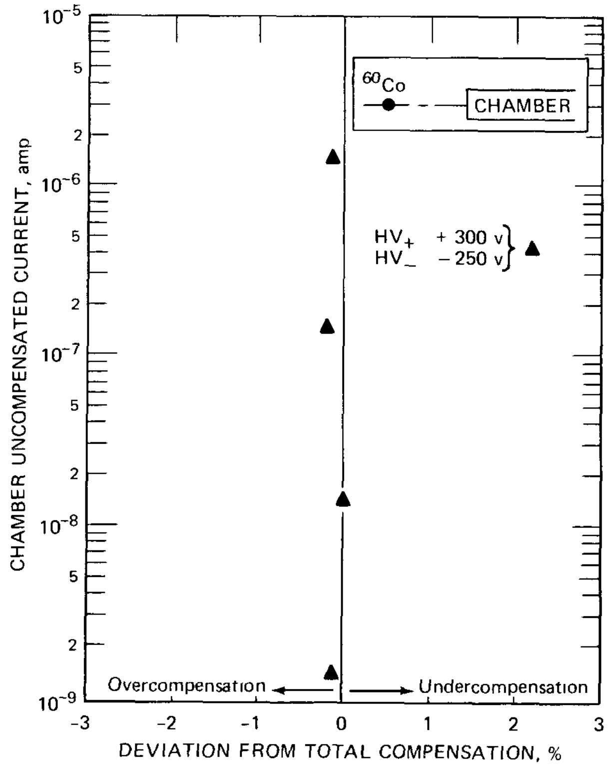

Fig 2.10—Gamma compensation as a function of chamber current[13]

also provides insight for measuring and testing compensation in an operating reactor

The use of a gamma-compensated detector extends the range, compared to that of an uncompensated detector, by about two decades Depending on the reactor, an uncompensated detector may be expected to cover three or more decades, a properly located compensated chamber can reasonably be expected to measure the reactor power over at least five decades Recent practice has generally been to operate with fixed voltage and to design safety systems that avoid dependence on as r ich as two decades of compensation

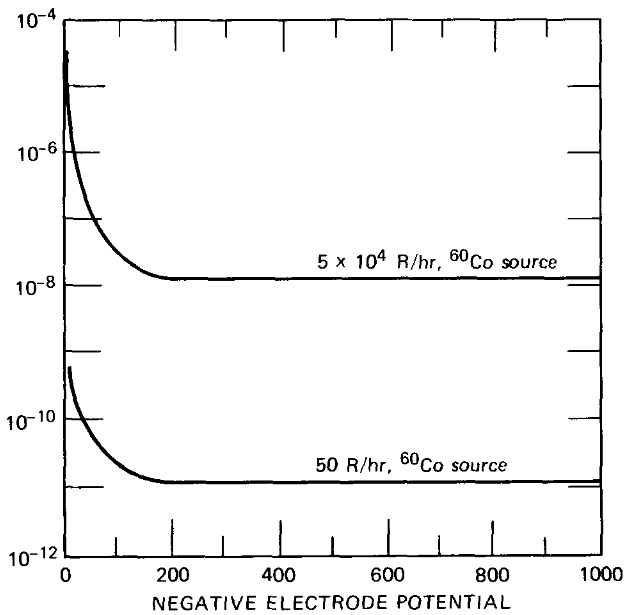

Fig. 2.11—Compensation characteristics in a compensated ionization chamber (*Courtesy General Electric Co.*)

2-2.3 Counters

A counter is an ionization chamber designed to deliver a current pulse for each ionizing event[17,18] A number of features are common with those of the more general ionization chamber In fact, superficially, chambers designed for the current and counting modes are indistinguishable There are commercial chambers designed to perform in both the current and counting modes, which, if the application is not demanding, can serve as well as a detector limited to a single mode

The difference stems from basic differences in the signal, i e , a pulse vs direct current. For large pulses that are easily distinguishable from one another, the ionization of each ionizing event must be collected quickly This is accomplished by careful design In addition, the gas fill of the chamber must be selected to maximize electron mobility There are a number of gas mixtures that are better in this respect than pure inert gases A high performance counter would use one of these gas mixtures

Because the signal is a pulse, the insulation quality of the chamber is not as critical The pulse height depends primarily on the capacitance, C, and resistance, R, of the system in which the counter is used Thus, if the time constant, RC, of the output circuit is 100 or more times the pulse rise time, negligible attenuation occurs Since a typical installation might have a capacitance of 2000 pF, a counter with a pulse rise of 0 2 μsec requires an output resistance of only 10,000 ohms to meet this test The insulation resistance then needs to be 10^6 ohms or more for satisfactory performance, a criterion that is easily met The faster the pulse rise, the less a high resistance is required If an electronic amplifier is introduced, the analysis is somewhat different from the above, however, the result is similar

In a counter the internal structure is given particular attention Capacitance is minimized (see Fig 2 4) The distances between electrodes is optimized to the range of the ionizing event Since discrimination between unwanted ionization events is usually required, some of the theoretical pulse height may be sacrificed for this end

Practical counting rates are determined by the pulse rise time If some resolution loss can be tolerated, say less than 10%, the maximum counting rate would be about $1/10\tau$, where τ is the rise time In a counter with a 0 2-μsec rise time, this corresponds to 5×10^5 counts/sec, a typical counting rate

The lower limit on counting rates is not a function of the counter structure but of the radiation background in which the counter is placed and of the electronic discrimination However, because of poor statistics, it is not good practice to rely on counting rates of less than 1 count/sec A state-of-the-art fission counter is good for five and a half decades in a gamma field of 10^5 R/hr with only small losses in counting efficiency In general, higher gamma fields can be tolerated if losses in efficiency are acceptable The trend is to develop counters with faster rise times and with corresponding improvements in maximum counting rate and gamma tolerance

The use of a counter is somewhat more involved than the use of an ionization chamber Not only must the counter be operated on a voltage plateau, but counts from the desired events must be separated from counts attributable to undesired events Figure 2 12 shows how this is done with a pulse height discriminator

Pulse height discrimination is one of the simpler methods of separating wanted pulses from unwanted pulses It has found many applications in reactor start up systems and is easiest to apply when the wanted pulses are larger than the unwanted pulses The usual way of determining the effectiveness of a counter and of the counting system is by an integral bias curve The discriminator setting corresponds to the number of counts, expressed in counts per second, of greater pulse amplitude In practice, only a single curve is measured Figure 2 12, however, has been constructed by measuring alpha and gamma curves in the absence of neutrons An arrangement such as that shown in Fig 2 13 can be used to measure these curves A knowledge of the integral bias curves is indispensable in selecting and using a fission counter

With a knowledge of the gamma background, possibly by measuring the integral bias curve, one can select the operating point to eliminate any desired function of the

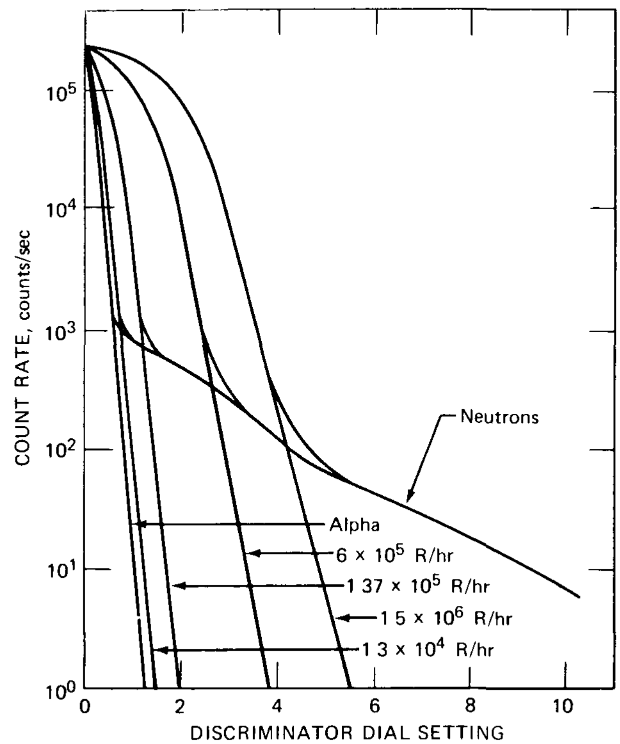

Fig 2.12—Integral bias curve for a fission chamber modified to show typical channel count rate limiting *(Courtesy Reuter Stokes Electronic Components, Inc)*

unwanted counts There is, of course, a corresponding loss of efficiency since the neutron integral bias curve has a slope This loss of efficiency is so well known that it is commonly equated with gamma discrimination Ideally, and in some radiation detecting instruments, this is nearly the case, the wanted counts form a horizontal line (zero slope) In this ideal situation there is no loss of efficiency One way to approach this ideal is to use a thin coating of sensitive material Figure 2 14 shows the effect of sensitive material thickness on discriminator response It is seen that very thin films do approach the ideal

Unless the chamber size were increased (with a consequent increase in gamma sensitivity) a great loss in sensitivity would occur if very thin films were used Thus, most practical designs favor a thicker film of sensitive material, typically 1 to 2 mg/cm^2, as a workable compromise The very thin films, however, are advantageous if absolute measurements must be made

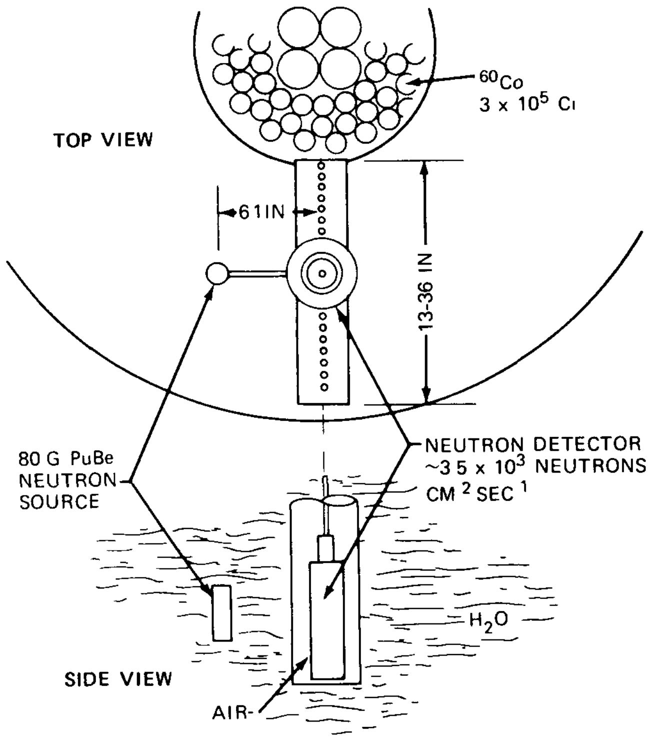

Fig 2 13—Arrangement for measuring counter characteristics (*Courtesy Battelle Northwest Laboratories*)

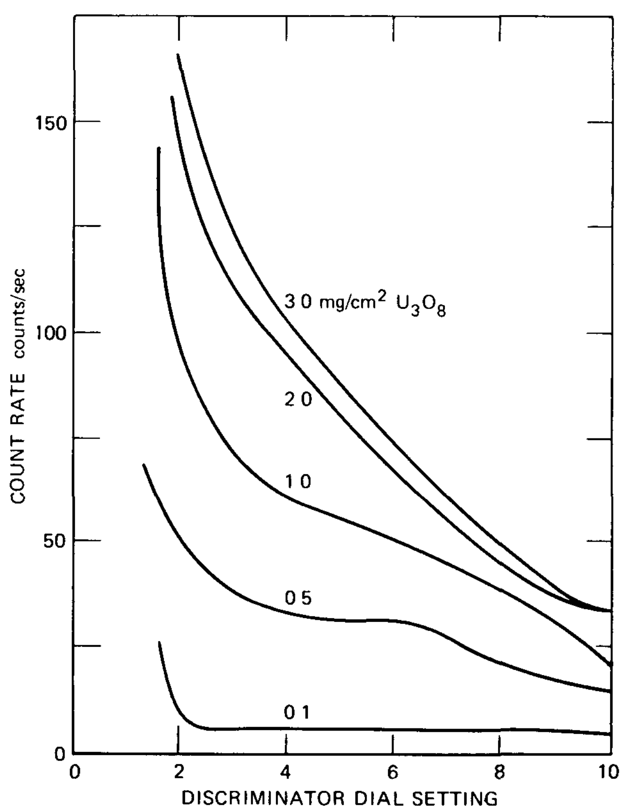

Fig 2.14—Variation of fission-counter integral bias curve with coating thickness [Adapted from William Baer and O F Swift, Some Aspects of Fission Counter Design, *Rev Sci Instrum* **23**(1) 55 (1952)]

2-3 MECHANICAL FEATURES OF GAS IONIZATION SENSORS

2-3.1 Structural Design*

In common with other reactor instruments, nuclear radiation detectors must be rugged This entails construction features that should be recognized by the user

The mechanical design is determined by the requirements of the manufacturing process, by the realities of handling and installation, and by the rigors of the environment in which it is to function During construction, a gas ionization detector must withstand the mechanical stresses when it is evacuated before being filled with gas It must also withstand the high temperature and vacuum used in the outgassing process After it is filled with gas, the detector must be able to withstand the pressure and temperature changes in the reactor environment These requirements in themselves are sufficient to ensure a high degree of ruggedness

The detector must also withstand mishandling and possible abuse during shipping and installation Some applications may require that the detector be moved during operation or between operating periods Unless the accelerations associated with movements are very small, the detector must have electrodes with exceptional mechanical stability to prevent vibration This must be ensured by proper design, e g , including adequate electrode supports

The detector environment is frequently subject to changes in temperature and pressure and to vibration or mechanical noise Differential thermal expansion within the detector is minimized by using materials with similar thermal expansion coefficients, by providing adequate constraints, or by permitting relative motion Any of these methods may make the detector microphonic The high voltage and considerable interelectrode capacitance of the detector greatly enhance the generation of microphonics This tendency can be minimized by careful design of the electrode assembly

2-3.2 Materials of Construction

The choice of materials of construction for a gas ionization detector is a compromise between radiological, mechanical, and thermal requirements For example, in a light structure made of materials of low atomic number, both the self-absorption and the buildup of detector radioactivity are reduced Reduction of both of these effects is desirable in all nuclear radiation detectors However, such a structure is not optimum for a gamma detector, gamma detection is based on generation of Compton scattered (recoil) electrons, a process that is most efficient in heavier structures made of materials with high

*Refer to Figs 2 3, 2 8, and 2 17

atomic number Moreover, a light structure may not meet the requirements for detector ruggedness

The primary criterion in materials selecting is to maximize the generation of the signal Selecting materials to maximize sensitivity to incident gammas involves different considerations from those involved in selecting materials for a neutron detector

In ionization chambers for gamma detection, construction is very important Sensitivity to incident gammas is maximized by increasing the thickness of chamber walls and electrodes, by using structural materials of high atomic number, and by using high density gases of high atomic number There are optimum values for most design features For example, chamber-wall thickness must not be so great that self-shielding causes excessive gamma attenuation In fact, wall thickness need not greatly exceed the range of the most energetic Compton electrons Gas pressure should not be so great as to cause excessive recombination of the ion pairs that are generated by the passage of Compton electrons through the gas The materials selected for a gamma chamber should have low cross sections for reaction with any neutrons that may accompany the incident gammas Moreover, it is preferable that any neutron reactions that do occur should generate a minimum of energetic ionizing radiations Figures 2 15 and 2 16 show the effect of material selection and construction features

On the other hand, if the ionization chamber is designed for maximum neutron sensitivity (with minimum gamma sensitivity), neutron-sensitive materials, i e , materials that create ionizing radiations when exposed to neutrons must be used The choice is influenced by consideration of the mechanical, thermal and radiation properties of the neutron sensitive material

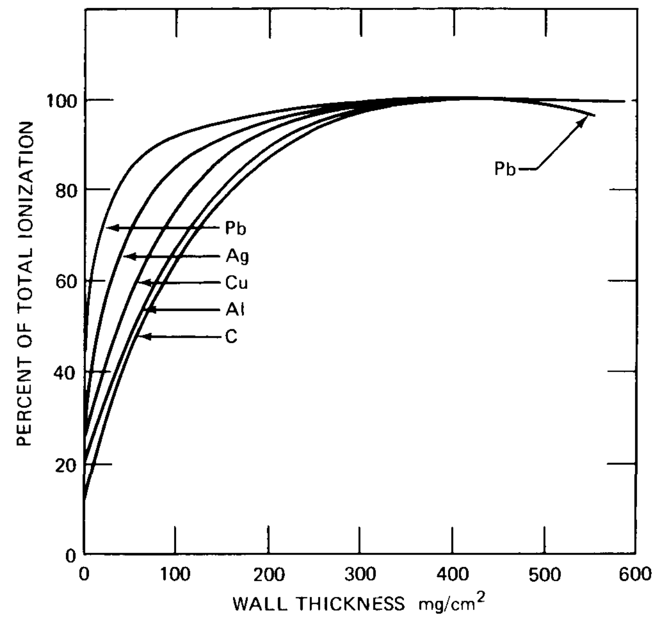

Fig 2 16—Variation of ionization current with wall thickness and chamber material using ^{60}Co radiation [From D V Cormack and H E Johns, The Measurement of High Energy Radiation Intensity, *Radiat Res* 1(2) 146 (1954)]

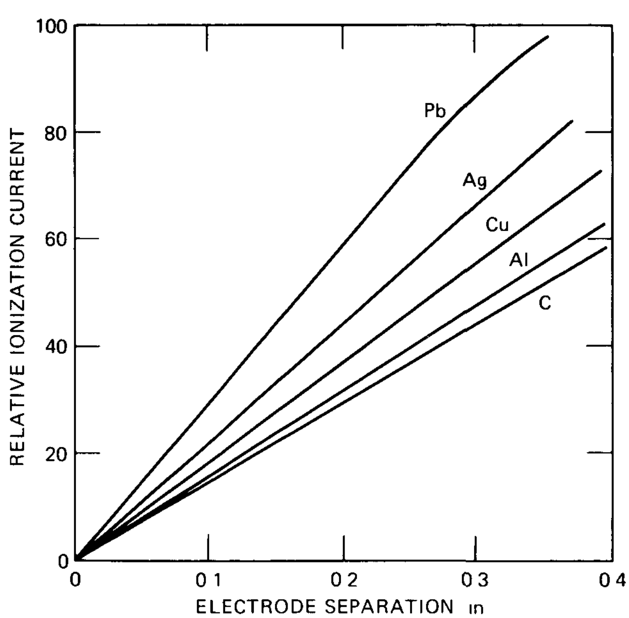

Fig 2.15—Variation of ionization current with size of air volume and chamber material using ^{60}Co radiation [From D V Cormack and H F Johns, The Measurement of High-Energy Radiation Intensity, *Radiat Res* 1(2) 151 (1954)]

2-4 OTHER RADIATION SENSORS

2-4.1 Proportional Counters

A proportional counter is simply an ionization chamber designed to operate using gas multiplication, a form of current amplification caused when the drift velocity of electrons and ions is sufficiently energetic to increase the total ionization [19-22]

Gas multiplication requires a strong voltage gradient, which is difficult to produce in a parallel plate chamber One electrode is a surface and the other electrode is a thin wire The thin wire creates a strong electric field gradient near its surface Figure 2 17 shows a proportional counter The percentage of the total gas volume in which multiplication takes place is adjusted by changing the spacing between electrodes The gain per pulse is most nearly constant when the detected particle is ionizing the non multiplying gas zone The collected ionization then passes entirely through the multiplying gas zone

Gas amplification is electrically adjusted by changing the applied high voltage The sharp gradient about the wire electrode permits operation at moderate voltage Thus, the high voltage supply may be interchangeable with the high voltage supply used for ionization chambers However, unlike an ionization chamber, the proportional counter is

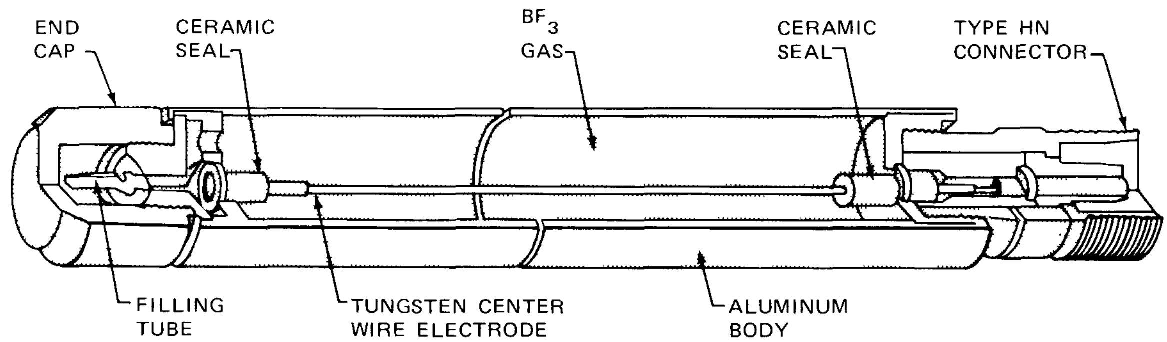

Fig. 2.17—A proportional counter. (*Courtesy Westinghouse Electric Corp.*)

extremely sensitive to voltage variation. A well-regulated high-voltage supply is essential.

The operating voltage of the proportional counter, like that of the ionization chamber, has a plateau.[23] In any particular design there is a range of amplification in which the pulses have a fixed range of amplitudes for a given type

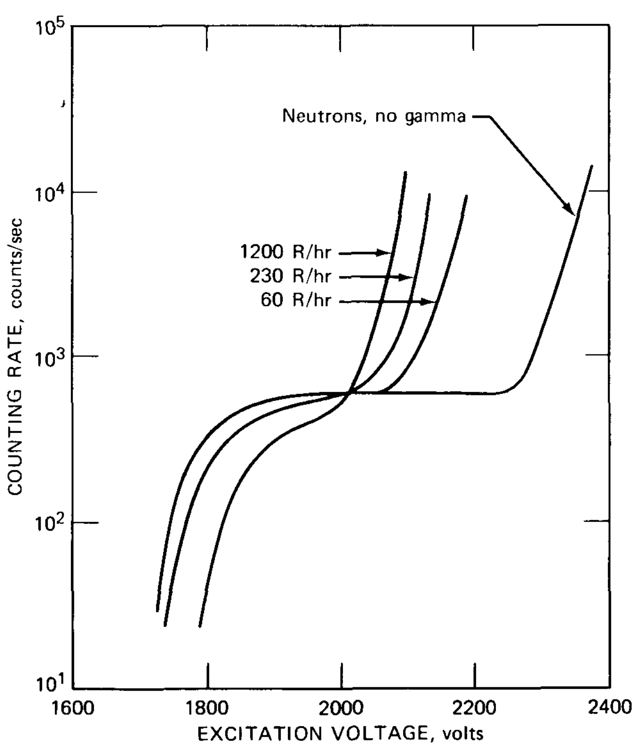

Fig. 2.18—Plateau characteristics of a BF_3 proportional counter under ^{60}Co gamma irradiation. [From O. F. Swift and R. T. Bayard, A Rugged BF_3 Proportional Counter, *Nucleonics*, **17**(5): 126 (1959).]

of radiation. When all pulses over some minimum voltage are counted (pulse height), the plateau is manifested as in Fig. 2.18. Operation on the plateau reduces sensitivity to voltage variation. However, the plateau is normally never as good as that for an ionization chamber.

When detecting neutrons, a proportional counter does not have a gamma tolerance as good as is possible with an ionization chamber; it is typically of the order of 10^3 R/hr. Proportional counters for reactor use are usually BF_3-filled or boron-coated. If boron-coated, a number of gas fills may be used. Figure 2.18 also shows the effect of gamma background. The gammas may be observed to have a deleterious effect on the plateau.

2-4.2 Self-Powered Detectors

Self-powered detectors[24] operate on the well-publicized principle of the nuclear battery. The incident-neutron flux activates a central electrode, which emits betas that are collected by a surrounding electrode. This type detector is usually designed for in-core neutron-flux sensing. It is discussed in Chap. 3, Sec. 3-3.3.

2-4.3 Activation Detectors

Neutron flux at a given position in a reactor can be measured by exposing a material object[25] to the flux, removing it from the flux, and determining the activity that has been induced by exposure to the flux. From the exposure time and the known properties of the exposed material, the incident-neutron flux can be determined. This method can be used in in-core neutron-flux mapping. The exposed material can be in the form of wire, foil, ribbon, etc. Even liquids and gases[26] can be used.

2-4.4 Solid-State and Scintillation Detectors

Solid-state and scintillation detectors[27-30] can only be used where the neutron- and gamma-flux levels are low, for example, in radiation-monitoring systems. Solid-state detectors convert directly to an electrical signal, while scintillation detectors require an intermediate photoelectric stage. There is a wide variety of types. Most, however, are not applicable at neutron fluences above 10^{15} neutrons/cm^2 and integrated gamma exposures of 10^{12} rad.

2-5 INSTALLATION

Once a nuclear radiation sensor has been selected, installation arrangements must be made (see also Chap. 10).

2-5.1 Cables

A mild environment (low temperature and noncorrosive media) poses few problems Sensors are available with cable fittings, and the cable choice can be made easily Over extended periods of time, the nuclear radiation field can interact with the gaseous medium in the vicinity of a sensor and cause corrosion If the medium is air, elimination of moisture during installation and prevention of moisture accumulation after installation is advisable (see Chap 10)

In a severe environment, a detector with an integral cable should be used In this case, the electrical parts of the sensor are effectively separated from the medium

2-5.2 Hardware

Radiological and mechanical requirements pose different installation problems Frequently, some radiation conditioning must be provided, i e , gamma or neutron shielding at the detector location If the exact conditions are known, permanent shielding or neutron thermalizers can be built Usually, some permanent shielding is installed, and flexibility is provided by adjusting the detector position In this case, all possible locations of the detectors must be considered and shielded as needed

It is often possible to provide some gamma shielding or neutron thermalization in the detector package A detector assembly is then needed The detector assembly must be positioned as a unit, which requires some provision for storing excess cable in or around the reactor shield This is particularly difficult for a detector with integral cable For counters a preamplifier must also be mounted as close to the detector as possible Frequently, the excess cable and preamplifier space can be combined

For a detector that is positioned vertically, gravity can usually be relied on A load-bearing cable is then required to support the detector, relieving the electrical connections of any possible stress If positioning is horizontal or at some angle to the vertical, constraints in both directions must be provided This can be done by using a fixed or a temporary rigid member If the position might be disturbed, for example, by moving a second detector in the same general location, a rigid connection or possibly a line-and pulley arrangement may be needed

2-5.3 Circuits

The more specialized circuits are covered in other chapters, particularly Chap 5, and the effects of reactor safety requirements are covered in Chap 12 Some special points are considered here

Interlocking circuits are customarily provided with each detector These interlocks provide a scram signal if the high voltage or signal connections to a detector are interrupted regardless of the cause of the interruption

Also it is generally desirable to prevent the establishment of a ground loop, i e , to prevent ground currents from flowing in the return or ground lead This is done by preventing the exposure of any bare metallic members of the return path Thus, cable connectors and the chamber itself are sometimes insulated The signal circuits are sensitive and of high impedance, so ground loops are a frequent source of trouble (see Chap 10)

2-5.4 Immersion in Coolant

Dry thimbles provide a common and convenient method of installing detectors in coolants The cost of installing dry thimbles is quite high, however, and, in addition, some installations may require cooling or circulating air to ensure dryness Then too, there is always some concern over possible leakage, particularly if the thimble is a penetration of a reactor

These difficulties can be reduced by using detectors suitable for immersion in the particular medium involved Detectors with integral cable have been developed for immersion in water and hot gas, and a detector for immersion in liquid sodium is being developed

Direct immersion, while generally advantageous, has some disadvantages There must still be some sort of channel to restrict the path of motion of the detector Also, the difficulty of making adjustments in position is increased Nevertheless, detectors for direct immersion are finding increased favor

2-6 ENVIRONMENT

Detector environment is largely determined by the type of reactor being instrumented In general, out-of core detectors can be placed in a milder environment than in-core detectors, especially if out of vessel locations are suitable The various environments are described in Chaps 15 to 18

The most important single environmental condition is temperature, which can vary from near room level remote from the reactor core to very high in the vicinity of the core of a gas-cooled or sodium-cooled reactor Ionization chamber detectors that can operate in temperatures up to 750°F (400°C) are available and are suitable for most existing reactors Experimental ionization chambers have been operated with varying degrees of success at temperatures as high as 1400°F (760°C) It is likely that the temperature ratings of commercially available detectors will increase in the future

Gamma background is also an important environmental condition for neutron detectors As reactor power densities are increased in the more sophisticated designs, there will be an increasing need for detectors that can operate in higher gamma backgrounds Improvements in gamma tolerance can be made only with great difficulty The successful use of neutron detectors in high gamma fields depends largely on the ingenuity and skill of the reactor and instrument designers and represents a source of continued difficulty Internal heating may be a problem in gamma fields exceeding 5×10^7 R/hr

High neutron backgrounds in neutron detectors do not normally cause difficulty, since neutrons are the principal instrumentation objective The trend, however, is toward power reactors that have a larger fast neutron fraction in their neutron spectrum Since the sensitivity of neutron detectors, which are primarily thermal neutron detectors, decreases as the energy of the neutrons increases, difficulties are to be expected The main difficulty is assurance that the detector senses neutrons that truly represent reactor power, i e , that vary in a regular way with power variation

In addition, to produce an adequate signal in a fast neutron flux, the detector may require exposure to a high neutron flux This can adversely affect the life and physical characteristics of the detector

Adverse environmental conditions can be avoided by moving the detector For example, start-up detectors that do not have to operate when the reactor is at power can be moved to regions of lower radiation intensity once they are out of range Similarly, other sensors may be moved to a more favorable environment as reactor power is increased The use of detector withdrawal might enable reliable instrumentation where the background is otherwise too severe Safety instruments should not be moved unless they are no longer required Satisfactory operation in the new position must be assured

Excessive neutron flux and gamma gradients may contribute to instrumentation faults In general, it is desirable to operate with a large signal to extend the sensor range In a high flux gradient, a part of a sensor may be operating in excess of its rating This implies operation with a lower input signal than proper use would provide In addition, the most effective gamma compensation is obtained in a low gradient gamma field Thus, to the extent that the gamma gradient is related to the neutron gradient, it is likely that compensation may be less effective and there will be a loss of range

2-7 LIFE AND RELIABILITY

Valid statistical data on the performance of out-of core neutron and gamma sensors are scarce However it may be inferred from examination of sensor designs and from general knowledge of the field that reliability has been good The most frequently reported difficulties have been from spurious signals attributable to microphonic and electrical effects (These are discussed in Chap 10) Since these effects can usually be observed in the debugging period, they can be rectified by modifying the system design

Ionization detectors generally have long lives The life of a neutron detector is, however, limited by consumption of sensitive materials Since the consumption is directly related to the neutron fluence, the loss may be calculated and compensated for by recalibration In early designs, flaking of sensitive material with subsequent deposition in insensitive parts of the chamber volume was occasionally experienced Generally, flaking is not a problem at present As might be expected, gamma detectors have an indefinitely long life since they contain no sensitive materials

In a number of ionization chamber detectors using special gas mixtures, gradual degradation results from radiologically induced changes in gas composition Since this type detector is normally used only for very special purposes, it is expected that the user would be alert to any possible difficulties Certain proportional counters fall in this category and are normally used only at moderate or low radiation levels

Scintillation and solid-state detectors are useful at low radiation levels only and can withstand only a limited total radiation exposure

2-8 TYPICAL SPECIFICATIONS OF COMMERCIAL GAS IONIZATION SENSORS

Typical specifications are summarized in Table 2 2 Since many different types are available, the values in the table have been entered as ranges

Tables 2 3 through 2 7 indicate the variety of neutron and gamma sensors available from one manufacturer The sensors listed are limited to those discussed in this chapter Commercial in-core neutron sensors are described in Chap 3

Table 2 2—Typical Specifications for Commercial Out of-Core Gas Ionization Detectors

	Gamma chambers	Ionization chambers	Compensated ionization chambers	Fission counters	Proportional counters
Sensitivity					
amp/(R/hr)	10^{13} to 10^{9}	10^{12} to 10^{10}	10^{12} to 10^{11}		
amp/nv*		10^{14} to 5×10^{13}	10^{15} to 10^{14}		
(counts/sec)/nv*				10^{4} to 2	3 to 40
Operating voltage	100 to 1500	200 to 1200	200 to 1500	200 to 1200	800 to 5000
Max temp °F	175 to 600	175 to 850	175 to 750	250 to 850	175 to 500
Diameter in	1 to 3	1 to 3 5	3 to 4	0 1 to 3	1 to 6
Length in	12 to 16	10 to 16	8 to 25	5 to 300	10 to 40

*Where nv is measured in neutrons cm ^{2} sec ^{1}

Table 2.3—Uncompensated Ionization Chambers*

Neutron-sensitive material	Thermal-neutron sensitivity, amp/nv†	Gamma sensitivity, amp/(R/hr)	Max. oper. thermal-neutron flux, nv†	Typical oper. voltage, volts (d-c)	Min signal resistance, ohms	Signal capacitance, pF	Max. oper. temp., °F	Detector insulator‡	Nominal dimensions: Length, Sensitive, in.	Length, Overall, in.	Detector O.D., in.
^{235}U	1.4×10^{-13}	4.2×10^{-11}	1.4×10^{10}	300–1000	10^{9}	150	300	Al_2O_3	6	11½	2
^{10}B	4.4×10^{-14}	4.5×10^{-11}	5.0×10^{10}	200–1000	10^{11}	170	300	Al_2O_3	7	13⅝	3
^{235}U	2.6×10^{-14}	3.0×10^{-11}	8.5×10^{10}	300–1000	10^{9}	140	300	Al_2O_3	6	11½	2
^{235}U	3.0×10^{-14}	4.2×10^{-11}	6.0×10^{10}	300–1000	10^{9}	150	300	Al_2O_3	6	11½	2
^{235}U	1.4×10^{-14}	4.2×10^{-11}	1.4×10^{11}	300–1000	10^{9}	150	300	Al_2O_3	6	11½	2
^{10}B	4.4×10^{-14}	4.5×10^{-11}	5.0×10^{10}	200–1000	10^{10}	170	575	Al_2O_3	7	13⅝	3
^{235}U	4.0×10^{-14}	4.0×10^{-11}	2.7×10^{10}	200–1000	10^{9}	160	575	Al_2O_3	7	13⅝	3
^{235}U	1.4×10^{-13}	4.2×10^{-11}	1.4×10^{10}	300–1000	10^{9}	150	300	Al_2O_3	6	11½	2
^{10}B	4.4×10^{-14}	4.5×10^{-11}	5.0×10^{10}	200–1000	10^{11}	170	300	Al_2O_3	7	13⅝	3
^{10}B	1.5×10^{-14}	3.5×10^{-12}	5.0×10^{10}	300–800	10^{13}	110	175	Rex	5½	10½	3½
^{235}U	2.8×10^{-14}	4.0×10^{-11}	5.0×10^{10}	300–1000	10^{9}	170	500	Al_2O_3	7	13⅝	3
^{235}U	5.1×10^{-14}	5.0×10^{-11}	2.7×10^{10}	300–1000	10^{7}	283	850	Al_2O_3	10	15⅞	1⅞
^{235}U	4.0×10^{-14}	4.0×10^{-11}	2.7×10^{10}	300–1000	10^{7}	150	700	Al_2O_3	7	13⅝	3
^{235}U	1.4×10^{-13}	4.2×10^{-11}	1.4×10^{10}	300–1000	10^{8}	1000	390	Al_2O_3	6	276	3
^{10}B	1.2×10^{-14}	3.0×10^{-12}	1.0×10^{10}	200–1000	10^{12}	1880	175	Al_2O_3	10	15⅛	1
^{10}B	3.0×10^{-13}	1.8×10^{-10}	2.5×10^{10}	300–1100	10^{13}	1850	175	Rex	108	113⅜	3½

**Courtesy Westinghouse Electric Corp.*

†Nv is expressed in neutrons cm^{-2} sec^{-1}

‡Al_2O_3 is a high alumina content ceramic Rex is a cross linked styrene

Table 2.4—Compensated Ionization Chambers*

Thermal-neutron sensitivity, amp/nv†	Uncomp. gamma sensitivity, amp/(R/hr)	Max. oper. thermal-neutron flux, nv†	Typical oper. voltage, volts (d-c)	Min. signal resistance, ohms	Signal capacitance, pF	Max. oper. temp., °F	Insulation type‡		Nominal dimensions		
									Length		Detector O.D., in.
							Detector	Conn.	Sensitive, in.	Overall, in.	
4 4 x 10^{14}	2 3 x 10^{11}	2 5 x 10^{10}	300–1000	10^{14}	275	175	Rex	Rex	14	$23\frac{5}{8}$	$3\frac{1}{8}$
4 4 x 10^{-14}	2 3 x 10^{11}	2 5 x 10^{10}	300–1000	10^{14}	275	175	Rex	Rex	14	$24\frac{1}{8}$	$3\frac{1}{8}$
4 4 x 10^{14}	2 5 x 10^{-11}	2 5 x 10^{10}	300–1000	10^{12}	315	575	Al_2O_3	Al_2O_3	14	$23\frac{3}{4}$	$3\frac{1}{8}$
4 4 x 10^{14}	2 3 x 10^{-11}	2 5 x 10^{10}	300–1000	10^{13}	275	175	Rex	Rex	14	$23\frac{5}{8}$	$3\frac{1}{8}$
1 5 x 10^{-14}	3 5 x 10^{12}	2 5 x 10^{10}	300–800	10^{13}	130	175	Rex	Rex	$5\frac{1}{2}$	$10\frac{1}{2}$	$3\frac{1}{2}$
1 5 x 10^{14}	3 5 x 10^{-12}	2 5 x 10^{10}	300–800	10^{13}	135	175	Rex	Rex	$5\frac{1}{2}$	$10\frac{1}{2}$	$3\frac{1}{2}$
4 4 x 10^{14}	2 3 x 10^{11}	2 5 x 10^{10}	300–1000	10^{13}	290	400	Al_2O_3	Al_2O_3	14	$19\frac{1}{8}$	$3\frac{1}{8}$
1 0 x 10^{15}	1 5 x 10^{13}	1 5 x 10^{12}	25–250	10^{11}	155	660	Al_2O_3	Al_2O_3	$2\frac{5}{16}$	$7\frac{5}{16}$	3
4 4 x 10^{14}	2 3 x 10^{11}	2 5 x 10^{11}	300–1500	10^{13}	290	300	Al_2O_3	Al_2O_3	14	$19\frac{1}{8}$	$3\frac{1}{8}$

**Courtesy Westinghouse Electric Corp.*

†Nv is expressed in neutrons cm ^{2} sec ^{1}

‡Al_2O_3 is a high alumina-content ceramic, Rex is a cross-linked styrene

Table 2.5—Fission Counters*

Thermal-neutron sensitivity, (counts/sec)nv†	Max. oper thermal-neutron flux, nv†	Typical oper. voltage, volts (d-c)	Min. signal resistance, ohms	Signal capacitance, pF	Max. oper. temp., °F	Insulator type‡		Nominal dimensions		
								Length		Detector O.D., in
						Detector	Conn	Sensitive, in.	Overall, in	
0 7	1 4 × 10^{5}	200–800	10^{9}	150	300	Al_2O_3	Al_2O_3	6	11½	2
0 2	5 0 × 10^{5}	200–800	10^{9}	140	300	Al_2O_3	Al_2O_3	6	11½	2
0 14	7 0 × 10^{5}	200–800	10^{9}	150	300	Al_2O_3	Al_2O_3	6	11½	2
1 25 × 10^{3}	1 0 × 10^{8}	250 500	10^{9}	55	575	Al_2O_3	Rex	⅜	53 5/16	0 210
0 52	2 0 × 10^{5}	200–800	10^{9}	150	300	Al_2O_3	Al_2O_3	6	11½	2
0 07	1 4 × 10^{6}	200–800	10^{9}	150	300	Al_2O_3	Al_2O_3	6	11½	2
0 7	1 4 × 10^{5}	200–800	10^{9}	160	575	Al_2O_3	Al_2O_3	7	13⅝	3
0 7	1 4 × 10^{5}	200 800	10^{9}	150	300	Al_2O_3	Al_2O_3	6	11½	2
0 7	1 4 × 10^{5}	200 800	10^{7}	150	700	Al_2O_3	Al_2O_3	6	11½	2
0 1	1 0 × 10^{6}	300 800	10^{9}	30	575	Al_2O_3	Al_2O_3	4¾	7⅞	1
0 14	7 0 × 10^{5}	200 800	10^{9}	170	500	Al_2O_3	Al_2O_3	7	13⅝	3
0 5	2 0 × 10^{5}	200 800	10^{7}	283	850	Al_2O_3	Al_2O_3	10	15⅞	1⅞
0 25	4 0 × 10^{5}	200 800	10^{7}	150	700	Al_2O_3	Al_2O_3	7	13⅝	3
5 × 10^{3}	2 0 × 10^{8}	350 650	10^{10}	40	750	Al_2O_3		1	5	2
0 7	1 4 × 10^{5}	75	10^{9}	160	500	Al_2O_3	–	7	14	3
0 35	2 8 × 10^{5}	200 800	10^{9}	150	300	Al_2O_3	Al_2O_3	6	11½	2
§	1 0 × 10^{8}	200 800	10^{9}	150	300	Al_2O_3	Al_2O_3	6	11½	2
0 7	1 4 × 10[illegible]	200–800	10^{8}	1000	390	Al_2O_3	Al_2O_3	6	276	3
2 2 × 10^{4}	5 0 × 10^{8}	250 800	5 × 10^{8}	2	500	Al_2O_3	–	5/16	1 1/16	0 220
1 5 × 10^{3}	1 0 × 10^{8}	300-500	10^{8}	260	500	Al_2O_3	Al_2O_3	⅜	243	0 210
1 × 10^{-5}	1 0 × 10^{11}	100–200	10^{9}	125	250	LF	Rex	11/32	63 5/16	0 090
0 18	6 0 × 10^{5}	200–800	10^{9}	45	575	Al_2O_3	Al_2O_3	8⅞	12	1
0 5	2 0 × 10^{5}	200–800	10^{8}	150	390	Al_2O_3	Al_2O_3	6	11½	2
0 35	3 0 × 10^{5}	200 800	10^{8}	90	390	Al_2O_3	Al_2O_3	3	8½	2

**Courtesy Westinghouse Electric Corp.*

†Nv is expressed in neutrons cm ^{2} sec ^{1}

‡Al_2O_3 is a high alumina-content ceramic Rex is a cross linked styrene

§Sensitive material is ^{238}U Sensitivity to ≳1 5 MeV neutrons = 10^{3} to thermal neutrons = 1 4 × 10^{4}

Table 2.6—Proportional Counters*

Thermal-neutron sensitivity, (counts/sec)/nv†	Max. oper. thermal-neutron flux, nv†	Gas fill press., cm Hg	Typical oper. voltage, volts (d-c)	Min. signal resistance, ohms	Signal capacitance, pF	Max. oper. temp., °F	Insulator type‡ Detector	Insulator type‡ Conn.	Nominal dimensions: Length Sensitive, in.	Nominal dimensions: Length Overall, in.	Nominal dimensions: Detector O.D., in.
					BF_3 Counters						
4 5	1 0 $\times 10^5$	55	2000	10^{11}	10	250	Al_2O_3	Rex	$8\frac{5}{8}$	12	1
13	4 0 $\times 10^4$	55	2000	10^{11}	20	250	Al_2O_3	Rex	26	$30\frac{3}{8}$	1
40	1 25 $\times 10^4$	55	2000	10^{11}	610	175	Al_2O_3	Rex	26	$39\frac{5}{8}$	$5\frac{7}{8}$
13	4 0 $\times 10^4$	55	2000	10^{10}	30	175	Al_2O_3	Rex	$8\frac{5}{8}$	$15\frac{7}{16}$	$2\frac{7}{8}$
13	4 0 $\times 10^4$	55	2000	10^{11}	15	250	Al_2O_3		26	$29\frac{5}{8}$	1
40	1 25 $\times 10^4$	55	2000	10^{11}	610	175	Al_2O_3	Rex	26	$39\frac{5}{8}$	$4\frac{13}{16}$
35	1 25 $\times 10^4$	55	2000	10^{11}	70	310	Al_2O_3	Rex	26	33	3
45	1.0 $\times 10^4$	55	2000	10^{10}	780	175	Al_2O_3		26	$33\frac{1}{2}$	§
19	2 6 $\times 10^4$	160	2200	10^{11}	10	250	Al_2O_3	Rex	12	$15\frac{7}{16}$	1
13	4 0 $\times 10^4$	160	4100	10^{11}	10	250	Al_2O_3	Rex	$8\frac{5}{8}$	12	1
35	1 4 $\times 10^4$	70	2100	10^{12}	10	300	Al_2O_3	Rex	12	$15\frac{7}{16}$	2
6 5	7 5 $\times 10^4$	55	2000	10^{11}	10	250	Al_2O_3	Rex	12	$15\frac{7}{16}$	1
20	2 5 $\times 10^4$	167	4700	10^{11}	10	250	Al_2O_3	Rex	12	$15\frac{7}{16}$	1
					^{10}B Counters						
10	5 0 $\times 10^4$	20	800	10^{12}	20	400	Al_2O_3	Rex	26	$30\frac{3}{8}$	1
3	1 7 $\times 10^5$	20	800	10^{12}	12	400	Al_2O_3	Rex	$8\frac{5}{8}$	$12\frac{13}{16}$	1
4	1 25 $\times 10^5$	20	800	10^{12}	14	400	Al_2O_3	Rex	$10\frac{1}{2}$	$14\frac{15}{16}$	1
3	1 7 $\times 10^5$	20	800	10^{12}	12	500	Al_2O_3	Al_2O_3	$8\frac{5}{8}$	12	1
31	1 7 $\times 10^4$	20	800	10^{11}	70	400	Al_2O_3	Rex	26	33	3
					^3He Counters						
22	2 5 $\times 10^4$	760	4500	10^{11}	10	300	Al_2O_3	Rex	6	$10\frac{3}{8}$	1
16	3 0 $\times 10^4$	152	900	10^{11}	10	300	Al_2O_3	Rex	$8\frac{5}{8}$	12	1

**Courtesy Westinghouse Electric Corp.*

†Nv is expressed in neutrons cm^{-2} sec^{-1}

‡Al_2O_3 is a high-alumina-content ceramic, Rex is a cross linked styrene

§Oval case $7\frac{15}{16}$ in and $3\frac{3}{16}$ in

Table 2.7—Gamma Chambers*

Gamma sensitivity, amp/(R/hr)	Max oper. gamma flux, R/hr	Typical oper. voltage, volts (d-c)	Min signal resistance, ohms	Signal capacitance, pF	Max. oper. temp., °F	Detector insulator†	Nominal dimensions: Length, Sensitive, in.	Length, Overall, in.	Detector O.D., in
$3 0 \times 10^{12}$	4×10^5	200–1000	10^{12}	1880	175	Al_2O_3	10	$15\frac{1}{8}$	1
$1 0 \times 10^{11}$	5×10^7	100 1200	10^{13}	125	575	Al_2O_3	8	$12\frac{3}{8}$	2
$1 0 \times 10^{10}$	3×10^7	100–1200	10^{13}	125	575	Al_2O_3	8	$12\frac{3}{8}$	2
$2 5 \times 10^{9}$	2×10^3	200–1500	10^{11}	170	300	Al_2O_3	7	$13\frac{5}{8}$	3

**Courtesy Westinghouse Electric Corp*

†Al_2O_3 is a high alumina content ceramic

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Chapter 3

Neutron Sensors — In-Core

Howard H Stevens

3-1 INTRODUCTION

In core neutron sensors accomplish one or more of the following (1) confirm calculated core performance (2) confirm core operating safety margins, (3) provide input data for fuel management and (4) detect the existence of xenon induced power asymmetries or oscillations (see Chap 1, Sec 1–3 6(a) for a discussion of xenon)

The first of a kind power reactor core is usually more thoroughly instrumented than cores of duplicate or similar reactors because of the need to confirm calculated nuclear and thermal performance This practice has become prevalent as core designers have become more dependent on computer codes for nuclear and thermal data and less dependent on critical experiments data The first of-a-kind plant therefore serves as a field laboratory to confirm design calculations It is not intended to generate new experimental data

When reactor complexity, size, power output, power density, or neutron flux level increases beyond certain limits, safe operation of the reactor over its lifetime cannot depend on data from out of core instruments The reactor operator must have available to him the outputs from in-core neutron sensors so he can determine if the core is operating within prescribed safety limits

In large power reactors in-core neutron sensors provide the data needed for carrying out an effective fuel management program and monitor for the existence of xenon induced power asymmetries or instabilities It is normally possible to detect the presence of such asymmetries or instabilities with out of-core instruments, but in-core sensors must be used to ascertain their exact nature and to provide the data from which an operator can carry out effective control actions (i e , equalizing asymmetries or damping out oscillations) In-core neutron sensors also provide the data for correlating core performance with the response of the out of-core sensors

To be effective, the in-core sensors should provide data continuously or, at a minimum, at periodic intervals while the reactor is operating in its normal mode Reactor shutdown should not be required to collect the data, such as would be the case if activation foils were used for flux distribution measurements or if gamma scanning of fuel elements were used for determining irradiation history

CHAPTER CONTENTS

3-2 IN-CORE ENVIRONMENT

The environment in which an in core sensor operates is hostile to both the sensor materials and the means of transmitting signals to the readout instruments In most cases the environment includes high neutron flux ($>10^{12}$ neutrons cm^{-2} sec^{-1}), intense gamma fields ($>10^8$ R/hr), elevated temperature (>500°F or 210°C), and high pressure (>1000 psi), along with other undesirable effects, such as vibration induced by coolant flow or boiling Although it is not reasonable to expect in-core sensors to last through the entire life of the reactor in such a hostile environment, nevertheless the sensors should be designed so they do not require removal or replacement more frequently than once

every time the reactor is refueled. Most in-core neutron sensors can last through several refueling cycles.

Another factor in the design of in-core sensors is the space limitation. Power reactors have closely spaced lattices of fuel rods and fuel assemblies; seldom is more than ½ to ¾ in. available for installing an in-core sensor. As a result, in-core sensors must be rugged enough to withstand the rigors of the nuclear radiations and the thermal and mechanical environment and small enough to fit in the available space.

At full power the thermal-neutron flux in the core of a power reactor is more than 10^3 times the out-of-core neutron flux. Typical values are 3 to 5 × 10^{13} neutrons cm^{-2} sec^{-1}, with peak values of over 10^{14}. Materials used in the construction of in-core neutron sensors must be resistant to neutron damage during the expected lifetime of the sensors. Similarly, the gamma field is more than 10^3 times that in out-of-core positions, where the exposure rate is usually 3 to 5 × 10^4 R/hr. Heating of the sensor materials by absorption of gamma energy must be considered in both the design and location of the sensor, and adequate cooling must be provided. Damage to the material from gamma exposure must also be taken into account.

The temperature in a power reactor at the location of an in-core neutron sensor is generally determined by the temperature of the reactor coolant at that location. Boiling-water reactors operate at saturated steam conditions that average 550°F (288°C). In some instances where higher pressure is used to extend unit capacity, the temperatures range up to 595°F (313°C). In pressurized-water reactors the core operating temperatures vary with load and location in the core but seldom fall below 520°F (271°C) or exceed 630°F (332°C). Gas- and sodium-cooled reactors operate at temperatures considerably higher than those in water reactors. Gas-cooled reactor temperatures range from 650°F (343°C) to 1450°F (788°C), depending on load and location in the core, and sodium-cooled reactor temperatures vary from 700°F (370°C) to 1000°F (540°C).

Water reactors characteristically operate at a higher pressure than gas- and sodium-cooled reactors because of the higher vapor pressure of water. Nominal operating pressure for boiling-water reactors is 1000 psi. Some of the early boiling-water reactors were capable of operation up to 1500 psi to obtain increased steam-flow capability at the turbine generator.

Pressurized-water reactors operate at pressures that maintain subcooled conditions in the reactor coolant system. Most pressurized-water reactors operate at 2250 psi. The external sheath or enclosure of an in-core neutron sensor must withstand these pressures without collapsing and must be watertight so moisture cannot degrade the insulation resistance of the sensor and cables. Likewise, the high operating pressure calls for careful design and installation of penetrations through the reactor vessel to preclude coolant leakage to the atmosphere.

In gas-cooled reactors operating pressures vary from 300 to 700 psi, and in sodium-cooled reactors the operating pressures are 200 psi. Pressure does not present as significant a problem in designing in-core neutron sensors and cables and seals for gas- and sodium-cooled reactors as does the high operating temperature.

The velocity of the reactor coolant through the core of pressurized-water reactors averages 15 ft/sec (4.6 m/sec). Bulk boiling takes place in the core of a boiling-water reactor. The dynamic forces resulting from coolant flow and bulk boiling must be factored into the design of in-core sensors.

3-3 IN-CORE NEUTRON-FLUX SENSING

In-core neutron sensors are most important because of the direct relation between the neutron-flux distribution and the thermal-power distribution in the reactor core.

Systems for determining neutron-flux distribution fall into two broad categories: systems using *fixed sensors* at a large number of fixed locations to provide data for generating one-, two-, or three-dimensional power-distribution information, and systems using *traveling (mobile) neutron-sensing devices* to provide a large number of neutron-flux scans of the core from which the desired power-distribution information can be derived. There are advantages and disadvantages to each system.

Fixed sensors can provide the operator with neutron-flux data at all times during reactor operation. They can also be adapted to sound an alarm or to control or protect against any power-distribution anomaly that develops during the time interval between successive scans of a traveling sensor. Because the sensors are fixed in position, they must be made so they require no maintenance; in fact, generally, no maintenance or replacement can be performed on a fixed in-core sensor without shutting down the reactor. However, because fixed sensors are continuously exposed to the in-core environment during plant operation, they suffer radiation degradation or damage and must be replaced at planned intervals during refueling periods. Fixed sensors distributed throughout the reactor volume provide data at discrete points; data at all other points must be obtained by interpolation through curve fitting, usually with a computer (either on-line or off-line). The errors in the interpolated data depend on the sensor spacing and the precision of the computer curve-fitting routines.

Traveling or mapping flux-sensor systems, although unable to provide flux-distribution information at all times for alarm, control, or protection, can provide a spatially continuous flux plot along the entire path over which they travel. Traveling sensors thus can detect flux perturbations not picked up by fixed sensors, such as the flux disturbances at fuel spacer grids and at the ends of control rods. Although these perturbations are seldom of great significance in reactor operation, since there is not much one can

do about them, the ability to sense them can lend confidence that the entire neutron-flux distribution is being observed, i e , an accurate one-dimensional picture of the real flux distribution is being observed The other two dimensions must still be filled in by interpolation through computer calculations unless, of course, there are traveling flux sensors in the other dimensions as well (which is not the case in present-day power reactors)

Although traveling or mapping neutron flux sensing systems incorporate motors and gear boxes that may require periodic maintenance, they are located where maintenance can be performed with minimum difficulty The flux sensors themselves may last the life of the reactor since flux maps are run only at relatively infrequent intervals and since the sensors are withdrawn from the core when not in use

All neutron-flux sensing systems measure the properties of the products of interactions between neutrons and the sensor materials (see Chap 2) When a neutron sensor is exposed for a long time to a neutron flux, its neutron sensitivity (output signal per unit neutron flux) usually decreases and its gamma sensitivity (output signal per unit gamma flux) remains unchanged This results in a steady decrease in the signal-to noise ratio with neutron exposure When the signal to-noise ratio decreases below a specified value, the lifetime of the neutron sensor is ended (by definition) For a given neutron sensor exposed to a mixed neutron and gamma flux, it follows that any design action that increases the initial value of the neutron to gamma signal ratio also increases the lifetime of the sensor

3-3.1 In-Core Fission Chambers

Fission chambers are most commonly used as in-core neutron flux sensors They are the backbone of the in-core neutron detection systems in the majority of boiling-water reactors (see Vol 2, Chap 16, Sec 16 2) The fission chamber is used as the neutron sensor in most traveling in core probe systems for both pressurized water reactors and boiling water reactors

Fission chambers feature relatively slow burnup of the uranium liner They provide satisfactory operation in all three basic modes (1) the pulse-counting mode, (2) the mean square-voltage mode, and (3) the mean-current (d-c) mode (see Chap 5, Sec 5 5, and Chap 2, Sec 2 2) In core fission chambers are thus suitable for use in source-range channels (where pulse counting is required because of the low value of the neutron flux) in the intermediate-range channels (where mean square voltage techniques extend the operating range), and in the power-range channels (where mean current techniques provide accurate power measurements for both fixed sensors and traveling probes) For each of these modes of operation, the optimum design is different with respect to size, materials, fill gas pressure, emitter–collector gap dimensions, neutron sensitivity, etc

Just as in out-of core neutron detectors, both the neutron and the gamma fluxes contribute to the total output of an in core fission chamber Many of the design parameters which may be changed to achieve a specific neutron-sensitivity characteristic also affect the gamma sensitivity Since the output signal attributable to incident gamma radiation is not unambiguously related to the reactor power level, the design of an in-core fission chamber is optimum if at the end of detector life the ratio of the output current due to neutron flux to the output current due to gamma radiation is still acceptable

The main design parameters that can be varied to meet the specific requirements for an in-core fission chamber are (1) the physical form of the uranium used, (2) the enrichment of the uranium, (3) the surface area and thickness of the uranium, (4) the type of fill gas used, (5) the fill-gas pressure, (6) the dimensions of the gap between the emitter and the collector, and (7) the dimensional tolerances Each of these is discussed below

(a) Uranium Form Two basic types of in-core fission chambers have been developed and manufactured One type incorporates an enriched uranium oxide layer plated on the inside of the detector housing that forms the outside wall of the sensitive volume (see Fig 3 1) The second type contains a machined sleeve of enriched uranium–aluminum alloy at the outer surface of the sensitive volume (see Fig 3 2) The more carefully the weight and thickness of the uranium coating or uranium–aluminum sleeve are controlled, the more accurately the neutron sensitivity of the detector can be controlled The majority of commercial detectors are manufactured with a ±20% tolerance on initial neutron sensitivity Under very special circumstances a ±5% tolerance on initial neutron sensitivity can be achieved by carefully controlling the uranium plating process or the uranium–aluminum alloy machining

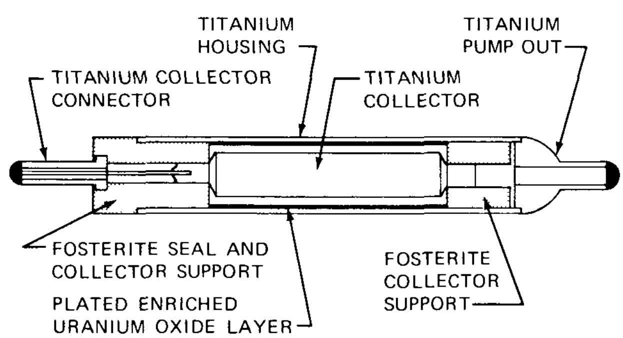

Fig 3.1—Uranium oxide coated in core fission chamber

(b) Uranium Enrichment. Because the enrichment of the uranium in a neutron sensor has no effect on the gamma sensitivity (total mass of uranium is constant), the best way to increase the signal-to-noise ratio is to increase the enrichment of the uranium used in the sensor Fully enriched uranium provides the maximum neutron sensitivity while maintaining the same gamma sensitivity.

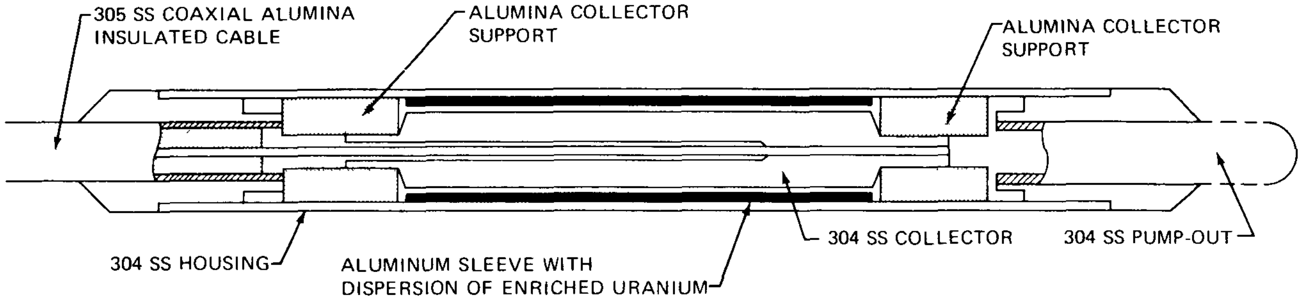

Fig. 3.2—Uranium–aluminum alloy sleeve in-core fission chamber.

(c) Uranium Surface Area. For a given total mass of the enriched uranium layer, the neutron sensitivity of an in-core fission chamber depends on the surface area of the uranium. Surface area is varied by changing the chamber diameter and length. The gamma sensitivity also varies when the chamber geometry is changed. Consequently, there is a combination of sensor diameter and length which yields the highest signal-to-noise ratio.

(d) Type of Fill Gas. Argon is the most commonly used fill gas. It has all the desired properties (chemically inert, good thermal conductivity, low thermal-neutron cross section, and suitable ionization properties). Other commonly used fill gases are helium and nitrogen or mixtures of argon and nitrogen.

Chemical inertness is desirable since a gas that is not inert may combine with chamber materials (particularly in presence of an intense nuclear radiation field) and thus reduce the gas available for ionization. High thermal conductivity is desirable to remove heat developed in the chamber by the signal-generating processes. If the thermal-neutron cross section is high, the fill gas will be depleted by nuclear transformation; in addition, neutrons absorbed by the fill gas are not available for reaction with the uranium.

(e) Fill-Gas Pressure. Neutron and gamma sensitivities of an in-core fission chamber are directly proportional to the fill-gas pressure as long as the range of fission fragments and gamma photons is greater than the gap between the emitter and collector. Most in-core fission chambers operate at several atmospheres pressure to achieve higher neutron and gamma sensitivities. Because both the gamma and neutron sensitivities are similarly increased, detector life is not appreciably affected by varying the fill-gas pressure.

(f) Emitter–Collector Gap. Of all the factors involved in in-core fission-chamber design, the most critical is the sizing of the gap between the neutron-sensitive emitter and the positively charged collector. Since the ionization current is a function of the number of fill-gas atoms, a large gap produces a large detector current. This characteristic is especially important at low flux levels, such as those existing in the source range. At higher flux levels the gap must be reduced to ensure detector saturation [Sec. 3-3.1(h)] up to and exceeding the highest neutron flux the detector is designed for.

(g) Dimensional Tolerances. As noted earlier, the accuracy of initial detector sensitivity is directly related to the dimensional tolerances applied to the neutron-sensitive material and to the emitter–collector gap. Because so many of the characteristics of in-core fission chambers are related directly to dimensions, the effects of tolerance accumulation are extremely important and must be carefully considered.

(h) Operating Characteristics. In-core fission chambers exhibit most of the operating characteristics of out-of-core neutron sensors. As pointed out in Chap. 2, Sec. 2-2.1, variation of chamber voltage provides three regions of detector performance: the low-voltage (presaturation) region, the plateau (saturation) region, and the multiplication region. The exact shape of the current–voltage curve depends on chamber construction parameters.

In view of this characteristic behavior of fission chambers, it follows that the voltage applied to the chamber should be high enough to keep it on the plateau region at or above the highest radiation flux in which it is expected to operate. If there is any question about the chamber voltage required to achieve saturated operation, it is preferable to err on the high side, since the chamber current is proportional to the incident radiation flux in both the saturation and multiplication regions but not in the presaturation region. For most in-core fission chambers being used in power reactors today, the neutron flux never exceeds 2×10^{14} neutrons cm^{-2} sec^{-1}, so an operating voltage of 125 volts d-c is sufficient to guarantee saturated operation. Figure 3.3 shows saturation curves for a typical in-core fission chamber.

The ideal detector plateau would be flat, but this is never achieved. Below 10^{13} neutrons cm^{-2} sec^{-1}, the plateau has a slope that is generally attributable to detector-cable leakage current. As the neutron flux increases, the plateau starting voltage (the low end of the plateau) increases and the multiplication starting voltage (the low end of the multiplication region) decreases. When the neutron flux increases to the point where the plateau starting voltage equals the multiplication starting voltage, the plateau disappears. This point is generally defined as the *upper flux limit* of the detector.

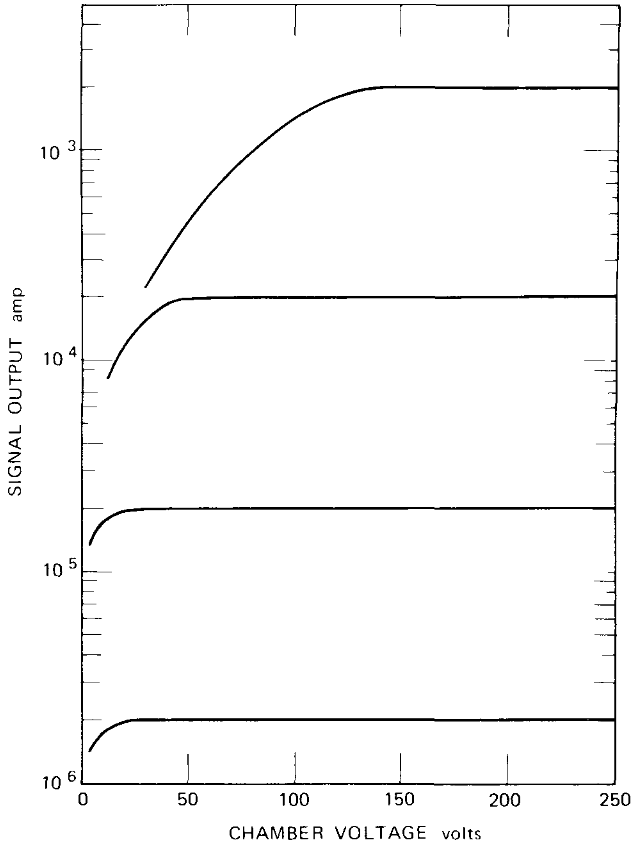

Fig 3 3—Typical in core fission chamber saturation characteristics

It is more important for an in core fission chamber operating in the mean square voltage mode* to stay in the plateau region than for one operating in the pulse counting mode or the mean current (d c) mode This results from the fact that the signal is a function of chamber current squared rather than chamber current alone Figure 3 4 shows that as a result the plateau starting voltage of a mean square voltage chamber is somewhat higher and the multiplication starting voltage somewhat lower than a d-c chamber

In the mean square voltage mode of operation, adjustment of the chamber voltage must be related to the band pass of the signal amplifier into which the chamber operates Pulses from the chamber are distributed in energy in accordance with the power frequency spectrum curves in Fig 3 5 The breaks in the curves occur at the frequencies corresponding to the ion collection time, T_i and the electron collection time, T_e Reducing the chamber voltage shifts the entire power frequency spectrum curve to lower frequencies because the time required to collect the ions and electrons in the chamber increases

The power frequency spectrum curve is divided into two distinct regions, the low-power range and the high power range At low reactor power the low pulse frequency

*The mean square voltage mode is discussed in detail in Chap 5

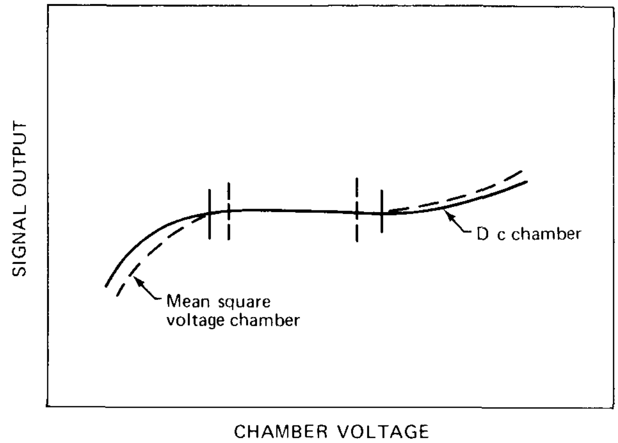

Fig 3 4—Saturation curves for d c chambers vs mean square voltage chambers

allows ample time for both the ions and electrons to be collected in the chamber At high reactor power the pulse frequency is so high that the ions are not collected, only electrons are collected The break in the curve occurs at the point where the transition from the collection of ions plus electrons to the collection of electrons alone is made

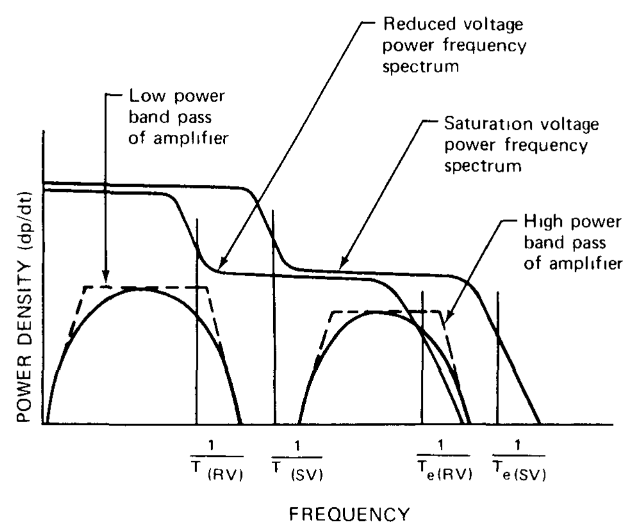

Fig 3 5—Mean square voltage chamber performance characteristics T_i = ion collection time T_e = electron collection time SV = saturation voltage and RV = reduced voltage

The best plateau characteristics in both the low power and high power ranges are obtained when the band pass of the amplifier is designed to be within the flat portion of the power frequency spectrum curve at saturated chamber voltage Improper setting of the chamber voltage shifts the frequency of the power frequency spectrum curve and drives the amplifier response off the flat portion of the curve Typical breakpoints in the low power and high power band-pass amplifier are defined in Vol 2, Chap 18, Sec 18-2 3(c)

There are three major factors creating nonlinear operation of in core fission chambers (1) gas migration between the active and the inactive volumes of the chamber owing to temperature differences, (2) operation in the presaturation region, and (3) operation in the multiplication region A change in reactor power level always causes gas migration in an in-core fission chamber Gas migration decreases the chamber sensitivity as reactor power increases and vice versa When the sensor is operated in the presaturation region, a further decrease in sensitivity occurs because the chamber current is not linear with neutron flux

In the saturation region the chamber current is linear with neutron flux, so the only source of nonlinearity is gas migration In the multiplication region the decrease in current due to gas migration is counteracted by the increase in multiplication due to the gas migration It may be desirable to set the chamber voltage somewhere in the multiplication region rather than in the saturation region to obtain maximum linearity on chambers with large gas migration

(i) Operating Ranges Table 3 1 summarizes the operating characteristics of typical in core fission chambers used in the pulse-counting mode, the mean square voltage mode, and the direct current mode Figure 3 6 shows the upper and lower boundaries of the operating ranges for in core fission chambers used to monitor reactor power from below source level to above the overpower trip level

Operating Range of Pulse Counting Fission Chambers The normal operating range of an in core pulse-counting fission chamber is from 10^3 to 10^9 neutrons cm^{-2} sec^{-1} The lower limit is determined by the statistics of pulse counting The variations in the neutron counting sensitivity of a pulse counting fission chamber noted in Table 3 1 result from variations in gamma flux at the detector The integral bias curves Fig 3 7, show the reduction in neutron counting sensitivity as the gamma exposure rate increases from 10^5 to 2 5 X 10^7 R/hr while the neutron flux remains constant Figure 3 7 also demonstrates the importance of the proper discriminator setting Any discriminator setting less than 3 would result in operation to the left of the plateau at higher gamma levels with attendant errors in count rate information At a neutron flux of 5 X 10^2 neutrons cm^{-2} sec^{-1} the chamber indicates approximately 1 count/sec, somewhat less than is desirable for statistical confidence Accordingly, the neutron source in the reactor should be sized to provide from 2 to 10 counts/sec

The upper limit of the pulse counting chamber is determined by the 1 MHz bandwidth of the signal amplifier and the 300-nsec rise time and collection time of the

Table 3 1—Operating Characteristics of Typical In-Core Fission Chambers

	Pulse-counting fission chamber	Mean-square-voltage fission chamber	Mean-current (d-c) fission chamber
Electrode coating	U_3O_8 enriched to >90% ^{235}U	U_3O_8 enriched to >90% ^{235}U	U_3O_8 enriched to >90% ^{235}U
Neutron sensitivity			
Pulse counting counts/sec/nv	0 5 to 2 5 x 10^{-3}		
Mean current (d c) amp/neutrons cm^{-2} sec^{-1}		7 x 10^{-18}	2 15 x 10^{-17} + 20%
Mean square voltage amp^2/neutrons cm^{-2} sec^{-1}		1 5 to 4 5 x 10^{-31}	
Gamma sensitivity			
Mean current (d c) amp/(R/hr)		2 5 x 10^{-14} + 20 %	2 0 x 10^{-14} + 30 %
Mean square voltage amp^2/(R/hr)		1 5 x 10^{-30}	
Neutron flux (max) neutrons cm^{-2} sec^{-1}	1 x 10^{10}	1 5 x 10^{13}	1 8 x 10^{14}
Gamma flux (max) R/hr	2 5 x 10^7		1 68 x 10^8
Operating voltage volts (d c)	200 to 700	100 to 200	100 to 200
Temperature (max) °C	540	540	315
Fill gas	Argon	Argon	Argon
Dimensions			
Sensitive length in	1 00	1 00	1 00
Case diameter in	0 250	0 250	0 230
Case material	Titanium	Titanium	Stainless steel
Collector material	Titanium	Titanium	Stainless steel
Collector to emitter insulator	Alumina	Alumina	Alumina
End seal	Titanium and Fosterite	Titanium and Fosterite	Titanium and Fosterite
Lifetime neutrons/cm^2	10^{19}		3 8 x 10^{21}

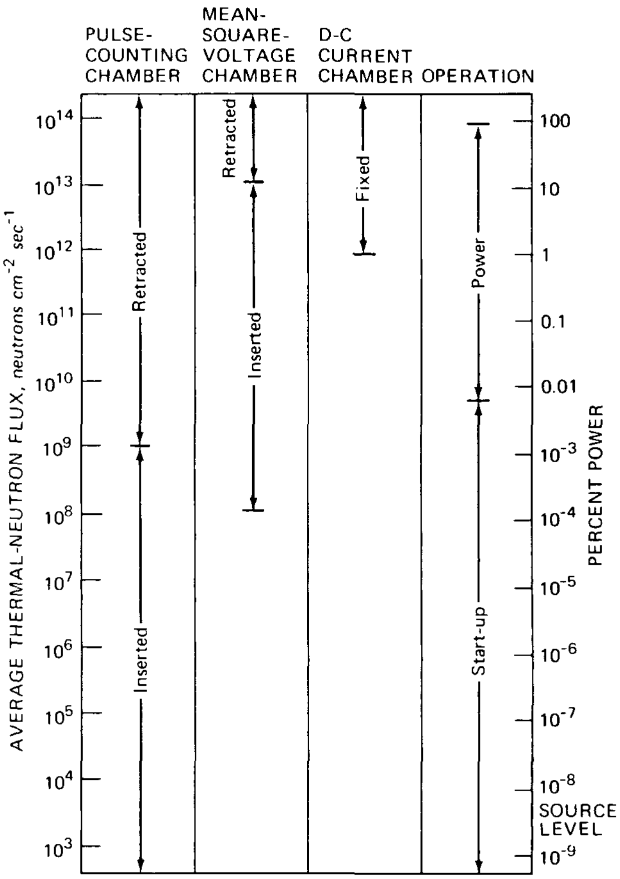

Fig. 3.6—Ranges of in-core fission chamber.

chamber pulses. At a true random input of 10^6 counts/sec, the counting loss is 23% of the true count rate. Since the pulse-counting chamber has a neutron counting sensitivity of greater than 10^3 counts/sec per unit flux (1 neutron cm^{-2} sec^{-1}) in a 10^5 R/hr gamma field, the upper limit of the neutron flux is 10^9 neutrons cm^{-2} sec^{-1} at 10^6 counts/sec.

When the in-core neutron flux exceeds 10^{10} neutrons cm^{-2} sec^{-1}, the pulse-counting chamber should be removed from the core to prevent depletion of the fissionable material.

Operating Range of Mean-Square-Voltage Fission Chambers. The operating range of the mean-square-voltage fission chamber is 10^8 to 10^{13} neutrons cm^{-2} sec^{-1}. The lower limit is set by the detector noise resulting from alpha emission from the uranium coating, prompt gamma radiation, and delayed neutrons at low reactor start-up levels. When the neutron flux is 10^8 neutrons cm^{-2} sec^{-1} or greater, the neutron-flux signal exceeds the noise signal.

The upper limit of the range of a mean-square-voltage chamber is reached when the plateau starting voltage becomes equal to the multiplication starting voltage, as described in Sec. 3-3.1(h). Because the plateau is shorter for chambers operating in the mean-square-voltage mode, the upper limit of their range is lower than the same chamber operating in the mean-current (d-c) mode.

When the in-core flux exceeds 10^{11} neutrons cm^{-2} sec^{-1}, the mean-square-voltage chamber should be removed from the core to prevent depletion of the uranium.

Operating Range of Mean-Current (d-c) Fission Chambers. The operating range of in-core fission chambers used in the mean-current mode is from less than 10^{12} neutrons cm^{-2} sec^{-1} to greater than 10^{14} neutrons cm^{-2} sec^{-1}. The lower limit is set primarily by the leakage current in the ceramic-insulated cable. The upper limit is reached when the plateau starting voltage is equal to the multiplication starting voltage. Because mean-current (d-c) chambers normally provide the signals that initiate reactor overpower trip and are calibrated against a reactor heat balance, they

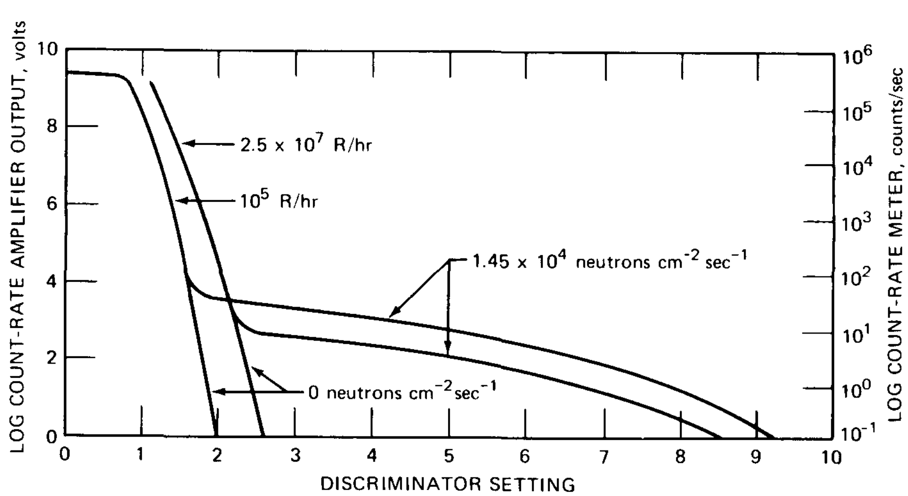

Fig. 3.7—Integral bias curve for pulse-counting chamber. Chamber voltage, 400 volts. Chamber sensitivity, 2×10^{-3} (counts/sec)/(neutrons cm^{-2} sec^{-1}) at 10^5 R/hr and 5×10^{-4} (counts/sec)/(neutrons cm^{-2} sec^{-1}) at 2.5×10^7 R/hr.

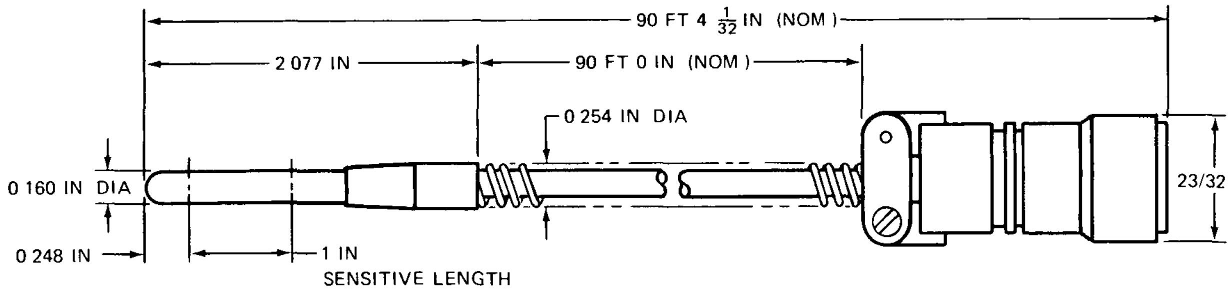

Fig 3 8—Travelıng ın core fıssıon chamber

must have good lınearıty over at least one decade of theır operatıng range

(j) **Traveling In-Core Fission Chambers.** The desıgn requırements for travelıng ın-core fıssıon chambers are the same as those for fıxed ın-core mean-current chambers except that the travelıng chambers must wıthstand the rıgors of perıodıc ınsertıon ınto and wıthdrawal from the core The travelıng ın core fıssıon chambers have the same requırements for operatıng range and lınearıty as the fıxed ın-core mean-current chambers Table 3 2 summarızes the characterıstıcs of travelıng ın-core fıssıon chambers commonly used ın power reactors Fıgure 3 8 shows a typıcal travelıng ın-core probe The helıcally wound outer sheath of the drıve cable engages the drıve gears to move and posıtıon the sensor

3-3.2 Boron-Lined Chambers

It ıs possıble, but not practıcal, to use ^{10}B-lıned chambers for fıxed ın-core neutron-flux monıtorıng ın power reactors They are not practıcal because the thermal-neutron cross sectıon for ^{10}B ıs more than sıx tımes that for ^{235}U and results ın too-rapıd burn out For example, the neutron sensıtıvıty of a fıssıon chamber ıs reduced to 50% of ıts ınıtıal value after nıne months of operatıon ın a thermal neutron flux of 4×10^{13} neutrons cm^{-2} sec^{-1} (typıcal for most water reactors at full power) In contrast, a ^{10}B-lıned ıon chamber under the same condıtıons ıs down to 50% of ıts ınıtıal sensıtıvıty ın 1½ months At the end of nıne months of operatıon, the ^{10}B lıned ıon chamber would have less than 2% of ıts ınıtıal sensıtıvıty Fıgure 3 9 compares sensıtıvıty vs tıme for the fıssıon chamber* and the ^{10}B-lıned ıon chamber ın a flux of 4×10^{13} neutrons cm^{-2} sec^{-1}

Boron-lıned ıon chambers can be used satısfactorıly as neutron sensors on travelıng ın-core probes sınce the total tıme of exposure to the neutron flux ıs only a small fractıon of the total operatıng tıme of the reactor The tıme requıred to run a complete core traverse seldom exceeds 3 mın, and the frequency of traversıng ıs seldom more than once a month, thus many years of satısfactory operatıon can be obtaıned from a boron lıned ıon chamber used on a travelıng ın-core probe The characterıstıcs of an ın core ıon chamber detector for travelıng ın-core probe servıce are descrıbed ın Table 3 2

*The useful lıfe of fıssıon chambers can be extended by usıng a mıxture of uranıum ısotopes e g 10% ^{235}U and 90% ^{234}U In such a mıxture the ^{234}U ıs transmuted to ^{235}U and the useful lıfe ıs thus extended beyond that achıeved wıth a ^{235}U lıned chamber

Table 3.2—Operating Characterıstics of Travelıng In-Core Fıssion Chambers*

Neutron-sensitıve material	Thermal-neutron sensitivity, amp/neutrons cm^{2} sec^{1}	Gamma sensitivity, amp/(R/hr)	Maxımum thermal-neutron flux, neutrons cm^{-2} sec^{1}	Typical operatıng voltage, volts (d-c)	Maxımum operatıng temperature, °F	Detector ınsulator	Nomınal Dımensıons: Sensıtıve length, ın	Nomınal Dımensıons: Detector O D , in
^{235}U	$2 0 \times 10^{17}$	$1 5 \times 10^{14}$	1×10^{14}	25 to 200	750	Al_2O_3	1	¼
^{10}B	$1 0 \times 10^{17}$	$1 0 \times 10^{14}$	1×10^{14}	25 to 200	750	Al_2O_3	½	3/16
†	$3 0 \times 10^{18}$	$2 0 \times 10^{14}$	5×10^{14}	25 to 200	650	Al_2O_3	1	¼
^{235}U	$6 8 \times 10^{18}$	$1 0 \times 10^{-14}$	3×10^{13}	25 to 300	650	Al_2O_3	1	0 090

*From Westınghouse brochure *Radıatıon Detectors Quıck Reference Guıde* November 1967
†The neutron sensıtıve materıal ıs a breeder mıxture of 90% ^{234}U and 10% ^{235}U

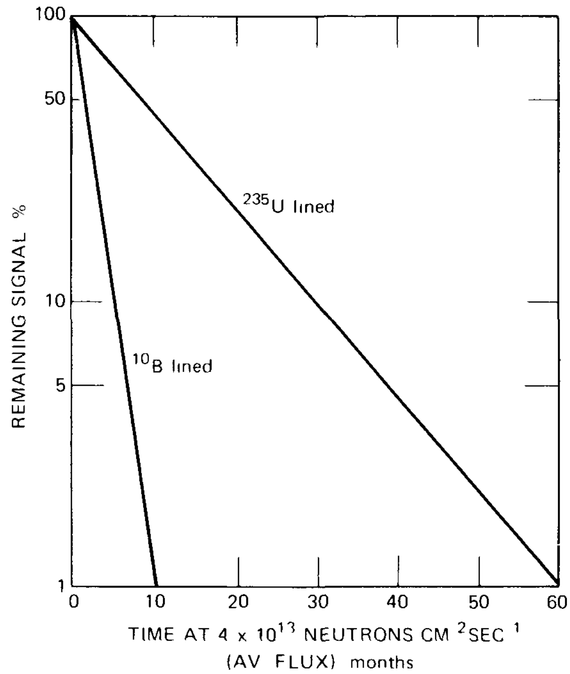

Fig 3 9 In core chamber burnup curves

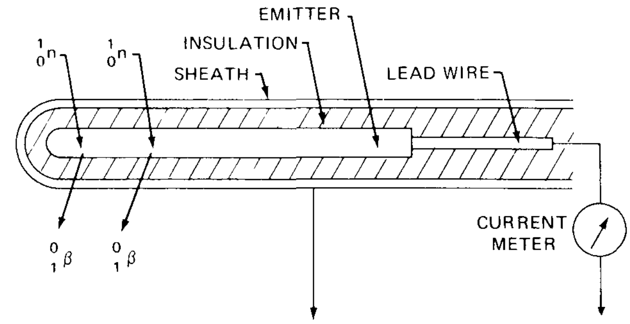

Fig 3 10—Operating principle of a self powered neutron detector

3-3 3 Self-Powered Neutron Detectors

The problems of manufacturing in core fission chambers and ion chambers small enough to fit the allowable space, rugged enough to withstand the in core environment, and inexpensive enough to permit extensive coverage of a power reactor core have led to efforts to develop other types of devices to measure neutron flux at fixed locations in a power reactor One device developed to solve these problems is the self powered neutron detector

The self powered neutron detector uses the basic radioactive decay process of its neutron activated material to produce an output signal As the name implies, no external source of ionizing or collecting voltage is required to produce the signal current The construction of the detector is quite different from that of an in-core fission chamber There is no gas filled region where ionization takes place, instead, the detector is of solid construction with a neutron-sensitive material connected to a lead wire, both being separated from the detector outer sheath by hard packed ceramic insulation The resulting detector is like a mineral-insulated coaxial cable, small in size and rugged

The simplicity of construction and operating principle lead to a number of advantages, including low cost, simplicity of readout equipment, low burnup rate, long lifetime, and ease of reproducing sensitivity

(a) Operating Principles. As shown in Fig 3 10, a typical self-powered neutron detector consists of four parts emitter, insulation, lead wire, and sheath (or collector) The emitter is a material of reasonably high thermal-neutron activation cross section which, after activation, decays by emission of high energy betas with a reasonably short half life The insulation is a solid that must maintain high electrical resistance in the in-core temperature and nuclear-radiation environment, it should ideally emit no betas or electrons (e g , from neutron activation) Both the lead wire and sheath, or collector must emit few betas or electrons compared to the emitter so that undesirable background signals are minimized

When the self-powered neutron detector is placed in a neutron flux and connected to ground through an electrical current meter, the current measured is proportional to the net beta escape from the emitter If the detector remains in the neutron flux until equilibrium beta emission is reached, the current is directly proportional to the incident-neutron flux

When the activity induced by thermal neutron absorption in the emitter is from a single radionuclide with a single half life, the detector output after exposure to the neutron flux for a time t is

$$I(t) = K\sigma_{act}QN\left[1 - \exp\left(-\frac{0.693t}{T_{1/2}}\right)\right]\phi \qquad (3\ 1)$$

where $I(t)$ = detector current (amp) at time t (sec)

K = a dimensionless constant determined by detector geometry and materials

σ_{act} = thermal neutron activation cross section of emitter material (cm^2)

Q = charge emitted by emitter per neutron absorbed (coulombs)

N = number of emitter atoms

$T_{1/2}$ = half life of radionuclide generated in emitter (sec)

ϕ = thermal-neutron flux (neutrons cm^{-2} sec^{-1})

Steady state is reached when the exposure time is several times the half-life, $T_{1/2}$, of the radionuclide

$$I_0(t) = K\sigma_{act}\,QN\,\phi \qquad (t \gg T_{1/2}) \qquad (3\ 2)$$

Table 3 3—Emitter Materials for Self-Powered Neutron Detectors

Material	Abundance, %	Activation cross section, barns	Half life	Maximum beta energy, MeV	Burnup at 10^{13} neutrons cm^{-2} sec^{-1}
^{7}Li	92 58	0 036	0 855 sec	13 0	Negligible
^{11}B	80 4	0 005	0 025 sec	13 4	Negligible
^{27}Al	100	0 23	2 30 min	2 87	Negligible
^{51}V	99 76	4 9	3 76 min	2 47	0 013%/month
^{55}Mn	100	13 3	2 58 hr	2 85	0 035%/month
^{99}Tc	Artificial	22	16 sec	3 37	0 058%/month
^{103}Rh	100	150 (11 + 139)	4 4 min 42 sec	2 44	0 40%/month
^{115}In	95 72	203 (4* 154 45)	54 min 14 sec	1 0 3 29	0 53%/month
^{109}Ag	48 18	92	24 sec	2 87	0 24%/month
^{107}Ag	51 82	35	2 4 min	1 64	0 092%/month

*Isomeric transition

where $I_0(t)$ is the steady state detector current at time t The inclusion of t is made necessary by the fact that the number of emitter atoms, N, is decreasing with time

$$N = N(t) = N_0 \exp(-K_\phi \phi \sigma t) \qquad (3\ 3)$$

where K_ϕ is the fraction of the detector constant K which accounts for the neutron self shielding in the emitter and σ is the thermal neutron-absorption cross section of the emitter material Introduction of the factor K_ϕ is necessary since atoms of the emitter are exposed to a neutron flux that has been attenuated by the intervening atoms of the sheath, insulation and the emitter itself Substitution of Eq 3 3 into Eq 3 2 gives the steady-state detector current

$$I_0(t) = K\sigma_{act} Q N_0 \exp(-K_\phi \phi \sigma t)\,\phi \qquad (t \gg T_{1/2}) \qquad (3\ 4)$$

The sensitivity of a self powered detector is defined as the change in the steady state detector current per unit change in the thermal-neutron flux

$$S(t) = \frac{\Delta I_0}{\Delta \phi} = [K\sigma_{act} Q N_0 \exp(-K_\phi \phi \sigma t)] \times (1 - K_\phi \phi \sigma t) \qquad (3\ 5)$$

The detector sensitivity is seen to decrease (because of burnup of the emitter material) approximately exponentially with time The rate of sensitivity decrease is determined by the thermal-neutron flux that the detector is exposed to, the thermal neutron-absorption cross section of the emitter material, and the neutron self shielding in the emitter

If the detector life is defined as the time during which the sensitivity decreases to a fraction f of its initial value when the detector is in a constant thermal-neutron flux, then Eq 3 5 shows that

$$f = e^{-T/\tau}\left(1 - \frac{T}{\tau}\right) \qquad (3\ 6)$$

where T = detector life in constant thermal neutron flux (ϕ)
f = S(t = T)/S(t = 0) = relative sensitivity at t = T
$\tau = 1/K_\phi \phi \sigma$ = time to complete burnup of emitter material assuming K_ϕ and ϕ are constant

The lifetime T can be calculated as a function of f from Eq 3 6 The values of T corresponding to f = 0 9, 0 8 0 7, 0 6, and 0 5 are found to be T = 0 05τ 0 11τ 0 17τ 0 24τ and 0 31τ respectively Thus for example, if the detector lifetime is defined as the time for the sensitivity to decrease to 60% of its initial value then the lifetime is 24% of its "complete burnup' time or T = 0 24τ = 0 24/$K_\phi \phi \sigma$

The constant K in the basic equation, Eq 3 1, takes into account several effects associated with the detector structure and materials Specifically, the detector current is reduced by a factor K_ϕ because the emitter atoms are partly shielded from the neutron flux (incident on the detector) by the atoms nearer the detector surface The detector current is also reduced by a factor K_β because some of the betas emitted by the radionuclides in the emitter are unable to escape from the emitter Finally, the detector current is reduced by a factor K_g because the geometry, particularly the insulation thickness, may not permit some betas to reach (or traverse) the detector sheath Thus the constant $K = K_\phi K_\beta K_g$

(b) Construction and Materials Self-powered neutron detectors can be manufactured in several ways using different construction materials and different manufacturing techniques Table 3 3 shows the various neutron-activated beta emitters that have been considered as potential candidates for the emitter material Of the materials listed, only ^{103}Rh and ^{51}V have been used in commercial applications Each of the others has been

rejected for one or more undesirable characteristics Because each has a low thermal neutron-activation cross section, ^{7}Li, ^{11}B, and ^{27}Al yield unacceptably low signal-to noise ratios With a 2 58-hr half life, ^{55}Mn results in too long a time constant if used in a detector Since ^{99}Tc does not occur naturally, it is not readily available, ^{115}In is unsatisfactory because 76% of its beta decay has a 54 min half-life Silver has both an acceptable cross section value and acceptable half-lives, but it would be difficult to compensate for burnup with the 24-sec ^{109}Ag burning up three times as fast as the 2 4-min ^{107}Ag

Neither ^{103}Rh nor ^{51}V has any of these undesirable characteristics Because of its larger thermal neutron-activation cross section, ^{103}Rh is used where short detectors are needed for measuring local flux Many ^{103}Rh detectors distributed throughout the reactor core can provide three dimensional power distribution information The relatively lower signal level of ^{51}V is more suited to long detectors designed to average the neutron flux over the full core height Such detectors cannot be used to determine power distribution along the axis of the reactor core, although several ^{51}V detectors dispersed throughout the core can provide data on the radial power distribution

Figures 3 11 and 3 12 show the two types of construction commonly used for self powered neutron detectors in commercial use today

The earliest, and in many respects the simplest, type of detector construction is shown in Fig 3 11 The 0 020-in -diameter rhodium wire emitter is fastened to the Inconel lead wire of a standard 0 040-in magnesium oxide insulated, Inconel sheathed, coaxial cable All parts are baked out before assembly and are maintained scrupulously clean during assembly The section of the detector sensitive to neutrons has a larger diameter than the coaxial cable The construction of a neutron-detector assembly containing several of these detectors can be complicated by the change in diameter

Figure 3 12 shows an alternate construction The neutron-sensitive emitter is fastened to the Inconel lead wire before the insulation is installed Magnesium oxide insulators are threaded over the emitter and lead wire The Inconel sheath is slid over the insulators, and the entire assembly is swaged down to a finished diameter of 0 062 in Bakeout before assembly and rigorous cleanliness during

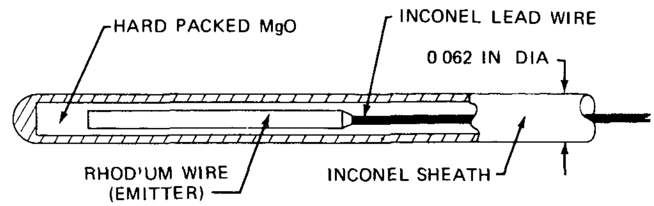

Fig 3 12—Self powered neutron detector

assembly are important procedures The resulting detector has a constant diameter over its length, and the magnesium oxide insulation is compacted tightly around the emitter

Only three insulation materials have been considered for self powered neutron detectors aluminum oxide, beryllium oxide, and magnesium oxide Aluminum oxide has been most frequently used when the detector is assembled as shown in Fig 3 11 Aluminum oxide is not suitable for detectors assembled as shown in Fig 3 12 because of the danger of damaging the emitter or lead wire during the swaging operation In addition, aluminum is activated by thermal neutrons and emits high-energy betas (see Table 3 3) which contribute to background and reduce the signal-to-noise ratio The characteristic 2 3-min beta decay of aluminum has been observed during irradiation of cables insulated with aluminum oxide Whether or not this is tolerable depends on the accuracy desired in the detector output signal Beryllium oxide has no significant advantage other than its extremely low thermal-neutron cross section This advantage, however, is more than offset by its high cost and toxicity Magnesium oxide is the most satisfactory of the three insulation materials because of its low cost, high resistivity, workability, and low noise potential

The two most commonly used sheath materials in detectors for pressurized-water and boiling-water reactors are type-304 stainless steel and Inconel because both are compatible with the reactor coolant Inconel is now standard in all commercial detectors The use of 304 stainless steel in the sheath of detectors intended for high-accuracy applications is problematical since manganese, which constitutes about 0 5 wt % of most stainless steels, is activated by thermal neutrons and emits betas (see Table 3 3)

Inconel is used universally as the lead wire material, although Nichrome was used successfully in earlier detectors

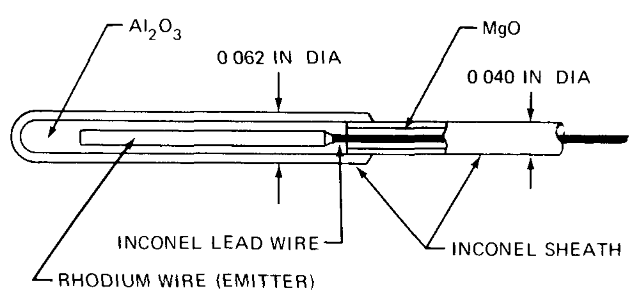

Fig 3 11—Self powered neutron detector

(c) Sensitivity The initial sensitivity of a self powered detector is given by Eq 3 5, with t = 0

$$S(0) = K\sigma_{act}QN_0\phi \qquad (3\ 7)$$

The number of emitter atoms at t = 0 is

$$N(t = 0) = N_0 = \rho\left(\frac{A_0}{A}\right)\left(\frac{\pi}{4}\right)d^2\ l \qquad (3\ 8)$$

where ρ = density of emitter material (g/cm^3)
A_0 = Avogadro's number = 6 02 X 10^{23}
A = atomic weight of emitter
d = diameter of emitter (cm)
l = length of emitter (cm)

The emitter is assumed to be cylindrical and made of a pure element It is further assumed that the emitter decays with the emission of a single beta, i e , Q = 1 60 X 10^{19} coulomb, the electron charge

As noted at the end of Sec 3 3 3(a), the constant K is the product of K_ϕ, K_β, and K_g, the constants that take into account the neutron self-shielding, beta self-shielding, and geometric effects Figure 3 13 shows the values of these constants as a function of emitter diameter for rhodium with 10 mils (0 25 mm) of MgO insulation Figure 3 14 shows the same constants for vanadium emitters

The initial sensitivity of a rhodium detector with a 20-mil (0 51-mm) emitter and 10 mils of MgO insulation can be calculated from Eqs 3 7 and 3 8 using K values from Fig 3 13 and the rhodium cross section from Table 3 3 (The density of rhodium is 12 4 g/cm^3) The result is

$$\frac{S}{l} = 1\ 3 \times 10^{-21} \text{ amp/(neutrons cm}^{-2} \text{ sec}^{-1})$$

A similar calculation for a vanadium detector with a 20 mil emitter and 10 mils of MgO insulation yields (vanadium density is 6 0 g/cm^3)

$$\frac{S}{l} = 7\ 1 \times 10^{-23} \text{ amp/(neutrons cm}^{-2} \text{ sec}^{-1})$$

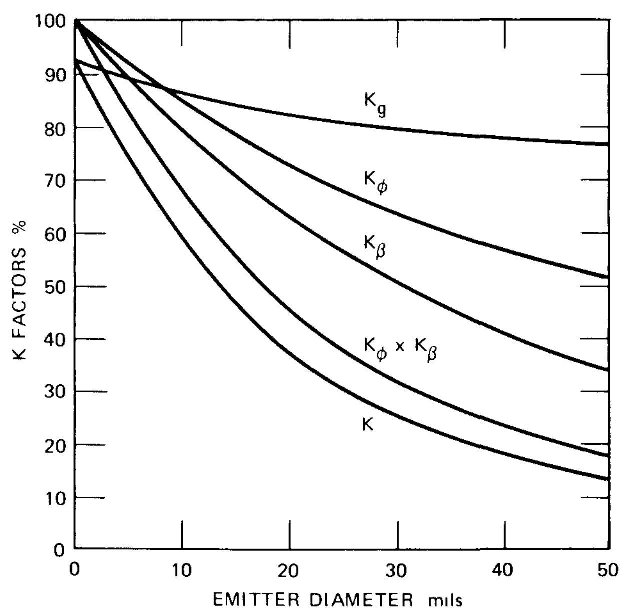

Fig 3 13— K factors for rhodium detectors with 10 mils of MgO

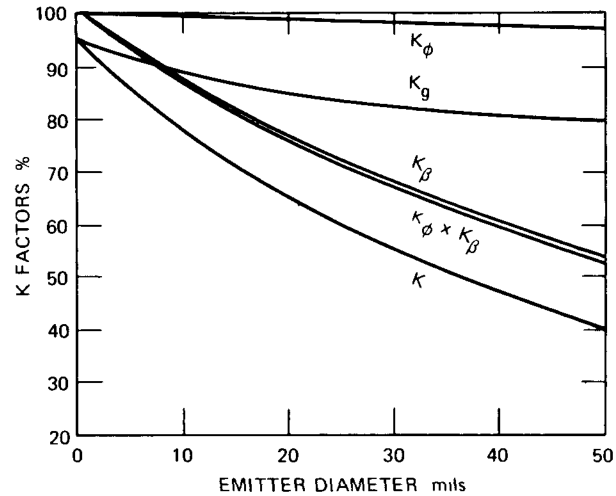

Fig 3 14—K factors for vanadium detectors with 10 mils of MgO

This value, as well as the one for the rhodium detector, is in good agreement with experimental values

Because of the rapid decrease in K with increasing emitter diameter, detector sensitivity depends more on emitter surface area than on emitter volume This is evident from Fig 3 15, where the detector sensitivity is shown as a function of emitter diameter The relation is nearly a straight line

Figure 3 16 shows the change in detector sensitivity when the detector length and diameter are varied but the emitter mass is kept constant

(d) Emitter Burnup. The depletion of the neutron sensitive emitter caused by its absorption of thermal

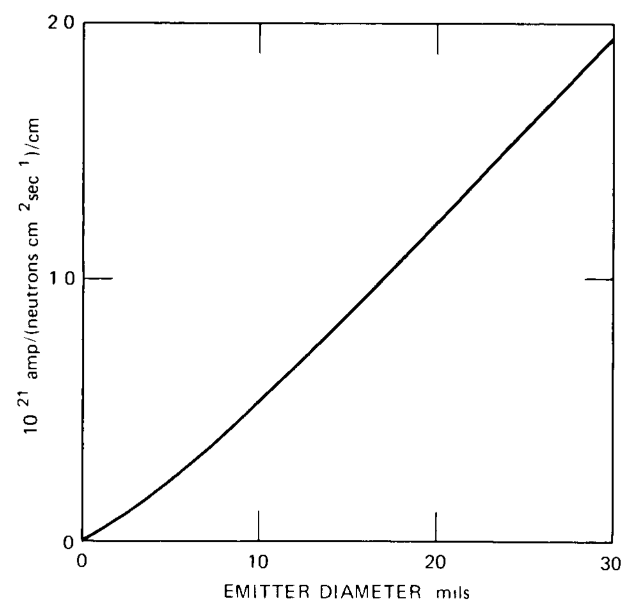

Fig 3 15—Rhodium detector sensitivity vs emitter diameter

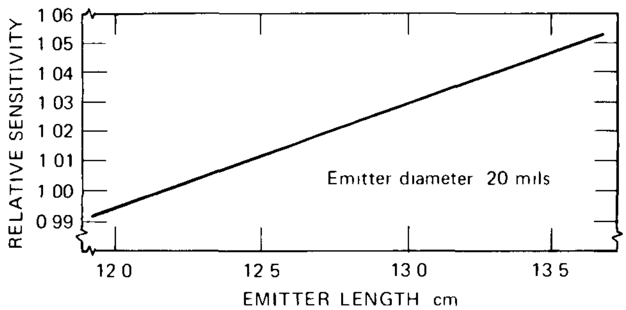

Fig 3 16— Rhodium detector sensitivity vs length at constant emitter mass

neutrons reduces the sensitivity of the detector (see Eq 3 5) In the derivation of Eq 3 5, it was assumed that all factors were constant except t However, the neutron self-shielding factor, K_ϕ, is not constant during prolonged exposure to neutrons it tends to increase as the emitter burnup increases because burnup removes (transforms) some of the self shielding atoms The resulting change in K_ϕ is not significant over a short period of operation, but it must be taken into account in any readout system that automatically compensates for detector burnup

From Eq 3 5 the relative detector sensitivity is

$$\frac{S(t)}{S(0)} = \exp(\ K_\phi \phi \sigma t)\,(1 \quad K_\phi \phi \sigma t)$$
$$= e^{t/\tau}\left(1 \quad \frac{t}{\tau}\right) \qquad (3\ 9)$$

where $\tau = 1/K_\phi \phi \sigma$

For a rhodium detector with a 20 mil emitter and 10 mils of MgO insulation, the characteristic burnup time τ is $0\ 913 \times 10^{22}/\phi$ In an average thermal neutron flux $\phi = 4 \times 10^{13}$ neutrons cm^{-2} sec^{1} the value of τ is 23×10^{7} sec, or 7 18 years When the detector is exposed to this flux for one year, its sensitivity relative to its initial value decreases to exp (−1/7 18) × [1 − (1/7 18)] = 0 75 In other words, its sensitivity is now 75% of its initial value In two years, the sensitivity decreases to 55% of its initial value From this it follows that the emitter burnup time is longer than the normal reactor refuelling cycle The emitter burnup rates given in Table 3 3 are based on the assumption that $K_\phi = 1$ As noted earlier, K_ϕ is less than 1, so the actual burnup rates will be lower than those given in the table

The product NQ in Eqs 3 1 through 3 4 is equal to the total charge (betas) generated in the emitter before it is used up (all atoms activated) Since K_β and K_g are the factors that identify how many betas escape to become useful detector output current, the total useful charge generated by the detector is

$$q = K_\beta K_g Q N \qquad (3\ 10)$$

If we use the K values from Fig 3 13 and calculate N from Eq 3 8, we find the total useful charge generated by a 20 mil rhodium detector with 10 mils of MgO insulation to be

$$q = 12\ 1 \text{ coulombs/cm of emitter length}$$

which is in good agreement with experimental values

(e) Response Characteristics The response characteristics of a self powered neutron detector are directly related to the radioactive scheme of the radionuclides formed in the emitter

Figure 3 17 shows the decay scheme for self-powered detectors that use vanadium as the emitter material All neutron absorptions in the emitter material, ^{51}V, which has a thermal neutron-activation cross section of 4 9 barns, result in the creation of ^{52}V The latter decays by beta emission to four excited states of ^{52}Cr which then immediately go to the ground state by gamma emission The half life of this decay scheme is 3 76 min (226 sec) The 2 4 MeV beta accounts for almost 99% of the beta emission and provides energetic betas for a good signal-to-noise ratio

Because the emitter radionuclide has a single beta decay period, the time response of the vanadium detector to a *step change in thermal neutron flux from ϕ to zero* is

$$I(t) = I_0\, e^{-0\ 693t/226} = I_0 e^{t/326} \qquad (3\ 11)$$

and the time response to a *step change in thermal neutron flux from zero to ϕ* is

$$I(t) = I_0(1 - e^{t/326}) \qquad (3\ 12)$$

where t is in seconds I(t) is the detector signal current, and I_0 is the steady state signal given in Eq 3 2 The mean life 326 sec, is the half life divided by 0 693, it is the time for I(t) to decrease by 1/e Figure 3 18 shows the response of a vanadium self powered detector to a step decrease in neutron flux (Eq 3 11) on a semilogarithmic scale T e vanadium detector response follows an exponential with a characteristic 3 76 min half-life (time constant = 3 76/0 693 = 5 4 min) and reaches 90% of the step change in 12 5 min Figure 3 19 shows the response of a vanadium self powered detector to a step decrease and a step increase in neutron flux, the curves are plotted on a linear scale

Figure 3 20 shows the decay scheme for rhodium emitters Neutron absorption by rhodium creates two radioisotopes of ^{104}Rh The total neutron activation cross section of rhodium is 150 barns The cross section for the creation of the ground state ^{104}Rh is 139 barns (92 7% of the 150 barns), and, for the creation of the metastable ^{104m}Rh, the cross section is 11 barns (7 3% of 150 barns) The metastable state decays by gamma emission to the ground state with a characteristic half life of 4 4 min (264 sec) The ground state ^{104}Rh decays by beta emission to the ground state ^{104}Pd with a half-life of 42 sec In this final beta decay process, 98% of the emitted betas have an

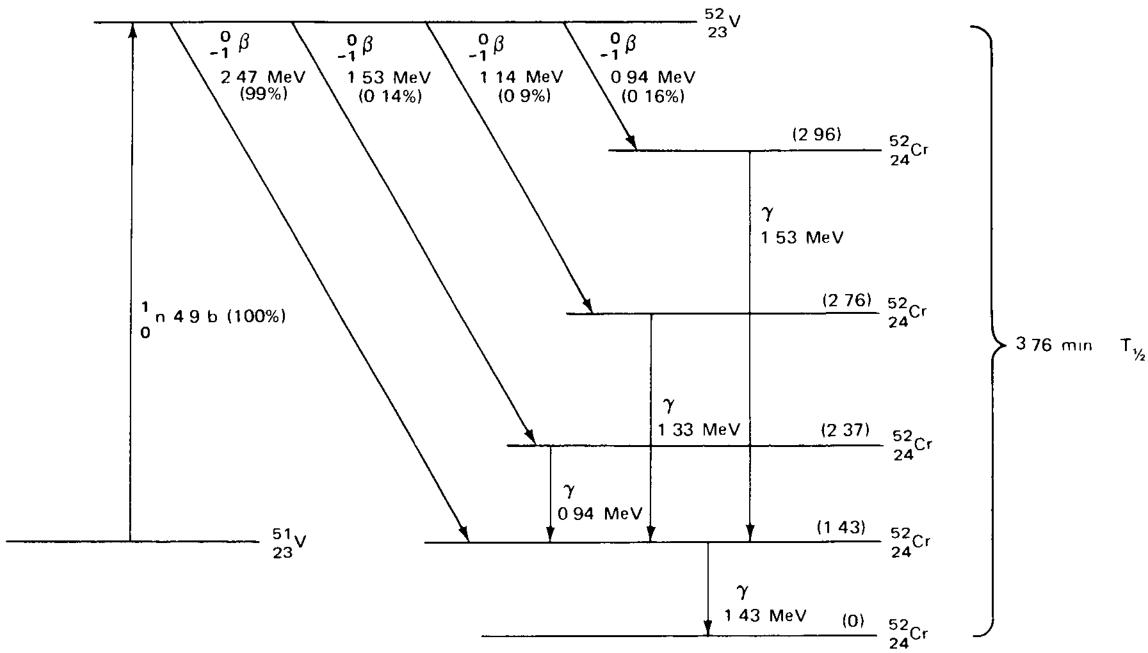

Fig. 3.17— Vanadium emitter decay scheme

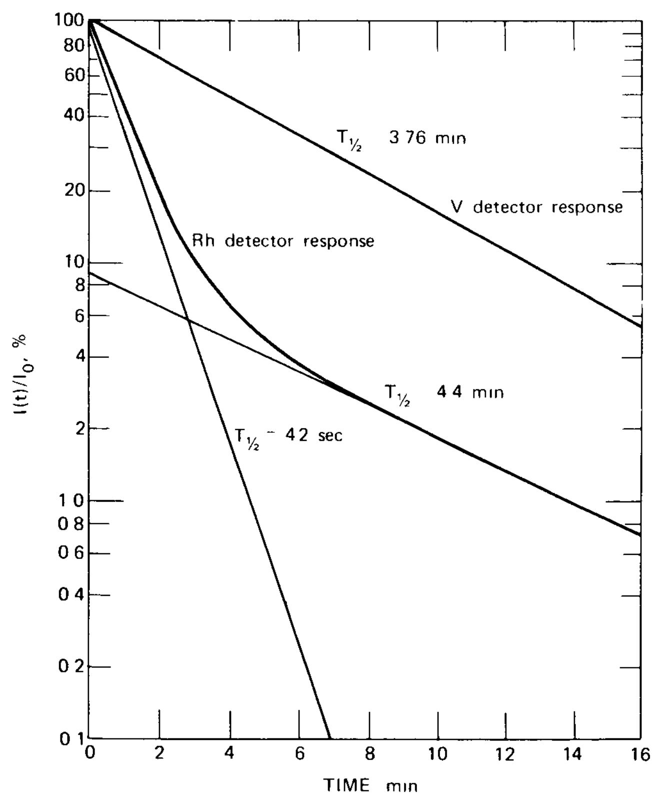

Fig. 3.18—Self powered neutron-detector response to step change in neutron flux from $\phi = \phi$ to $\phi = 0$

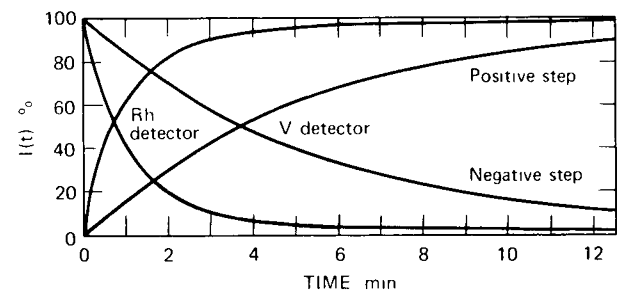

Fig. 3.19—Self powered neutron detector response to step change in neutron flux

energy of 2.44 MeV, sufficiently high to provide adequate signal-to-noise ratio

Because it has an emitter with two beta-decay constants, the time response of a rhodium self-powered detector to step changes in neutron flux involves two exponentials For a *step change in neutron flux from ϕ to zero,*

$$I(t) = I_0\left[\left(1 - 0.073\,\frac{381}{381-61}\right)e^{-t/61} + 0.073\,\frac{381}{381-61}\,e^{-t/381}\right]$$

$$= I_0(0.913\,e^{-t/61} + 0.087\,e^{-t/381}) \qquad (3.13)$$

where t is in seconds and 61 (= 42/0.693) and 381 (= 264/0.693) are the mean lives in seconds of ^{104}Rh and ^{104m}Rh, respectively Similarly, for a *step change in the thermal neutron flux from zero to ϕ*, the time response is

$$I(t) = I_0[1 - (0.913\,e^{-t/61} + 0.087\,e^{-t/381})] \quad (3.14)$$

Figure 3.18 shows I(t)/I$_0$ vs time on a semilogarithmic plot for a step decrease in thermal-neutron flux on a rhodium detector For the first 3 min after the step change, the detector signal is dominated by the 42-sec half-life (61-sec time constant), beyond 6 min after the step change, the

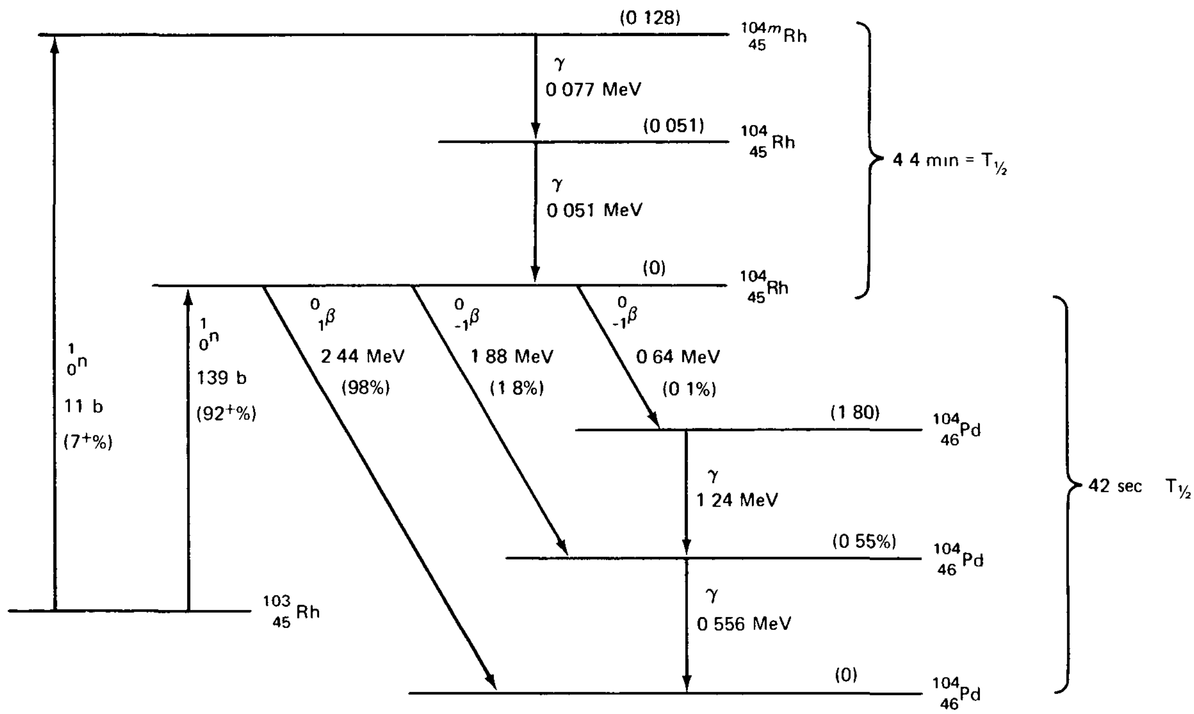

Fig 3.20—Rhodium emitter decay scheme

rhodium detector signal follows the 4 4-min decay of ^{104m}Rh The signal reaches 90% of the step change in less than 3 min The y-intercepts of the two half-life curves in Fig 3.18 correspond to the coefficients of each exponential in Eq 3 13 Figure 3 19 shows the time responses of a rhodium detector to step decreases (Eq 3 13) and to step increases (Eq 3 14) in flux, plotted on a linear scale

(f) Connecting Cables. The connecting cables required to bring the self-powered detector signals out of the core should produce as little background signal as possible As shown in Figs 3 11 and 3 12, the cables commonly used are 40 or 62 mils in outside diameter with magnesia insulation and Inconel lead wire and sheath The neutron cross section for Inconel is negligible, so neutron-induced signals are negligible The major sources of noise signals are Compton electrons and photoelectrons generated when gamma rays are absorbed or scattered by the lead wire and sheath The noise signals are prompt in responding to changes in incident gamma flux

Compton electrons and photoelectrons originating in the wire and absorbed in the sheath produce positive background signals Electrons originating in the sheath and absorbed in the lead wire produce negative background signals Equal absorption of electrons in the wire and sheath would result in a zero background signal, ideal for maximum neutron signal The larger mass and surface area of the sheath tend to make a negative background signal for most connecting cables Appropriate selection of emitter and sheath materials and dimensions should make it possible to build cables with essentially zero background signal

Chapter 4

Process Instrumentation

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CHAPTER CONTENTS

CHAPTER CONTENTS (Continued)

4-1 INTRODUCTION

The term "process instrumentation" in nuclear power plants refers to all the out-of-core (exposed to $<10^{11}$ fast neutrons $cm^{-2}\ sec^{-1}$) instrumentation except nuclear-radiation instrumentation.

Emphasis in this chapter is on the techniques used to measure the most important plant operating parameters—temperatures, pressures, flow rates, and coolant properties. Many other process instruments are involved in nuclear power plant operation, ranging from those associated with auxiliary chemical processes (waste treatment, coolant purification, etc.) to those involved in maintaining the plant atmosphere (air filtration and conditioning, ventilation, etc.).

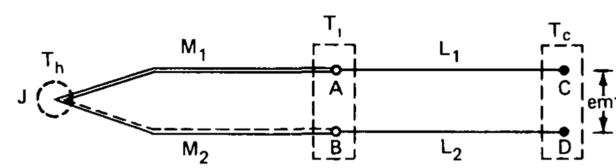
Certain process instrumentation is so closely associated with specific plant components (e.g., control-rod position sensing) or with a particular reactor type (e.g., moisture detection in gas-cooled reactors) that it is more properly discussed in other chapters. Cross references are provided in these cases.

No single book (and certainly no single chapter in a book) can cover all significant aspects of even one category of process instrumentation in nuclear power plants.

4-2 TEMPERATURE SENSING

4-2.1 Thermocouples

(a) Basic Considerations. A thermocouple (Fig. 4.1) is a device that generates a small electromotive force (millivolts) almost directly proportional to the temperature difference between its "cold" and "hot" junctions (Seebeck effect). The degree of departure of the voltage–temperature relation from linearity depends on the materials used in the thermocouple (Fig. 4.2).



$T_h > T_I > T_c$

Fig. 4.1—Basic principle of thermocouple operation. M_1 and M_2 are dissimilar metals joined at J (hot junction) and connected at A and B to lead (extension) wires L_1 and L_2. The lead wires are connected to a potential measuring device at C and D (cold junction). The electromotive force (Seebeck emf) across C and D depends on M_1, M_2, and on $T_h - T_c$ provided (1) C and D are at the same temperature, (2) A and B are at the same temperature, and (3) the materials L_1 and L_2 are such that emf's across L_1 and L_2 due to the temperature difference $T_I - T_c$ are the same as the emf's that would exist if L_1 were replaced by M_1 and L_2 by M_2. (Note: Terminals A and B do not, in general, have to be at exactly the same temperature. However, it is good practice to have them at the same temperature.)

In a circuit made up of wires of dissimilar metals, the existence of emf's other than those at the junctions was discovered by Thomson (Lord Kelvin). An examination of this effect led to the conclusion that in general an emf exists between any two regions at different temperatures in a single conductor. In other words, a *thermal gradient* in a homogeneous material creates an emf, the direction of the emf is reversed when the thermal gradient is reversed. The effect is usually negligible in thermocouple applications since there are equal and opposite thermal gradients around the circuit. Moreover, the practice of keeping both legs of

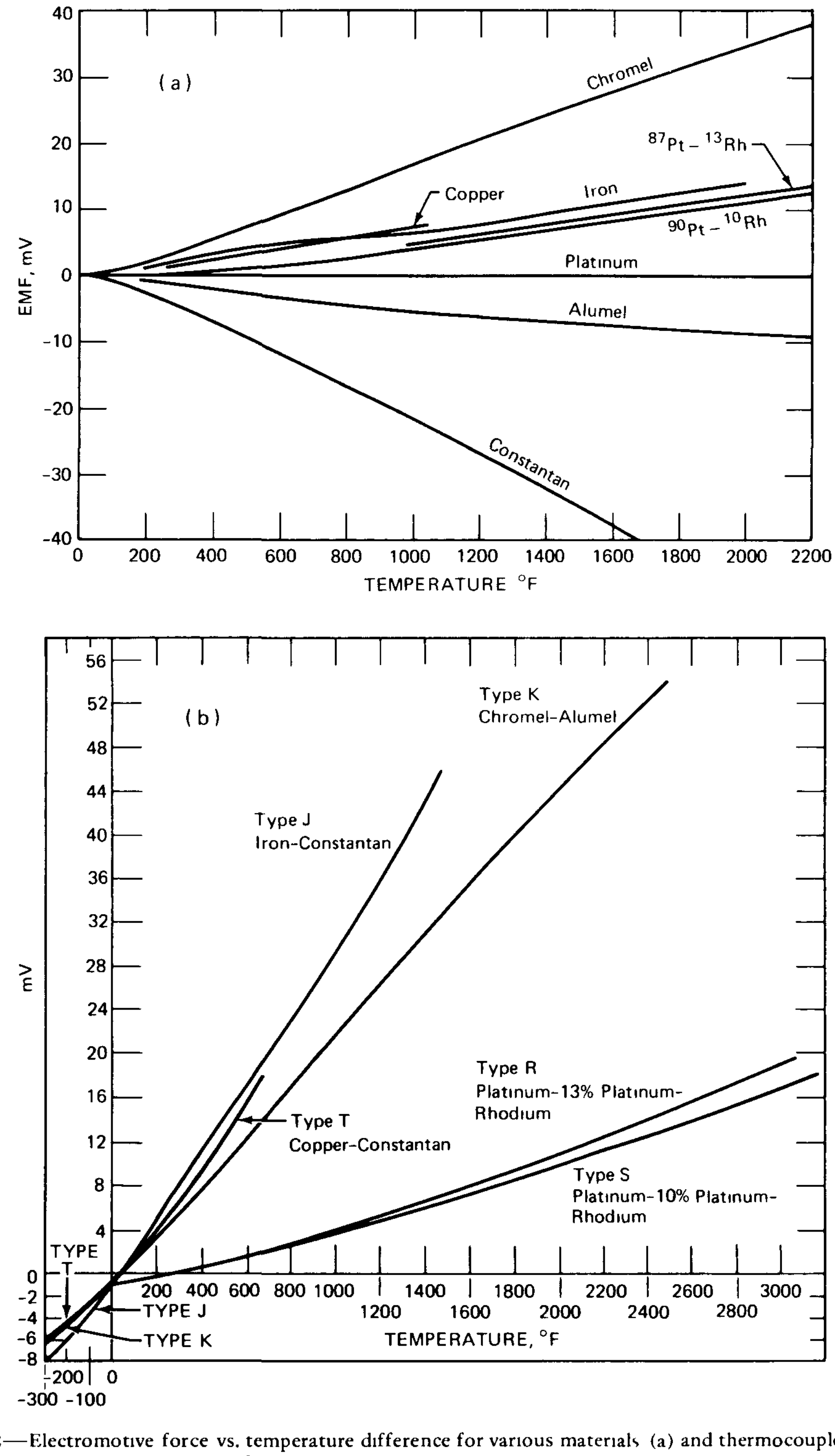


Fig. 4.2—Electromotive force vs. temperature difference for various materials (a) and thermocouples (b). In (b) the reference junction is at 32°F. [From (a) Instrument Society of America, R.P. 1.6, Aug. 1, 1954, (b) American Society of Mechanical Engineers, Power Test Code 19-3, 1961.]

thermocouple circuits in the same thermal gradients ensures that the Thomson effect can be neglected

Of greater importance are changes in the properties of thermocouple materials after prolonged exposure to elevated temperatures and steep temperature gradients such as exist near the hot junction. The thermocouple wires become inhomogeneous along their length, the degree of inhomogeneity depending on temperature, time, and the environment (air, steam, water, etc.) If there is a thermal gradient along the region where the homogeneity varies, then an emf can be generated (as if there were a thermocouple composed of fresh and altered material). This

effect can be taken into account by thermocouple calibration or replacement. However, the calibration must be made in the same thermal gradient as that which will exist when the thermocouple is used.

(b) Thermocouple Lead (or Extension) Wire. The cold junction of a thermocouple circuit is almost always located at the indicating or controlling instrument itself. The instrument usually has means for automatically compensating for variations of the cold junction caused by variations in the ambient temperature. Indicating instrument and sensor are sometimes separated by substantial distances (as much as a few hundred feet). The thermocouples should be made long enough to extend from the point of heat measurement to the indicators. If the thermocouple were made of platinum–rhodium, it would be prohibitively expensive. Therefore, lead (or extension) wires of cheaper metals that have thermoelectric characteristics matching the thermocouple over a limited temperature range must be used. This range is based on the ambient temperature expected at the point where the thermocouple extension wires connect to the thermocouple and where the greatest range of ambient temperature is expected.

(c) Thermocouple Materials. Thermocouple materials are available for use within the approximate limits of −300 to +3200°F (−185 to +1760°C). No single thermocouple meets all application requirements, but each possesses characteristics desirable for selected applications. Platinum is generally accepted as the standard reference material against which the thermoelectric characteristics are compared.

Thermocouples are classified into two groups identified as *noble metals* and *base metals*.

Noble metals

1. Platinum vs platinum–10% rhodium is used for defining the International Temperature Scale from 630.5°C (1166.9°F) to 1063°C (945.4°F). It is chemically inert and stable at high temperatures in oxidizing atmospheres. It is widely used as a standard for calibration of base-metal thermocouples. This couple will match the standard reference table to ±0.5% of the measured emf.

2. Platinum vs platinum–13% rhodium is similar to 1 and produces a slightly greater emf for a given temperature.

3. Platinum–5% rhodium vs platinum–20% rhodium and platinum–6% rhodium vs rhodium are similar to 1 and 2 but show slightly greater mechanical strength.

Base metals

1. Copper–constantan is used over the temperature range of −300 to +700°F (−185 to +370°C). The constantan is an alloy of approximately 55% copper and 45% nickel.

2. Iron–constantan is used over the temperature range of −200 to +1400°F (−130 to +760°C) and exhibits good stability at 1400°F (760°C) in nonoxidizing atmospheres.

3. Chromel–alumel is used over the temperature range of −200 to 2300°F and is more resistant to oxidation than other base-metal combinations. Chromel-P is an alloy of approximately 90% nickel and 10% chromium. Alumel is approximately 94% nickel, 3% manganese, 2% aluminum, and 1% silicon. This combination must be protected against reducing atmospheres. Alternate cycling between oxidizing and reducing atmospheres is particularly destructive.

4. Chromel–constantan produces the highest thermoelectric output of any conventional thermocouples. It is used up to 1400°F (760°C) and exhibits a high degree of calibration stability at temperatures not exceeding 1000°F (538°C).

The upper temperature limits for the various thermocouple materials depend on the wire sizes and the environment in which the thermocouples are used. Table 4.1 lists the recommended upper temperature limits for thermocouples protected from corrosive or contaminating atmospheres.

The ranges of applicability and limits of error for thermocouples and extension wires of standard sizes are given in Table 4.2. See National Bureau of Standards Circular 561 for expanded reference tables of these thermocouples, emf vs temperature, and temperature vs emf, °F, and °C.

(d) Thermocouple Charts. Thermocouple data are usually presented as tables of emf (millivolts) vs. temperature (°C or °F) with the 0°C or 0°F as the reference (cold junction) temperature. Tables 4.3 and 4.4 present the data

Table 4.1—Recommended Upper Temperature Limits (°F) for Protected Thermocouples*

	Upper temperature limit, °F				
	AWG 8† (0.128 in.)	AWG 14 (0.064 in.)	AWG 20 (0.032 in.)	AWG 24 (0.020 in.)	AWG 28 (0.013 in.)
Copper–constantan		700	500	400	400
Iron–constantan	1400	1100	900	700	700
Chromel–alumel	2300	2000	1800	1600	1600
Platinum–platinum + 10% rhodium or platinum + 13% rhodium				2700	

*From American Society of Mechanical Engineers, Power Test Code 19.3, p. 23, 1961.
†American Wire Gauge number and size.

Table 4.2—Range of Applicability and Limits of Error* for Commercially Available Thermocouples and Extension Wires†

Type	Thermocouples			Extension wire		
	Temperature range, °F	Limits of error		Temperature range, °F	Limits of error, °F	
		Standard	Special		Standard	Special
Copper–constantan	−300 to −75		±1%			
	−150 to −75	±2%	±1%			
	−75 to +200	±1½°F	±¾°F	−75 to +200	±1½	±¾
	200 to 700	±¾%	±⅜%			
Iron–constantan	0 to 530	±4°F	±2°F	0 to 400	±4	±2
	530 to 1400	±¾%	±⅜%			
Chromel–alumel	0 to 530	±4°F		0 to 400	±6	
	530 to 2300	±¾%				
Platinum–platinum + 10% rhodium or platinum + 13% rhodium	0 to 1000	±5°F		75 to 400	±12	
	1000 to 2700	±0.5%				

*Does not include use or installation errors.
†From American Society of Mechanical Engineers, Power Test Code 19.3, p. 23, 1961.

Table 4.3—Electromotive Force vs. Temperature (°F) for Thermocouples*

°F	Chromel–alumel (type K)	Iron–constantan (type J)	Copper–constantan (type T)	Chromel–constantan (type E)	Platinum–platinum + 10% rhodium (type S)	Platinum–platinum + 13% rhodium (type R)
0	0.00	0.00	0.000	0.00		
50	1.08	1.39	1.059	1.61	0.156	0.154
100	2.20	2.83	2.187	3.29	0.321	0.319
150	3.34	4.30	3.381	5.06	0.501	0.499
200	4.50	5.80	4.637	6.89	0.695	0.695
250	5.65	7.31	5.950	8.78	0.900	0.906
300	6.77	8.83	7.317	10.73	1.117	1.129
350	7.88	0.37	8.734	12.73	1.342	1.360
400	8.99	11.92	10.195	14.77	1.574	1.603
450	10.11	13.46	11.700	16.86	1.812	1.853
500	11.25	15.01	13.245	18.97	2.056	2.111
550	12.39	16.54	14.827	21.11	2.305	2.376
600	13.54	18.07	16.443	23.27	2.558	2.646
650	14.70	19.61	18.091	25.46	2.816	2.922
700	15.86	21.15	19.770	27.67	3.077	3.202
750	17.03	22.68	21.475	29.88	3.340	3.486
800	18.21	24.21		32.11	3.606	3.776
850	19.38	25.74		34.34	3.875	4.069
900	20.57	27.29		36.59	4.146	4.363
950	21.75	28.84		38.84	4.419	4.662
1000	22.94	30.41		41.08	4.696	4.967
1050	24.12	32.01		43.33	4.974	5.275
1100	25.31	33.61		45.58	5.256	5.587
1150	26.49	35.25		47.83	5.540	5.904
1200	27.66	36.90		50.06	5.826	6.224
1250	28.83	38.60		52.29	6.115	6.545
1300	30.00	40.32		54.52	6.407	6.872
1350	31.17	42.08		56.73	6.701	7.202
1400	32.33	43.85		58.94	6.997	7.535
1450	33.48	45.64		61.13	7.269	7.873
1500	34.61	47.42		63.32	7.598	8.215
1550	35.75	49.20		65.49	7.903	8.559

*From Instrument Society of America, Recommended Practices 1.7, Aug. 1, 1954.

Table 4 4—Electromotive Force vs Temperature (°C) for Thermocouples*

°C	Chromel–alumel (type K)	Iron–constantan (type J)	Copper–constantan (type T)	Chromel–constantan (type E)	Platinum–platinum + 10% rhodium (type S)	Platinum–platinum + 13% rhodium (type R)
0	0 00	0 00	0 000	0 00	0 000	0 000
50	2 02	2 58	2 035	3 04	0 299	0 298
100	4 10	5 27	4 277	6 32	0 643	0 645
150	6 13	8 00	6 703	9 79	1 025	1 039
200	8 13	10 78	9 288	13 42	1 436	1 465
250	10 16	13 56	12 015	17 18	1 868	1 918
300	12 21	16 33	14 864	21 04	2 316	2 395
350	14 29	19 09	17 821	24 97	2 778	2 890
400	16 40	21 85	20 874	28 95	3 251	3 399
450	18 51	24 61		32 96	3 732	3 923
500	20 65	27 39		37 01	4 221	4 455
550	22 78	30 22		41 05	4 718	5 004
600	24 91	33 11		45 10	5 224	5 563
650	27 03	36 08		49 13	5 738	6 137
700	29 14	39 15		53 14	6 260	6 720
750	31 23	42 22		57 12	6 790	7 315
800	33 30	45 53		61 08	7 329	7 924
850	35 34	48 73		64 99	7 876	8 544
900	37 36			68 85	8 432	9 175
950	39 35			72 68	8 997	9 816
1000	41 31			76 45	9 570	10 471
1050	43 25				10 152	11 138
1100	45 16				10 741	11 817
1150	47 04				11 336	12 503
1200	48 89				11 935	13 193
1250	50 69				12 536	13 888
1300	52 46				13 138	14 582
1350	54 20				13 738	15 276
1400					14 337	15 969
1450					14 935	16 663
1500					15 530	17 355
1550					16 124	18 043

*From Instrument Society of America Recommended Practices 1 7, Aug 1 1954

for six thermocouples in Fahrenheit and Centigrade, respectively The use of these tables is described below

If the emf is measured, then the temperature can be determined For example, suppose an emf of 26 50 mV is observed for an iron–constantan thermocouple with a cold-junction temperature of 70°F From Table 4 3, 70°F is 1 68 mV (linear interpolation) with 0°F cold-junction reference temperature The unknown temperature thus corresponds to 26 50 + 1 68 = 28 18 mV with 0°F reference temperature From Table 4 3, this is seen to correspond to 960°F

In some situations the temperature is assumed to be known and the emf is to be determined For example, a potentiometer (P) having cold-junction compensation (i e , the millivolt readings correspond to the cold junction at 32°F) and calibrated for a type K (chromel–alumel) thermocouple is to be checked at 1450°F by means of the output of a potentiometer (S) of known accuracy From Table 4 3, the temperature 1450°F for a type K thermocouple corresponds to 33 48 mV with a cold junction temperature of 0°F The emf between 0°F and 32°F is also seen to be 0 69 mV (linear interpolation in the table), so the temperature 1450°F with a cold-junction temperature of 32°F corresponds to 33 48 – 0 69 = 32 79 mV This is the potential that should be observed on potentiometer "S" when potentiometer P is checked at 1450°F

In the charts usually supplied with thermocouple devices, the temperature interval is smaller than the 50°F (or 50°C) interval of Tables 4 3 and 4 4 This reduces the labor of interpolation

(e) Series-Connected Thermocouples. In one method for averaging temperatures, each thermocouple is connected in series with the others (Fig 4 3) using extension wires of the correct materials Note that the extension wires are connected at the instrument from each couple in the series This permits proper cold-junction compensation The emf developed at the terminal G is the sum of the emf's

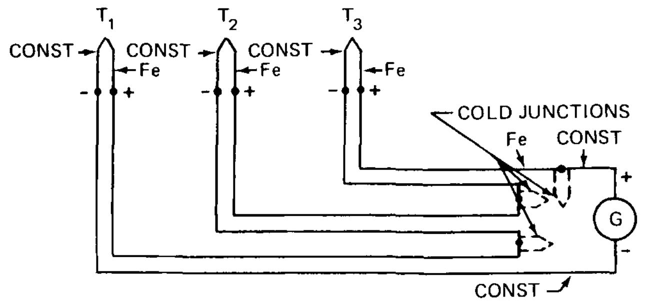


Fig. 4.3—Series-connected thermocouples (iron = Fe, constantan = const.). [From W. H. Kirk, Thermocouple Primer, *Instrum. Control Syst.*, **41**: 78(March 1968).]

developed by all the thermocouples. Consequently, instruments used with this type of circuit must be calibrated for the total emf of all the thermocouples, and the cold-junction compensation must be adjusted to compensate for the greater millivoltage change due to ambient temperature changes.

The advantages of this method are (1) a large emf is developed for a given temperature and (2) burnout of any single thermocouple is immediately apparent

The disadvantages are (1) a special calibration is required, (2) a short circuit, which might materially reduce the emf of one couple, might not be detected by observation of total emf, (3) on a multipoint installation the same number of thermocouples must be used in series at each point, and (4) grounded thermocouples cannot be used.

(f) Parallel-Connected Thermocouples. Temperatures can be averaged by connecting thermocouples in parallel (Fig. 4.4). Here the net emf developed at G is the average of the potential drops across each individual branch of the

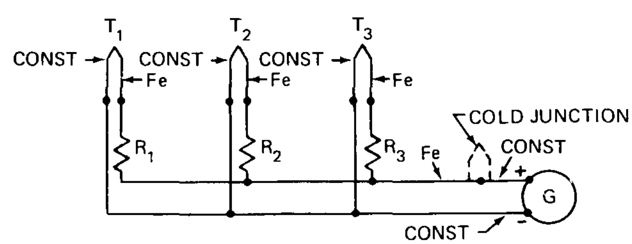


Fig. 4.4—Parallel-connected thermocouples (iron = Fe, constantan = const.). [From W. H. Kirk, Thermocouple Primer, *Instrum. Control Syst.*, **41**: 79(March 1968).]

circuit rather than an average of the emf's. Since current circulates among the thermocouples when the temperatures T_1, T_2, and T_3 are different, the resistance of each individual thermocouple circuit must be equalized by resistors R_1, R_2, and R_3 (swamping resistors).

The resistance of the actual thermocouple will also vary with its temperature. The effect of this variation can be minimized by making the values of R_1, R_2, and R_3 high (500 ohms typical) in comparison with the resistance changes encountered R_1, R_2, and R_3 are of equal value The resistances of the swamping resistors are limited by the sensitivity of the indicator (amount of current required to actuate it) and the number of thermocouples in the arrangement. Maximum sensitivity is achieved when the total impedance (resistance in this case) of the thermocouple circuit (all thermocouples and swamping resistors) is equal to the internal impedance (resistance) of the indicator. The resistance of a thermocouple circuit can be measured with a millivoltmeter and rheostat (Fig. 4.5).

The advantages of parallel connection are (1) standard instrument calibrations and cold-junction compensation for a single couple can be used and (2) if one couple fails, operation can be continued.

The disadvantages are (1) failure of a single couple is not readily apparent and (2) grounded thermocouples cannot be used.

These thermocouples are used for measuring the efficiency of heat exchangers

(g) Differentially Connected Thermocouples. Two typical arrangements for differentially connected thermocouples are shown in Fig. 4.6. Figure 4.6(a) illustrates the basic circuit in which one couple senses one temperature and a second couple senses another temperature. Note that the similar metals are interconnected and that *it is not necessary to refer the cold junction back to the galvanometer.* This is because the one couple constitutes a hot junction and the second the cold junction. Also, both leads to the galvanometer are of the same material, and each of these leads joins a third metal at a point where there is no temperature difference. As a result, even though two junctions of dissimilar metals are formed, they have no effect because there is no temperature difference. There are no unbalanced thermocouple emf's created when the copper leads of the galvanometer are both connected to the constantan leads at a point where no temperature difference exists.

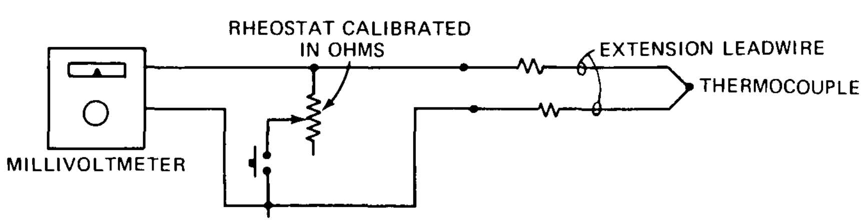


Fig. 4.5—Method for measuring thermocouple-circuit resistance [From W H Kirk, Thermocouple Primer, *Instrum. Control Syst*, **41**: 81(March 1968)]

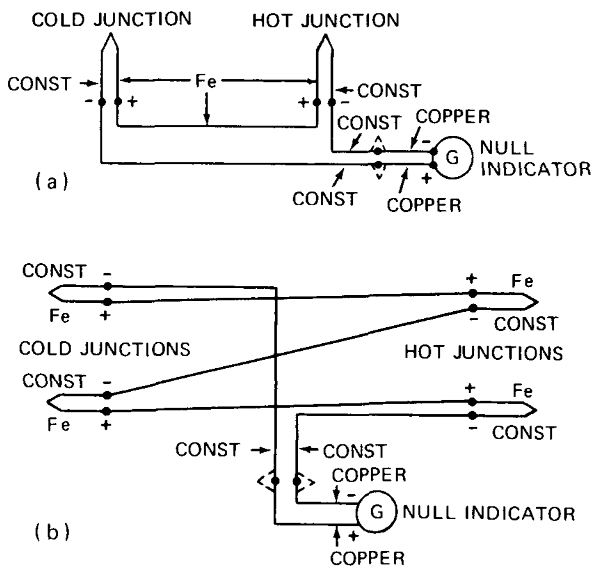


Fig. 4.6—Two typical arrangements of differentially connected thermocouples (iron = Fe, constantan = const.). [From W. H. Kirk, Thermocouple Primer, *Instrum. Control Syst.*, **41**: 79 (March 1968).]

Figure 4.6(b) shows a circuit using differentially connected couples in series to provide larger emf's with small temperature difference Note that the basic differential circuit in Fig. 4 6(a) is duplicated in Fig. 4.6(b) Any number of couples may be connected similarly to produce a desired emf.

When differentially connected couples are used, cold-junction compensation is not required in the indicator or controller since, from the basic nature of the circuit, there is no cold junction located at the indicator as in all the other circuits discussed.

Applications of differentially connected couples include measurement of temperature differences across pumps and heat exchangers, the detection of temperature differences across large furnaces, etc.

(h) Indicators and Controllers. The two most popular types of measuring devices are the galvanometer and the potentiometer. The former finds application for control and indication in noncritical industrial processes The potentiometer is more suited for critical processes that demand great stability in their control

In early potentiometer circuits a galvanometer that was sensitive to vibration was used. Comparatively complex devices were required to "feel" or determine the galvanometer pointer position. These complex devices and relatively slow responding galvanometers limited instrument speed and required considerable maintenance

Figure 4.7 shows a basic galvanometer type instrument. The No. 6 dry cell provides a constant current through the slide-wire. This current is held constant by periodically shifting the standardizing switch to the "standard" position and comparing the voltage of the No 6 dry cell with that of the standard cell. If they are not equal (the galvanometer being deflected from its null position), the standardizing rheostat is adjusted until the galvanometer does not deflect in switching from the No 6 dry cell to the standard cell The "standard" switch is then set at the "run" position.

The thermocouple is now in the galvanometer circuit, and, by moving the slide-wire contactor along the slide-wire, a point will be reached at which the thermocouple voltage is matched by the voltage drop across the slide-wire. The scale located above the slide-wire is calibrated in terms of temperature in place of voltage, thus a conversion from voltage to temperature is avoided.

The circuit of Fig. 4.7 shows the essentials of the potentiometer type measuring instrument In practice the measuring slide-wire is one arm of a bridge circuit that includes temperature-compensation circuits and ratioing resistors as well as calibration resistors. A galvanometer was used in these circuits until about 1940, at which time an electronic amplifier replaced the galvanometer.

At the present time, temperature transmitters, which are solid-state high-gain amplifiers, have come into wide use. Having no slide-wires or other moving parts, they may, for all practical purposes, be considered maintenance-free devices They are very useful in a modern coordinated plant control system because their output (typically 4 to 20 mA), which is proportional to the input, can be used in many ways, e.g., in conversion to pneumatic signals and in driving recorders, indicators, and controllers. Temperature transmitters may also serve as one of the inputs to Btu-calcu-

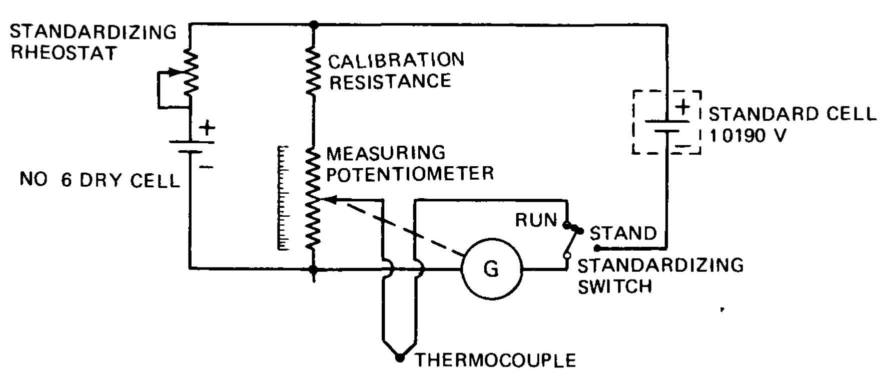


Fig. 4.7—Basic measuring circuit using potentiometer and galvanometer.

lating devices and as inputs for temperature compensation in flow-measuring and -recording meters Figure 4.8 is typical of a 4- to 20-mA temperature transmitter.

(i) Thermocouple Response Time. The rate at which a thermocouple reaches the temperature of the medium in which it is immersed (or which it contacts) depends primarily on the rate of heat transfer (conduction) through its protecting sheath.

In Fig. 4.9 the time lag between the thermocouple temperature and the medium temperature is shown for three thermocouple arrangements. The medium is stirred water heated at a constant rate. The time lag is shown for a bare 20-gage thermocouple, a thermocouple embedded in a silver plug that is in contact with the bottom section of the thermocouple well, and a thermocouple (14-gage) butt-welded and forced against the bottom of the well. With respect to the bare couple, the average time lags are about 20 sec for the well-and-plug arrangement and over 90 sec for the couple forced against the bottom of the well.

The silver-plug arrangement (so-called "high-speed couple") reduces the response time considerably Further reduction could be achieved by reducing the wall thickness of the well, however, operating conditions may not permit such reduction.

In Sec. 4-2.3(c) the structure of thermometer wells is discussed in detail.

(j) Testing Thermocouples. To realize the degree of accuracy obtainable with a modern industrial pyrometer, thermocouples are carefully manufactured to match published temperature–emf calibration tables within specific

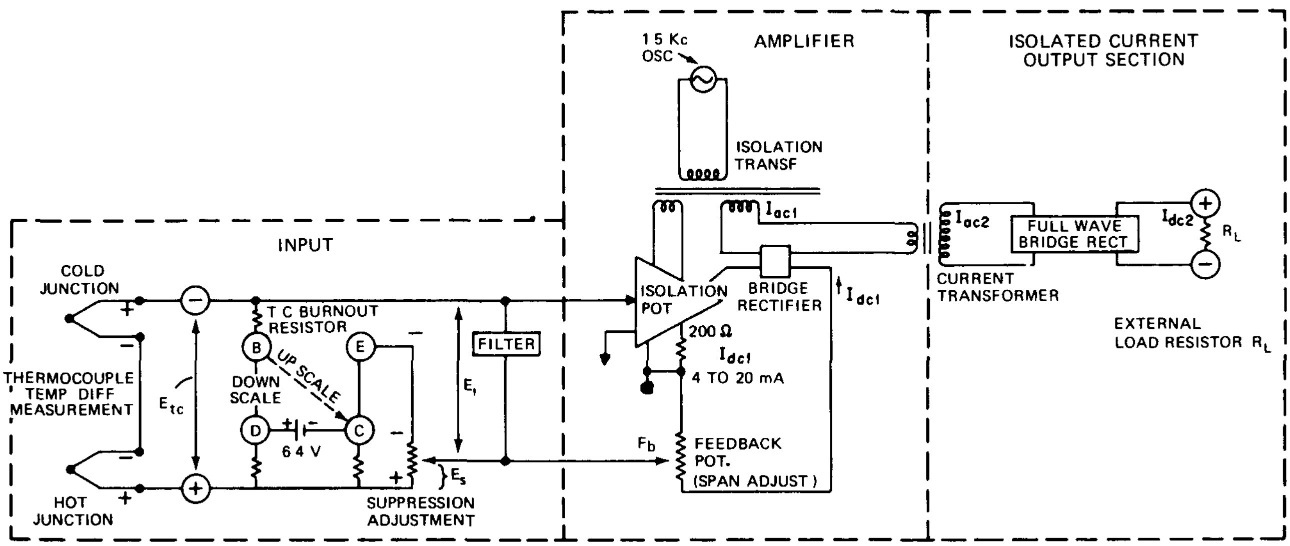


Fig. 4.8—Typical temperature transmitter circuit. This is a simplified schematic of a solid state transmitter. [From W. H. Kirk, Thermocouple Primer, *Instrum. Control Syst.*, 41: 82(March 1968).]

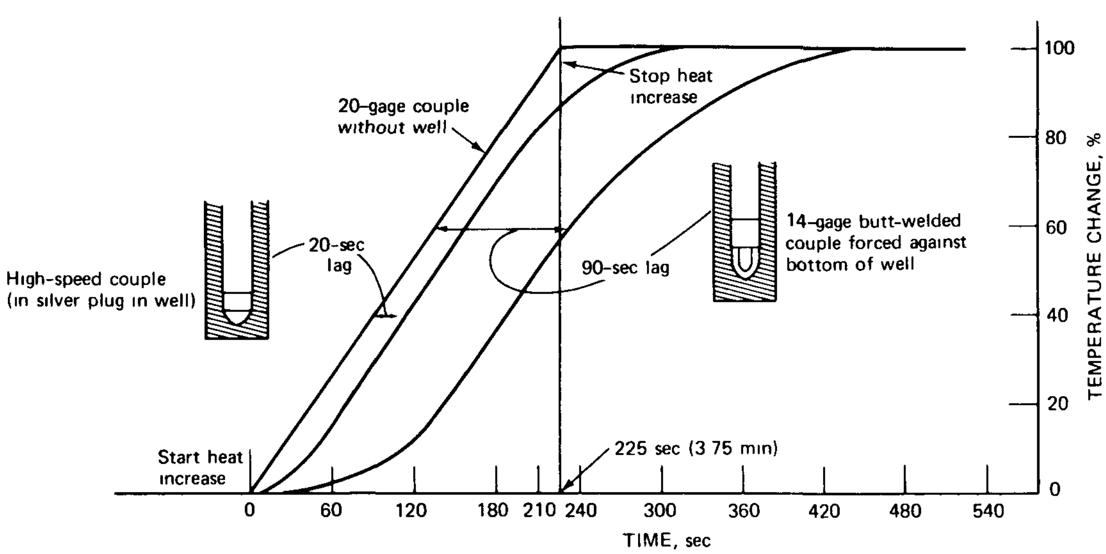


Fig. 4.9—Thermocouple response time in several arrangements. See text for details.

tolerances. Consequently, there is seldom any need to check the calibration of a new thermocouple.

While an oxidizing atmosphere has a greater effect on the life and calibration of iron–constantan thermocouples, a reducing atmosphere has a more severe effect on chromel–alumel couples.

It is *not* recommended that a used thermocouple be removed from the installation for testing in a laboratory furnace since it is practically impossible to duplicate in the laboratory furnace the temperature gradients of the actual installation. It is advisable to test a used thermocouple under the same conditions and in the same installation where it is normally used.

Two basic methods are used for checking the accuracy of thermocouples (1) the fixed-points method in which the emf is measured when the couple is immersed in standard liquid metals at their freezing points or in water at the boiling point or in subliming CO_2 or boiling liquid oxygen and (2) the comparison method in which the emf of the couple is compared with the emf of a standard couple Table 4.5 summarizes the methods used for testing the major types of thermocouples Note that in all except

Table 4.5—Thermocouple Testing Methods*

Type of thermocouple	Methods of calibration	Temperature range, °F	Calibration points	Accuracy at observed points, °F	Method of interpolating	Uncertainty of interpolated values
Platinum–platinum + 10% rhodium	International temperature scale (fixed points)	1166 9 to 1945 4	Freezing points of Sb, Ag, and Au	0 36	Equation $E = a + bt + ct^2$	0 54
Platinum–platinum + rhodium†	Fixed points	32 to 2642	Freezing point of Zn, Sb, Ag, and Au	0 36	Difference curve from reference table	0 9 to 2012 and 3 6 at 2642
	NBS standard samples, fixed points	32 to 2642	Freezing point of Sn, Zn, Al and Cu	0 36	Difference curve from reference table	0 9 to 2012 and 3 6 at 2642
	Comparison with standard thermocouple	32 to 2642	About every 200° F	0 54	Difference curve from reference table	0 9 to 2012 and 3 6 at 2642
	Comparison with standard thermocouple	32 to 2642	About 1100 and 2000° F (or more points)	0 54	Difference curve from reference table	1 8 to 2012 and 5 4 at 2642
Chromel–alumel	Comparison with standard thermocouple†	32 to 2012	About every 200° F	0 9	Linear	1 8
	Comparison with standard thermocouple†	32 to 2012	About 900, 1500, and 2000° F (or more points)	0 9	Difference curve from reference table	3 6
	Comparison with standard resistance thermometer‡ or at fixed points	32 to 662	About every 200° F	0 18	Difference curve from reference table	0 9
	Comparison with standard resistance thermometer‡	32 to −310	About every 100° F	0 18	Difference curve from reference table	0 9
Iron–constantan	Comparison with standard thermocouple‡	32 to 1400	About every 200° F	0 9	Linear	1 8
	Comparison with standard thermocouple‡	32 to 1400	About 200 600 900, and 1400° F	0 9	Difference curve from reference table	1 8
	Comparison with standard resistance thermometer‡ or at fixed points	32 to 662	About every 200° F	0 18	Difference curve from reference table	0 9
	Comparison with standard resistance thermometer‡	32 to −310	About every 100° F	0 18	Difference curve from reference table	0 9
Copper–constantan	Comparison with standard resistance thermometer‡ or at fixed points	32 to 572	About every 200° F	0 18	Equation $e = at + bt^2 + ct^3$ or difference curve from reference table	0 36
	Comparison with standard resistance thermometer‡	32 to 212	About 122 and 212° F	0 09	Equation $e = at + bt^2$ or difference curve from reference table	0 18
	Fixed points	32 to 212	Boiling point of water	0 09	Equation $e = \frac{a(t - 32)}{1\ 8} + \frac{0\ 04(t - 32)^2}{3\ 24}$	0 36
	Comparison with standard resistance thermometer‡	32 to −310	About every 100° F	0 18	Equation $e = at + bt^2 + ct^3$ or difference curve from reference table	0 36
	Fixed points	0 to −310	Sublimation point of CO_2 and boiling point of O_2	0 18	Difference curve from reference table	0 54

*From American Society of Mechanical Engineers, Power Test Code 19 3, Chap 9, 1961

†Either 10 or 13% rhodium

‡In stirred liquid bath

high-precision laboratory work the comparison method is used to test and calibrate thermocouples.

To test a used thermocouple, you must have a reference standard that is known to be accurate. A new thermocouple whose calibration has been determined by comparison with a primary standard or directly against platinum may be used as a reference standard. It should then be labeled accordingly and reserved for this purpose. Since the original characteristics of the reference couple (like that of any used thermocouple) will change as it is used in testing, such a reference standard should be tested at intervals determined by the frequency of use and replaced when it is beyond the desired limits of accuracy

The method selected for testing used thermocouples depends on the type of installation. The success of each method depends primarily on the stability of the temperature during tests. The following methods are recommended in the order in which they are listed.

1. Insert a reference standard into the same protecting tube the used thermocouple is in if the size of the tube permits. Connect each thermocouple to a portable potentiometer through a selector switch, and compare the emf's developed

2. Install a reference standard adjacent to the fixed thermocouple. Drill a hole as close to the fixed installation as practicable, and install the standard in such a manner that the ends of the two protecting tubes are as close together as possible To ensure a fair comparison, use thermocouples of the same size and protecting tubes of the same size and type. Connect the couples to the instrument as in method 1, and compare readings.

3. Compare readings of successive installations of used and reference thermocouples. Test the used thermocouple first by reading the emf developed at a selected temperature. Remove it from its protecting tube, and replace it with the reference standard. Note that the standard should always be inserted in the protecting tube to the same depth as the used thermocouple. Insert the assembly to the same depth as the one tested, wait for the reference thermocouple to come to equilibrium, and then read the emf developed and compare it with that of the used thermocouple to come to equilibrium, and then read the emf others because it requires that the temperature remain constant for a longer period.

4-2.2 Resistance Thermometers

(a) Basic Considerations. The resistance thermometer is based upon the inherent characteristic of metals to change electrical resistance* when they undergo a change in temperature. The electrical resistance of very pure metals varies with temperature from about 0.3 to 0 6% resistance change per degree at room temperature (or about 0.17 to 0.33% per degree Fahrenheit). Industrial resistance-thermometer bulbs are usually made of platinum, copper, or nickel.

An impurity or alloying constituent in a metal decreases the temperature dependence markedly except for a few unusual alloys. Pure platinum in a fully annealed and strain-free state has a resistance—temperature relationship that is especially stable and reproducible. For this reason, pure platinum has been chosen as the international standard of temperature measurement in the temperature range from the liquid oxygen boiling point to the antimony melting point. For the resistance element, platinum is drawn into wire with utmost care to maintain high purity, and the wire is formed into a coil that is carefully supported so that it will not be subjected to mechanical strain caused by differential thermal expansion. Rugged designs are required in military and other applications so that vibration and mechanical shocks will not give momentary or permanent detrimental strain to the platinum coil.

Pure nickel has also been widely used for industrial and many military applications where moderate temperature ranges are involved Tungsten, copper, and some other metals are also used

The fractional change in electrical resistance of a material per unit change in temperature is the temperature coefficient of resistance for the material. The coefficient is expressed as the fractional change in resistance (ohms per ohm) per degree of temperature change at a specific temperature. For most metals, the temperature coefficient is positive.

For pure metals the change in resistance with temperature is practically linear, at least over a substantial range of temperature The relationship can be expressed as

$$R_t = R_0 \ (1 + \alpha t) \tag{4.1}$$

where R_t equals the resistance in ohms at temperature t, R_0 equals the resistance in ohms at 0°C (or some other reference temperature), and the coefficient α is the temperature coefficient of resistance. In differential form the relationship is

$$\alpha = \frac{1}{R_0}\frac{dR}{dt} \tag{4 2}$$

When the resistance does not vary linearly with the temperature, it is customary to include quadratic and cubic terms

$$R_t = R_0 \ (1 + \alpha t + bt^2 + ct^3) \tag{4.3}$$

where the coefficients α, b, and c are determined from measurements of the resistance at three or more temperatures uniformly spaced over the working range of temperature.

*For many metals the change is completely reversible over fairly large temperature ranges.

The resistance–temperature relation for platinum is given by the Callendar–VanDusen equation:

$$\frac{R_T}{R_0} = 1 + \alpha\left[T - b\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right) - \beta\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right)^3\right] \quad (4.4)$$

where T is the temperature in degrees Centigrade and β is taken as zero for T above 0°C.

(b) Comparison of Resistance Materials. In Fig. 4.10 the resistance R and dR/dT vs. temperature T for a typical platinum resistance sensing element are normalized to 1.00 ohm at 0°C.

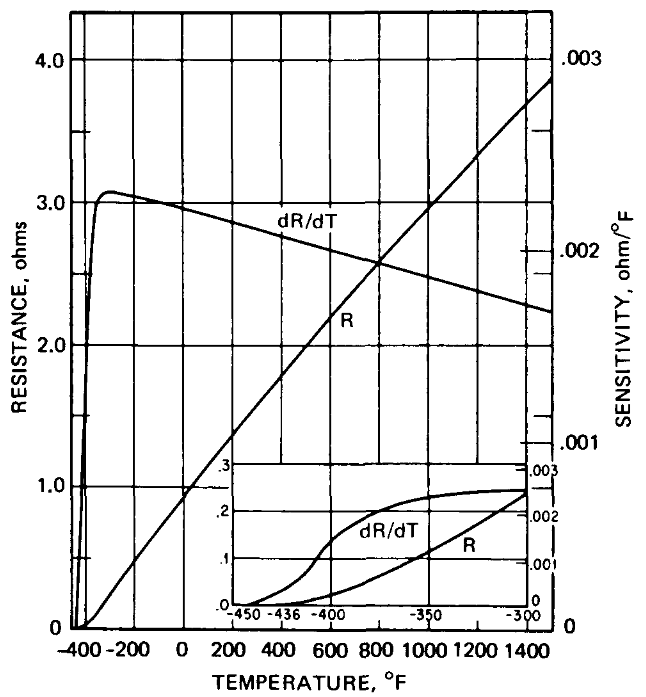


Fig. 4.10—Resistance and sensitivity versus temperature for various materials. Figure is for platinum with a resistance of 1.00 ohm at 32°F.

Tables 4.6 and 4.7 give the values of resistance vs. temperature for platinum, nickel, and copper.

Platinum. As noted earlier, platinum is the standard reference material for resistance thermometers. Recently, sensors made of very thin platinum films deposited on a substrate (usually a ceramic) have come into use. This method of constructing resistance thermometers leads to small sensing elements with high impedance (resistance) values.

Copper. Copper is inexpensive and has the most nearly linear relation of known metals over a rather wide temperature range. Copper has low resistance to oxidation above moderate temperatures and has much poorer stability and reproducibility than platinum in most applications. The low resistance of copper is a disadvantage when a high-resistance element is desired.

Nickel. Nickel has been widely used as a temperature sensing element over the range from about −100 to +300°C (−150 to 570°F), principally because of its low cost and the high value of its temperature coefficient. Above 300°C (570°F), the resistance–temperature relation for nickel changes character. Nickel is very susceptible to contamination by certain materials, and the relation of resistance to temperature is not as well known nor as reproducible as that of platinum.

Tungsten. The resistance vs. temperature relation of tungsten is not as well known as that of platinum. Full annealing of tungsten is impractical, and therefore tungsten sensors have been found to be less stable than well-made platinum sensors. Tungsten has been shown to have good resistance to very high nuclear-radiation levels and compares with platinum in this respect. Because of its mechanical strength, extremely fine tungsten wires are rugged, and sensors having high resistance values can be manufactured.

Table 4.6—Resistance vs. Temperature (°F) for Platinum, Nickel, and Copper Resistance Elements*

	Platinum		Nickel		Copper
°F	10 ohms	100 ohms	100 ohms (type I)†	200 ohms (type II)‡	10 ohms at 25°C
0	9.290	91.165	89.94	227.190	8.358
32	10.000	98.129	100.00	235.116	9.042
50	10.398	102.030	105.84	239.696	9.428
100	11.496	112.807	122.79	252.890	10.498
150	12.585	123.495	140.92	266.811	11.568
200	13.665	134.095	160.34	281.498	12.638
250	14.736	144.605	181.16	296.993	13.708
300	15.798	155.027	203.51	313.341	14.778
350	16.851	165.361	227.51	330.589	
400	17.895	175.606	253.26	340.787	
450	18.930	185.762		367.986	
500	19.956	195.829		388.242	
550	20.973	205.808		409.614	
600	21.981	215.699		432.162	
650	22.980	225.500			
700	23.970	235.213			
750	24.951	244.838			
800	25.922	254.374			
850	26.885	263.821			
900	27.839	273.179			
950	28.783	282.449			
1000	29.719	291.630			
1050	30.646	300.723			
1100	31.563	309.727			

*From Scientific Apparatus Makers Association Standard RC 21-4-1966.

†Type I nickel resistance thermometers include a series padding resistor to match a specific curve with nickel of varying purity.

‡Type II nickel resistance thermometers include a series and shunt padding resistor to facilitate linear temperature readout.

Table 4.7—Resistance vs. Temperature (°C) for Platinum, Nickel, and Copper Resistance Elements*

	Platinum		Nickel		Copper
°C	10 ohms	100 ohms	100 ohms (type I)†	200 ohms (type II)‡	10 ohms at 25°C
0	10.00	98.129	100.00	235 116	9 042
50	11.976	117 521	130.62	258.923	10.968
100	13.923	136.625	165.20	285.141	12 894
150	15.841	155.442	204.44	314.013	14.820
200	17.729	173.972	249.02	345 809	
250	19.588	192.215		380 825	
300	21.418	210.171		419.386	
350	23 218	227.840			
400	24.990	245.221			
450	26.732	262.315			
500	28 444	279.122			
550	30.128	295.642			
600	31.782	311.875			

*From Scientific Apparatus Makers Association Standard RC 21-4-1966.

†Type I nickel resistance thermometers include a series padding resistor to match a specified curve with nickel of varying purity.

‡Type II nickel resistance thermometers include a series and shunt padding resistor to facilitate linear temperature readout.

Table 4.8 lists some typical characteristics of the principal resistance thermometers.

(c) Resistance-Element Structure. The elements of resistance thermometers can be constructed in a variety of ways, varying from a cage-like open array of resistance wires within a guard screen to a coil wound on a mandrel and encased in a rugged well. The choice of structure depends on such factors as (1) compatibility of the resistance material with the environment, (2) requirements for speed of response, (3) extent of immersion permitted, and (4) expected mechanical stresses to be experienced.

Figure 4.11 shows six types of resistance elements, and Fig. 4.12 shows a typical resistance element assembly in a protecting well.

(d) Resistance-Thermometer Instrumentation. The instrument measuring the changes in resistance usually employs some form of Wheatstone bridge circuit and may be either an indicator or a recorder. The bridge may be the balanced or unbalanced type. Potentiometric methods of measuring the resistance are used occasionally.

Figure 4.13 is a diagram of a typical Wheatstone bridge used for resistance-thermometer measurement a and b are ratio arms of equal resistance, and r is a variable resistance, the value of which can be adjusted to balance the bridge so that, except for lead resistance, r = x, x being the resistance of the thermometer resistor.

Copper lead wires have a temperature coefficient of the same order of magnitude as that of a thermometer resistor, and, if their resistance is appreciable in comparison with that of the thermometer resistor, the lead wires may introduce large and uncertain errors into the measurement of temperature. Since the thermometer resistor usually must be placed at a considerable distance from the bridge, the resistance of the lead wires must be compensated. Figure 4.13 illustrates one method of accomplishing this result. Three wires (A, B, and C) connect the measuring instrument and the thermometer resistor (x). Of these, A and C should be identical in size, length, and material and should be placed side by side throughout their length so as to be at the same temperature. The B wire, which is one of the battery wires, need not be similar to the others, however, it is common practice to form the three wires into a cable and make them all alike. A and C are in the thermometer resistor arm (x) and the variable resistance arm (r), respectively. Their resistance remains equal although their temperature conditions may change, and, hence, with a one-to-one bridge ratio, such changes have no effect on the bridge reading.

No variable contact resistances should be included in the bridge arms, because the variations in bridge balance introduced at the contacts may be sufficient to affect the reliability of the measurements. The effect of these variations, as well as those resulting from unequal lead resistances, may be reduced by using a resistor of several hundred ohms resistance in the thermometer.

Table 4.8—Characteristics Typical of Resistance Thermometers*

Element	Temperature range, °F	Tolerance Standard	Tolerance Special
10- and 100-ohm Pt	−330 to +300	±1½°F	±¾°F
	Above +300°F	±½% of temp. rdg.	±¼% of temp. rdg
Ni (type I)	−40 to 400	±1°F or ±½ of temp. rdg, whichever is greater	
Ni (type II)	−150 to −40	±2 0°F	
	−40 to 400	±0 5°F	
	400 to 600	±¼% of temp. rdg	
Cu	100 to 300	±½°F	±⅕°F

*From Scientific Apparatus Makers Association Standard RC 21-4-1966.

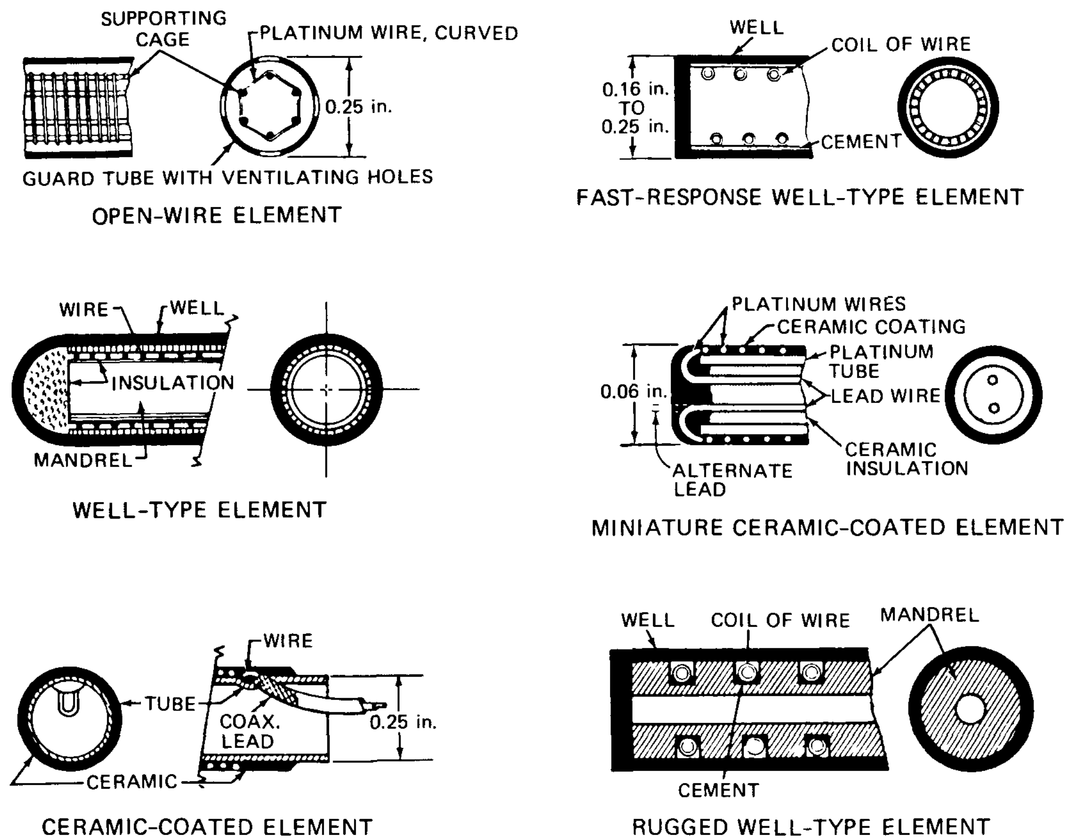


Fig. 4.11 —Typical structures used in resistance thermometers.

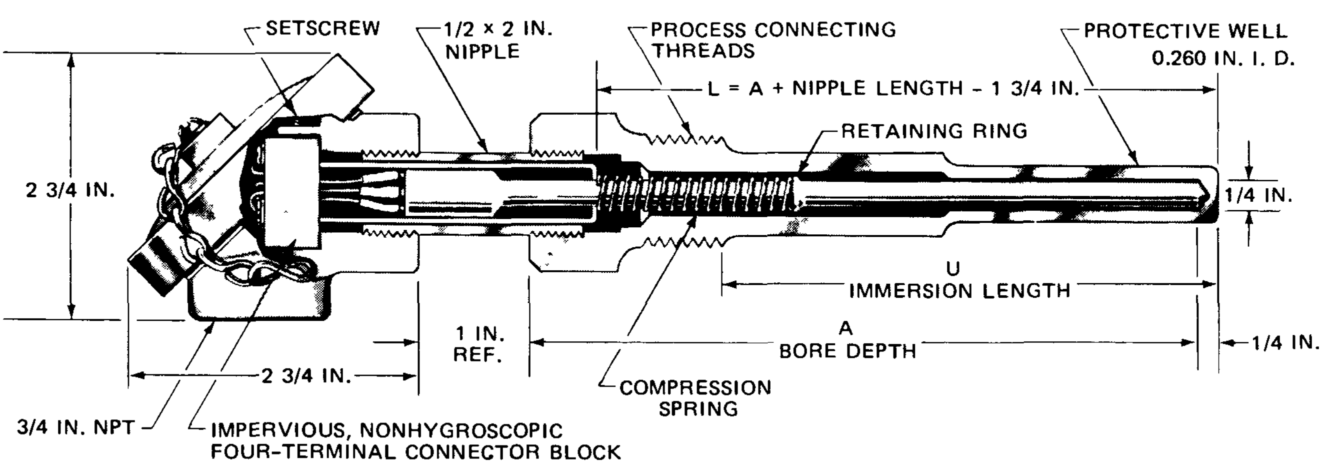


Fig. 4.12—Resistance element assembly in a protecting well. This spring-loaded design keeps the element and well in constant firm contact, assuring vibration as a single unit and improving response time. Installation and removal is simplified since it is not necessary to disassemble anything. The installation instructions for this typical resistance element assembly are (a) thread well, nipple, and head firmly into process equipment; (b) unscrew head over and insert element assembly down into well (connector block will be approximately ½ in. from seating position when element tip bottoms in well), and (c) push connector block against spring, force to seating position, and screw setscrew into mating hole in connector block.

(e) Comparison with Other Sensor Types. *Thermocouples.* A comparison of thermocouples with platinum resistance temperature sensors or any other resistance sensor would indicate that thermocouples have certain advantages. For thermocouples the temperature-sensitive zone can be extremely small, and the measurement can be made with an extremely sensitive potentiometric device. Thermocouples are also well suited for relatively high

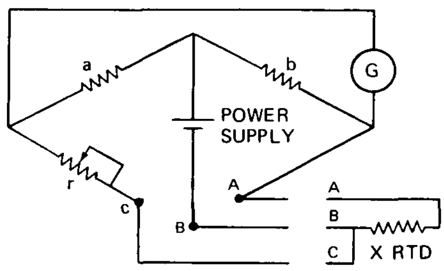


Fig 4 13—Wheatstone bridge circuit

temperatures and are relatively easy to install However, at low temperatures, higher output and higher accuracy are much in favor of resistance sensors

Some of the principal advantages of resistance sensors over thermocouples are

1 A much higher output voltage can be obtained

2 Related recording, controlling, or signal conditioning equipment can be simpler, more accurate, and much less expensive because of the higher possible bridge output signal

3 The output voltage per degree for resistance sensors can be chosen to be exactly as desired over wide limits by adjusting the excitation current and/or the bridge design

4 A reference-junction temperature or compensating device is unnecessary

5 The shape of the curve of output vs temperature can be controlled, within limits, for certain resistance sensor bridge designs

6 The output of a resistance sensor bridge can be made to vary with temperature and another variable by causing the excitation to vary with the second variable

7 Because of the higher output voltage, more electrical noise can be tolerated with resistance sensors, therefore, longer lead wires can be used

8 Sensitivity to small temperature changes can be much greater

9 In moderate temperature ranges, absolute accuracy and calibration and stability of calibration for resistance elements can be better by a factor of 10 to 100

Thermistors. Thermistors are relatively inexpensive and are very sensitive to temperature The change in resistance per unit change in temperature is large They are available in small sizes and are available with unusually high resistance values when desired Thermistors have a particularly nonlinear resistance–temperature relation Because of the nonlinear relation, relatively numerous calibration points are necessary, and the expense of calibration at many points is frequently a major part of the cost of a thermistor temperature sensor

Semiconductors The resistance–temperature relation for the semiconductors consisting of alloy combinations is very complex and therefore requires many more calibration points than platinum sensors At very low temperatures semiconductor thermometers consisting of doped germanium sensors have been looked upon with much favor, at least for applied thermometry, as compared to all other methods of measuring temperature When it is necessary to make continuous measurements over the range from approximately 1 to 40°K, they can be used to good advantage

Carbon Resistors At extremely low temperatures carbon resistors are very sensitive to temperature They have been widely used, mainly for research purposes, for temperature measurements from about 0 1 to 15 or 20°K with good results Their stability is less than might be desired

4-2.3 Thermowells

Thermowells are protective devices for the sensors of temperature indicating, recording, and controlling instruments As used in out-of core locations in a nuclear power plant, temperature sensors may be exposed to a wide range of pressures and temperatures and to a variety of potentially corrosive materials

This section includes a description of the basic types of thermowells and their materials of construction, a summary of methods for ensuring that the thermowell design will survive the mechanical stresses met in service, and a guide to the selection of thermowell materials

(a) Connection to Process Vessel. A thermowell is usually secured to a process vessel by threads, flanges, or welding (Fig 4 14)

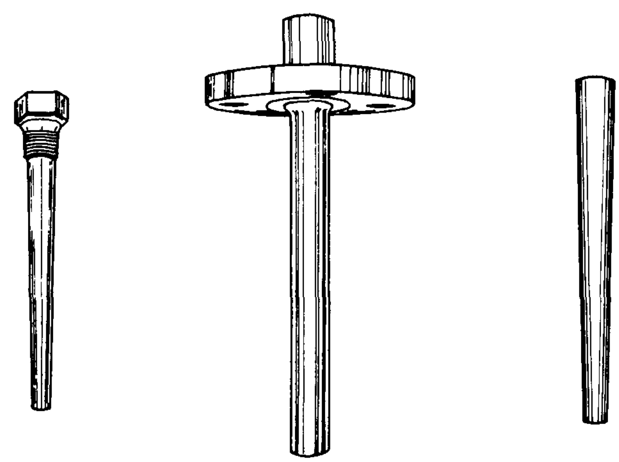


Fig 4 14—Commonly used connections for securing thermowells to process equipment. (Courtesy Pall Trinity Micro Corp.)

The threaded connection, normally using standard-taper pipe threads, is most popular owing in large measure to its simplicity and low cost Standard threaded well connections range in size from ½ in to 1 in NPT, with specials ⅛ in to 2 in NPT meeting most requirements

Flanged assemblies of any size and/or pressure rating are available Normal means of well mounting are provided by ASME-approved welding techniques, with follow-up

machining to provide any standard sealing-face configuration. Flanges are commonly used to seal long thermowells or those wells which are inserted into large vessels. An alternate flange type well is the nonwelded Van Stone well with integral flange, using a lap-joint flange to hold it in place. Also available is the ground-joint type with a machined ball that mounts in a socket between a pair of mating flanges. These latter two designs have an advantage in that as thermowell replacement becomes necessary, flanges may be reused with the new assembly.

Welded connections are normally used where process pressures are too great for flanged or threaded assemblies or where long-term inexpensive connections are desirable The welded-in type is commonly used in conjunction with high-pressure, high-velocity steam lines. This type well is frequently furnished with close tolerance limits on outside diameters in the area to be welded. These are tapered-stem wells with greater wall thickness in the weld area but with relatively low mass at the end to improve response with tip-sensitive temperature-measuring devices.

(b) Length, Bore, and Wall Thickness. Overall well length is determined not only by desired insertion length but also by external extension of the connection end. Most threaded connection wells require an additional 2 in. of nonimmersed length to provide threads and wrenching surface. Welded or flanged wells normally require at least 1.25 in. of extra length for instrument-connection threading and welding surface. Where there are layers of thermal insulation, a lagging extension should be added between the process connection and the instrument connection.

Bore size (both length and diameter) depends on the thermal sensing element to be used. The fit between the sensor and the inner wall of the thermowell must be good if accuracy and rapid response are to be achieved [Sec. 4-2.1(i)]. Care should be taken to prevent heat loss to surroundings and to avoid variations caused by stratification of process fluids. Where clearances between measuring element and bore are minimal and welding must be performed in the field, a counter bore of 10 to 20 mils greater diameter than the bore should be made. This counter bore should be carried sufficiently far past the welded area to avoid distortion in the bore due to heat of welding.

To withstand mechanical stresses, the thermowell wall should be thick. However, to provide rapid response to process-temperature changes, the wall should be thin (and the immersed well mass should be minimum). These conflicting requirements have been met by using tapered thermowells, in which the tip has a thin wall for optimum heat transfer and a thick mounting for improved strength. The design of these wells is discussed in the next section.

(c) Design of Power Test Code Thermowells. The American Society of Mechanical Engineers recommends a standardized Power Test Code thermometer well, as shown in Fig. 4.15. Wells of this design, with $\frac{3}{16}$ in. minimum wall thickness, are expected to satisfy 95% of the present needs.

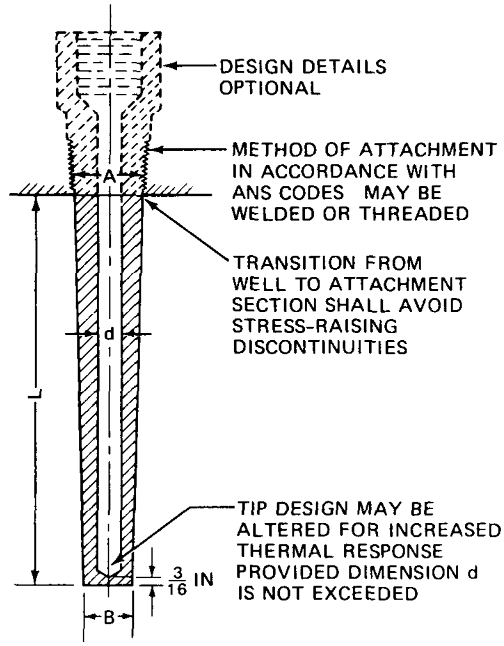


Fig. 4.15—Power Test Code thermometer well (From Scientific Apparatus Makers Association Standard RC 21-4-1966.)

The following design procedure enables a user to determine if a well selected for thermometry considerations is strong enough to withstand specific application conditions of temperature, pressure, velocity, and vibration. This design procedure does not allow for effects due to corrosion or erosion. If corrosion or erosion is anticipated, additional wall thickness must be allowed in all exposed sections to prevent premature well failure.

The nominal size of the sensing element is considered here to vary between $\frac{1}{4}$ in. (6.35 mm) and $\frac{7}{8}$ in. (22.225 mm). For this range the dimensions of the thermowell are assumed to be those given in Table 4.9.

Table 4.9—Thermowell Dimensions (in.)*

	Nominal size of sensing element				
Dimension	1/4	3/8	9/16	11/16	7/8
A (min.)	1 3/16	1 5/16	1 1/8	1 1/4	1 7/16
B (min.)	5/8	3/4	15/16	1 1/16	1 1/4
d (min.)	0 254	0 379	0 566	0.691	0 879
d (max.)	0.262	0 387	0 575	0 700	0 888

*From Scientific Apparatus Makers Association Standard RC 21-4 1966

A thermometer well must be able to withstand (at the operating temperature) the static stress associated with the maximum operating pressure of the process vessel. The maximum allowable pressure is computed from the formula

$$P = K_1 S \tag{4.5}$$

where P = maximum allowable static gage pressure (psig)
K_1 = a stress constant depending on thermowell geometry
S = allowable stress for thermowell material at the operating temperature as given in the ASME Boiler and Pressure Vessel or Piping Codes (psi)

For wells constructed as shown in Fig. 4.15 with dimensions as given in Table 4.9, the stress constant has the values listed in Table 4.10. For wells of other dimensions, the stress constant is given by

$$K_1 = \left(\frac{B-d}{2B}\right)^2 \frac{F_B}{2} \tag{4.6}$$

where (see Fig. 4.15) B is the minimum outer diameter (inches) at the well tip and F_B is a factor varying between 2 0 and 1.0 as shown in Table 4.11.

Table 4.10—Values of the Stress Constants K_1, K_2, and K_3*

Stress constant	Nominal size of sensing element: 1/4	3/8	9/16	11/16	7/8
K_1	0.412	0 334	0 223	0 202	0.155
K_2	37 5	42 3	46 8	48 7	50 1
K_3	0 116	0 205	0.389	0.548	0.864

*From Scientific Apparatus Makers Association Standard RC 21-4-1966.

Thermometer wells rarely fail in service from the effects of temperature and pressure. Since a thermowell is essentially a cantilevered beam, vibrational effects are of critical importance If the well is subjected to periodic stresses that have frequency components matching the natural frequency of the well, then the well can be vibrated to destruction. In nuclear power plants the temperature of high-velocity fluid streams (steam, water, etc.) must be measured Thermowells immersed in these streams (thermowell axis transverse to flow direction) are subject to periodic stresses attributable to the cyclic production of vortices in the wake of the flowing fluid, the "von Kármán vortex." The frequency of these stresses, f_w, is

$$f_w = 2.64 \frac{V}{B} \text{ (in Hz)} \tag{4.7}$$

where V = fluid velocity (ft/sec) and B = well diameter at tip (in), see Fig. 4.15. The natural frequency of the thermowell (cantilever structure) is

$$f_n = K_f \left(\frac{E}{\gamma L}\right)^{1/2} \text{ (in Hz)} \tag{4 8}$$

where E = elastic modulus of well material at the operating temperature (psi)
γ = specific weight of well material (lb/in.^{3})
L = length of well (in.) (see Fig 4.15)
K_f = a factor depending on well dimensions (Table 4.12)

The wake frequency f_w should not go above 80% of the natural well frequency, f_n,

$$r = \frac{f_w}{f_n} \leqslant 0\ 8 \tag{4.9}$$

If the ratio r is over 0.8, the well will tend to vibrate to failure.

Table 4.11—Values of F_B*

(Note t = B − d, D = 2B)

t/D From	t/D To	F_B	t/D From	t/D To	F_B
0 084	0 091	2 0	0 150	0 169	1 5
0 092	0 099	1 9	0 170	0 199	1 4
0 100	0 114	1 8	0 200	0 219	1 3
0 115	0 129	1 7	0 220	0 239	1 2
0 130	0 149	1 6	0 240	0 249	1 1
			0 250	Up	1 0

*From Scientific Apparatus Makers Association Standard RC 21 4 1966

Table 4.12—Values of K_f*

Well length (L), in.	Nominal size of sensing element: 1/4	3/8	9/16	11/16	7/8
2½	2.06	2 42	2.97	3.32	3.84
4½	2 07	2 45	3 01	3.39	3 96
7½	2 08	2 46	3 05	3.44	4 03
10½	2 09	2 47	3 06	3 46	4 06
16	2.09	2 47	3.07	3 47	4 08
24	2 09	2 47	3.07	3.48	4.09

*From Scientific Apparatus Makers Association Standard RC 21-4-1966

In any practical situation, the fluid velocity, V, is fixed, and the parameters under the instrumentation engineer's control are the well dimensions. Once the size of the sensing element is decided on (e.g., on the basis of speed of response, ruggedness, etc.), the thermometer-well outer diameter B is fixed (Table 4.9), and the wake frequency (Eq 4.7) is determined. The only well parameter remaining (except materials of construction, see next section) is the well length, L. Since f_n decreases with increasing length (Eq. 4.8), the requirement for f_w/f_n to be less than 0 8 imposes a limitation on the length, L.

The maximum length of a thermometer well for a given service depends not only on the vibratory stresses imposed by the flowing limit but also on the steady-state stresses

(drag) of the flowing fluid. These stresses limit the well length according to the following formula

$$L_{max} = \frac{K_2}{V}\left[\frac{v(S - K_3 P_0)}{1 + F_m}\right]^{1/2} \text{ (in in.)} \qquad (4.10)$$

where V = fluid velocity (ft/sec)
v = specific volume of fluid (ft^3/lb)
S = allowable stress for well material at operating temperature per codes (psi)
P_0 = static operating pressure (psig)
K_2, K_3 = stress constants (Table 4 10)

The factor F_m is a "magnification factor" dependent on the ratio r of wake frequency to the natural frequency of the well

$$F_m = \frac{r^2}{1 - r^2} \qquad r = \frac{f_w}{f_n} \qquad (4\ 11)$$

Example To clarify the use of the above formulas, consider the following example It has been determined that a 4½-in. well is required to accommodate a 9/16-in. sensing element that will measure the temperature of superheated steam at 2000 psia, 1050°F, and flowing at a velocity of 350 ft/sec. If the thermometer well is to be made of type 316 stainless steel dimensioned according to Table 4.9, will the well be safe?

Step 1 Obtain the necessary data as follows

v	Specific volume of steam	0 4134 ft^3/lb	ASME Steam Tables, 1967
L	Modulus of elasticity at 1050° F	22 35 × 10^6 psi	B31 1 0 1967, App C
γ	Specific weight of metal at 70° F	0 290 lb/in^3	
S	Allowable stress at 1050° F	9725 psi	ASME Code, Sec VIII

Step 2 Maximum static pressure (Eq 4.5)

$$P = 0.223 \times 9725 = 2170 \text{ psig} > 2000 \text{ psia (satisfactory)}$$

Step 3 Frequency calculations
(a) Natural frequency (Eq 4.8)

$$f_n = \frac{3.01}{4.52}\left(\frac{22.35 \times 10^6}{0.290}\right)^{1/2} = 1305 \text{ Hz}$$

(Use of dimensions and specific weight values for 70°F instead of for 1050°F is partially compensatory and causes no significant error.)
(b) Wake frequency (Eq. 4.7)

$$f_w = 2.64 \times \frac{350}{15/16} = 986 \text{ Hz}$$

(c) Frequency ratio (Eq. 4.9)

$$r = 986/1305 = 0.755 < 0\ 8 \text{ (satisfactory)}$$

Step 4 Maximum length calculation
(a) Magnification factor (Eq. 4.11)

$$F_m = \frac{0.755}{(1 - 0.755^2)} = 1.325$$

(b) Maximum length (Eq. 4.10)

$$L_{max} = \frac{46.8}{350}\left[\frac{0.4134(9725 - 0.389 \times 2000)}{(1 + 1.325)}\right]^{1/2}$$
$$= 5\ 33 \text{ in.} > 4\tfrac{1}{2} \text{ in. (satisfactory)}$$

Conclusion The well selected is satisfactory for the application.

An example of the installation of a typical thermocouple or resistance thermometer is shown in Fig 4 16 The thermowell shown is a heavy-duty weld-in well.

(d) Materials Used in Thermowells. Because of their ability to withstand chemical attack from process fluids, stainless steels are most frequently used in thermowells Customarily, stainless steels are put in three groups martensitic, ferritic, and austenitic.

The martensitic steels contain 11 5 to 18% Cr, <2.57% Ni, and 0.06 to 1.20% C They have a ferritic structure when annealed but take on the properties of a martensite when cooled. They can be heat-treated, hardened, and tempered to provide a wide range of mechanical properties for use in abrasive environments or where particularly high strength is required. Martensitic steels are in the 400-series stainless steels, excepting the ferritic grades, and are strongly magnetic. Examples are the AISI types 403, 410, 414, 416, 420, 431, and the 440 letter series.

The ferritic steels contain 11.5 to 28% Cr, no Ni, and 0 06 to 0.35% C. They are always magnetic and do not respond to heat treatment. They are strong and ductile when properly annealed and are generally more corrosion-resistant than the martensitics. Examples are the AISI types 405, 430, 430F, 442, and 446.

The austenitic grades are chrome–nickel alloy steels with a maximum carbon content of 0.25% and with 7 to 30% Cr and 6 to 36% Ni. They are nonmagnetic in a fully annealed condition but become slightly magnetic with cold working They are generally tougher and more ductile than martensitic and ferritic steels and have a much higher corrosion resistance The austenitic steels belong to the 300-series.

Selection of a stainless steel requires consideration of which properties are most desirable for the application corrosion resistance, strength at operating temperature, oxidation resistance, particularly at elevated temperatures, availability in a form suitable for fabrication, or ease of fabrication (machinability, weldability)

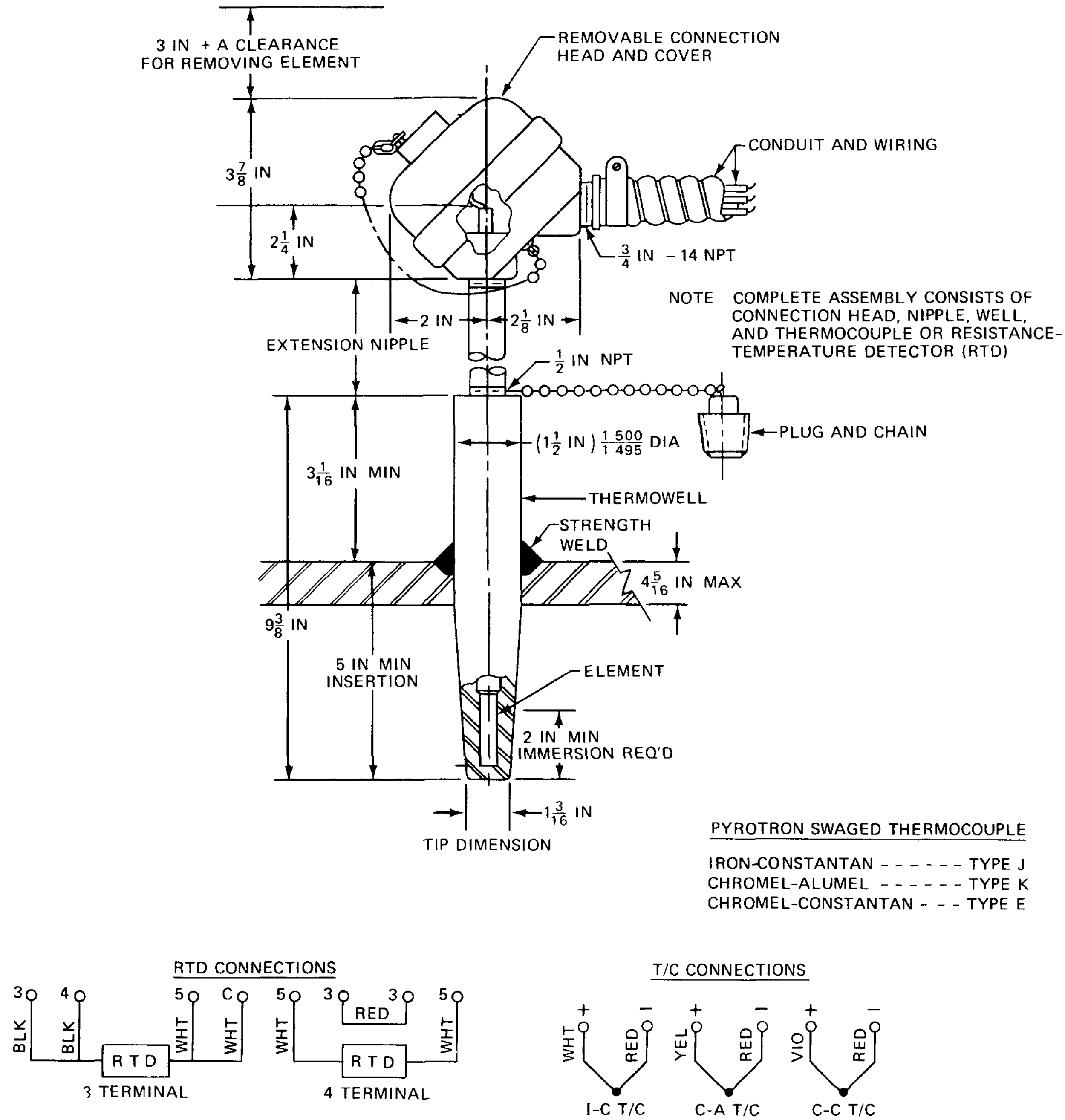


Fig. 4.16—Typical thermocouple and resistance element installed in heavy-duty thermowell. (Courtesy Bailey Meter Co.)

The principal properties of commonly used grades of stainless steels are summarized in Table 4.13.

Other materials may be used in thermowells. Tables 4.14 and 4.15 give the recommended allowable stress values and maximum operating temperatures for a number of thermowell materials.

4-2.4 Temperature Sensors in Gas-Cooled Reactors

The measurement of temperatures in gas-cooled reactors requires certain specialized sensors, e.g., sensors based on the transmission of acoustic energy through gases. For a complete discussion, see Vol. 2, Chap. 18, Sec. 18-2.2.

4-3 PRESSURE SENSING AND TRANSMITTING

4-3.1 Sensors

This section deals with elastic sensing elements that respond to a system pressure change and, in so doing, generate a measurable physical quantity, such as position or

Table 4.13—Properties of Stainless Steels Used for Thermowells*

AISI type No.	Principal properties
304	General purpose chrome–nickel steel, corrosion resistant, nonhardenable, nonmagnetic when annealed
304L	Similar in corrosion-resistant properties to type 304 but contains lower carbon percentage, used extensively to limit carbide precipitation where welding must be performed without heat treatment
309	Chromium–nickel steel with high heat resistance to scaling, nonmagnetic, nonhardenable through heat treatment
310	Somewhat higher chrome–nickel content than type 309, resists oxidation to 2000° F and has greater strength at elevated temperatures
316	Because of higher nickel content, this type has superior corrosion resistance to 304 and has somewhat better heat-resisting characteristics
316L	Low-carbon version of type 316, used in place of type 304L where improved corrosion resistance is required
321	Titanium-stabilized chrome–nickel steel, used where welding must be performed without final annealing, somewhat better strength properties than type 304L
347	Columbium–tantalum stabilized chrome–nickel steel, similar in use to type 321
410	Hardenable martensitic straight chrome steel, used in general-purpose heat and corrosion-resistant applications, good abrasion resistance
416	Hardenable martensitic steel similar to type 410, contains sulfur, which improves machinability, inferior to type 410 in impact properties and corrosion and heat resistance
430	Nonhardenable ferritic steel, corrosion and heat resistance superior to type 410
446	Nonhardenable ferritic steel, owing to high chromium content and low carbon, it has superior oxidation resistance (to 2100° F) and excellent corrosion resistance, used successfully in carburizing atmospheres, not as strong as type 309 and not as readily weldable
Nickel 200	Commercially pure wrought nickel, excellent corrosion- and heat-resistant properties, easily welded and fabricated
Monel 400	Nickel–copper alloy, very good corrosion resistance and formability, retains its strength properties over a wide range of temperatures
Inconel 600	Nickel–chrome–iron alloy, highly oxidation resistant (to 2150° F), good strength properties at high temperatures although somewhat inferior to AISI type 310
Inconel X750	Nickel–chromium–iron alloy, age hardenable by addition of aluminum and titanium, retains spring temper to 1200° F
Incoloy 800	An austenitic nickel–chrome–iron alloy steel, high strength and resistant to oxidizing and carburizing at elevated temperatures

*Courtesy Pall Trinity Micro Corp

Table 4.14—Recommended Allowable Stress Values (psi) for Thermowell Materials*

Material	0° F	300° F	500° F	700° F	900° F	1100° F	1300° F
Aluminum (1100)	2,350	1,850					
Aluminum (6061-T6)	6,000	5,000					
Nickel	10,000	10,000	9,500				
Steel†	11,200	11,200	11,200	11,000	6,500		
304 s.s	18,700	14,000	12,100	11,000	10,100	8,800	3,700
310 s s	18,700	15,800	14,100	12,700	11,600	5,000	700
316 s.s.	18,700	14,600	12,400	11,300	10,800	10,300	4,100
347 s s	18,700	16,000	14,000	12,900	12,600	9,100	2,200
410 s.s.	16,200	14,900	13,900	13,100	10,400		
446 s s	17,500	16,100	15,000				
A182-F11 (Chrome-Moly)	17,500	17,500	17,500	16,100	13,100	4,000	
A182-F22 (Chrome-Moly)	17,500	17,500	17,500	17,500	14,000	4,200	
Copper	6,000	5,000					
Admiralty brass	10,000	10,000					
Monel 400	16,600	13,600	13,100	13,100	8,000		
Inconel 600	20,000	18,800	18,500	18,500	16,000	3,000	
Incoloy 800‡	15,600	12,100	10,400	9,600	9,100	8,800	4,150
Hastelloy B§	25,000	24,750	21,450				
Hastelloy X¶	23,350	18,850	16,000	15,500	15,500	15,500	9,500

*Courtesy Pall Trinity Micro Corp Values from ASMF Boiler and Pressure Vessel Code, Sec. VIII—Pressure Vessels, 1971

†ASME Spec. Min Tensile = 45,000 psi

‡ASME Code, case 1325 (special ruling)

§ASME Code, case 1323 (special ruling)

¶ASME Code, case 1321 (special ruling)

Table 4.15—Recommended Maximum Operating Temperatures of Common Thermowell Materials*

Material	Maximum operating temp., °F	Melting point, °F
Copper	600	1980
Aluminum	700	1200
Monel	1000†	2450
Carbon steel	1200	2760
304 s.s.	1650	2600
309–310 s.s.	2000	2550
316 s.s.	1650	2525
321–347 s.s.	1600	2575
430 s.s.	1550	2725
446 s.s.	2000†	2725
Inconel 600‡	2100†	2575
Hastelloy X §	2300†	2350
Nickel	2300†	2625
Inconel X750	2400†	2570
Tantalum	4500†	5425

*From Pall Trinity Micro Corporation, *Thermocouple Guidebook*, TT-335, Courtland, N. Y.

†At high temperature, the effect of process atmosphere on the thermowell may cause severe limitations in service life The values listed constitute mill recommended maximums under average circumstances

‡Huntington Alloys Division, International Nickel Company

§Material Systems Division, Union Carbide Corporation

mechanical or electrical force. Each sensor is a differential element, and atmospheric pressure is constantly applied in opposition to the system pressure. To sense the absolute pressure, you must apply a second element (e.g., a calibrated spring) in opposition or place that part of the sensor that is normally at ambient (atmospheric) pressure within an evacuated containment.

(a) Materials. In out-of-core pressure sensors, materials coming in contact with the measured fluid must be noncorrosive, must not otherwise deteriorate, and must not contain elements that may become dangerously radioactive by accidental exposure to neutrons. The objective is a device capable of continuous, dependable pressure sensing over an extended period of time. Sensor materials contacting the measured fluid should be compatible with the fluid This is the same problem that is involved in choosing thermowell materials. Stainless steels, type 304 or better, are frequently used. Sometimes Inconel is used. Teflon materials for seals and O-rings are avoided as are any components containing cobalt. If the most highly desirable materials are not available at the sensor, diaphragm seals described in Sec. 4-3.4(b) are used.

(b) Basic Types. *Elastic metal sensors*, available in a variety of forms, consist of slack and rigid diaphragms, multiple or stacked diaphragms, corrugated bellows, and the Bourdon tube in a variety of forms, from single-turn and torsion-bar to helical and spiral multiple-turn designs. Each manufacturer has his own series of ranges for the various designs based upon the sizing of components and the required performance of a complete linkage system or other device that depends on this initiating element for its successful operation. Table 4.16 gives some typical ranges, and Sec. 4-3 6 gives a sample set of performance specifications.

Strain gages consist of a fine wire or an array of fine wires usually bonded into an assembly for mechanical strength. Under an applied stress the array of fine wires is stretched, this results in an increase in its electrical resistance. If this array is incorporated in a suitable arrangement, the resistance change can be made directly proportional to the imposed pressure. Close temperature control must be maintained by comparing the strain wire with unstressed wire (or compensation), electrical shielding of the sensor wire is also important. In some designs the strain wire may be mounted (bonded) on a Bourdon tube, bellows, or mechanical structure, such as a beam or ring * In Fig. 4.17 the strain gage is in the form of a short tube sealed by a diaphragm. Note the variable resistance is applied as a leg of a conventional Wheatstone measuring bridge Because the fractional change in strain-gage resistance is very small, electrical amplification and signal conditioning are usually required before use in readout and action modules.

Piezoelectric sensors are similar to strain-gage sensors with a crystal used for stress sensing instead of a wire. The crystal responds to a pressure change (usually expressed by a force in a predetermined direction with respect to the crystal axes) by generating a small electrical potential difference. The latter depends on the magnitude of the imposed stress and on the crystal properties Again, temperature control or compensation, as well as amplification and signal conditioning of the output, are essential.

Silicon wafer piezoelectric sensors now available are capable of sensing range spans from 0 to 6 psig to 0 to 1500 psig. Output is 10 to 50 mA d-c. Features include a range span adjustment of 4 1 for a given diaphragm and the capability of elevating the range span (zero suppression) to the maximum pressure range for the unit. Thus a 0- to 1500-psi range device would be expected to calibrate for 1100- to 1500-psig range input for a 10- to 50-mA d-c output.

4-3.2 Range Selection

A common practice is to specify the pressure interval in which the sensor is to be used so that the sensor is normally operating at a pressure between ⅓ and ⅔ of the range span. Data for the elastic-metal sensors are given in Table 4.16. The basic ranges shown in the table may be modified.

*See L M. Vanderpyl, *A Bibliography on Bourdon Tubes and Bourdon Tube Gages*, ASME Paper 53 IRD-1, and A. C. Arobone, *Strain Gage Transducers for Measurement and Control*, Product Engineering Co., Columbus, Ind., 1952.

Table 4.16—Typical Ranges of Elastic-Metal Pressure Sensors

Design	Material available	Range span Min.	Range span Max.	Maximum over-range pressure, psig
Thin diaphragm	316 s.s	0 5 in H_2O	10 in. H_2O	50
Thick diaphragm	316 s.s.	25 psig	2000 psig	500 to 4000*
Bellows	Inconel or AM350 steel†	10 in H_2O	1000 in H_2O	6000‡
Bourdon tube	Ni-Span C,§ 316 s.s., or beryllium–copper	30 psig	8000 psig	Max. range x 1.25

*See discussion of force balance in Sec. 4-3 2
†Modified type-304 stainless steel adapted for welding and stress relieving.
‡And 100 psig on gases
§Constant-modulus alloy.

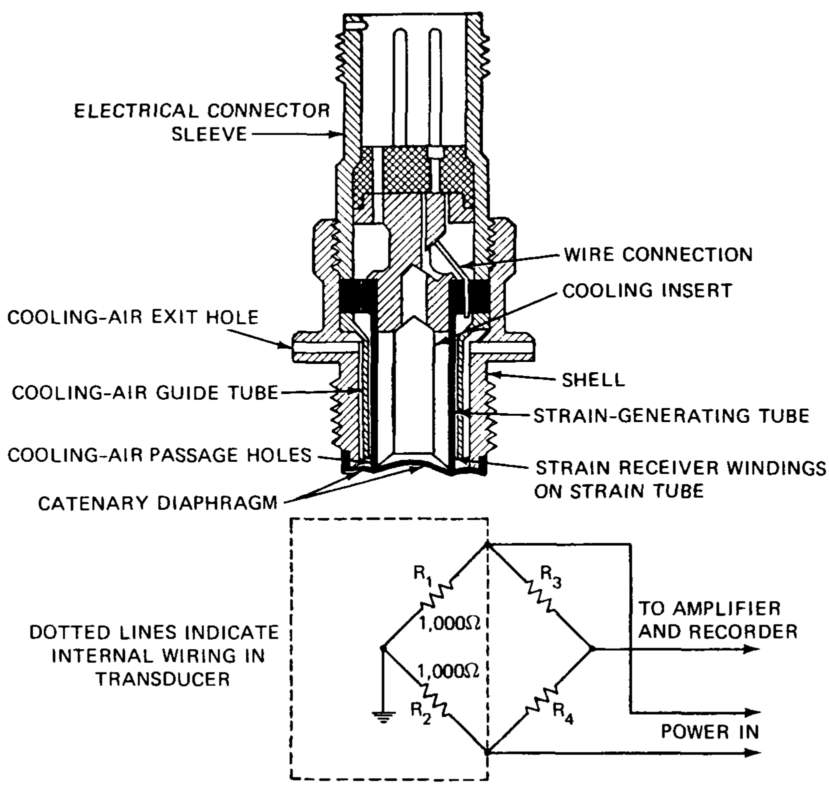


Fig. 4.17—Catenary-diaphragm sensing element and typical bridge circuit. (From D. M. Considine, *Process Instruments and Controls Handbook*, p. 3-42, McGraw-Hill Book Company, Inc., New York, 1957.)

Modifications include ranges having an elevated zero (compound range) and suppressed ranges where the minimum pressure is greater than atmospheric zero.

Motion balance refers to the mechanical system whereby the sensor motion is transferred by linkage or other means to a pointer, recording pen, or transducer mechanism, such as an armature or core (see Fig. 4.24). Typical motion-balance mechanisms are shown in Figs. 4.18, 4.19, and 4.20. Where restraining members are used, they are limited to providing means for adjusting zero or permitting calibration within the initial range capability of the sensing element, in no way should the restraining members restrict the sensing action within the intended range span of the device.

Force balance refers to the system whereby the free motion of the sensor is limited and actively opposed by some mechanical or electrical means. In effect this reduces the actual mechanical motion of the sensor to a very few thousandths of an inch throughout its range. An example of such a device is shown in Fig. 4.21. The mechanism is capable of highly elevated ranges. One design features four interchangeable diaphragms or capsules (Table 4.17).

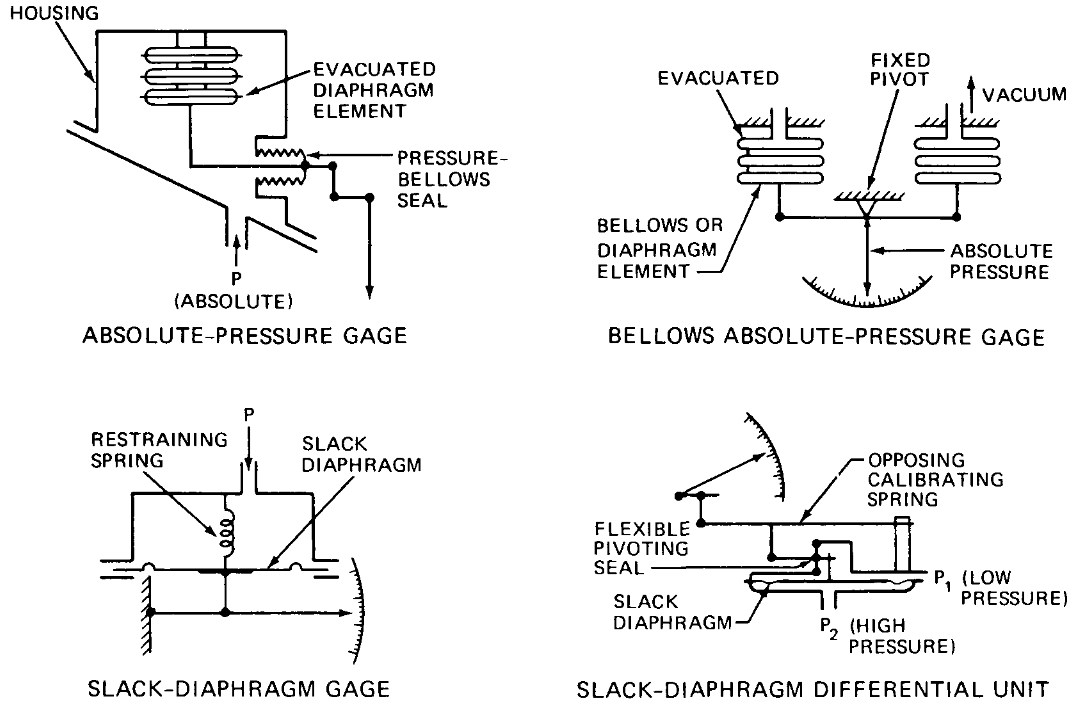


Fig. 4.18—Typical bellows and diaphragm pressure gages. Sensor motion is transmitted to indicator by mechanical linkage (motion-balance mechanisms).

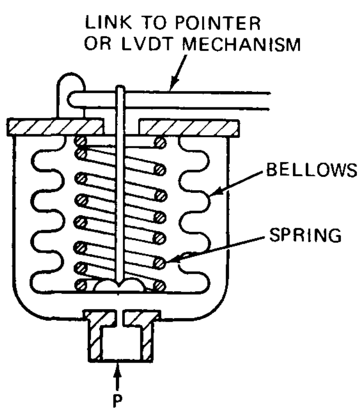


Fig 4.19—Sectional view of a motion-balance pressure gage. (From D. M. Considine, *Process Instruments and Controls Handbook*, p. 3 15, McGraw-Hill Book Company, New York, 1957.)

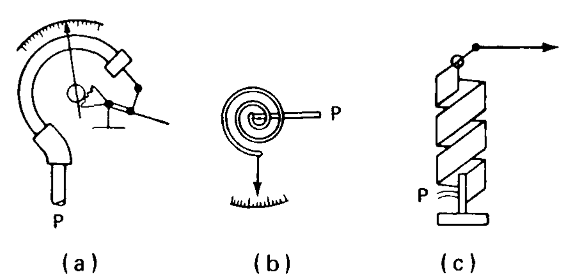


Fig. 4.20—Types of Bourdon gages. (a) C type, (b) spiral, (c) helical. (From D M. Considine, *Process Instruments and Controls Handbook*, p 3-16, McGraw-Hill Book Company, New York, 1957.)

4-3.3 Installation

An in-line sensor or a tap to an adjacent mounted sensor must be located in a position where errors due to local disturbances, such as turbulence and vibration created by the process or adjacent machinery, are avoided For accuracy in lower pressure ranges, the sensor should include provisions for compensating for the weight of liquid in connecting lines so that the transmitted or observed pressure is that in the main piping or containment

An ANSI Piping Code recommends that the pressure take-off size not be less than ⅜-in. pipe for operating up to 900 psi and 800°F and not less than ¾-in. pipe above these values. An acceptable method for installing a take-off is to weld a Weld-O-let or similar adapter to the main pipe or vessel and then drill through the adapter and pipe or vessel wall a ¼-in.-diameter hole (or larger if desired) to produce a sharp clean edge at the inner wall. Actual size of the hole should be large enough to avoid plugging. Alignment of the axis of the opening should be perpendicular to the direction of flow to avoid false pressure readings due to impact velocity effects. Material specification and controls should comply with ASME Nuclear Piping Systems of proper class 1, 2, or 3.

The pressure sensor is mounted adjacent to the take-off in such a way as to reduce transmission of piping- or vessel-expansion strains, process heat, or system vibrations to the sensor mechanism Figure 4.22 illustrates a common

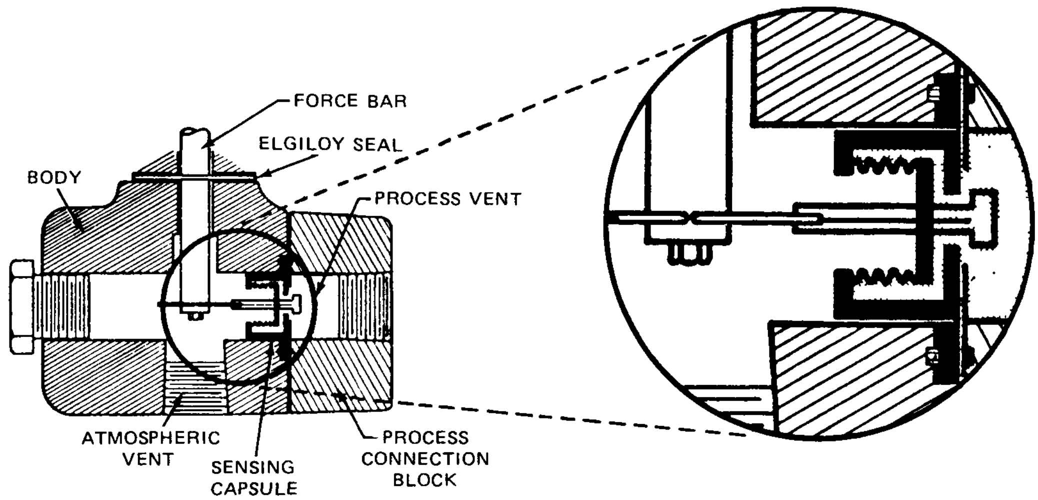


Fig. 4.21—Sectional view of a force-balance pressure transmitter.

Table 4.17—Force Balance with Four Interchangeable Capsules*

Capsule	Range limit,† psi	Range-span limits,† psi	Max. over-range pressure, psi
A	−15 to 350	25 to 250	500
B	−15 to 750	50 to 500	1000
C	−15 to 1500	100 to 1000	2000
D	−15 to 3000	200 to 2000	4000

*With this design, for example, an A capsule may be adjusted for an operating range span of 210 to 250 psi with an expected accuracy to ±2 psi (±0.5% range span). A range span of −15 to +10 psig involves the lowest range and narrowest range span possible using an A capsule.

†Basic industry terminology is given in Bailey Meter Company Instruction Sec. E41-6.

installation practice featuring ½-in.-O.D. tubing or equivalent pipe pitched to facilitate draining and maintenance. Full support of connecting tubing is recommended, unsupported tubing must take a lower pressure rating. Root valves at take-offs must be the same size as the take-off. Above 900 psi and 800°F, the take-off may be swaged or reduced to allow a ½-in. root valve, but the size at the main piping or vessel may not be reduced. Blow-down valves for drain must be at least ⅜-in. pipe size. Instrument shut-off valves may be ¼-in. pipe size and threaded to match standard instrument casing connections, this latter practice facilitates disassembly and routine maintenance and calibration.

4-3.4 Accessories

(a) Pulsation Dampeners. Dampeners may be included in sensing take-off lines and are available in stainless-steel construction in ¼-in. and ½-in. pipe sizes. (In Fig. 4.22 item 14 is a typical pressure dampener.) One design consists of a sintered stainless-steel disk or cylinder held in a stainless-steel body; another a captive stainless-steel pin in an orifice opening. Plugging may present a problem; so periodic cleaning may be required. Some sensors have electronic dampening of the output signal to avoid a mechanical dampener.

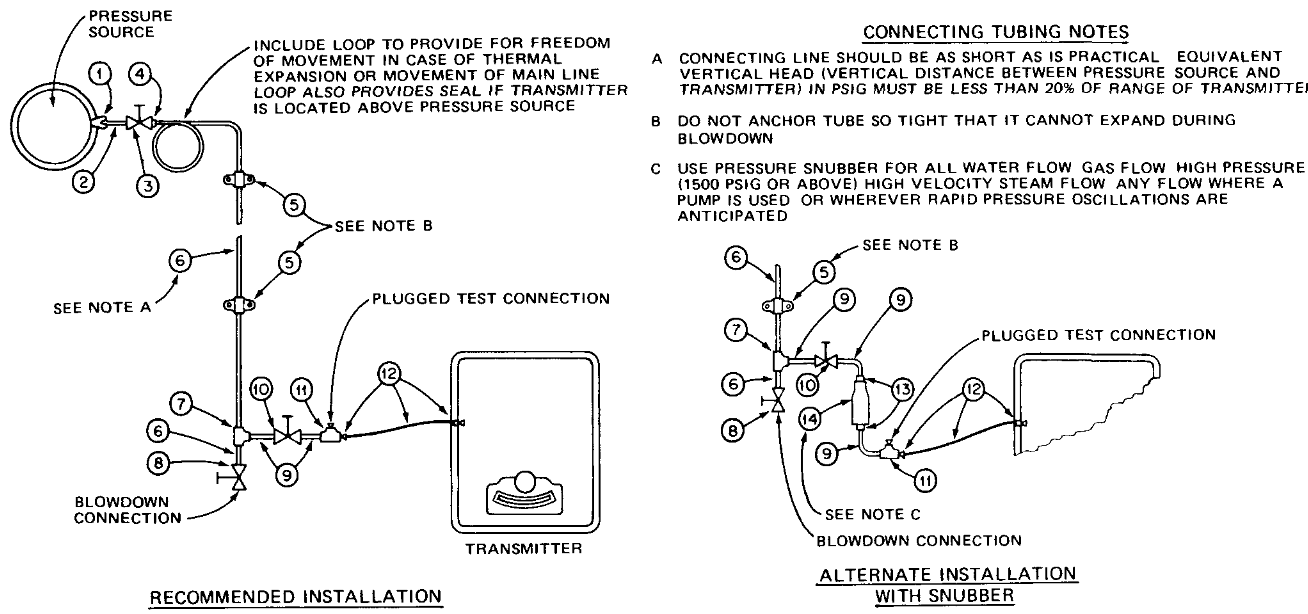
(b) Diaphragm Seals. Stainless-steel diaphragm seals can be used when a sensor is not corrosion resistant or is subject to possible contamination. The space between the sealing diaphragm and the sensor is filled with a suitable liquid whose pressure duplicates that on the process side of the diaphragm. Fluids satisfactory for temperatures up to 350°F service are common. The seals are usually assembled in the factory to ensure a complete fill. Diaphragm seals are commonly used on Bourdon tubes and in force-balance capsules involving minimum displaced volume. Excessive displacement may involve an error arising when the spring rate of the seal diaphragm is added to the measured pressure. A seal diaphragm is part of the design in Fig. 4.17.

(c) Overpressure Devices. Pressures in excess of the normal design rating of the sensor may be encountered. For such emergencies a self-operating shut-off valve may be installed between the take-off and the sensor and set to close at preset point to protect the sensor. Stainless-steel guards are available in ¼-in. and ½-in. pipe sizes for operation up to 9000 psi.

(d) Siphons. Siphons or loops in take-off piping are used to keep hot fluids from contacting the sensor mechanism, which has usually been calibrated at ambient. Performance tests on the sensor indicate the maximum temperature that can be tolerated. The strain-gage sensor in Fig. 4.17 includes coolant connections.

4-3.5 Calibration Standards

Whether the sensor has readout capability or not, its proper calibration involves subjecting it to precise pressures



ITEM	MATERIAL
1	1/2-IN , 3/4-IN , OR 1-IN WELDING ADAPTER, SIZE DEPENDING ON SIZE OF NIPPLE ITEM 2
2	1/2-IN NIPPLE FOR SERVICE UP TO 900 PSIG OR 800°F 3/4-IN NIPPLE } 1-IN NIPPLE } FOR SERVICE 901 PSIG OR 801°F OR HIGHER
3	1/2-IN , 3/4-IN , OR 1-IN GLOBE VALVE, SUITABLE FOR MAXIMUM SFRVICE PRESSURE AND TEMPERATURE, SIZE DEPENDING ON SIZE OF NIPPLE, ITEM 2
4	FITTING OR BUSHING IF REQUIRED SIZE DEPENDING ON SIZES OF VALVE ITEM 3 TUBING, ITEM 6
5	ANCHORING CLIP OR OTHER DEVICE
6	TUBING, WITH NECESSARY FITTINGS 1/2-IN O D TUBING OR 3/8-IN PIPE (OR LARGER) FOR SERVICE UP TO 1500 PSIG 5/8-IN O D TUBING OR 1/2-IN PIPE (OR LARGER) FOR SERVICE 1501 PSIG OR HIGHER
7	REDUCING TEE 1/4-IN OUTLET TO INSTRUMENT, SIZE OF STRAIGHT-THRU SECTION DEPENDING ON SIZE OF TUBING ITEM 6
8	GLOBE NEEDLE VALVE SUITABLE FOR MAXIMUM SERVICE PRESSURE AND TEMPERATURE SIZE DEPENDING ON SIZE OF TUBING ITEM 6
9	1/4-IN STEEL NIPPLE, LENGTH AS REQUIRED
10	1/4-IN GLOBE NEEDLE VALVE, SUITABLE FOR MAXIMUM SERVICE PRESSURE AT 100°F
11	1/4-IN STEEL TEE AND PLUG
12	FLEXIBLE TUBING CONNECTOR, PT NO 681853A1 18-IN-LONG STAINLESS STEEL TUBING WITH 1/4-IN MALE CONNECTORS AT EACH END SUITABLE FOR 5000 PSIG AT 100°F
13	STEEL BUSHING, IF REQUIRED, DEPENDING ON SIZE OF SNUBBER ITEM 14
14	1/4-IN OR 1/2-IN PRESSURE SNUBBER ASCROFT OR EQUAL

ALL SIZES AND MATERIALS LISTED CONFORM TO THE LATEST REVISION OF THE CODE FOR PRESSURE PIPING ASA B31 1 WHERE MATERIALS ARE NOT NOTED OR WHERE DIFFERENT FITTINGS ARE TO BE USED ALWAYS SELECT MATERIALS THAT CONFORM TO SAID CODE DO NOT CHANGE ANY SIZE TO ONE WHICH WILL NOT MEET THE CODE

Fig. 4.22—Recommended connecting tubing or piping for pressure transmitters. (Courtesy Bailey Meter Company)

and reading out on accurate gages. Correct readout voltmeters, ammeters for use with component signal conditioners, and other necessary accessories are recommended by the various manufacturers. Equipment for developing pressure varies according to the magnitude of the desired pressure.

For very low pressures, water, oil, and mercury manometers can be used. The bore should be large enough to provide an accurate column reading of the deflection scale. Air pressure from a compressor or a vacuum-pump source is also needed for a complete setup.

For medium pressures, transfer gages having calibration traceable to the U. S. Bureau of Standards can be used. Where water is used in the gage, the readings must be corrected for the weight of water unbalance between the sensor and the master gage.

For high pressures, a deadweight tester must be used. These are available for pressures from 15 to 10,000 psi. Constructed of stainless steel, using distilled water, and including a self-contained hand pump, the deadweight tester is an important calibrating device and may be used to calibrate master transfer gages for medium-pressure work.

4-3.6 Dynamic Testing and Performance Standards

Sensor manufacturers subject their designs to a series of tests simulating actual operating conditions to determine the on-line operating characteristics. Standard definitions are given in the Scientific Apparatus Makers Association (SAMA) publication PMC-20, *Measurement and Control Terminology*.

A sample performance report on a motion-balance sensor is given below

Description
- Pressure-sensing mechanism Bourdon tube (316 stainless steel)
- Electric transmission
- Output-signal ranges
  - ±10 volts d-c, ±50 mV d-c, 0 to 100 mV d-c

Operating Conditions
- Ambient temp. nominal, 75° F, reference, calibration ±5° F, normal, 40 to 140° F, operative limits, −10 to 200° F
- Supply voltage nominal, 118 volts a-c, normal, 107 to 127 volts, operative limits, 100 to 135 volts
- Frequency nominal, 50 or 60 Hz, normal, 48 to 62 Hz, operative limits, 45 to 75 Hz
- Ambient temp. effect Zero-shift error/100° F temp. change, −1% range span, Range-shift error/100° F temp change +1% range span

Reference Performance Characteristics (% range span)
- Accuracy 0.5%
- Dead band 0.2%
- Hysteresis 0.5%
- Linearity 0.25%
- Repeatability 0.25%

Design Data
- Source impedance a-c signal coil, 200 ohms, d-c signal demodulator, 180 ohms
- Minimum external load a-c transmitted signal, 2000 ohms, d-c transmitted signal, 30,000 ohms
- Maximum ripple 0.15% a-c ripple
- Case classification NEMA (National Electrical Manufacturers Association) type 2 or NEMA type 7D
- Over-range protection $1\frac{1}{4}$ times max. scale measured pressure

Performance data on a force balance sensor is given as

Description
- Pressure-sensing capsule 316 stainless steel
- Electric transmission 2 wire d-c
- Output signal range 10 to 50 mA d-c

Operating Conditions
- Power supply 63 to 85 volts d-c
- Supply voltage effect 0 25% per 10-volt variation

Performance characteristics (% range span)
- Accuracy 0 5%
- Dead band 0.005%
- Repeatability 0.15%

Design Data
- Output load limits 600 ohms (+10%, −20%)
- Case classification NEMA type 4, hazardous area Class I Group D, Div. 1

4-3.7 Transmitting Devices

(a) Pressure Switches. These are widely used to actuate alarms or initiate sequential operations. A Bourdon tube or similar sensor is linked to a snap-acting mechanical switch. (In some cases an enclosed mercury switch is used.) The switch may be indicating or nonindicating, have range-setting capability, and provide necessary logic at predetermined pressures.

(b) Electric Modulating Transmitters. These produce an electrical output proportional to input pressure (or force) applied to the sensor. Either the motion-balance or the force-balance principle may be involved. The output may be a voltage or a current of suitable value and range for input to readout devices, such as recorders, indicators, computers, and control loops to action equipment. A sample circuit for the motion-balance example of Sec. 4-3.6 is shown in Fig. 4.23. Forms of the linear voltage differential transformer (LVDT) mechanism and a sample output curve are shown in Fig. 4.24.

(c) Pneumatic Modulating Transmitters. Differential-pressure sensors installed with one side open to the atmosphere and the other side connected to a pressure source can be used The device shown in Fig. 4.35 can be used and the pneumatic force-balance principle applied to obtain a pneumatic output proportional to sensor gage pressures at connection H (or L, as desired).

4-4 FLOW SENSING

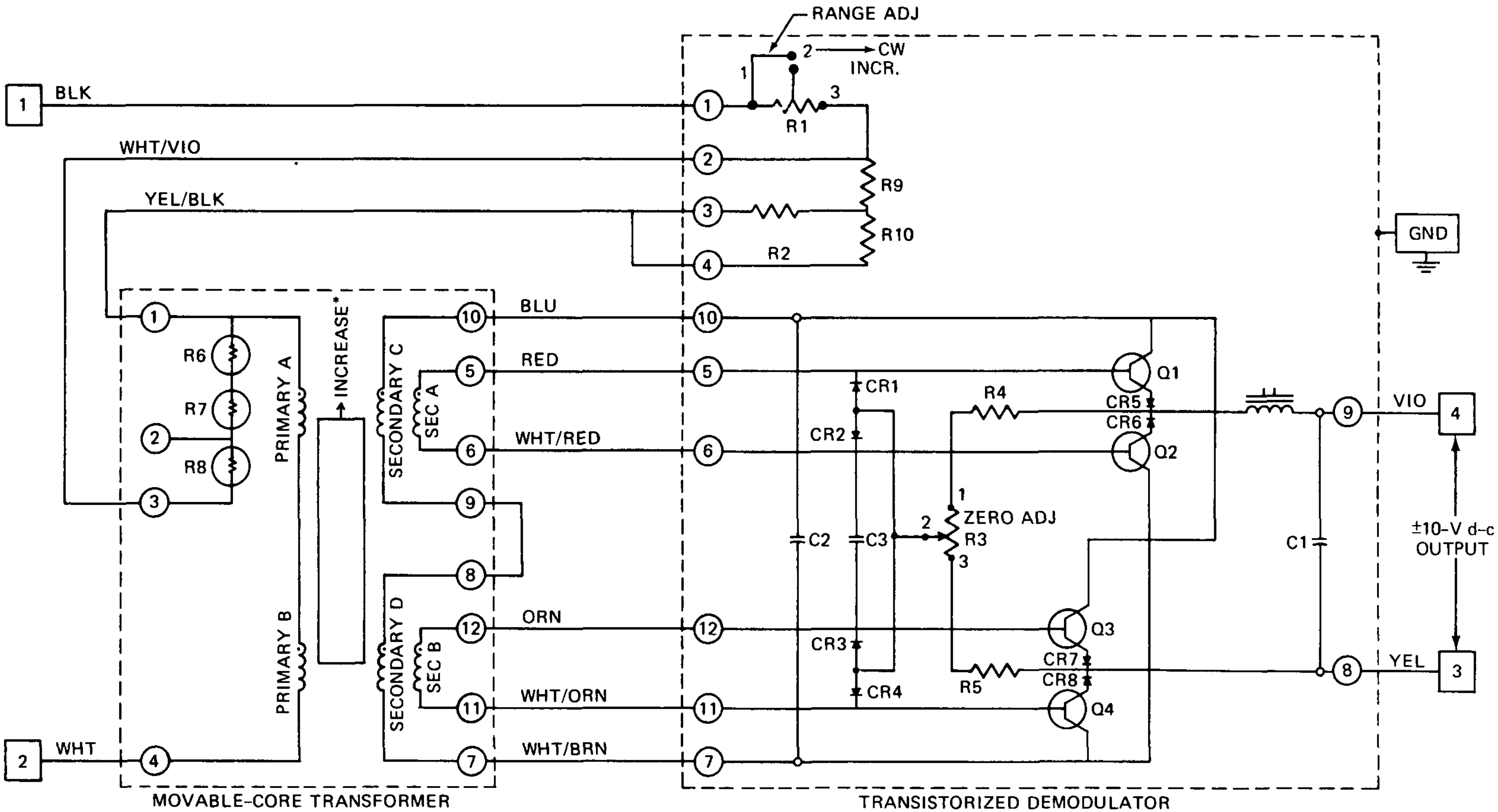
4-4.1 Differential-Pressure Flowmeters

(a) Basic Considerations. All flowmeters are considered to consist of two parts a primary element, which contacts the flowing fluid, and a secondary element, which indicates or otherwise displays the desired information.

In the common differential-pressure or head-type flowmeter, the primary element is an obstruction placed in the pipe to create a pressure drop, and the secondary element is a device to measure this pressure drop and convert it to rate of flow. The secondary element itself may consist of two parts, a transmitter and a receiver, in case the information is to be displayed at some distance from the point of measurement The primary element is usually one of three types orifice plate, flow nozzle, or Venturi tube.

(b) Orifice Plates. The orifice plate is a thin disk clamped between gaskets in a flanged joint, with a usually concentric circular hole smaller than the internal pipe diameter. This is the simplest type of primary element and the most easily reproducible. It can be used without individual calibration with the greatest assurance of accuracy.

Flow through a sharp-edged orifice plate is characterized by a change in velocity, which reaches a maximum at a point slightly downstream from the orifice. At this point, called the vena contracta, the flowing stream has its greatest convergence. Beyond this point the flowing stream diverges until it again fills the entire pipe area, the velocity is reduced back to its original value (assuming fluid density and pipe cross section are the same upstream and down-



*MCT CORE MOVES TOWARD PRIMARY A ON MEASURED VARIABLE INCREASE.
ACTUAL DIRECTION OF TRAVEL DEPENDS UPON LINKAGE REQUIRED FOR PARTICULAR INSTRUMENT.
▭ CUSTOMER CONNECTIONS

Fig. 4.23—Schematic of a linear voltage differential transformer (LVDT) and demodulator circuit.

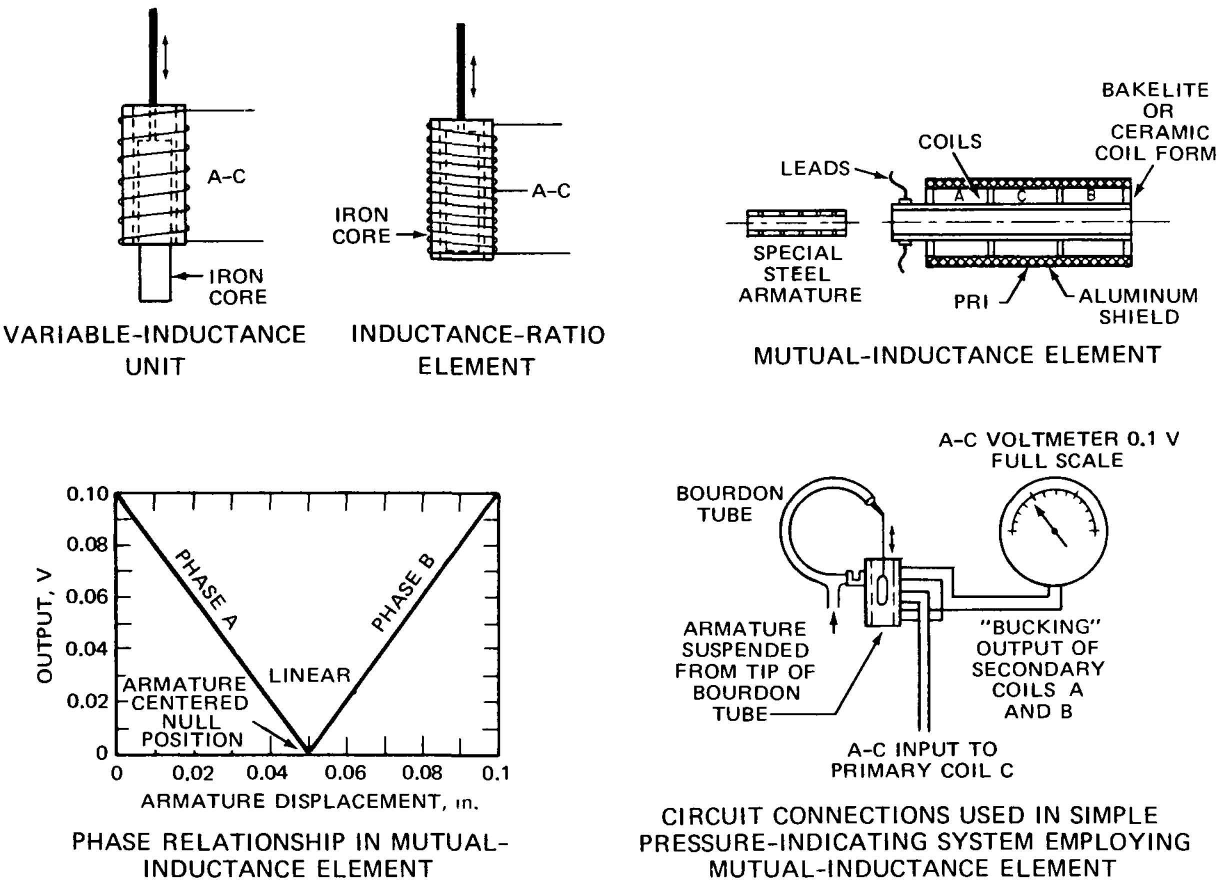


Fig. 4.24—Examples of inductance elements for LVDT's

stream of the orifice), and the pressure increases to a value less than its original value.

Several locations for metering connections are shown in Fig 4 25.

Vena Contracta Taps The high-pressure connection is one pipe diameter upstream from the orifice, and the low-pressure connection is at the vena contracta. This tap arrangement is commonly used, particularly in the power industry. It has a slight advantage in that the connections are in regions of nearly constant velocity, thereby offering some tolerance in tap location without a noticeable change in differential pressure

1D and ½D Taps These are an approximation of vena contracta taps. The high-pressure connection is one pipe diameter upstream from the orifice, and the low-pressure connection is one-half pipe diameter downstream from the orifice inlet.

Flange Taps These have connections drilled through the edges of the flanges 1 in. from the adjacent orifice surface. Flange taps are widely used in the gas and chemical industries because they are convenient to use and install "Orifice flanges" are readily available with pressure connections and jackscrews to spread the flanges to facilitate orifice replacement

Corner Taps These have effective connections immediately adjacent to the orifice plate. Corner taps are commonly used in Europe but are seldom used in this country because they require special flange machining. They are used in some small orifice pipe assemblies furnished by several instrument manufacturers

(c) Flow Nozzles. The flow nozzle, usually of ASME long-radius high-ratio design (Fig 4.26), has an elliptically flared inlet and a cylindrical throat section. There is no vena contracta effect, because maximum velocity takes place in the throat. The flow nozzle passes approximately 60% more flow than an orifice with the same differential pressure and the same ratio of throat diameter to internal pipe diameter. (This latter ratio is the β of the flow nozzle, see Sec. (e) below.) A flow nozzle can be installed in welded piping but cannot be used to meter flow in either direction. The flow nozzle can be used successfully in some installations where limited length of straight pipe would not be suited to the use of an orifice.

A throat-tap nozzle, with downstream connection installed directly in the wall of the flow nozzle throat (Fig 4.27), has been developed by turbine engineers and is strongly recommended by them for the performance testing of turbines.

(d) Venturi Tubes. A Venturi tube has conical sections between the cylindrical pipe and throat, with curved transitions (Fig. 4.28) Its capacity is similar to that of a

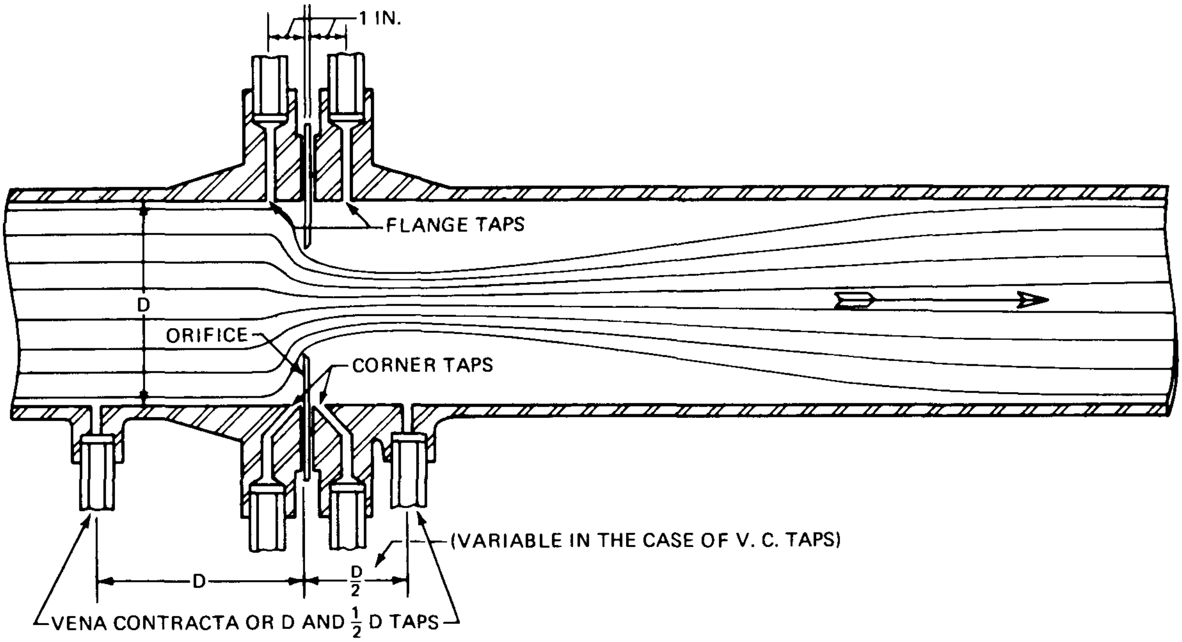


Fig. 4.25—Tap locations for orifice meters.

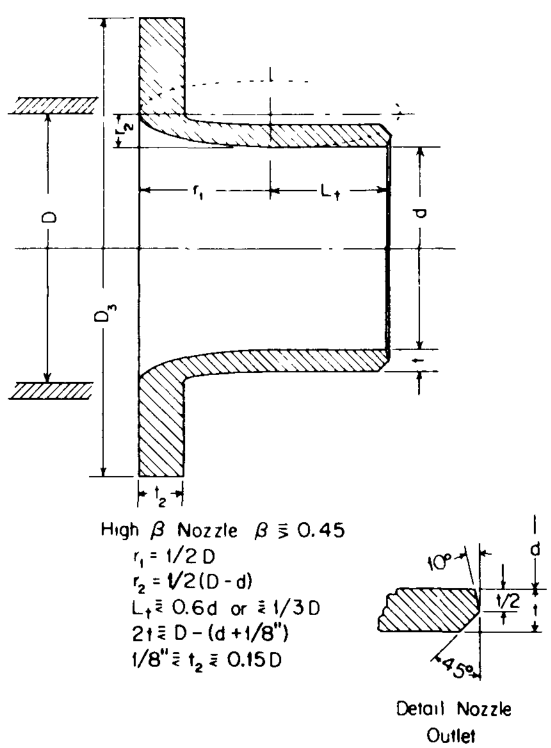


Fig. 4.26—Flow nozzle, ASME long-radius high-ratio design. (From *Fluid Meters,* Fig. II-III-14, p. 217, American Society of Mechanical Engineers, N. Y., 1971.)

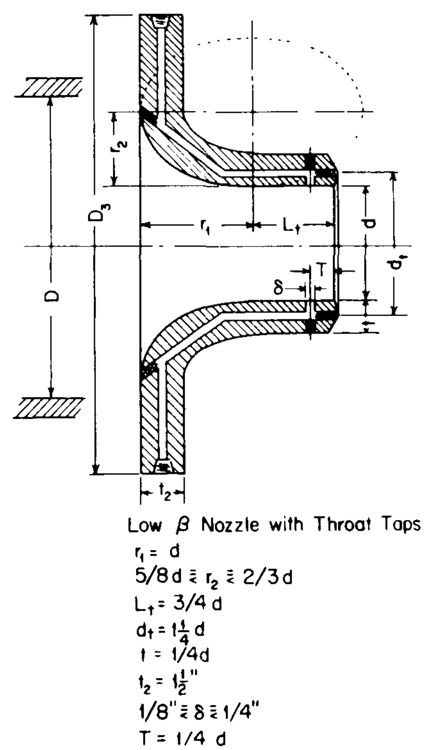
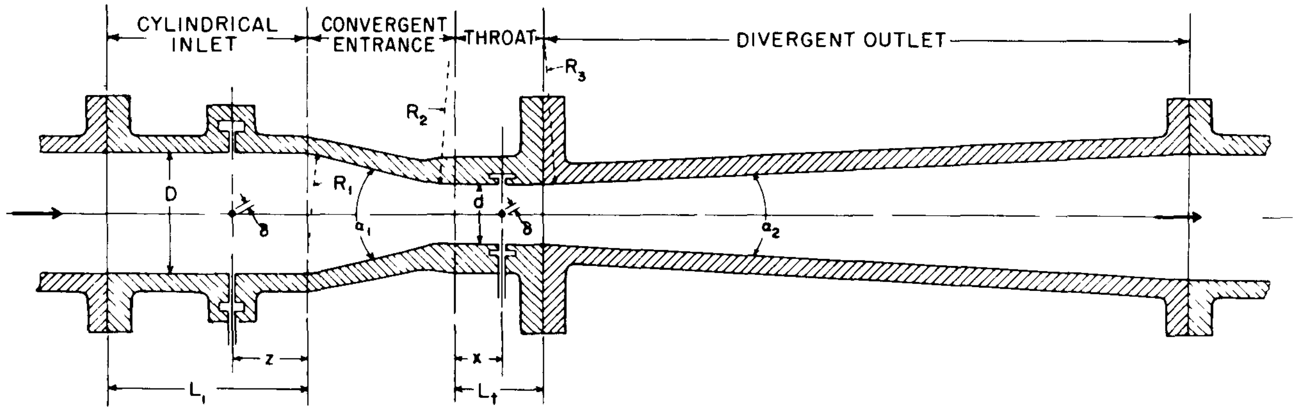


Fig. 4.27—Throat-tap flow nozzle. (From *Fluid Meters,* Fig. II-III-14, p. 217, American Society of Mechanical Engineers, N. Y., 1971.)

flow nozzle, but pressure restoration is more complete because of minimized turbulence in the outlet cone. The Venturi tube may have piezometer rings or annular chambers surrounding the inlet and throat to average pressures at four or more points. These rings also have the beneficial effect of permitting an installation to be made with a minimum length of straight pipe.

A nonstandard Venturi tube, with equal angles of taper in the inlet and outlet cones, can be used to meter reversing flow.



$L_1 \gtreqless D$ or $L_1 \gtreqless (D/4 + 10'')$
$z \gtreqless D/2 \pm D/4$ for $4'' \gtreqless D \gtreqless 6''$
$D/4 \gtreqless z \gtreqless D/2$ for $6'' \gtreqless D \gtreqless 32''$
$L_t \gtreqless d/3$
$y \gtreqless d/6$
$5/32'' \gtreqless \delta \gtreqless 25/64''$ and
$\delta < 0.1\,D$ or $0.13\,d$

$R_1 = 1.375\,D \pm 20\%$
$R_2 = 3.625\,d \pm 0.125\,d$
$5d \gtreqless R_3 \gtreqless 15d$
$a_1 = 21° \pm 1°$
$7° \gtreqless a_2 \gtreqless 8°$ or $7° \gtreqless a \gtreqless 15°$

Fig. 4.28—Herschel or classical Venturi tube. (From *Fluid Meters*, Fig II III 26, p. 231, American Society of Mechanical Engineers, N Y , 1971.)

Several modified Venturi tubes or flow tubes, shorter than the standard Venturi tube but claiming a lower unrecovered pressure drop, are now available. One such tube is shown in Fig 4.29 In general, these tubes take advantage of (1) an impact component to increase the pressure felt at the high-pressure connection and (2) a change in direction of the flow in the boundary layer at the low-pressure connection to decrease the pressure at that point. The result is that, for a specified differential pressure and flow rate, the throat diameters of these modified Venturi tubes are larger than those of conventional tubes, thus the overall pressure loss for a given flow rate may be less.

(e) Sizing Primary Elements. The basic equation for a differential-pressure flowmeter, using an orifice, flow nozzle, or Venturi tube, may be stated

$$W = \frac{359Cd^2\ F_aY(\gamma h)^{1/2}}{(1 - \beta^4)^{1/2}} \qquad (4\ 12)$$

where C = coefficient of discharge (dimensionless)

d = primary-element throat or hole diameter (in.)

F_a = thermal expansion factor accounting for change in cross sectional area (dimensionless)

h = differential pressure (inches of water at 68°F)

W = rate of flow (lb/hr)

Y = expansion factor accounting for density decrease at downstream pressure (dimensionless)

β = ratio of throat diameter to inside pipe diameter (dimensionless)

γ = density (lb/ft^3)

This equation exists in other forms, e.g., for convenient use in gas measurement where flow rate in volumetric units and density at standard or base conditions are involved

The coefficient of discharge, C, may be presented by curves or in tables as a function of pipe Reynolds number, R_D, or of throat Reynolds number, R_d Sometimes C is replaced by a combined coefficient, already divided by the denominator of Eq 4.12, then it is labelled the "coefficient K with velocity-of-approach factor included " Rather than including here sufficient information to permit complete and accurate flow determinations to be made by measuring differential pressure across a primary element of any type and dimensions, this text is limited to presenting a method for determining approximate dimensions. These are suitable for estimating purposes or for assessing the acceptability of a proposed piping installation for flow-measurement purposes.

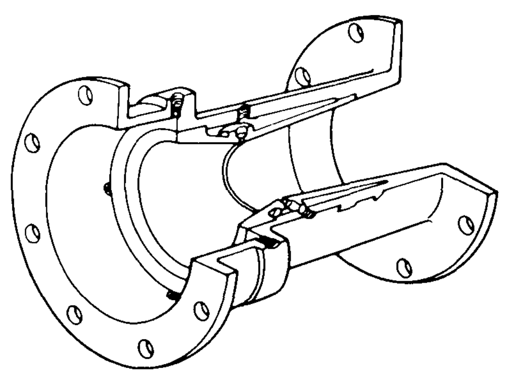


Fig. 4.29—Typical short modified Venturi tube. (From D. M. Considine, *Process Instruments and Controls Handbook*, p. 4-52, McGraw-Hill Book Company, Inc., New York, 1957.)

The diameter ratio, β, is determined from Fig 4 30 with a calculation of the capacity factor, I, from the applicable equation

For liquids

$$I = \frac{W}{D^2 (h\gamma_f)^{1/2}}$$

or

$$I = \frac{Q_L \gamma_s}{7.48 D^2 (h\gamma_f)^{1/2}} \qquad (4.13a)$$

For steam

$$I = \frac{W}{D^2 (h/v)^{1/2}} \qquad (4.13b)$$

For gases

$$I = \frac{Q_G \gamma_s}{D^2 (h\gamma_f)^{1/2}}$$

or

$$I = \frac{Q_G [G(T + 460)]^{1/2}}{21.5 D^2 (hP)^{1/2}} \qquad (4.13c)$$

where D = internal pipe diameter (in.)
G = specific gravity (dimensionless)
I = capacity factor (dimensions consistent with above equations)
P = pressure at primary-element inlet (psia)
Q_G = gas flow rate [ft^3/hr at standard or base conditions, often abbreviated "scfh" (standard conditions are usually 30 in Hg and 60°F)]
Q_L = liquid flow rate [gal/hr at standard or base temperature (usually 60°F for petroleum products, but flowing temperature for water)]
T = temperature (°F)
v = specific volume (ft^3/lb)
γ_s = density (lb/ft^3 at standard or base conditions)
γ_f = density (lb/ft^3 at flowing conditions)

In general, a primary-element β ratio of 0 50 to 0 70 may be considered normal. Higher ratios may be expected in high-pressure or high-temperature applications where pipeline economics suggests using the smallest acceptable size with consequent high velocities. An extremely low β value might indicate that the pipe size is larger than required or that a meter of lower differential-pressure rating would be preferable. The low β ratios of throat-tap nozzles are desirable in turbine testing to provide high differential pressure which may be read with accuracy on a manometer. The high differential pressure can be tolerated during the short duration of a test (after which the nozzle is removed)

The minimum and maximum limits of the diameter ratio, β, for various primary elements are shown in Table 4.18. These β values are important in the selection of maximum meter differential pressure. For compressible fluids (steam, air, and gases), the value of the maximum differential in inches of water should not exceed the operating pressure in psia in order to avoid inaccuracies due to variations in the expansion factor, Y, that are not taken into account.

(f) Installation. Accurate flow measurements require that the primary element be in a "normally turbulent" flow pattern, with fully developed velocity profile and without spiral motion or velocity stratification. Because of this

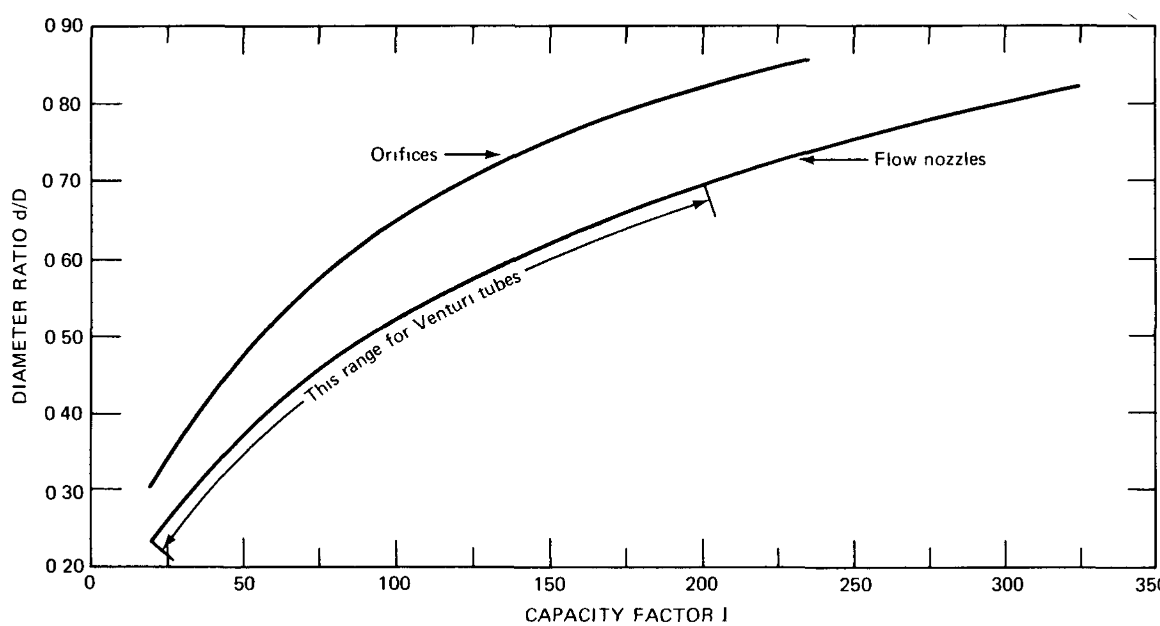


Fig. 4.30—Capacity factor, or coefficient of discharge, vs diameter ratio for orifices, flow nozzles, and Venturi tubes. (Courtesy Bailey Meter Company.)

Table 4.18—Maximum and Minimum Diameter Ratios for Orifices, Flow Nozzles, and Venturi Tubes

Type of element	Connection location	Pipe size, in.	Beta Min.	Beta Max.
Concentric orifice	Flange	1½	0 17	0 70
		2	0 125	0 70
		3	0 10	0 70
		⩾4	0 10	0 75
Concentric orifice	Vena contracta	1½	0 17	0 70
		2	0 125	0 75
		⩾3	0 10	0 80
Eccentric orifice		⩾4	0 30	0.80
Segmental orifice		⩾4	0 35	0.85
Flow nozzle	Pipe wall		0 20	0 80
	Throat		0 25	0.50
Venturi tube		⩾2	0 25	0 75

requirement, the primary element must be installed in a straight pipe section of adequate length.

It is generally accepted that the required pipe length depends only on the diameter ratio, β, and on the structure of the fitting or combination of fittings preceding the straight pipe. On this basis the curves of Fig 4.31, originally published by the American Society of Mechanical Engineers (ASME), have been developed. It should be emphasized that longer lengths are desirable when the arrangement of building and equipment permits, the minimum lengths represented by the curves are a compromise and may not result in complete removal of an abnormal inlet turbulence.

(g) Accuracy of Primary Elements. Any meter manufacturer can be expected to furnish conventional primary elements (orifices, flow nozzles, or Venturi tubes) sized in accordance with the standard equations and discharge coefficients published by ASME These coefficients are average values that may be considered to be correct within tolerances that vary with β, Reynolds number, and pipe size. The approximate accuracy of these coefficients is as follows

±1.0 for concentric orifices with flange or vena contracta taps, $D \geqslant 2.0$ in., $0.20 \leqslant \beta \leqslant 0.70$
±2.25% for same, $\beta = 0.75$
±0.75% for Venturi tubes
±2.0% for flow nozzles
±1.4% for eccentric orifices, $D > 4$ in.
±2.0% for segmental orifices

When greater accuracy is required, the primary element in its pipe section may be calibrated at a hydraulic laboratory to establish, as nearly as possible, the true value of its individual coefficient of discharge. Ideally the calibration should be performed at Reynolds numbers corresponding to expected operating conditions. This may not be possible, however, because the application may involve the flow of steam, or high-temperature water, at low viscosity (hence a high Reynolds number), and in the laboratory it is necessary to use low-temperature water with relatively high viscosity, which limits the maximum Reynolds number available in the calibration runs If the coefficient curve is stable and flattens out at the high flow rates available in the laboratory, it is considered satisfactory practice to extrapolate to obtain a coefficient at the higher Reynolds number expected in actual service. The uncertainty of a coefficient so determined may be approximately 0.5%. Greater accuracy may be expected, although it is difficult to guarantee, in view of the number of variables that must be measured during the calibration.

(h) Pitot Tubes. The Pitot tube is a primary flow-sensing element. It consists usually of a small-diameter tube pointed upstream with a pressure tap in its side (Fig. 4.32). The second (static) connection may be a trailing connection inside the pipe. Sometimes both connections are in the sides of a straight cylindrical probe. The Pitot tube measures velocity pressure itself, rather than the change in static pressure resulting from a change in cross-sectional area and velocity.

The equation for the Pitot tube may be written

$$V = C_p K_p (2gH)^{1/2} \tag{4.14}$$

where V = average velocity in the pipe line (ft/sec)
C_p = ratio of average velocity to velocity at the Pitot tube tip
K_p = coefficient based on Pitot tube design
H = differential pressure (in feet of flowing fluid)
g = acceleration due to gravity (32.17 ft/sec²)

From Eq 4.14 an equation can be derived similar to the basic orifice equation

$$W = 359 C_p K_p D^2 (h_w \gamma_f)^{1/2} \tag{4.15}$$

where W = rate of flow (lb/hr)
D = internal pipe diameter (in.)
h_w = differential pressure (inches of water at 68°F)
γ_f = density at flowing condition (lb/ft³)

If the sensitive tip of the Pitot tube is located at or near the center of the pipe, C_p may be 0.70 to 0.81 The value of K_p is usually supplied by the manufacturer, it may be close to 1.00 for a laboratory Pitot tube such as that shown in Fig. 4 32, or approximately 0.82 for a commercial Pitot tube such as that shown in Fig. 4.33.

The Pitot tube is normally used in temporary installations and for estimating. It is not generally accepted for permanent installation because (1) the small passages tend to plug, which makes the meter insensitive or inoperative, (2) a traverse must be made across the pipe to establish the point of average velocity required to evaluate the correction factor, C_p, (3) the differential pressure usually encountered is small, and (4) the device cannot be adjusted to provide a given value of flow at a selected differential pressure.

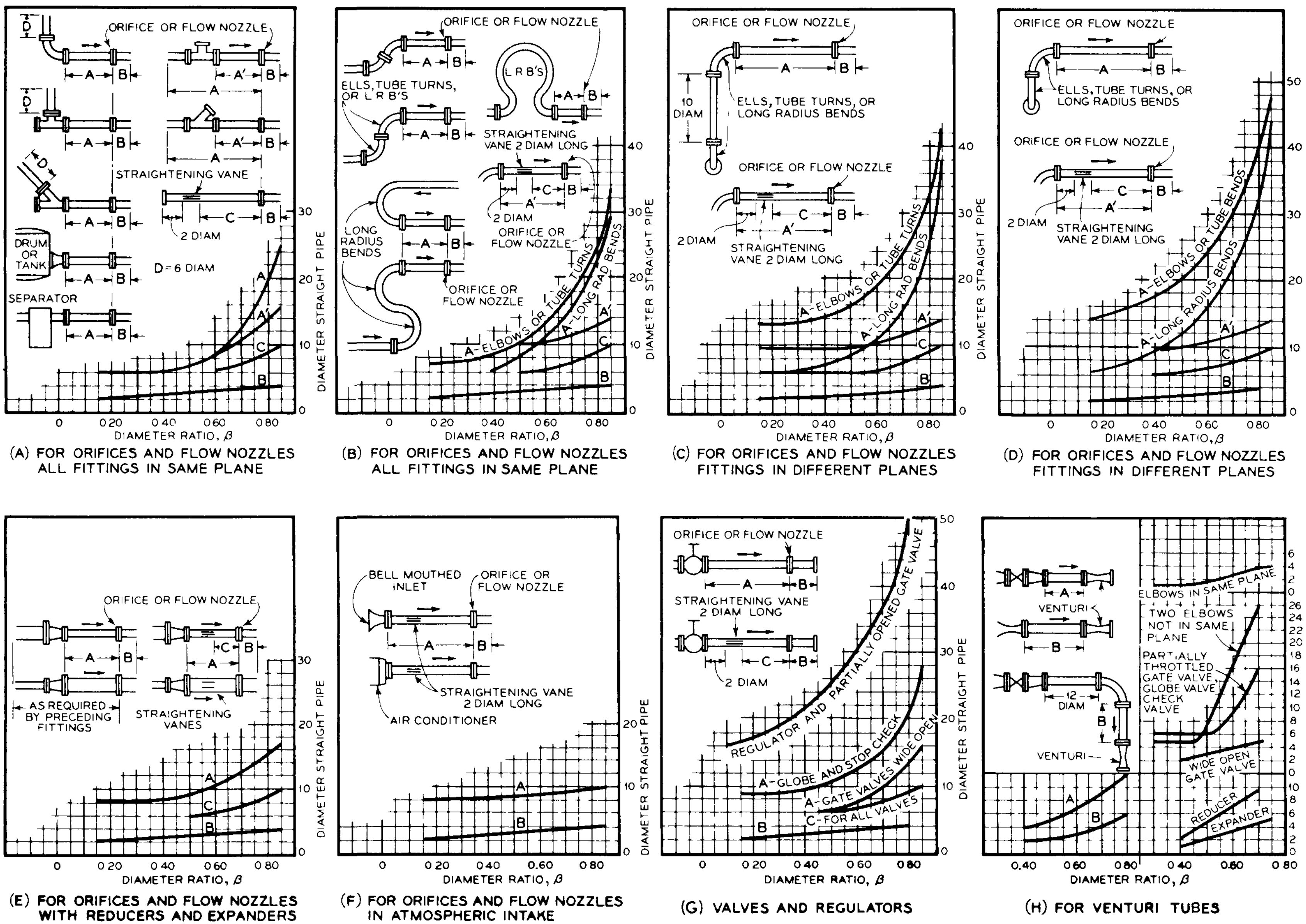


Fig. 4.31—Piping requirements for orifices, flow nozzles, and Venturi tubes. (From *Fluid Meters,* Fig. II-II-1, p. 180, American Society of Mechanical Engineers, N. Y., 1971.)

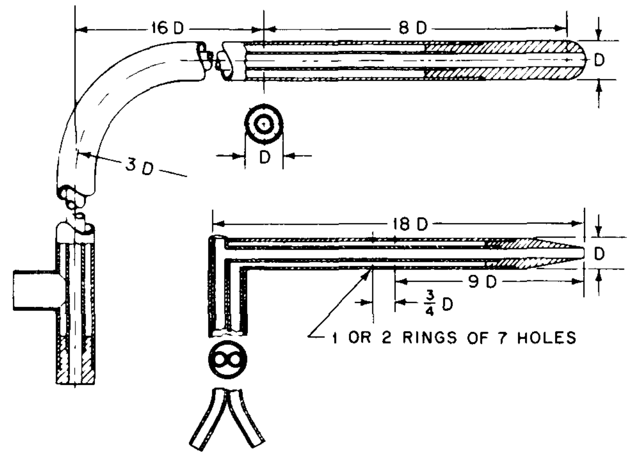


Fig. 4.32—Two commendable designs of Pitot-static tubes. Values of D between $\frac{3}{16}$ and $\frac{5}{16}$ in. inclusive are suitable. (From *Fluid Meters*, Fig. I-7-18, p. 102, American Society of Mechanical Engineers, New York, 1971.)

(i) Secondary Elements. In a nuclear plant, the selection of a secondary element to measure and interpret the differential pressure is limited by the need to avoid the presence of mercury, a common flowmeter sealing fluid, and, in the majority of cases, the requirement for a remote transmission system between the measuring mechanism and the display equipment.

In a remote transmission system, the secondary element is considered to include both the transmitter containing the measuring mechanism and the receiver (i.e., the components for recording, indicating, integrating, etc.). In effect, the direct mechanical connection of a self-contained secondary element is replaced by a pneumatic or electric position-transmitting mechanism.

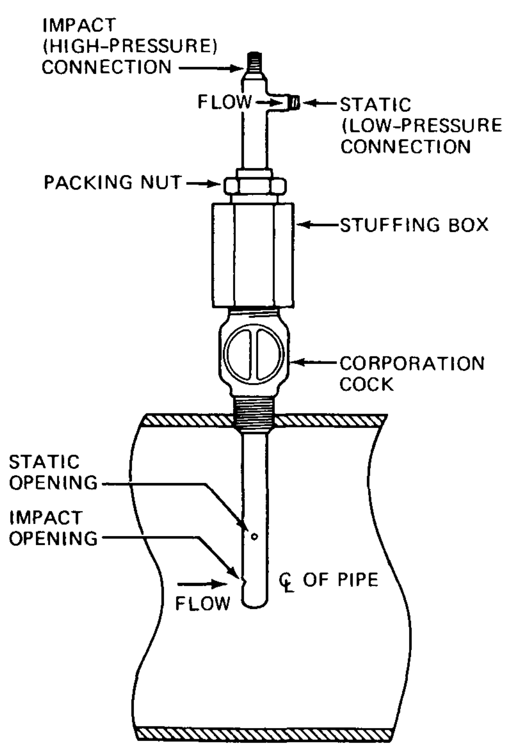


Fig. 4.33—Commercial Pitot tube. (From L. K. Spink, *Principles and Practice of Flowmeter Engineering*, Fig. B-2165, The Foxboro Company, Foxboro, Mass., 1967.)

As noted in Sec. 4-3.2, measuring mechanisms of differential-pressure transmitters are of two general classes: motion balance and force balance. In a motion-balance system, the differential pressure exerted on a bellows or diaphragm displaces it, and the displacement is opposed by a spring, the force exerted by the spring being directly proportional to the applied differential pressure. A typical motion-balance-type electric transmitter is shown in Fig. 4.34.

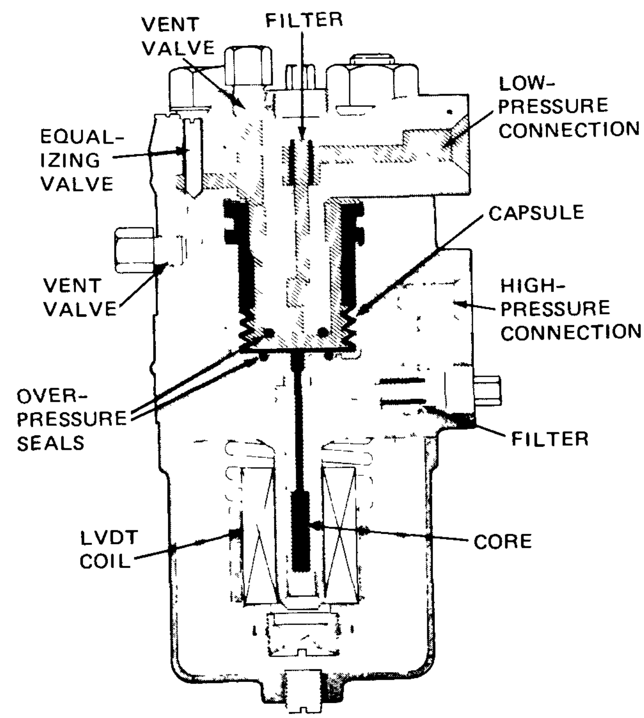


Fig. 4.34—Electric motion-balance transmitter. (From Instruction, Sec. E21-17, Fig. 26, Bailey Meter Co., Wickliffe, Ohio.)

In a force-balance system, the output signal is supplied to a pneumatic bellows or electromagnet that opposes the force exerted by the measuring mechanism. In a typical pneumatic force-balance transmitter (Fig. 4.35), a change in differential pressure changes the air gap at a nozzle tip, thereby changing the nozzle pressure, which is then amplified to provide the output signal. The changed output pressure changes the force opposing the measuring force, restoring equilibrium at a new value of the opposing forces with only an imperceptible change in nozzle air gap.

The receiver of a flowmeter may contain two features peculiar to flow measurement, a square-root extractor and an integrator. The square-root extractor is required if the pointer motion is to be directly proportional to flow rate

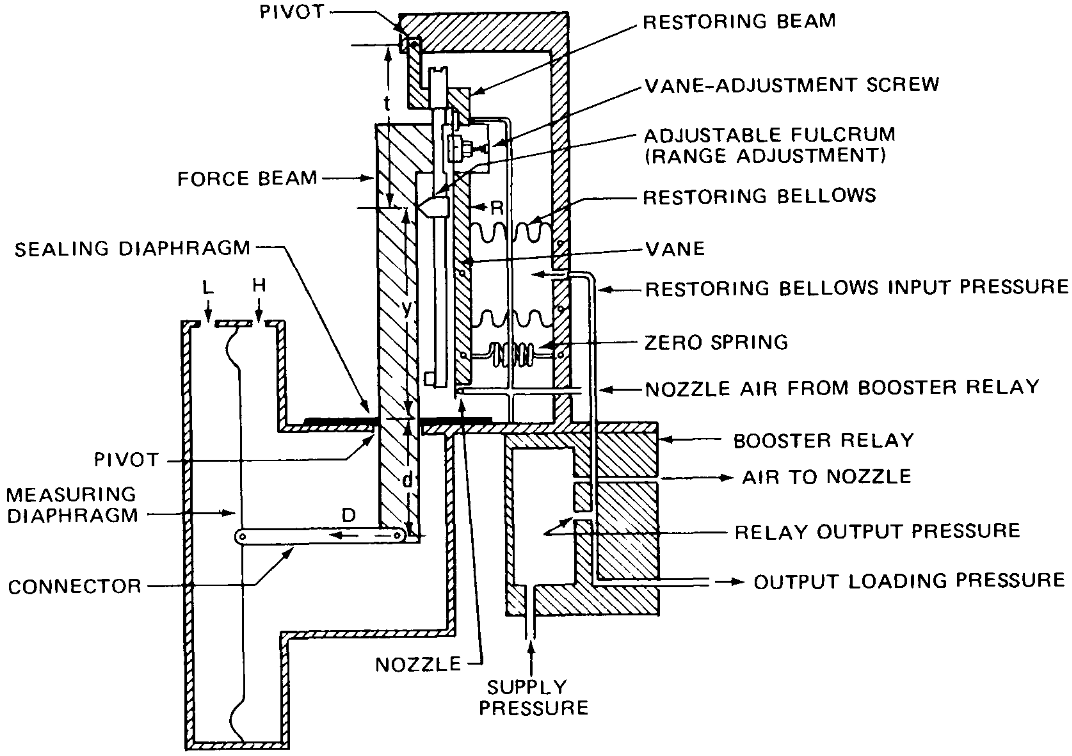


Fig. 4.35—Schematic of pneumatic force-balance transmitter (From Instruction, Sec. P21-19, Fig. 21, Bailey Meter Co., Wickliffe, Ohio.)

instead of to differential pressure. The integrator is required to convert flow rate to total flow for accounting purposes.

Because the rate of flow is proportional to the square root of differential pressure, a flow scale on a differential-pressure meter is not uniform, the divisions at the low end of this scale are compressed close together and difficult to read. The square-root extractor interposes a variable gain between the measuring mechanism and the display, magnifying the motion significantly at lower flow rates to make the scale divisions uniform. The extractor may be in the transmitter of a transmitting system, in the receiver, or in a separate unit installed between transmitter and receiver. A simple mechanism that performs this function pneumatically is shown in Fig. 4.36 In the figure, the rise d is proportional to the differential pressure, and the pointer motion indicating flow is proportional to the angle α A cam follower operates through a vane and nozzle to maintain a light contact with the cam. For low values of α (i.e., d is very small compared to the beam length R) the value of α is almost exactly proportional to the square root of d.

The integrator is a counter that is usually driven by a constant-speed motor through a friction clutch and cam-operated escape mechanism in such a way that the counter rotates during a portion of cam rotation, the duration being proportional to rate of flow or point of position. The amount registered during any time period therefore is the total flow in that period. A diagram of a typical integrator is shown in Fig. 4.37.

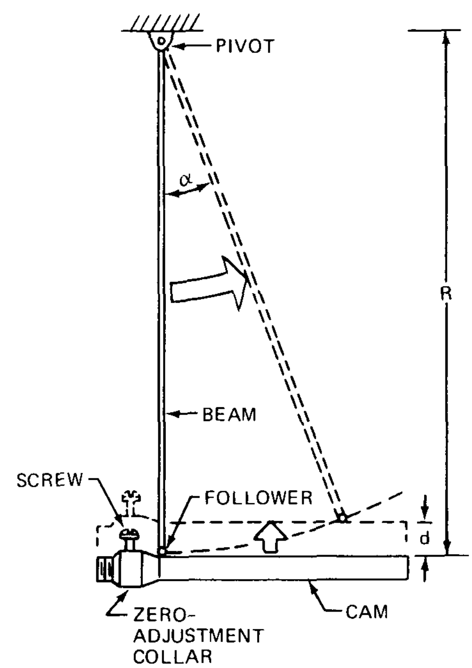


Fig. 4.36—Square-root extraction. (From Instruction, Sec. P22-8, Fig. 5, Bailey Meter Co., Wickliffe, Ohio.)

(j) Accuracy of Secondary Elements. Secondary-element accuracy may be represented as a single tolerance or as an individual tolerance for each component, such as transmitter, square-root extractor, receiver, and integrator.

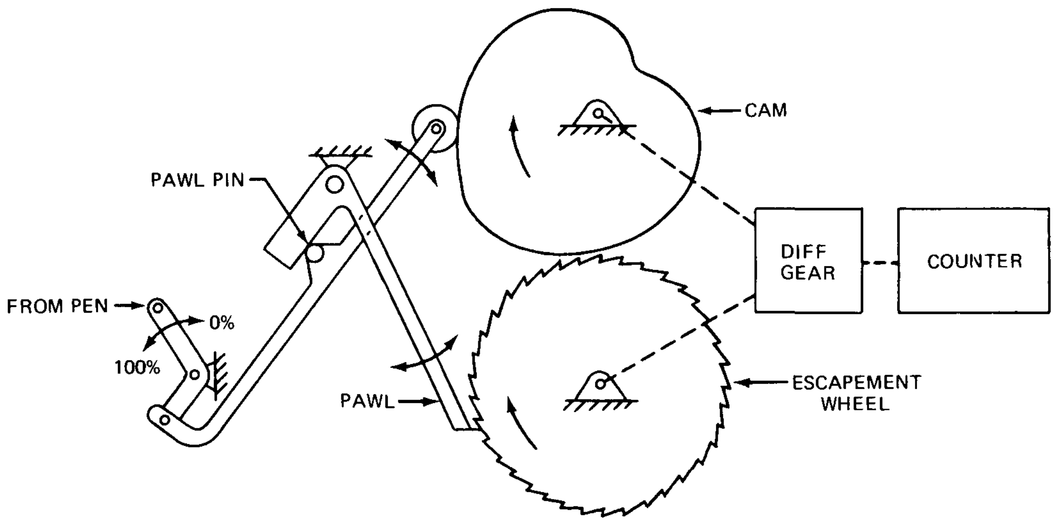


Fig. 4.37—Schematic diagram of integrator with cam and escapement mechanism. (From Instruction, Sec. G92-1, Fig. 1, Bailey Meter Co., Wickliffe, Ohio)

For several tolerances to be combined, they must be expressed on the same basis, i.e , in terms of differential pressure or of flow, and as percent of maximum or of actual reading. The square root of percent maximum differential is percent maximum flow, and a tolerance in percent of maximum flow is divided by percent of scale to determine the percent of actual flow.

For instance, at mid-scale on a differential-pressure transmitter, a tolerance of ±1% of maximum would represent an actual flow tolerance of 1% since the square root of $(0.50 - 0.01)/0.50 = 0.99$, but, at 25% scale, the flow tolerance is 2% since the square root of $(0.25 - 0.01)/0.25 = 0\ 98$ The addition of individual tolerances may be made on a root-mean-square basis and stated as such.

Because the high gain action of the square-root extractor at low flow rates magnifies uncertainties as well as the flow signal itself, the rangeability, or turn-down ratio, of a differential-pressure meter is practically limited to about 25% of maximum flow (6.25% of maximum differential) When operation at wider range is required, multiple primary elements or multiple transmitters can be used with automatic switching, which simultaneously changes meter capacity and integrator speed. Alternately, a meter with linear output might be specified.

4-4.2 Linear Flowmeters

(a) Area Meters. In an area flowmeter the fluid flows upward, displacing an obstructing float or piston. The float or piston is arranged so that the unobstructed area increases with upward displacement, the float or piston then moves until the area is open enough to permit the flow to pass. The basic theory of area flowmeters is the same as that of a differential-pressure meter, but, since differential pressure is held constant, or reasonably so, square-root extraction is not required A measurement of float or piston position is a measurement of unobstructed area, and thus of flow. Area meters are of two general types rotameters and piston-type meters.

A *rotameter* (Fig 4 38) consists of a float inside a tapered tube, the small end of the tube being at the bottom The force exerted in the tube by the flow moves the float upward until the area of the annular space between float and tube is sufficient to permit a flow-created differential pressure to balance the weight (less the buoyancy force) of the float. Differential pressure is determined by the weight of the float and its cross-sectional area. A scale is marked on the outside of the transparent, tapered tube so that float position can be read directly. Since the unobstructed area permitting flow is almost exactly proportional to float rise (for a slightly tapered tube), the scale markings indicating flow can be uniform. For high-pressure applications or for transmitters, the tube can be metal, and the float position can be sensed by a magnetic pickup.

In a *piston-type area meter,* upward motion of the piston or plug uncovers ports in the sleeve or cage, increasing the area of the opening in direct proportion to plug movement and to flow rate. A spring pulls downward on the plug to increase the differential pressure beyond that which might be obtained by the weight of the parts. The vertical position of the plug establishes the rotational position of a spindle, which extends through a packing gland to operate an indicating pointer and transmitting mechanism (either pneumatic or electric).

(b) Positive-Displacement Meters. The flowing fluid is divided into separate discrete volumetric portions that are counted by a mechanical register built into the meter Alternately, the rotation of the meter mechanism may be made to generate an electrical signal with frequency proportional to the rotational speed, the signal can then be transmitted to a remote register or recorder.

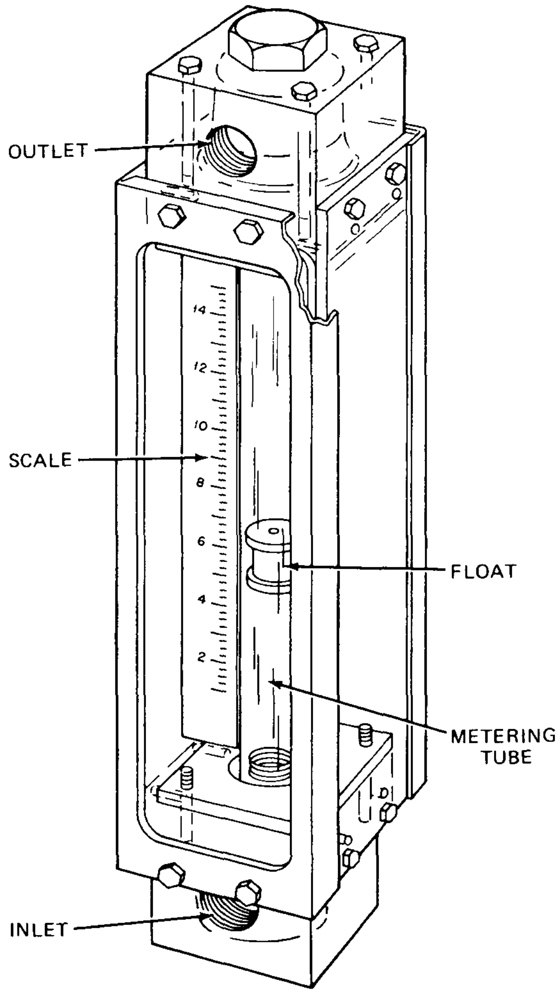


Fig. 4.38—Rotameter (From D M. Considine, *Process Instruments and Control Handbook*, p 4-63, McGraw-Hill Book Company, Inc , New York, 1957)

(c) Velocity Meters. A *turbine meter* is a line-mounted meter with a rotor having helical blades Rotation generates a series of electrical pulses, which are sensed by an externally mounted electrical pickup. The receiver may be arranged to display total flow by counting the pulses by digital techniques or to display rate of flow by measuring the pulse frequency. These meters are accurate through their recommended range from maximum flow rate to about 10% maximum. At lower flow rates friction tends to cause the meter to read low. Since the bearings are exposed to and lubricated by the flowing fluid, maintenance involves removal of the meter from the line for inspection or replacement of bearings. The turbine meter is sensitive to changes in fluid viscosity and is usually individually flow-calibrated. It was developed for and has gained wide acceptance in the Aerospace industry.

A *magnetic meter* is an electrically insulated section of pipe with an imposed magnetic field, perpendicular to the pipe axis, through which a conductive fluid develops an electrical potential (perpendicular to magnetic field and pipe axis) directly proportional to its average velocity through the pipe section Electrodes flush with the pipe wall are connected to a circuit for measuring the generated voltage The magnetic meter is accurate and linear through a wide range of flow rates and is available in a wide range of sizes Because it has no internal parts to trap sediment, it is widely used for slurries and dirty fluids, it can be recommended, however, for any flow of an electrically conductive fluid where minimizing the pressure drop is important The pressure drop is no greater than that of a straight pipe of the same length. This type flowmeter is used in sodium-cooled reactors (see Vol 2, Chap 17)

4-4.3 Liquid-Metal Flowmeters

In power reactors that use liquid-sodium coolant, flow is usually measured with magnetic meters, as noted in the preceding section. Differential-pressure devices, however, have also been used to measure liquid-sodium flow rates. The principles of operation and the methods for correcting for thermal effects, wall effects, etc , in magnetic flowmeters are described in Vol. 2, Chap 17.

4-5 LEVEL AND POSITION SENSING

A variety of sensors are used to locate the position of devices or liquid levels in vessels They are described in other chapters in connection with the devices or vessels with which they are usually mechanically integrated.

Techniques for sensing and indicating the positions of control rods are discussed in Chap. 7, Sec. 7-3.7 and in the examples of Sec. 7-4

There are many examples of level sensing in pressurized-water and boiling-water reactors (Vol. 2, Chaps. 15 and 16), for example, sensing the water level in a boiling-water-reactor vessel Usually, the sensors are differential-pressure transducers or a series of pressure-actuated switches. In sodium-cooled reactors, level sensing can also be accomplished with resistance or induction probes or with acoustic devices. These sensors are described in Vol. 2, Chap 17, Sec. 17-4.3

The steam systems of all nuclear power plants (and of fossil-fueled plants as well) include a variety of level sensors, ranging from simple sight tubes to pressure transducers.

4-6 STEAM PROPERTIES SENSING

4-6.1 Quality

(a) Definitions. *Steam quality* The percentage by weight of dry steam in a mixture of saturated steam and suspended droplets at the same temperature.

Moisture The percentage by weight of suspended droplets of water in a mixture of dry saturated steam and water droplets at the same temperature.

(b) Sample Collection. Sample collection is carried out according to ASTM D1066 or ASME Performance Test Code, Part II. A few salient points are extracted here. It is important to note that the ASME Performance Test Code does not recommend using the electrical conductivity method for determining the moisture content of steam. A recommended form of sampling nozzle is shown in Fig. 4.39.

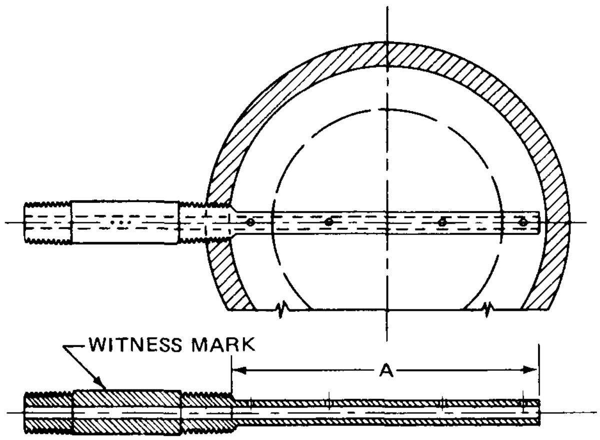


Fig. 4.39—Recommended sampling nozzle. (From American Society of Mechanical Engineers, Supplement to Power Test Codes, PTC 19.11, Part II, p.6, 1970.)

The pipe or tube in the sampling nozzle extends across the pipe on a diameter to within 0.25 in. of the opposite wall. The drilled holes face upstream in the pipe and are spaced so that each port represents an equal area of pipe section. For a representative steam sample, the hole size in the sample tube must be chosen so the rate of sample flow is equal to the rate of steam flow. The shortest possible connection should be used between the sampling nozzle and the calorimeter or cooling coil.

(c) Moisture Determination. *Throttling Calorimeter.* This is a simple device (Fig. 4.40). Its essential details are a throttling orifice admitting steam to an expansion chamber and a thermometer well entirely surrounded by the low-pressure steam from the throttling orifice. The principle of operation is the equality of initial and final enthalpies when steam passes through an orifice from higher to lower pressure, provided there is no heat loss and the difference between initial and final kinetic energies is negligible. Two conditions are necessary in the use of a throttling calorimeter: (1) there must be a significant pressure difference between steam in the sample and steam in the expansion chamber and (2) the quality of the sample must be high enough to produce a measurable degree of superheat (8°F) in the calorimeter.

For example, if the pressure in the expansion chamber is atmospheric, the temperature is 280°F, and the sample pressure is 135 psia, the constant enthalpy line on a Mollier chart shows the initial moisture to be 1%, or 99% quality.

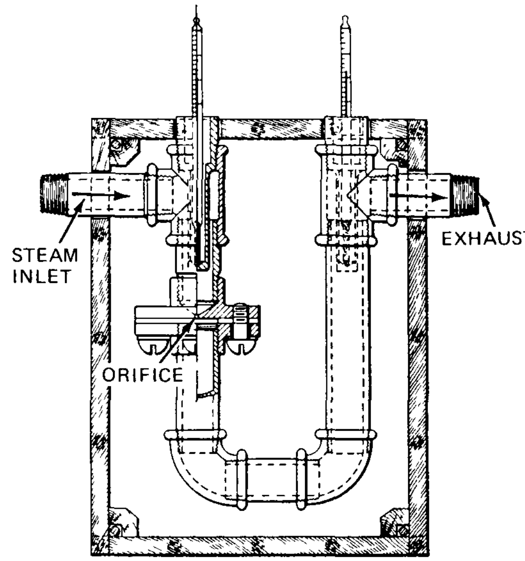


Fig. 4.40—Throttling calorimeter. (From American Society of Mechanical Engineers, Supplement to Power Test Codes, PTC 19.11, Part II, p.14, 1970.)

Quality can be calculated from the following formula:

$$X = \frac{h_2 - h_f}{h_{fg}} \times 100 \qquad (4.16)$$

where X = the quality (%)
h_2 = the enthalpy of superheated steam at the calorimeter pressure and temperature
h_f = the enthalpy of saturated liquid in the mixture prior to throttling
h_{fg} = the enthalpy of vaporization of steam entering the calorimeter

Separating Calorimeter. The throttling calorimeter cannot be used when the enthalpy in the calorimeter chamber is equal to or less than the enthalpy of saturated steam. Either a separating or universal instrument must be used. In the separating calorimeter (Fig. 4.41), water is separated out from the steam and read in a graduated gage glass. The quality (%) is

$$X = \frac{M + R}{W + M} \times 100 \qquad (4.17)$$

where M = the weight of dry steam condensed after passing through the calorimeter
W = the weight of water as read from the gage-glass scale
R = the weight of water corresponding to heat loss by radiation

With an insulated calorimeter, the radiation loss can be neglected.

The accuracy of the separating calorimeter is somewhat less than that of the throttling calorimeter.

Throttling Separating Calorimeter. The throttling separating calorimeter is made up of two calorimeters, a

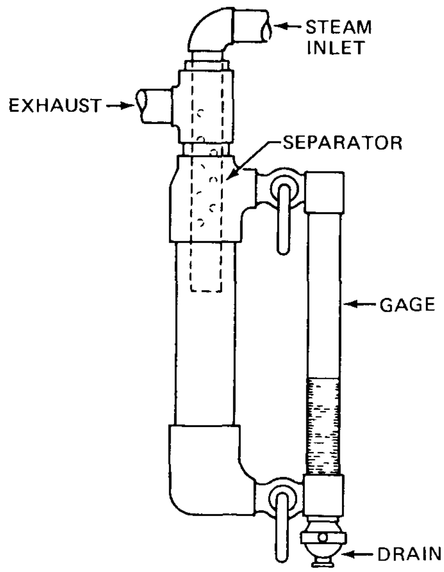


Fig. 4.41—Separating calorimeter. (From American Society of Mechanical Engineers, Supplement to Power Test Codes, PTC 19.11, Part II, p. 21, 1970.)

throttling calorimeter and a separating calorimeter of low and high range, respectively, in series The steam first passes through a throttling orifice and, if the moisture is not excessive, the quality is determined as in a throttling calorimeter If the moisture is outside the throttling-calorimeter range, the separating calorimeter is at once available and no delay is caused by its use

Separating Throttling Superheating Calorimeter. A throttling calorimeter can be connected to the exhaust of a separating calorimeter if the separation of moisture in the separating calorimeters is not complete. The quality of the original sample can be found by multiplying the qualities for each process.

Radioactive Tracers. Radioactive tracers can be used to determine steam quality from a boiling-water reactor. This method is generally limited to steam pressures under 1000 psi because of the occurrence of volatilized salts in the steam. Concentrations of specific radionuclides in condensed steam and boiler-water samples are determined with a multichannel analyzer Steam quality, in percent, is calculated from the tracer activities as follows

$$X = 100\left(1 - \frac{A_s}{A_w}\right)$$

where A_s is the activity in steam and A_w is the activity in boiler water.

4-6.2 Purity

(a) Definition. *Steam purity* refers to the solid matter in steam. Solid matter is defined as materials in steam which are solids at room temperature and which are capable of deposition as solids in superheaters, steam lines, turbines, or other steam-utilizing apparatus so as to reduce capacity, efficiency, or utility. Solids in the steam may be in different proportion to each other than the solids in the water from which the steam is derived.

(b) Gravimetric Determination. The steam is evaporated to dryness, and the residue is chemically analyzed in the classical manner. The method is described in ASTM D1069, Tentative Method of Test for Suspended and Dissolved Matter (Suspended and Dissolved Solids) in Industrial Water and Industrial Waste Water.

(c) Electrical Conductivity Method. The conductivity of a condensed steam sample is proportional to the concentration of ionizable constituents dissolved in the sample. The conductivity, expressed in micromhos, is meaningful only if it is compared with data from a gravimetric determination. The gravimetric-determination data are the primary standard. Usually the steam sample is given a preliminary treatment through degassers to remove most of the gaseous impurities that contribute to the measured conductivity. Unfortunately, degassers are not very effective in removing amines, hydrogen sulfide, and sulfur dioxide.

There are four sources of interference with respect to the calibration of electrical conductivity measurements

1. Dissolved volatile substances, such as ammonia, amines, H_2S, H_2, CO_2, and SO_2, increase conductivity. Ammonia and hydrazine are commonly used in once-through boilers for pH adjustment and dissolved-oxygen scavenging.
2. Dissolved solids, such as the oxides of silicon, copper, and iron, ionize very little and therefore have little influence on conductivity.
3. The conductivity of pure water, as small as it is, must be subtracted from the combined conductivity.
4. The current-carrying capability of each ion species is different at any one temperature, and temperature coefficients are different, therefore, calibration depends on an assumed composition that may change in any one system and is almost certain to be different in different systems.

(d) Sodium Tracer Method for High-Purity Steam. The method is described in ASTM D2186. Generally, this method assumes that the ratio of sodium concentration to impurity concentration in the steam is equal to the ratio of sodium concentration to impurity concentration in boiler water

$$S_t = S_s \frac{W_t}{W_s} \tag{4 18}$$

where S_t = concentration of impurities in steam
S_s = concentration of sodium in steam
W_t = concentration of total solids in boiler water
W_s = concentration of sodium in boiler water

The values on the right-hand side of this formula are determined by ASTM methods

The principal advantages of this method are its freedom from interferences, its ability to measure extremely small concentrations of impurities, and its rapid response to transient conditions. Sample temperature control is not required in the method.

(e) Determination When Silica and Metal Oxides Are Present. Electrical-conductivity measurements are not always reliable when significant quantities of the oxides of metals or silicon are present. These oxides do not ionize significantly. Eliminating these impurities in the feedwater is the best precautionary measure. Metal oxides carried over into the turbine can plate out on the blades and impair efficiency. If these substances are present in significant quantities, determination should be made from one of the following ASTM methods D857, aluminum, D859, silicon, D1068, iron, D1687, chromium, D1688, copper, and D1886, nickel.

Table 4.19—Feedwater Quality Standards*

Maximum total solids (dissolved and suspended), ppb	50
Maximum dissolved oxygen, ppb	7
Maximum total silica (as SiO_2), ppb	20
Maximum total iron (as Fe), ppb	10
Maximum total copper (as Cu), ppb	2
pH at 77° F (adjusted with ammonia)	9 3 to 9.5
Total hardness†	No specification listed
Organics‡	0
Lead§	0

*From Babcock and Wilcox Nuclear Power Generation Division, Water Chemistry Manual, Part 8, p 8-1

†Hardness constituents should be eliminated because of deposition on steam generator surfaces

‡Organic contamination can lead to resin fouling

§Lead contamination should be kept below the lowest value detectable by acceptable methods to avoid problems with Inconel-600 in oxygenated water

4-7 WATER PROPERTIES SENSING

4-7.1 Steam-Generator Feedwater Specifications

Feedwater conditioning is required to maintain operational capability of the steam generator The steam-generating surfaces remain clean and heat-transfer capabilities are favorable if good water quality is maintained The minimum standards given in Table 4 19 should be maintained for satisfactory feedwater quality.

4-7.2 Usual Impurities in Water Supply

Table 4.20 lists the impurities usually found in water supplies and indicates their properties, effects, and methods for treatment and removal.

4-7.3 Effect of Impurities in Steam-Generator Feedwater

(a) Total Solids (Dissolved and Undissolved). The total solids in the feedwater is a general indicator of how much material is collecting in the steam generator. Insoluble materials are deposited on the steam-generator surfaces. The soluble material (e.g., NaCl, NaOH, and Na_2SO_4) is carried over in the steam with the remaining material and tends to collect on the steam-generator tubes. The types of constituents in the feedwater depend on the preboiler characteristics. The quantity of soluble material should be larger than the quantity of insoluble material. Turbidity is a measure of the undissolved constituents, and electrical conductivity is a measure of the dissolved constituents

(b) Dissolved Oxygen. Dissolved oxygen promotes corrosion in the steam generator and therefore should be kept as low as possible. Deaeration removes much of the dissolved oxygen. Hydrazine, a good oxygen scavenger, can eliminate the remaining oxygen. A high level of dissolved oxygen could indicate a malfunctioning deaerator or an air leak in the area of the condenser.

(c) Total Silica. Silica should be maintained at a low level for two reasons (1) silica can concentrate in the steam generator and subsequently plate out on heat-exchange surfaces thereby reducing steam generation and (2) silica may carry over and plate out in the turbine causing turbine inefficiency. A higher than allowable silica concentration implies a demineralizer breakthrough. Switching to the spare demineralizer while the exhausted resin is regenerated or changed can probably eliminate the high silica level.

(d) Total Iron. Iron tends to build up in the steam generator and reduces its efficiency by degrading the heat-transfer characteristics. The level of iron in the feedwater affords some measure of the degree and rate of corrosion in the system.

(e) Total Copper. Copper should be avoided where possible in the feedwater system. Equipment in contact with the feedwater should be ferritic or austenitic stainless steel. Copper in the feedwater system can be carried into the steam generator in solution and plate out there. The copper plate can then make it necessary to clean the steam generator in a two-stage process one for copper and another for iron. Copper carryover in the steam can plate out on the turbine and lower its efficiency Copper alloy tubes in the condenser should be satisfactory because the temperatures and pressures are reduced and the dissolution of the copper is less likely.

(f) Total Lead. Lead in the feedwater concentrates in the steam generator This can result in problems with Inconel in oxygenated water containing lead Satisfactory instrumentation for monitoring traces of lead is not available at the present time

(g) Conductivity. Cation (positive-ion) conductivity cells can be used to monitor the feedwater Measurements

Table 4.20—Impurities in Water Supplies*

Impurity	Formula	Molecular weight	Equivalent weight	Solubility	Probable effect in boiler	Methods of treatment and removal
Calcium bicarbonate	$Ca(HCO_3)_2$	162 10	81.05	Moderate	Scale and sludge, liberates CO_2	In external treatment of calcium and magnesium compounds, lime and soda softeners plus coagulation and filtration give partial removal, Zeolite softeners and evaporators give more complete removal, the former replacing calcium and magnesium with sodium, corrosive compounds require alkali treatment
Calcium carbonate	$CaCO_3$	100.08	50.04	Slight	Scale and sludge, liberates CO_2	
Calcium hydroxide	$Ca(OH)_2$	74.10	37.05	Slight	Scale and sludge	
Calcium sulfate	$CaSO_4$	136.14	68.07	Moderate	Hard scale	
Calcium silicate	Variable			Slight	Hard scale	
Calcium chloride	$CaCl_2$	110 99	55.50	Very soluble	Corrosive, scale and sludge	
Calcium nitrate	$Ca(NO_3)_2$	164.10	82.05	Very soluble	Corrosive, scale and sludge	
Magnesium bicarbonate	$Mg(HCO_3)_2$	146.34	73.17	Moderate	Deposits, liberates CO_2	
Magnesium carbonate	$MgCO_3$	84.32	42.16	Slight	Deposits, liberates CO_2	
Magnesium hydroxide	$Mg(OH)_2$	58.34	29.17	Very slight	Deposits	
Magnesium sulfate	$MgSO_4$	120.38	60.17	Very soluble	Corrosive, deposits	
Magnesium silicate	Variable			Slight	Hard scale	
Magnesium chloride	$MgCl_2$	95.23	47.62	Very soluble	Corrosive, deposits	
Magnesium nitrate	$Mg(NO_3)_2$	148 34	74.17	Very soluble	Corrosive, deposits	
Sodium bicarbonate	$NaHCO_3$	84.00	42.00	Very soluble	Increases alkalinity and soluble solids, liberates CO_2	Excess sodium alkalinity may be reduced by boiler blowdown, it sometimes is neutralized with sulfuric acid externally, phosphoric acid and acid phosphates also are used evaporation is best practical means of re moving sodium compounds from feedwater, boiler blowdown is used for internal reduction of soluble solids
Sodium carbonate	Na_2CO_3	106.00	53 00	Very soluble	Increases alkalinity and soluble solids, liberates CO_2	
Sodium hydroxide	NaOH	40.00	40.00	Very soluble	Increases alkalinity and soluble solids	
Sodium sulfate	Na_2SO_4	142 05	71.03	Very soluble	Inhibitor for caustic embrittlement, increases soluble solids	
Sodium silicate	Variable			Very soluble	Increases alkalinity, may form silica scale	
Sodium chloride	NaCl	58 45	58 45	Very soluble	Increases soluble solids, encourages corrosion	
Sodium nitrate	$NaNO_3$	85.01	85.01	Very soluble	Increases soluble solids	
Iron oxide	Fe_2O_3	159 68	26.61	Slight	Deposits, encourages corrosion	Coagulation and filtration, evaporation, blowdown
Alumina	Al_2O_3	101 94	16.99	Slight	May add to deposits	Coagulation and filtration, evaporation, blowdown
Silica	SiO_2	60.06	30.03	Slight	Hard scale, acts as binder for deposits	Precipitation with aluminates, coagulation and filtration, evaporation, blowdown
Dissolved oxygen	O_2	32.00	16.00	Slight	Corrosive	Deaeration preferred
Carbonic acid or dissolved CO_2	H_2CO_3	62 02	31.01	Very soluble	Retards hydrolysis of carbonates, reduces alkalinity	Deaeration and alkali treatment
Hydrogen sulfide	H_2S	34 08	17 04	Very soluble	Corrosive	Deaeration and alkali treatment
Acids, organic and mineral				Very soluble	Corrosive	Neutralization by alkali treatment
Oil and grease				Slight	Corrosive, deposits, foaming and priming	Coagulation and filtration, skimming
Organic matter				Very soluble	Corrosive, deposits, foaming and priming	Coagulation and filtration, evaporation

*From R. T. Kent, *Mechanical Engineers' Handbook*, Power, 12th ed , p. 7 51, John Wiley & Sons, Inc , New York, 1950

should be made after removal of the ammonia that is used to regulate the pH

(h) Corrosion. The principal accelerators of corrosion are dissolved oxygen, acids, surface deposits, especially those electronegative to steel, dissimilar metals in contact, and electrolytes.

Common methods to prevent corrosion are removal of dissolved gases, especially oxygen, neutralization of acids and maintenance of desirable alkalinity and pH, periodic mechanical cleaning, and avoiding excessive salt concentrations.

4-7.4 Acidity (pH)

(a) Definition. The pH is defined as the logarithm (to the base 10) of the reciprocal of the hydrogen-ion concentration in moles per liter

$$pH = \log \frac{1}{H^+ \text{ concentration in moles per liter}}$$

Figure 4.42 shows pH vs. hydrogen-ion concentration. Points indicate the pH values of various common acids and bases.

All water solutions owe their chemical activity to their relative H^+ and OH^- concentrations In water, the equilibrium product of the H^+ and OH^- concentrations is a constant 10^{-14} at 25°C. When concentrations of H^+ and OH^- in pure water at 25°C are equal, the H^+ concentration is 10^{-7} and, from the definition, the pH is 7.0 Note that the scale of pH values is not linear with concentration A change of one unit in pH represents a 10-fold change in the effective strength of the acid or base

The pH value depends only on the concentration of hydrogen ions actually dissociated in a solution and not on the total acidity or alkalinity. Therefore, because dissociation of water increases with temperature and pH is a measure of H^+ concentration only (and not the ratio of H^+ to OH^-), the pH of pure water increases above 7.0 if the temperature is increased above 25°C. There is no simple way to predict the pH of a solution at a desired temperature from a known pH reading at some other temperature.

(b) Measurement Techniques. *Chemical Indicators* The pH of a sample may be determined by adding a small quantity of an indicator solution to the sample and comparing the color with that of a color standard. When good color standards are available in steps of 0.2 pH unit and observations are made in a comparator, the limit of accuracy is considered to be 0.1 pH unit. Turbid and colored solutions cannot be observed with accuracy, and indicators are not stable in many strongly oxidizing or reducing solutions. Table 4.21 lists some common pH indicators and their range of use.

Potentiometric pH Measurement. A potentiometric pH-measuring system consists of (1) a pH-responsive electrode, such as glass, antimony, quinhydrone, or hydrogen, (2) a reference electrode, usually calomel or silver–silver chloride, and (3) a potential-measuring device, such as a pH meter, usually some form of vacuum-tube voltmeter Figure 4.43 shows a typical potentiometric system.

Table 4.22 lists the characteristics of six pH-measuring electrodes. Glass electrodes are electrically sensitive to hydrogen-ion concentration The voltage response to hydrogen-ion concentration is

$$E = E^0 - 0.0591 \log H^+ \text{ (at 25°C)}$$

where E^0 is the voltage of the particular glass electrode at pH zero

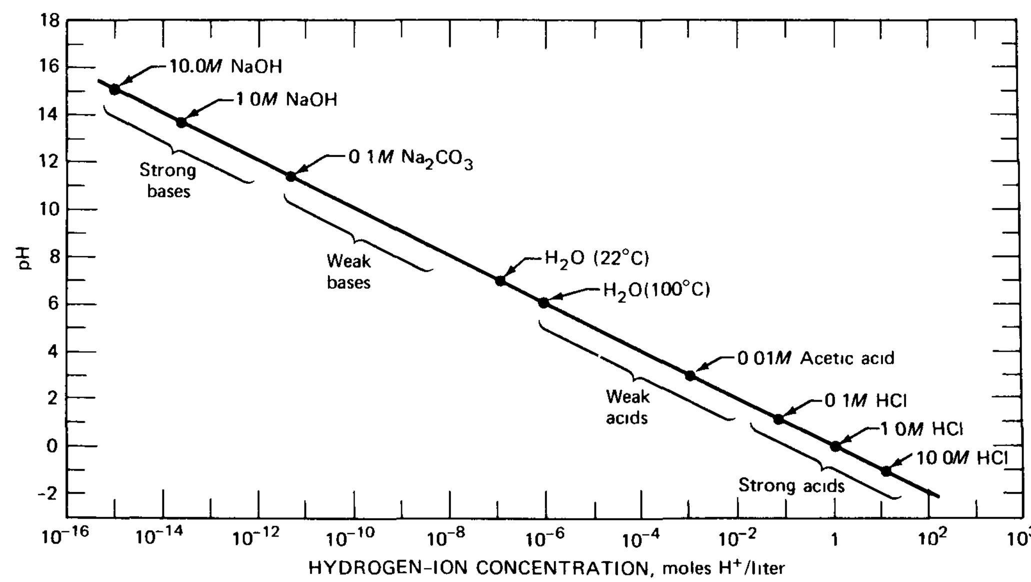


Fig. 4.42 —pH vs. hydrogen-ion concentration. (From D. M. Considine, *Process Instruments and Controls Handbook,* p. 6-96, McGraw-Hill Book Company, Inc., New York, 1957.)

Table 4.21—Range of Use of Chemical pH Indicators*

Indicator	pH range
p-Naphtholbenzein	0 – 0.8
Picric acid	0.1 – 0.8
Malachite green oxalate	0.2 – 1.8
Quinaldine red	1 – 2
4-Phenylazodiphenylamine	1.2 – 2.9
m-Cresolsulfonephthalein (meta cresol purple)	1.2 – 2.8
Thymolsulfonephthalein (thymol blue)	1.2 – 2.8
p(*p*-Anilinophenylazo)benzenesulfonic acid sodium salt (orange IV)	1.4 – 2.8
o-Cresolsulfonephthalein (cresol red)	2 – 3
2,4-Dinitrophenol	2.6 – 4.4
3′,3″,5′,5″-Tetrabromophenolsulfonephthalein (bromophenol blue)	3 – 4.7
Congo red	3 – 5
Methyl orange	3.2 – 4.4
3-Alizarinsulfonic acid sodium salt	3.8 – 5
Propyl red	4.6 – 6.6
3′,3″-Dichlorophenolsulfonephthalein (chlorophenol red)	4.8 – 6.8
p-Nitrophenol	5 – 7
5′,5″-Dibromo-*o*-cresolsulfonephthalein (bromocresol purple)	5.2 – 6.8
3′,3″ Dibromothymolsulfonephthalein (bromothymol blue)	6 – 7.6
Brilliant yellow	6.6 – 7.9
Neutral red	6.8 – 8
Phenolsulfonephthalein (phenol red)	6.8 – 8.4
o Cresolsulfonephthalein (cresol red)	7.2 – 8.8
m-Cresolsulfonephthalein (meta cresol purple)	7.4 – 9
Ethyl bis(2,4-dinitrophenyl)-acetate	7.5 – 9.1
Thymolsulfonephthalein (thymol blue)	8 – 9.6
o Cresolphthalein	8.2 – 9.8
Phenolphthalein	8.3 – 10
Thymolphthalein	9.4 – 10.6
5-(*p*-Nitrophenylazo)salicylic acid sodium salt (alizarin yellow R)	10 – 12
p-(2-Hydroxyl-l-naphthylazo) benzenesulfonic acid sodium salt (orange II)	10.2 – 11.8
p-(2,4-Dihydroxyphenylazo)-benzenesulfonic acid sodium salt	11.2 – 12.7
2,4,6-Trinitrotoluene	11.5 – 13
1,3,5-Trinitrobenzene	12 – 14

*From D. M. Considine, *Process Instruments and Controls Handbook,* p. 6-104, McGraw Hill Book Company, Inc , New York, 1957.

In Figs. 4.44 to 4.47, some pH-measuring meters are illustrated. The feedback type pH meter (Fig. 4.49) has a circuit capable of good performance if matched tubes are employed to minimize drift The electrodes must be checked periodically against standards for asymmetry.

Figure 4.48 shows the theoretical curve for the pH at 25°C vs. the concentration of ammonia. Figure 4.49 gives the temperature correction for the ammonia curve.

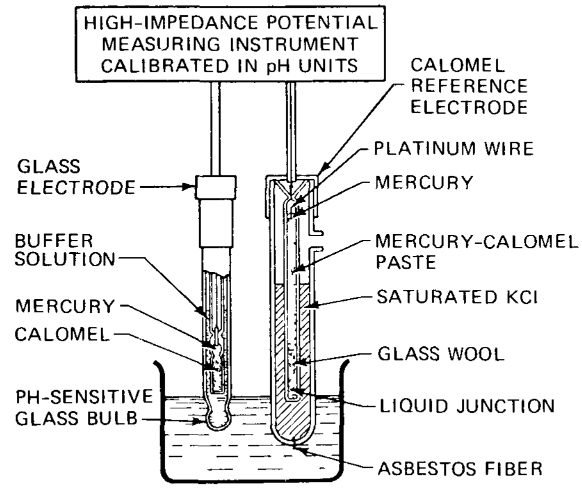


Fig. 4.43—A potentiometric pH-measuring system. (From D M Considine, *Process Instruments and Controls Hand book,* p. 6-106, McGraw-Hill Book Company, Inc., New York, 1957.)

Figure 4.50 shows the theoretical curve for the pH at 25°C vs. the conductivity of ammonia. Conductivity measurements can be used to monitor the pH of the feedwater or the ammonia concentration in the feedwater (Fig. 4.51).

Limitations and Practical Considerations.

1. Glass electrodes can develop cracks, which allow some diffusion between the inner filling solution and the sample. When diffusion occurs responses are erratic and nonreproducible.
2. Glass is soluble in strongly alkaline solutions and thus has a shorter service life. Special alkali-resistant electrodes should be used for these applications.
3. If the glass becomes coated, the response is sluggish.
4. High sodium-ion concentration for extended periods of time results in loss of sensitivity.
5. Avoid temperature transients.
6. New electrodes should be soaked several hours before use to improve stability.
7. Avoid electrical leakage in the high-impedance input circuit by preventing moisture buildup on the glass electrode body and lead. Electrical leakage is sometimes caused by the buildup of humidity and dust inside the instrument case.
8. Grounding problems Many pH meters provide for separate grounding of the amplifier chassis and case. The ground of the amplifier is maintained at the glass-electrode potential by connections with feedback circuits.
9. Shorting of the electrodes causes polarization. The pH reading drifts under these conditions.
10. Colloids are sensitive to salt and may precipitate at the liquid junction as the result of the diffusion of the salt-bridge electrolyte or may form a film on the glass-electrode bulb. Slurries cause similar trouble.
11. Glass is attacked by soluble silicates and by acid fluorides. Special alkali-resistant electrodes are available.

Table 4.22—Characteristics of pH-Measuring Electrodes*

Electrode type	Operating range			Limitations	Advantages
	pH	Temp., °C	Pressure, psi		
Glass (pH-sensitive)	0–13	0–100	0–100	Has high internal resistance, requires shielding, excellent insulation, and electrometer-type voltmeter, error occurs in high conc. of alkali, attacked by fluoride solutions	Wide pH and temperature range, not affected by oxidizing or reducing solutions, dissolved gases, or suspended solids, not affected by moving liquids except at high velocity
Antimony (pH-sensitive)	4–11 5	0–60	Not limited	Electrode poisoned by Bi, As, Cu, Ag, Hg, and Pb, affected by some oxidizing and reducing solutions, tartrates and citrates cause errors, dissolved O_2 must be present to maintain pH-sensitive oxide coating, active surface must be periodically scraped and reformed	Very rugged and durable for use in abrasive slurries, has low cell resistance, shielding and special voltmeter not required
Quinhydrone (pH-sensitive)	0–8 5	0–37	Not limited	Limited pH range, "salt error," cannot be used in presence of oxidizing and re ducing agents, "protein errors," quinhydrone may change pH of unbuffered solution	Simple electrode, low resistance
Hydrogen (pH sensitive)	Not limited	Not limited	Atmospheric pressure	Cannot be used in presence of oxidizing or reducing agents, cannot be used in presence of elements below hydrogen, slow to reach equilibrium, large samples required	Standard of reference, no alkaline error
Calomel (reference)	Not limited	Life shortened at high temperatures	Atmospheric pressure or below except for special designs	No interferences except from contamination from high-pressure test solutions	Can be used with any pH-sensitive electrodes
Silver–silver chloride (reference)	Not limited		Atmospheric pressure or below except for special designs	Interference by contamination from high-pressure solutions	Mercury-free, may be used with any pH-sensitive electrodes

*From D M Considine, *Process Instruments and Controls Handbook*, p. 6-105, McGraw-Hill Book Company, Inc , New York, 1957

12. Radioactivity in sample solutions may result in ion collection in the high-impedance input circuit, which, in turn, may produce error signals.

13. Glass electrodes respond to high concentrations of sodium, potassium, and lithium ions Sodium-ion corrections are usually available from the electrode manufacturer. The need for correcting data for high concentrations of other ions should be investigated.

4-7.5 Hardness

(a) Definition. Dissolved salts of calcium and magnesium impart the property of "hardness" to water. Hardness is characterized by the formation of insoluble precipitates, or curds, with soaps. Temporary hardness, caused by calcium and magnesium bicarbonate, is removed by boiling, which causes these salts to decompose, liberating CO_2 and

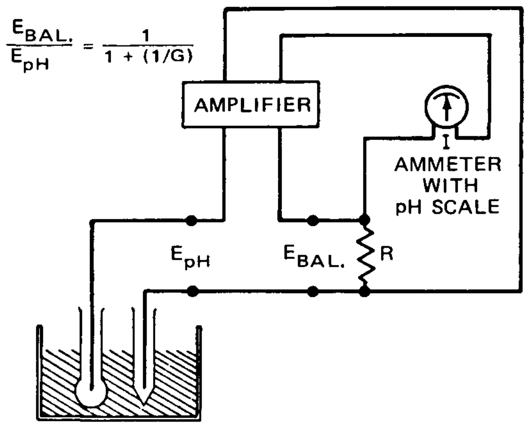


Fig. 4.44—Feedback-type pH meter. (From D. M. Considine, *Process Instruments and Controls Handbook*, p. 6-113, McGraw-Hill Book Company, Inc., New York, 1957.)

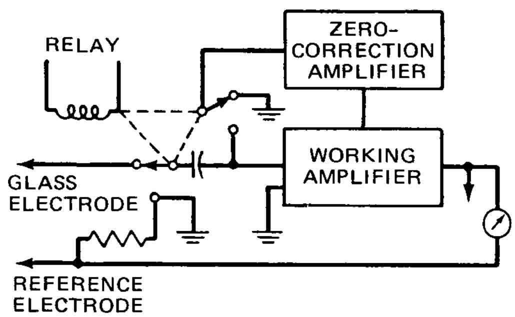


Fig. 4.45—Direct-current feedback pH amplifier with automatic zero adjustment. (From D. M. Considine, *Process Instruments and Controls Handbook*, p. 6-113, McGraw-Hill Book Company, Inc., New York, 1957.)

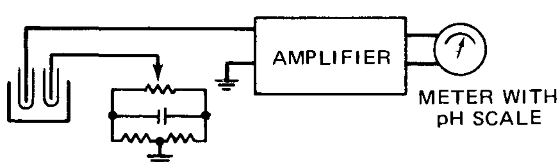


Fig. 4.46—Direct-current amplifier direct-reading pH meter. (From D. M. Considine, *Process Instruments and Controls Handbook*, p. 6-114, McGraw-Hill Book Company, Inc., New York, 1957.)

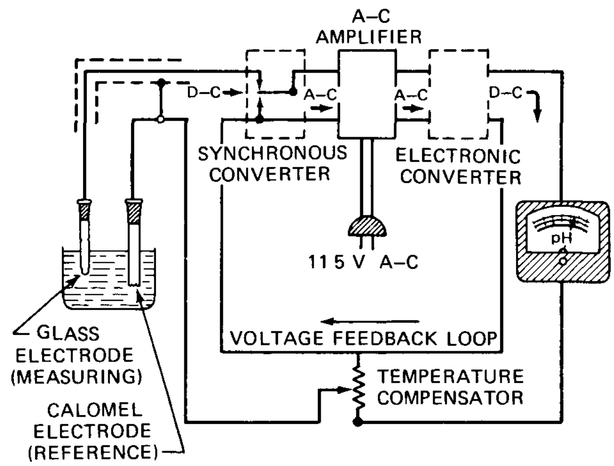


Fig. 4.47—Alternating current amplifier pH meter. (From D. M. Considine, *Process Instruments and Controls Handbook*, p. 6-113, McGraw-Hill Book Company, Inc., New York, 1957.)

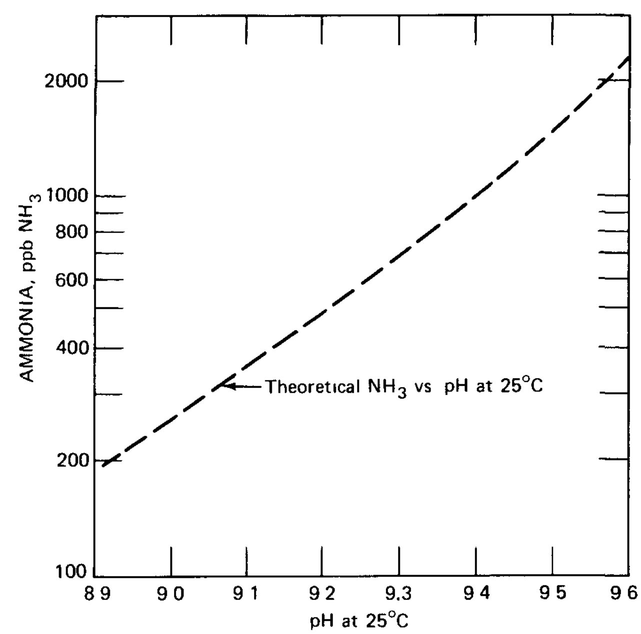


Fig. 4.48—Theoretical relationship for ammonia concentration vs. pH at 25°C (From J. H. Hicks, *Babcock and Wilcox Nuclear Power Generation Division Water Chemistry Manual*, Part 13, Curves, 1969.)

precipitating carbonates. Permanent hardness is due to the sulfates, chlorides, and all the soluble calcium and magnesium salts other than the bicarbonates. Permanent hardness is not removed by boiling.

(b) Measurement Techniques. *Total hardness* is determined by adding a standard soap solution to a measured amount of sample and shaking the mixture vigorously between additions of the soap solution until an unbroken lather is maintained for 5 min on the water surface. The volume of soap used is referred to a chart or multiplied by a factor. The result is expressed in parts per million.

Chloride concentration is determined by titrating a measured volume of sample with standard $AgNO_3$ solution, using potassium chromate as an indicator The end point is red coloration.

Equivalent sodium sulfate determination is made by titrating with sodium hydroxide solution, with phenolphthalein as indicator, after adding an excess of benzidine sulfate to a measured sample. The benzidine sulfate precipitates the sulfate in the sample. After standing, filtering, and washing, the precipitate is titrated with NaOH. Turbidity-measuring instruments, described in Sec. 4-7.6, can be used for sulfate determination Barium

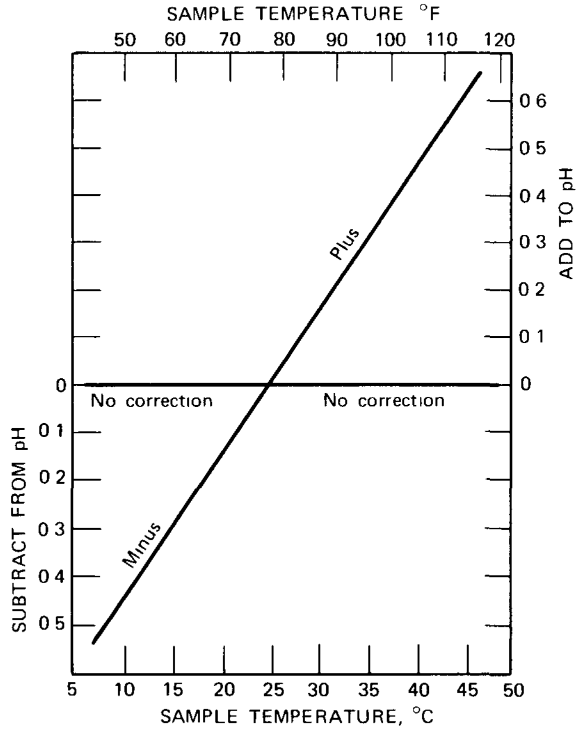


Fig 4.49—Temperature correction to 25°C for pH (ammonia solutions). (From J H Hicks, *Babcock and Wilcox Nuclear Power Generation Division Water Chemistry Manual*, Part 13, Curves, 1969)

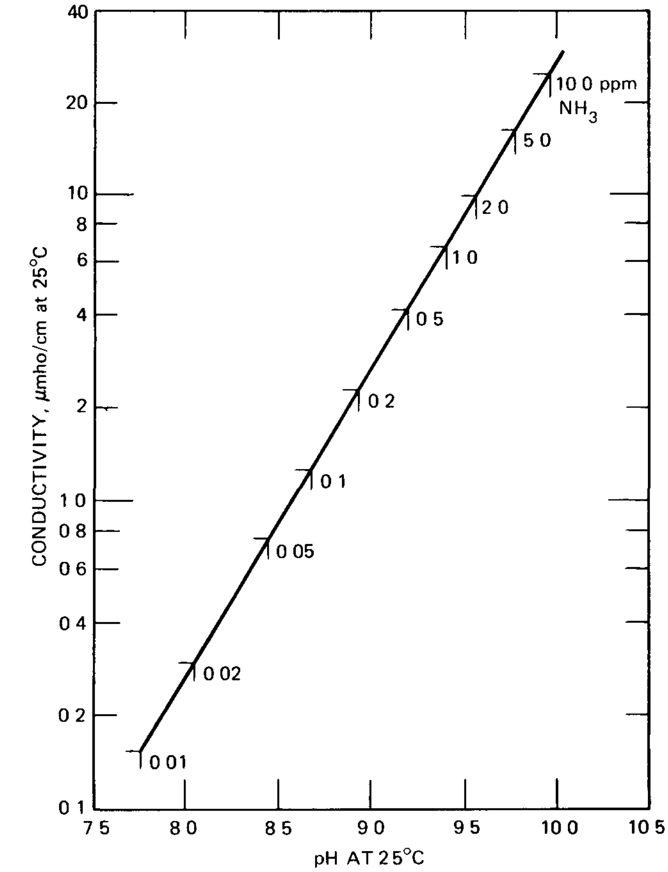


Fig. 4 51—Relationship between conductivity and pH for ammonia solutions. (From J H. Hicks, *Babcock and Wilcox Nuclear Power Generation Division Water Chemistry Manual*, Part 13, Curves, 1969)

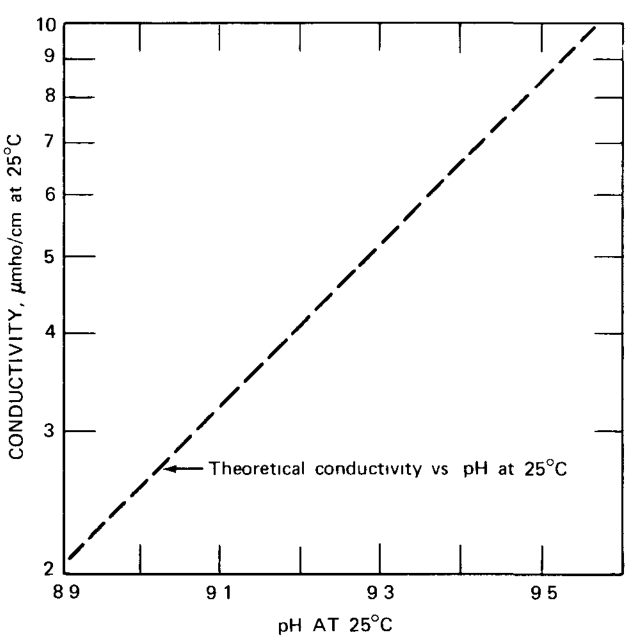


Fig. 4.50—Theoretical relationship between pH and conductivity for ammonia (From J. H. Hicks, *Babcock and Wilcox Nuclear Power Generation Division Water Chemistry Manual*, Part 13, Curves, 1969.)

chloride and hydrochloric acid added to the measured sample cause a white precipitate of barium sulfate to form. The resulting turbidity is measured and is an indication of sulfate concentration.

4-7.6 Turbidity

A turbidity transmitter depends upon the principle that suspended solids in a liquid absorb and scatter part of any light passing through the liquid. The transmitter is an integral assembly of a light source, a flow tube, and a light-intensity detector (Fig. 4.52). The change in radiant energy reaching the detector varies the resistance in one arm of a Wheatstone bridge A compensating filament in the second arm of the bridge corrects for ambient temperature.

4-7.7 Electrical Conductivity

(a) Discussion. Electrical conductivity (see also Sec. 4-9.1) is related to the concentration of total dissolved solids. The purest water is a very poor conductor Pure water has a conductivity approaching very closely the theoretical minimum of approximately 0.05 µmho/cm at 25°C, which is due to the dissociation products of water itself.

(b) Measurement Techniques. Alternating current is generally used in a measuring system because direct current produces progressive changes in concentration near the

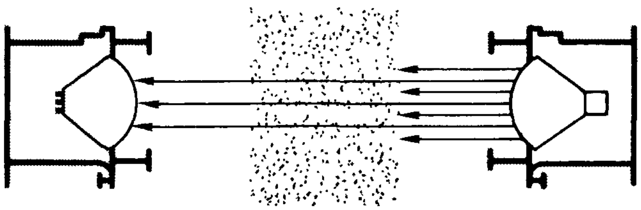


Fig. 4.52—Turbidity measurement. The liquid is passed between the light source (right) and the bolometer (left). The amount of radiant energy detected by the bolometer has a definite relation to the concentration of suspended solids. (From *Product Specification E74-1*, Bailey Meter Co., Wickliffe, Ohio, 1966.)

electrodes. Also, products of the electrode reactions (with direct current) may set up a voltaic cell and an appreciable back emf. Figure 4.53 shows an a-c Wheatstone bridge circuit for measuring electrical conductivity. In the figure R_X is the resistance of the electrolyte measured between two electrodes of a conductivity cell, R_3 and R_4 are end resistors whose function is to establish the limits of bridge calibration, and R_5 is a calibrated slidewire which does not enter into the arms of the bridge, and therefore variable values cause no error in bridge readings. The condition for balance of the Wheatstone bridge is $A/B = R_S/R_X$, and this

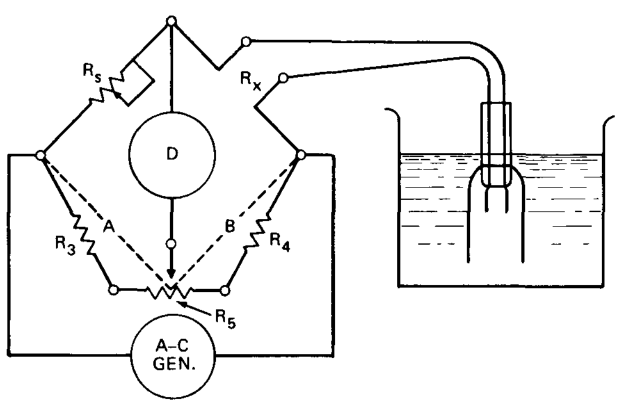


Fig. 4.53—Alternating-current Wheatstone bridge. (From D. M. Considine, *Process Instruments and Controls Handbook*, p. 6-162, McGraw-Hill Book Company, Inc., New York, 1957.)

condition is indicated by no current flow through detector D (a galvanometer or microammeter).

4-7.8 Specific Weight of Compressed Water

The specific weight of water varies markedly with temperature. The effect of pressure on specific weight is less dramatic but still significant. The curves of Fig. 4.54 illustrate the effects of temperature and pressure on the specific weight (lb/ft^3) of water.

4-8 GAS PROPERTIES SENSING*

4-8.1 Humidity and Dew Point

(a) Definitions. *Absolute Humidity.* The number of pounds of water vapor in one pound of dry air.

Relative Humidity. The ratio, usually expressed as a percentage, of the partial pressure of water vapor in the actual atmosphere to the vapor pressure of water at the prevailing temperature.

Percentage Humidity. The quotient of the number of pounds of water vapor carried by 1 lb of dry air divided by the number of pounds of water vapor which 1 lb of dry air would carry if it were completely saturated at the same temperature, multiplied by 100.

Dew Point. The temperature at which a given mixture of air and water vapor is saturated with water vapor.

Dry-Bulb Temperature. The temperature of an atmosphere. The qualification "dry-bulb" is used to distinguish the normal temperature measurement from the temperature measured by the wet bulb.

Wet-Bulb Temperature. The dynamic equilibrium temperature attained when the wetted surface of an object of small mass (bulb of a thermometer) is exposed to an air stream. Evaporation of water causes cooling, which is counterbalanced by heat absorbed from the air.

(b) Measurement Methods. *Condensation.* The surface in contact with the atmosphere is cooled until condensate (dew) appears. A variation of this method is to cool a sample by adiabatic expansion so that condensation appears as a fog. The expansion ratio to produce a fog and the initial temperature allow calculation of the dew point.

Dimensional Change. Most organic materials change dimensionally with changing humidity. A typical instrument uses human hair arranged so its expansion with increasing humidity actuates a mechanism. For many materials the expansion is, to a close approximation, a linear function of the relative humidity. Animal membranes, wood, and paper have also been used to sense relative humidity.

Thermodynamic Equilibrium (Wet-Bulb Thermometer). The bulb of a thermometer is wrapped in a cloth wick that is kept wet with water. The wrapped bulb is exposed to an air stream, and the temperature observed is the wet-bulb temperature. This reading, in combination with a reading of the air temperature (dry-bulb temperature) is a measure of the moisture content of the air. Variations of this basic design use ceramic sleeves instead of cloth wicks. In one design, the wick is eliminated, and the temperature of the air stream is measured after cooling by saturation from a water spray. The basic design is known as a wet- and dry-bulk psychrometer. A sling psychrometer has glass thermometers in a frame designed to be swung through the air rapidly to secure sufficient air velocity.

*The sensing of moisture in gas-cooled reactors is covered in Vol. 2, Chap. 18, Sec. 18-3.3.

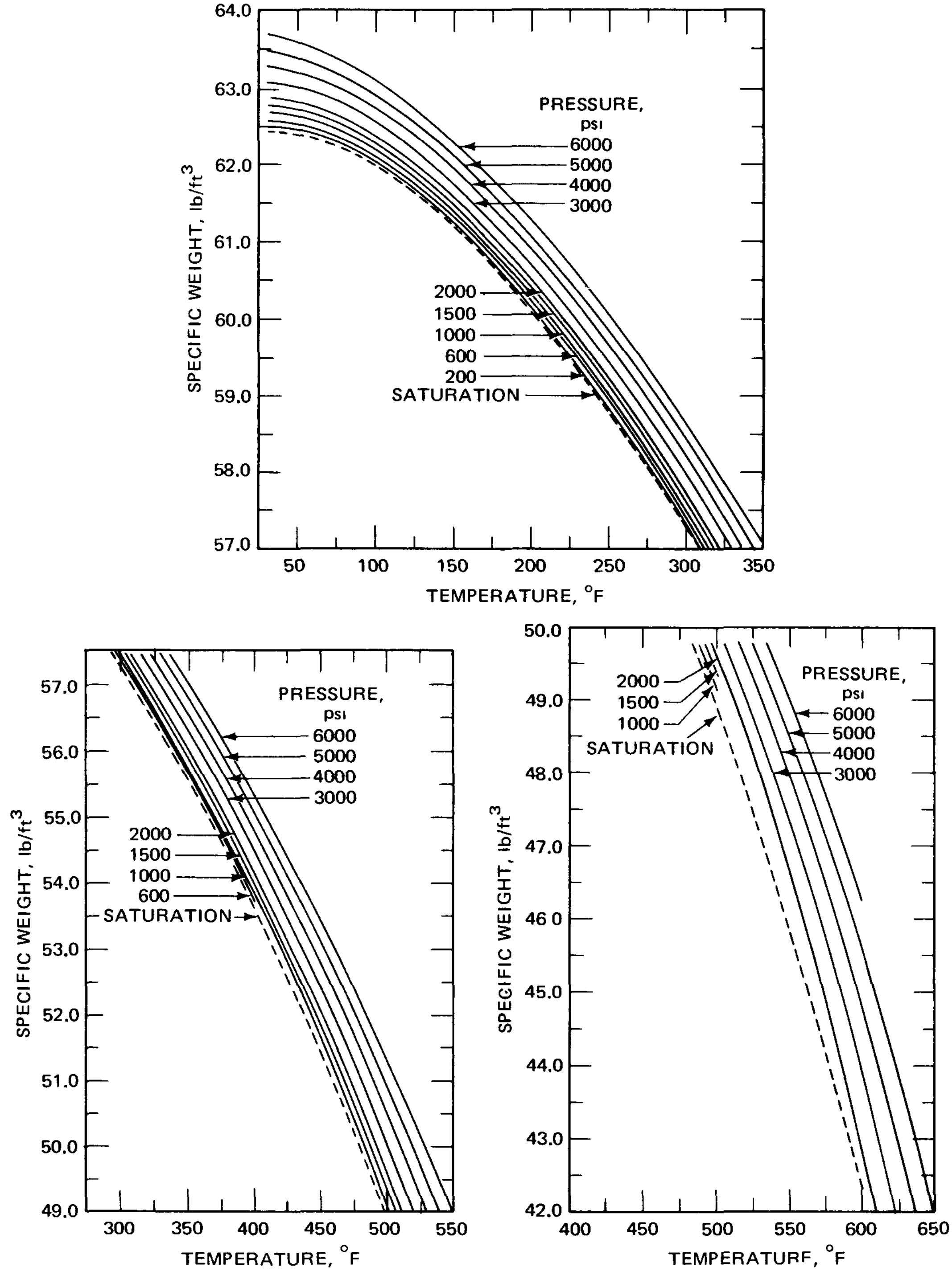


Fig. 4.54—Effects of temperature and pressure on the specific weight of water. (Courtesy Bailey Meter Company.)

Absorption (Gravimetric). A measured volume of air is passed through a water-absorbing material, such as phosphorous pentoxide. The gain in weight of the absorbent is the moisture content of the known volume of air. In a variant of this technique, the change in pressure when the absorbent is brought into contact with air in a sealed vessel is measured.

Absorption (Conductivity). The amount of water absorbed by a quantity of a hygroscopic salt varies with temperature and humidity. The absorption changes the electrical conductivity between two electrodes in contact with the salt. The conductivity, when corrected for temperature, usually automatically, can be interpreted as relative humidity. An on-line sensor and readout is commercially available using the technique of surface conductivity measurement of an inert non-conductor at or near the dew point. An intermeshed grid embedded in the surface of a nonporous epoxy-filled glass cloth exhibits a specific

resistivity at a given ambient moisture concentration and temperature. Sensor surface temperature is measured by a thermocouple embedded in the sensor surface

Electrolysis. The moisture in a measured flow of air is absorbed by phosphorous pentoxide and simultaneously decomposed by electrolysis. By Faraday's law, the electrolytic current is directly proportional to the rate of decomposition of water and hence to the moisture content of the air.

Heat of Absorption. The absorption of water vapor on a solid absorbent releases heat. A measurement of temperature change when water vapor is alternately absorbed and desorbed is interpreted as moisture content.

Vapor Equilibrium. A saturated solution of a hygroscopic salt is maintained at the temperature at which it is in vapor-pressure equilibrium with the atmosphere. The temperature of the salt converts directly to dew-point temperature. Conductivity of the solution is used to control heating and to maintain the equilibrium temperature.

Absorption (Infrared) Water vapor and most other compounds absorb radiation in certain portions of the infrared region. A measurement of the infrared absorption can be interpreted in terms of moisture content.

4-8.2 Chemical Composition*

(a) Physical Methods. *Condensation and Fractional Vaporization.* Separation of condensable vapors, generally in groups. Identification and quantitative evaluation is performed by other methods. Curves of vapor pressure vs. temperature of possible components must be known.

Fractional Distillation. Separation, identification, and quantitative evaluation of condensable hydrocarbons even in complex mixtures.

Adsorption or Absorption and Desorption (Chromatography). Separation, identification, and quantitative evaluation of many gases and vapors even in complex mixtures.

Diffusion. Separation of hydrogen and some isotopes.

Thermal Diffusion. Separation of some isotopes.

Electric Discharge. Separation of nonionizable gases.

(b) Chemical Methods. *Selective Absorption.* Separation and quantitative evaluation of gases and vapors already known. There is a need for selective reagents. Quantitative analysis can be accomplished by (1) volumetric or barometric methods, (2) gravimetric methods, (3) titrimetric methods, (4) electrical conductivity, (5) colorimetry, or (6) calorimetry.

(c) Combustion Analysis. *Fractional Combustion* Separation, identification, and quantitative evaluation, mainly of H_2, CO, and hydrocarbons

Complete Combustion. Quantitative evaluation of H_2, CO, and hydrocarbons.

(d) Absorption of Electromagnetic Radiation. *Magnetic Susceptibility.* Quantitative evaluation of O_2, NO, ClO_2, and NO_2, not mixed with each other. Mainly used for O_2

Visible. Quantitative evaluation of colored gases, not mixed with each other (NO_2, Cl, etc.)

Ultraviolet. Quantitative evaluation of O_3, NO, C_6H_6, $C_6H_5(CH_3)$, etc.

Infrared. Identification and selective quantitative evaluation of CO, CO_2, hydrocarbons, NH_3, SO_2, SO_3, etc.

Visible Spectroscopy Identification of various substances, quantitative evaluation doubtful.

Ultraviolet Spectroscopy. Identification of various substances, quantitative evaluation doubtful.

Infrared Spectroscopy. Identification and quantitative determination of H_2O, CO, CO_2, hydrocarbons, organic compounds, etc. Can detect composition of highly diluted mixtures.

Mass Spectrometry. Identification and quantitative evaluation of a large number of substances. Precise and capable of detecting composition of highly diluted mixtures.

(e) Hydrogen Determination. The determination of hydrogen is normally the last to be performed. When all other constituents have been determined, the remaining gas can be considered as a binary mixture. Analysis for hydrogen can then be performed by one of the following methods

Sonic Analyzer. The velocity of sound, S, is related to the molecular weight of the gas through which it is propagating

$$S = \left(\frac{kRT}{m}\right)^{1/2}$$

where R = gas constant
T = absolute temperature
k = ratio of specific heats ($k = c_p/c_v$)
m = molecular weight

Two sound waves of identical frequency are passed through two similar tubes, one filled with a reference gas and the other with the mixture. Different sound velocities in the two tubes result in a phase difference between the two waves reaching the ends of the tubes. This difference is used to compare the velocity of sound in the two gases. The mean molecular weight of the mixture can be derived, and the hydrogen content can thus be calculated.

Interferometry (Optical). A monochromatic light beam is split and passed through two identical tubes, one filled with a reference gas and the other with the mixture. Usually the reference gas chosen is the major constituent in the binary mixture. Because of the difference in the velocity of light in the two gases, the light beams emerge with a difference in phase and can be made to produce interference bands. The spacing of the bands is related to the relative concentrations of the components of the gas

*Gas analysis of the coolant in gas-cooled reactors is discussed in Vol. 2, Chap. 18, Sec. 18-3.3.

mixture and the refractive indices of the sample and the reference gas

$$n_{ab} = n_a \frac{P_a}{P} + n_b \frac{P_b}{P}$$

where n_{ab} = refractive index of a binary mixture (A + B)
n_a and n_b = refractive indices of the components A and B
P = pressure of the gas mixture
P_a and P_b = partial pressures of the components

When the refractive index of the mixture is known, the partial pressure of one component can be deduced and hence the concentration can be estimated. Interferometers are capable of great accuracy provided they are used with skill and provided pressure and temperature corrections are applied.

Thermal Conductivity. In binary mixtures thermal conductivity can vary linearly with the concentration of one component Absolute evaluation of thermal conductivity is very difficult, and normally only relative values are determined. For this purpose a hot wire Wheatstone bridge is used. Sample gas passes through a cell that contains a resistance wire. A second cell containing a compensating resistance is filled with a reference gas, which is usually the major constituent in the mixture. The heat-loss difference between the two arms, due to the different thermal conductivities of the gases, unbalances the bridge The bridge output must be calibrated against standard gas mixtures.

This method is highly suitable for hydrogen because the thermal conductivity of hydrogen is considerably higher than that of other gases The thermal conductivities of some gases relative to normal air at 0°C are air = 1, H_2 = 7, CH_4 = 1.27, CO = 0.96, and CO_2 = 0.59.

Diffusion. Hydrogen could be determined by taking advantage of its high diffusivity through porous diaphragms. The method is time-consuming, but its accuracy is good.

When the analysis for hydrogen is required in a mixture containing more than two components, other methods must be used.

Combustion Analysis. If the gas mixture contains no hydrocarbons, hydrogen may be estimated by measuring the water formed by oxidation. Actually, hydrogen is usually found mixed with other hydrogenated combustible gases that also produce water on oxidation. If there are no more than two other hydrocarbons, the identity of which must be known, combustion analysis is still possible provided carbon dioxide is also estimated. This requires the solution of three equations.

Other Methods. Hydrogen is also determined by gas chromatography and mass spectrometry. Infrared spectroscopy cannot be used since hydrogen has no absorption bands in the region of the spectrum.

(f) Oxygen Determination. *Paramagnetic Analyzer.* A continuous stream of gas is passed through an annular tube and crossed by a transverse connection tube The latter is wound with a heating spiral, one end of which passes through a strong magnetic field. Any oxygen molecules in the gas are attracted toward the magnet more from the left side of the transverse tube than from the right. Warm molecules are less susceptible to the effect of the magnet. As a result continuous flow is established through the transverse tube. The gas flow through the transverse connection depends upon the oxygen concentration. The temperature gradient along the heater winding depends upon gas flow. Therefore, oxygen concentration is measured by temperature gradient.

Electrochemical Gas Analyzer. A heated zirconium oxide tube sets up a current when there are different concentrations of oxygen in two gases that flow inside and outside the tube. The unknown gas is passed inside the tube, and the reference gas (air) is passed outside the tube. The electrical output of the tube is proportional to the logarithm of the ratio of the oxygen concentration of the two gases. The advantages of the method are that it is accurate, requires no fuel, is unaffected by high SO_2 or SO_3 concentrations, is unaffected by high CO_2 concentrations, reads net O_2, and has a fast response.

(g) Summary of Methods Used for Gas Analysis. Table 4.23 summarizes the various methods that may be used for gas analysis. Instrumental procedures for gas analysis tend to supersede classical laboratory methods. Laboratory methods are often used as standard references. Instruments are used as the ordinary tools of the investigation.

For simple analysis (CO_2, CO, O_2, H_2, and CH_4), the nondispersive infrared analyzer, the magnetic oxygen analyzer, and the sonic analyzer for hydrogen are suitable. For mixtures of increased complexity, chromatography is recommended. It is economical and quick. It can fractionate mixtures into single or groups of components, which can be useful before applying infrared or mass spectrometry.

(h) Mass Spectrometry. The material to be studied is subjected to an ionizing process, separated according to mass by electromagnetic means, and the resulting mass spectrum is analyzed, quantitatively and qualitatively, by comparing it with the spectra of known calibrating materials.

Ions are produced by four methods (1) electron bombardment, in which the unknown, if it is gaseous, is bombarded in an evacuated chamber by electrons, (2) direct emission of ions from the surface of some solid materials by heating a filament that is covered with a thin layer of the material to be analyzed, (3) the crucible method, in which materials (e.g., halides) are evaporated from a small furnace, and subsequently the vapor is ionized by electron bombardment, and (4) the spark method, in which a high-voltage spark between electrodes of the material to be analyzed yields ions of that material. Positive ions are accelerated by electric fields between a system of electrodes. Ions are focused in their passage through slits or apertures in the electrodes. The ion source in a mass

Table 4.23—Summary of Gas-Analysis Methods*†

Method	Average sample size† (s.t.p.), cm^3	Average time required‡	Average accuracy†	H_2	O_2	CO_2	SO_2	SO_3	CO	Alcohols	Ethers	Aldehydes	Organic acids	Organic peroxides	CH_4	Other hydro-carbons
Fractional distillation	10^4	6 hr	0.5													A
Gas chromatography	10	5 min–1 hr	0.1 T.A.	B	B	B			B	A	A	A	A		A	A
Diffusion	200	20 min	0.1	A												
Combustion and gravimetric analysis	1 to 4 x 10^3	6 hr	T.A.	B		A			A						A	A_1
Cambridge	10	16 hr	0.01	A	B	A			A			A_2			A	A_1
Modified Cambridge	10	3 hr	0.01			A			A			A_2			A	A_1
Simplified Cambridge	10	20 min	0.01			A										
Interferometry§	4000	5 min	0.01	A	B	A			A						A	
Sound velocity§	500	5 min	1	A	B	B									B	
Thermal conductivity bridge§	f.s.	i.d.	0.001	A		B			B							
Paramagnetic detector	f.s.	i.d.	0.05		A											
Nondispersive infrared	f.s.	i.d.	0.001			A	A		A	A		B	B		A	B
Infrared spectrometry	20	20 min–1 hr	0.1			B	B		B	A		B	B		A	A
Mass spectrometry	0.01	15 min–1 hr	T.A.	B	B	B	B		B	A	A	A	A	B	B	A
Special laboratory methods							A	A		A	A	A	A	A		

*From G. Tine, *Gas Sampling and Chemical Analysis in Combustion Processes,* p. 86, Pergamon Press, Inc., New York, 1961.

†Abbreviations: i.d. = instrumental delay (sec)

A = particularly suitable method

B = possible method

A_1 = undifferentiated estimation

A_2 = estimation of formaldehyde only

T.A. = trace analysis

f.s. = analysis can be performed also on flowing streams

‡The actual sample sizes, time consumptions, and accuracies depend upon the particular apparatus that is used and, in many instances, upon the gas to be detected.

§Only suitable for binary mixtures of known components.

spectrometer is a combination of the region where the ions are generated (this region usually has an electron gun to provide the electron bombardment) and the ion-accelerating region.

The ions are separated by one of these four basic methods a magnetic analyzer (masses separate according to their momenta in a magnetic field), a time-of-flight analyzer (ions with same kinetic energy but different masses have velocities inversely proportional to the square root of the mass and become separated if injected into a field-free "drift" region), a linear-accelerator analyzer (accelerated ions are segregated by electrostatic deflection), and an ion-resonance analyzer (ions move in a region where a radiofrequency electric field is set up at right angles to a magnetic field and, if the frequency is in resonance with the spiralling ions, the ions spiral out of the field and are collected)

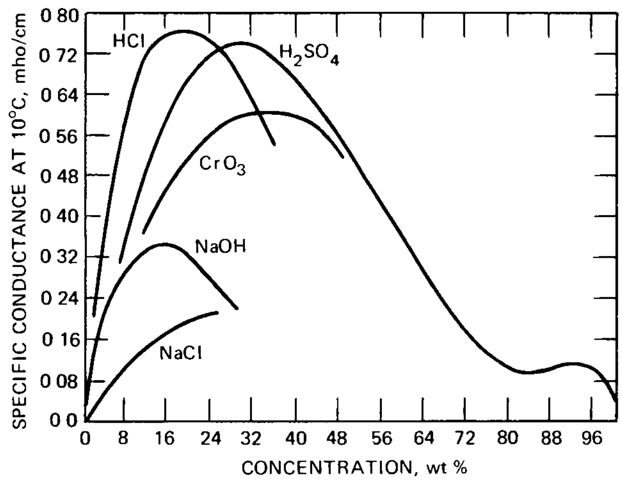


Fig. 4.55—Conductivity–concentration curves for certain electrolytes (From D M Considine, *Process Instruments and Controls Handbook*, p 6 159, McGraw Hill Book Company, Inc , New York, 1957)

4-9 OTHER SENSORS

4-9.1 Electrical Conductivity

(a) Discussion of Applications. Electrical conductivity of a solution is a measure of all ions present. Pure water is a very poor conductor. The conductivity of a water solution is, in practice, almost exclusively due to ions other than the hydrogen (H^+) and hydroxyl (OH^-) ions. Figure 4.55 shows the conductivity of certain electrolytes as a function of their concentration in water.

Most practical applications of electrical-conductivity measurements fall into one of the following categories

1. Concentration in simple water solutions. Common examples are sodium chloride, sodium hydroxide, and sulfuric acid In such cases the concentration–conductivity curve must be known in advance, or the system must be experimentally calibrated.

2. Boiler steam quality detection. The exact nature of the electrolyte is usually less important than its magnitude. Nuclear installations require extremely pure feedwater

3. Measuring the extent of a reaction. Reactions such as precipitation, neutralization, and washing soluble electrolyte from insoluble materials can be monitored by conductivity measurements. These procedures require calibration or a comparison between conductivities of streams before and after the reaction.

4. Detecting contaminations. Leaks in heat exchanger with the resultant contamination. Any sudden change in conductivity of the heat-exchange medium is taken as leakage. Salt-water contamination of freshwater can be detected as well as breaks in condenser tubes.

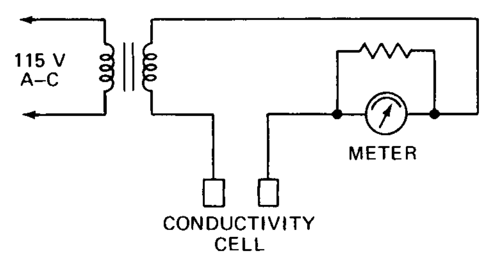


Fig. 4 56—Conductivity-measuring system using a simple ohmmeter circuit. (From D M. Considine, *Process Instruments and Controls Handbook*, p 6 163, McGraw Hill Book Company, Inc , New York, 1957)

(b) Measurement Methods. *Measuring Circuits* The a-c Wheatstone bridge circuit (Fig. 4.53) is the most widely used technique. It is sensitive, stable, and accurate. An ohmmeter circuit (Fig. 4.56) can also be used. The current is a function of cell resistance, the system is sensitive to voltage variations In addition to these circuits, an a-c crossed-coil electrodynamometer can be used in a conductivity-measuring circuit. One of the two crossed moving coils responds to the current flow in the conductivity cell circuit, the other responds to the source voltage. It is a relatively simple technique, but it is not as accurate or sensitive as the Wheatstone bridge.

Conductivity Cells. The first criterion in selecting a conductivity cell is that the *cell constant* must be such that the resistance of the solution under test falls within the limits of the cell range. When high electrolytic resistance is being measured, as in the determination of steam purity, a capacitative impedance in series with the cell has a negligible effect on bridge readings, on the other hand, capacitative impedance in parallel impairs the sharpness of bridge balance. Impedance varies inversely with frequency. Therefore, low bridge frequencies are desirable when measuring high resistance. A relatively low cell constant, such as K = 0.1, has large electrodes close together and is suitable for measuring high resistance systems. Spreading the plates apart and constricting the electrolyte cross section increases the cell constant.

The mechanical features of conductivity cells are illustrated in Fig. 4.57. There are four basic types: *dip cells,* designed for dipping or immersing in open vessels; *screw-in cells,* designed for permanent installation in pipelines and tanks; *insertion cells* with removal devices, designed to permit removal of the element without closing down the line in which they are installed; and *flow cells,* glass or plastic with internal electrodes close to the wall to offer little resistance to the flowing medium. (In small sizes, the flow-cell tubes are connected to the system with rubber or plastic tubing; in large sizes standard pipe flanges are used.)

Temperature, flow velocity, and presence of solids have significant effects on conductivity-cell performance. Temperature should be held as nearly constant as possible. The conductivity of most solutions increases about 2.5% for each 1°C rise in temperature. The flow velocity should be sufficient to ensure circulation of liquid between the electrodes. Entrained solids and high velocity increase the scouring effect. Low velocity can result in the accumulation of solids and the plugging of the cell chamber.

Chemical considerations are important. Strong electrolytes, such as hydrochloric acid, can slowly dissolve platinum electrodes. Tantalum or graphite electrodes should be used. Hydrofluoric acid measurement requires cells of tetrafluoroethylene and platinum. Conductivity measurements of condensed steam or demineralized water

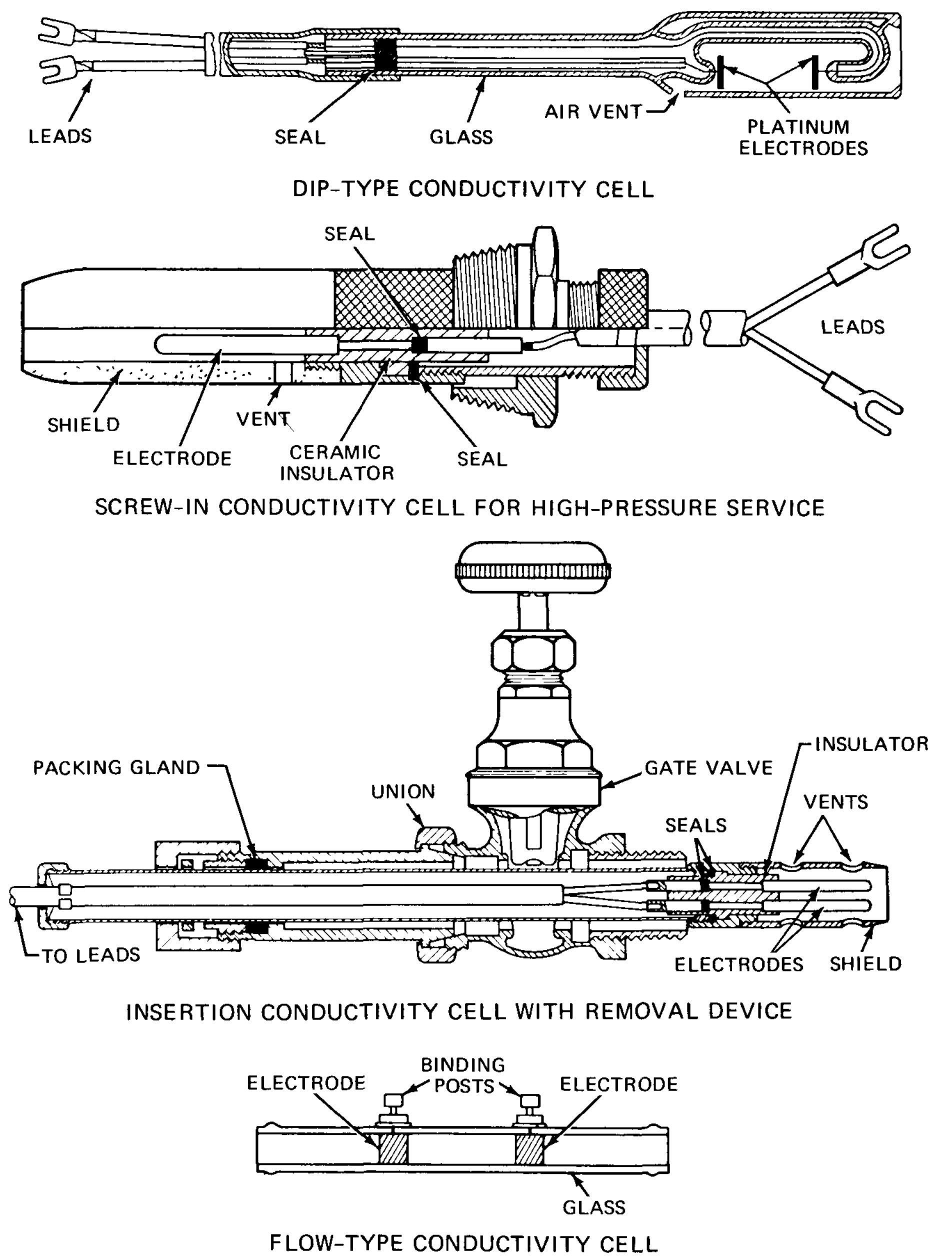


Fig. 4.57—Basic types of conductivity cells. (From D. M. Considine, *Process Instruments and Controls Handbook*, p. 6-163 through 6-165, McGraw-Hill Book Company, Inc., 1957.)

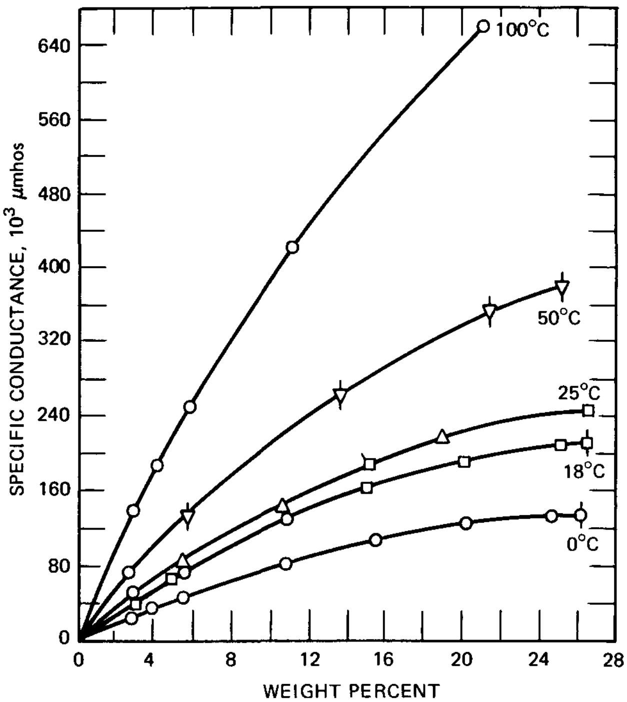


Fig. 4.58—Specific conductance of sodium chloride solutions for various temperatures. (From D M. Considine, *Process Instruments and Controls Handbook,* p. 6-170, McGraw-Hill Book Company, Inc., New York, 1957)

can be made with borosilicate glass, dense ceramic, and most plastics. Types 304 and 316 stainless steel, nickel, gold, and platinum structural parts and electrodes are suitable. The use of fluxes in the fabrication of electrodes should be avoided so that there will be no subsequent contamination by leaching of electrolyte material. Avoid contamination by eliminating such items as pipe-joint compounds and dopes. Thoroughly wash items after chemical cleansing or replatinization.

Temperature compensation is particularly important. As shown in Fig. 4.58, the conductivity of sodium chloride solutions is temperature dependent. At uniform concentration the conductivity increases about 2.5%/C°. The most common means of temperature correction is the inclusion in one of the bridge arms of an adjustable resistor calibrated in temperature units. The calibration is based on an average temperature coefficient of conductance. This technique is used where variations in temperature are small. A knob is set to correspond to the temperature reading at the conductivity cell. It is best to avoid frequent knob settings by maintaining a constant sample temperature external to the cell by the use of throttling valves. Automatic temperature-compensation methods can be used. A second conductivity cell dipping into an isolated sample forms the variable-resistance arm of the bridge. Changes in temperature will affect both the thermal cell and the measuring cell to the same extent, canceling out the temperature effect. Other automatic temperature compensators include bimetallic strip electrodes, expanding or contracting metallic bellows coupled to the variable resistor, a rising mercury column in a special thermometer to shunt the standard arm of the bridge, a resistance thermometer that automatically adjusts the standard arm resistance, and thermistors of high negative temperature coefficient.

(c) Sources of Error. Errors in conductivity measurements may be attributable to

1. Insufficient circulation. Sluggish response is a symptom.
2. Contaminated cell. Sluggish response to great concentration changes.
3. Need of electrode revitalization. Characterized by broad null point or stepwise change in recorder.
4. Electrical leakage in conductivity cell, characterized by erratic results.
5. Leaching of electrolytes. Characterized by drift toward higher conductance.
6. Temperature errors. Characterized by drifting when concentration is known to be constant
7. Reference temperature. Characterized by inability to obtain check reading from two different instrument systems even though each bridge and cell checks out against data.
8. Bridge calibration. Bridge will not check fixed resistor values. Check resistors in bridge circuit.
9. Change of cell constant. Characterized by inability to obtain correct instrument reading in known solution.

4-9.2 Special Sensors for Sodium-Cooled Reactors

There are a number of special sensors used in sodium-cooled power reactors. These are discussed in Vol. 2, Chap. 17. Most of the sensors are associated with monitoring sodium purity, e.g., the "plugging meter" that senses when impurities in the sodium have reached specific concentration levels, the electrochemical oxygen meter that monitors the activity of oxygen in the sodium coolant, the carbon meter that measures the carburizing potential in liquid sodium, etc. These are discussed in Chap. 17, Sec. 17-5.3, rather than in this chapter because of their rather specialized association with sodium-cooled reactors.

4-9.3 Special Sensors for Gas-Cooled Reactors

Gas-cooled reactors also require a number of specialized sensors. Sonic and acoustic thermometry have been noted elsewhere in this chapter. The critical importance of minimizing moisture in the primary gas coolant (analogous to the minimizing of oxygen in the sodium coolant in sodium-cooled reactors) has led to the development of moisture-sensing systems. These are discussed in Vol 2, Chap 18, Sec 18-3 3 In addition to moisture, coolant purity is also required This has led to the development of gas analyzing systems in the high temperature gas-cooled reactors These are also discussed in Sec 18-3 3

Chapter 5

Neutron-Flux Signal Conditioning

K J Moriarty, F H Just, and L J Christensen

5-1 INTRODUCTION

Neutron flux measuring channels in nuclear power plants are generally classified according to the neutron flux range involved

Start up channel	10^0 to 10^5 neutrons cm ^{2} sec ^{1}
Intermediate channel	10^4 to 10^{10} neutrons cm ^{2} sec ^{1}
Power channel	10^6 to 10^{10} neutrons cm ^{2} sec ^{1}

The channels successively overlap one another (Fig 5 1) to provide continuous measurements of the neutron flux level at all power levels (see also Chap 2 Sec 2 2 3)

Control circuits are provided in conjunction with one or more of the channels Reactor power is varied by the action of circuits associated with the neutron flux measuring equipment High power operation is controlled with the

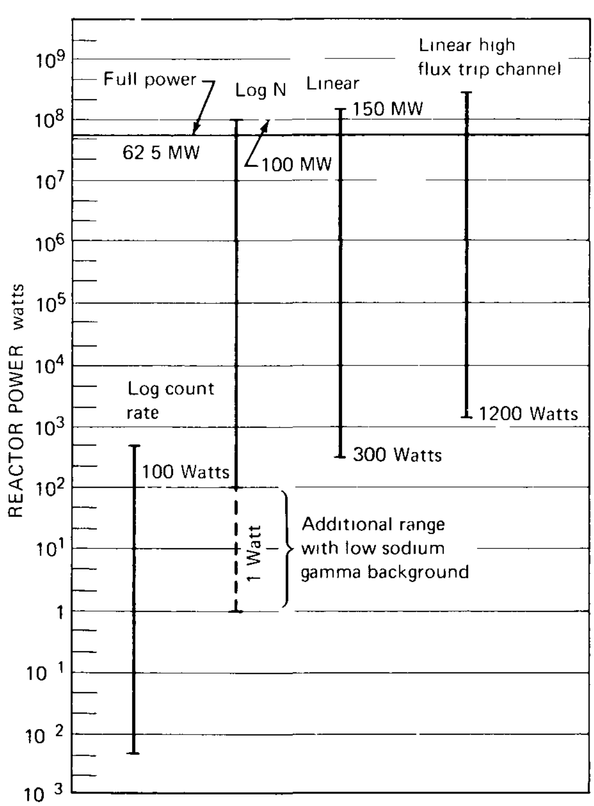


Fig 5 1—Nuclear instrument range chart

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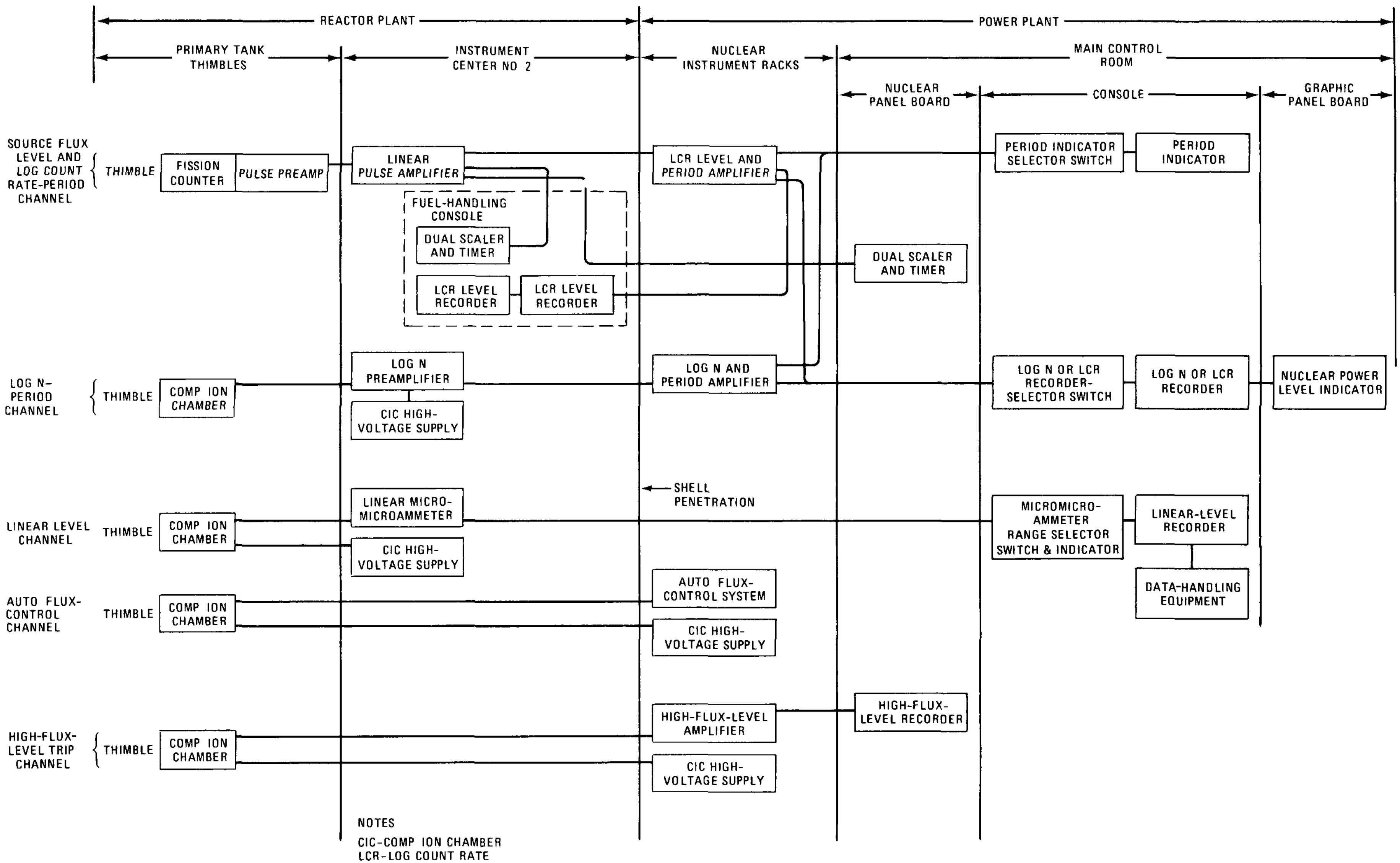


Fig. 5.2—Nuclear-instrumentation block diagram.

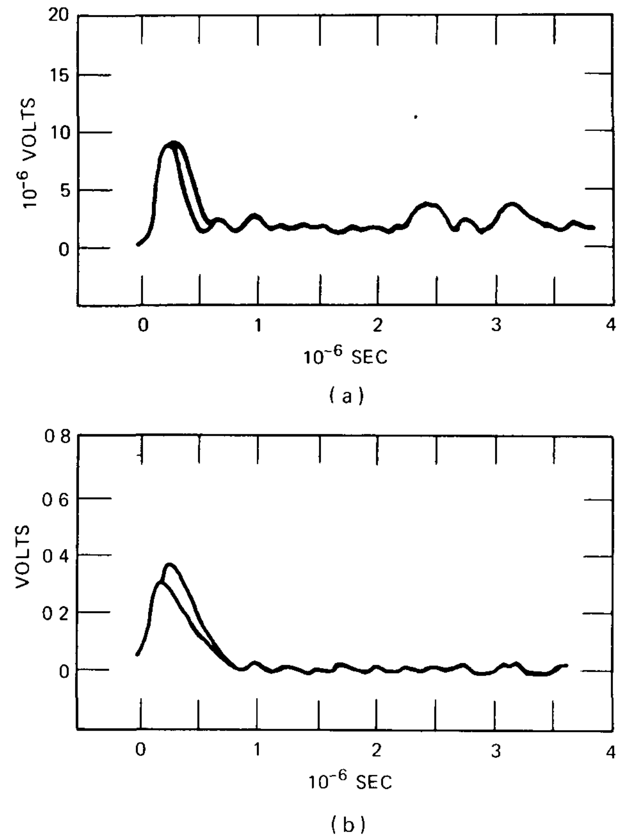


Fig. 5.3—Typical pulse shapes. (a) Background noise and low energy particles. (b) Preamplifier output pulse.

power channel. The neutron-measuring systems must be capable of providing alarm set points and annunciator units to warn the reactor operator.

In conjunction with the alarm features are the reactor-protection mechanisms. When an alarm set point is exceeded, appropriate automatic action must be taken to reduce the reactor operating power to a safe level. The type of protective circuits and action (see Chap. 12) varies from reactor to reactor, from a simple reduction in reactivity (cutback) to a scram where essentially all the negative reactivity available is inserted.

The neutron-measuring equipment and circuits must be designed to minimize reactor downtime caused by unit maintenance, component failures, and spurious noise alarms. Redundancy and independent systems are used for each power-level channel.

5-2 START-UP CHANNEL

5-2.1 Introduction

A typical start-up channel, shown in block form in Fig. 5.2, consists of the following major components: (1) sensor, (2) pulse amplifier, (3) high-voltage power supply, (4) amplifier–discriminator unit, (5) count-rate meter with control functions, and (6) readout equipment.

5-2.2 Sensor

Because the neutron flux in a shutdown reactor is low, the output of the neutron detector (see Chap. 2) is a series of pulses proportional to the neutron flux resulting from a neutron source in the reactor. The detector must have a high neutron sensitivity with a very low sensitivity to gammas.

The fission chamber is widely used because of its inherent ability to discriminate against gamma-generated signals. A fission chamber 2 in. in diameter and 12 in. long typically will have a neutron sensitivity of 0.7 (count/sec)/(neutron cm^{-2} sec^{-1}) with a gamma sensitivity of 4×10^{14} amp/(R/hr). The neutron signal generated in the fission-chamber circuit is of the order of 100 μV with a pulse width of approximately 0.5 μsec. The gamma pulses produced in the chamber are smaller in amplitude. A typical ratio of gamma to fission pulse height is of the order of 10^{-2} to 1. This ratio makes successful discrimination possible.

Gamma pulses generated in the chamber can become a problem when the detector is located in a gamma field of 5×10^4 R/hr or more. A pulse pileup in the discriminator circuit causes gamma pulses to be counted as neutrons. Special techniques, such as pulse clipping or reshaping of the pulses, are used to minimize and protect against this. Typical pulse shapes are shown in Fig. 5.3.

5-2.3 Pulse Preamplifier

(a) Introduction. The pulse generated in the sensor must be amplified for transmission and for driving standard counting electronics. The ideal pulse preamplifier must have high gain, wide bandwidth, stability, and low noise characteristics.

Until recently fission sensor preamplifiers used vacuum tubes and were located as close to the sensor as possible. In the last few years, good-quality solid-state preamplifiers have replaced the vacuum-tube units. There are advantages and disadvantages with both types.

A vacuum-tube preamplifier can be placed near the fission detector, i.e., in the same radiation field as the sensor. However, radiation damage to the preamplifier components decreases their life and increases spurious noise so that maintenance is required. Vacuum-tube preamplifiers produce a large output pulse, ideal for counting equipment, but the vacuum tubes deteriorate with steady use and must be replaced regularly or suffer loss of gain. Generally, substantial maintenance is required per hour of successful operation.

Solid-state preamplifiers, usually charge-sensitive, can be located at considerable distance (up to 90 ft) from the sensor but, in any event, must be out of the radiation field. This makes maintenance more convenient and increases channel availability. However, this arrangement is susceptible to noise pickup in the cable between the sensor and the preamplifier. The output pulse from solid-state preamplifiers, typically 10V, is generally smaller than that from a

vacuum-tube preamplifier Because of the lower signal output, the counting equipment must be capable of accepting a low-level signal and processing it for use in the readout and control equipment that follows it in the channel

(b) Vacuum-Tube Preamplifier. A vacuum-tube preamplifier is shown in Fig. 5.4. The amplification is provided by the four RCA 7586 (nuvistor) vacuum tubes The preamplifier has a gain of 30, a rise time of 5×10^{-8} sec, and a fall time of 2×10^{-7} sec Because vacuum tubes are used in this preamplifier, it can operate in a radiation field. The tube-filament heaters are d-c powered to minimize a-c noise pickup The capacitors are ceramic, both for improved temperature stability and for reduced susceptibility to radiation damage Capacitor C1 is used to isolate the detector high voltage from the preamplifier and to couple the sensor pulse to the preamplifier input circuit. The life expectancy of this preamplifier is approximately 600 hr in a 10^6 R/hr gamma flux (0 5- to 1 5-MeV gammas)

(c) Solid-State Preamplifier (Current Input). The solid-state preamplifier shown in Fig 5 5 is a voltage amplifier, as opposed to the charge-sensitive amplifier to be discussed in the next subsection The active elements are transistors The input stage is a grounded-base transistor, which has low input impedance, high output impedance, wide bandwidth (high frequency), high bias stability, and good voltage gain.

The interconnecting coaxial cable between the sensor and the preamplifier is terminated into its characteristic impedance. A resistor in series with the emitter is selected to do this matching. This circuit eliminates cable ringing or reflections and provides a low impedance path for the current pulse generated in the sensor The pulse is capacitance-coupled to the input stage, and the capacitor also blocks the sensor d-c voltage The input current pulse from the detector is converted in transistor Q1 to a voltage pulse The remainder of the preamplifier is a high-gain standard operational amplifier with feedback. The preamplifier can amplify pulses at a repetition rate of 10^6 Hz or 10^6 neutrons/sec Typical preamplifier characteristics are

Gain	0 5 volt/μA
Input impedance	50 to 120 ohms
Output	$\pm$3 volts into 50 ohms
Rise time	$<$5% for 200-nsec pulse width
Power	$\pm$15 volts at 40 mA

As noted above preamplifiers mounted at a distance (20 to 40 ft) have noise problems associated with cable pickup Every effort must be made to shield against stray noise in the form of electrostatic or electromagnetic voltages between the sensor and the preamplifier

In summary, the principal advantages of locating the preamplifier at a distance from the sensor are (1) sensor cooling is not so critical, (2) maintenance is simplified, and (3) system availability is increased.

(d) Solid-State Preamplifier (Charge-Sensitive). A third type of preamplifier is a charge-sensitive unit (Fig. 5.6). This preamplifier is a fast-rise-time charge-sensitive preamplifier with dual-polarity output The input signal is coupled to the pulse-shaping and amplifier input module A1 by capacitor C4, which blocks the high voltage. A Shockley diode connected to ground at the input to amplifier A1 protects the input from momentary breakdown of the detector or cable shorts. The output of A1 feeds a cable driver with dual-polarity output

Amplifier module A1 is a special fast-pulse amplifier connected in a charge-sensitive configuration. This is accomplished by connecting a stable small-value capacitor from the amplifier output back to its inverting input. This negative feedback will attempt to keep the amplifier input very near zero volts, thus making it a virtual ground.

Incoming charge is collected on the input plate side of the feedback capacitor, C_f This will cause some voltage shift at the input of A1 and, as a result of its inverting gain, a much larger inverted shift at the output Negative feedback action through C_f will restore the input to its normal zero-volt level. The magnitude of the output voltage shift is directly proportional to the amount of charge received, $V = Q/C_f$

It is very important that the amplifier have a very short rise time with respect to the incoming pulses, otherwise the virtual ground cannot be maintained, and charge may be diverted to ground through shunt protective devices or other circuit elements.

When only the feedback capacitor, C_f, is used, the circuit has become a charge-to-voltage converter. However, this configuration is limited by the ultimate saturation of its output as more and more charge is accumulated. For this reason the negative feedback resistor, R_f, has been added to discharge C_f between incoming input pulses The parallel combination of these two components, C_f and R_f, forms the clipping-time constant of the preamplifier, $T = R_f \times C_f$ This clipping time also serves to provide the best pulse shape required by subsequent circuits

The output of A1 is fed through C5 to Q1, which provides two outputs of opposite polarity by means of the output driver amplifiers. These driver amplifiers consist of parallel-connected Q2–Q3 and Q4–Q5 transistors that function as emitter followers to provide low output impedance suitable for driving any reasonable length of terminal coaxial cable

5-2.4 Log Count-Rate Meter

The log count-rate meter (LCRM) is a pulse-counting component used to convert input pulses from the detector and preamplifier analog signal for use in control components The LCRM has five basic functions (1) pulse-height discrimination, (2) count-rate indication, (3) period indication, (4) scaler output signal, and (5) adjustable alarm output Each of these functions is discussed below.

Figure 5.7 is a block diagram of an LCRM. The unit has all the items listed above along with a built-in calibrator,

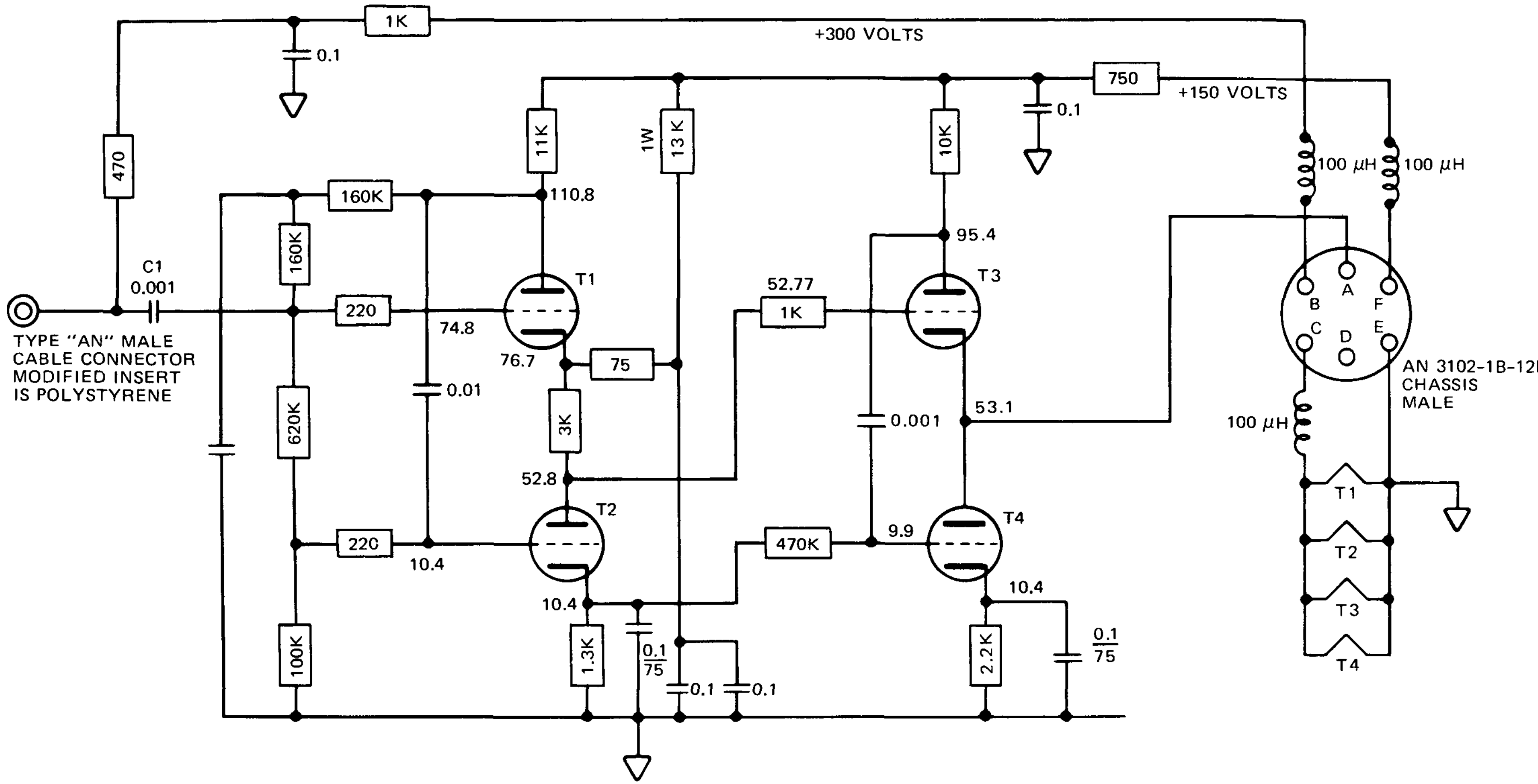
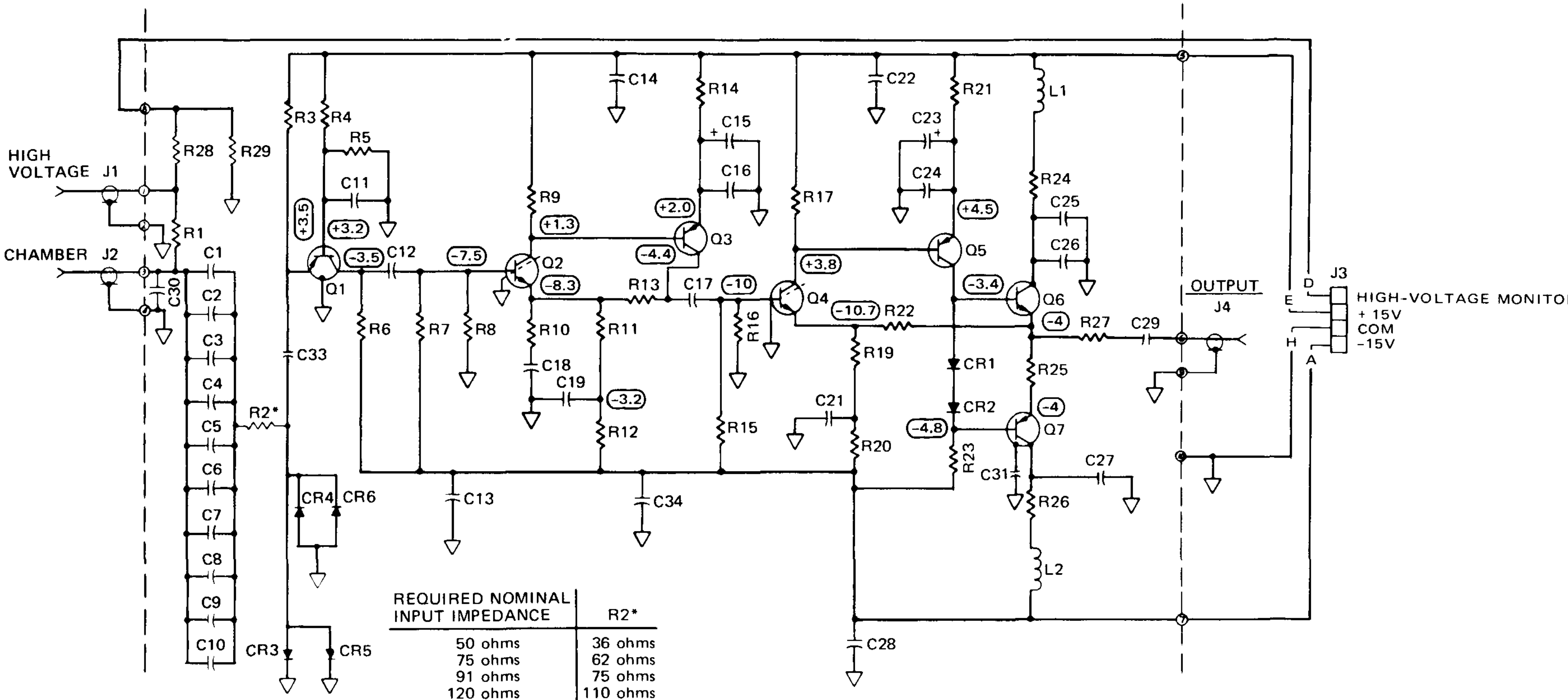


Fig. 5.4—Vacuum-tube preamplifier.



REQUIRED NOMINAL INPUT IMPEDANCE	R2*
50 ohms	36 ohms
75 ohms	62 ohms
91 ohms	75 ohms
120 ohms	110 ohms

Fig. 5.5—Solid-state pulse preamplifier.

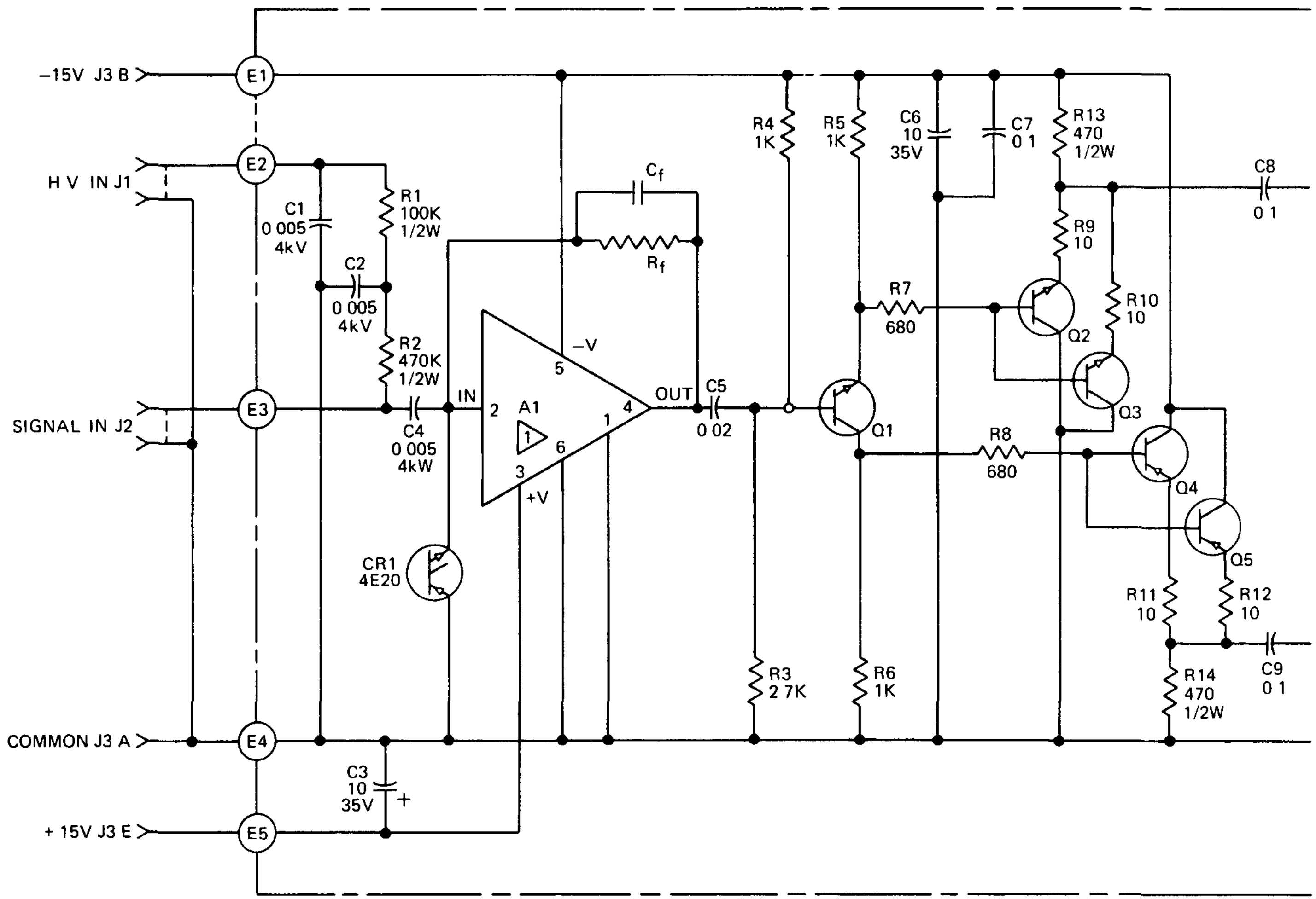


Fig. 5.6—Charge-sensitive preamplifier.

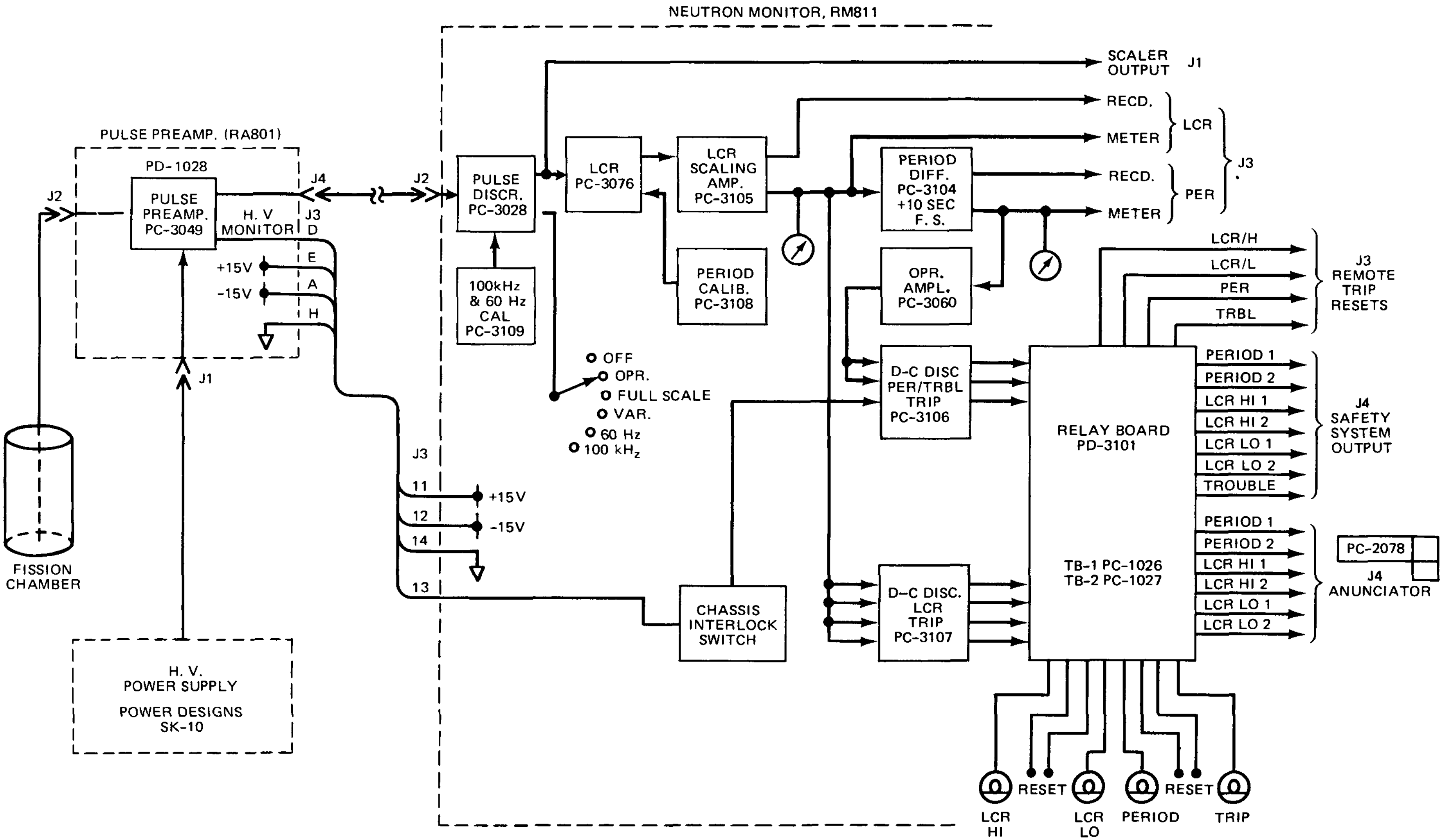


Fig. 5.7—Neutron-pulse monitoring system.

power supply, and test source. The unit uses all solid-state elements for improved reliability and low maintenance

(a) Pulse-Height Discriminator. The solid-state pulse-height discriminator shown in Fig 5.8 performs three functions (1) provides for pulse-height discrimination, (2) reshapes pulses for counting, and (3) provides a scaler output signal The heart of the pulse discriminator is the dual n–p–n transistor and the potentiometer R3. Resistor R3 is a 10-turn potentiometer mounted on the front panel of the LCRM. Resistor R3 provides a d-c bias on one-half of the dual n–p–n transistor. This turns this half of the transistor on while the input half is off. A pulse applied to the input with amplitude greater than the d-c bias turns the input transistor on, forces the biased half off, and generates an output pulse for the counting circuits A pulse of height less than the d-c bias has no effect on the output and is thus uncounted. The discriminator then allows only pulses of amplitude larger than a set threshold to be counted, thus providing a convenient means for eliminating low-amplitude noise pulses generated in the sensor and cable.

The pulses from the discriminator are reshaped in a trigger circuit so that each pulse has the same height and width, essentially a square wave. Transistor Q9 provides a pulse output for a scaler, and transistor Q8 provides a pulse output for the LCRM counting circuitry.

(b) Count-Rate Indication. Figure 5.9 shows a Cook–Yarborough log circuit. The function of this circuit is to convert the constant-width and constant-height pulses into an analog signal. Since five or six decades of counts are to be covered by the LCRM, the circuit provides a logarithmic signal.

The diode pump is composed of CR5 to CR25, C7 to C27, and resistor R10 to R20. The purpose of the diode pump is to convert from a count rate to a d-c voltage. This is accomplished in the following manner. Consider components R10, C7, CR4, CR5, and CR6. Component CR6 is a pulse-coupling capacitor Component CR4 is a positive-voltage clipper which prevents a positive voltage from appearing at the cathode of diode CR5 Diode CR5 and capacitor C7 form a low-impedance charge circuit for negative pulses. After the negative pulse has passed through CR5, the diode prevents C7 from discharging back through CR1 or the input circuit Hence the capacitor C5 must discharge through resistor R10. The time constant is then R10 times C5. Should a second pulse follow the first pulse rapidly, the capacitor will not have time to discharge, and, as a result, the input to the d-c amplifier through R10 is essentially a d-c or rectified a-c voltage.

There are 11 such circuits with various time constants, varying from 40 sec to 8 msec. Resistors R10 to R20, C7 to C27, and CR5 to CR25 serve the same purpose.

The pulses are thus converted to a d-c voltage output proportional to different count rates. The d-c outputs for high count rates are provided for by the shorter time-constant circuits (C27 and R20), whereas the circuits with long time constants provide a voltage output for both low and high count rates.

The output of the diode pump is a d-c voltage amplified in the scaling amplifier. The output of the scaling is properly sized for meter operation and for a potentiometric recorder output The analog signal from the scaling amplifier is also fed to a differentiator circuit for period and to the level alarm circuits.

(c) Period Indication. The reactor period, T, is the reciprocal of the fractional change in the neutron population per unit time (see Chap 1, Sec 1-3.1)

$$\frac{1}{T} = \frac{dn/n}{dt} = \frac{dn/dt}{n} = \frac{d(\ln n)}{dt} \tag{5 1}$$

where n is the neutron density, ln is the natural logarithm, and t is time

Figures 5.10 and 5.11 show two circuits used to obtain a period signal from the rate of change of the log-count-rate (LCR) signal The circuit shown in Fig. 5.10 uses operational amplifier A2 with feedback to achieve the period signal Operational amplifier A1 serves only as a circuit calibrator and to provide for a test ramp signal to A2. The output signal from the diode pump is supplied to A2. Amplifier A2 differentiates any input-signal changes in level and provides an output signal for the time rate of change of the input signal

The circuit shown in Fig. 5.11 is similar in function to that shown in Fig. 5.10. The circuit is essentially an operational amplifier with a high-impedance input, FET A8, a resistive feedback element, R29, and an input capacitor, C12. The output voltage is then of the form

$$e_0 = Rk = RC\frac{de_i}{dt} \tag{5 2}$$

where de_i/dt is a measure of the time rate of change of the neutron flux When dn/dt is constant, dT/dt is unity (assuming T and t to be measured in the same units). The output voltage produced by the period amplifier will be some base level to keep the meter reading up scale A change in dn/dt produces a change in period-amplifier output

The output from the period differentiator drives an operational amplifier for proper signal scaling for the meter, recorder, and period-trip (alarm) board

(d) Scaler Output. Associated with the discriminator in Fig. 5.8 is a pulse output stage used to drive a pulse scaler or counter. (The scaler itself is discussed in Sec. 5-2.6.) The pulse-generating equipment consists of the circuit described in Sec (a) above and also transistor Q9. Transistor Q9 is used to isolate the scaler output from the LCR circuit

(e) Alarm Unit. The alarm unit provides a signal at selected and adjustable values, such as low count rate, high

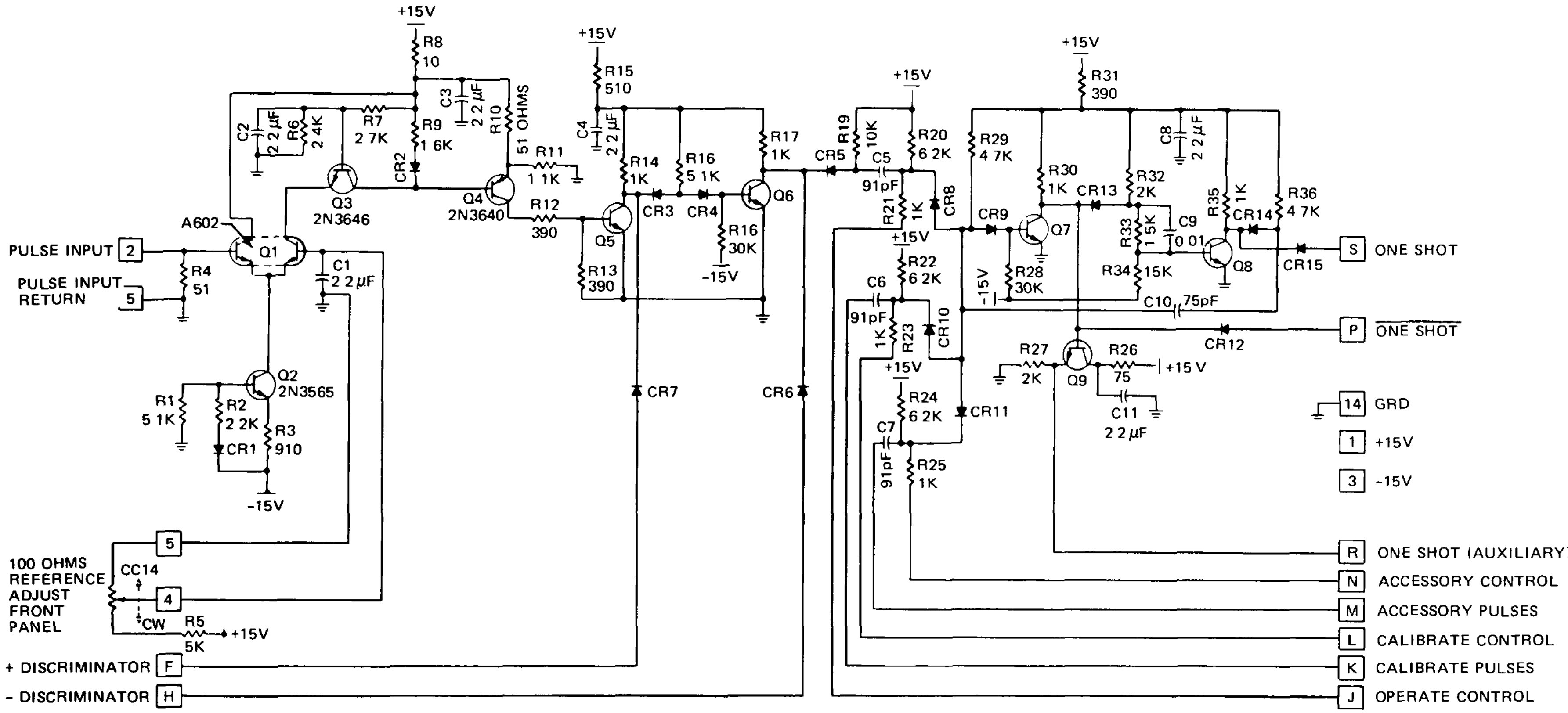


Fig. 5.8—Pulse-height discriminator

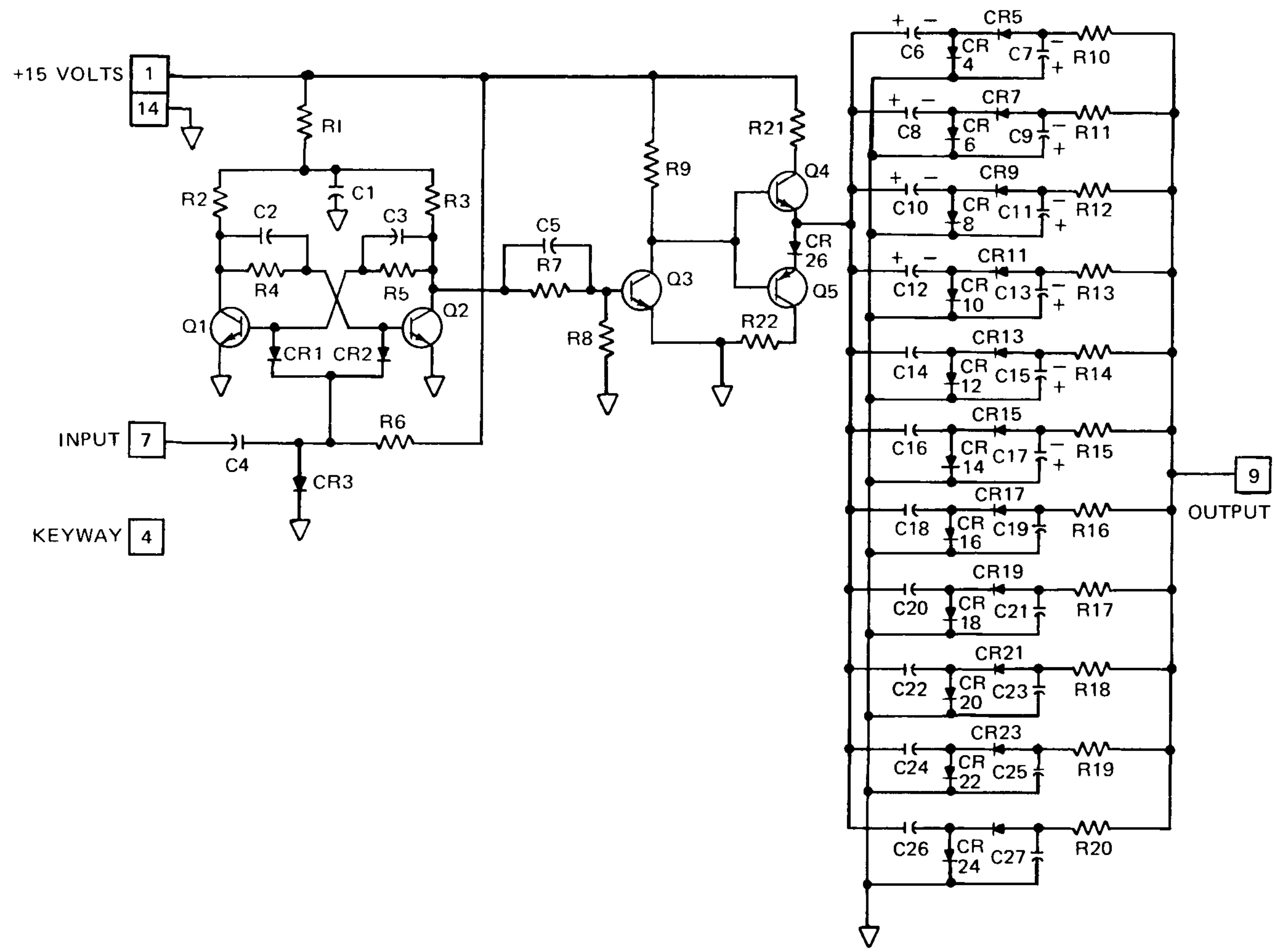


Fig. 5.9—Printed log diode circuit board

count rate, period, or loss of chamber high voltage A solid-state alarm (trip) unit is shown in Fig 5.12 Relays R1 and R2 are deenergized when the set point is exceeded. Transistors Q3 and Q7 must change from the saturated to the unsaturated (off) condition. The output of Q1 or Q2 will change any time the input-signal voltage levels exceed the set-point voltage as determined by potentiometers R28 and R29.

Each alarm function has two identical trip amplifiers similar to the one shown. The redundancy is necessary to decrease the probability of a failure in the operation of the alarm unit This is very important for reactor protection since the output transistor Q3 or Q7 could short between collector and emitter, in which case the relay would not deenergize (fail to trip) when the set point was exceeded. The contacts of the trip relays are connected in series so that either relay deenergizing will cause an alarm

5-2.5 Interconnecting Cables and Grounding

Proper cables must be used for interconnecting nuclear instrumentation to reduce noise and to transmit the best possible signal to the readout equipment. See Chap. 10 for additional information on grounding, shielding, and selection of cables

Noise-free cables must be used in the start-up instrumentation Noise pulses will be amplified and counted as neutron pulses. Besides the inaccuracies in counting, noise bursts can cause period and level scrams at low reactor power levels

When a vacuum-tube preamplifier is used, the sensor and preamplifier are usually connected together as a unit or with a few feet of coaxial cable The cable used must have an impedance that matches the preamplifier input. The signal cable used between the vacuum-tube amplifier and the LCRM should be coaxial and match the impedances of the two units If the cable is routed through high-noise areas, a triaxial cable should be used with the outer braid connected to ground.

Power-supply cables between the power supply and vacuum-tube preamplifier should be shielded conductors to minimize the noise level The power-supply ripple voltage should not exceed 10 mV for satisfactory operation of the sensor and attached preamplifier.

The greater the distance between the detector and the preamplifier, the more important is the cable quality. For

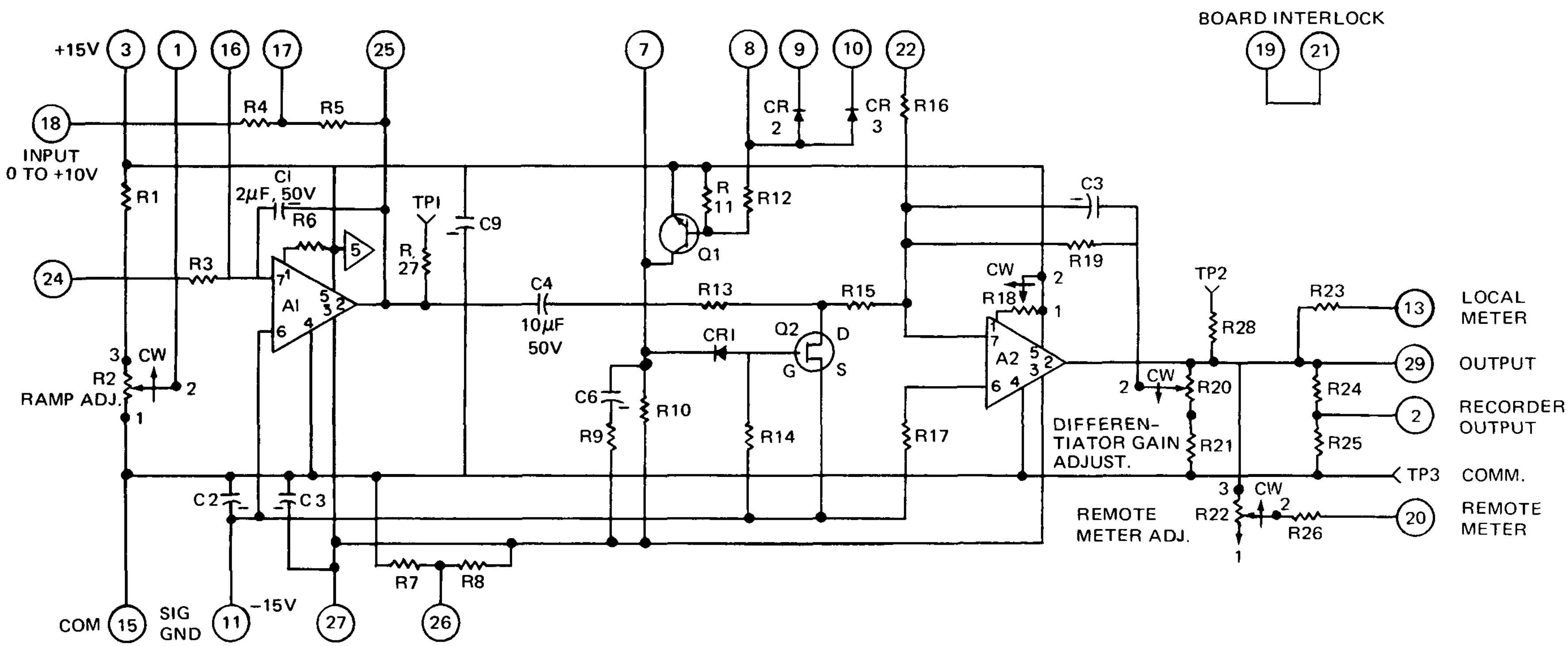


Fig. 5.10—Period rate circuit.

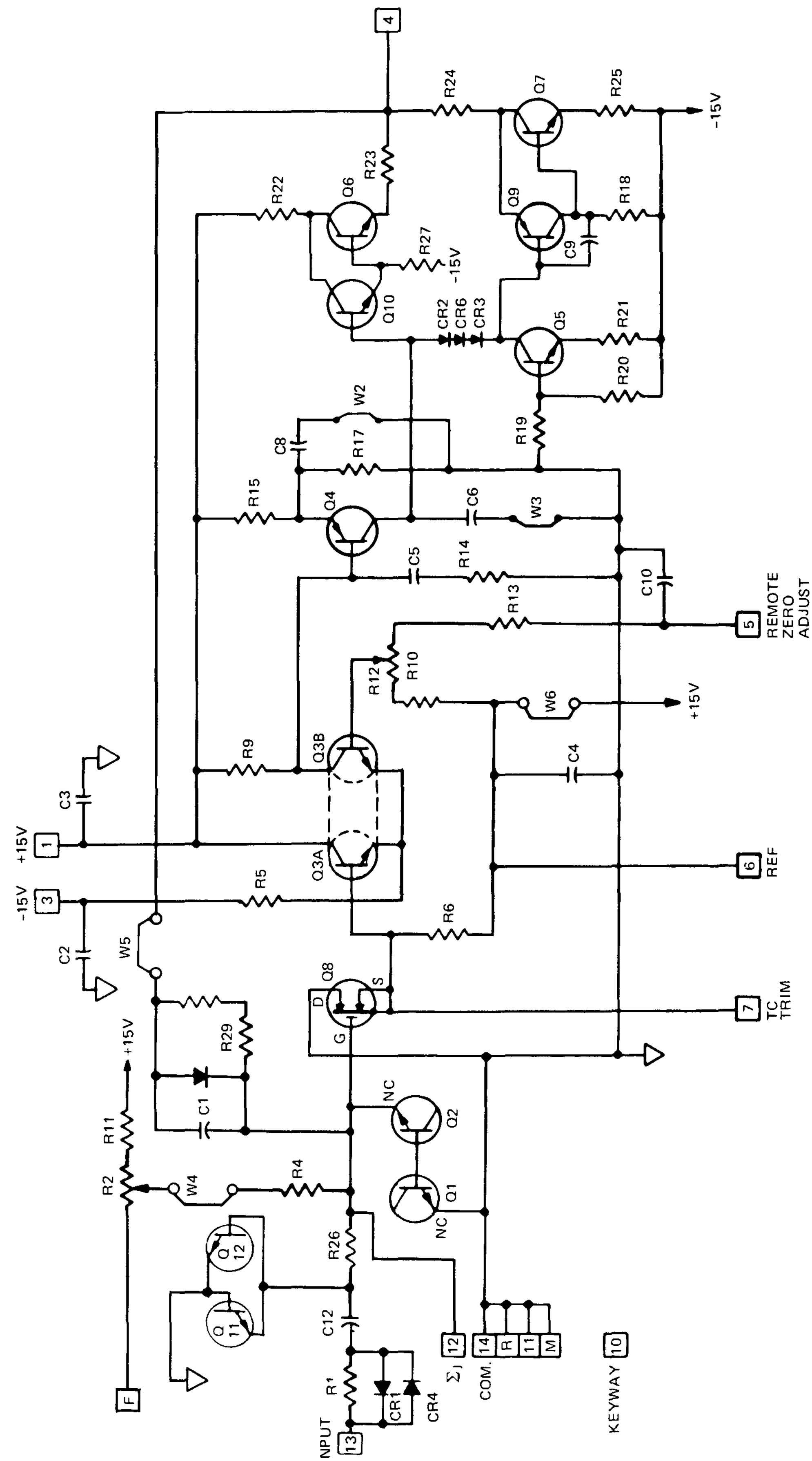


Fig. 5.11—Period differentiator.

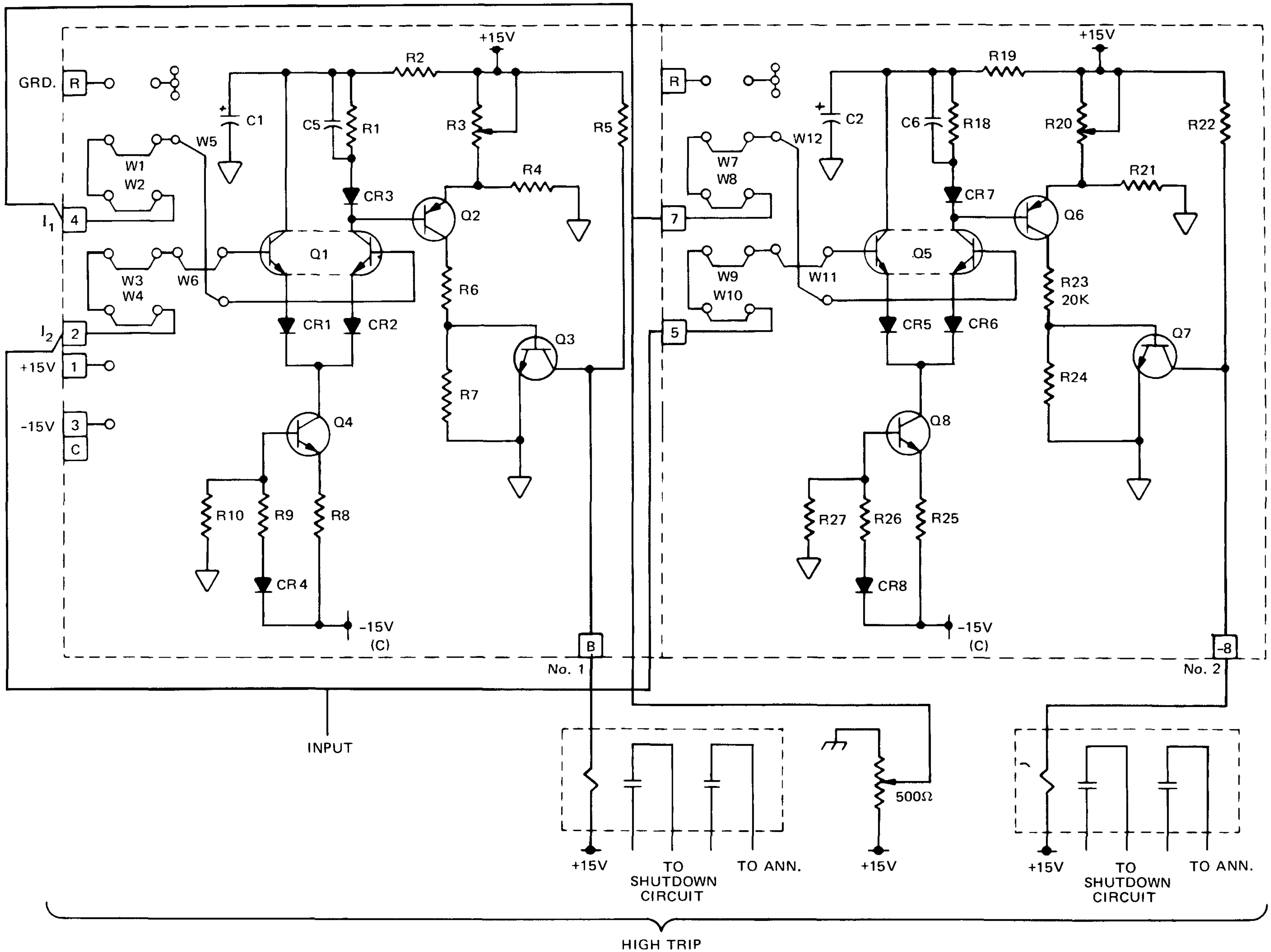


Fig. 5.12—Solid-state alarm (trip) circuit.

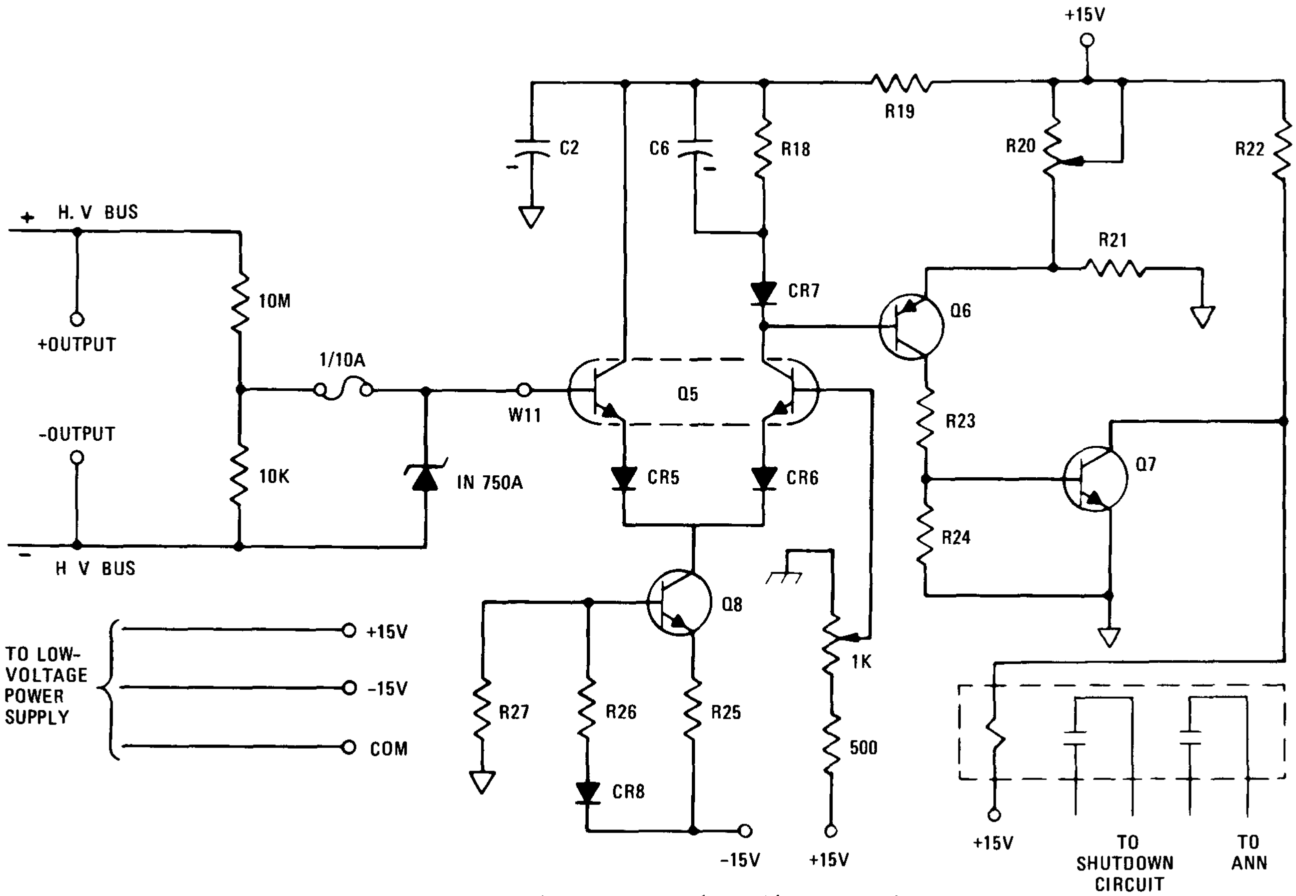


Fig. 5.13—High voltage monitor with variable set-point alarm

solid-state preamplifiers the importance of the cable cannot be overemphasized. There is one positive procedure for noise reduction complete the installation, and, using one or more of the methods outlined in Chap. 10, experiment until the noise has been reduced to a minimum. Neutron sensors for use at high temperatures are under development Cables and connectors for use with these sensors must operate at high temperature without producing noise pulses Radiation-resistant cables should be used to increase the time between replacement, to reduce maintenance costs, and to improve availability. Cables and connectors are available for high-temperature use, but extreme care must be exercised in their use Avoid use of high-temperature components if at all possible, they are subject to changes in resistance which adversely affect both signals and high-voltage cables

A triaxial cable should be used to minimize the noise introduced between the sensor and solid-state preamplifier The outer braid of the triaxial cable should be tied at both ends to the inner braid. The impedance of the cable must match the input impedance of the preamplifier to reduce pulse reflections on the cable.

5-2.6 Power Supplies for Detectors and Electronic Equipment

(a) High-Voltage Power Supplies. Solid-state power supplies with excellent characteristics are available for powering the nuclear detectors Solid-state power supplies reduce the package size, the heat generated, and the maintenance time Many power supplies are capable of supplying power to two or more detectors connected in parallel When power supplies are used to provide for two or more detectors, the detectors must be isolated from ground. Also, note that on a common-failure basis the units are not independent and cannot be used as redundant units in a shutdown circuit. It is desirable that the loss of one power supply will not cause a scram.

The high-voltage power supplies must have a voltage monitoring circuit or an output voltage proportional to the high-voltage output which can be used to monitor the high voltage The high-voltage monitor is used to give an alarm when the high voltage drops below a predetermined value Figure 5.13 shows a high-voltage monitor unit with a variable set-point alarm. The 10-turn potentiometer dial reading corresponds to the trip voltage

The high-voltage power supplies should have short-circuit protection. Protection against voltage surges at the input is also desirable.

(b) Low-Voltage Power Supplies. Power supplies used in the counting equipment must have excellent regulation and stability. The low-voltage supplies should have internal short-circuit protection to prevent supply damage due to overcurrent demands from the unit. Because the counting equipment is of solid-state design, it is important that the

voltage supplied to the printed circuit boards be limited below a value that would cause component damage.

Power supplies with built-in protection are commercially available and should be specified when ordering the nuclear equipment. An inexpensive method of providing overvoltage protection is shown in Fig. 5.14. The Zener diodes prevent the voltage from exceeding a given value. Excessive current drawn from the supply through the Zener diodes will cause the fuse to open before circuit damage has occurred.

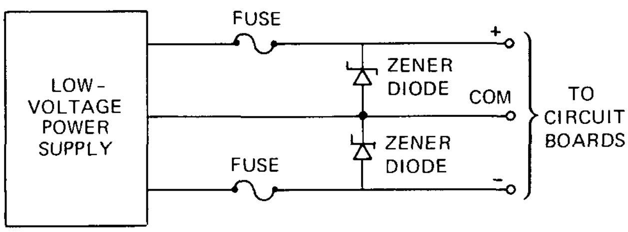


Fig. 5.14—Printed-circuit board power-supply regulator.

5-2.7 Calibration and Checkout Control

(a) Log Count-Rate Meter. The LCRM has a count-rate circuit for control and readout, it will also have period and level circuits that must be calibrated periodically to ensure proper alignment of the unit

The counting circuits can be checked by using a built-in oscillator to provide pulses at two or more repetition rates to the discriminator output The frequency of the oscillator can be verified by using scaler output and a scaler The meters and recorders can then be calibrated

The period circuits can be calibrated from a built in ramp generator The ramp generator provides signals that increase linearly with time and at various rates The signal is applied to the operational amplifier that feeds the differentiator The period circuit differentiates this signal and provides a constant period indication for calibration of the readout circuits This also provides a means for setting the period trip level.

(b) Channel Checkout. Some means should be provided at the preamplifier input for checking and calibrating the complete channel Ideally, a neutron source inserted near the neutron sensor would provide complete system checkout. Since this is generally not possible, the system is checked from the preamplifier A calibrated pulser provides the input signal to the preamplifier, and meter, recorder, and scaler readings are verified Level and period trips are also verified

5-2.8 Control and Safety Circuits*

A start-up channel system is shown in Fig 5 15 The system consists of independent channels for control and local indication but with a common recorder for switch selection of a desired readout channel. The three channels provide the redundancy necessary to satisfy safe operation of the reactor and also provide for sufficient channels so that loss of a single instrument need not result in lost reactor operating time. The shutdown circuits associated with the three channels are arranged in a two-out-of-three shutdown logic, i.e., two instruments must trip before scram is initiated. The initiating shutdown circuit is shown in Fig 5.15

*See also Vol 2, Chap. 12.

5-3 INTERMEDIATE POWER CHANNEL

5-3.1 Introduction

An intermediate power channel, shown in Fig 5.16, consists of a compensated ionization chamber (CIC), a dual-voltage power supply, a log N unit, and readout equipment Each of these units is discussed below.

5-3.2 Ionization Chamber and Power Supplies

(a) Sensor. Compensated ionization chambers are used as neutron sensors in the intermediate-range channel. Ionization chambers operate in the mean-current mode as opposed to pulse counting, which is used at lower fluxes (see Chap. 2, Sec 2-2.3). The CIC produces a current proportional to the sum of the neutron and gamma fluxes, but, through a compensation chamber, a current is produced that cancels about 95 to 99% of the gamma current (see Chap. 2, Sec 2-2.2).

(b) Power Supplies. The requirements of the power supplies for the intermediate-range power channels are essentially the same as those described for the start-up channel in Sec. 5-2.6, the only difference is the requirement of the CIC to have both positive and negative voltages. The positive high voltage is 600 to 1000 volts, whereas the negative high-voltage requirement is from 100 to 1600 volts.

High-voltage monitors must be provided to monitor and alarm on loss of positive high voltage These alarms, as described previously, are connected to the shutdown circuits.

5-3.3 Interconnecting Cables and Grounding

Because the chamber signal generated in the CIC is a current and not a pulse, noise generated in the cable between the chamber and log N amplifier is not nearly so critical as that with a pulse channel Noise pulses are suppressed in the log N amplifier—integrator circuits No electronics are installed near the CIC in the high-radiation area. If cables with high radiation resistance are used, the operating time between cable changes can be increased.

The output signal produced in the CIC varies from about 10^{-15} to 10^{-2} amp Ground loops between the detector and the log N amplifier should be avoided in order to reduce stray signal pickup. The detector is insulated

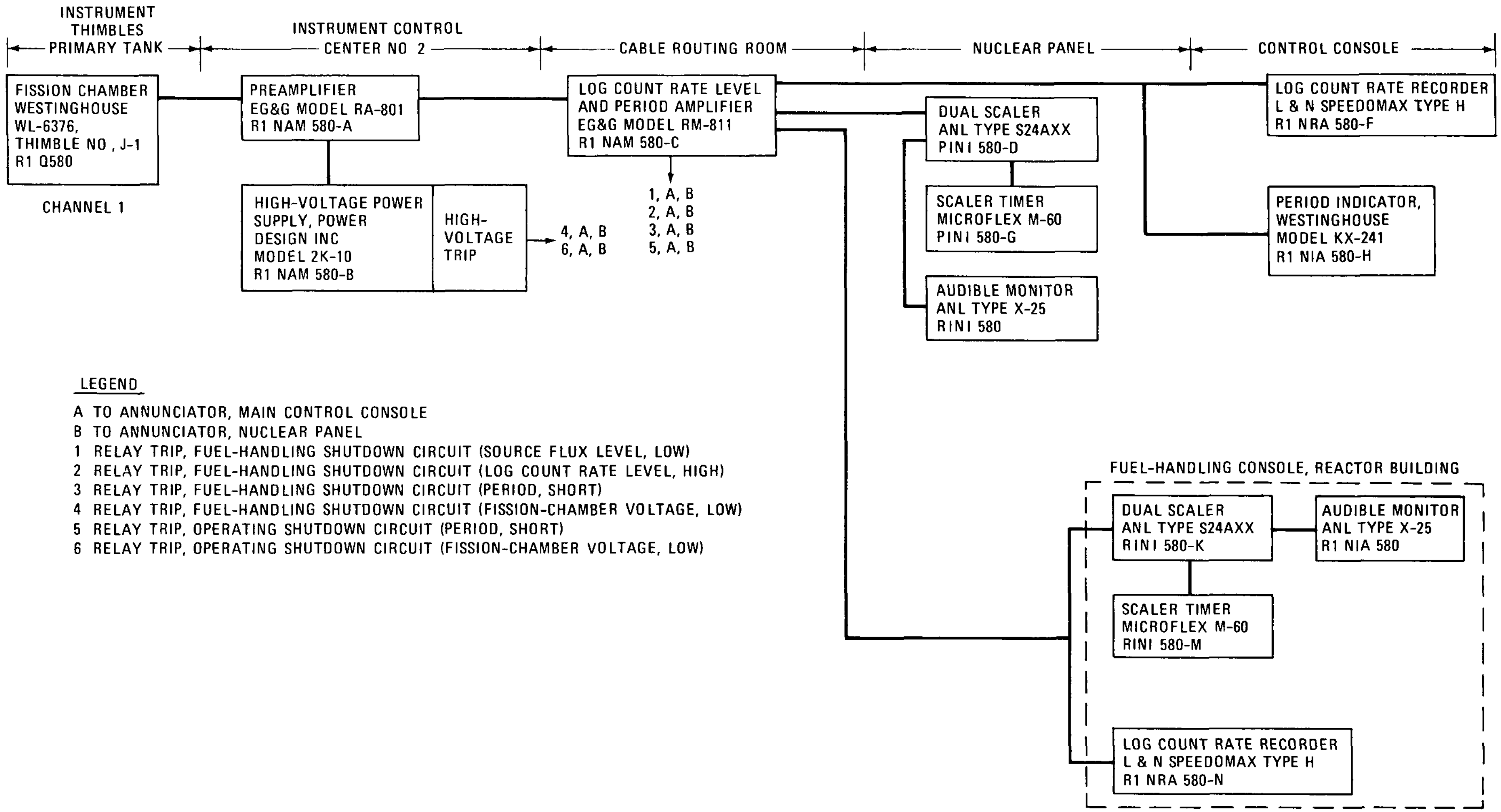


Fig. 5.15—Block diagram of source range channels 1, 2, and 3

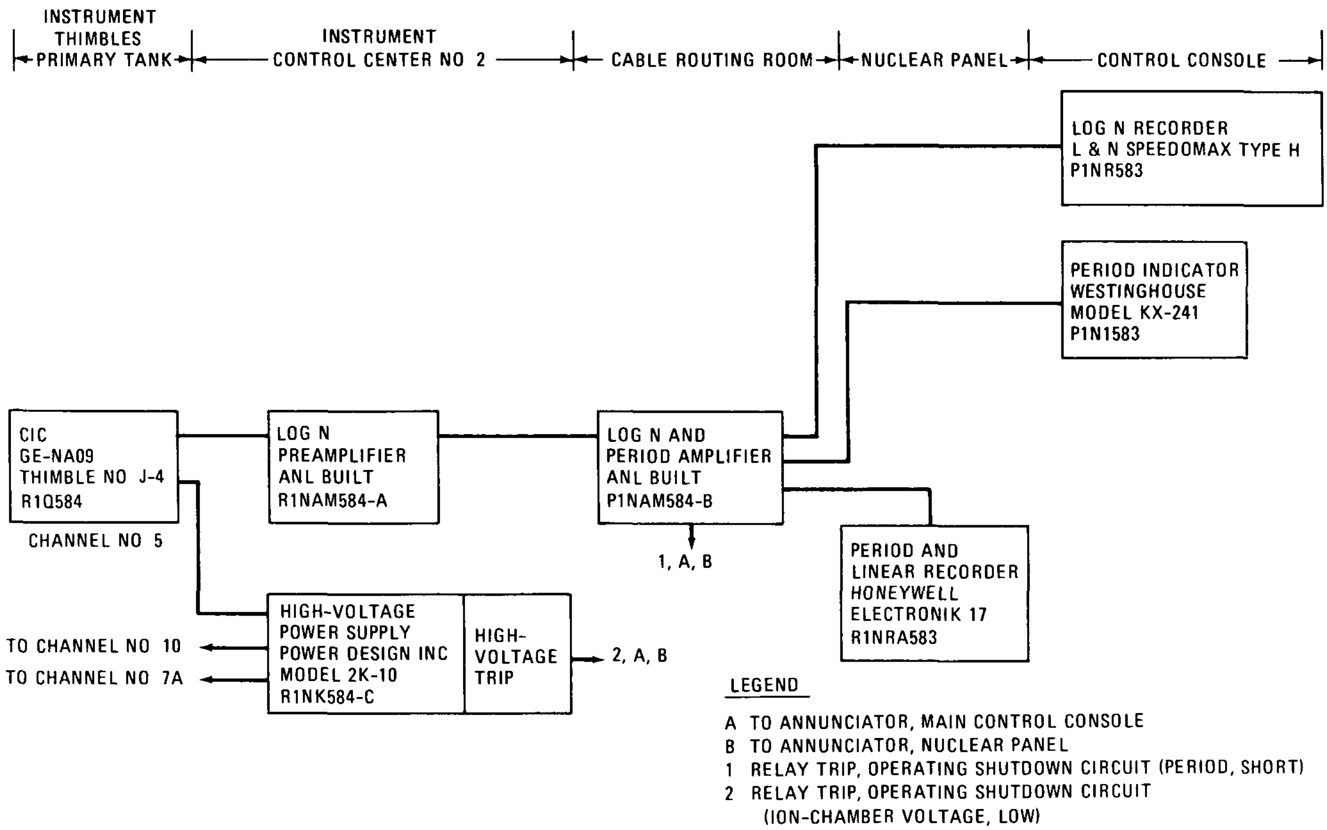


Fig. 5.16—Block diagram of intermediate-range channels 4, 5, and 6.

from the detector thimble by ceramic standoff insulators, which are impervious to radiation damage. The shields of the coaxial cables are connected to the chassis, which should be grounded to nuclear instrumentation ground at one point, effectively reducing or eliminating the ground loops (see Chap. 10).

5-3.4 Logarithmic Amplifier

A block diagram of a logarithmic amplifier (log N) is shown in Fig. 5.17. The log N amplifier has two essential circuits for signal conditioning. The first is the log section, which converts the detector signal to a logarithmic output The second circuit is the period differentiator circuit

The input signal is biased to range over nine decades. So that this signal can be continuously monitored, it is converted to a log signal in the log amplifier circuit The circuit consists of an operational amplifier with an active feedback element, namely, the grounded-base transistor. The circuit can be described by the following equation

$$e = -E_0 \log \frac{i}{I_0} \qquad (5\ 3)$$

where e = output voltage

E_0 = offset voltage of the operational amplifier

i = input current from the CIC

I_0 = offset current of the operational amplifier

The output voltage then changes by a factor of 9 for an input current change of nine decades

The log N amplifier circuit is followed by an amplifier that conditions the signal for the meter and recorder outputs and provides a signal for the period differentiator.

The operation of the period differentiator circuit is the same as that for the circuit described in Sec 5-2.4(c) The output of the period differentiator circuit drives a meter and recorder and provides a signal for the period trip circuit. The period trip circuit alarms when the preset time value is exceeded. The trip circuit is described in Sec 5-2.4(e).

5-3.5 Calibration and Checkout

The log N amplifier shown in Fig 5.17 has two built-in calibrators for checking out the system. The first is a current source with several fixed ranges used to calibrate the log N circuits, meters, and recorder. The second calibration device is a ramp generator for checking the period-differentiator circuit, meter trip, set point, and recorder The period calibrator is described in Sec 5-2 7 These two calibrators provide a means for checking the entire system.

5-3.6 Control and Safety Circuits

The log N period amplifier provides an alarm (trip) when the period exceeds the set-point value The trip module and shutdown circuit are described in Sec. 5-2 8.

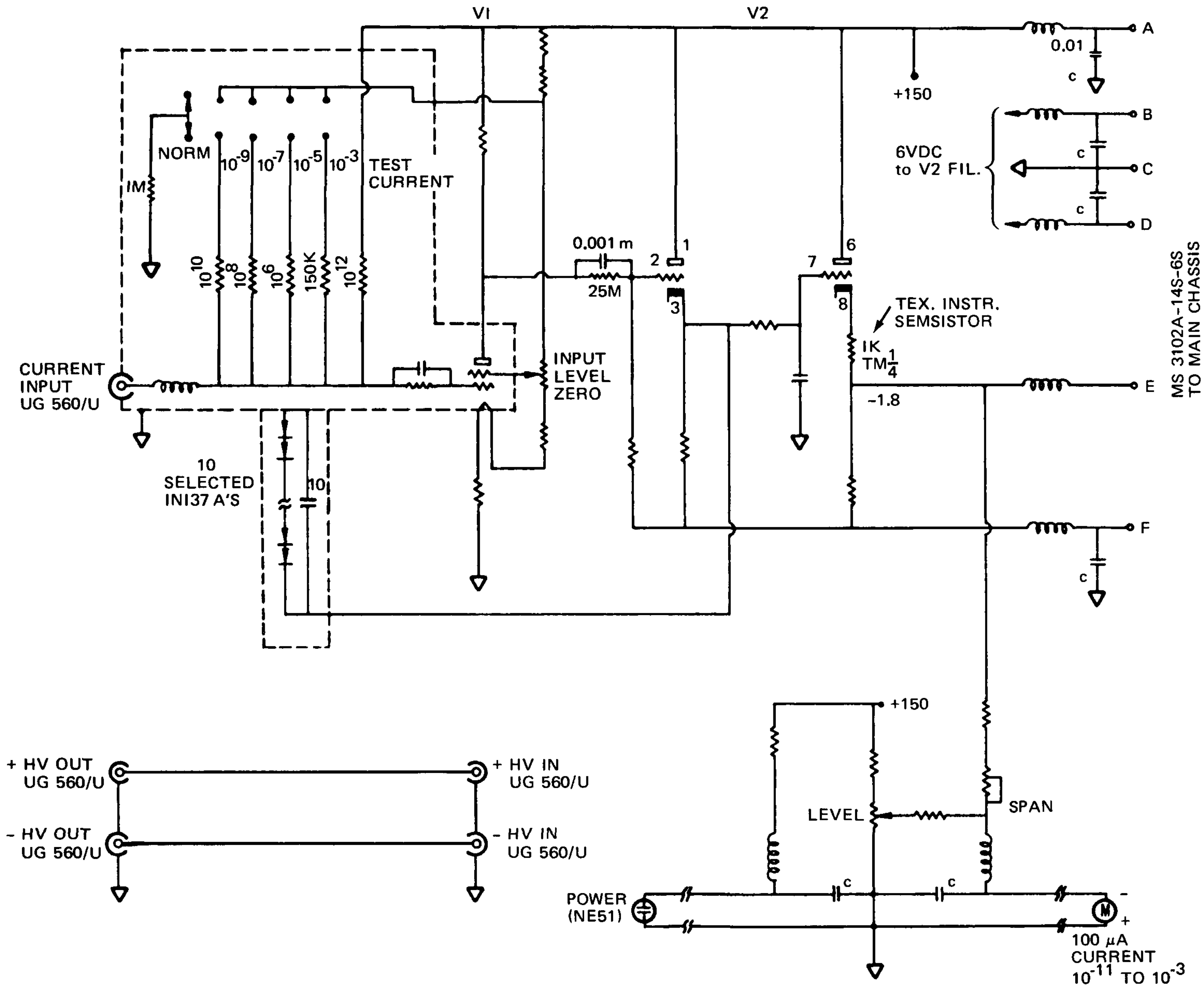


Fig. 5.17—Circuit diagram of preamplifier for log N channel.

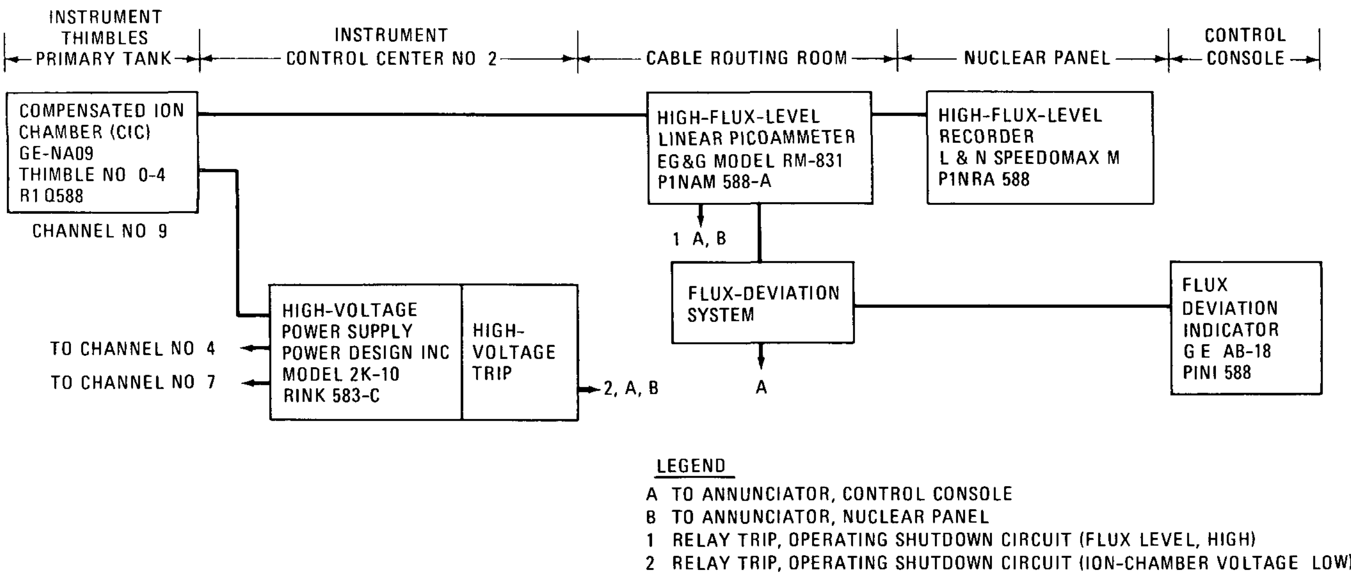


Fig. 5.18—Block diagram of high-flux channels 9, 10, and 11

5-4 POWER-RANGE CHANNEL

5-4.1 Introduction

In the power-range channels, neutron-flux-measuring circuits monitor the neutron flux when the reactor is operating at or near full power. The channels provide information necessary for either manual or automatic control of the reactor

The power-range channels cover linearly one decade of power, thus providing a much finer control of power level than is possible with the logarithmic channels The system provides a linear display of power level over a wide range, the range being changed by switching

A power-range channel, shown in Fig 5 18, consists of a CIC, high-voltage supply, linear picoammeter, and readout and control signals Each of these items is discussed in the following paragraphs.

5-4.2 Sensor

A CIC with the same characteristics as those used in the intermediate-level channel is used [see Sec. 5-3.2(a) and the discussion of CIC's in Chap. 2, Sec 2-2 2].

5-4.3 High-Voltage Supplies

See Sec 5-3.2(b).

5-4.4 Linear Picoammeter

The signal from the CIC is monitored by a linear picoammeter with either manual or automatic range control. In a manually operated unit, the current range is predetermined and normally provides an accurate indication of power level only for the highest two decades of power. Figure 5 19 shows an automatic range-changing picoammeter that gives continuous coverage from a few watts to full power The unit automatically changes range on an increasing and decreasing signal at the range set points

The basic current-measuring device of the picoammeter is an electrometer with appropriate feedback resistors to determine the range of operation. The electrometer, shown schematically in Fig 5.20, consists of a very high input impedance operational amplifier.

5-4.5 Readout Indication

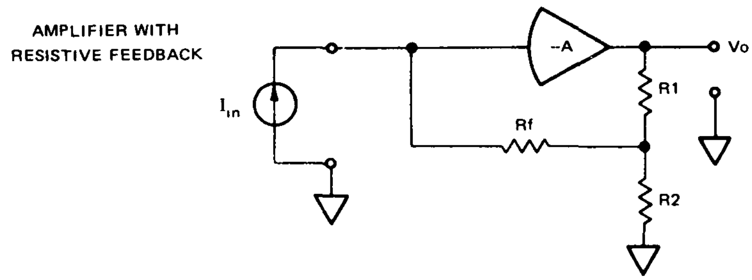
Signals generated from the picoammeter are presented to the operator in several ways The range is indicated by readout lamps, the level is displayed on meters and recorders marked 0 to 100% The level can also be displayed on a digital readout unit

5-4.6 Control and Safety Circuits

Alarm units are provided in the picoammeter for initiating a reactor shutdown if the power level exceeds a predetermined maximum value The alarm unit is described in Sec 5 2.4(e) The relays are connected in a two-out-of-three sequence to increase system reliability against single failures causing reactor shutdown (see Chap. 11)

5-4.7 Calibration and Checkout

As with the other channels described in this chapter, a built-in test source is provided to check the system response from the picoammeter The test source also provides a means for setting and checking the alarm units



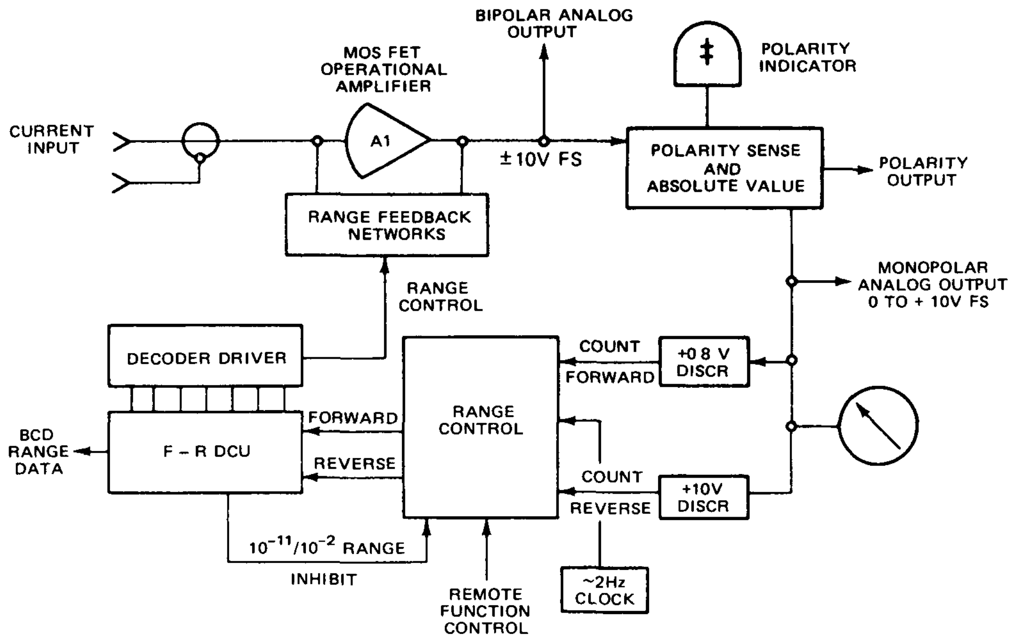


Fig. 5.19—Automatic range-changing picoammeter

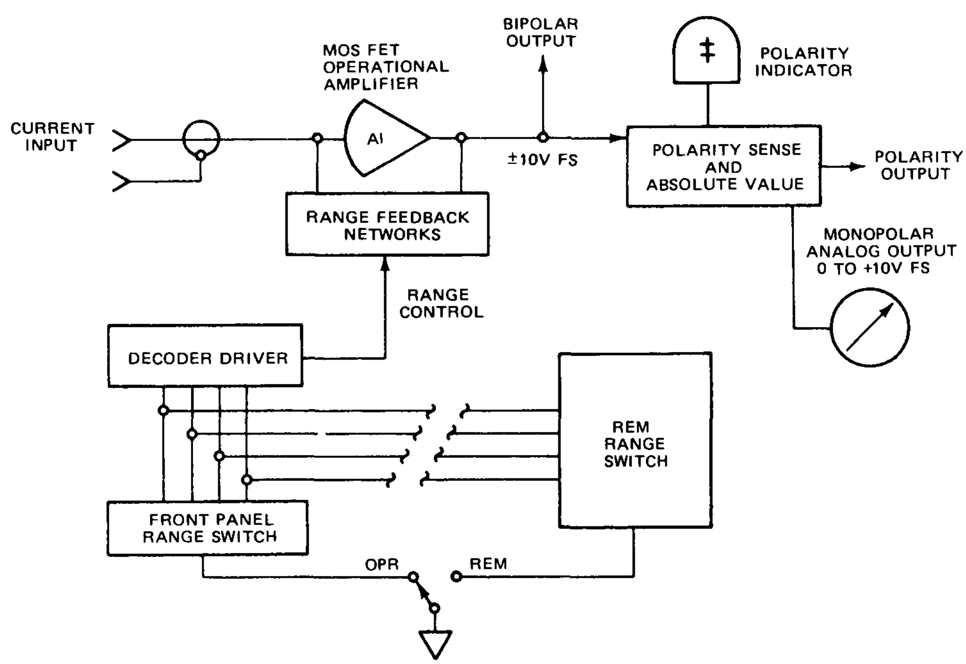


Fig. 5.20—Electrometer.

5-5 MEAN-SQUARE-VOLTAGE (MSV) METHODS*

5-5.1 Basis of Method

The MSV method depends on the fact that, if the time distribution of pulses from a nuclear radiation sensor is a Poisson distribution, the variance (mean of the squares of the deviations from the mean) is a direct measure of the mean. (See Table 5.1 for relevant definitions and formulas) For all practical purposes this condition is met by boron and fission counting chambers

There are at least three advantages to be gained from using MSV methods increased gamma discrimination (compared to compensation), improved operation when chambers and cables are exposed to elevated temperatures, and more efficient use of chambers (sensors).

So that the advantages of the method can be realized, a measure of a quantity proportional to the square of the charge (or current) is made. One way to do this is to subtract the mean signal with a differentiator and measure the temperature rise in a resistor, as is done in a true root-mean-square meter commonly used in the shop or laboratory Another way is to pass the variable (a-c) signal through a half- or full-wave rectifier measuring, as a result, the average magnitude or average magnitude squared This latter technique is accurate at only one frequency for which a correction factor can be applied More generally, the pulses can be passed through an electronic squaring amplifier and the output read without correction as a linear measure of the mean square If a mean-square signal is sent to a log converter circuit, the output is again proportional to the log of the mean.

Table 5.1—Poisson Distribution Definitions and Formulas

Definitions

n = number of events observed

$\bar{n}$ = average (mean) number of events observed

$n - \bar{n}$ = deviation from mean
= deviation of the observed number of events from the average

$\overline{(n - \bar{n})^2} = \sigma^2$
= variance
= mean of the squares of the deviations

Formulas

Poisson distribution

$$P(n) = \frac{e^{-\bar{n}}\bar{n}^n}{n!} \quad (1)$$

$$\sum_{n=0}^{\infty} P(n) = 1 \quad (2)$$

For Poisson distribution

$$\bar{n} = \sum_{n=0}^{\infty} nP(n) = \bar{n} \quad (3)$$

$$\overline{n^2} = \sum_{n=0}^{\infty} n^2 P(n) = \bar{n}^2 + \bar{n} \quad (4)$$

$$\sigma^2 = \sum_{n=0}^{\infty} (n - \bar{n})^2 P(n) = \overline{n^2} - \bar{n}^2 \quad (5)$$

Substitute (4) into (5) and obtain

$$\sigma^2 = \bar{n} \quad (6)$$

Note If n is the number of counts indicated by a sensing device in a given time interval, then n = count rate × time interval

5-5.2 Gamma Discrimination

Gamma discrimination must be compared with "compensation" for gammas as accomplished in the CIC discussed in Sec 2-2 2 of Chap 2. In a CIC a compensating signal generated in a volume not sensitive to neutrons is subtracted electrically from the gamma-plus-neutron signal In practice the compensating volume and the mass of material forming the neutron and compensating volumes cannot be matched exactly, through engineering compromise the compensation is usually between 95 and 99% of the gamma signal Although in theory the compensation could be much better, it just cannot be achieved Commercial units use two concentric volumes that are adjusted so that overcompensation in some gamma range is avoided. Overcompensation would result in negative readings and confusion to control-system functions Manufacturers usually guarantee a gamma/neutron signal ratio of 1/20 and a maximum of 1/100, the latter to avoid overcompensation

With MSV methods the compensation or discrimination is not dependent on the mechanical construction of the chamber Only one ionization volume is involved, and advantage is taken of the charge ratio of a fission fragment to a gamma-scattered beta particle If the number of events is N per unit time and the charge collected per event is Q, then an average voltage $E_{d\text{-}c}$ is developed

$$E_{d\text{-}c} = \bar{N}\,\bar{Q} \int_0^{\infty} h(t)\, dt \quad (5.4)$$

where $\bar{N}$ is the mean number of events, $\bar{Q}$ is the mean charge per event, and h(t) is the circuit response to a single pulse of unit charge. By definition the mean-square voltage is

$$E_{ms} = (E_{d\text{-}c})^2 + \bar{N}\,\overline{Q^2} \int_0^{\infty} [h(t)]^2\, dt \quad (5.5)$$

The voltage $E_{d\text{-}c}$ is made zero if h(t), the circuit response, is limited to acceptance of a-c signals alone In this case

$$E_{ms} = \bar{N}\,\overline{Q^2} \int_0^{\infty} [h(t)]^2\, dt \quad (5.6)$$

*Since the equivalence of the variance and the mean in certain nuclear radiation measurements was first studied by Campbell [N R. Campbell, Study of Discontinuous Phenomena, *Proc Camb Phil. Soc.*, **15**: 117, 310, 513 (1909-1910).], the MSV method is frequently referred to as the "Campbell technique "

It is not difficult, as indicated earlier, to make the circuit such that E_{ms} is the lone acceptable result. A differentiation circuit at the input of the squaring circuit will do the job.

The relation between the resulting signals can be established if a chamber operating in the d-c mode is compared to a similar chamber operating in the MSV mode. If a subscript n is used for neutron events and a subscript β for gamma effects (since gammas scatter β particles or electrons into the chamber), the discrimination in the d-c mode for gammas is (from Eq. 5.4)

$$D_{d\text{-}c} = \frac{\overline{N}_n \overline{Q}_n}{\overline{N}_\beta \overline{Q}_\beta} \tag{5.7}$$

and the discrimination for the MSV mode is

$$D_{ms} = \frac{\overline{N}_n \overline{Q}_n^2}{\overline{N}_\beta \overline{Q}_\beta^2} \tag{5.8}$$

The ratio of the discriminations is thus

$$\frac{D_{ms}}{D_{d\text{-}c}} = \frac{\overline{Q}_n^2}{\overline{Q}_n}\frac{\overline{Q}_\beta}{\overline{Q}_\beta^2} \simeq \frac{\overline{Q}_n}{\overline{Q}_\beta} \tag{5.9}$$

The ratio $\overline{Q}_n^2/\overline{Q}_\beta^2$ has been set equal to $(\overline{Q}_n)^2/(\overline{Q}_\beta)^2$ in deriving Eq 5.9 since it can be shown that in practical cases this is a good approximation.

The ratio $\overline{Q}_n/\overline{Q}_\beta$ is about 10^3 for a fission chamber Compared to a compensated chamber, this means an assured 10^3 discrimination against gammas instead of the 20 to 100 In practice, experimental results show a nearly hundredfold improvement in gamma discrimination, mainly because the 1/20 ratio of gamma to neutron signal is more realistic for a CIC than the 1/100 ratio.

5-5.3 Temperature Effects

In practice, temperature effects are not entirely separable from the gamma effect If it is assumed that there is no need for gamma discrimination, at elevated temperature the cable insulation resistance is seen to decrease as the temperature increases whereas the breakdown voltage, which creates noise or a mean deviation, is relatively constant Thus the effect of noise is minimal whereas the mean current attributable to neutrons can be completely obscured by direct-current leakage.

Quantitative results have not been reported. The first reported use of MSV methods was for in-core units of about 1 cm^3 volume operating at about 600°F (316°C) The mean signal was obscured by leakage, but the MSV signal was still present The gross effect has been discussed by DuBridge et al (see the Bibliography at the end of this chapter).

From these observations it can be concluded that, if neutron-sensitive chambers and their associated cables are to be operated at elevated temperatures, the proper method is to use MSV measurements instead of mean-current measurements.

5-5.4 Wide-Range Neutron Monitoring Channels

As noted in Sec 5-1, the large range of neutron-flux values to be monitored in a power reactor requires the use of several separate channels with two decades of overlap between the channels With the MSV technique it has been possible to develop monitoring systems that cover 10 decades of reactor power. The signal from a single fixed-position fission chamber is used with what has come to be called counting-MSV or counting-Campbelling circuits. The combination of count rate and MSV can be read out as a linear indication of power, much as is done with a range-switched picoammeter (see Sec 5-4.4), or a log output can be taken from which period can be derived.

The wide-range instrumentation permits the use of fewer sensors, recorders, meters, cables, and sensor thimbles. This represents a significant saving in power-reactor instrumentation costs.

5-5.5 System Descriptions and Components

Figure 5 21 is a block diagram of an average-magnitude-squared channel that covers 10 decades of reactor power The MSV portion of the channel uses the combination pulse-charge or current preamplifier, band-pass amplifier, rectifier, log amplifier, and d-c amplifier The noise level for the Campbell part of the channel is reduced by special shielding of the 40-ft cable between the chamber and the double-shielded preamplifier. The impedance and signal levels out of the preamplifier are such that essentially any reasonable length of conventional coaxial cable to the rest of the circuit may be used with good results As shown in Fig. 5.21, the wide-range log power channel consists of an LCR circuit and a log-Campbell circuit working out of the same fission chamber and preamplifier Their output signals are combined to give a single output indication of log power and, at the same time, to eliminate normal limiting errors of each one.

The high-frequency components of the signal pass through a conventional LCR circuit using a discriminator, flip-flop, and multiple-diode log pump circuit This circuit gives an output voltage, E_1, that is proportional to the log of the count rate from about 0.3 to 300,000 counts/sec. A biased diode, D_1, limiter is used to cut off that portion of the response which is adversely affected by resolution counting loss (usually about 2×10^5 neutrons cm^{-2} sec^{-1}) As is customary with LCR circuits, the log diode pump uses fixed low-temperature-coefficient components to obtain the log relation. The pump circuit output passes through a d-c operational amplifier with adjustable gain and bias, so output volts per decade and volt level for a particular flux level can be established.

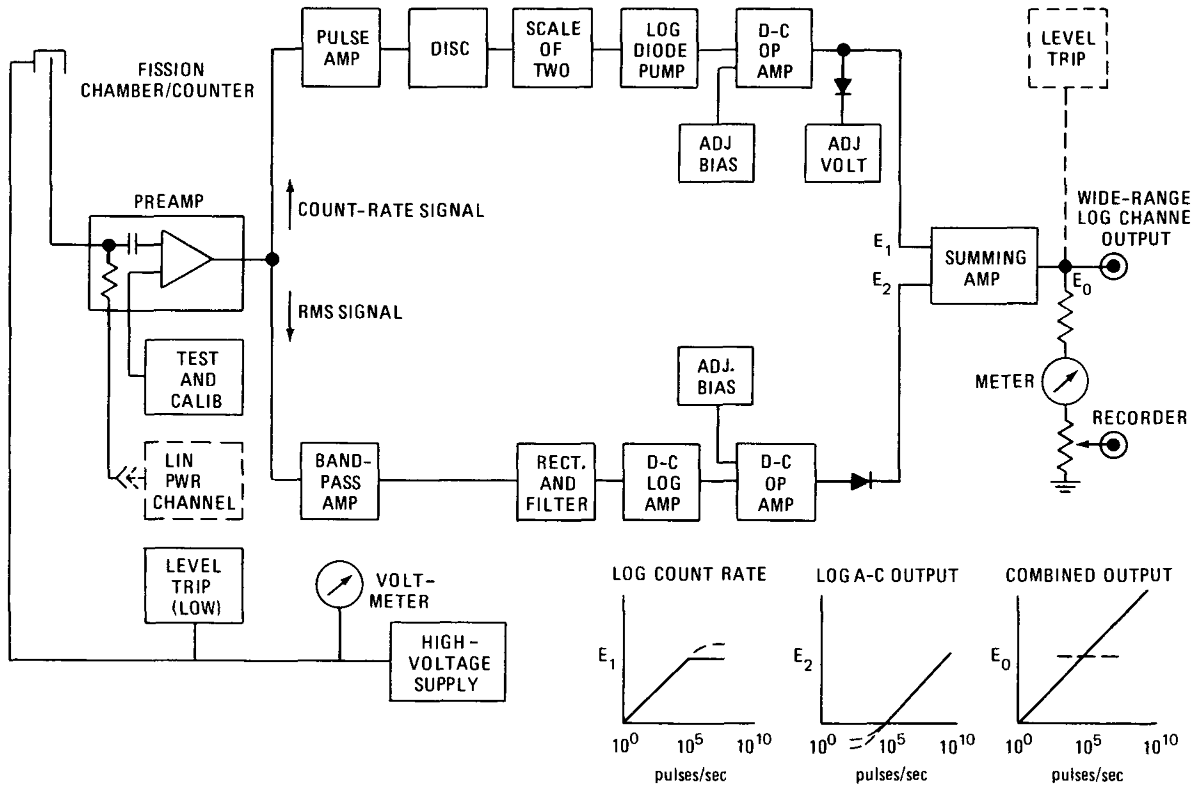


Fig. 5.21—Wide-range log channel

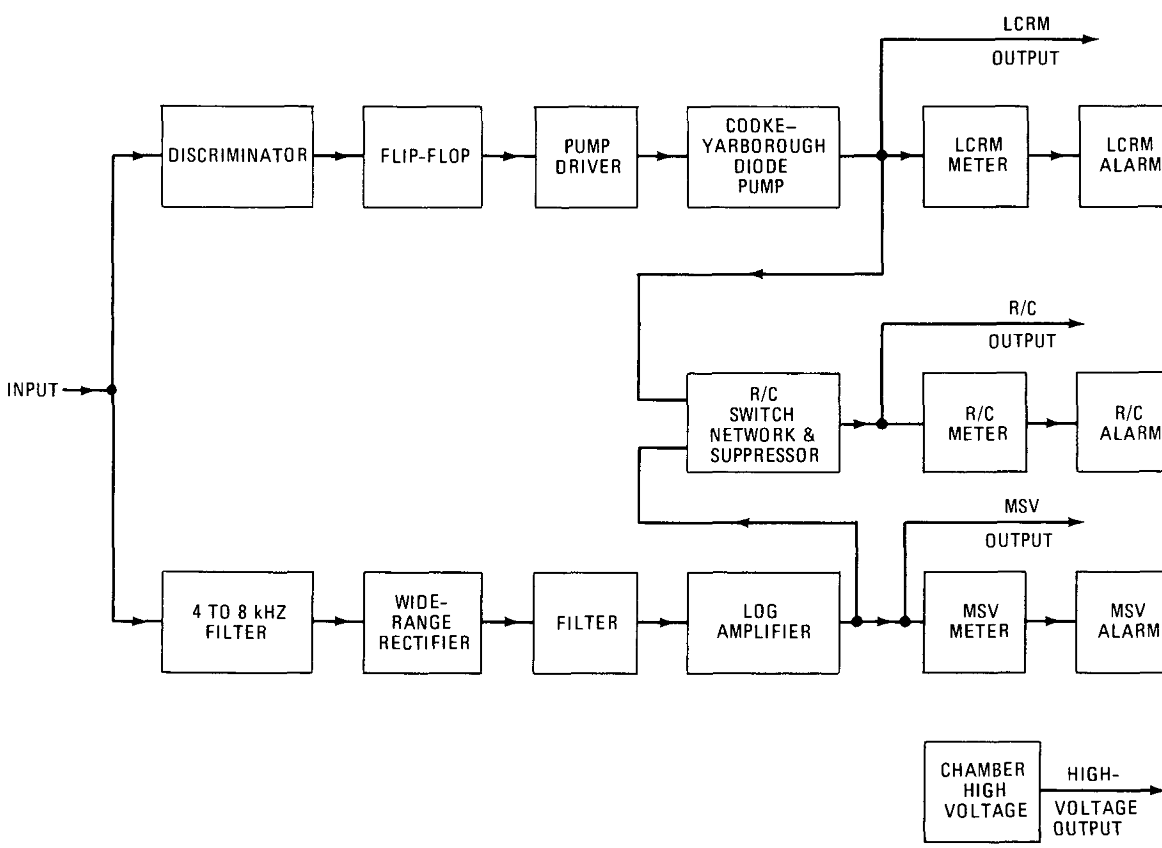


Fig. 5.22—Wide-range power monitor.

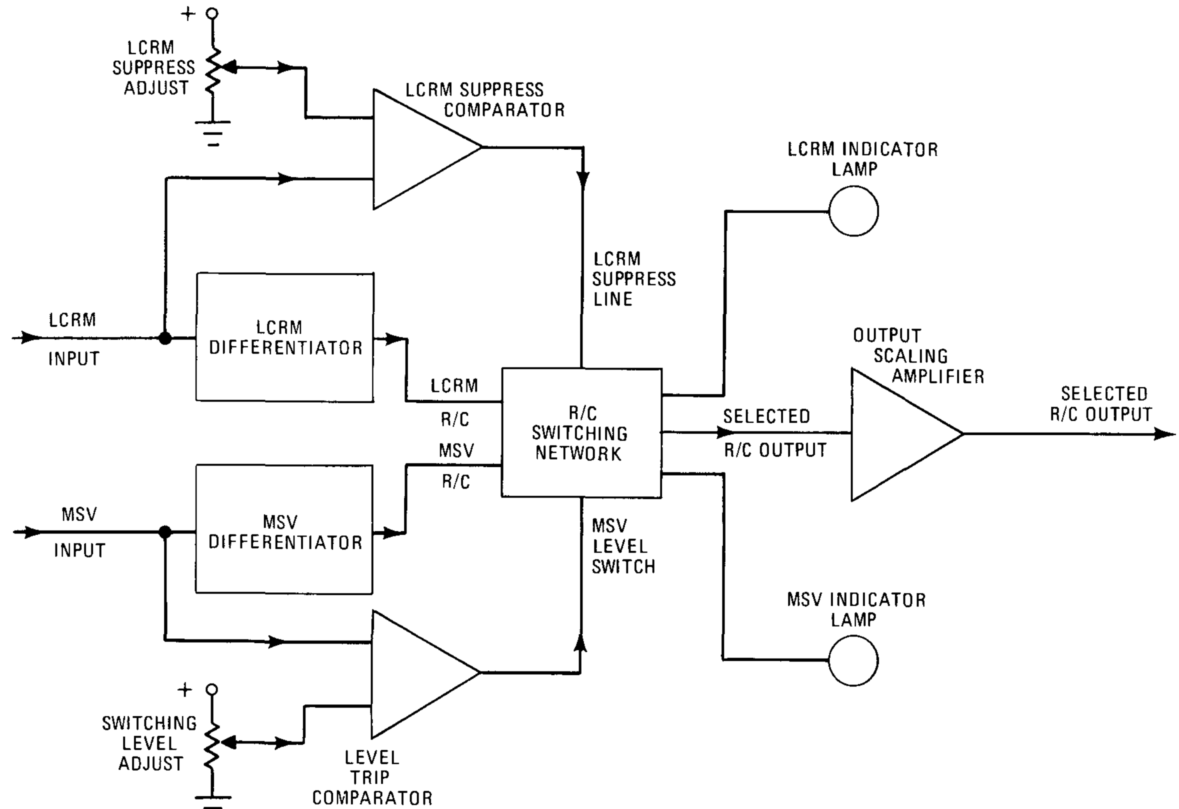


Fig. 5.23—Rate of change switching circuit for wide-range power monitor

The low-frequency components governed by the Campbell band-pass amplifier pass through the linear rectifier, filter (T = 50 msec), and through a stable d-c log amplifier to give a log indication of power from 2×10^5 to 2×10^{10} neutrons cm^{-2} sec^{-1} The diode D_2 allows only signals above zero to pass, therefore, if the output of the log amplifier is biased, the lower end of the response curve below 2×10^5 neutrons cm^{-2} sec^{-1} can be eliminated. This portion of the curve may be adversely affected by gamma and alpha background, noise, imperfect rectification, and lack of pulse overlap. A gain adjust at the output of the log amplifier allows the slope of E_2 to be properly adjusted to match that of E_1 Since the bias cutoff points can be adjusted to coincide, a smooth, fast, all-electronic transition is made from counting to Campbelling or vice versa

Since misalignment or drift might produce an offset at the crossover point (2×10^5 neutrons cm^{-2} sec^{-1}) and cause an exaggerated false period indication in that region, great emphasis has been placed on stability of the circuits and on a built-in calibration and test circuit that will allow proper alignment without the use of a reactor High-gain solid-state operational amplifiers (some integrated circuits) with feedback through stable circuit elements were used throughout. The principal temperature problem, as usual, was associated with the log amplifier in the Campbell circuit, and this was solved by using two operational amplifiers and two sets of logging diodes thermally coupled to obtain a temperature-compensated log response. Temperature tests were performed between 50°F and 150°F (10°C and 66°C) Temperature drift results in an output error of less than 1 5% from 50°F to 120°F and only a slight further degradation up to 150°F.

Another average-magnitude-squared channel is shown in Fig. 5.22. The circuit is divided into two portions, as shown in the figure The signal from the radiation sensor enters the instrument and is routed both to the log count rate circuit (LCRM) and the statistical level amplifier (MSV) Pulses within the range of 1 per second to 10^6 per second pass through the LCRM discriminator into a flip-flop, a driver network, and then to a Cooke–Yarborough diode pump log converter, where the pulse rate is converted to a d-c output At that point the signal is amplified to the desired output level and routed to the front panel meter and other instrument inputs When the input signal enters the MSV portion of the instrument, it is first applied to a filter that passes only the portion of the signal between 4 and 8 kHz This signal is then applied to a wide-range rectifier, thus providing a half-wave rectified signal to a smoothing filter, which then routes the d-c output to a log amplifier and hence to the output meter and other external devices The output of the MSV circuit is scaled to read two decades of output for each decade of input current to provide the square in the mean-square measuring technique

A third meter on the instrument measures the rate of change of both the LCRM and MSV channels alternately, switching from the LCRM channel to the MSV channel

automatically as the LCRM reaches near full scale and as the MSV channel begins to operate. Since this portion of the circuit is somewhat novel, it is detailed in Fig 5 23.

In operation the output levels from the LCRM and MSV circuits are each applied to a separate differentiator circuit that operates continuously. The two outputs are routed through a solid-state switching network that is controlled by the magnitude of the MSV input signal such that below a preset level of the MSV circuit the signal from the LCRM differentiator enters the output scaling amplifier and above this level the MSV differentiator controls the output scaling amplifier. The output of the scaling amplifier is fed to the rate-of-change meter, which reads from −1 to +9 decades per minute

Another feature of the rate-of-change circuit is the "LCRM suppress" feature This involves a circuit to suppress rate-of-change movements on the lower portion of the LCRM channel and thus has the effect of preventing rate-of-change meter movements where counting statistics cause an erratic signal

In addition to the rate-of-change circuits, the instrument generates pulses for calibrating the LCRM, ramp functions for checking the rate-of-change circuits, and a variable-level 5-kHz signal for calibrating the MSV circuit Furthermore, all meters have electronic level trip circuits that read the output level of a particular circuit and produce both an automatic resetting alarm and one that latches and must be reset manually after an alarm is produced by an excessively high or low level reading on any one of the three front panel meters.*

5-5.6 MSV Vs. AMS Systems

The circuits described in the previous section operate on the average-magnitude-squared (AMS) principle and are

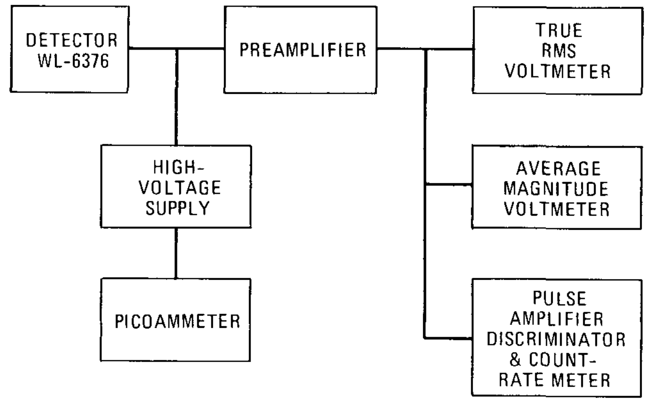


Fig. 5.24—System block diagram

therefore frequency-sensitive Adjustments must be made in the band-pass filter to make the system fit a particular reactor The lower cutoff at 4 kHz, indicated above, corresponds to about 25,000 radians/sec, this is below the

*Neither system described allows final use as a current chamber for overpower monitoring

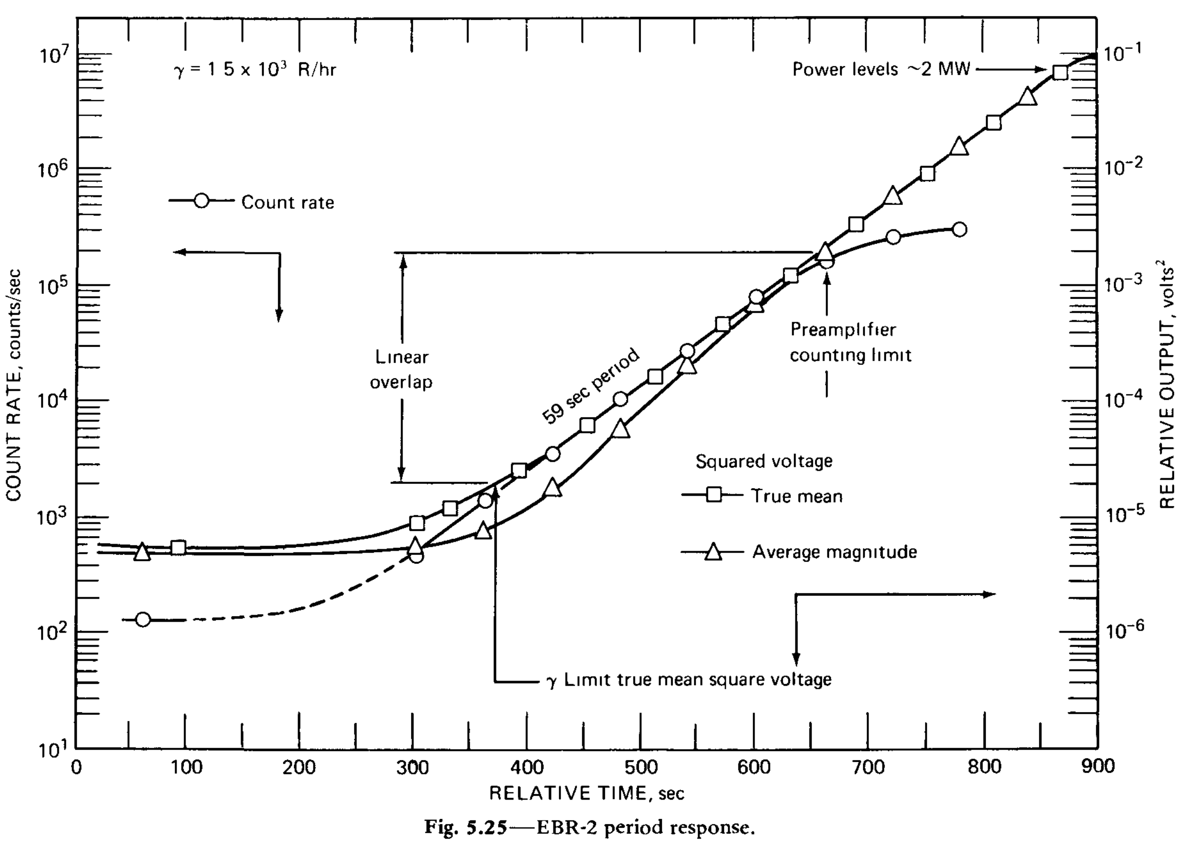


Fig. 5.25—EBR-2 period response.

β/l cutoff of a fast reactor (where the roll-off in the transfer function is at about 70,000 radians/sec.)

The principle involved is to use the lower frequency components of the band to assist in pulse overlap Thus there is an incentive to use a lower frequency cutoff (The high-frequency cutoff is selected for noise rejection.) As the low-frequency cutoff is raised in the AMS system, the overlap with the pulse-counting range decreases

In a test run in 1967, the AMS and true MSV systems were compared using the instrument setup shown in Fig. 5.24. The data shown in Fig 5.25 were obtained with a band pass of about 250 to 500 kHz The EBR-2 was put on a 59-sec period, and, because of its wide flux range before reaching power feedback conditions, this is constant over four decades or more. As shown by the data, the MSV system had a correct signal for nearly two decades before the AMS signal became correct. Had a lower band pass been used, this could have been corrected, but the low pass of the band selected is not important to the true MSV system and bands above 250 kHz are used for other reasons

If on Fig 5.21 the blocks representing the band-pass filter and rectifier were replaced with a Hewlitt–Packard true RMS convertor, the signal would be as shown in Fig 5 25 At present, the use of this converter adds materially to the number of components in the system, and commercial suppliers are hesitant to supply such systems.

5-5.7 MSV Vs. Mean-Current CIC

Data taken on a commercial CIC were compared with commercial log-average-magnitude-squared (LAMS) units operating off fission counters in the EBR-2 shutdown gamma field of about 2×10^5 R/hr. The resulting curves, shown in Figs 5.26 and 5.27, are multivalued on the ordinate to emphasize the overlap As shown, the overlap for the CIC is only a factor of 2 compared to the overlap of

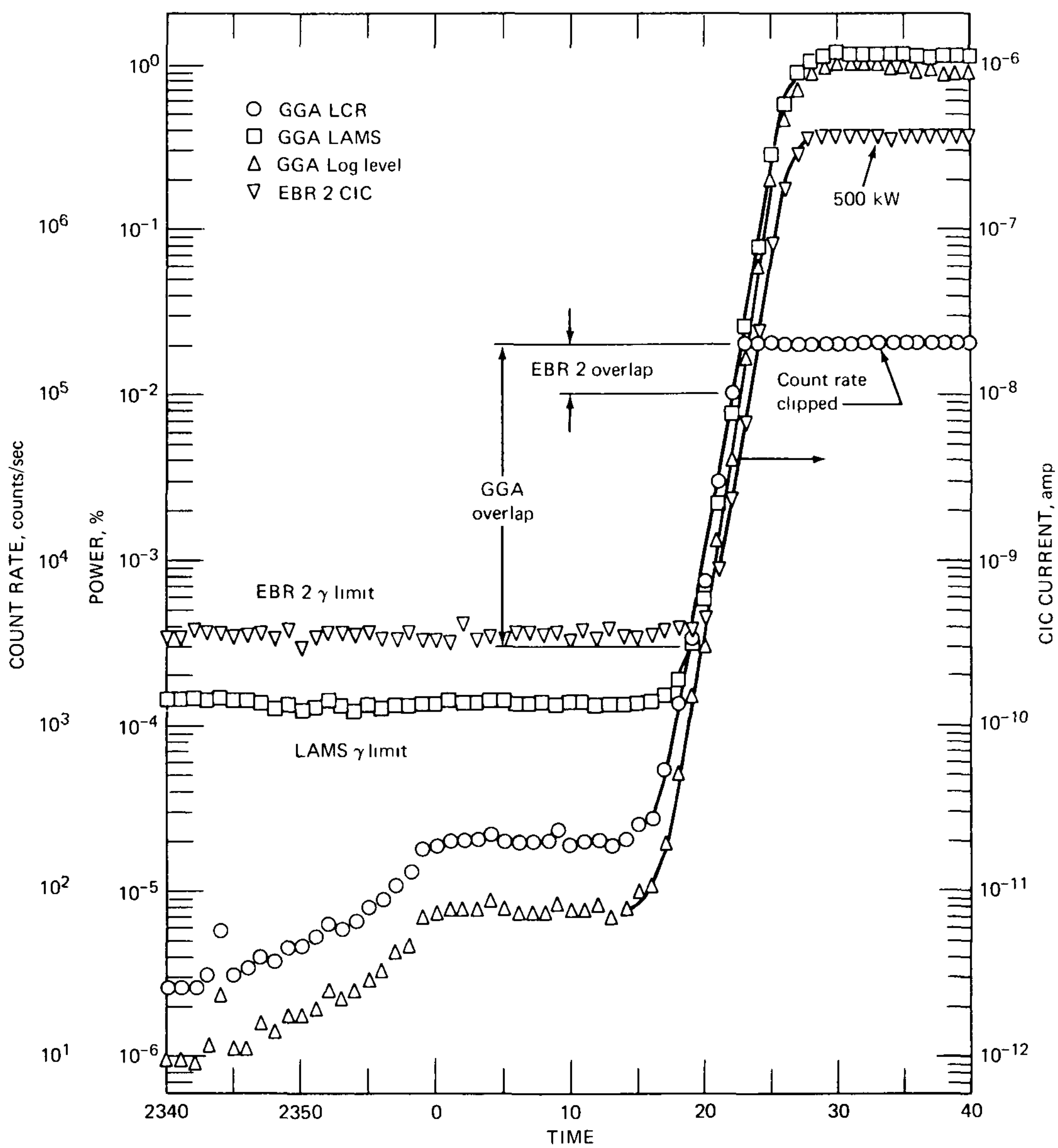


Fig. 5.26—Comparison of CIC and LAMS units (Run 1).

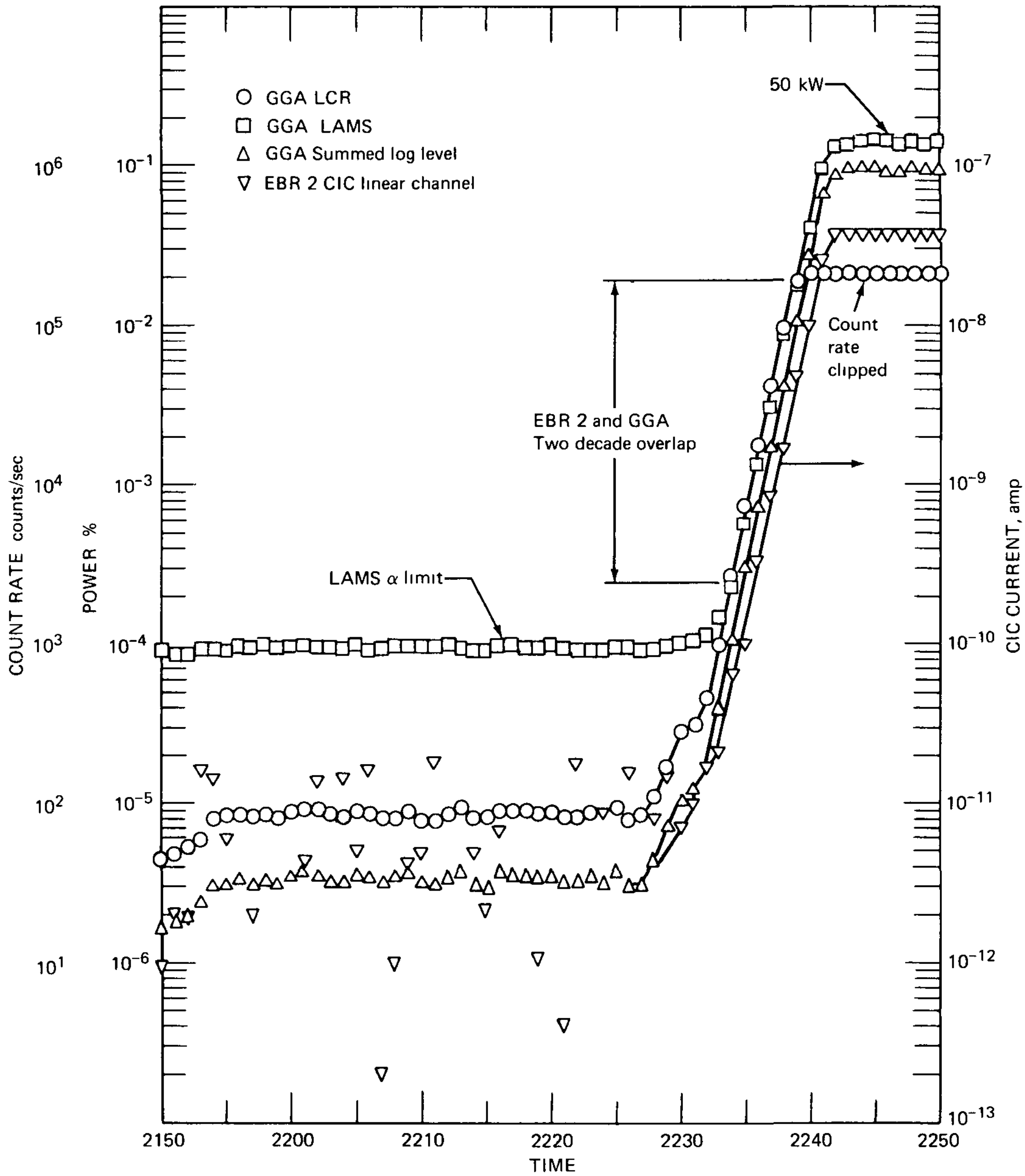


Fig 5.27—Comparison of CIC and LAMS units (Run 2)

Table 5.2—Typical Discrimination Ratios*

	R/hr / nv†
Fission chamber	
D-c mode	0 0062
True mean-squared mode	5.8
Average-magnitude-squared mode	5.8
Compensated ionization chamber	
95% compensation	0.027
99% compensation	0 13

*Calculated by G. F. Popper, Argonne National Laboratory.

†Neutrons cm ^{2} sec^{-1}

the Gulf General Atomic counters of 100 If a true LRMS system had been used, the overlap would be the same or greater The improvement over a CIC is evident

Had the gamma field been more intense, the CIC overlap would be nil but the LAMS or log mean square voltage would still be 150. Table 5 2 shows comparative values of the discrimination ratio for the various systems

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Chapter 6

Transfer-Function Measurement Systems

J. A. Thie

6-1 FUNDAMENTAL CONCEPTS

6-1.1 Time and Frequency

The dynamic behavior of systems can be considered from either of two viewpoints as a function of time (time domain) or as a function of frequency (frequency domain) This dualism is quite natural, especially to mathematicians, because it stems from the well-known Fourier theorem a function of time can be represented by the sum (or integral) of sinusoidal functions of various frequencies. In this chapter both points of view are considered, although in certain specific applications we follow historically developed conventions.

Table 6.1 lists the principal functions of time and frequency used in studying dynamic behavior. The functions are given as equivalent pairs, i.e., if one is known, the other can be obtained by computation. Thus we can measure functions in either the time or the frequency domain, whichever is the more convenient, and subsequently we can compute the Fourier transform function if it is preferred for purposes of interpretation.

6-1.2 Transfer Functions

The concept of transfer functions was introduced in reactor plant analysis because of its proven utility in electrical engineering. As defined in Table 6.1, the transfer function is the ratio of output complex amplitude to input complex amplitude, this ratio is a complex number that depends on the amplitude ratio and the phase difference between two sinusoidal signals in a system of two or more dynamically related variables, all of which are oscillating at a given frequency. We may speak of a transfer function between any two variables. However, if the input driving function is oscillatory, it is conventionally used as one of the variables, in which case the transfer function is the output amplitude per unit input amplitude of sine-wave excitation. Several zero-power transfer functions are given in Fig. 6.1

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Complete specification of a transfer function involves both an amplitude value and a phase difference given as a function of frequency. A complete specification of the dynamics of a system would involve all the transfer functions between all the pairs of variables given for the

Table 6.1—Principal Frequency-Domain Functions and Their Corresponding Time-Domain Functions

Symbol	Name	Definition	Relation to corresponding time or frequency function
G(f)	Transfer function	(Output complex amplitude)/(input complex amplitude)	$= \int_{\infty}^{\infty} h(t)\, e^{-i\omega t}\, dt$
P(f)	Spectral density	$\frac{1}{T} \left\| \int_{-T/2}^{T/2} x(t)\, e^{-i\omega t}\, dt \right\|^2$	$= \int_{-\infty}^{\infty} C(\tau)\, e^{-i\omega\tau}\, d\tau$
$P_{xy}(f)$	Cross spectral density	$\frac{1}{T} \int_{-T/2}^{T/2} x(t)\, e^{i\omega t}\, dt \int_{-T/2}^{T/2} y(t')\, e^{-i\omega t'}\, dt'$	$= \int_{-\infty}^{\infty} C_{xy}(\tau)\, e^{-i\omega\tau}\, d\tau$
$Co_{xy}(f)$	Cospectrum	Fourier cosine transform of $C_{xy}(\tau)$	$= \int_{\infty}^{\infty} C_{xy}(\tau) \cos \omega\tau\, d\tau$
$Qu_{xy}(f)$	Quad-spectrum	Fourier sine transform of $C_{xy}(\tau)$	$= \int_{\infty}^{\infty} C_{xy}(\tau) \sin \omega\tau\, d\tau$
h(t)	Impulse response	Time response to a narrow pulse	$= \int_{\infty}^{\infty} G(f)\, e^{i\omega t}\, df$
$C(\tau)$	Autocorrelation function	$\frac{1}{T} \int_{-T/2}^{T/2} x(t)\, x(t+\tau)\, dt$	$= \int_{\infty}^{\infty} P(f)\, e^{i\omega\tau}\, df$
$C_{xy}(\tau)$	Cross-correlation function	$\frac{1}{T} \int_{-T/2}^{T/2} x(t)\, y(t+\tau)\, dt$	$= \int_{\infty}^{\infty} P_{xy}(f)\, e^{i\omega\tau}\, df$

entire band of frequencies of physical interest Often, however, the two most meaningful variables are related In reactor dynamics these variables might be the reactivity and the power of a reactor.

Table 6.2 contains a simple example of two variables, x and y (one input and one output), related by a differential equation having one time constant the complex transfer function is $(1 + i\omega\tau_c)^{-1}$ and has an amplitude $(1 + \omega^2\tau_c^2)^{-1/2}$ and a phase $\arctan(-\omega\tau_c)$ or real and imaginary parts of $1/(1 + \omega^2\tau_c^2)^{1/2}$ and $-\omega\tau_c/(1 + \omega^2\tau_c^2)^{1/2}$, respectively.

Since almost all reactor dynamics analyses involve linear systems, linear systems are assumed in this chapter. In a linear system the transfer function at a given frequency is independent of the absolute magnitude used in its measurement. Usually a sufficiently large amplitude will cause nonlinear behavior in any system, but these cases are not treated with the techniques discussed in this chapter.

It should be mentioned, however, that the transfer-function concept may be applied to almost-linear systems. Smets[1] has presented a "describing function" approach to nuclear-reactor dynamic measurements

$$\text{Describing function} = \text{(amplitude of fundamental Fourier component of output signal)/(amplitude of sinusoidal input signal)} \quad (6\ 1)$$

where the input signal is $x(t) = a \sin \omega t$ and the output signal is

$$y(t) = A_1 \sin(\omega_1 t + \phi_1) + A_2 \sin(\omega_2 t + \phi_2) + \ldots \quad (6.2)$$

The describing function is thus A_1/a If A_1 is not linear in a, then the describing function depends on the magnitude of the input amplitude a. If the system is linear, the describing function is synonymous with the transfer function.

6-1.3 Impulse Response

As implied by its name and defined in Table 6.1, the impulse response, h(t), is the system output, y(t), when its input, x(t), is a very narrow pulse (i.e., a unit pulse of time duration much less than the smallest important time constant of the system). The impulse response is also the Green's function or weighting function. It is appropriate to discuss the impulse-response function in connection with transfer functions since, as shown in Table 6.1, it is the Fourier transform of the transfer function. To date the impulse-response function has not enjoyed the popularity of the transfer function as an analytical tool. Recently, however, Dorf[2] pointed out that since digital computers greatly facilitate time-domain analyses of systems the impulse-response function should become more popular

Table 6.2 gives an example of the impulse response of a system with a single time constant. Evidently excitation by an input pulse, x(t), having a width much less than the system time constant stretches this pulse to a width or duration of the order of the system time constant. A physical interpretation of this is that the output, y(t), "remembers" an input pulse and shows its effect (up to about the time constant) after the input pulse.

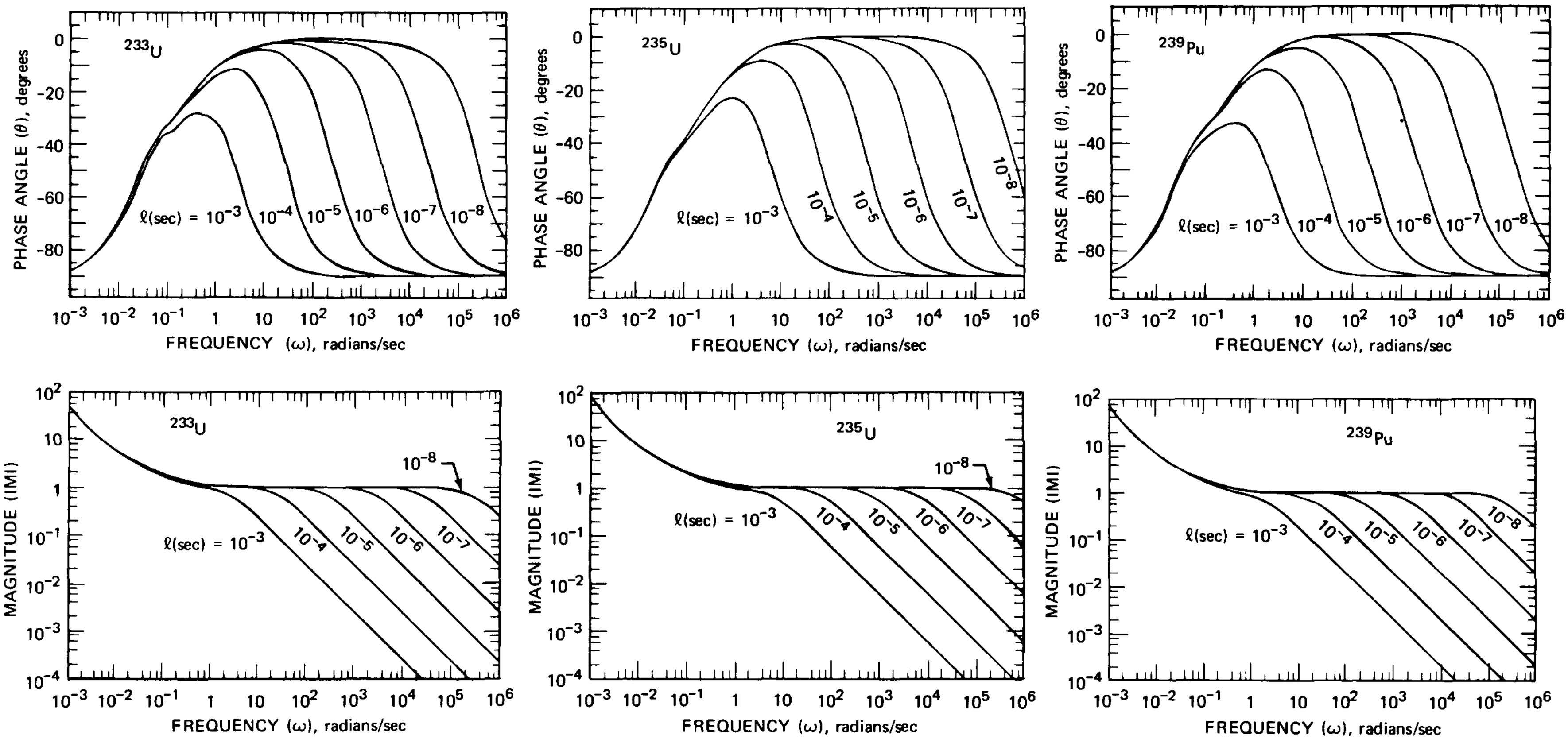


Fig. 6.1—Magnitude and phase of zero-power reactor transfer function vs. frequency for ^{233}U, ^{235}U, and ^{239}Pu. Curves are shown for various values of l, the neutron lifetime.[3]

Table 6 2—Illustration of Dynamic Functions for a System Having a Single Time Constant, τ_c, One Input, and One Output

Description	Frequency-domain expression	Time-domain expression
Differential equation of the system and its Laplace transform	$x(s) = (1 + i\tau_c\omega)\, y(s)$	$x(t) = y(t) + \tau_c \frac{dy(t)}{dt}$
Transfer function	$G(\omega) = \frac{y(\omega)}{x(\omega)} = \frac{1}{1 + i\tau_c\omega}$	
Impulse response		$h(t) = 0 \quad (\tau < 0)$ $h(t) = \frac{e^{-t/\tau_c}}{\tau_c} (\tau \geqslant 0)$
Spectral density of output for an arbitrary input	$P_y(\omega) = \frac{P_x(\omega)}{1 + \tau_c^2\omega^2}$	
Cross spectral density of input and output (for an arbitrary input)	$P_{xy}(\omega) = \frac{P_x(\omega)}{1 + i\tau_c\omega}$	
Autocorrelation function of output for a constant spectral-density (uncorrelated) input		$C(\tau) = e^{-\lvert\tau\rvert/\tau_c}$
Cross-correlation function of output with a constant spectral-density input		$C_{xy}(\tau) = 0 \quad (\tau < 0)$ $C_{xy}(\tau) = e^{-\tau/\tau_c} \quad (\tau \geqslant 0)$

Finally, another insight into the nature of the impulse response comes from using it as a weighting function in relating arbitrary input and output time functions

$$y(t) = \int_0^\infty h(t')\, x(t - t')\, dt' \tag{6 3}$$

Here the integral may be viewed as a sum of sequential pulses, $x(t - t')$, weighted according to how long ago they occurred. The Fourier transform of this equation allows one the corresponding viewpoint in the frequency domain

$$y(\omega) = G(\omega)\, x(\omega) \tag{6.4}$$

i e , the transfer function, $G(\omega)$, is a weighting factor that, when applied to the input amplitude at each frequency, gives the output amplitude at that frequency.

6-1.4 Spectral Density

Whereas the transfer function treats the dynamic relation between two variables in the frequency domain, the spectral density characterizes a single variable, also in the frequency domain. Table 6.1 gives its definition in terms of the Fourier amplitude of a signal as well as its relation to the autocorrelation function (discussed below) Figure 6.2 shows the physical interpretation of the spectral density it is the power, P(f) df, in the frequency band df present in the signal x(t). In this conceptual measurement it is the time average of the current and voltage across a unit resistor.

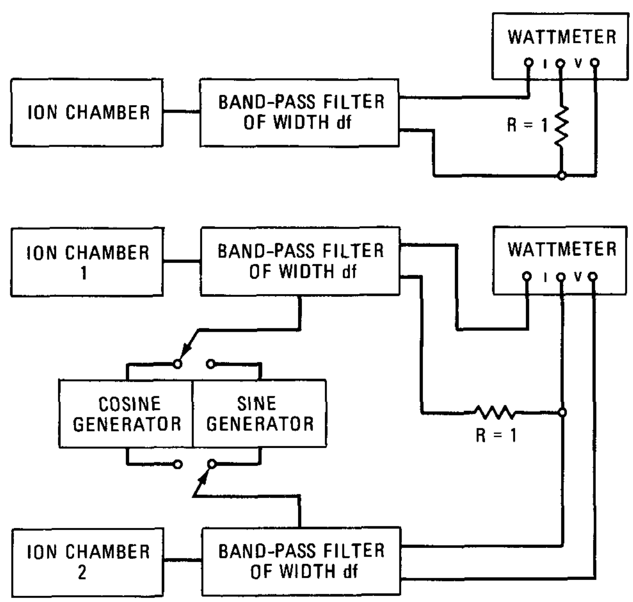


Fig. 6.2—Conceptual experimental arrangements to measure the spectral density of an ion chamber (upper) or the cross spectral density of two chambers (lower) with the current, i, and voltage, v, inputs of a time-averaging wattmeter

A signal considered as a function of time may consist of three contributions

1. A steady-state, or d-c, value, which is the time average of the signal.

2 Discrete frequency components, $a_1 \sin(\omega_1 t + \phi_1)$, $a_2 \sin(\omega_2 t + \phi_2)$, etc

3. A continuum of frequency components make up the randomly fluctuating or nonperiodic part of the signal.

The spectral-density concept applies primarily to the last. Spectral densities associated with the first two contributions are additive with the total of the third

$$P_{total} = (\bar{x})^2 + \left(\frac{a_1^2}{2} + \frac{a_2^2}{2} + \qquad \right) + \int_{-\infty}^{+\infty} P(f)\, df \qquad (6\ 5)$$

If the signal is a current through a resistor, the three terms are, respectively, the d-c power, the a-c power of discrete frequencies, and the a-c power of random noise The usefulness of the spectral-density concept is in characterizing the last term, and hence P(f) is sometimes called a random-noise spectrum.

Fundamental relations associated with spectral density are given in Table 6.3. As also indicated in Table 6.1, the

Table 6.3—Formulas Associated with Spectral-Density Analysis of a Random Signal, x(t), Having a Zero Mean Value

Description	Formula
Fourier integral relations between x(t) and its transform X(f)	$x(t) = \int_{-\infty}^{\infty} X(f) \exp(i\omega t)\, df$
	$X(f) = \lim_{T \to \infty} \int_{-T/2}^{+T/2} x(t) \exp(-i\omega t)\, dt$
Spectral density from Fourier amplitude	$P(f) = \lim_{T \to \infty} \frac{\lvert X(f) \rvert^2}{T}$
Total spectral power = variance = square of standard deviation = autocorrelation function at zero lag	$P_t = \int_{-\infty}^{\infty} P(f)\, df$
	$= \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} [x(t)]^2\, dt = \overline{x^2}$
	$= \sigma^2 = C(0)$

spectral density may be obtained from Fourier amplitudes or, alternatively, by integration of an autocorrelation function. Ideally the signal duration, T of Table 6.3, would be infinite. In practice, the finite duration of the signal available for spectral analysis is an important experimental limitation (see Sec 6-7).

6-1.5 Cross Spectral Density

Just as the spectral-density function, P(f), is used to display the relative importance of various frequency components in a single random signal, the cross spectral density, $P_{xy}(f)$, is used to show the joint importance of these frequency components in two related random signals, x(t) and y(t). Its definition in terms of Fourier amplitudes and in relation to the cross-correlation function is given in Table 6.1. Evidently the cross spectral density is a more general concept, which reduces to the simple spectral density, P(f), for the case x = y.

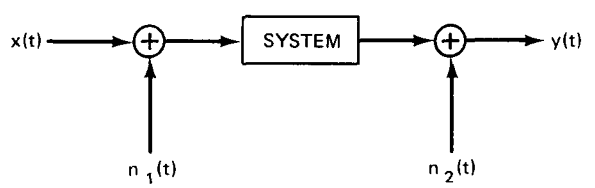
Figure 6.1 shows conceptually how one might measure the cross spectral density using a wattmeter and filters with switchable phased outputs. With the switches in the positions indicated, a quadrature spectral density is indicated by the time-average value of the current from one chamber and the 90° phase-shifted voltage from another, if the filters are switched in phase, the meter shows the cospectral density. In both instances the extent to which the two signals are similar in a frequency band df is being measured.

Unlike the spectral density, P(f), but like the transfer function, the cross spectral density, $P_{xy}(f)$, requires two numbers at each frequency for its specification. These may be the "co" and "quadrature" spectral values or the amplitude and phase, with the relations

$$\begin{aligned} \lvert P_{xy} \rvert^2 &= (\text{cross-spectrum amplitude})^2 \\ &= (\text{cospectrum amplitude})^2 + (\text{quadrature spectrum amplitude})^2 \\ &= (Co_{xy})^2 + (Qu_{xy})^2 \end{aligned} \qquad (6.6)$$

$$\begin{aligned} \theta &= \text{phase angle} \\ &= \arctan \left| \frac{\text{quadrature spectrum amplitude}}{\text{cospectrum amplitude}} \right| \\ &= \arctan \frac{Qu_{xy}}{Co_{xy}} \end{aligned} \qquad (6\ 7)$$

Because of the similarities in the descriptions of the transfer function and the cross spectrum, it is not surprising to find that these are related, as shown in Fig 6 3. In spite



Transfer-function relation $Y(s) = G(s)\,[X(s) + N_1(s)] + N_2(s)$

where $N_1(s)$ and $N_2(s)$ are Fourier transforms of n_1 and n_2

Spectral-density relation $P_y = \lvert G \rvert^2\, [P_x + P_{n_1}] + P_{n_2}$

Cross-spectral-density relation $P_{xy} = GP_x$

Fig. 6.3—Input–output relations of Fourier transforms and spectra in a system having uncorrelated additive noise signals, n_1 (t) and n_2 (t), at its input and output

of additional signals (such as unwanted noise) at the input and output, a simple relation exists the transfer function, G, times the input spectral density, P_x, is the cross spectral density, P_{xy} On the other hand, only when the unwanted signals can be neglected are the input and output spectral densities related by the square of the transfer function.

A quantity called coherence, $c_{xy}(f)$, has been defined to quantitatively assess the extent to which the presence of

the additional uncorrelated signals are not negligible when relating x and y

$$|c_{xy}(f)|^2 = \frac{|P_{xy}|^2/|P_x|^2}{P_y/P_x} = \frac{|P_{xy}|^2}{P_xP_y} \quad (6.8)$$

Its square is the ratio of $|G|^2$ (the numerator) to the spectral-density ratio (the denominator), the latter being $|G|^2$ plus effects from extraneous signals n_1 and n_2, according to Fig. 6.3. In frequency ranges over which $c_{xy}(f)$ is 1 or nearly so, the input and output can be related with negligible effects from other uncorrelated signals. Conversely, the input and output can be considered virtually uncorrelated in frequency ranges where $N_1(f)$ and/or $N_2(f)$ are large enough to cause $c_{xy}(f)$ to be near zero Evidently the ease of making transfer-function measurements will be in proportion to how near $c_{xy}(f)$ is to 1.

6-1.6 Autocorrelation

Table 6.1 shows that the function in the time domain that corresponds to the spectral density is the autocorrelation function $C(\tau)$. The definition indicates that it is a measure of the amount of correlation existing at a time interval τ in a signal x(t). It has its largest values at $\tau = 0$ and at other time intervals during which the signal has essentially the same value, it is smallest during time intervals over which signal values are uncorrelated. In the example shown in Table 6 2, the autocorrelation function decreases from 1 to e^{-1} in a time τ_c and approaches zero when τ is large. Thus τ_c may be called a correlation time within which signal values are similar and beyond which they are rather unrelated.

Table 6.1 shows that the spectral density, P(f), can be obtained from either the square of the Fourier transform of x(t) or from the transform of its autocorrelation function. Conversely, the autocorrelation function can be obtained by transforming P(f). However, x(t), when random, cannot be reconstructed from either P(f) or $C(\tau)$.

6-1.7 Cross Correlation

The concept of cross correlation is more general than that of autocorrelation since the latter is a special case of the former in which the two signals are the same. The cross-correlation function defined in Table 6.1 is an application to continuous time functions of the digital concept of a correlation coefficient of statisticians if x_i and y_i are two time series of variable values spaced in time (x_i being at the same time as $y_{i+(\tau/\Delta t)}$) in which the degree of correlation is sought, then

$$C_{xy} = \sum_{i=1}^{N} \frac{x_iy_i}{N} \quad (6.9)$$

is a measure of this. However, it is customary to define a normalized correlation coefficient in terms of fluctuations from means.

$$\phi_{xy} = \frac{1}{N\sigma_x\sigma_y}\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y}) = \frac{C_{xy} - \overline{xy}}{\sigma_x\sigma_y} \quad (6.10)$$

where σ_x and σ_y are the standard deviations $\phi_{xx}^{1/2}$ and $\phi_{yy}^{1/2}$ This is +1 or −1 for perfect correlation or anticorrelation, respectively, and is 0 if there is no correlation. The integral expression for cross correlation in Table 6.1 is evidently digitally evaluated in Eq. 6.9.

In the example in Table 6.2, C_{xy} is zero for $\tau < 0$ because the output cannot "know" ahead of time what the perfectly random input, x(t), will be. A significant input–output correlation, however, does exist for values of τ up to the order of τ_c, the correlation time of the system. In other more complex systems, the maximum value of C_{xy} might occur at some time other than zero, in which case a time-lag effect between x and y will have been identified.

Table 6.1 shows the frequency-domain function corresponding to $C_{xy}(\tau)$ to be the cross spectral density, $P_{xy}(f)$ These are Fourier-transform pairs, and, if one is known, the other can be found from the relations shown.

6-2 REACTOR APPLICATIONS

6-2.1 Neutron Kinetics

For a study of the time behavior of reactors, the equations giving the time dependence of the neutron density, N + n (mean value plus deviations therefrom), and the *jth* group of delayed-neutron precursors, $C_j + c_j$, are

$$l\frac{dn}{dt} = [k(1-\beta) - 1](N+n) + \sum_j l\lambda_j(C_j + c_j) + lS \quad (6\ 11)$$

$$\frac{dc_j}{dt} = -\lambda_j(C_j + c_j) + \frac{\beta_j k(N+n)}{l} \quad (6\ 12)$$

where the sum of the delayed-neutron fractions, β_j, is the total fraction, β, λ_j is the decay constant of a precursor, S is a source, l is the prompt-neutron lifetime, and k is the effective multiplication constant that, when not unity, represents the departure of the reactor from exact criticality,

$$\rho = 1 - \frac{1}{k} \quad (6.13)$$

being the excess reactivity.

The solution to these equations, under conditions of all variables undergoing small oscillations about their mean values, is the zero-power transfer function, G_0, defined as

$|G_0|$ = [(amplitude of power oscillation)/(average power)] /(amplitude of reactivity oscillation) (6 14)

and having the phase

Phase angle = 360° × (fraction of a cycle that the power lags behind the reactivity oscillation) (6.15)

The zero-power transfer function can also be regarded as the quotient of the Fourier transforms of the power and reactivity divided by the average power.

Table 6.4 gives explicit formulas for this transfer function in terms of reactor constants and the frequency.

Table 6.4—Forms of the Complex Amplitude of the Zero-Power-Reactor Transfer Function $G_0(\omega)$

Conditions	Formula for complex amplitude of $G_0(\omega)$
No approximations	$\dfrac{1 - i\omega \sum_{j=1}^{6} \beta_j/(\lambda_j + i\omega)}{1 - k + i\omega\left[l + k \sum_{j=1}^{6} \beta_j/(\lambda_j + i\omega)\right]}$
$\omega > 2\bar{\lambda}$	$[1 - k(1 - \beta) + i\omega l]^{-1}$
One delay group	$\left[1 - k + i\omega\left(l + \dfrac{k\beta}{\bar{\lambda} + i\omega}\right)\right]^{-1}$
One delay group and $\omega < \dfrac{1}{2l}[1 - k(1 - \beta)]$	$\left[1 - k + i\omega \dfrac{k\beta}{\bar{\lambda} + i\omega}\right]^{-1}$

Also, G has been tabulated in detail in Ref. 3. In essentially all but subcritical reactor applications, k may be set equal to 1 to further simplify the approximations there. At mid-frequencies, where $2\bar{\lambda} < \omega < 0.5\beta/l$, a very simple result, $G \cong 1/\beta$, exists. At these frequencies the physical interpretation is

Percent power oscillation about its mean

$$= \frac{1}{\beta} \times \text{(percentage reactivity amplitude)}$$

$$= \text{reactivity amplitude in cents} \qquad (6.16)$$

where β is typically 0.007.

6-2.2 Zero-Power Measurements

Historically the rod-oscillator measurement of the zero-power transfer function is one of the oldest reactor-dynamics measurements,[4] dating back to CP-2. Since then it has been repeated many times on many reactors with the techniques detailed below.

Basically, a sinusoidal reactivity excitation provided by a rotating or reciprocating control rod causes a power oscillation that is detected by ion chambers. The purpose of these measurements may be any of the following:

1. To determine β/l for a particular reactor by fitting the measurement to a formula in Table 6.4.
2. To verify experimental techniques on a known transfer function.
3. To compare reactivity effects of small samples by the amplitude of the resulting power oscillation.

A considerable number of methods in addition to the rod oscillator have proved useful in obtaining dynamics information, i.e., in determining quantities closely related to the reactor transfer function. These methods are listed and classified in Table 6.5. Methods having no reactor excitation by external equipment depend on the random fluctuations or noise in the neutron population, as detected by counters or ion chambers, to provide information about reactor characteristics. The following incentives for applying such methods differ slightly from those for the rod oscillator:

Table 6.5—Experimental Methods of Obtaining Dynamic Information from Zero-Power Reactors

Method	External excitation	Detection equipment
Rod oscillation or pseudorandom motion	Control rod	Ion chamber or gamma detector
Source oscillation or pseudorandom changing	Neutron-source generator	Ion chamber
Rossi alpha	None	Coincidence counting
Correlation and spectral analysis	None	Ion chamber or gamma detector (or pair for correlation)
Variance to mean	None	Gate scaler counting, or ion-chamber current integrating
Probability of neutron events	None	Coincidence counting

1. To determine specific reactor parameters, such as β/l at critical, the subcritical reactivity, or the absolute reactor power.
2. To verify experimental techniques on a known system.
3. To investigate spatial neutron effects.

Experiments on the dynamic behavior of zero-power reactors have been numerous and also somewhat repetitious owing to similarities among the reactors and kinds of equipment used. The particular reactors studied along with the classes of information obtained are given in Table 6.6. It will suffice here to point out that the quantities being measured are the constant parameters appearing in the neutron kinetics equations and the transfer function. (The numerous cases in which samples have been oscillated to make reactivity measurements are omitted since the emphasis here is on transfer functions.)

Table 6.6—Results Achieved in Zero-Power Dynamic Studies

Method and excitation	Reactors used	Results
Random pulsing of a neutron source	GE Critical Assembly,[5] Rubeole and Ulysse,[6] UFTR,[7,8] University of Florida subcriticals,[9,10]	β/l, subcritical reactivity
Oscillating control rod	CP-2,[4] DFR,[11] EBR-1 and EBR-2,[12,13] EBWR,[14] Fermi,[15] GTRR,[16,17] KEWB,[18] Kiwi-A,[19] LPTR,[20] LAMPRE-1,[19] NORA,[21] Pathfinder,[22] Penn State,[23] PTR,[24] SHE,[25] SPERT,[26] Zephyr and Zeus[11,27]	β/l, verification of equipment performance
Variance to mean (no excitation)	AGN-201,[28] Cornell,[29] Ford,[30] Homogeneous D_2O Facility,[31] NORA,[21 32] Russian subcritical,[33] SPERT-2 and SPERT-4,[34,35] Tokyo Inst of Technology,[36] ZPR-4,[37,38] ZPR-5[37]	β/l, absolute power level
Pseudorandom control rod	ATSR,[39] Brookhaven,[40] Godiva-II,[41] JRR-3 and SHE,[42 44] MSRE,[44a] Saxton,[45] UFTR[8]	β/l, verification of equipment performance
Spectral analysis and/or autocorrelation (no excitations)	Atomics Int ,[46] Babcock & Wilcox Test Reactor,[47] BSR,[48-49] Battelle Plutonium Assembly,[50] Brookhaven High Flux,[50a] EBWR,[51] Daphne and Jason,[52,53] GLEEP,[54], HFIR,[55] HTR, JRR-1, SHE, and TRR-1,[42 43,55a,55b] Iowa State Univ., UTR-10,[56] KEWB and SRE,[57] LFR,[58] MSRE,[59] NORA,[21] ORNL Pool,[60,61] Penn State,[23] Savannah,[62] Saxton,[63] SPERT-1,[34] SPERT-3, ATRC, ARMF-1, and PBF,[64] SNAP-10A and ETR,[65,66] UFTR,[7,8] Westinghouse CES,[67] ZPR-3, ZPR-4, ZPR-5, ZPR-7, and Argonaut,[68] ZPR-6[68a]	β/l, subcritical reactivity, absolute power level
Two-detector cross correlation (no excitation)	GTRR,[16] JPDR,[55a] Karlsruhe Argonaut,[68b] ORNL Pool,[69] Penn State,[69a] STARK,[70] Savannah SR-305 Pile,[71] TRR-1,[72] ZPR-9[73]	β/l, subcritical reactivity, local power distribution

Section 6-3, Methods of Measurement, summarizes the features of the various methods and how the results in Table 6.6 are obtained

Although neutron detectors have been used in virtually all the zero-power dynamics studies to date, there has been some theoretical[73a] and experimental[23,69a] work involving gamma detectors. Čerenkov detectors and liquid scintillators have been found suitable for monitoring the fluctuations of prompt gammas from fission. The emission of these gammas, like the neutrons, exhibits statistical fluctuations that depend on the reactor's zero-power transfer function. Since gammas travel farther than neutrons in a reactor, the prompt gammas offer a means of using peripheral detectors to monitor deep into the core of a large reactor In one novel application[69a] two widely separated gamma detectors were pointed in collimated fashion at various fuel elements, and relative local power values were obtained by cross correlation.

6-2.3 Power-Reactor Feedback

The neutron kinetics equations (Eqs. 6 11 and 6.12) that were applied to zero-power reactors also hold for power reactors However, additional relations exist here between reactor power and reactivity because the former is high enough to cause effects on the latter (see Fig. 6.4). This feedback of reactor power to reactivity is the important characteristic of power-reactor dynamics. As might be expected, transfer-function measurements are used to obtain information about this feedback.

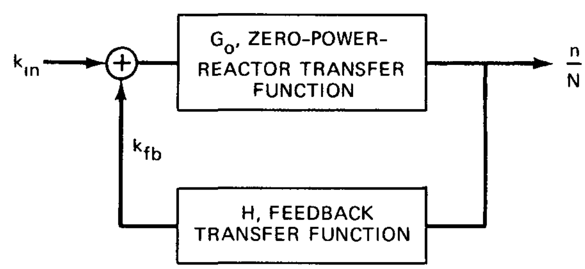


Fig. 6.4—Relations between the feedback and the zero-power transfer functions which make up the transfer function of a power reactor

Equations that relate power to reactivity can be numerous and complex, depending on the system. Specific forms for boiling- and pressurized-water reactors have been summarized [74] Where commonly a set of linear differential equations adequately represent the system, the feedback transfer function from power to reactivity may be written

$$\frac{k_{fb}(s)}{n(s)/N} = H(s) = \sum_i \gamma_i \frac{\prod_j (1 + \tau_{ij} s)}{\prod_k (1 + \tau_{ik} s)} \qquad (6.17)$$

Table 6.7—Results Achieved in At-Power Dynamics Studies

Method and excitation	Reactors used	Results
Oscillating control rod	BORAX-4 and BORAX-5,[75,76] DFR,[11] EBR-1 and EBR 2,[12,13 77] EBWR,[14,78] Fermi,[15] GE BWR,[79] HTR,[80] JPDR,[80a] SPERT 1,[26] SRE,[81] VBWR[82]	Stability study, feedback determination
Pseudorandom control rod	Kiwi-A3,[41] MSRE,[44a,83] Saxton,[84,85] JRR-3[85a]	Stability study, control-system study
Spectral analysis (no excitation)	BORAX-1, -2, -4, and -5,[75,76,86] Chapelcross,[87] Dresden,[88] EBR-2,[89] EBWR,[90-92] Elk River,[93] GTR,[94] HBWR,[95] HFIR and ORR,[59,96,97] HFBR,[98] HRE-2,[99] HTR and JRR-1 and JRR-2,[42,43,80,100,100a] Indian Point, Savannah, and Yankee,[62] JPDR,[55a,100a] Kyoto Univ.,[101] ML-1,[102] Pluto,[53] Saxton,[63] SPERT-4,[103] SRE,[81] THOR,[104] Trino,[85] VBWR[105,106]	Stability study, noise-source determinations
Pseudorandom plant control	Nerva,[107] Phoebus 1A,[108] SNAP[109]	Intervariable transfer functions
Cross correlation and spectral analysis	DFR,[110] DMTR,[110a] SNAP,[46] Pathfinder[111]	Stability study, intervariable transfer functions, noise-source determinations

where $s = i\omega$ and the values of τ are time constants associated with a system variable that has a feedback reactivity change of γ_i percent for a 1% power change (in the limit of very slow transients).

The transfer function between an external excitation reactivity, k_{in}, such as an oscillator rod, and the reactor power is the solution of Eqs 6 14 and 6.17 if $k = 1 + k_{in} + k_{fb}$ is used

$$G(s) = \frac{G_0(s)}{1 - G_0(s)\, H(s)} \qquad (6.18)$$

Since G_0 is well known, this equation is generally used to obtain H(s) or G(s) from the other

6-2.4 Power-Reactor Measurements

Measuring the dynamic characteristics of power reactors is commonly accepted to be an integral part of testing during reactor commissioning. Transient response to externally induced system changes is perhaps the most popular category of such tests. However, transfer-function and noise-spectrum measurements are also common It is not unusual for the latter to be required by AEC licensing in the interest of safety.[74a] The incentive for transfer-function and noise testing usually stems from the desire for a more detailed knowledge than is possible from the transient tests.

The possibility that the denominator of Eq. 6.18 will approach zero and result in an unstable oscillatory system is one important reason for measuring and understanding G(s). On the other hand, for reactors known to be quite stable, measurements of G(s) can give H(s) if Eq 6.18 is used. The term H(s) gives information about reactor and plant parameters, such as the constants in Eq 6 17

Transfer-function measurements in power reactors are not restricted to rod-oscillator tests. The next section shows that a considerable variety of methods involving variables other than just reactivity and power are used Table 6.7, listing the many power-reactor transfer-function and related spectral-analysis experiments, gives an idea of the wide applicability of the techniques given in Table 6 8

In power-reactor dynamics it is often desirable to know transfer functions among a variety of variables, not necessarily just between reactivity and power. Thus it is not uncommon to simultaneously measure a number of transfer functions, or spectral-density functions, by simultaneously measuring pairs of system variables over a period of time In the experiments listed in Table 6 8, the primary interest is

Table 6 8—Experimental Methods of Obtaining Dynamic Information from Power Reactors

Method	External excitation	Detection equipment
Rod oscillation or pseudorandom motion	Control rod	Ion chamber and other transducers
System excitation	Valve, pump, etc	Ion chamber and other transducers
Correlation and spectral analysis	None	One (or more for correlation) ion chamber and other transducers
Event analysis	Any cause	All detectors that respond to the transient event

usually in the neutron-flux fluctuations, but other fluctuation variables have also been analyzed, namely, pressure, flow, acoustical noise, temperature, gamma flux, valve position, and pump speed. These, along with the reactivity and power, represent principal variables of interest in dynamics analyses.

6-3 METHODS OF MEASUREMENT

6-3.1 Reactor Excitation

To determine the dynamic characteristics of a system, one must measure variables that are changing with time Furthermore, the variations must have the following properties

1. Amplitudes sufficient to override unwanted effects that could reduce accuracy.
2. A sufficiently long duration or a sufficient number of repetitions to provide the desired accuracy
3. Frequencies in the ranges to be investigated

If the intrinsic variations, or random noise, of a system are used, the system is said to be self-excited. On the other hand, a system is said to be externally excited if a perturbation is introduced by a signal-generating device. In both instances transducers responsive to the variations of interest provide the experimental data.

Table 6.9 lists the kinds of excitation that have been used to date. The relative popularity of the various forms of excitation (Tables 6.6 and 6.8) is indicated somewhat arbitrarily by the number of dynamics experiments that have used each form. Transfer functions and related functions have been emphasized in Tables 6.6 and 6.8 Many other* dynamics tests (such as valve-position changes in power plants, rod drops, positive-period tests, and Rossi-alpha coincidence counting) are not represented even though they may be somewhat related to the tests discussed here. With this understanding the predominance of self-excitation experiments indicated in Table 6.9 can be attributed, at least in part, to their experimental simplicity (from the standpoint of reactor hardware). Also, although this table shows more periodic devices than random devices used as externally induced excitation, a trend in recent years to increased use of random excitation must be noted.

For externally excited experiments, a variety of methods is used (see Table 6.10) Except for the occasional use of on-line electronic analyzer methods, most experiments do not give transfer functions until the recorded data are processed off-line. Both electronic analyzers and digital computers are used for this processing.

As noted in Table 6.8, the excitation may be sinusoidal or pseudorandom and either a control rod or some other plant control device may be used to excite the system In sinusoidal excitation the transfer function between the excitation variable (such as the reactivity of a control rod) and the system output variable (such as the reactor power) may be obtained at the excitation frequency by any one of the following approaches

1. Using the separately measured fundamental frequency amplitudes and phases of input and output, applying Eq 6.1 or Table 6.1.
2. Applying the appropriate electronic gain and phase to the output and using it to "null out" the input signal (see Sec. 6-5.2).
3. Cross-correlating the input and output signals, using Eq 6.9 in digital processing or Table 6.1 in continuous processing (see Sec. 6-5.4)

The last approach is commonly used at present.

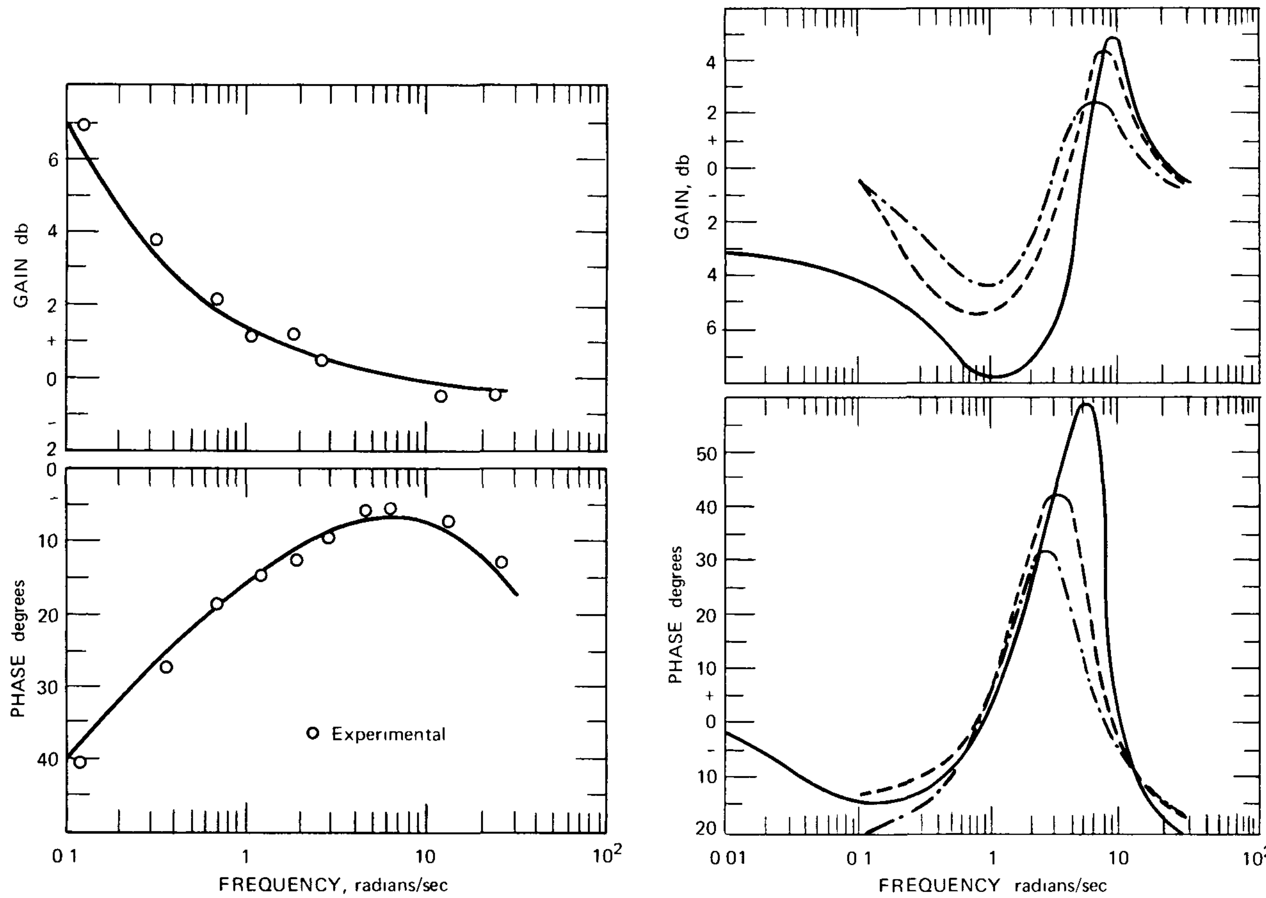
Table 6.9—Relative Use in Reactor Dynamics of Excitation Devices for Measurement of Transfer Functions and Allied Functions

Type of fluctuations	Percentage of zero-power-reactor (ZPR) or power-reactor (PR) experiments using a particular excitation device							
	Neutron source		Control rod		Other		Self-excited	
	ZPR	PR	ZPR	PR	ZPR	PR	ZPR	PR
Periodic–sinusoidal	0	0	22	23	0	0	0	0
Nonperiodic–random	6	0	8	6	0	6	64	65
Total, %	6	0	30	29	0	6	64	65

Table 6.10—Data-Acquisition and Data-Processing Techniques Used in Externally Excited Reactor Dynamics Experiments

On-line acquisition device	Off-line processing device	References to typical applications
Chart or film recorder	Digitizer, digital computer	18, 76
Electronic analyzer	None	11, 14
F-m tape recorder	Electronic analyzer	44, 85
F-m tape recorder	Digitizer, digital computer	44, 107
Digitizer, tape recorder	Digital computer	53, 78

*These tests may be used to measure specific effects rather than to extract transfer functions



Power MW	Zero (6 kW)
Pressure psi	150
Center rod, in	13 6
8-rod bank, in	14 5
Peak reactivity % for 1-in peak stroke	0 087

Curve	— · —	– – –	——
Power MW	5 4	9 7	19 9
Pressure, psi	550	550	550
Center rod in	13 6	13 8	23 7
8-rod bank in	24 1	29 0	33 0
Peak reactivity % for 1-in peak stroke	0 071	0 089	0 043

Fig. 6.5—Transfer functions of the Experimental Boiling Water Reactor at various power levels as obtained by the rod-oscillator null-balance method.[14] Curves at left show frequency response at zero power Curves at right are for 5.4, 9 7, and 19.9 MW(th)

Figure 6.5 shows typical rod-oscillator test results for a boiling-water reactor. In such tests one is interested in the difference between the at-power transfer function and the zero-power transfer function for this can determine the feedback, H, in Eq 6 17. In addition, the height and width of the resonance (in this example at ω = 7 radians/sec) are of interest because they indicate the extent to which an instability of self-sustained oscillations is being approached

In pseudorandom excitation you attempt to introduce all frequencies in the band of interest into the system at once rather than sequentially as in sinusoidal testing. In the commonly used binary excitation, an input control signal has two values, such as +1 and −1, however, ternary signals (having values +1, 0, and −1) have been suggested[112] Rather than letting the duration of +1 and −1 values be determined by an ideal random process, it is more advantageous to use a repetitive almost-random signal,[41] such as that shown in Fig 6 6

In analyzing data in pseudorandom excitation experiments, you obtain the cross-correlation function by either on-line or off-line integration

$$C_{xy}(\tau) = \frac{1}{T} \int_{-T/2}^{T/2} x(t)\, y(t + \tau)\, dt \qquad (6.19)$$

using the time-shifted product of the input variable, x(t), and the output variable, y(t). Figure 6.7 shows a typical experimental result. Using the relations in Table 6.1, you obtain the transfer function from $P_{xy}(f)$, the Fourier transform of $C_{xy}(\tau)$

$$G(f) = \frac{P_{xy}(f)}{P_x(f)} \qquad (6.20)$$

With x(t) perfectly random, it can be shown that $C_{xy}(\tau)$ in Eq 6.19 is the system impulse-response function[41] and $P_x(f)$ in Eq. 6.20 is a constant. The transfer function in Fig. 6.7 was obtained in this manner.

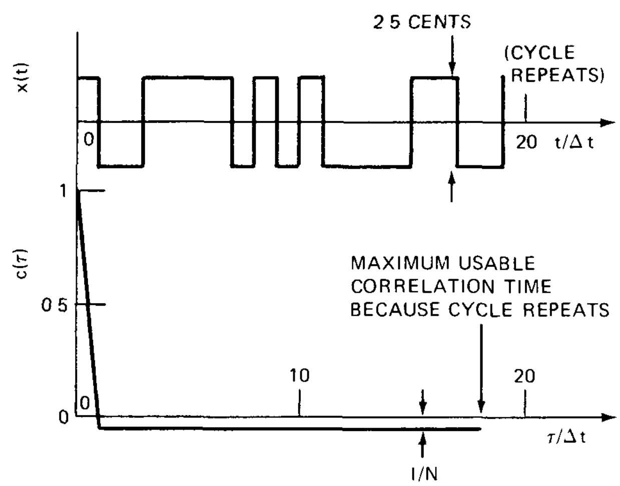


Fig. 6.6—A simple pseudorandom signal (above) that has been tailored to give the almost ideal autocorrelation function (below)[113]

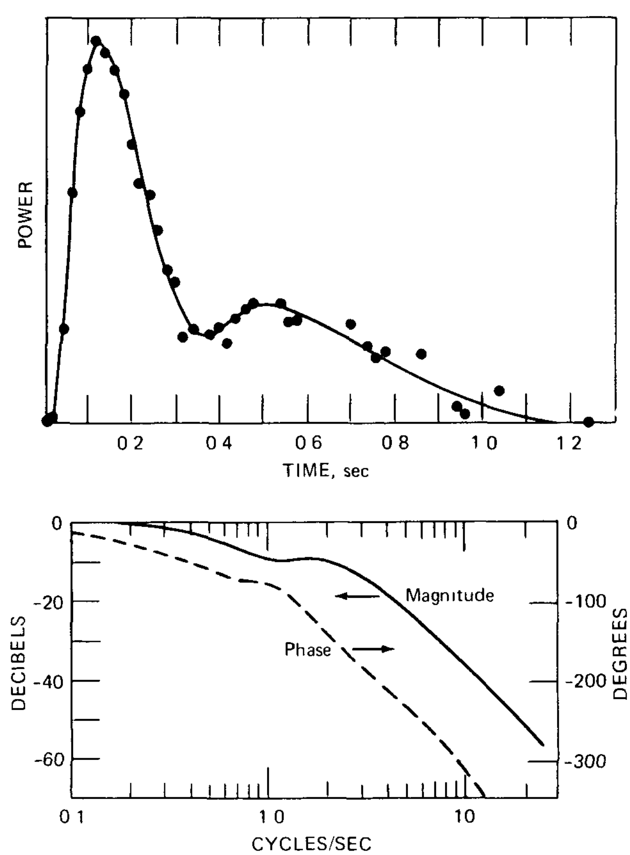


Fig. 6.7—Impulse response obtained by cross-correlating reactor power and a pseudorandom control rod in Kiwi A3 (upper curve) and the transfer function of this reactor (lower curves)[113]

It is not usual to measure transfer functions by pulse or step excitation, although this is possible.[59] In the method the quotient of Fourier amplitudes is taken from an analysis of the input and the output signals to obtain the transfer function However, it is preferable to have a series of pulses or steps, such as pseudorandom excitation, because the added signal energy helps overcome unwanted noise.

6-3.2 Noise Methods

Noise techniques, the class of reactor dynamics experiments in which no external excitation signal is used, are among the categories listed in Table 6 6, namely

1. Variance-to-mean method (sometimes called the Feynman method)
2. Spectral analysis or the time-domain equivalent, autocorrelation.
3. Cross spectral analysis or the time-domain equivalent, cross correlation.

Other noise-analysis techniques (such as various kinds of probability analysis of individual pulses) are not sufficiently related to transfer functions to warrant discussion here, but they have been treated in Refs. 113, 113a, and 113b along with the three techniques cited above. In power reactors only the last two methods are used, whereas in zero-power reactors all three methods can be used.

Whether reactor dynamics are studied by introducing external excitation or by relying on the reactor's intrinsic self-induced noise, the data-acquisition and data-processing hardware are almost the same. Noise methods, of course, process no signals from excitation equipment Table 6.11, having much in common with Table 6.10, shows the types of equipment used in the various noise-analysis experiments described briefly here. Most of the equipment is used for spectral and cross spectral analysis, and only that involving the gate scaler or ion-chamber current integrator is used for the variance-to-mean method

Table 6.11—Data-Acquisition and Data-Processing Techniques Used in Reactor-Noise-Analysis Experiments

On-line acquisition device	Off-line processing device	References to typical applications
Chart recorder	Digitizer, digital computer	90, 111
Electronic analyzer	None	67, 72, 113c
F-m tape recorder	Electronic analyzer	46, 63, 110
F m tape recorder	Digitizer, digital computer	109
Digitizer, tape recorder	Digital computer	92, 95
Digital computer	None	68a, 73
Pulse tape recorder	Gate scaler, digital computer	30
Gate scaler	Digital computer	34, 35
Ion-chamber current integrator	Digital computer	38

In the variance-to-mean method, the dynamic constants in the neutron kinetic equations can be determined by using a digital computer to give

1 The variance of neutron-detector counts $[\overline{c^2} - (\bar{c})^2]$ taken many times over a time interval or "gate," τ.

2. The average count, $\bar{c}$, during τ

Results for various gate times[30] can be shown to conform to the following equation

$$\frac{\overline{c^2} - (\bar{c})^2}{\bar{c}} = 1 + 1.59\epsilon \sum_{j=1}^{7} \frac{A_j}{\gamma_j} G_0(\gamma_j) \left(1 - \frac{1 - e^{-\gamma_j \tau}}{\gamma_j \tau}\right) \quad (6.21)$$

Figure 6 8 shows an example of this relation.

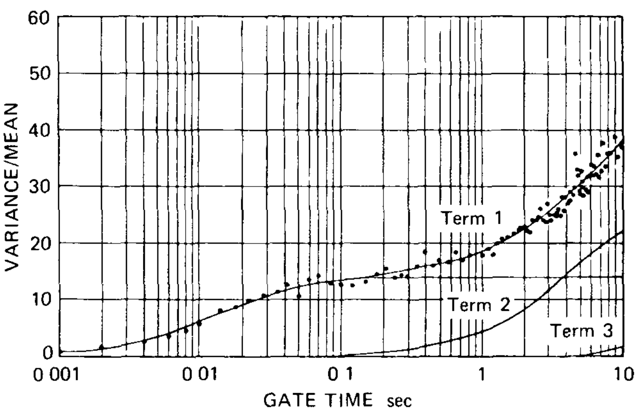


Fig. 6.8—Results of determinations of the variance-to-mean ratio for many counter gate times on the Ford reactor.[113]

The constants of Eq 6 21 appear in the zero-power transfer function

$$G_0(\omega) = \sum_{j=1}^{7} \frac{A_j}{\gamma_j + i\omega} \quad (6.22)$$

and are given in Table 6.12. By fitting Eq. 6.21 to data, as in Fig 6.8, you can evaluate the constants, especially $\gamma_1 = (\beta - \rho)/l$

Related to this method are others, such as the Mogil'ner method,[33] based on the probability of no counts in a time interval, and a count interval-distribution method of Babala [32] These and many similar techniques of time-domain analysis of neutron pulses in zero-power reactors have been extensively reviewed in Refs 113a and 113b

The constant ϵ in Eq 6.21 is important in noise measurements of zero-power reactors It is the detector efficiency and is defined as

$$\epsilon = \frac{\text{number of counts/sec}}{\text{number of reactor fissions/sec}} \quad (6.23)$$

Evidently ϵ is the probability of detecting an individual fission. Counters are located in or quite near the reactor core to obtain the values above about 10^{-5} which are needed for a successful experiment. For very large reactors only a zone near the detector contributes neutrons and determines an effective efficiency.

Spectral analyses of ion chambers or fluctuations of other variables are usually accomplished experimentally in one of two ways (1) by passing the signal through a narrow band-pass filter tuned sequentially to the various desired frequencies or (2) by obtaining the autocorrelation function of the signal and then performing a Fourier analysis at the various desired frequencies. (Direct Fourier analysis of the signal is rarely done.) Table 6.11 indicates the various combinations of equipment that can be used to accomplish one or the other of these approaches

In spectral analysis of the signal from an ion chamber in a zero-power reactor, the shape of the transfer function, G_0, is obtained directly from the measured P(f) of the detection of particles by using the relation[113]

$$\frac{P(f)}{\epsilon F_0} = 1 + 0.795\, \epsilon |G_0(f)|^2 \quad (6.24)$$

where F_0 is the number of reactor fissions per second Again ϵ must exceed about 10^{-5} for successful experiments

For the ion-chamber noise in a power reactor, the spectrum $P_n(f)$ of n(t) in Fig 6 4 is measured, its fluctuations being induced by an internal noise source, $k_{in}(t)$ Evidently,

$$P_n(f) = |k_{in}(f)|^2 \; |G(f)|^2 \quad (6.25)$$

where G(f) is given by Eq 6 20 Thus ion chamber noise analysis in a power reactor gives information about both the transfer function and the input reactivity noise

Table 6.12—Constants Associated with the Zero-Power Transfer Function for a ^{235}U-Fueled Reactor Near Delayed Criticality

	j = 1	j = 2	j = 3	j = 4	j = 5	j = 6	j = 7
γ_j	$\frac{\beta - \rho}{l}$	2.89	1.02	0.195	0.068	0.0143	-11.6ρ
A_j	$\frac{1 - \beta}{l}$	29	20	11.2	6.1	1.2	11.6
$G_0(\gamma_j)$	$\frac{1 - \beta}{\lambda(\beta - \rho)}$	164	186	237	284	343	$415 - (0.5/\rho)$

Figure 6 9 shows typical results for power operation and how the spectrum differs from the zero-power spectrum Figure 6 10 indicates that large pressurized-water reactors of similar structure have similar noise spectrums

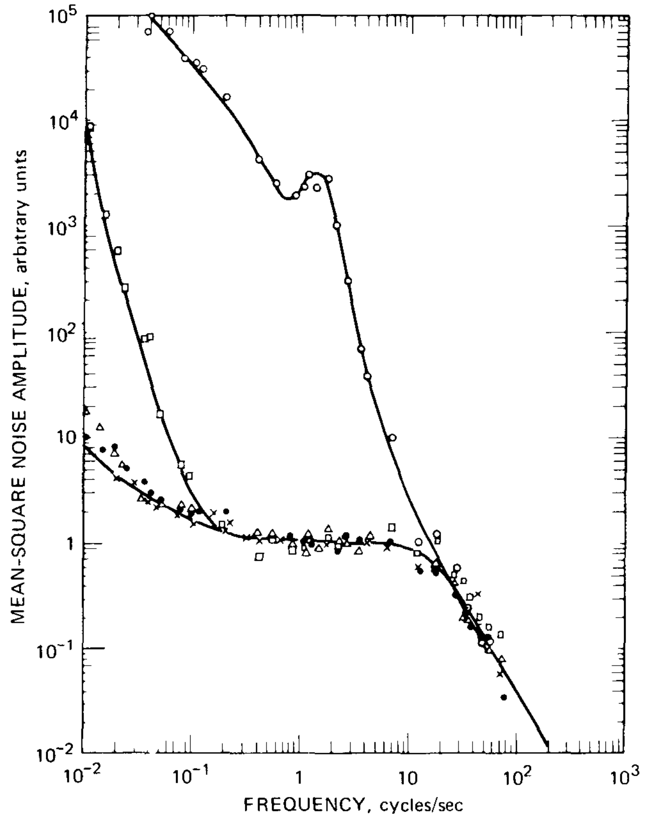


Fig. 6.9— Spectral density measurements of ion-chamber noise in the Hanford Test Reactor at powers of 1 watt (x), 5 watts (●), 500 watts (△), 5 kW (□), and 100 kW (○) [80]

In the more informative power reactor experiments, two signals are observed simultaneously and correlated to obtain a transfer function between them One way to do this follows from Eqs 6.19 and 6 20 The terms x(t) and y(t) are any two system variables whose fluctuations are related After their cross correlation function has been measured, their cross spectrum can then be determined An accurate transfer function can be obtained from Eq. 6 20 if x(t) and y(t) depend primarily on the same noise-source excitation, i e , if they have a high coherence, Eq 6 8.

As indicated in Table 6 11, a cross-spectrum analyzer can be used directly, it is not necessary to determine the cross-correlation function first Equation 6.20 is still used to obtain a transfer function As in cross correlation, only two variables at a time are treated in multivariable systems

In Table 6.6 a number of cross-correlation and cross-spectrum experiments in zero-power reactors are noted This approach has been used to measure a quantity proportional to just the second term of Eq 6 24 since the cross spectral density of detection events in two ion chambers is[70,72]

$$P_{xy}(f) = 0.795\epsilon_1\epsilon_2 F_0 \, |G_0(f)|^2 \qquad (6\ 26)$$

where ϵ_1 and ϵ_2 are their efficiencies Although accuracy analysis[70] indicates that $G_0(f)$ may theoretically be determined to the same precision from Eq 6 24 or 6 26 (assuming the same total detection volume, location, and data-collection time for the single detector and the pair of detectors), experimentalists have indicated preference for the method using two detectors

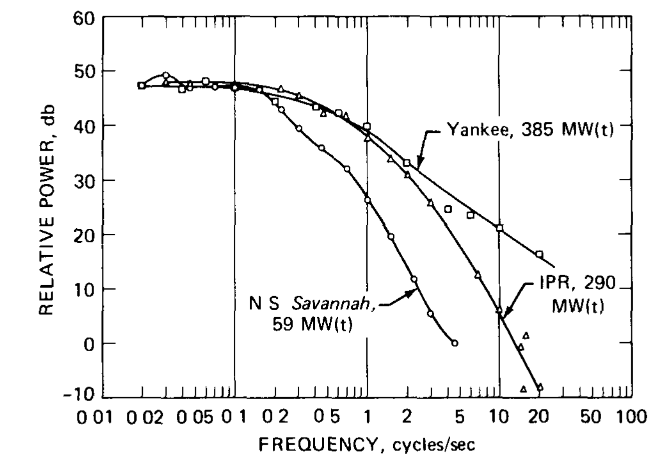


Fig. 6.10—Spectral-density measurements in three large pressurized-water reactors [62] □, Yankee, 385 Mw(th) △, Indian Point, 290 MW(th) ○ N.S. *Savannah*, 59 MW(th). All show the usual reduction in frequency content at higher frequencies caused by intrinsic values of system time constants

6-3.3 Comparison of Methods

When the various methods of obtaining information about the reactor transfer function are compared (from the standpoint of which might be the most appropriate to use), many factors appear

1 Structure, operating conditions, and physical limitations of the reactor system

2 Available time, personnel, equipment, and money

3 Type of information desired

4 Accuracy desired

5 Established operating and experimental policies of the plant

The various methods described in preceding sections are treated here with this set of determining factors in mind

A distinction is made between methods involving system excitation by external apparatus and those which rely on internally generated noise. In Table 6.13 an attempt is made to evaluate the methods in a general fashion, however, it should be noted that variations in the methods or special "ground rules" for comparison may lead to exceptions

Whether an input excitation signal is applied to a neutron absorber or to a plant control device will depend

primarily on the information desired and secondarily on convenience. When this selection has been made, the signal may then be chosen to be either sinusoidal or pseudorandom In recent years there has been some preference for pseudorandom signals which simultaneously measure all frequencies in the band of interest Pseudorandom excitation has been preferred[107] because smaller perturbing amplitudes can be used and less reactor time is required for obtaining a given frequency resolution (see also Sec 6-7).

Table 6.13—A General Qualitative Comparison of Excitation Experiments with Intrinsic Noise-Analysis Experiments

	Excitation	Noise
Experimental complexity and cost	More	Less
Interpretation of data	Easy	Difficult
Disturbance to reactor system	Some	None
Measures transfer function	Always	Sometimes
Measures spectra	No	Yes
Typical precision	High	Medium

For the noise methods there is no input signal injection However, there must be sufficient internally generated noise in the frequency band of interest to excite the one or more variables being investigated. If this is the case, then selection of the appropriate data-acquisition and data-processing devices is the major consideration, as is also true for excitation experiments In the following sections the types of equipment are described and their relative merits are assessed

Whether one or more than one signal is used in noise analysis depends on the information desired Transfer functions in power reactors normally require two signals Furthermore, these must have sufficient coherence, Eq 6 8, in the frequency band covered to achieve the accuracy desired, i e , the effects of the same noise source—to a larger extent than separate independent noise sources—must be seen in both signals Besides giving the amplitude and phase of transfer functions, these multisignal experiments also may provide insight into the cause of the intrinsic noise

6-4 REACTOR EXCITATION EQUIPMENT

6-4.1 Excitation Signal

In experiments using external excitation, a plant control device, often a reactor control rod, is moved in accordance with a prescribed signal while the prescribed signal and one or more output variables are recorded The signal is usually either sinusoidal or pseudorandom (such as Fig. 6.6) With the former the transfer function expressed in complex form is simply

$$G(\omega) = \frac{B}{A} e^{i\phi} \qquad (6\ 27)$$

for an output variable B sin ($\omega t + \phi$) With a pseudorandom signal the input and output must be cross correlated and a Fourier transform carried out on the result (see Sec 6-3)

As a signal generator in these experiments, one of the following may be used a function generator (of sine waves usually), a stored function on tape (usually pseudorandom), or a random or pseudorandom electronic noise generator It is important that the function-generator output not deviate significantly from a constant frequency and that it contain no significant harmonics The function generator might take any of the following forms a constant-speed motor driving a control actuator, an electronic oscillator driving a control-positioning circuit, or a square wave ("up" or "down") or ternary signal ("up," "hold," or "down") driving a control switch. Regarding pseudorandom noise generation, a stored tape has been used[41] as well as an on-line generator [107] Some experiments use commercial random-noise generators [84]

An important characteristic of the excitation variable is its amplitude The amplitude must be large enough to overcome unwanted noise without requiring excessively long experimental times It will be shown in Sec 6-7 that the amplitude, unwanted noise, and test duration all combine to determine the accuracy of the result

The amplitude cannot be made arbitrarily large, however, since nonlinear aspects of the system can complicate data analysis It can be shown[91] that, because of nonlinearities in the neutron kinetics equations, Eqs 6 11 and 6 12, one type of nonlinearity resulting from a sinusoidal reactivity excitation is a power function

$$N(t) = N_0 + N_1 \sin(2\pi ft) + N_2 \sin(4\pi ft + \theta) + \qquad (6\ 28)$$

where the harmonic to-fundamental ratio is

$$\frac{N_2}{N_1} = \frac{1}{2}\frac{N_1}{N_0}\frac{|G_0(2f)|}{|G_0(f)|} \qquad (6\ 29)$$

This usually means that the harmonic content is of the same order of magnitude as the modulation fraction, N_1/N_0

Another important characteristic of the excitation signal is its frequency band The frequency content desired depends on the information to be obtained It is sufficient that frequencies cover the band

$$\frac{0\ 5}{\tau_{max}} < 2\pi f < \frac{2}{\tau_{min}} \qquad (6.30)$$

if τ_{max} and τ_{min} are the largest and smallest system time constants of interest In practice the amplitudes and frequencies attainable may not be those desired because of equipment limitations, so compromises may be required. Although there is little difficulty in attaining the lowest frequency desired, either the available power or the

limitations of materials are likely to place a limit on the highest frequency attainable. Also, the inverse relation between amplitude and frequency, if constant-speed motors are used (e.g., to drive a control rod in and out in a periodic triangular wave shape), places limits on the maximum frequency

$$\text{Peak-to-peak amplitude} = \frac{\text{linear rod speed}}{2 \times \text{frequency}} \qquad (6.31)$$

6-4.2 Control Device

In reactor dynamics experiments the variable directly excited affects reactivity either directly, as in the motion of a control rod, or indirectly, as in the alteration of some system parameter (flow, pressure, etc.) Some ways in which reactivity can be varied are

1. By a specially installed rotary or reciprocating control rod.
2. By moving the normal control rod of the reactor through special switching or signal injection into the automatic control system.
3. By changing valve position, pump output, etc, usually by signal injection into its control system.

It is not surprising that 2 and 3 are more commonly encountered than 1, except perhaps in special-purpose experimental reactors, since they require relatively little modification of the existing system.

Among the specially installed rod oscillators, there is some preference for the rotary type over the reciprocating type, usually because of the higher frequencies attainable. Rotary types use the following methods to vary reactivity (see Fig 6.11) eccentric neutron absorbers rotating in a flux gradient,[19,26] eccentric fuel rotating in a flux gradient,[11] or neutron absorbers rotating past similar stationary absorbers which act as time varying shields[18] Usually neutron absorbers are oscillated with typical reactivity amplitudes being in the 0.5¢ to 5¢ range In zero-power fast reactors, fuel can be oscillated, however, this is unusual.

Regardless of the device used to perturb the reactor, there are a number of aspects to be considered, especially when high precision is important

1. Backlash and related effects causing phase uncertainty.
2. Random (long-term or short-term) variations in excitation frequency
3. Transfer function of the control device if only its input (rather than its output) is measured.
4. Unwanted harmonics when striving for a pure sinusoidal input
5. Reactor conditions affecting the excitation device.

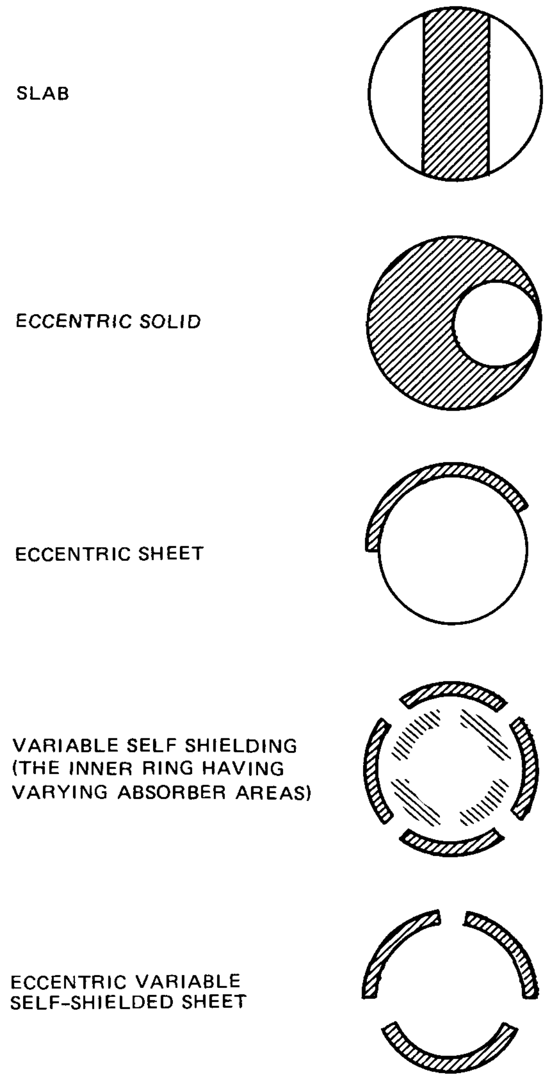


Fig. 6.11—Top view of some typical cylindrical rotary oscillator rods.

In the last of these considerations, it should be remarked that more than just the integrity of materials is desired For example, the reactivity worth of an oscillator rod can depend on reactor power and flux distribution, for this reason it is often desirable to have a sufficiently high frequency available to calibrate the oscillator rod against the zero-power transfer function in a frequency range where feedback is expected to be negligible.

6-5 TRANSFER-FUNCTION ANALYZERS

6-5.1 Usage

Experimental data from transfer-function tests consist of records of signals from which transfer functions or related quantities are to be extracted. Tables 6.10 and 6.11 indicate that there are a variety of approaches to data acquisition and analysis This section treats those which operate on the signals in the time domain to obtain a transfer function Section 6-6, Frequency Analyzers, is devoted to analysis in the frequency domain.

The signals to be analyzed can consist of any or all of the following components a single frequency, a continuum

of frequencies having meaning to the test, and unwanted frequencies, either discrete or continuous. In general, the purpose of an analyzer is to separate these three with the primary purpose of picking out the first two in the presence of the third.

Results from time-domain analyzers can be expressed ultimately in the frequency domain. For tests where a single frequency is excited, the combined results from a number of sequential tests at various frequencies constitute a transfer function evaluated at those frequencies If a continuous frequency is used in external excitation or self-excitation, the correlation function obtained in the time domain may be subsequently Fourier analyzed, as indicated in Table 6.1, to obtain the desired frequency function.

6-5.2 Null-Balance Analyzer

The principle behind the null-balance method of analyzing sinusoidal excitation experiments is one of nulling or bucking out the output signal with the input signal. Here the transfer function is simply the gain and phase adjustment used on one signal or the other to achieve this cancellation. A number of rod-oscillator tests have used this method successfully.[14,15,26] However, the method is not applicable to analysis of a continuum of frequencies, as in pseudorandom excitation

Figure 6.12 shows schematically how the oscillating component of the ion-chamber current, $I_1 \sin(\omega t + \theta)$, is nulled against a mechanical oscillating signal to a sine potentiometer from the excitation device By having a sinusoidal resistance variation in the potentiometer through which the ion-chamber current flows, you obtain a mixed signal whose $\sin \omega t$ components are nulled by resistance and mechanical phase adjustments Usually the output (Fig 6 12) is sent through a band-pass filter (for frequencies near that of the oscillator and observed by an operator making the nulling adjustments Some skill is required for high precision.

6-5.3 Synchronous Transfer-Function Analyzer

A specially constructed analyzer has been used in rod-oscillator experiments[11,15] and has been found to give high-precision results The basic principle, as indicated in Fig. 6 13, is to multiply the ion-chamber signal (with its steady-state component bucked out) by $\sin \omega t$ or $\cos \omega t$ using a synchro-resolver whose mechanical input signal is precisely in phase with the rod-oscillator device Since

$$I_1 \sin(\omega t + \theta) = I_1 \sin \omega t \cos \theta + I_1 \cos \omega t \sin \theta \qquad (6\ 32)$$

integration of $\sin \omega t$ or $\cos \omega t$ times the right-hand side of Eq 6 32 over an integral number of cycles gives a result proportional to $I_1 \cos \theta$ or $I_1 \sin \theta$, respectively. The amplitude and phase of the ion-chamber current may then be obtained from these two integrated outputs

$$\text{Amplitude} = [(I_1 \cos \theta)^2 + (I_1 \sin \theta)^2]^{1/2} \qquad (6\ 33)$$

$$\text{Tangent of phase} = \frac{I_1 \sin \theta}{I_1 \cos \theta} \qquad (6\ 34)$$

As indicated in Fig. 6.13, the signal at the point of the modulator modulates a carrier (typically several hundred Hertz), which is later demodulated at the demodulator

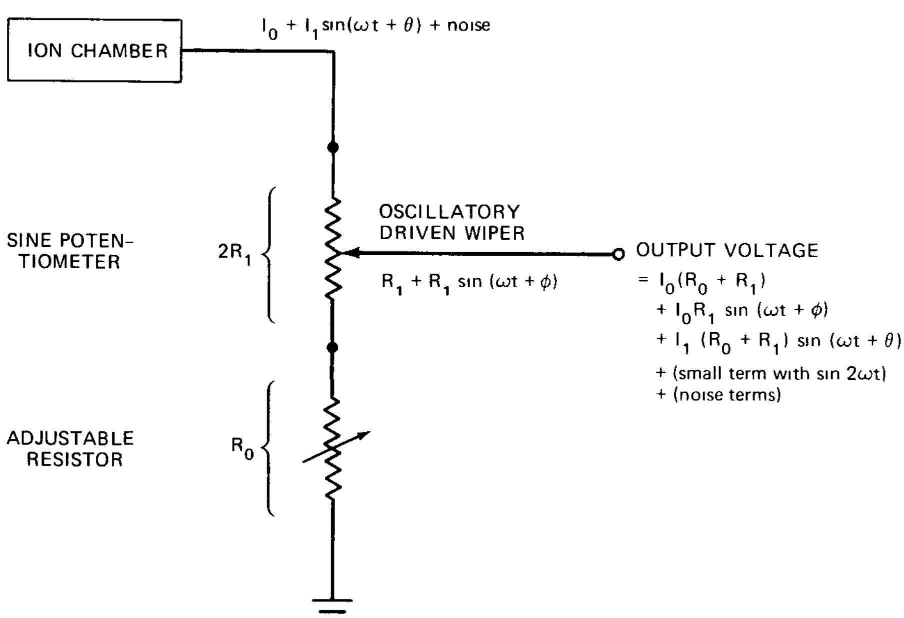


Fig. 6.12—Simplified schematic operation of a null-balance analyzer. At balance the adjustable phase, ϕ, of the potentiometer wiper equals $\theta + \pi$ and $I_0 R_1 = I_1 (R_0 + R_1)$ by adjustment of R_0, so the output contains no $\sin \omega t$ component

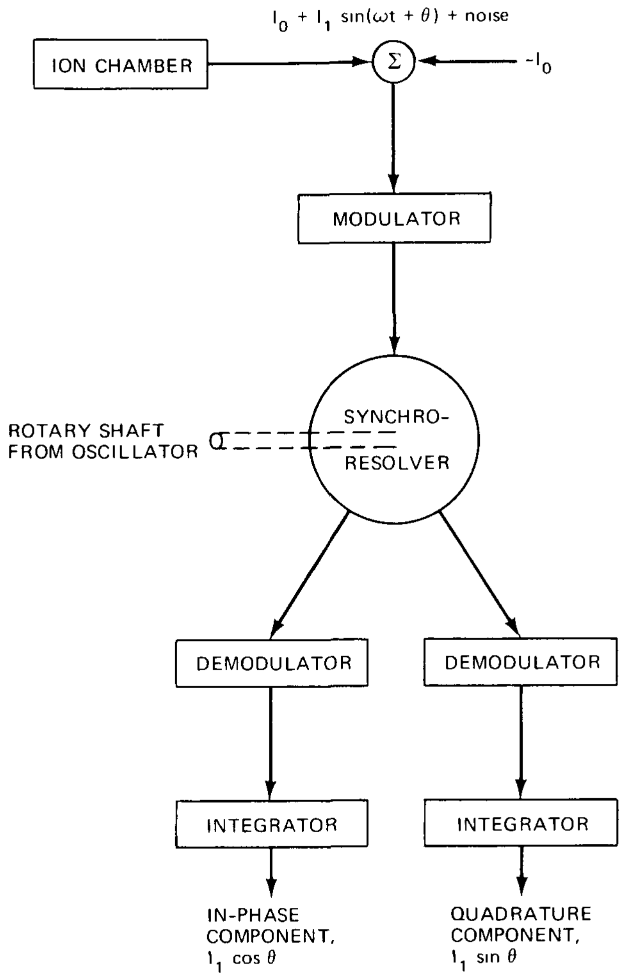


Fig. 6.13—Block diagram of a transfer-function analyzer

Regarding the noise accompanying the signal $I_1 \sin(\omega t + \theta)$, the analyzer acts as a sharply tuned filter at ω. The noise near ω will cause randomness in successive determinations of I_1 and θ, the randomness being proportional to the noise and inversely proportional to the integration time

6-5.4 Cross Correlators

Devices involving the principles of Figs. 6 12 and 6 13 are usually restricted to sinusoidal excitation experiments A technique that is more generally applicable in transfer-function determinations involves the use of cross correlation. In addition to being used with sinusoidal excitation, cross correlation is commonly used with self-induced noise or types of excitation other than sinusoidal.

The method consists in determining the cross-correlation function, $C_{xy}(\tau)$, over a range of the time-lag τ Either the digital definition, Eq 6.9, or the continuous integral (Table 6.1) definition may be used, depending on the experimental approach It is convenient to handle only the fluctuating parts of variables, i.e., $x(t) - \overline{x}$ and $y(t) - \overline{y}$, such as in Eq. 6.10 After $C_{xy}(\tau)$ is known, either from an on-line or off-line device, it must be Fourier analyzed to obtain the cross spectrum, $P_{xy}(f)$ (see Table 6 1), and the transfer function,

$$G(f) = \frac{P_{xy}(f)}{P_x(f)} \qquad (6\ 35)$$

where $P_x(f)$ is the spectrum of the input variable, x(t)

The three operations of time delay, multiplication, and integration required to obtain $C_{xy}(\tau)$ are indicated in Fig 6 14 Here x(t) may be either a fluctuating signal in the system or an excitation signal The operations shown have been done on-line[41] for pseudorandom excitation by using "0" and "1" signals (read at the appropriate values of τ from a tape containing the input sequence) in a simple switching multiplier

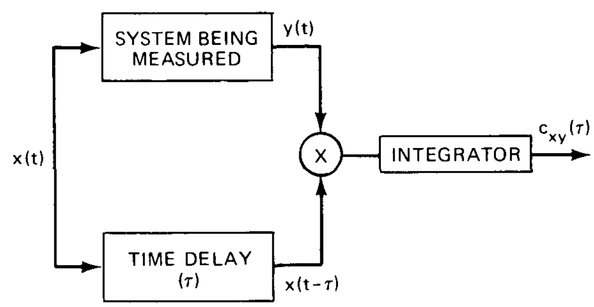


Fig. 6.14—Block diagram of a cross correlator of two signals, x(t) and y(t)

Frequently, however, the two signals x(t) and y(t) are recorded on a frequency-modulation (f-m) magnetic-tape system.[40 95 100] Off-line playback is carried out using tape heads that are displaced to give the y(t) and $x(t - \tau)$ input to the multiplier–integrator combination of Fig 6 14 Analog-computer components are typically used to perform the operations required to give $C_{xy}(\tau)$ In the special case where x(t) = y(t), the autocorrelation function may be obtained in this manner.

6-5.5 Digital Techniques

Although on-line digital-computer analysis of reactor dynamics is possible[73] and perhaps will be prevalent in the future, it has been the practice until now to perform digital analysis off-line. As shown in Table 6 11, the digitizing process may be on-line (creating the proper magnetic-tape format for a computer) or off-line The off-line digitizing may be automatic from an f-m tape or semiautomatic, as in the case of manually operated strip-chart readers whose electrical output punches cards In any event the result is that one or more sequences (x_1, y_1, etc) of variables at time spacings Δt are generated in a form suitable for input to a digital computer

The selection of a digitizing interval, Δt, and of a total duration of the data collection, T, is discussed in Sec 6-7 4 It will suffice here to note that the digitizing interval determines the upper frequency limit, $f_{max} = 1/(2\Delta t)$, of the analysis and the total duration is associated with the

frequency resolution (i e , minimum frequency interval between independently determined spectral values) and accuracy of results The quotient, $T/\Delta t$, is the number of digital values per signal and may be 10^3 to 10^5 in typical experiments

A number of versatile programs are available to users of the various commercial computers for statistical analysis of large quantities of data Typical of these are the Biomedical Computer Programs,[115] a series of 42 programs that are useful not only in biomedical research but also in any field requiring analysis of data for frequency counts, variances, correlations, and related functions Table 6 14 lists the

$$C_{kn}(\tau) = \frac{1}{2} |G| N k_0^2 \cos(\omega\tau - \theta) \quad (6\ 36)$$

$|G|$ and θ may be determined from as few as two values, $C_{kn}(0)$ and $C_{kn}(\pi/2\omega)$

Whether the digital approach discussed here or the continuous-signal approach discussed in previous sections should be used depends on a variety of factors, some of which are mentioned in Table 6 15 The digital approach has been more common in recent years as digitizing costs and computer rental costs per data point decrease and as demands for computer versatility (see Table 6.14) increase

Table 6.14—Functions Generated in Computer Analysis[115] of Three Variables

Function	Variables used in computing the functions				
	x(t)	y(t)	z(t)	x(t) and y(t)	x(t) and z(t)
Autocorrelation function	x	x	x		
Power spectrum	x	x	x		
Cross-correlation function				x	x
Cross-spectrum amplitude and phase				x	x
Transfer-function amplitude and phase				x	x
Coherence				x	x

available computer outputs from just one of these 42 programs (BMD-02T) if one has, for example, three related system variables All possible time-correlation functions and their Fourier transforms are computed with x(t) regarded as an input signal Evidently there is sufficient versatility and generality to permit adaption to almost any type of transfer function experiment

Even more versatile than the Biomedical Computer Programs series is the BOMM system of programs [116] Here the user describes in few-word control statements the step by-step data-handling operations to be performed on a time series, such as finding the mean, doing a cross correlation, or plotting an answer These control statements call in standard subprograms to the computer that perform all the detailed calculations Thus individualized data-processing needs can be satisfied with BOMM, although more effort is required to list the control statements than in the Biomedical Computer Programs

Although a computer is a virtual necessity for performing the required analysis on random fluctuations, it is not necessarily required in the special case of obtaining transfer functions from strip-chart recordings of sinusoidal oscillations where the signal-to-noise ratio is good [15 76] For example, the transfer function of the BORAX-4 reactor[113] could be obtained to an accuracy of ±5% by chart reading and simple hand calculations, even though the root-mean-square oscillatory amplitude, $|G|Nk_0/(2)^{1/2}$, excited by $k_0 \sin \omega t$ was only about twice the root-mean-square boiling noise In this technique the digitally determined (Eq. 6.9) normalized cross-correlation function, C_{kn}, of the reactivity and the power [which is $|G|Nk_0 \sin(\omega t + \theta)$ + noise] is equated to its theoretical expectation

However, for applications requiring many repetitive determinations of a single function, the special-purpose continuous analyzer is strongly entrenched The considerations of Table 6 15 also apply to frequency domain analysis, as discussed in the following sections

Table 6.15—General Comparison of Digital and Continuous Analysis Methods

	Digital	Continuous
Usual use of equipment	Rental	Own
Relative amount of use to date	Little	Much
On-line results	Rarely	Often
Versatility of analysis	High	Medium to low

As the use of on-line digital computers becomes more prevalent and accepted in reactor operation, on-line digital analysis of noise may be expected to be used competitively with other methods Cohn[68a,73] has demonstrated the ability to sample noise as often as every 0 5 μsec and to do on-line correlations with a digital computer. Polarity correlating (i e., replacing the noise amplitude value by +1 or −1 for its fluctuation about an average of zero in computing correlation functions) was found useful in this application.

6-6 FREQUENCY ANALYZERS

6-6.1 Usage

In the preceding section analyzers suitable for handling data in the time domain were considered. These analyzers

are used mostly for correlations or for obtaining transfer functions from single-frequency excitation However, there is an alternative approach, used primarily foi data having a continuum of frequencies, in which the various frequencies in the signal are separated and analyzed in the frequency domain Correlators seek the amount of correlation at various time intervals, whether within one signal or between two signals Frequency analyzers, on the other hand, seek the relative amounts of various frequencies in one signal or existing in a related fashion in two signals In both approaches Table 6.1 is used to compute the corresponding functions in the time or frequency domain from those functions which are obtained by experiment

The analyzers discussed in this section are most often used for directly obtaining the spectral power density, $P_x(f)$, and the cross spectral power density, $P_{xy}(f)$ This implies that, in the system being analyzed, a continuum of excitation frequencies exists and has been generated by either internal or external excitation sources In many instances the spectral power density contains the required information about the dynamics of the reactor system In other instances both $P_{xy}(f)$ and $P_x(f)$ are determined, and then, by using Eq 6 20, the transfer function between x and y is obtained

6-6.2 Spectrum Analyzers

In contrast to a cross spectrum analyzer, a spectrum analyzer of a single variable has just one input, x(t), and a single-number output, P(f), at each frequency A multichannel analyzer displays $P(f_1)$, $P(f_2)$, , simultaneously,[4 6] but the more commonly encountered single-channel analyzer obtains $P(f_1)$, $P(f_2)$, , sequentially, requiring an analysis time T for each This means that the same recorded signal is reanalyzed off line at various frequency values, whereas on-line the same reactor conditions are preserved during each analysis time T to maintain the same spectral characteristics

The three basic parts of an analyzer are its filter, detector, and averager In the bottom half of Fig 6 1 the detection–averaging function is shown as a wattmeter receiving the output of the filter In Fig 6 15 these functions are separated since they correspond to distinct components in most analyzers The slowly varying amplitude, E(t), of the filter output is detected first, usually by squaring or rectification After detector fluctuations have been averaged out, $P(f_1)$ or $[P(f_1)]^{1/2}$ is obtained

It is worth noting that the output of an analyzer is, in fact,

$$P(f_1) = \frac{\int_{f_1-(1/2)\Delta f}^{f_1+(1/2)\Delta f} P(f)\, B(f)\, df}{\int_{f_1-(1/2)\Delta f}^{f_1+(1/2)\Delta f} B(f)\, df} \qquad (6\ 37)$$

where B(f) is the spectral-window function of the analyzer If P(f) is a function varying substantially within the

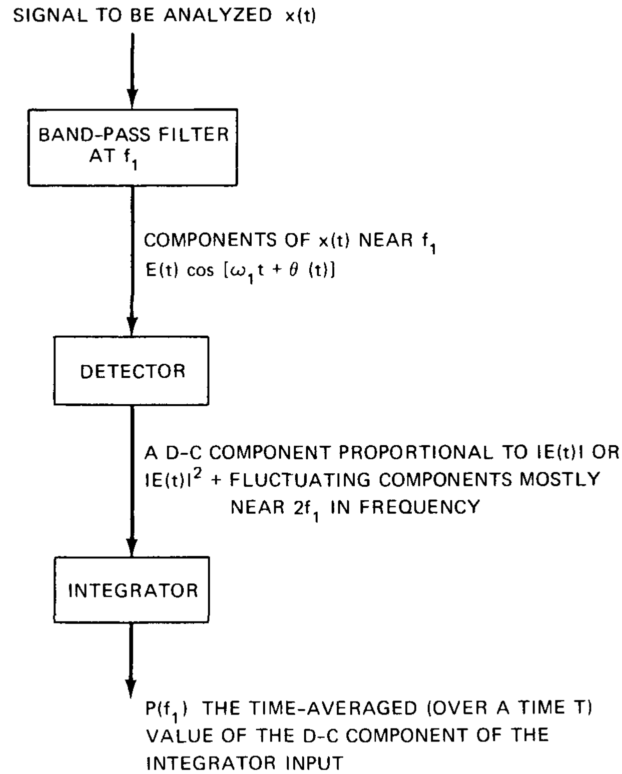


Fig 6 15—Operation of the three essential elements (filter, detector, and averager) in a spectrum analyzer

resolution band, Δf, then it is desirable that B(f) resemble the ideal filter of Fig 6 16 as closely as possible (This is discussed further in Sec 6-6 4)

Spectrum analyzers that have been used in reactor experiments can be classified as follows specially designed and constructed,[6 2] based on commercially available analog-

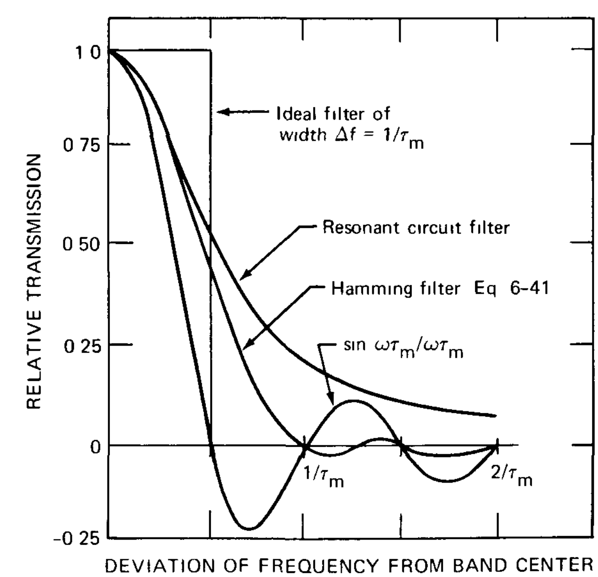


Fig. 6.16—Shapes of some spectral windows used in spectral analysis Here τ_m is the maximum lag used in the correlation function associated with the spectra

computer components,[48] and a commercially available spectrum analyzer [117] Some spectrum analyzers use electrical filters resonant at the desired frequency, f_1, others use a heterodyne technique in which the signal modulates a high-frequency carrier, f_c, that is subsequently filtered in a narrow band. Since all these approaches perform the same P(f) determination, such factors as cost, convenience, and availability are usually the deciding factors for experimenters

6-6.3 Cross-Spectrum Analyzers

The purpose of a cross-spectrum analyzer is to measure the cross spectral density, P(f), of two correlated signals, x(t) and y(t) This is done, one frequency at a time, by integrated multiplication of band-pass-filter outputs, as indicated in Fig 6.17. A comparison of Figs 6 15 and 6 17 shows that this cross-spectrum analyzer is a slight generalization of an ordinary spectrum analyzer using a multiplier as a detector

In some analyzers[70 72] tuned-circuit band-pass filters are used In others[84 109] the input to the multiplier is the result of passing a modulated pair of signals, x(t) cos $(\omega_1 t + \phi_x)$ and y(t) cos $(\omega_1 t + \phi_y)$ (constructed by multiplying the signals by oscillator outputs), through a low-pass filter The broken line in Fig 6.17 indicates the ability to control the relative phase in the two modulations at ω_1 in-phase operation gives the cospectral density, $Co_{xy}(f)$, with 90° between the two signal channels, the output is the quad-spectral density, $Qu_{xy}(f)$ Then Eqs 6 6 and 6 7 can be used to determine the cross spectrum, $P_{xy}(f) = Co_{xy}(f) - i\, Qu_{xy}(f)$

As in the discussion of the spectrum analyzer (Sec 6-6.2), the major parameters selected by the experimentalist are the frequencies at which $P_{xy}(f)$ is determined, the frequency resolution, Δf (defined in Fig. 6 16), and the analysis time, T. Quantitative criteria for making these selections are given in Sec 6-7

6-6.4 Digital Spectrum Analysis

In Sec 6-5 5 it was noted that digitizing plus subsequent computer analysis can be used as an alternative to continuous-signal analysis The computer programs in use give not only time-domain functions (usually computed first in the program) but also their Fourier transforms, as indicated in Table 6 14. Thus the programs discussed may be regarded as frequency analyzers too

Although not indicated in Figs 6 15 and 6 17, the incoming signal may be "conditioned" before analysis In the continuous analysis this could often consist in filtering out frequencies above and/or below those of interest in the analysis Similarly, in digital analysis it is not only customary to remove any nonzero mean values (i e , d-c components) from the signals but also to do some of the following detrending, i e , removing a linear trend in time, filtering, such as prewhitening, and normalizing signal magnitudes by dividing deviations from the mean by the signal's standard deviation

Digital filters,[113] computer arithmetic operations on the sequential data points of x(t) that have the effect of changing its spectrum, can be used to advantage Thus, in prewhitening, the filter characteristic is modified so that the spectrum is one more nearly like white noise [i e., P(f)

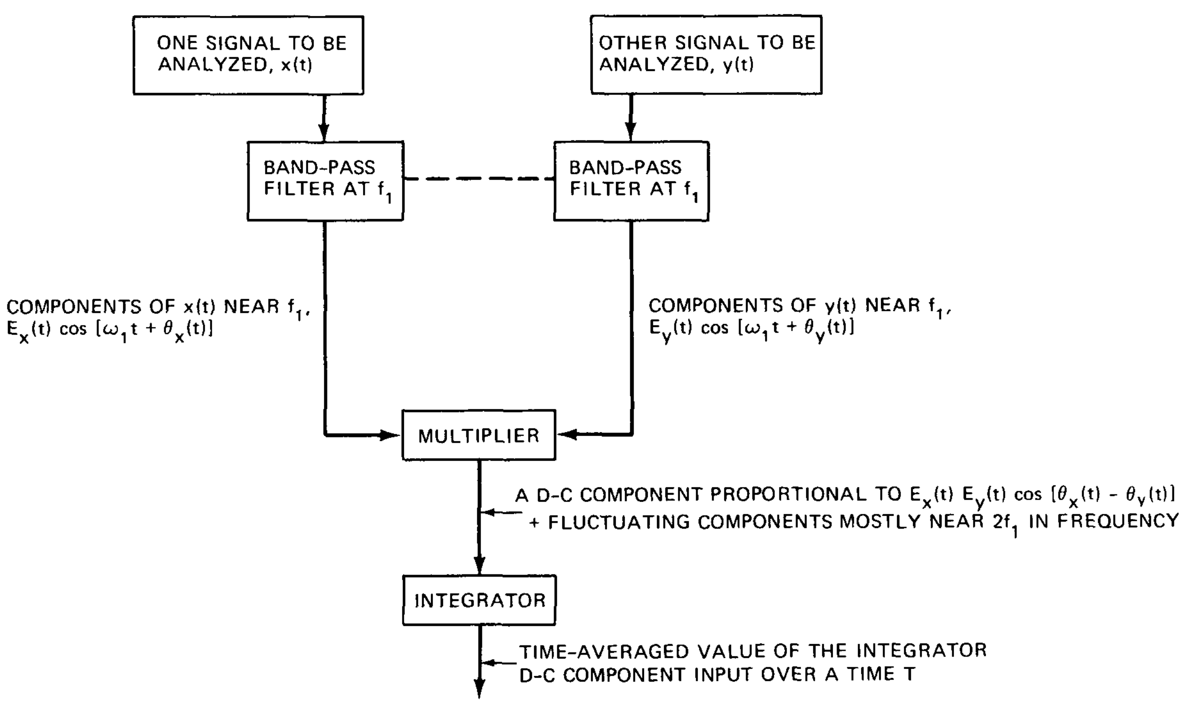


Fig. 6.17—Operation of the four essential elements in a cross-spectrum analyzer

is made to be approximately constant] and more amenable to analysis

Computer programs usually calculate autocorrelation and cross correlation functions from the data and for values of τ only up to τ_m, this value is generally some small fraction (typically 10% or less) of the data duration T in order to secure good accuracy Then the computer Fourier analyzes the correlation functions

$$P_x(f) = 2\int_0^{\tau_m} C_x(\tau)\cos 2\pi f\tau \, d\tau \qquad (6\ 38)$$

$$P_{xy}(f) = \int_{-\tau_m}^{\tau_m} C_{xy}(\tau)\cos 2\pi f\tau \, d\tau - i\int_{\tau_m}^{\tau_m} C_{xy}(\tau)$$

$$\times \sin 2\pi f\tau \, d\tau = Co_{xy}(f) - i\,Qu_{xy}(f) \qquad (6\ 39)$$

for the spectrum and components of the cross spectrum, respectively Equations 6 38 and 6 39 give spectral values at

$$f_1 = \frac{1}{2\tau_m},\ f_2 = \frac{1}{\tau_m},\ f_3 = \frac{3}{2\tau_m},\ f_4 = \frac{2}{\tau_m} \qquad (6\ 40)$$

Since these spectral results correspond to the less desirably shaped $(\sin \omega\tau_m)/\omega\tau_m$ spectral window of Fig 6 16, the so called "hamming filtering" operation is usually performed for final results

$$P(f) = 0\ 23P\left(f - \frac{1}{2\tau_m}\right) + 0\ 54P(f) + 0\ 23P\left(f + \frac{1}{2\tau_m}\right) \qquad (6\ 41)$$

to obtain the more desirable window shown

6-7 EXPERIMENTAL CONSIDERATIONS

6-7.1 Error Sources

When the transfer function, G(f), between x(t) and y(t) is measured, the transducers of the signals to the analyzer may have a frequency dependence In addition, the analyzer may have a transfer function of its own, e g , if its amplifier gains are frequency dependent As a consequence significant corrections may have to be applied to transfer function measurements to obtain the ideal function desired Calibration, using known sinusoidal amplitudes or white noise generators, is frequently necessary

Unwanted signals, such as random noise (as from instrumentation or a digitizing process) or periodic signals (as in 60-Hz hum), are usually introduced by the devices measuring a system Moreover, the system itself may mix unwanted signals with the signals observed at the transducer inputs Since all these effects influence accuracy, they must be eliminated or lessened Some techniques for coping with the problem are

1 Reduce or eliminate the unwanted signals at or near their source

2 Increase the desired signal levels

3 Filter the signals, emphasizing frequencies of interest over others

4 Correlate pairs of related signals, as in cross-correlation and cross-spectral analysis

5 Use long durations of data or many repetitions

6-7.2 Frequency Limits

There are three important frequencies in a transfer function or spectrum measurement the highest frequency of interest (f_{max}), the lowest frequency of interest (f_{min}), and the resolution (Δf)

Regarding f_{max}, it is not unusual for a characteristic of an instrument transfer function or excitation device to be such that there is considerable attenuation of frequencies above some particular frequency value If the frequency content is significant above the maximum frequency of physical importance, then the higher frequencies are usually attenuated by a low pass electronic (or digital) filter The electronic filter is designed to give an attenuation of 3 db or more at frequencies of $2f_{max}$ and above The digital filter selects the digitizing time interval, Δt, such that

$$2f_{max} = f_N = \frac{1}{2\Delta t} \qquad (6\ 42)$$

where f_N is the so called "Nyquist frequency" which sets an upper limit in digital analysis

The lowest frequency measured, f_{min}, is usually considerably greater than 1/T, where T is the duration of the measurement, consequently the measurement is effectively averaged over many cycles (An exception to this is sinusoidal excitation at f_{min} with an amplitude well in excess of system noise levels, the duration of the measurement may be kept as small as $1/f_{min}$ in this case) Usually a high pass filter is used to prevent frequencies below f_{min} from entering the analyzer

Reference has already been made to the resolution Δf in Eq 6 37 and Fig 6 16 Continuous spectra are averaged over Δf In excitation with discrete frequencies, the interval between frequencies is effectively the resolution The value of Δf is usually selected to be just small enough to obtain the detail required in the spectrum Too small a value is disadvantageous from the standpoint of accuracy, as is seen in Table 6 16 Two common situations affecting a choice of Δf are

1 The gross variation of a nonresonant spectrum over a few decades of frequencies is desired, in which case Δf can be as large as a half to one octave, thus giving about 3 to 5 points per decade of frequency

2 The details of a resonant peak in the spectrum are desired, in which case Δf must be somewhat less than the width of the peak to obtain several points across the peak

Table 6.16—Statistical Errors of Correlation and Spectral Measurements[113c] Expressed in Terms of Signal Bandwidth (B), Duration of Data (T), and Resolution of Analyzer (Δf)

Function (computed from x and y having zero means)	Standard deviation of function / Function	Condition of applicability
Autocorrelation, $C(\tau)$	$\frac{1}{(2BT)^{1/2}}\left[1+\frac{C(0)^2}{C(\tau)^2}\right]^{1/2}$	$BT > 5, T > 10\lvert\tau\rvert$
Cross correlation, $C_{xy}(\tau)$	$\frac{1}{(2BT)^{1/2}}\left[1+\frac{C_x(0)\,C_y(0)}{C_{xy}(\tau)^2}\right]^{1/2}$	$BT > 5, T > 10\lvert\tau\rvert$
Spectrum, P(f)	$\frac{1}{(T\,\Delta f)^{1/2}}$	$T\,\Delta f > 5$
Cospectrum or quad-spectrum	$\frac{< 1^*}{(T\,\Delta f)^{1/2}}$	$T\,\Delta f > 5$

*An upper bound to the error. The true error is well below this for highly coherent signals in which statistical effects are minor.

6-7.3 Statistical Accuracies

Formulas for computing the expected variation due to the statistical nature of an experiment are vital in optimum planning. Table 6.16 contains formulas useful in ascertaining the precision of the various functions involved in noise analysis. The meaning of the fractional-error formulas is that, if many values of a function were determined (at a particular f or τ), 68 3% would lie within the average ± this fractional error

In all cases the error varies inversely as the square root of the measuring time and inversely as the square root of either the bandwidth, B, or the resolution, Δf

B = upper frequency limit of P(f), which is approximately constant from 0 to B and thereafter near zero (6.43)

or

$$B = \frac{1}{2\tau_c} \text{ if } C(\tau) \text{ is approximately } C(0)e^{-\tau/\tau_c} \quad (6\ 44)$$

$\Delta f = \dfrac{1}{\tau_m}$ for the ideal and hamming windows of Fig 6 16 (6 45)

or

$\Delta f = \pi$ times the half-power bandwidth of a sharply tuned circuit (6.46)

The half-power bandwidth is also defined as the resonant frequency divided by the so-called resonance Q

The above pertains primarily to continuous frequency analysis, however, there is also statistical error associated with sinusoidal excitation experiments because random noise is also present For determination of a transfer function by the cross-correlation function method of Eq 6 36, the presence of noise having a variance of σ_y^2 along with the output causes the following fractional error[118]

$$\frac{\text{Standard deviation of } |G|}{|G|} = \frac{\sigma_y/[|G|Nk_0/(2)^{1/2}]}{(BT)^{1/2}[1+(\omega^2/4B^2)]^{-1/2}} \quad (6.47)$$

The numerator is evidently the ratio of noise of bandwidth, B, to signal, the denominator is the square root of the number of effectively "independent" measurements

6-7.4 Spectral-Analysis Data Planning

In a spectrum or cross-spectrum measurement, the desired accuracy and three frequency parameters (highest and lowest frequency of interest and the resolution) must be chosen. For digital analysis

$$\text{Fractional error in } P(f) = \frac{1}{(T\Delta f)^{1/2}} = \frac{1}{(N/M)^{1/2}} \quad (6\ 48)$$

$$f_{max} = \frac{1}{2\Delta t} = \frac{N}{2T} \quad (6\ 49)$$

$$f_{min} = \Delta f = \frac{1}{\tau_m} = \frac{1}{M\Delta t} \quad (6\ 50)$$

where N is the number of data points, T/Δt, and M is the maximum number of lag intervals, $\tau_m/\Delta t$ If, when these equations are applied, it is found that some of the parameters so determined are not readily attainable (if, for example, too many digits are required), then obviously suitable compromises must be made between the limitations of the analysis and the desired results In continuous analysis one evidently optimizes just Δf and T of Eqs 6.48 and 6 50 somewhat independently of the f_{max} selected.

An illustration of selections made in an ion-chamber noise analysis[90] of the Experimental Boiling Water Reactor to measure a resonance at 1.7 Hz is

N = 3331	Fractional error in P(f) = 0 3
M = 300	f_{max} = 10 Hz
Δt = 0 05 sec	$f_{min} = \Delta f$ = 0 067 Hz

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Chapter 7

Control-Rod Drives and Indicating Systems

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7-1 INTRODUCTION

7-1.1 Reactor Kinetics*

A nuclear reactor that is generating heat at a constant rate is a chain-reacting system in which the number of neutrons being produced in nuclear fission processes exactly balances the number of neutrons being absorbed in or escaping from the system. If it is desired to change the rate of heat generation (number of fissions per second), means must be provided to increase or decrease the absorption and escape of neutrons Once the heat-generation rate has reached the desired new level, means must be provided to restore the neutron balance so the system will once again generate heat at a constant rate The specific means used in present-day power reactors to alter the heat-generation rate upward or downward or to keep it constant are discussed in this chapter.

In the steady state (constant rate of generating heat), the reactor is critical when the effective multiplication constant k (sometimes written as k_{eff}) is just equal to 1 To increase or decrease the power level of the reactor requires that k be increased or decreased above or below unity during the interval when the power level is changing. Once the desired power level has been reached, k must be restored to unity so the reactor can again operate in a steady state, albeit at a new power level. The fractional deviation of the effective multiplication constant from unity is defined as the reactivity[1]

$$\text{Reactivity} = \rho = \frac{k - 1}{k} = 1 - \frac{1}{k}$$

or

$$\text{Reactivity} = \frac{\delta k}{k} \quad (\text{with } \delta k = k - 1)$$

*The fundamentals of reactor kinetics are summarized in Chap. 1.

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Because k is very close to 1 at all times in an operating power reactor, the reactivity ρ or $\delta k/k$ is often abbreviated to δk or "excess k" if $\delta k > 0$. In terms of reactivity, the basic types of reactor performance are

$$\rho = \delta k/k = 0 \text{ constant power level}$$
$$\rho = \delta k/k > 0 \text{ power level increases}$$
$$\rho = \delta k/k < 0 \text{ power level decreases}$$

When the reactivity is not zero, the reactor power level increases or decreases with a characteristic time constant (reactor period) that is primarily dependent on the value of the reactivity, the prior operating history of the reactor, and the reactor configuration (arrangement and composition of fuel, moderator, coolant, etc) Period is the time

required for the neutron level to increase (or decrease) by a factor of "e" (2.718) (see Chap. 1). The reactor period becomes too short for practical control if the reactivity is increased above zero by an amount equal to the delayed-neutron fraction, β. For most presently operating power reactors, $\beta \simeq 0.007$. This means that a positive ρ or $\delta k/k$ is always between zero and about 0 06% During operation at power, reactor control systems normally make adjustments at rates in the general range from 10^{-3}/sec to 10^{-5}/sec in $\delta k/k$ per second. Although the control adjustments during operation involve relatively small changes in reactivity, this is not necessarily true during reactor start-up and shutdown. The control system must be capable of "adding negative reactivity" to balance out the reactivity excess built into the reactor, and, if an emergency exists, it must do so rapidly. Under certain conditions reactivity changes of ~ -0 1/sec in $\delta k/k$ per second may be required The excess reactivity built into a power reactor depends on many factors, it can be more than 10% in $\delta k/k$ For this reason control (and safety) systems must be capable of accomplishing large changes in reactivity during reactor start-up and shutdown. In addition, they must be capable of compensating for the effects of changing concentrations of the fission products ^{135}Xe and ^{149}Sm These can involve reactivity changes of several percent (see Sec 1-3.6 of Chap 1)

7-1.2 Reactivity Variations During Operation

A number of inherent reactivity variations occur during the operation of a power reactor and must be considered in designing reactor control systems. Some of these can be used to assist in reactor control, others require attention in the control-system design.

A key effect to be considered is the temperature coefficient of reactivity. Temperature variations change neutron cross sections and dimensions of reactor materials and thus change the reactivity. A desirable condition is for the reactivity to decrease as the reactor temperature increases. Such a negative temperature coefficient has a stabilizing effect since, as the power increases and raises the reactor temperature, the negative temperature coefficient reduces the reactivity and tends to limit or level out the rise in power. Most of today's reactors have a negative temperature coefficient of reactivity, usually $\sim -10^{-4}/^{\circ}F$ in $\delta k/k$ at operating temperatures

In boiling-water reactors (Vol. 2, Chap 16), the reactivity changes as the void volume in the core changes. Since the water (steam) acts both as neutron moderator and absorber, the void coefficient of reactivity can be either positive or negative

A generalization often used in preliminary calculations is to lump all the reactivity effects into a single power coefficient of reactivity, the change in reactivity resulting from a unit change in reactor power. This coefficient is typically $\lesssim 10^{-4}$ decrease in $\delta k/k$ per megawatt (thermal) change in power level

A power reactor is inherently stable The degree of stability is temperature dependent since the reactivity coefficients are temperature dependent. Thus a reactor may be less stable when cold than at operating temperatures. When inherently stable, the negative temperature effects dominate the positive, and the requirements placed on the control system are less stringent. In fact, with a net negative coefficient of reactivity, some reactors may be controlled over a limited range without resorting to control-rod movement.

Long-time inherent changes in reactivity are those attributable to the increase of fission-product poisoning and fuel depletion. These can be controlled by chemical shimming or by incorporating burnable poisons in the fuel

7-1.3 Methods of Reactivity Control

Most power reactors are controlled by rods that are inserted into or withdrawn from the reactor core The rods contain neutron-absorbing or fissionable material or a combination of the two Some power reactors have been controlled by the rotation of control drums on the core periphery, the control drums being made of combinations of neutron-reflecting and neutron-absorbing materials.

For power reactors where changes in neutron level may be accomplished over relatively long time periods, but where constant power levels are wanted once full power is achieved, burnable poisons and chemicals dissolved in the coolant (so-called "chemical shimming") have proved effective Burnable poisons can be added to the fuel elements to decrease fuel-element absorption of neutrons in proportion to the decrease in the fissionable material content of the fuel elements. Either type of control, chemical shimming or burnable poisons in the fuel, reduces the total reactivity that must be offset by the control-rod system

7-2 REACTOR CONTROL SYSTEM

A basic reactor control system is shown schematically in Fig. 7.1 During operation at power, the demand signal is an output of the plant control system. This demand signal is compared with the measured neutron level, and the reactivity is correspondingly adjusted by programming the control-rod actuators to increase or decrease reactor power.

In reactors that are inherently stable, it is possible, though not necessarily preferable, for an operator to keep the power at the demand level by manually adjusting the control-rod position. When a reactor is not inherently stable, a continuous feedback control system, usually a servo-controlled rod, is essential.

There are four distinct phases of reactor operation the approach to criticality, power increase or decrease, power operation, and shutdown Each phase imposes different requirements on the reactor control system.

7-2.1 Approach to Criticality

The reactor is manually controlled by an operator during the approach to criticality. The control rods are

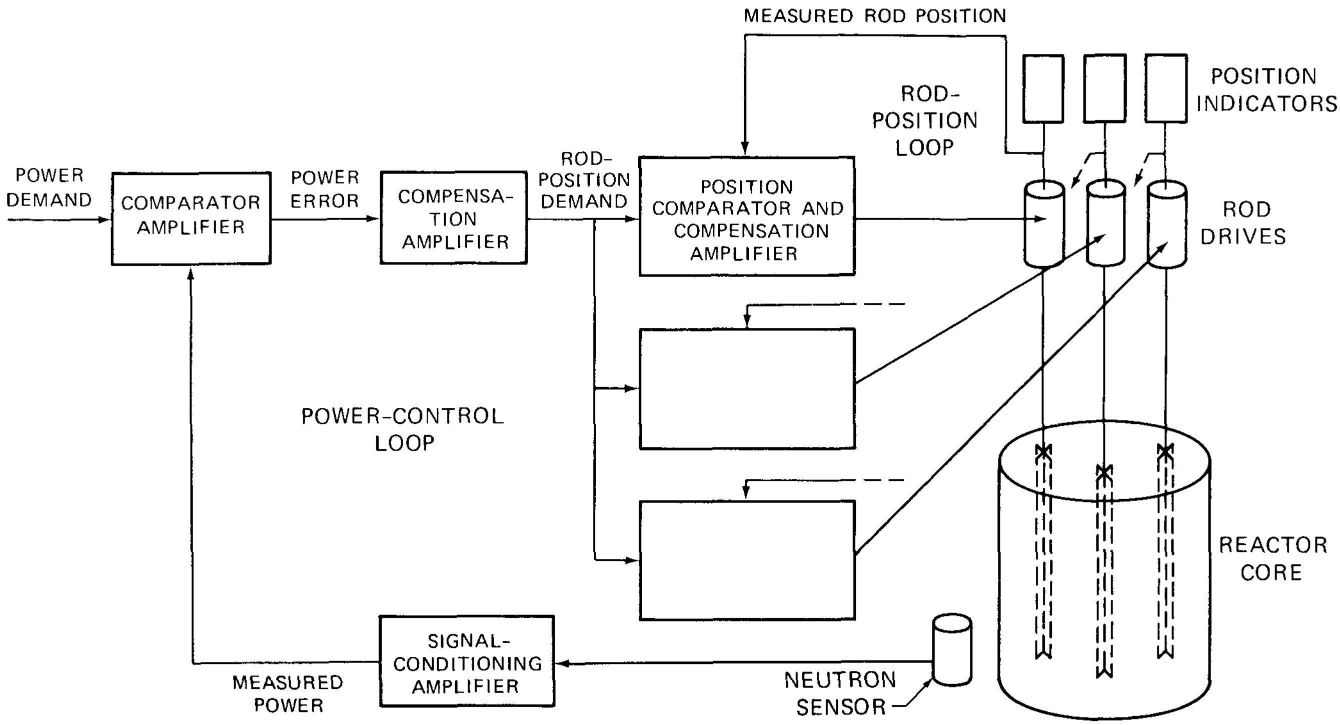

Fig 7.1—Basic reactor control system

moved intermittently to add reactivity until the reactor is critical. At this juncture the reactivity is zero and the rate of neutron production from fission is just equal to the rate of neutron loss The magnitude and rate of rod motion is governed by the need for maintaining the reactor period longer or slower than some predetermined value

The following requirements are imposed on the control system in this phase of reactor operation

1. The control rods must be capable of motion in increments small enough to insert very low values of δk. Rod drives subject to uneven motion, e g , because of friction, must be avoided

2 The rod actuation system must be capable of measuring necessary reactor performance data during the initial start-up. Typical measurements required are total and incremental rod worths. (Ganging several control rods which are then driven by one actuator sometimes makes this measurement difficult.)

3. The control system must be able to insert reactivity at a maximum rate consistent with the start-up time requirements.

7-2.2 Power-Increase Phase

The power-increase phase is normally started by establishing coolant flow, adjusting power and flow to equal the demanded values, and closing the automatic control loops As the coolant flow is then increased, the power level is also increased, and the reactor temperature rises to the operating value. The reactor control system responds to the plant control demand by causing appropriate motion of the control rods. The coolant flow and power level may be increased simultaneously or separately, with the flow reaching full value before power.

The primary requirements on the control system during this phase are

1 The control rods must smoothly adjust the reactivity in accordance with the plant controller demands. The amount of rod motion depends on the reactivity change associated with the incremental rod worth and the reactor temperature and pressure conditions. Particular attention must be given to the transient conditions during changes of reactor power and flow, since excessive overshoots in temperature or pressure might cause intolerable damage to the reactor core.

2. Since full-power conditions are being approached, the relative control-rod position becomes important to ensure uniform power distribution throughout the core.

7-2.3 Power Operation Phase

During this phase the reactor must respond to the plant control-system demands to deliver the desired power, maintain the reactor operating conditions, and remain within predetermined reactor parameter limits. The required dynamic characteristics of the control system are different for each reactor type (PWR, BWR, and gas-cooled or liquid-metal-cooled reactors).

Some of the important factors that must be considered in the design of the control system for this phase of reactor operation are

1 Since the reactor in this phase is at or near full power, the control system must respond to the plant

power system demands rapidly enough to meet plant requirements and yet maintain the core temperatures within prescribed limits (such as the hot-spot temperature limit) To derive the maximum power, the designer faces a trade off between the desirability of operating close to the maximum temperature limits of the reactor and the associated requirements of more accurate temperature measurement and dynamic response of the control system

2 In addition to the requirement that the reactor rod-actuation system be accurately positioned in response to a demand, the banks of rods must also be positioned accurately relative to each other Inaccuracies in relative positioning of control rods causes local power increases in the region adjacent to those rods that are farthest withdrawn Positioning inaccuracies can result in a smaller margin between the limiting temperatures and the normal operating conditions of the reactor core

3 Increments of control rod motion must be of such magnitude that thermal transients do not increase the temperatures or temperature gradients to undesirable values For example, the reactivity insertion steps resulting from unit rod motion in stepping-motor systems must be kept within allowable limits Excessive friction and control deadbands must also be considered in designing the overall control system

4 Some of the fission products produced during power operation absorb neutrons and necessitate the addition of reactivity by control-rod movement The most important of these are ^{135}Xe and ^{149}Sm (see Sec 1 3, Chap 1) The reactivity, $\delta k/k$, to overcome the fission-product poisoning under equilibrium operating conditions is a function of reactor design but normally varies from 0 3 to 3 0% The control rods must be capable of compensating for the buildup of these neutron absorbers About 10 hr after shutdown, the ^{135}Xe poisoning increases to a value higher than the equilibrium value at full power The poisoning peaks at about 10 hr after shutdown and then diminishes This leads to the requirement that the control rods be capable of introducing sufficient neutron absorber at a rate that will maintain the reactor in a shutdown condition as the ^{135}Xe poisoning is reduced

5 The reactivity must be compensated for the reduction of fissionable material attributable to burnup during power operation This compensation is normally provided by the control system, which automatically positions the control rods to maintain full power The control-rod worth designed into a reactor is a function of the amount of fuel depletion anticipated during the interval between reloadings In some reactors a burnable poison, such as ^{10}B, is introduced into the core As neutrons are absorbed by the boron, the number of remaining boron atoms available for neutron absorption decreases The amount of burnable poison introduced into a reactor is governed by the desire to have this effect compensate for fuel depletion In this manner the total reactivity control requirement of the rod system is reduced

7-2.4 Shutdown Phase

The shutdown phase of operation is usually accomplished by a controlled insertion of the control rods in response to a reduction in power demand A second type of shutdown is a scram* in which the reactivity and reactor power must be reduced in a short time to prevent exceeding the reactor or plant limits The control system must be designed such that sufficient negative reactivity is available to shut down the reactor under all conditions

To simplify the control rod drive system for normal power operation, the rate of control-rod motion is normally the same in either direction However, the rate of change of reactivity can still be varied significantly by using only one or a few rods at a time when increasing the reactivity and using all rods simultaneously when decreasing the reactivity

7-3 SELECTION OF REACTIVITY-CONTROL METHOD

7-3.1 System Requirements

The requirements that must be met by the reactor control system, including sensors and control rods, may be divided into the following categories

1 Amount of reactivity controlled and rod positioning accuracy

2 Rate of change of reactivity for normal operation, including initial start-up, planned shutdown, and restart

3 Emergency shutdown

4 Reliability

The excess or maximum reactivity requirements of a reactor are dependent on the planned rate of fuel depletion, fission-product buildup, inherent reactivity effects (e g , temperature), and control range desired Table 7 1 shows that the range of total rod reactivity for a number of typical power reactor plants varies from 6 to 25% in $\delta k/k$

The control rod drive must be capable of making small changes in reactivity to maintain a flat neutron flux distribution (uniform generation of heat throughout the core) and to be able to adjust the power level of the reactor with sufficient precision throughout full-power operation Typically, changes in $\delta k/k \lesssim 10^{-5}$ are required In terms of positioning accuracy, this means that the control rod drive system must be able to position a rod to an accuracy of about 0 02 in This value can vary widely, however, depending on the particular reactor design and the individual rod worth, values from 0 01 in to several inches are possible [2]

The reactor designer determines the required rate of change of reactivity by examining how rapidly power must be changed to maintain proper operation during both

*A scram system quickly reduces reactivity, normally by rapid insertion of the control rods The system is usually initiated by a signal or series of signals that indicate an unsafe or potentially unsafe condition (see Chap 12)

Table 7.1—Typical Drive-System Characteristics for Nuclear Power Reactors

Reactor	Thermal power, MW	Temp. compensation, % δk	Poisons, % δk	Fuel depletion, MWd/ton % δk	Rod total, % δk	Rod-control velocity, δk/sec	Rod-scram velocity, δk/sec	Rod-position accuracy, δk	Total number rods	Rod length, ft
Boiling-water										
Dresden	686	7.7	3 6	12,000/6.0	14	$1\ 3 \times 10^{-4}$	0.136	Continuous	80	8.5
EBWR	100	3.13	3.36	11,000/6.0	15	$1\ 4 \times 10^{-4}$	0.38	Continuous	9[a]	5.0
Humboldt Bay	165[b]	3.6	3.1	10,000/12.3	17.3	4×10^{-4}	0.042	0.0004	32[c]	6.6
Pressurized-water										
Shippingport 1	231	2.6	3.8	4500/11.0	25.6	1.07 to $1\ 38 \times 10^{-4}$		Continuous[b]	32[d]	6.0
Shippingport 2	505	4.3	2.8		16.0				20	8.0
Yankee	485[b]	4.1	3.0	7830/7.1	15.1	0.8×10^{-4}		0.0003	24	7.54
Gas-cooled										
Bradwell	538	2.0	1.7		7.5[e]	2×10^{-4}		Continuous	108[f]	28.00
Calder Hall 2	285	2.19	1.7		6.6	2×10^{-4}	0.01	Continuous	48[g]	33.3
Hunterston	535	1.9	1.7	3600/10.1	8.5	3×10^{-4}			156	
Berkeley	565	1.64	~1.76		4 5	3×10^{-4}		Continuous	132	25.5
Peach Bottom	115	2.6	3.0		2.3 (12.0)	7.7×10^{-5}	0.23 (0.0048)	Continuous	36[h]	7 0
Sodium-cooled										
EBR-2	62.5	1.5	negl.	--/2.4	6.1	3.8×10^{-5}	0 055	Continuous	14[i]	1 16

Reactor	Actuator control velocity, in./sec	Actuator scram velocity, in./sec	Actuator type	Actuator position interval, in.	Actuator position indicator	Actuator position readout	Actuator type scram
Boiling-water							
Dresden	6.0	102 0	Hydraulic		Magnet in piston	Mag.-actuated switches	Hydraulic
EBWR	0.1–0.467	41.0 (av.)	Rack and pinion	±0.025	Syn. trans. and speed reducer	Syn. receiver	Gravity
Humboldt Bay	3 (0.7)	28.4 (av.)	Locking piston	3 steps @±1.0	Magnet in piston	Mag.-actuated switches	Hydraulic/ gravity
Pressurized-water							
Shippingport 1	0.046–0.133	56.4 (av.)	Lead screw/col. Rotor/v.f.ind. motor	+1 5 or ±0.125	Magnetic coil or inverter reluctance		Gravity
Shippingport 2							
Yankee			Magnetic jack	±3 0	30 transformers	Lights in secondaries	Gravity
Gas-cooled							
Bradwell	0.00085	8.5 (av.)	Var freq motor				Mag. clutch/ gravity
Calder Hall 2	0.00834 out 0.00167 in	48 0	Var. freq. motor	±1.0	2-in mag slip transmitter	Mag. slip receiver	Gravity
Hunterston							
Berkeley	0.00721		Var. freq. motor				Gravity
Peach Bottom	0.72	120 0					Hydraulic (battery and motors)
Sodium-cooled							
EBR-2	2.85		Rack and pinion	±0.01	Syn. trans and gear reduction	Syn receiver	Mag clutch/ gravity

[a]Plus 1 oscillator [b]Initially. [c]Plus 8 peripheral. [d]Four groups. [e]From 80 rods [f]Plus 11 shutoff. [g]46 coarse. [h]Plus 19 emergency [i]12 shim.

(Table 7 1 continues on next page)

Table 7.1—(Continued)

Reactor	Controller type	Controller feed-back signal	Controller rods controlled	Coupling type	Scram time, sec
Boiling water					
Dresden	Manual	N.a.	All	Mech., 90° rotation	3.0
EBWR	Manual	N.a. (signals cause loss of power)	All in, one out	Mag. clutch	1.35
Humboldt Bay	Manual	N.a.	All	Mech.	3.0
Pressurized water					
Shippingport 1	Manual or temp.	Coolant resistance thermometers	All for scram, all by sequence	Roller out dir. coupling	1.5
Shippingport 2	Temp.				1.35
Yankee	Temp.		All		2.0
Gas cooled					
Bradwell	Zone outlet temp., reactor power	Gas temp., turbine speed	28 any of 80	Chain and sprocket	5.0
Calder Hall 2	Manual	N.a.	All or one	Steel cable/drum	5.0
Berkeley	Zone outlet temp., reactor power	Gas temp., turbine speed	9	Chain and sprocket	6.0
Peach Bottom			All (one at a time above 10% power)		1.0
Sodium cooled					
EBR 2	Manual	N.a.			0.6

normal and emergency operation. For conventional start up and power phases, periods of 30 sec or longer are normal. This requires reactivity adjustments in the range of 10^{-3} to 10^{-5} δk/sec, with an average value of 2×10^{-4} δk/sec.* This same rate is usually satisfactory for steady-state control. For linear control rods, this corresponds to about 10 in./min as an average, although it can vary[2] (with reactor design) from 3 to 300 in./min. For a directly coupled rotational system, where the control drum may rotate 180°, this rate corresponds to about 0.2°/sec. During shutdown the reactivity (and thus the reactor power) is usually decreased more rapidly than its rate of increase during start up. As noted earlier, this requirement is often satisfied by moving the control rods at the same rate used for start-up, but moving all rods simultaneously rather than a few at a time.

For scram or emergency shutdown, the required rate of reactivity reduction normally exceeds the insertion rate for power control by a factor of 10 to 100. Higher rates of reactivity reduction do not yield significant benefits since, after the reactivity becomes about 1% below critical ($\rho = \delta k/k = -0.01$), the reactor power decreases as the delayed-neutrons decrease. Of more importance in shutdown is the release time or turnaround time following receipt of a shutdown command. Small delays in beginning the reduction of reactivity can result in significant power excursions. The usual practice is to design for release times of about 10 to 50 msec. When this rapid initiation is coupled with a reactivity insertion rate of about 5×10^{-2} δk/sec, the reactor can be shut down on a nominal negative period of 5 sec or less.

It is common practice to satisfy both normal performance and safety requirements with one reactivity adjustment mechanism. It is also common practice to design the scram mechanism to operate in a fail-safe mode, i.e., to operate in the event of loss of primary power. (The primary-power loss may be inadvertent or it may be initiated by another part of the scram system.) There are many ways of designing the rod-drive mechanism to fail safe. One general practice is to use gravitational force to store energy for scram. A simple example of this practice is to place a coupling device between the control rod and its drive mechanism that has the same primary-power source as that which supplies the control-rod actuator. If the primary power is lost, the control rod is released and gravity forces the rod into the reactor. Springs and hydraulic devices can also be used to store energy and to release it on power failure. If higher scram velocities are desired, a spring may be incorporated to increase the acceleration of the control rod into the reactor. If springs are used, the actuator may be designed such that the rod is held against force, and, if the primary power is lost, the spring returns the control rod rapidly to the shutdown position. The spring can also serve to eliminate backlash and thus reduce the deadband in the control loop.

*The expression 2×10^{-4} δk/sec means 2×10^{-4}/sec = δk/sec. This notation is commonly used in nuclear engineering.

The reliability requirements for the control-rod drive system are influenced by considerations of safety and maintainability For safety reasons there must be a high level of confidence that the scram system will operate correctly, i e , it will be reliable (see Vol 2, Chap 12) The required confidence that this system will work is significantly higher than that required of the control system during normal operation In addition, the availability of the control-rod drive system is essential This means the system must be available for operation during all scheduled operational periods, except during normal preventive-maintenance periods when the reactor is shut down A failure in the control-rod drive system normally requires that the reactor be shut down in view of the possibility of unsafe operation (loss of control of output power or loss of scram capability) The reactor is then unavailable for the total time required to shut down, correct the failure, and restart Hence, unscheduled maintenance must be avoided Nuclear power plants are designed for a life of about 30 years, with scheduled shutdowns for maintenance at intervals of 6 to 18 months Since the control-rod drive systems can be serviced during the scheduled maintenance periods, their reliability requirements are correspondingly reduced In essence, control-rod drive systems must be highly reliable, but only for relatively short periods of time For an increase in overall reactor reliability, some systems are designed so a failure of one control-rod drive does not require shutdown In these systems failures may occur during operation, but corrective maintenance is not required until the next scheduled maintenance period If unscheduled maintenance is required because a rod-drive mechanism fails and forces a shutdown, it is very desirable to minimize the time required for corrective maintenance This time can be reduced if the designer has considered this requirement during the initial design phase

The requirements discussed above result from nuclear design operational considerations and are applicable to reactors controlled through a primary control loop on nuclear power In establishing the requirements for a control-drive mechanism, the designer must first consider the reactivity span and the rate of change needed, these are used to calculate the desired period and steady-state operating conditions However, since an automatic control loop is normally used, the designer must also ensure that the control system can operate in a stable closed-loop manner The requirements on the control-drive mechanism that must be met to provide stable closed loop operation during all feasible transients and perturbations may be more severe than those for satisfactory period and steady-state operation These requirements are identified by dynamic control analysis of the complete reactor system

As shown in Fig 7 1, the control-rod position loop is usually an inner loop of the automatic power control loop Although the speed of response of the power-control loop is selected to provide the desired reactor performance, a dynamic control-systems analysis would indicate that the speed of response of the rod-position loop must be from 2 to 10 times more rapid to result in stable (nonoscillatory and nondiverging) operation when all control loops are closed

The basic power-control loop, as shown in Fig 7 1, is sometimes supplemented by a trim loop that controls the temperature of the primary-coolant flow This latter would be an outside loop on power control which compares a measured temperature with a demanded value and produces a supplemental power-demand signal More stringent requirements are placed on the drive mechanism when the reactor controllers are complicated by introducing coolant temperature, or variables from the steam side of the power plant loop, because of the interaction of these parameters and the normal dynamic requirement to make all inner loops respond about six times faster than outer loops

The requirements of the amount of reactivity controlled, the rod-positioning accuracy, reactivity rate of change under various situations, and the reliability and availability have been met in many power reactors by using low-maintenance, high-reliability a-c motors for the control-rod drive The coupling to the control rod is usually by a rack-and-pinion mechanism or a lead screw and nut However, other techniques have been used, including d-c motors, hydraulic cylinders and motors, linear induction motors, and magnetic jacks The designer must establish the requirements for a given reactor design and then review all available systems and components to select the most appropriate The advantages and disadvantages of a number of systems and typical applications are discussed in the following sections

7-3.2 Means of Control

The control rods selected for water reactors are usually linear structures of a neutron-absorbing material designed to be moved vertically into and out of the core The amount of neutron absorber in the core is determined by the position of the rods with respect to the core At shutdown, the rods are positioned with the maximum amount of neutron absorbing material within the core As the rod is withdrawn from the core, the reactivity and neutron population increase by an amount generally proportional to the amount of neutron-absorbing material removed

Although control rods of neutron-absorbing material are used in most reactor installations, in some instances neutron-reflecting and neutron-moderating or fuel-bearing rods are used Another type of control, a cylindrical device called a drum, has its surface comprised partly of neutron absorbing material and partly of neutron-reflecting material, or there can be combinations of absorber–fuel or absorber–moderator Several of these drums are located in a vertical position around the core periphery and have rotary control motion, the extent of drum rotation determining the core reactivity

Reactivity control by a neutron-absorbing liquid may be heterogeneous, with the liquid flow in a sealed pipe or

pipe system adjacent to the reactor core, or homogeneous, with the liquid mixed with the reactor coolant water and extracted by ion-exchange equipment For example, mercury can be used in a heterogeneous system and boric acid can be introduced into the reactor coolant water system in a homogeneous system

7-3 3 Materials

The conventional control rod for water cooled reactors is made of stainless steel with neutron absorbing material either supported and clad by the rod structure or alloyed with the rod material The neutron absorbing material absorbs thermal neutrons, which reduces the effective multiplication constant, k, below unity The most commonly used neutron absorbing or poison materials in control rods are cadmium, boron, and hafnium Other less commonly used materials are silver, europium, and indium Factors determining the usefulness of a control rod material include not only thermal-neutron absorption properties but also availability, cost, and structural and machinability properties The material must be fabricated into various shapes and must not be affected appreciably by the temperature or pressure of the particular environment in which it is to be used Its susceptibility to corrosion and nuclear-radiation damage must be low In some instances alloys of the poison materials with other materials improve their suitability for control-rod application

Table 7 2 indicates the relative worth of commonly used control-rod absorber materials

Table 7 2—Control Worth for Various Materials*

Material	Relative effectiveness in a water-cooled reactor
3 0 wt % ^{10}B in stainless steel (dispersion of minus 100 mesh particles of 90% enriched ^{10}B)	1 12
Dispersion† containing 10 vol % B_4C (90% enriched ^{10}B)	1 06
Hafnium	1 00
0 97 wt % ^{10}B in stainless steel (alloy)	0 98
Ag–22 wt % In alloy	0 96
15 wt % Eu_2O_3 in stainless steel (dispersion)	0 96
Indium	0 93
Silver	0 88
Cadmium	0 80
8 7 wt % gadolinium–titanium	0 77
Tantalum	0 71
2 7 wt % Sm_2O_3 in stainless steel (dispersion)	0 70
Haynes Stellite 25(Co–20 wt % Cr–15 wt % W–10 wt % Ni)	0 68
Titanium	0 24
Zircaloy 3	0 05
2S aluminum	0 02

*Based on data from C R Tipton, Jr (Ed), *Reactor Handbook* Vol 1, Materials, 2nd ed p 779 Interscience Publishers Inc , New York, 1960, and W K Anderson and J S Theilacker (Eds), *Neutron Absorber Materials for Reactor Control* p 117 Superintendent of Documents, U S Government Printing Office Washington, D C , 1962

†Dispersion assumed to have a nonabsorbing matrix and to be clad with 0 02 in of nonabsorbing materials

7-3.4 Rod Shape

The shape, dimensions, and number of reactor control rods are dependent on the core mechanical design and the amount of negative reactivity needed for shutdown To function efficiently as a neutron poison, a control-rod material must have sufficient thickness to absorb most of the flux at the rod surface In light-water reactors the slowing-down length, i e , the distance required for a fission neutron to be reduced to thermal energy, is short Therefore, to be effective in absorbing thermal neutrons, the poison material must be physically close to the fuel surface and have a high surface-to-volume ratio A cruciform shape with thin wide blades of poison material fulfills these requirements Figure 7 2 shows typical control-rod configurations for power reactors Since a light-water reactor has a neutron spectrum with an appreciable fraction of epithermal neutrons, materials with large absorption cross sections for these energies, such as hafnium and indium, are used in addition to the usual thermal neutron absorbers, such as cadmium or boron

7-3.5 Rod Configuration

Control rods are arranged in symmetrical patterns within the core structure and around the core periphery The total absorption capability in all the rods largely determines the shutdown reactivity of the core Shutdown reactivity is defined as the increase in reactivity required to bring the reactor to critical from a fully shutdown condition

Safety rods are specifically designed to effect rapid shutdown or scram should a hazardous reactor or plant condition occur These rods normally contain poison material and are withdrawn to a maximum degree before start-up and are kept in that position during power operation They are designed for rapid release and acceleration into the reactor Separate safety rods are seldom used in the present generation of power reactors, but their scram function is combined into the shim rods (Vol 2, Chap 12)

Shim rods comprise the greatest number of rods and control the greatest amount of reactivity Shim rods are used to remove shutdown reactivity during start up and to offset the effects of temperature, xenon, samarium, and fuel depletion during power operation Controlled shim-rod motion is very slow during power operation and may be only a few inches or tenths of inches per day Shim rods are usually arranged in groups or banks, only one of which can be moved at a time In any group, one or several rods can be moved at the same time, at the option of the operator

The regulating rod, similar in design to a shim rod, is used for fine control of reactor power level Small changes of reactivity are needed Regulating-rod motion may be

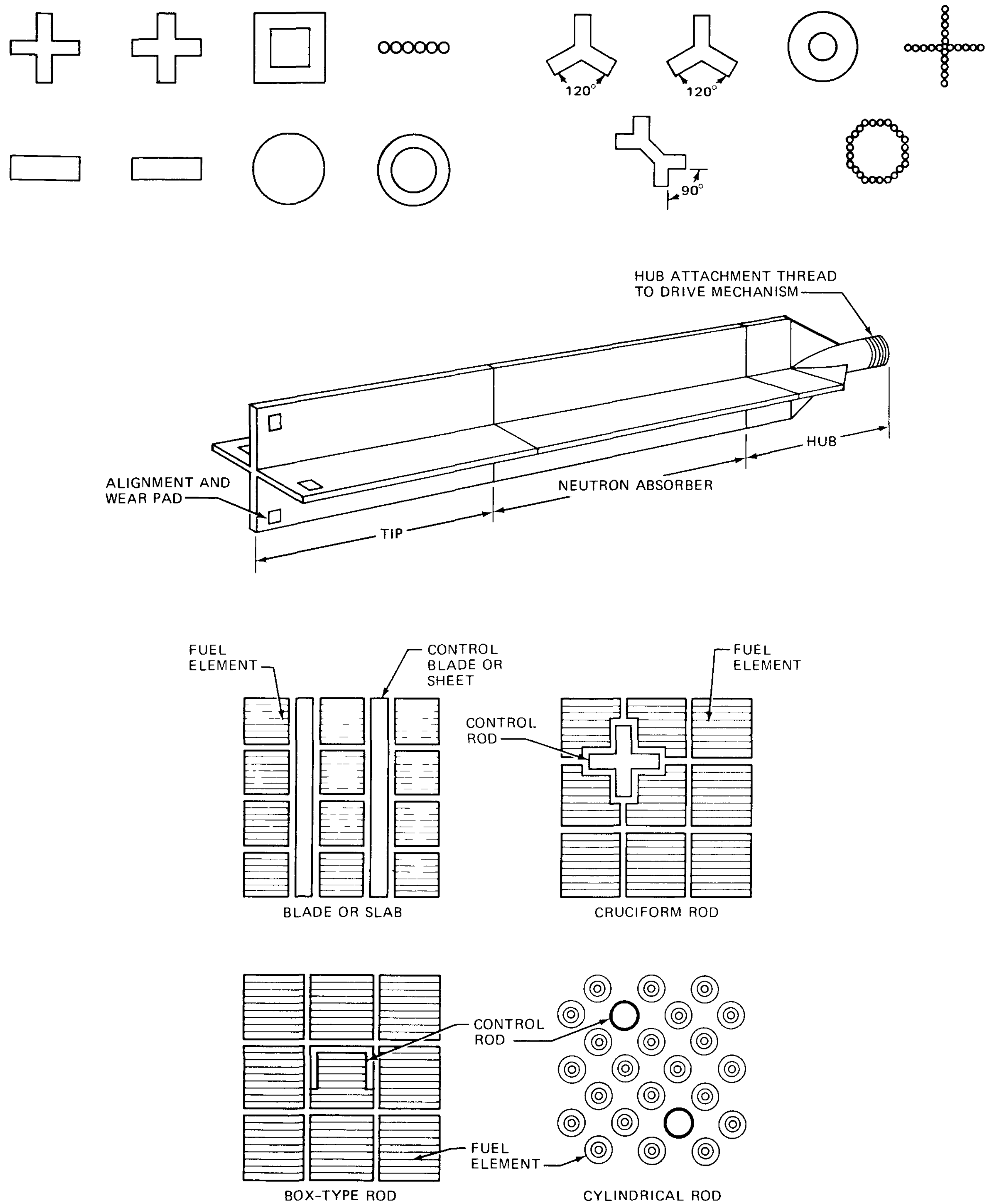

Fig. 7.2—Representative cross sections (not to scale) of control rods. Heavily outlined cross sections indicate clad absorber sections. The center figure shows the typical structure of cruciform rods used in some water-cooled power reactors. (From Wm. E. Ray, *Fabrication of Control Rods for Nuclear Reactors*, p. 5, Rowman & Littlefield, Inc., New York, 1963.) The bottom figure shows how several control shapes fit into fuel-element arrays.

manually controlled, but usually the regulating rod is driven by a servomechanism in a feedback control loop that finely regulates power or flux To satisfy the performance requirements of automatic control, the drive mechanism for the regulating rod has more stringent performance requirements than the drives for shim or safety rods

7-3.6 Types of Drives

In the usual water reactor configuration, the control rods may be raised or lowered out of the core Each rod may have a follower section of some inert material to fill the void left when the rod poison section is moved out of the core Without the follower section, the void would fill with water, a good moderator material, and a neutron-flux peak would develop in that region

The control rod can be coupled to a drive mechanism by any one of a number of different devices Commonly, an electromagnetic coupling is used in which a d-c solenoid section on the drive mechanism couples to the steel section of the control rod The details of this type coupling vary widely The coupling may be a direct-lift device, a rotary clutch, or a magnetically held latch that firmly locks the rod to the mechanism An advantage of the electromagnetic coupling is that release is simple, reliable, and rapid (10 msec is typical) These characteristics are necessary for safe operation of the reactor

When a reactor undergoes a sudden rapid increase in neutron-flux level, the amount of poison (negative reactivity) that can be inserted in the first few milliseconds is extremely important (see Sec 7-3 1) It must be sufficient to put the reactor on a negative period Rod release and insertion under the force of gravity is not enough All drive mechanisms provide for preloading to insert the rod rapidly in the event a fast shutdown or scram is necessary The preloading may be accomplished by springs located within the latching mechanism or by a pressurized-air cylinder, for example To prevent damage to the rod and reactor, shock absorption with pneumatic or hydraulic cylinders is used to cushion the bottoming of the rod when it is driven into the reactor in a scram situation

The type of rod drive used depends to some extent on whether the reactor system being controlled is pressurized or nonpressurized The simple rack-and-pinion or screw nut control drives depicted in Figs 7 3 and 7 4 are generally used for nonpressurized research or test reactors For pressurized-water reactors the control rods can be connected to external drive systems either through a system of shaft seals or by means of a magnetic coupling system Shaft seals have been used in some installations, but they are generally not preferred since the packing material can leak and can be deteriorated by exposure to nuclear radiation Any water leaks through the seals are accompanied by entrained radioactive material and gas Moreover, a shaft seal represents a potentially weak point in the system since it tends to interfere with the free movement of the control rod Shaft seals have been usually applied in installations where rotary shaft motion is translated through the seals to a rack-and-pinion or screw-nut driven assembly located in a pressurized environment Magnetic coupling through a pressure-containment material in the path of the magnetic flux can be accomplished in a number of ways The containment material must, of course, be nonmagnetic

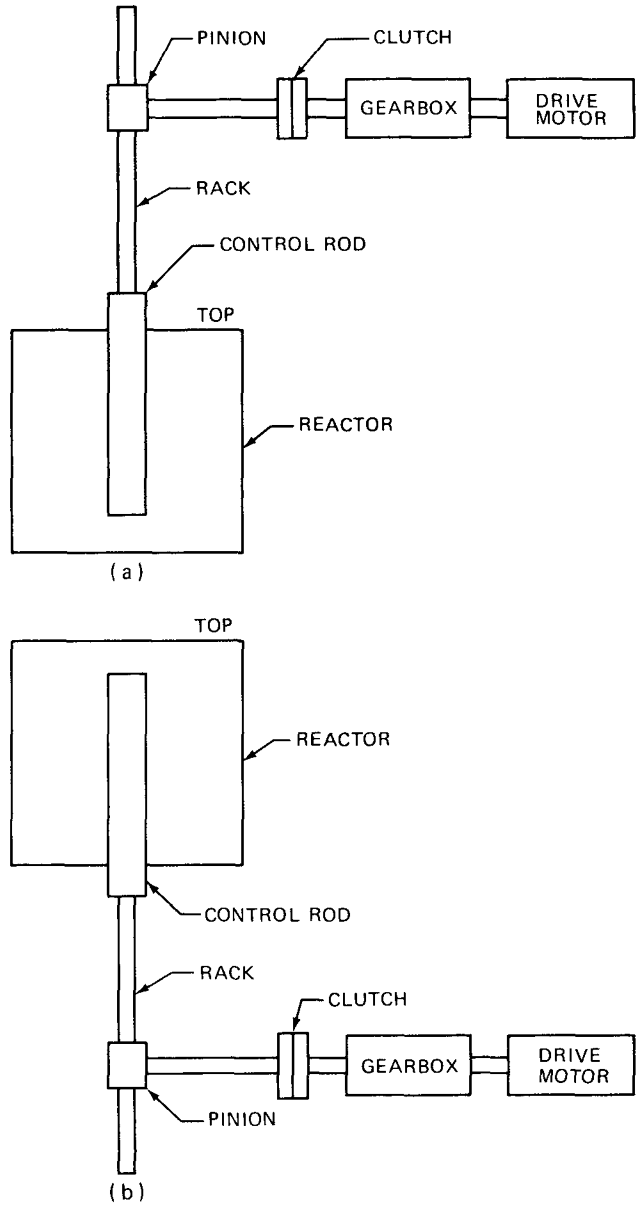

Fig 7 3—Rack and pinion drive for control rod (a) Top entry (b) Bottom entry (From M A Schultz, *Control of Nuclear Reactors and Power Plants,* 2nd ed , p 227, McGraw-Hill Book Company, Inc , New York, 1961)

Another method for driving control rods in pressurized reactors is by means of the "canned" motor Figure 7 5 shows the construction of this type drive It was originally developed for very low speed operation, enabling the gearing between the rotor shaft and the ball-screw mechanism for the control rod to be minimized All moving parts,

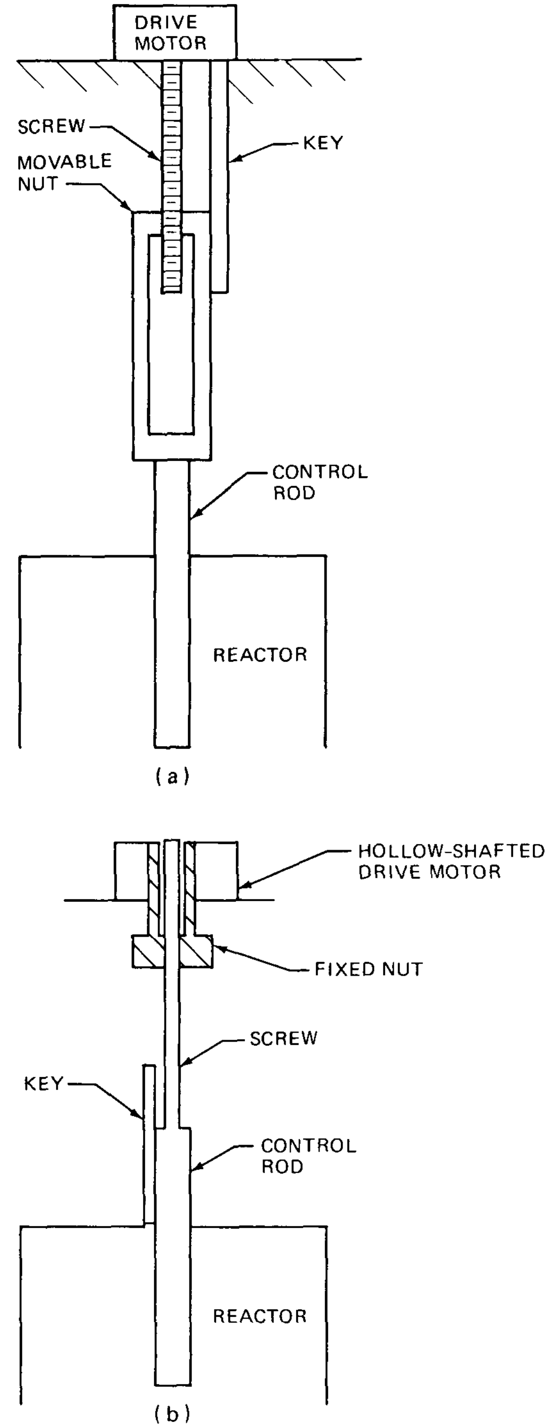

Fig 7 4—Screw and-nut control-rod drives (a) Fixed screw (b) Fixed nut (From M A Schultz, *Control of Nuclear Reactors and Power Plants* 2nd ed p 228, McGraw Hill Book Company, Inc , New York, 1961)

including the canned motor, are designed to operate completely submerged in water A thin Inconel shell located in the 0 020-in gap between motor and stator effectively seals the stator assembly from the water Backed by the metal construction of the stator, this shell is the pressure barrier. Typical design characteristics are normal speeds, 0 to 50 rpm, torque, 6 to 8 ft-lb, cooling water

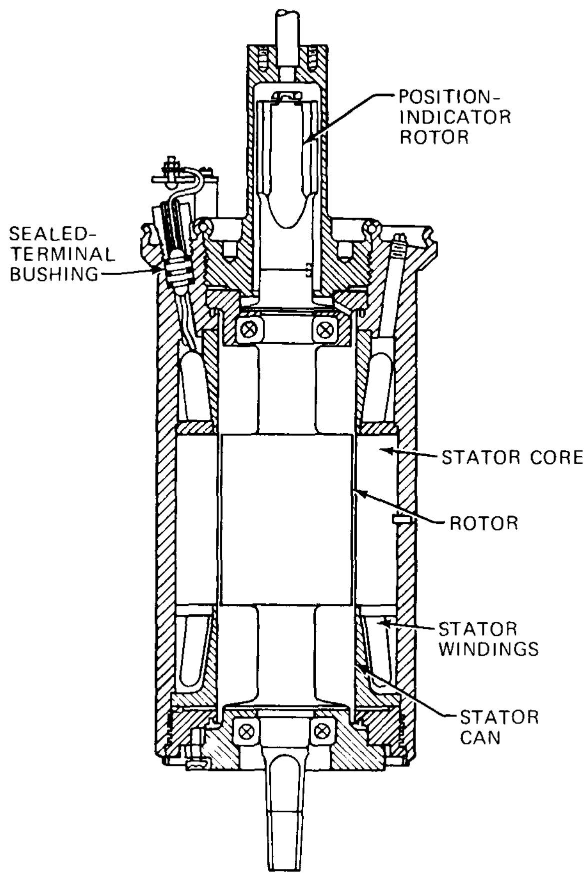

Fig 7.5—Pressurized synchronous reluctance motor (Courtesy Westinghouse Electric Corporation)

flow, 0 15 gal/min at 130°F maximum inlet temperature, pressure, 2500 psi

The problem of converting external rotary motion to linear motion inside a reactor pressure vessel, as required with the canned motor, is eliminated by the linear inductance motor This motor has the unusual capability of producing linear motion without an intermediate rotary motion

The design of this motor can be visualized if the synchronous reluctance motor (used in the canned motor)[3] is considered As described in *Control of Nuclear Reactors and Power Plants* by Schultz,[2] "if this cylindrical motor were figuratively to be sliced open at one axial place, flattened out, and then rolled up again at right angles to the previous cylinder, a structure similar to the cross section of Fig 7 6 would be obtained Here the field coils are nothing but circular doughnuts around a long tube The armature consists of a series of ringlike poles on a long bar The winding slots are cut into a thick magnetic cylinder, and the inner walls of this cylinder are backed up by the windings to take the pressure from the inside of the motor. To complete the magnetic path and also to assist in restraining internal pressures, a magnetic sleeve is placed outside the field coil structure The windings may be connected either in two phase or three phase, and the operation and drive

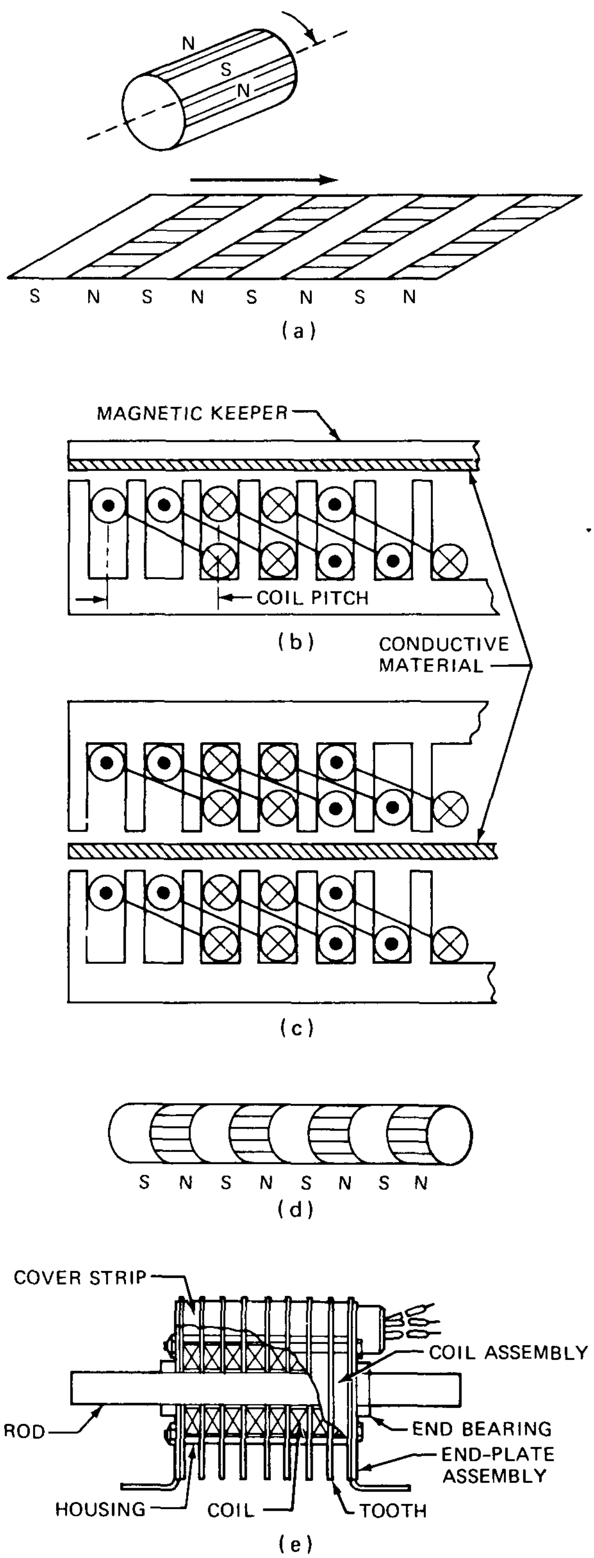

Fig. 7.6—Flat and round rod linear induction motors Development from cylindrical structure to a flat structure shown in (a) and to a rod structure shown in (d) Cross section of single-sided type of flat linear induction motor shown in (b), cross section of double-sized type shown in (c). Typical construction of round-rod linear induction motor shown in (e) [From Wm. J Adams, Linear Induction Motors, *Mach Design*, **42**· 165 (Mar 19, 1970).]

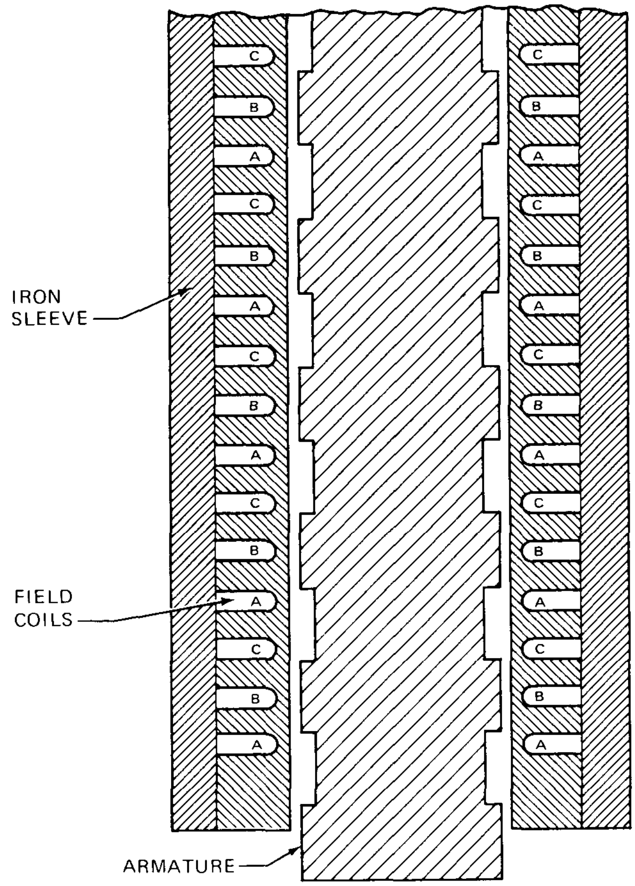

Fig 7 7—Linear induction-motor drive system for a pressurized water reactor

systems are identical with those of the rotating synchronous reluctance motor " A complete linear motor drive system for a pressurized reactor is indicated in Fig 7 7

Another type of rod drive where magnetic coupling is used between the rod and the drive unit is the magnetic jack The most successful version, shown in Fig 7 8, has magnetic moving and holding devices The pressure shell contains the control rod and a sliding armature section Power applied to the lift, grip, hold-down and hold coils in certain sequences (see Sec 7-5 3) holds the rod stationary and lifts or lowers it in definite increments, when all power is released, the rod can be suddenly dropped or scrammed The power unit controlling rod movement consists of a reversible sequential switching device and a d-c power supply

7-3.7 Rod-Position Indicators

Two aspects of position indication are essential for the operation of control rods in a reactor the measurement of control-rod position with respect to the core and the determination of rod position with respect to the drive mechanism The first is far more important. The second is relevant to systems where the rod can be separated from

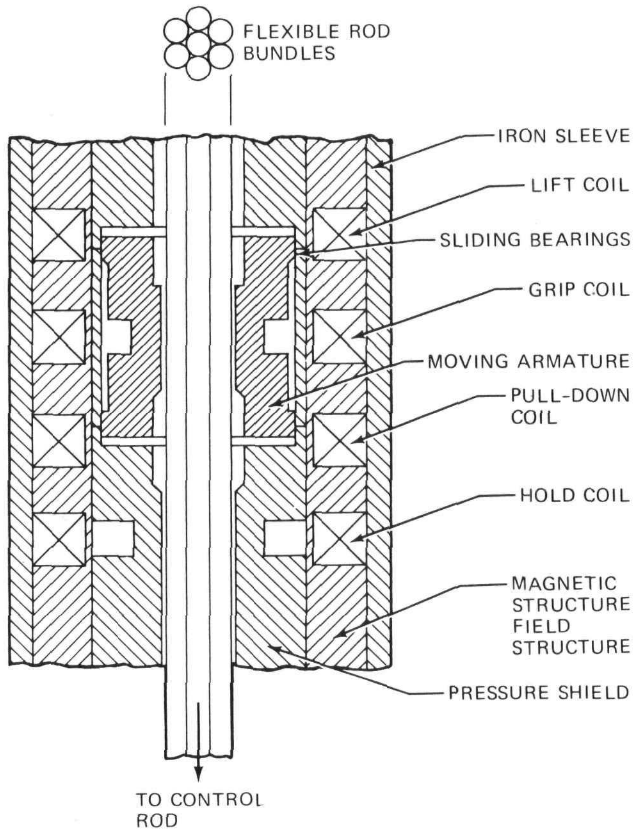

Fig. 7.8—Magnetic-jack configuration.

the drive, as is often the case in drive systems that satisfy both the shim or control and safety requirements.

Pickup or release of a control rod and full insertion or full withdrawal are usually indicated by panel lights controlled by relays or sensing switches actuated by magnetic or mechanical coupling to the control rod. These switches or relays generally have auxiliary contacts used in the control logic circuits. An example is the logic that initiates movement of a bank of shimming control rods when the automatic regulating rod has exceeded its normal control range. Another is a permissive logic circuit that often takes the form of withholding control power at start-up until all rods are completely down or fully inserted in the reactor and all drives are down and engaged to their respective rods.

Whenever more than one group of shim rods is used on reactor start-up, limit-sensing switches can be used to permit or initiate movement of a second bank of rods when the first has reached a programmed "full-out" position.

Once the condition of major rod position and attachment to drives has been satisfied, knowledge of the position of rods with respect to the core is essential to reliable control of a reactor. Both absolute position and relative movement must be measured with an accuracy sufficient to establish safe conditions during start-up and power adjustment and to establish predetermined power distribution patterns in the core. The position of rods relative to each other can also be used to diagnose reactivity anomalies within the core. A study of the history of the reactor operating characteristics makes it possible to predict rod position under various operating conditions. If an indication differs markedly from its expected value, it is usually a sign of anomalous behavior in the core, control system, instrumentation, or rod-drive system. Analysis can often pinpoint the malfunctioning item.

Position indication may be direct, when the control rod actuates the sensing device, or indirect, when the position sensor is coupled to the drive mechanism. The control system is arranged so that after rod release the drives are automatically returned to zero position.

In all reactor operation, indication of rod position is displayed at the control console. Panel-mounted dial indicators driven by synchro-receiver units with the synchro-transmitters directly geared or coupled to the driven mechanisms, synchro-driven bar indicators, tapes, or digital counters are conventional. The bar or tape indicators give an immediate and graphic nonambiguous indication of absolute rod position, thereby minimizing possible operator error.

In conjunction with the previously mentioned "all-in" and "all-out" position indication and indication of relative position, position switch sensing of intermediate position is valuable for interlocking with rod-programming circuits and for giving the operator an independent indication of where the rods are under all circumstances. Intermediate position measurements can be used to signal definite rod positions on a bar or tape indicator, thereby providing a backup measurement that also prevents operator misinterpretation of absolute rod position.

Rod-position sensing in sealed systems, in which the drive as well as the rod is in a pressurized high-temperature coolant environment, is usually accomplished magnetically. Here extreme in/out positions and also intermediate points may be indicated by having magnetic coupling to coils located at the various points along the pressure-seal housing around a control-rod extension. Accurate and continuous sensing of rod position along the entire length of travel, however, is more difficult.

An example of rod-position sensing and indication in a sealed system is the magnetic-jack control rod in the San Onofre Atomic Power Plant (see Sec. 7-4.2). Lights on the control panel indicate rod position. Thirty transformers are mounted around the control-rod-extension pressure housing. Each of the 30 secondary windings is connected to its own individual light on the control panel. As the magnetic portion of the control-rod extension passes each transformer, the coupling between primary and secondary windings is increased to the point where each lamp in the row is successively lighted and stays lit as rod movement progresses. Although these lights give only approximate position, there is no ambiguity. A secondary scheme for securing indirect position indication uses synchro-repeater indication of the rotation of the cam shaft that actuates the jacking mechanism from the power supply.

Another magnetic readout device for a sealed system uses a winding distributed around the thimble (pressure housing) around the rod extension. The winding is part of an induction bridge with readout on a panel meter. As the rod is withdrawn, the magnetic portion enters the solenoid and changes the inductance of the winding as it progresses. Through suitable design of the coil, its spacing and number of turns, the indication can be made approximately linear with rod displacement.

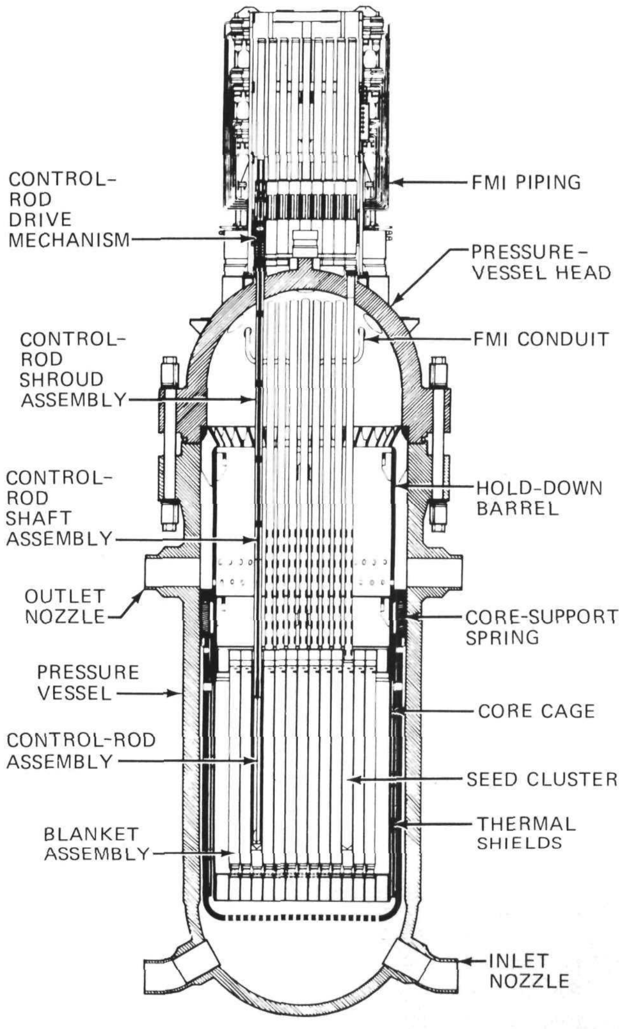

Fig. 7.9—Shippingport Pressurized Water Reactor, center-lines section. (From *The Shippingport Pressurized Water Reactor*, p. 62, Addison–Wesley Publishing Company, Inc., Reading, Mass., 1958.)

7-4 EXAMPLES OF REACTIVITY-CONTROL SYSTEMS

7-4.1 PWR Power Plant at Shippingport

The Shippingport reactor is a pressurized-water reactor with 32 vertical hafnium control rods, both manually and automatically controlled, to adjust the power level (Figs. 7.9 and 7.10). Since the reactor coolant system is completely sealed, the control rod and the driving element must be within the pressure barrier of the coolant system. For this application the "canned" motor shown in Fig. 7.6 is used. The rod-drive mechanism is a roller nut attached directly to the motor rotor; it operates on the lead-screw portion of a control-rod extension as shown in Fig. 7.11. Since the coupling between the rotor and roller nut is direct, i.e., no reduction gearing is used, a special very slow (22 rpm) motor is required.

The motor torque is applied by magnetic coupling through the pressure barrier (the thin "can" between the rotor and stator). For the control-rod lead screw to disengage quickly from the roller-nut mechanism, the nut is split into halves that are held together by a magnetic flux generated in the stator winding. Thus cutting the power to the motor also scrams the rod. The split roller nut must be kept from reengaging until the rod has fully inserted to prevent damage to the mechanism.

The motor winding is designed for a three-phase power supply to produce a rotating field similar to that of the ordinary 60-Hz induction motor, except that it operates on alternating current with a frequency variable from zero (direct current) to a few hertz. The d-c power (zero frequency) is required, as pointed out earlier, to keep the nut engaged to the lead screw and to maintain the rod at the selected position. Even though the frequency can be reduced to zero to stop rod motion, the voltage must be kept applied to maintain the latch of the roller nut to the rod. This implies the requirement that the alternating current be changed to direct current without any change in value. Another requirement is for phase sequence to reverse the direction of rod motion.

A low-frequency d-c to a-c converter is used to meet these unusual power supply requirements (see Fig. 7.12). Basically, this converter is a circuit of series-connected resistors formed into a closed ring and mounted on an insulated commutator disk. Each junction point of the resistors is connected to one of the commutator segments arranged in a ring. Two diametrically opposite points on the ring of resistors are permanently connected to a d-c power supply. A rotating brush structure, with three insulated brush segments 120° apart, picks off a three-phase voltage from the commutator segments. Shorting-type brushes are used to prevent circuit interruption as the brushes move from one segment to the next. The a-c voltage is taken from the brushes through slip rings on the rotating brush structure. The frequency of the rod-motor voltage is determined by the speed of a small d-c motor that drives the brush structure. The peak a-c voltage is determined by the value of the d-c voltage applied to the series-resistor rings. Stopping the brush rotation automatically results in applying a d-c voltage to the motor stator fields so that the motor is held stationary.

In the Shippingport reactor two sets of brushes are incorporated into each resistor-commutator assembly. Each set of brushes supplies power to two rod-drive motors in

parallel. With this arrangement four control rods are moved simultaneously whenever a commutator assembly is rotated. If four rods from different portions of the core are selected to operate off each commutator assembly, the core power and the desired symmetrical distribution of neutron flux can be more easily maintained at the various power levels. For the 32 rods 8 inverters are used; 2 spare inverters are available.

In addition to four rods being controlled by one inverter, the rod programming plan for this reactor divides the rods into two or more groups, each having subgroups of four rods. Group 1 is necessary to bring the reactor from shutdown to initial criticality. Sixteen rods were selected for this group. They are moved individually in multiples of four in sequence such that any subgroup is never more than 3 in. beyond the position of the remainder of the group. This procedure, together with a maximum limit on rod speed, meets the criteria for the maximum rate of insertion of reactivity. The remaining 16 rods are programmed in groups of 8, 4, and 4. The rod-programming equipment is designed to place 16, 20, 24, 28, or 32 rods in the first group, leaving any remaining rods grouped in multiples of 4.

Versatile combinations of rod speed and grouping are necessary to provide for a rapid and uniform burnout of ^{135}Xe after a scram or a power reduction. Although a scram causes all rods to drop, there are some situations demanding a fast or "safety" insertion in which power must be rapidly reduced a relatively small amount without a full-scale scram. (The latter, incidentally, also demands a correlative reduction or shutdown of the power-plant output.)

Each rod position is displayed on the control console by an individual column of indicator lights. Each light is connected to a small transformer on the control-rod-extension housing. As the magnetic material of the control-rod extension passes through each transformer, the coupling between the windings increases, and the lamp is lit.

Automatic control of reactor power is provided by a power and temperature control system. The reactor is inherently self-regulating through a negative temperature coefficient of reactivity that compensates for reactor coolant-temperature variations caused by variations in steam load at the turbine. The accumulation of fission-product poisons makes gradual adjustment necessary. As in

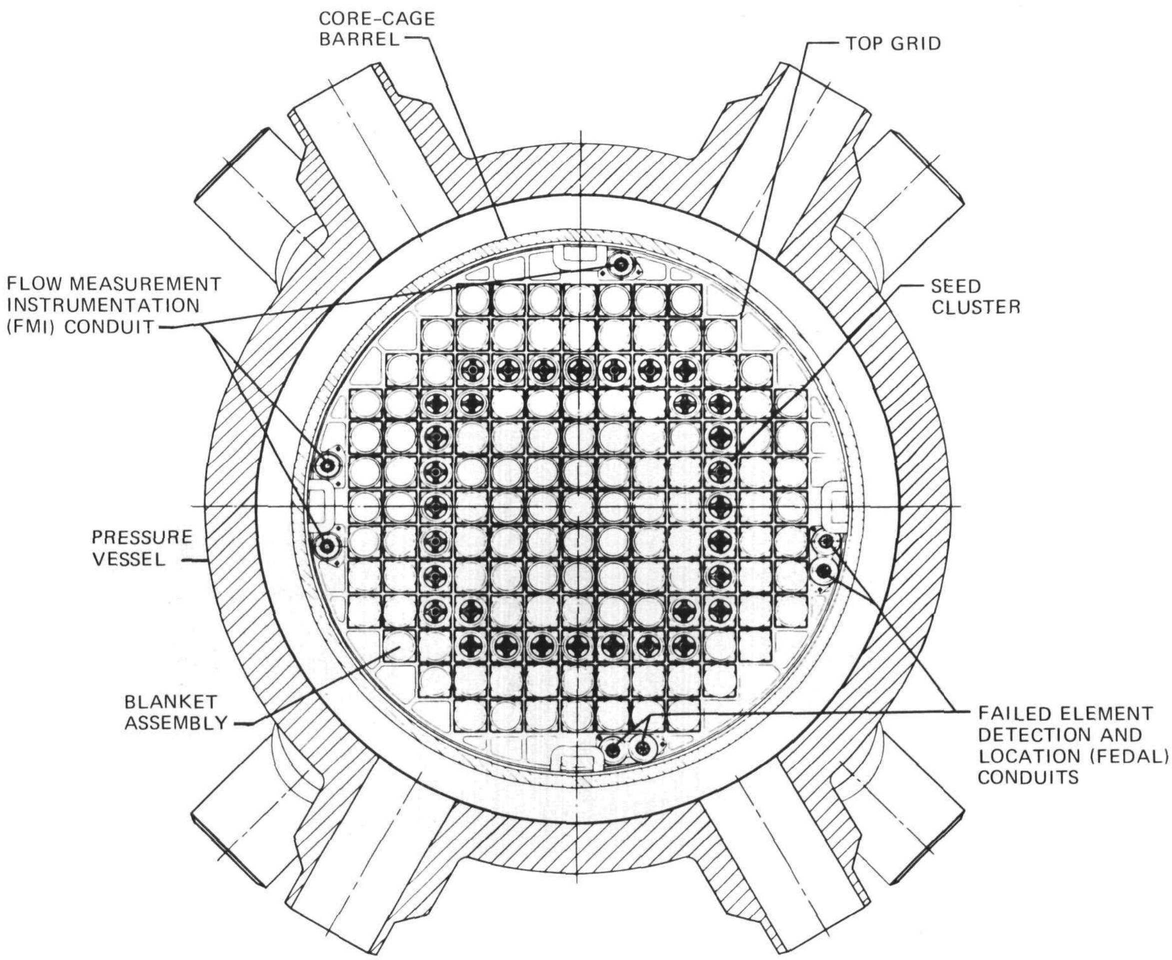

Fig. 7.10—Shippingport Pressurized Water Reactor, cross section through nozzle. (From *The Shippingport Pressurized Water Reactor,* p. 61, Addison–Wesley Publishing Company, Inc., Reading, Mass., 1958.)

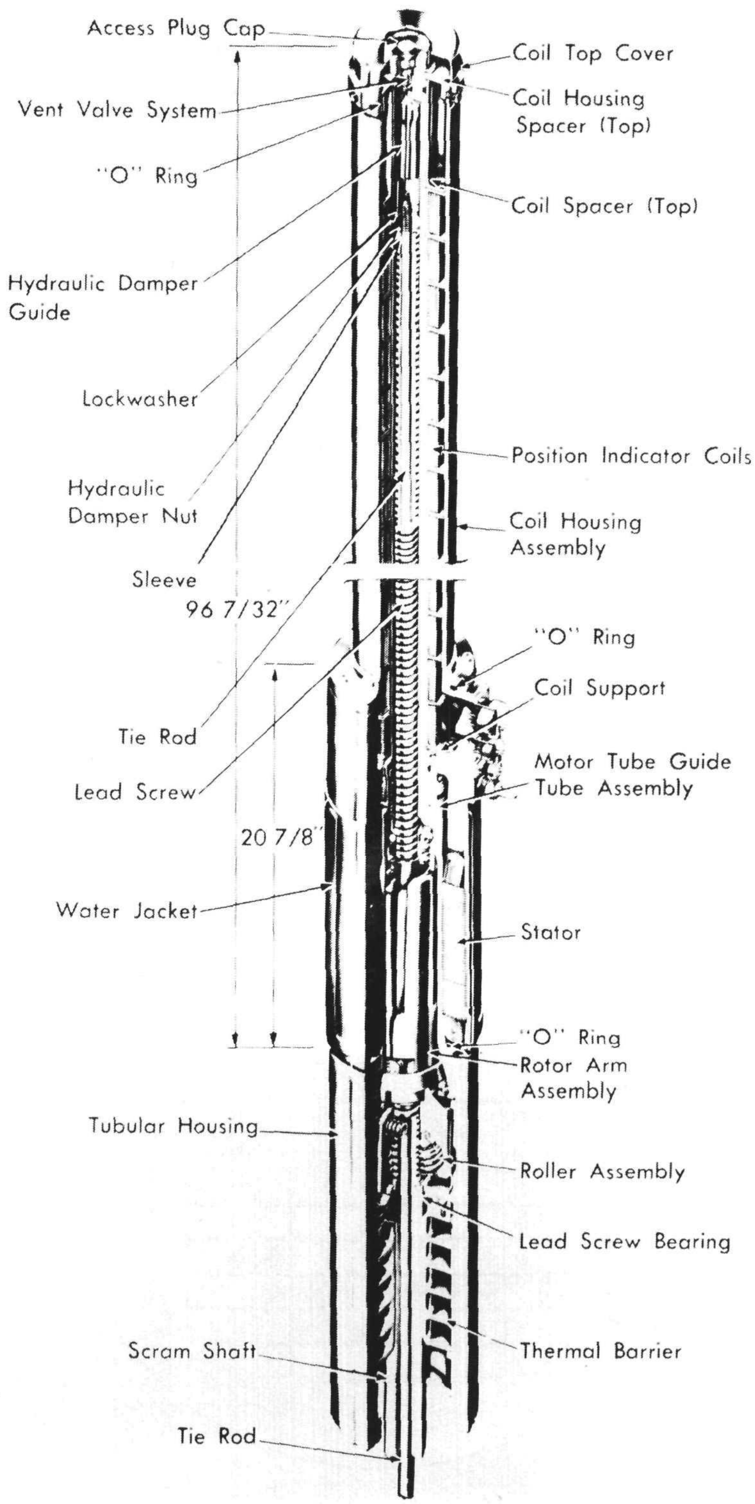

Fig. 7.11—Shippingport Pressurized Water Reactor, control-rod drive mechanism. (From *The Shippingport Pressurized Water Reactor,* p. 97, Addison–Wesley Publishing Company, Inc., Reading, Mass., 1958.)

most reactors, rod movements must be fairly frequent immediately after start-up or a load change.

7-4.2 San Onofre Atomic Power Plant

The San Onofre Atomic Power Plant in San Clemente, Calif., has a pressurized-water reactor similar to that at Shippingport except for the method of rod drive and control. Each of the 45 control rods for this reactor (Fig. 7.13) consists of a 5-in.-square spider-like cluster of 16 absorbing rods, 126-in. long, each fabricated from an alloy of silver, indium, and cadmium and hermetically sealed within a stainless-steel sheath. The cluster of absorber rods fits into guide thimbles in a fuel-rod assembly (Figs. 7.14 and 7.15) and is attached to a driven vertical shaft extending through the top of the reactor to the rod-drive mechanism. Boric acid is added to the coolant water to control reactivity during both operating and shutdown periods to reduce the required number of control rods and to achieve uniform neutron absorption throughout the core.

Whereas each rod drive of the Shippingport reactor uses a canned motor to rotate the nut mechanism attached to a lead-screw extension of the control rod, the San Onofre reactor rod-drive mechanism uses a form of the magnetic jack. There is a similarity between the two in that motion is produced magnetically through the pressure barrier. The motion is rotary in the Shippingport reactor; it is linear with the magnetic jack.

The rod-drive mechanism (Fig. 7.16) consists of a latch assembly and a rod-drive assembly that operate within a thimble, all at reactor pressure. A stack of operating coils surrounds the rod-drive portion of the thimble. A 120-in.-long coil stack over the upper part of the thimble, into which the control-rod extension travels as the control is raised, is used for rod-position indication. The reactor coolant water fills the pressure-containing parts of the mechanism and cools and lubricates the moving parts of the drive.

The drive shaft has circular grooves, spaced ⅜ in. apart, machined into its surface along its entire length. Magnetically operated gripper latches lock into the grooves to hold the drive shaft stationary with the drive. The operating coil stack consists of the lift coil, movable gripper coil, and stationary gripper coil. These are energized in a fixed sequence by cam switches actuated by a rotating cam shaft. The coils induce magnetic flux through the pressure housing and operate the latch components. Within the pressure housing, two sets of latches lift or lower the grooved drive shaft. Turning the cam shaft one revolution causes the lifting mechanism to cycle once and quickly moves the rod out in one ⅜-in. step. Reversing the rotation of the cam shaft reverses the direction of rod motion. Latch actuation is produced by pole piece motion for the three magnets.

Since the magnetic jack develops a lifting force of 400 lb and the total drive shaft weight is 144 lb, there is

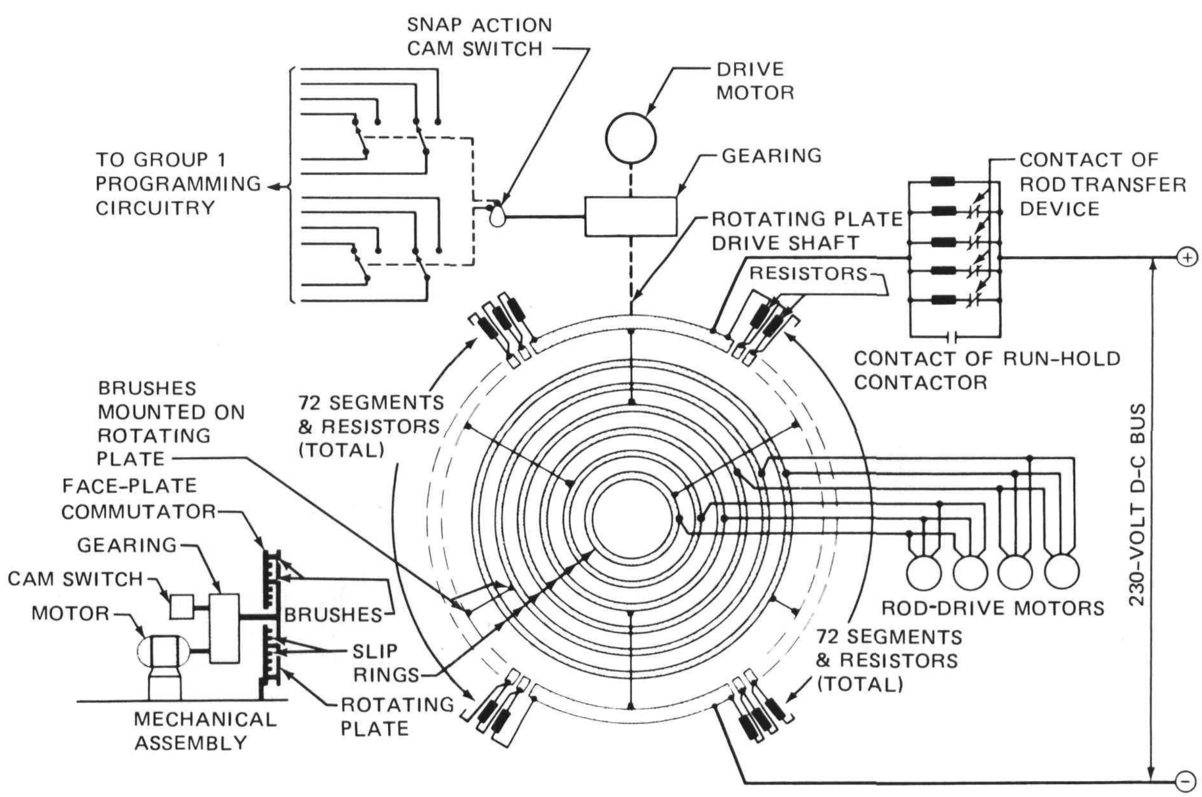

Fig. 7.12—Shippingport Pressurized Water Reactor, schematic diagram of rod-control d-c to a-c power inverter. (From *The Shippingport Pressurized Water Reactor,* p. 282, Addison–Wesley Publishing Company, Inc., Reading, Mass., 1958.)

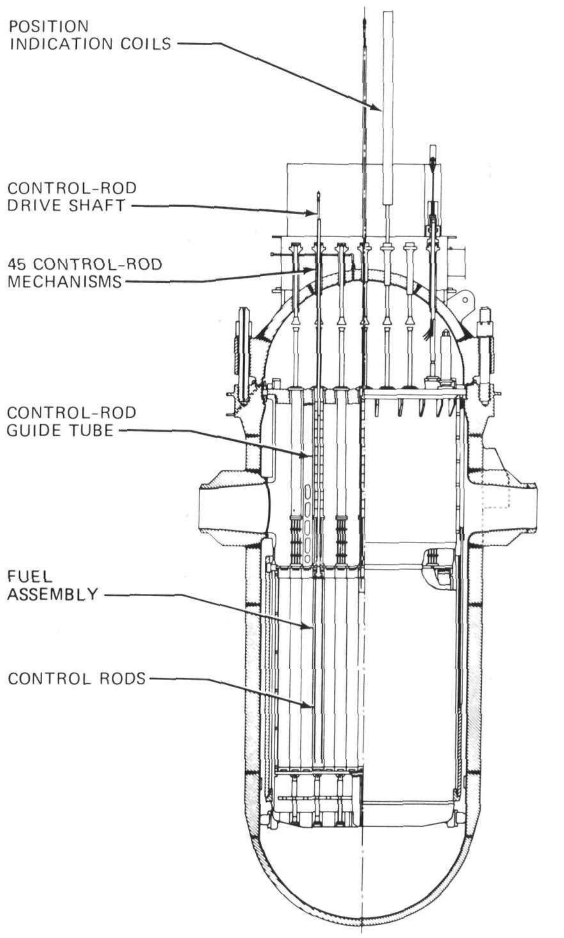

Fig. 7.13—Vertical section of the San Onofre reactor. The reactor vessel has 8-in. walls clad on the inside with 0.109 in. of type 304 stainless steel.

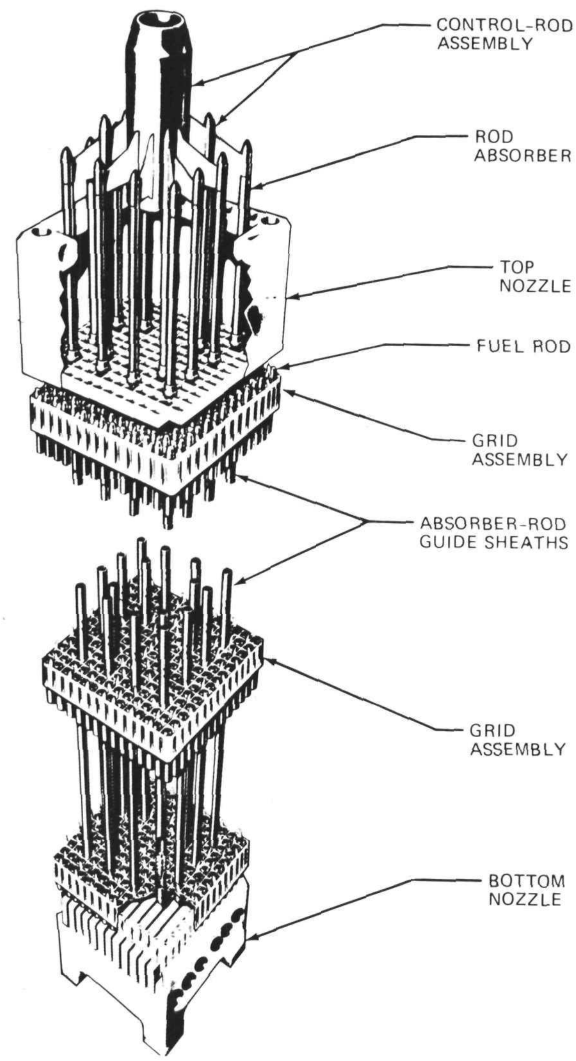

Fig. 7.14—Rod-cluster assembly, San Onofre Atomic Power Plant.

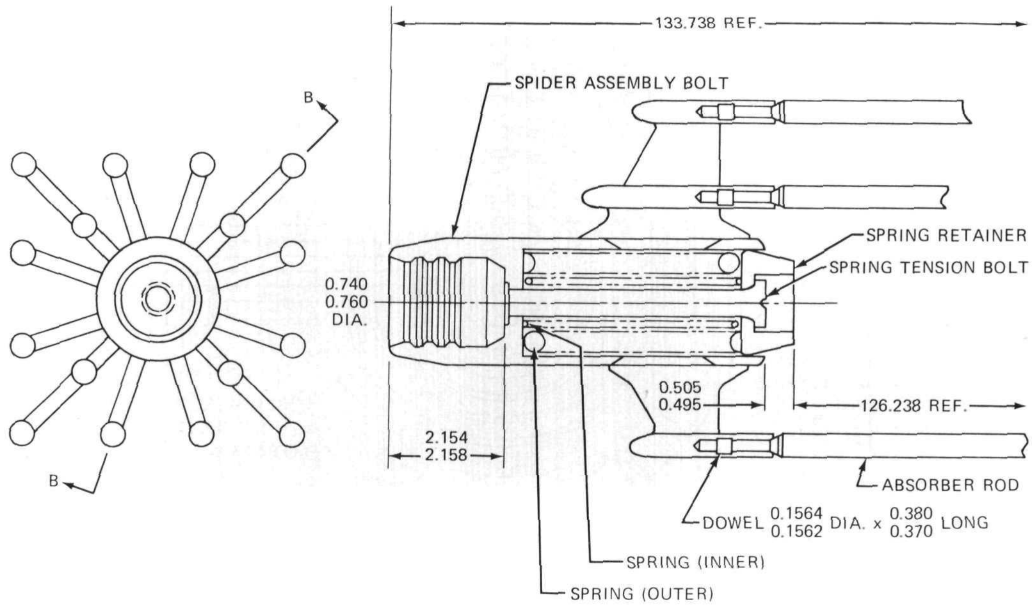

Fig. 7.15—Control rods for San Onofre reactor.

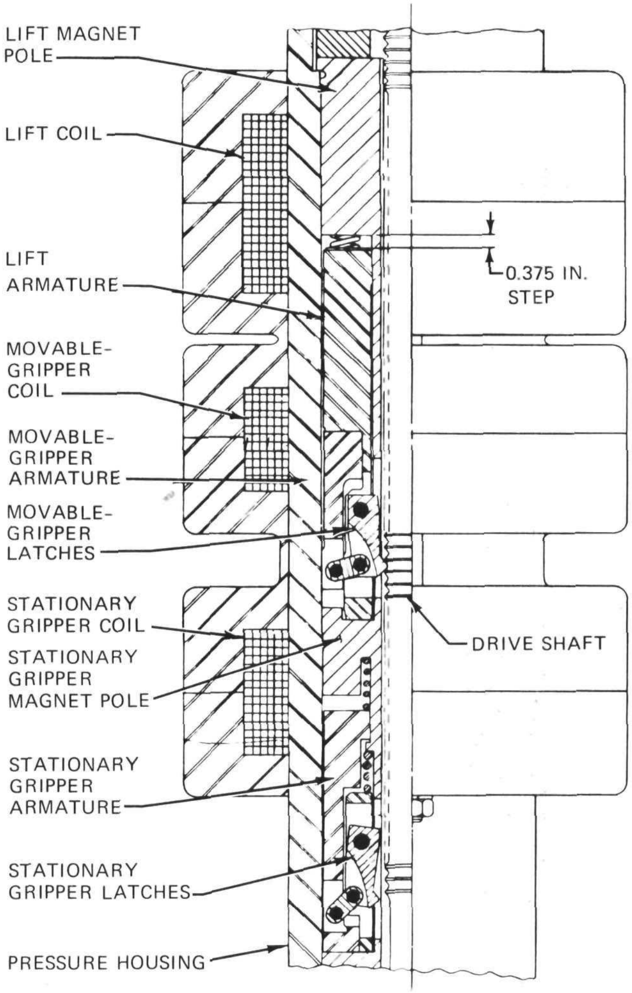

Fig. 7.16—San Onofre reactor rod-drive mechanism.

ample capacity to overcome friction in the system. For rod insertion, gravity furnishes the driving force and overcomes the friction load.

The upper set of latches operates to raise or lower the drive shaft in $\frac{3}{8}$-in. steps. After one lift step the lower latches are engaged in a shaft groove and raise the rod $\frac{1}{32}$ in. to unload the upper latches so they may be reset to lift the rod another increment. The latches are actually linked to sliding armature or pole pieces that move when their respective magnet coils are energized or deenergized.

Table 7.3 gives a detailed description of the sequence of steps in control-rod actuation at the San Onofre plant.

Table 7.3—Detailed Description of San Onofre Control-Rod Actuation*

Control-Rod Withdrawal: Sequence of Operations

1. Movable gripper coil—On.
2. Stationary gripper coil—Off.
3. Lift coil—On. The $\frac{3}{8}$-in. gap between the lift armature and the lift magnet pole closes, and the drive rod rises one step length.
4. Stationary gripper coil—On. The stationary gripper armature rises and closes the gap below the stationary gripper magnet pole. The three links, pinned to the stationary gripper armature, swing the stationary gripper latches into a drive-shaft groove. The latches contact the shaft and lift it $\frac{1}{32}$ in. In this manner, the load is transferred from the movable to the stationary gripper latches.
5. Movable gripper coil—Off. The movable gripper armature separates from the lift armature under the force of three springs and gravity. Three links, pinned to the movable gripper armature, swing the three movable gripper latches out of the groove.
6. Lift coil—Off. The gap between the lift armature and lift magnet pole opens. The movable gripper latches drop $\frac{3}{8}$ in. to a position adjacent to the next groove.
7. Movable gripper coil—On. The movable gripper armature rises and swings the movable gripper latches into the drive-shaft groove.
8. Stationary gripper coil—Off. The stationary gripper latches, and the armature moves downward by gravity until the load of the drive shaft is transferred to the movable gripper latches. It then swings out of the shaft groove.

The sequence described above, where the control rod moves $\frac{3}{8}$ in. for each cycle, is termed "one step" or "one cycle." The sequence is repeated at a rate of up to 40 steps per minute. The control rod is thus withdrawn at a rate of up to 15 in. per minute.

Control-Rod Insertion: Sequence of Operations

1. Stationary gripper coil—On.
2. Movable gripper coil—Off.
3. Lift coil—On. The movable gripper latches are raised to a position adjacent to a shaft groove.
4. Movable gripper coil—On. The movable gripper armature rises and swings the movable gripper latches into a groove.
5. Stationary gripper coil—Off. The stationary gripper armature moves downward and swings the stationary gripper latches out of the groove.
6. Lift coil—Off. Gravity separates the lift armature from the lift magnet pole, and the control rod drops down $\frac{3}{8}$ in.

*From the operating manual for the San Onofre plant.

7-4.3 Dresden Nuclear Power Plant

The Dresden plant has a boiling-water reactor system using a dual steam cycle and forced circulation. Figures 7.17 and 7.18 depict two views of the reactor vessel. Eighty cruciform-shaped control rods are interspersed through the array of fuel assemblies. Figure 7.19 shows how the control rods are arranged in the core.

The control rods were originally made of 2% boron–steel alloy but were replaced by stainless-steel sheet packed with boron carbide powder. The 80 control rods enter the reactor through thimbles in the bottom of the pressure vessel and enter the bottom of the core through holes in the core support plate. A tube for each control rod extends upward from the bottom of the vessel to the bottom core support plate to guide the rods in this region. Each rod is equipped with its own drive mechanism located within the pressure-vessel thimble and operating in the reactor pressure environment.

In most other reactors using vertical control-rod motion, upward rod movement increases the core reactivity by moving the poison section out of and above the core. The Dresden reactor, however, has its control rods fully in

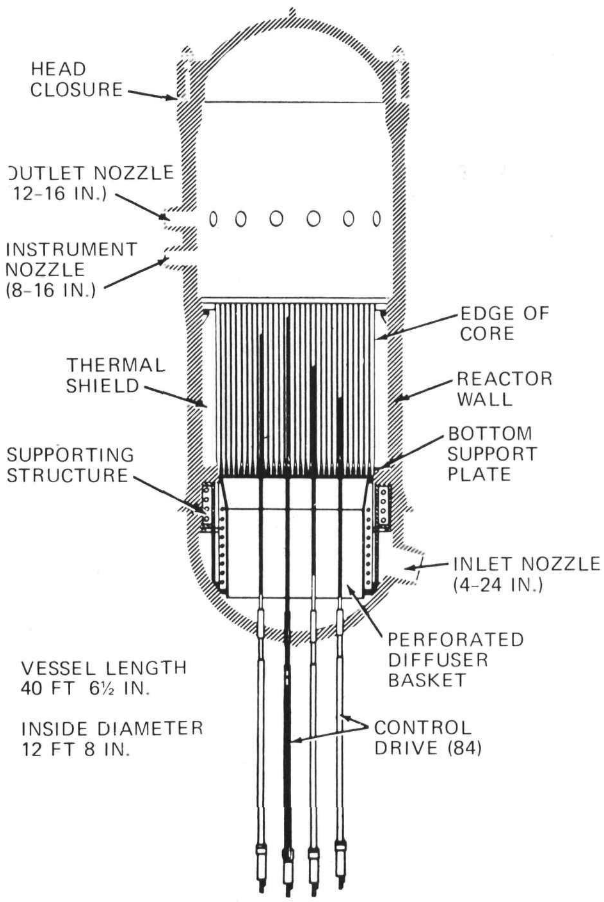

Fig. 7.17—Longitudinal section of the Dresden reactor showing control-rod drives mounted below the reactor. (From Andrew W. Kramer, *Boiling Water Reactors,* p. 461, Addison–Wesley Publishing Company, Inc., Reading, Mass., 1959.)

the reactor in the "up" position. Reactivity is increased by lowering the control rod below the core. The control-rod drive mechanism is basically a hydraulic cylinder. Normal controlled movement of the rod is attained by applying reactor feedwater regulated at 200 psia above reactor pressure to either the top or bottom surface of the piston rod and simultaneously connecting the opposite side to a vent tank held at 30 psia above reactor pressure. This movement, however, cannot be effected until the locking ball located in a slot between the control-rod piston and the cylinder wall is released by the unlocking piston (Fig. 7.20). For rod "up" motion (direction toward decreasing reactivity) pressure is applied on the bottom of the piston rod. The control-rod piston, secured by the ball to the spring-loaded locking piston, moves upward a small but sufficient distance against the spring to release the ball into the annulus in the unlocking piston and free the rod. The rod continues to move upward as long as pressure is kept applied to the "up" inlet port. When the inlet pressure is shut off, reactor pressure is applied through the shuttle valve, and upward movement continues until the next notch in the piston reaches the ball. At this point, the spring loading of the locking piston is enough to lock both pistons together and prevent further movement.

For "down" motion, the high pressure is applied to the "down" inlet port and the "up" inlet port is switched to the vent tank. In this condition, the high pressure is applied to the top surfaces of both the rod piston and the unlocking piston. The unlocking piston moves down against a spring load and exposes an annulus that frees the locking ball, allowing the main rod piston to be moved. If the down pressure is maintained, rod down movement continues. If the pressure is applied only momentarily, the ball is freed long enough to allow the piston to move to the next slot where it again engages the locking piston and stops.

There are 12 slots along the 8.5-ft travel of the control rod, and rod movement in 8-in. steps can be obtained. The maximum rate of reactivity insertion from this control rod is 1.3×10^{-4} δk/sec. The interlocking circuits allow movement of only one rod at a time.

For scramming, a 1400-psi accumulator tank is supplied for every three drives. For each drive two solenoid valves provide pressure to the "up" inlet port and open the "down" inlet port to a dump tank. The rod movement for scram is completed in 2.5 sec.

Rod position is indicated by a series of magnetically operated switches located inside an inner cylinder along the drive stroke. A magnet built into the rod piston actuates the switches as it passes them, and corresponding indicating lights on the control panel show the rod position.

The effect of scram-system failure is minimized by the use of independent systems for every three rods. If a large-scale failure occurs, however, a chemical poison-injection system containing sodium pentaborate at a pressure much higher than that of the reactor is actuated.

7-4.4 Gas-Cooled Reactors

Gas-cooled reactors can be considered as being either low-temperature or high-temperature gas-cooled reactors.

The low-temperature gas-cooled reactors are typified by the natural-uranium graphite-moderated CO_2-cooled units in the United Kingdom and similar installations in Italy, France, and Japan. These reactors are very large structures owing to the low excess reactivity available from natural-uranium fuel. For example, 40- to 70-ft diameter and 40-ft height are typical. The number of control rods is correspondingly large, 100 or more. The control rods (usually boron steel) are generally mounted and operated vertically. They are suspended by steel cables wound around a drum which is driven by a low-speed motor equipped with induction braking. A typical control-rod drive mechanism is shown in Fig. 7.21.

The control problems in low-temperature gas-cooled reactors arise chiefly from spatial variations in fission-product (especially ^{135}Xe) poisoning. To cope with these problems, for example, the Hunterston reactor in Scotland is divided into one central zone and eight radial zones, with the control rods distributed throughout. The central zone

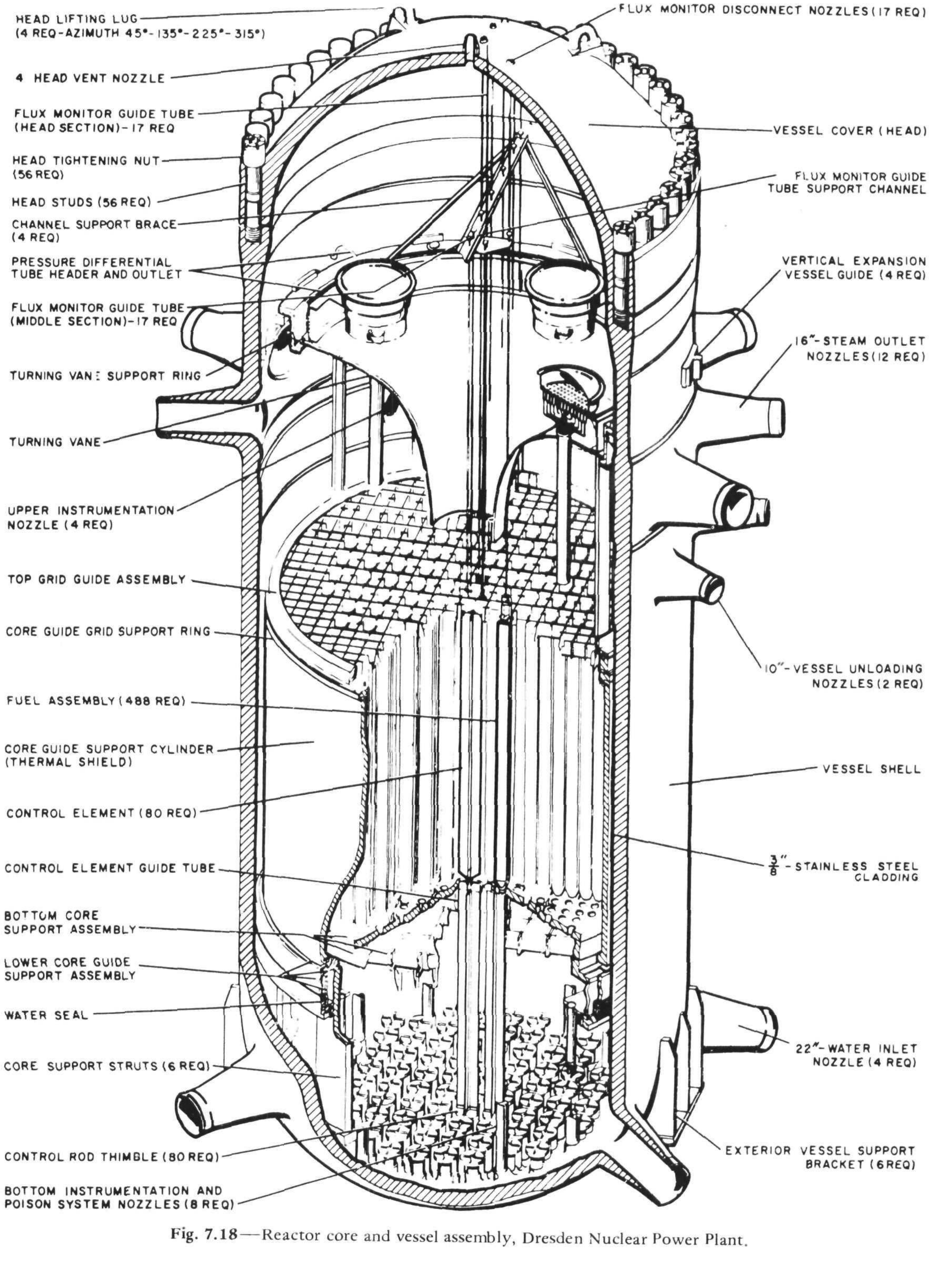

Fig. 7.18—Reactor core and vessel assembly, Dresden Nuclear Power Plant.

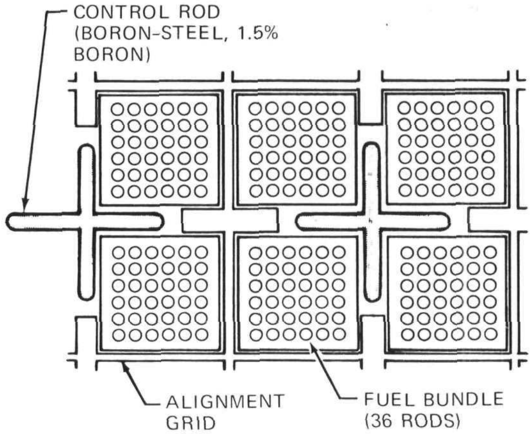

Fig. 7.19—Dresden reactor fuel-element and control-rod array. Fuel elements are 36-rod assemblies of UO_2 contained in Zircaloy-2 tubes. Cruciform control rods fit in spaces between the elements. (From Andrew W. Kramer, *Boiling Water Reactors,* p. 464, Addison–Wesley Publishing Company, Inc., Reading, Mass., 1958.)

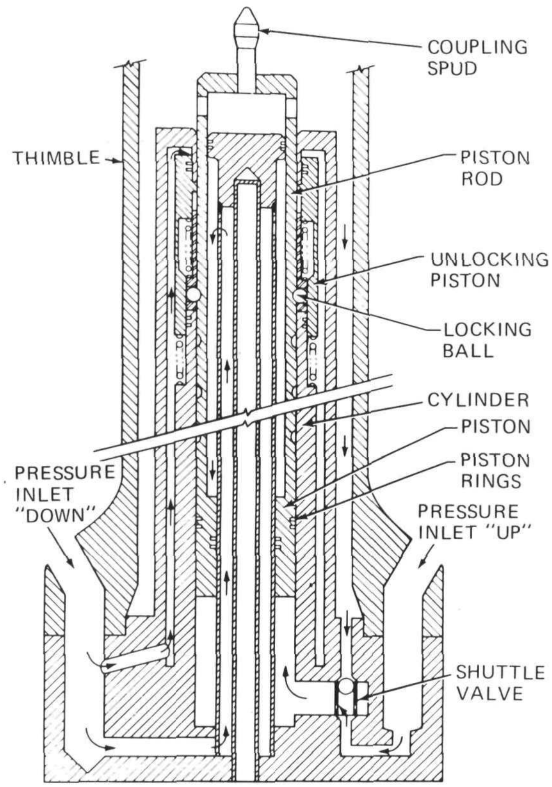

Fig. 7.20—Control-rod drive mechanism, Dresden Nuclear Power Plant.

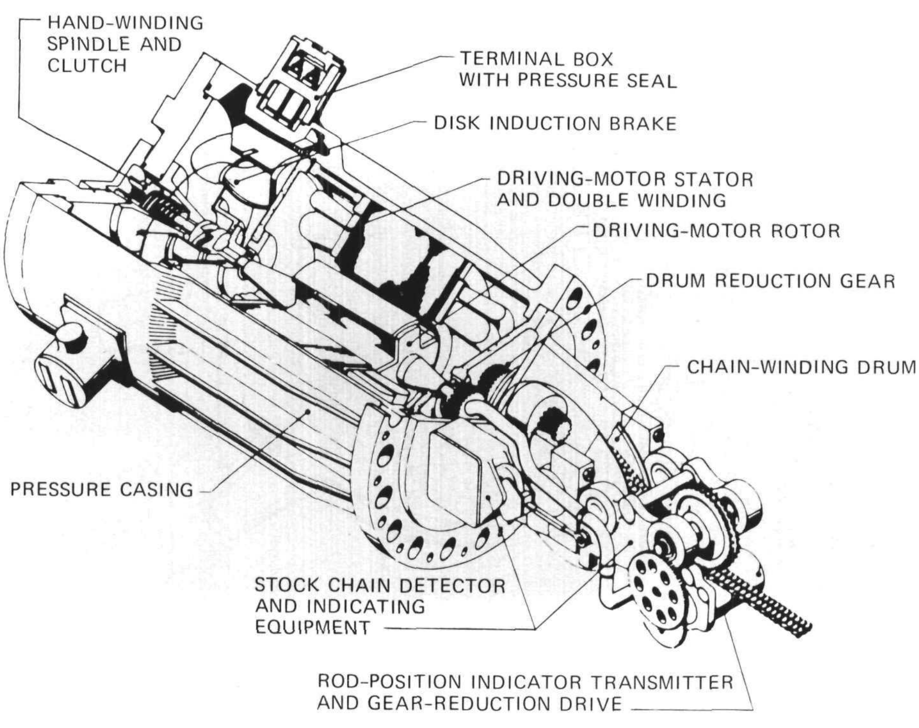

Fig. 7.21—Typical control-rod drive mechanism for a low-temperature gas-cooled reactor.

has the largest number of rods per unit cross section area The rods in each zone are grouped for control purposes and each rod can be independently operated.

The normal rate of addition of reactivity is very low in the low-temperature gas-cooled reactors. In the Berkeley (England) reactor, for instance, the rate is 2×10^{-6} δk/sec Start-up from a cold shutdown condition to critical takes 6 or 7 hr, to increase from critical to full power takes 11 hr because of the negative temperature coefficient.

High-temperature gas-cooled reactors (HTGR's) use enriched-uranium fuel and are much smaller in size than the low-temperature reactors. Graphite is used as moderator A variety of coolant gases may be used, including N_2, CO_2, H_2, He, and air In the United States, helium is used, elsewhere, carbon dioxide is the favored coolant for gas-cooled power reactors

The Peach Bottom HTGR and the Fort St Vrain HTGR, two U. S nuclear power stations, are described in some detail in Vol. 2, Chap. 18. In Chap. 18, Sec. 18-6, there is a discussion of their control-rod drive and position-indicating systems The brief description of the Peach Bottom control-rod drive mechanism presented here overlaps the Chap. 18 material to some extent. However, the emphasis is different. Specifically Unit 1 of the Peach Bottom Power Station in Pennsylvania is considered here The core, located near the bottom of a 25-ft-high cylindrical pressure vessel, is approximately 9 ft in diameter and 7.5 ft high There are 36 control rods, each worth 0.007 δk (average), mounted below the reactor where the drive mechanisms are in a mild environment ($\leqslant 200^\circ$F and ~10 R/hr gamma flux) The location provides for easy access to maintain the drives and leaves the top of the pressure vessel free for fuel-handling operations. The control rods are stainless-steel tubes containing boron carbide.

The basic drive mechanism (Fig. 7.22) is an axial piston-type hydraulic motor that turns a ball screw and produces linear motion of a ball-nut assembly The ball-nut moves a push rod, which, in turn, raises or lowers the control rod Each control-rod port (extension of the pressure vessel) contains the entire drive mechanism including the hydraulic motor, regulating and scram valves, position transmitters, rotary-to-linear motion ball-nut screw device, scram-energy accumulator, and scram-action snubber

Hydraulic turbine oil is used for the motor and is supplied to the drive from two header connections One is a low-pressure supply that produces the normal operating speed of the control rod. The high-pressure line maintains the fluid level in a scram accumulator, pressurized by helium, which drives the rod at the scram speed of 10 ft/sec. A return header is supplied for the effluent from the motor The regulating and scram speeds of the motor are established by two sets of solenoid valves. One set, the regulating valves, admit low-pressure hydraulic oil for rotating the motor in either direction. The other set, scram valves, apply high-pressure oil to the motor for one direction of rotation only, namely, that for driving the rod upward into the core. Total rod movement is 7 ft. The regulating or control speed is 0.06 ft/sec or 0.72 in./sec, corresponding to a rate of change of reactivity of 1.1×10^{-4} δk/sec (maximum) Except for rod-removal operations, the drive is never detached from the rod. Monitoring of the coupling between the drive and the rod depends on an electrical circuit between the two, which, if broken, trips an annunciator at the operator's console. Downward motion of the rod increases core reactivity, and scram motion is upward. Control of rod direction is by manual activation of solenoid valves through remote switches or from an automatic "on-off" control circuit.

A clutch-brake on the hydraulic-motor shaft prevents downward drift of the rod when no hydraulic pressure is being applied to the motor. This is accomplished by means of a friction brake and an over-running clutch that allows completely free rotation of the shaft to produce rod motion upward (decreasing reactivity) but applies a reverse torque at 1.75 to 2.5 times that produced by the deadweight of the rod and attached drive parts acting vertically. The operation of the hydraulic motor, however, easily overcomes this friction when rod-down motion is desired. A mechanical latch holds the rod in the "up" (full-in) position after insertion. The latch has to be actuated when the rod is withdrawn down past the latch Mechanically, the latch cannot be withdrawn if the rod weight is on the latch. Safety requires that no more than three rods at one time be in a position intermediate between latched in and full out.

There are two independent emergency shutdown systems. One is a group of 19 electrically driven emergency shutdown rods. These rods are operated by conventional Acme thread screw-nut mechanisms driven by simple and rugged d-c motors. Batteries, located in an extension of the rod port housing, supply power to drive the motors in the scram direction External d-c supplies are used to provide withdrawal power to these drives. Operation of these rods is by operator manual control only. They are used only in the event that normal scram operation fails. Complete rod insertion is attained in 24 sec, and the design provides very large torques that can overcome a resistive force as high as 10,000 lb, in which case insertion takes 1 min. Such operation was provided for the remote possibility that reactor damage (warping or debris) could restrict the normal movement of the rods The other emergency shutdown system, located in the top section of the guide tubes for each of the control and emergency shutdown rods, is a set of 55 gravity-drop neutron absorbers that are thermally released by abnormally high core temperature. This system is intended to operate in the event the other rod systems fail to act

Rod-position indication is provided by four selsyn receivers and by limit lights Each control-rod drive mechanism contains a selsyn transmitter geared to 170° rotation for full rod travel. Each position indicator has a graphical display (column type, ~$5\frac{1}{2}$-in scale corresponding to 0 to 84-in. rod travel, position accuracy ±2%) and a

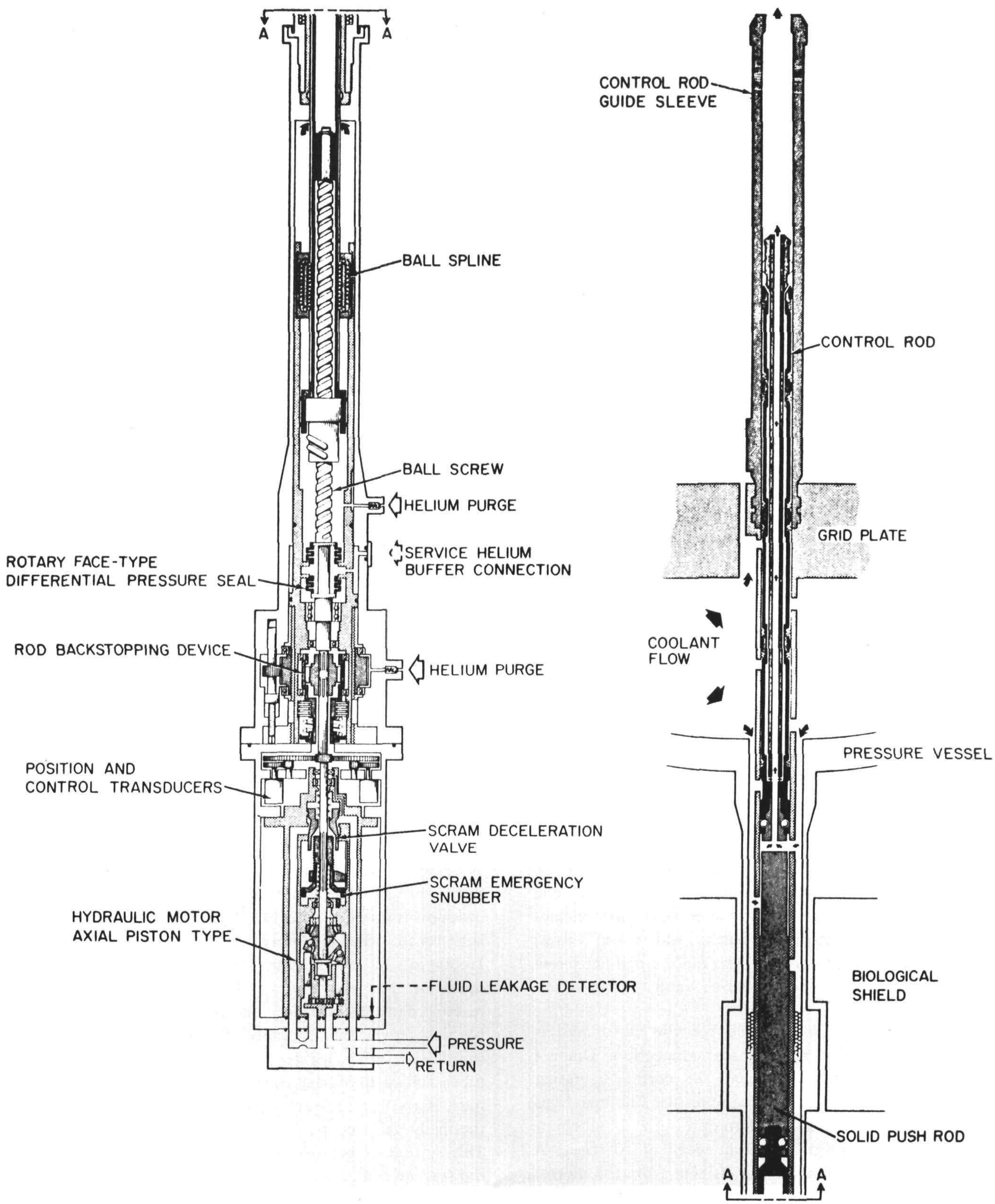

Fig. 7.22—Control-rod drive for Peach Bottom gas-cooled reactor.

digital display (three digit counter calibrated in inches, indication of rod position ±0 12 full scale, full-scale slewing time <6 sec)

When operating at power, the reactor is controlled by a group of three rods in the center region of the core The particular rods in the group are continuously monitored by the synchro position indicators at the reactor operator's console The fourth indicator is switched to the individual rod being moved and thus serves as a check on the synchro-receiver normally on that particular rod. The remainder of the rods not being used for control are either full in or full out, as indicated by a green or red background light in the particular control-rod window on the operating console, the lights are operated by upper and lower limit switches In addition, a precision potentiometer is driven from each rod-drive gear train to provide for testing rod response and operation and for checking rod-position indication if a synchro-transmitter malfunctions

7-4.5 Fast Reactors

The control systems for fast reactors (EBR-2 and Fermi) are described in Vol 2, Chap 17, Sec 17-2

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Chapter 8

Process Computer Applications and Data Handling

Garth Driver and Robert E. Mahan

8-1 INTRODUCTION

The meaning of "automatic control" has changed over the years along with the advance of control technology, the change being mainly one of scope. At one time describing a servomechanism, the term was broadened to include feedback control of a single process parameter, now it usually denotes the untended operation of complex processes or entire plants. The word "automation" was coined to indicate the elimination of the actions and decisions of human operators, it will be applied in this chapter to the internal control of nuclear reactor facilities. However, just as advances in automatic control were expansions of scope based on previous technology, we may expect that automation will soon be taken to imply optimum operation under changing external influences, such as product markets and raw materials costs.

The instrument engineer has recently been given the chance to begin applying several decades of theory to the control of real industrial processes.[1] The means were provided by those digital computer manufacturers who designed or modified their equipment for on-line data handling and control and who developed the beginnings of process program systems. Because of the important part computers play in automation, this chapter will deal mainly with the special problems that arise in the design, procurement and application of digital computer control systems.

The past growth of the field of computer control has shown an exponential trend that is typical of a newly introduced technology.[2] The increase may eventually be expected to slow down to more of a linear rise as the demand stabilizes, however, it is likely that the limiting influence will not be the usual market saturation but rather the lack of a sufficient number of knowledgeable applications engineers.

The history of computers in control shows an early and continuing preponderance in the petroleum and other chemical industries with applications in electric-power and metals production running not far behind.[3] On the other hand, computer control of nuclear facilities is among the

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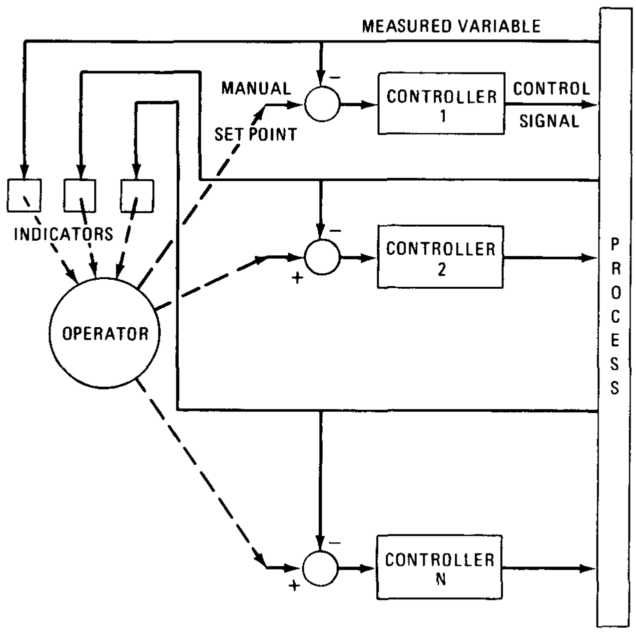

Fig. 8.1—Analog feedback control system

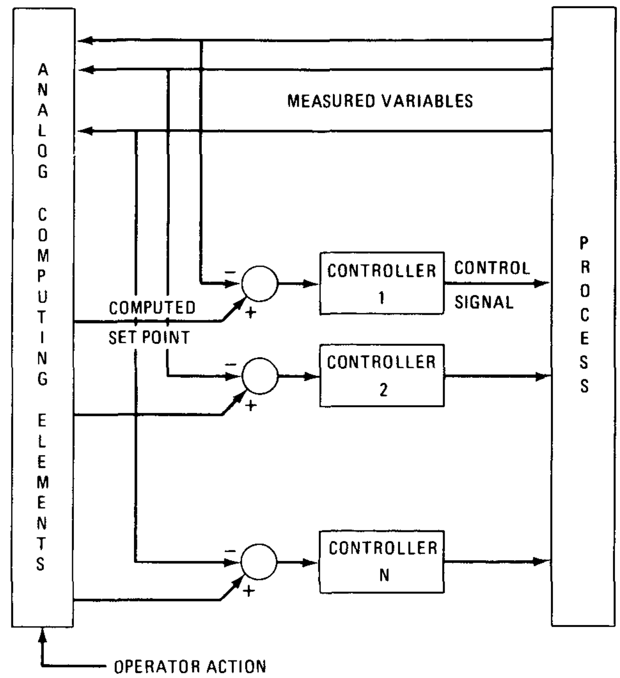

Fig. 8.2—Analog automatic control system

least developed of the industrial areas, a state of affairs due largely to the plant builders' and the operators' uneasiness over acceptance by licensing authorities[4] Once this barrier has been surmounted, we expect nuclear-plant applications to catch up quickly with the rest of industry Moreover, the combination of an expanding competitive nuclear power business, the unusually thorough mathematical representations of nuclear reactors the continuing improvements in computer speed and reliability, and the ability of the computer to solve complex problems affords an unprecedented opportunity for the engineer to apply advanced control methods[5]

Control systems can be described in terms of the extent to which they provide automatic plant operation and the kind of equipment used to do it First, a system type may be classed by whether its primary implementation method is analog, digital, or a combination of both. This classification provides an indication of automation since it implies certain automation capabilities. A second classification concerns the degree of automatic control provided, the criterion being how completely the equipment replaces the human operator's decisions and actions Third, the system can be described according to its scope, i e , the proportion of the total plant that is under automatic control These three categories will be discussed further in the following section

An underlying objective of automation is improved economics of plant operation, and the anticipated amount of improvement is the measure of the justification for control-system cost This objective will be achieved in different ways depending on the mission of the facility. A power-producing plant with proven components needs a redundant system with moderate data handling to provide maximum operating continuity, whereas a prototype requires less emphasis on high plant factor and more on data acquisition and analysis The effect of facility mission on control-system design will be treated later in some detail because of its heavy influence on system size and cost

8-2 SYSTEM COMPARISONS

The shift from analog to digital hardware is providing greater capability for automation[6] The use of more digitally oriented process-control equipment tends to overcome the disadvantages in cost or reliability of an analog predecessor

8-2.1 Analog Control Systems

Before the advent of the transistor, analog controllers, independently serving individual process loops, became the design standard As shown in Fig 8.1, this system provides process control under one set of conditions Changes in the operating status of the process are accommodated by manually adjusting the set point and the analog controller characteristics These devices incorporate proportional, integral, and derivative control action as appropriate to the process

When the transistor introduced solid-state control electronics more-elaborate analog systems became feasible. Figure 8 2 shows schematically the components of such a system. Automation is achieved through relieving the operators of having to adjust set points for changes in process conditions A distinguishing feature of this system

is that the analog computer has available to it all significant process variable signals This permits feed-forward, cascade, and multivariable control modes

In contrast to the controller bank of Fig 8 1, the number of operators needed does not necessarily grow with increasing size and complexity of the process under control The control system grows, and the cost of installing and maintaining an extensive configuration limits large-scale analog automation even with solid-state hardware

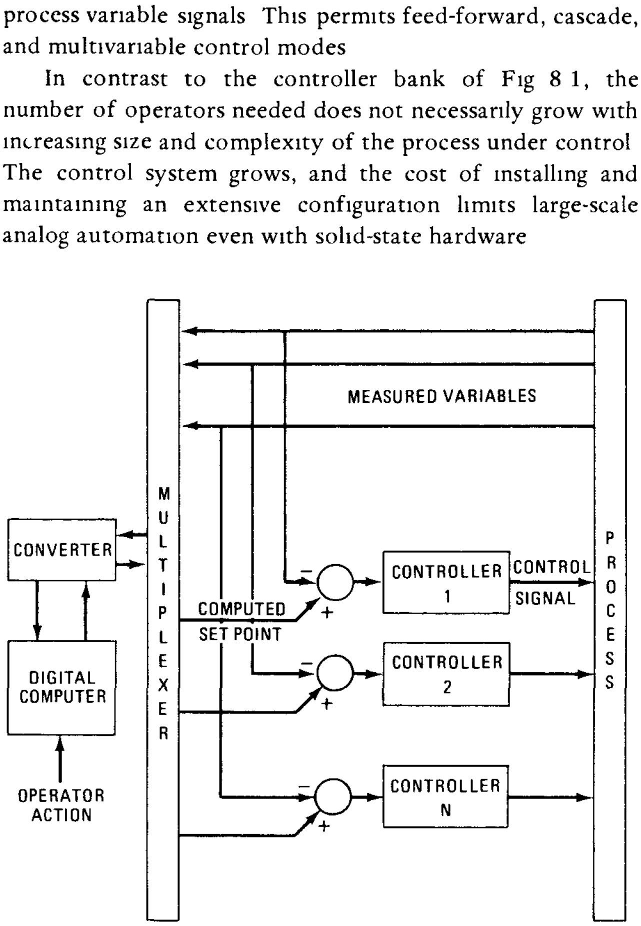

Fig. 8.3—Hybrid automatic control system

8-2.2 Hybrid Control Systems

Although the transistor gave needed improvement to analog devices its effect in the digital field was outstanding Vacuum-tube digital computers required a great deal of maintenance and almost continuous adjusting As transistors improved in time response and reliability, larger and faster machines were built The continued advance into integrated circuits lowered the cost of smaller models into the realm of process control

The utility of the digital computer lies in its inherent time-shared nature and its memory One set of arithmetic elements serves the calculating needs of all control loops one at a time, and the computer remembers the inputs, outputs, limit values, and decisional requirements of each loop between turns These features make the digital computer superior to analog computing elements, the configuration shown in Fig 8 3 was that seen in most of the early digital applications Since the digital computer was added to feedback control systems already in operation, it was visualized as "supervising" the process by monitoring and alarming out-of-limits conditions, adjusting analog controller set points, and generally performing the simpler tasks of a human operator Thus the hybrid arrangement is often called "supervisory control," although the term will not be used here because it has several other meanings

As seen in Fig 8 3, the hybrid approach adds even more equipment to the system But the multiplexer, which scans the inputs and distributes the set-point signals, is the only major component whose size is proportional to the number of measurements and control loops In a basic setup there is one set of input/output equipment to change analog inputs to digital, digital outputs to analog, and to perform the required amplification, there is one computer to do the timing, logic, and arithmetic The cost of these two items rises slowly with greater system size Hence, as the controlled process gets larger, there exists a point where the hybrid becomes less expensive than the analog system, this is one reason for using hybrid automatic control

8-2.3 Digital Control Systems

The analog controllers in a hybrid system are usually there because they were already there, they are familiar to and are trusted by the plant operators, and they do a job that would otherwise require a bigger computer and more programming Their inputs are differences between measured variables and corresponding set points, and their outputs are signals to process actuators, such as valve motors and heater relays The controller amplifies, integrates, or differentiates the input and combines the results to produce an output that makes a portion of the process respond to set points and process disturbances in a stable fashion

The function of the controller can be done easily by the digital computer, so the analog feedback-loop hardware need not be present [7] The result is a digital automatic control system as illustrated in Fig 8 4 The defining characteristic of the digital configuration is that all major control loops pass through the computer The system is often called "direct digital control," which, because it implies the exclusive use of digital control signals, will not be used *in this chapter* In the practical case digital actuators for some process components have not yet been developed

The schematic diagram of the digital system indicates that less equipment is needed for a large number of control loops than with the analog or hybrid However, the complexities of design are still there As will be shown later, they have been largely transferred from the hardware to the computer programs

8-3 DEGREE OF AUTOMATION

The preceding section treated control systems from the standpoint of the kind of hardware used, analog or digital, the amount of automatic operation provided was a secon-

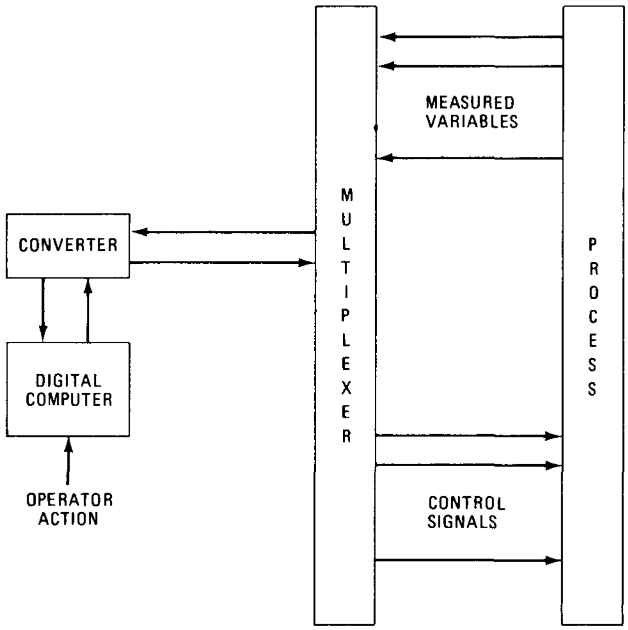

Fig. 8.4—Digital automatic control system

dary consideration In this regard it should be noted that the presence of a digital computer implies no special level of automation For example, many digital systems have been installed which perform only the control functions of a set of analog feedback controllers with the added benefit of automatic data logging

To avoid hardware implications, we will take the functional approach and use the degree of automation to define the extent to which the operator is removed from the immediate closed loop

8-3.1 Operator Control

The defining property of this system is that no significant logical decisions are made by the hardware, either on the display side or in the control channels In a system like that shown in Fig 8 1, the feedback controllers provide only process control at a given static operating level All control actions are taken by the operator and are based on the information he obtains by observing the process variables displayed at the consoles and his interpretation, through experience and training, of this information in terms of needed process changes

8-3.2 Monitored Operator Control

Hardware logic may be placed in the path from the operator to the process to prevent a control action at the wrong time or under adverse conditions These may range from simple electrical interlocks to a complicated set of prerequisites in a plant start-up sequence Such systems are now seldom seen in the absence of other automatic control features They are mentioned here only to illustrate one aspect of automation easing the operator's decision-making burden

8-3.3 Operator Guidance

In a large plant the amount of data generated cannot be assimilated by one operator or even a staff of operators In many installations digital computers are used only to get process information to the operator quickly and in meaningful form This involves data acquisition, on-line analysis, and information display, and it often results in a highly complex instrumentation system made practical only through the use of a digital computer The essence of the operator guidance system is that it comprises nearly all the hardware elements needed for fully automatic control, the only missing item being the part of the computer–process interface which sends control signals back to the process

The operator guidance system appears to produce a low degree of automation, nevertheless, it provides all the aspects of automatic control except direct feedback action No data analysis or decision making is required of the operator In practice, however, the operator is seldom reduced to a robot On the contrary his effectiveness is enhanced by his possession of a continuous and up-to-date knowledge of the process This includes energy balances, anticipatory alarms based on predicted plant behavior, or instructions for optimizing the process, all requiring that data be processed faster and more accurately than is possible by humans

8-3.4 Automatic Control

When under a given set of conditions a process is run efficiently without human direction, its operation represents the highest degree of automation Input data are analyzed, decisions are made, and control actions are taken entirely under the guidance of the control equipment

Automating a facility to a high degree may allow a significant reduction in the size of the control-room staff, although resulting operating cost savings may be partly offset by the need for computer programmers and more highly skilled maintenance specialists More importantly the operators are relieved of trivial and routine tasks requiring continual alertness and are allowed to perform more complex functions, such as general surveillance and emergency intervention, which are beyond the capability of a control system of reasonable cost [8]

8-4 SCOPE OF AUTOMATION

To complete a description of the extent of plant automation, one must discuss the proportion of facility operation that is under automatic control This is here called "scope" and comprises two distinct aspects (1) the physical portion of the facility involved and (2) the number of different plant operating conditions included

Reactor safety circuits (see Vol 2, Chap 12) are not treated in this chapter since they are not considered a part of the control system

8-4.1 Conventional Processes

A reactor facility can usually be divided into two parts according to whether or not the operation of the component processes is markedly affected by using a nuclear reactor for a source of heat Thus the generators, turbines, and steam loops in a pressurized water-reactor power-generating unit could be considered conventional equipment Their operation is not substantially different from that of a fossil fuel plant, so automatic control systems that have proven successful for this part of a nonnuclear station can be applied to a nuclear plant Nevertheless, extensive computer control of only the conventional part of a nuclear plant is uncommon There are several interrelated reasons for this (1) computers are installed primarily for data acquisition and display, (2) basic feedback control by computer to date has shown little or no cost advantage over analog controllers, and (3) the more serious control problems involve complex modes (such as multivariable, feed-forward, or cascade) which include controlling a part of the nuclear plant as well, again introducing concern by the designer over acceptance by licensing authorities

8-4.2 Nuclear Processes

When computer control extends into the nuclear part of the facility, the engineer becomes involved with design procedures not common to a conventional plant Radiation and radioactive materials reduce access to many components of the control system and constitute potential hazards that demand extra care in system design and strict conformance to safety criteria The division between conventional and nuclear processes is made to emphasize those control functions requiring the most thorough reliability analysis[9]

8-4.3 Auxiliary Processes

During the early planning of a process computer system, the following question arises "How much of the facility is going to be under computer control?" One must decide whether or not to include equipment not directly related to the main plant process, such as coolant makeup units, coolant-purification loops, and standby power plants Added functions of this kind are not being included in current plant designs The hardware cost savings are outweighed by the expense of greater system size and complexity

An exception to the above is the control of a certain class of on-line instrumentation comprising coolant samplers, chromatographs, mass spectrometers, neutron-flux scanners, etc These are characterized by their need for precisely timed control signals with a resulting data input to the computer The control signals are normally of a fixed-sequence kind, independent of the reading of the instrument, and do not effect closed-loop control actions in the usual sense

A second exception is monitoring and procedural control of reactor refueling operations If so programmed, the control system keeps track of the reactivity status of the reactor at all times Given the incremental reactivity of a replacement fuel element, the computer can predict the new reactivity status at each stage in the refueling sequence This, coupled with a step-by-step comparison between fuel-handling machine control actions by an operator and a prescribed checklist in the computer, can substantially improve the charge–discharge process

8-4.4 Start-Up and Shutdown

The preceding sections were concerned with the processes in a facility that were placed under computer direction There remains the question of how extensively should the control system cover the full range of operating conditions

If our only worry were to keep a reactor plant going in stable fashion at full power, it would be difficult to justify computer control The task of regulating processes under minor perturbations usually can be done adequately by analog controllers Even operation at different predetermined power levels can be provided, although in a large plant this begins to reach the practical limit of analog capability An example is automatic power reduction, sometimes called "power setback," where several combinations of out-of limits measurements can automatically cause the plant to go to a selected lower power, thus avoiding the stresses of a full scram and the consequent restart troubles

The greatest need for computer control arises during operation at reduced or changing power levels Changes in power level may be planned, as in start-up or shutdown, or unforeseen, as in recovery from transients and response to equipment failure The superiority of a computer-based system under such conditions is due to one or more of the following

1 There are a large number of interdependent procedural steps to be taken that a computer can execute in considerably less time and with a lower probability of erro than with human operators using conventional controls Reactor start up and steam turbine run-up are in this class[10] Both are being included in current reactor plant designs

2 The controlled variables are changed at different operating levels One way to start up a reactor is to maintain a fixed and safe period up to about 1% of power, then to raise the level while keeping below a predetermined maximum power rate of rise to avoid damaging thermal stresses, and finally to control at full power with power level as the input to the control program The decision-making ability of the computer can be used to make these changes in control organization at the optimum points in the ascent-to-power routine

3 Control elements, processes, and sensors are nonlinear Fixed controller settings can provide good regulation over a limited part of the plant operating range but produce inefficient or unstable behavior at others Again the ability of the computer to make decisions allows it to adjust its

own transfer function automatically to fit changing plant characteristics and to provide nearly optimum control under all conditions

4 Corrective actions often require a faster speed of response than human operators can provide Automatic power reduction is a good example The combination of fast logical analysis of a large amount of data and the ability to take quick remedial action permits the computer system to reduce reactor power or to shut down the plant in a controlled manner and to avoid situations that would cause reactor scrams This results in two very real benefits (1) reducing reactor scrams lessens the chance of damage by thermal and mechanical stresses, thereby reducing maintenance and increasing the useful plant lifetime, and (2) lowering power only as far as is necessary allows rapid recovery to full power and raises the plant factor

8-4.5 Nonprocess Functions

The time-shared nature of a process computer system makes it capable of doing nonessential off-line tasks at the same time that it is controlling the plant The central processor idle time could be used to compile and run FORTRAN calculating routines, assemble new subroutines, or modify and expand the process control programs [11] However outweighing the benefit of greater machine utilization are the following drawbacks

1 The operating speed of a nuclear-plant control system does not permit interchanging whole programs between core and drum (or disk), so the core memory must be larger

2 Greater keyboard–printer capacity is needed

3 A much more complex monitor is required

4 There is a finite probability that the time-shared systems software will derail the control program, although this probability can be made small through a computer memory-protect feature.

Taking all these into consideration, with nuclear safety to emphasize the last item, power-reactor control engineers have not included on-line program preparation as a system function An exception, discussed in Sec 8-5 4, is a configuration of redundant central processors where one is on standby and may be used by a programmer until interrupted to take over the control task [12]

8-4.6 Typical Applications

Examples of computer applications to specific power-reactor functions are given in the chapters on instrumentation systems in boiling water reactors (see Vol 2, Chap 16, Sec 16-9), sodium-cooled reactors (see Vol 2, Chap 17, Sec 17-5 5), and gas-cooled reactors (see Vol 2, Chap 18, Sec 18-6 3)

8-5 SYSTEM DESIGN

The relative importance of the steps in control system design and the order in which they should be taken depend on the kind and size of the facility, the project components to which the design tasks are assigned, and the time and money constraints imposed No matter what the design procedure, experience has shown the importance of formulating and documenting certain design procedures A schedule and a set of rules must be established early in the project, even if they will be changed many times later

The design of a computer-based data-acquisition system or a computer-based control system differs in many ways from that of their analog counterparts The main reason for these differences is that a large part of the system design resides in the computer programs This fact goes a long way toward explaining why the schedule, vendor responsibility, costing, and specification are so unlike those for analog equipment [13]

8-5.1 Schedule

One aspect of the difference between the two systems is apparent from examination of the control-system part of a

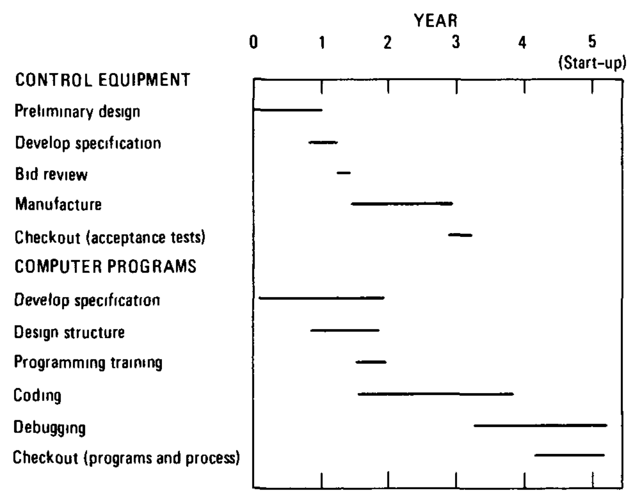

Fig 8.5—Sample project schedule (see text)

project schedule A typical schedule (Fig 8 5) is developed by taking the target date for reactor start-up as the completion time for the control system The previous 12 to 18 months are then reserved for the major programming effort, which is on-site program development and debugging after equipment delivery Coding starts as soon as the computer model is chosen and finishes when the programs have been tried out on the computer after it has been installed in the plant Still working backward in time, a year or two is allowed for equipment manufacture and checkout The length of this period depends on the complexity of the system and how much of nonstandard hardware is to be put together by the supplier Finally, a few months are added for vendor selection and contract negotiation and a few more for writing the specification. At this point the control engineer finds that he is already behind schedule or, at best, that he will reach the specification deadline having

dangerously little information about the processes that his system is going to control

Then begins the task of shortening the various segments of the chart to produce a properly timed, but realistic, set of goals To be done right, this job requires familiarity and experience with both computer systems and reactor projects Factors that must be considered are

1 The minimum amount of plant design data needed to develop a sound specification

2 The extra control-system capacity that should be specified as a contingency against further plant design changes

3 The anticipated delays because of prevailing procurement policies

4 The probable system suppliers and their reputations for making accurate delivery-schedule estimates

5 The available programming personnel

6 The likelihood of a postponement of the plant start up date and the estimated number of months extension

These and many other factors influence the control-system schedule, which becomes a firm guideline for acquiring, programming, and installing the equipment It will, of course, be modified from time to time as the project progresses toward completion

8-5.2 Preliminary Design

It is unlikely that complete plant automation will come about in big jumps It is interesting to contemplate and discuss an imagined power station with everything from control rods to switchgear under computer control, but that stage will be reached in small steps over a long period of time, just as analog control technology has developed

Lacking a charter to automate the whole plant, the engineer must select the type of control (analog, hybrid, or digital) to be applied to the constituent processes and the degree and scope of automation appropriate to those under the command of the computer Every facility has one or more process elements for which conventional control devices are inadequate, these are the prime targets for computer control [14] Next come those elements for which computer control promises a substantial cost savings either in capital investment or in greater operating efficiency Finally, there are those functions where the advantages of either digital or analog control are comparable The scope of computer applications will depend heavily on the strength and completeness of the control engineer's system analysis Examples of the results of this stage of planning can be found in recent and current reactor plant designs, several of which are described in Sec 8-7

Up to now this section has dealt with computer control, but from here on our discussion of control equipment and software must include their other functions data acquisition and display. All new reactor plants will have a computer-based data-handling and data-display system, the control functions can be considered as an extended use of equipment already planned A small percentage in hardware cost will buy computer-control capability However, adding control programs raises the level of complexity of the system software in proportion to the number of functions provided

8-5.3 Program Description

The programs discussed in this section are those necessary to perform data handling, control, and routine self checking They are called process programs and are recognized by their being always in the computer system and routinely or potentially operative when the computer is on line as a part of the operating plant A second kind, called systems programs, are those used to write and debug the process programs These include the programmers console routines, loaders, assemblers, compilers, and editors They are discussed in the section on equipment specifications because they are always part of the computer procurement

For an analog control system, the engineer can develop a set of functional specifications, most of which can be translated into equipment requirements based on a one-to-one correspondence among the set of input-data points, control-system channels, and control-signal outputs This simple relation between function and hardware is shown in Fig 8 2 However, there is no such correspondence in a computer-based system As seen in Fig 8 4, only the process interfaces can be sized according to the system functions, the rest of the hardware must be specified on the basis of the computer programs needed to perform the data acquisition and display and control tasks

So the computer-system designer starts by compiling the usual functional specification, setting forth what the system must do, and the process and operator inputs that will be needed to implement them The next step is to develop a detailed description of the computer programs required to make the hardware function as specified This task is the most demanding part of the design procedure If it is not done well, an adequate system procurement specification cannot be written

The program description can be developed in three stages for convenience in planning and carrying out the separate activities

1 The process software is divided into major programs The level of the division is dictated by the need for each program to have a distinct and identifiable function The number of programs on the list should be such as to make it easy to assign them to different engineers on the programming staff Too few program elements will overload the programmers, too many will make it difficult to combine them into a working whole

2 The memory required for each program is estimated An accurate estimate requires a detailed knowledge of process requirements in terms of precision and response times, the programs that provide the control functions, and how they are to be accomplished by computer-program

instructions The engineer may have to write trial routines in a typical process assembly language

3. Each program is labeled as to whether it will normally reside in core, in auxiliary memory, or partly in each The results of this step determine the proportion of computer memory which must be provided by high- and low-speed devices

Table 8.1—Major Control Programs

Program	Number of words and residence: Core	Drum or Disk
Executive monitor	1500	
Input/output	2000	1000
Service routines	1500	1500
Process control	3000	6000
Display	1200	2400
Log	500	5000
Diagnostic/alarm	1400	500
Historical record	300*	
Calibration		2200

*Does not include data storage

The results of the preceding three activities are summarized in a deceptively brief compilation similar to that shown in Table 8 1 These data, along with roughly estimated execution times, form the basis for specifying memory sizes, computation speed, and capabilities of peripherals, such as line printers and high-speed operator displays

It is important that one recognize the disparity in level of the different programs on the list The one titled "executive-monitor," for example, is of the highest level It is the master program that ties all the others into a coordinated system. Its development requires the talents of the best process programmer On the other hand, programs such as the calibration routines can be handled by more junior personnel

8-5.4 Redundancy

The relation between redundancy and reliability, which is treated in Chap. 11, is discussed here only on a large scale The minimum addition in providing a dual or backup computer control system is adding another central processor, further duplication of equipment then depends on plant-design concepts, such as whether or not the reactor will be operable if the computer fails Also to be considered is duplication of critical functions by independent hardware. Analog and manual backup are examples [15]

Table 8.2 shows some of the reasons for having or not having redundant computers The use of a nonredundant system is usually justified by the requirement that the reactor and processes be capable of at least steady-state operation if the computer fails This implies either extensive analog backup control or a plant small enough to be handled manually by the control-room staff A second reason is that a high plant-availability factor is not essential, therefore the reactor safety instrumentation can take care of computer failure. These are the cautious approaches to computer control which place little reliance on the computer part of the system They are becoming less evident since experience and familiarity with digital systems have influenced plant designers to allow shutdown in case of total control-system failure if redundancy is used [16]

Table 8.2—Some Reasons for Single and Redundant Systems

Plant	Computer	Justification
Single	Single	Analog or manual backup Low plant factor
Single	Dual	High plant factor Plant data essential Off-line service
Dual	Dual	High plant factor
Dual	Triple	High plant factor Off line service

Restating the above if a high plant factor is important, then frequent shutdown cannot be tolerated and a redundant control system is required. This is the predominant reason for dual computers A second reason, especially applicable to prototype facilities, is the importance of maintaining continuity of plant operating data, a criterion that applies to pure data-acquisition equipment as well as control systems. A third justification is that a standby computer can be used for off-line program preparation and data processing but can be automatically interrupted when the unit is called into service to replace the operating computer

It has become common to design nuclear power stations with two complete reactor–generator units operating independently At first sight it seems that reliable computer control could be effected by placing a control system on each reactor unit using the computers as backup for each other, at least for the essential control functions Although this configuration has been given much consideration, few, if any, such systems have been built Both computers would have to be larger, peripheral switching to one or the other would be difficult, and developing the complex switching programs would be very costly. The result is that dual plants usually have three computers, one as standby for an operating system on each reactor unit.[17]

The basic justifications for the triple control system are the same as for redundancy in general the importance of reliability, as it affects plant factor, and the convenience of having a standby for off-line programming

The final objective of redundancy is to improve plant availability or, in project terms, to ensure that the system

Table 8.3—Cost-Comparison Chart

Item	Number required	Cost, $
Analog System		
Panels		20,000
Meters	500	10,000
Recorders	12 (multipoint)	50,000
Annunciators	4000 (points)	240,000
Control hardware*		260,000
Data logger	4000 (points)	420,000
Spare parts		100,000
	Total	$1,100,000
Computer System		
Central processors	2	150,000
Process input/output	4000 (points)	450,000
Mass storage	Drums, disk, and magnetic tapes	125,000
Operator input/output	Printers, typers, and consoles	75,000
Displays	Cathode-ray tubes and interfaces	100,000
Spare parts		25,000
Programming		350,000
	Total	$1,275,000

*Only for those functions which the digital system would perform.

will permit attaining the target plant factor The immediate objective is to make the control system more reliable However, a precise estimate of the reliability of a redundant computer system cannot be made because the reliabilities of the constituent parts—processor, peripherals, interfaces, and displays—are not precisely known. So it is not surprising that past and present justifications for replicating components are commonly based on judgment and inference from statistically inadequate data on past operating experience. This state of affairs will prevail until reactor power plants with computer control are commonplace, at which time the need for stringent justification will be far less.

8-5.5 Cost Estimates

After the program description and the equipment configuration have been developed, the control engineer has enough information to make a preliminary estimate of system cost He compares the conceptual computer system with a conventional analog layout designed to perform the same basic tasks, which shows whether or not the computer control system is economically acceptable The analog equipment will include panels, panel meters, data loggers, strip-chart recorders, alarm annunciators, and controllers Some controllers must be capable of three-mode, feed-forward, and cascade operation. The systems should have equivalent orders of reliability and redundancy.

In all likelihood the computer control hardware required for a reactor power plant will have a lower cost estimate than the analog configuration but will have a higher estimate when the cost of computer programming is included (see Table 8 3) If so, the decision to use a computer system has to be justified on the basis of services beyond those which analog systems can provide The values of such advantages are difficult to assess, they depend on such things as future savings in plant operating cost, benefits in case of a plant accident of low probability, and capability of readily accommodating later plant modification. Examples of some advantages are

1. The computer can lessen the time and effort applied to system installation and checkout For instance, several hundred sensors and cables can be connected and tested all at once by using a short computer program to detect and print out faulty channels Such procedures substantially lower installation time and cost compared with the standard method of "ringing out" each signal path by hand

2. The control-room staff can possibly be reduced because of greater efficiency in data acquisition and display Considering the cost of an operator over the lifetime of the plant (diminished by the initial cost of training personnel in the capability, programming language, and structure of the computer-based system), this factor can tip the scales in favor of a computer system Large offsetting increases in other activities usually are not expected, for example, the number of maintenance personnel should be about the same with either kind of hardware, although they will generally be more highly paid for maintaining computer hardware.

3. At some time during its life, the plant will undergo changes in components, operating mode, or power level. The cost of altering the instrument and control system to provide for such changes will vary greatly but will be less with a computer system The cost of adapting to plant modification is hard to forecast except when such action is planned from the beginning. The latter is illustrated by a full-scale prototype power plant that is currently under construction.[18] At start up and during initial testing, the plant will run with saturated steam, later to be changed to superheated steam to produce full-design electric power. It is estimated that the changeover will be done in a few hours by loading new computer programs, in contrast to a many-month-long job of altering conventional analog equipment.

4 The ability to format and output both transitory and permanent data in report form is an asset These data include postincident data, fuel exposure and inventory, and management reports on plant operation.

5. Reactivity balance, control-rod calibration, reactivity coefficient, and other complex on-line calculations can materially aid in efforts to achieve optimum reactor operation.

After all factors such as the above are taken into account and given conservative cost values, the total is

incorporated into the initial system cost for comparison against an analog configuration.

The reader is cautioned that the figures in Table 8.3 are composite and illustrative. The cost ratios of the separate items will differ greatly for the various types of reactors and different plant operating modes

8-6 SYSTEM SPECIFICATION

The basic criteria for judging a system specification are the same for a computer-based control system as for analog equipment. There are, however, additional items in a computer system which even an experienced designer may sometimes overlook. It is therefore advisable for the specification writer to have a checklist of items available or to consult the procurement documents of a successful control system

A complete outline of the sample specification is presented in Table 8 4. In this section a sample specification is presented and discussed section by section. The sample shows what should be included in a specification that requires the manufacturer to provide computer systems programs but not the control software. Not all the items shown in the sample will appear in every specification. Many systems will not require double precision and floating-point hardware, memory protect, automatic restart, etc On the other hand, the sample specification does not include special-purpose electronics that might be supplied by the computer manufacturer

We stress the point that the following specimen is for illustration only. It would not be used for an actual procurement because

1. There will usually be some items that are undergoing improvement and field testing of which the specification writer is unaware. A "functional" specification for such items may allow a supplier to offer equipment that would not meet strict performance specifications but is actually best suited to the application.

2. The detailed requirements in the specimen represent performance at or near the state of the art In the interest of a lower price and better competition, these should be relaxed wherever possible to correspond to the needs of the plant

3. System suppliers are continually developing executive programs and adding applications programs to their software packages. By using as much of the supplier's proven control software as appropriate to the application, the designer can realize a considerable project cost saving

4. Design engineers often prefer to evaluate computer speed by finding the running time of a bench-mark program that includes arithmetic, logic, transfer, and input/output instructions in about the proportions that they will occur in the actual application. Besides providing a good functional criterion for acceptance, this method can reveal deficiencies in computer architecture that might not show up if only the operating speeds of the individual computer functions were analyzed.

8-6.1 Introductory Sections

The specification should begin with a short description of the reactor the computer is to be associated with and what the computer is expected to do. The bidder must be given a thorough and unambiguous concept of the whole system. Following this summarizing statement, the broad specifications of the computer itself should be described. A list of the major equipment should be presented in the order in which the equipment is described in the body of the specification.

The sample section below shows how the introductory sections of the system specification might be written.

SPECIFICATION FOR XPR-1 COMPUTER SYSTEM

SUMMARY

This specification details the requirements for the digital-computer system to be installed as an integral part of the XPR-1 instrumentation and display system The computer system will operate on-line to the reactor and provide the necessary equipment for reactor systems support, analysis, control, and reporting

This application supports the operation of XPR-1 (Experimental Power Reactor Number One), a 1000 MW(e) nuclear facility designed for the generation of electric power The computer system will support this facility by providing data acquisition, analysis, control, display, and reporting The reactor is characterized by both on—off and continuous data-acquisition and control processes On—off operations are typified by block valves, start—stop pump, supply utilities, etc Continuous monitoring and control is applied to neutron flux, temperature, flow, etc The success of this installation will depend on the reliability of the system, thus, meeting the reliability and quality assurance requirements is important

1.0 GENERAL DESCRIPTION

This specification describes a general-purpose digital computer of the binary, core-memory, parallel, single-address type with indirect and indexed addressing The computer system is to be used as the basis of a real-time control system performing control functions in the operation of a nuclear power reactor The computer system is required to respond to both analog and digital inputs, provide analog control signals, and store data in on-line bulk storage Operator communication is by keyboard and interactive cathode-ray tube display

2.0 MAJOR EQUIPMENT LIST

2 1 24-bit general-purpose computer with 16K of core memory.
2 2 250K word disk storage unit
2 3 100 line-per-minute line printer
2.4 300/100 character-per-second paper-tape reader/punch.
2 5 Two 21-in color cathode-ray-tube display consoles
2 6 An analog input facility for 2000 points.
2.7 A digital input facility for 2000 points
2 8 An analog output facility for 20 points

8-6.2 Central Processor

The requirements of the central processor are then listed. An acceptable range of word lengths, the result of a detailed analysis of data-handling and computation needs, is stated. The instruction set, memory requirements, and the

Table 8.4—Specification Outline (Summary Description)

1 General description

2 Major equipment list

3 Central processor
- 3 1 Core memory
  - 3 1 1 Word length
  - 3 1 2 Word capacity
  - 3 1 3 Speed
  - 3 1 4 Parity
  - 3 1 5 Protect
- 3 2 Arithmetic unit
  - 3 2 1 Hardware arithmetic
  - 3 2 2 Execution times
- 3 3 Addressing
  - 3 3 1 Direct
  - 3 3 2 Indirect
  - 3 3 3 Indexing
- 3 4 Priority interrupts
- 3 5 Direct memory access
- 3 6 Clocks
- 3 7 Stall alarm
- 3 8 Operator's console
  - 3 8 1 Console switches
  - 3 8 2 Display
  - 3 8 3 Console teletype

4 Process input/output
- 4 1 Input/output channels
- 4 2 Speed
- 4 3 Input/output parity
- 4 4 Input/output addressing
- 4 5 Digital inputs
  - 4 5 1 Capacity
  - 4 5 2 Logic definition
  - 4 5 3 Speed
- 4 6 Analog outputs
  - 4 6 1 Number of channels
  - 4 6 2 Output range
  - 4 6 3 Data input
  - 4 6 4 Accuracy and linearity
  - 4 6 5 Monotonicity
  - 4 6 6 Sag
  - 4 6 7 Slew rate
  - 4 6 8 Settling time
  - 4 6 9 Short circuit capability
- 4 7 Analog inputs
  - 4 7 1 Multiplexer
    (Subheadings Input switches, Number of channels, Input configuration, Sampling rate, Input impedance, Full scale input voltage, Crosstalk, Scatter, Common-mode rejection, Maximum common mode voltage, Full-scale output voltage, Address modes)
  - 4 7 2 Analog-to digital converter
    (Subheadings Number of bits, Conversion speed, Aperture time—sample and hold, Acquisition time—sample and hold, Sag—sample and hold, Accuracy, Monotonicity, Linearity, Overscale indicator, Display)

5 Standard peripherals
- 5 1 Disk memory
  - 5 1 1 Capacity
  - 5 1 2 Access time
  - 5 1 3 Error control
  - 5 1 4 Write lock
- 5 2 Line printer
  - 5 2 1 Print speed
  - 5 2 2 Number of columns
  - 5 2 3 Character spacing
  - 5 2 4 Character size
  - 5 2 5 Character registration
  - 5 2 6 Character set
  - 5 2 7 Character replacement
  - 5 2 8 Line spacing
  - 5 2 9 Line registration
  - 5 2 10 Paper handling
  - 5.2.11 Ribbon
  - 5 2 12 Printer cabinet soundproofing
  - 5 2 13 Paper storage
- 5 3 Paper-tape reader/punch
  - 5 3 1 Speed
  - 5 3 2 Code
  - 5 3 3 Tape take up and supply
- 5 4 Display—Alphanumeric and graphic
  - 5 4 1 Display area
  - 5 4 2 Phosphor
  - 5 4 3 Spot size
  - 5 4 4 Random positioning time
  - 5 4 5 Positioning repeatability
  - 5 4 6 Jitter
  - 5 4 7 Resolution
  - 5 4 8 Contrast ratio
  - 5 4 9 Brightness
  - 5 4 10 Vector data format
  - 5 4 11 Vector end point registration
  - 5 4 12 Vector writing rate
  - 5 4 13 Character plot
  - 5 4 14 Character sizes
  - 5 4 15 Number of characters displayed
  - 5 4 16 Aspect ratio
  - 5 4 17 Intensity
  - 5 4 18 Light pen
  - 5 4 19 Keyboard
  - 5 4 20 Memory
  - 5 4 21 Enclosure

6 Software
- 6 1 Executive
- 6 2 Compiler
- 6 3 Assembler
- 6 4 Correction program
- 6 5 Diagnostic and utility programs
- 6 6 Input/output programs
- 6 7 Maintenance programs
- 6 8 Delivery form
- 6 9 Documentation

7 Environmental and miscellaneous characteristics
- 7 1 Temperature
- 7 2 Humidity
- 7 3 Power
- 7 4 Enclosure
- 7 5 Spare parts
- 7 6 Documentation
- 7 7 Reliability
- 7 8 Quality-assurance program

other items in this section must reflect the type of application whether it emphasizes data acquisition, data analysis, or process control. Taken together, these items should also force the bidders to confine their offerings to heavy-duty industrial-grade equipment to the exclusion of light laboratory computers, desk computers, and machines designed for scientific or business data processing.

The central-processor section of the sample specification is as follows.

3.0 CENTRAL PROCESSOR

3.1 Core Memory

3.1.1 Word Length
The computer shall utilize a basic word length of 24 bits excluding memory parity and memory protect.

3.1.2 Word Capacity
A minimum of 16,384 twenty-four-bit words of core memory shall be provided. The computer shall be capable of field expansion to at least 32,768 words.

3.1.3 Speed
The maximum read/restore memory cycle time shall not exceed 2.0 μsec.

3.1.4 Parity
Memory parity shall be provided for each word in memory such that each transfer to, or from, memory is checked for correct parity. An error shall cause an interrupt signal which identifies the location of the word in error.

3.1.5 Protect
Memory protect shall be provided for each word in memory. This bit shall be selectable under program control for each individual word. When an attempted violation is detected by the computer, an interrupt signal shall be generated which identifies the location of the attempted violation.

3.2 Arithmetic Unit

3.2.1 Hardware Arithmetic
Hardware arithmetic shall be provided to perform (1) single precision, (2) double precision, and (3) floating-point add, subtract, multiply, and divide.

3.2.2 Execution Times
Execution times shall not exceed those listed below.

	Single precision, μsec	Double precision, μsec	Floating point, μsec
Add	4.0	4.0	20
Subtract	4.0	4.0	20
Multiply	20	20	100
Divide	30	30	100

3.3 Addressing

3.3.1 Direct
The computer shall be capable of directly addressing a minimum of 2048 memory locations.

3.3.2 Indirect
Multilevel indirect addressing shall be provided with a capability of reading a minimum of 32,768 memory locations. Each level of indirect address shall add no more than one (1) memory cycle to an instructions execution time.

3.3.3 Indexing
At least three (3) dedicated index registers shall be provided.

3.4 Priority Interrupts
At least 32 channels of multilevel hardware interrupt shall be provided such that any higher priority channel can interrupt the processing of a lower priority channel. Each interrupt shall have a separate dedicated memory location (32 total) that contains space for the necessary instructions to initiate a device service routine. All interrupts except those assigned to the stall alarm and the power fail safe shall be capable of being individually turned on or off under program control.

3.5 Direct Memory Access
A minimum of two (2) direct-memory-access (DMA) ports shall be provided. Each port's transfer rate shall be at least 500,000 twenty-four-bit words per second. Multiplex capability for two channels at 250,000 twenty four-bit words per port shall be provided.

3.6 Clocks
Two (2) basic clocks shall be provided, a real-time clock and an interval timer. The real-time clock shall have a basic frequency of 60 Hz. The interval timer shall have a crystal-controlled rate of 100 kHz with an accuracy of ±10 Hz per day. Additional registers shall be provided with the interval timer such that they can be loaded from memory under program control and incremented or decremented by the clock. The timer shall provide an output signal (for use as an interrupt) when the register reaches zero.

3.7 Stall Alarm
A stall alarm shall be provided that detects machine looping or stalls. The method used shall be discussed in the response to bid.

3.8 Operator's Console
An operator's console shall be provided and shall include a tabletop working surface of at least 200 sq in.

3.8.1 Console Switches
A data entry switch corresponding to each bit in a word shall be provided. It shall be possible to enter data "manually" to "memory" and to all registers that are software accessible.

3.8.2 Display
The console shall provide for the display of the status of the following registers or their equivalent

A-register (A-accumulator)
B-register (B-accumulator)
P-register (program counter)
I-register (instruction register)
M-register (memory address register)
X-register (index register)

In addition, the console display shall provide a run–halt indicator, an input/output hold indicator, and a protect–violation indicator.

3.8.3 Console Teletype
A KSR-35 teletype, or equivalent heavy-duty machine, shall be interfaced to the computer for use as an operator's console.

8-6.3 Process Input/Output

The process input/output are the communicating links between the plant and the computer. The multiplexer and converters are first specified individually as to number of

points, speed, and addressing. Then, because of the complex interrelations involved, a tendency toward functional specification is introduced, the requirements are placed on the entire input or output channel rather than on individual components Since the input/output list (see sample below) is a summary of many of the process interfaces, it is important to make sure that the two sets of requirements agree

The input/output sample specification is as follows

4 0 PROCESS INPUT/OUTPUT

4.1 Input/Output Channels
In addition to the direct-memory-access channel specified in Sec. 3 (Central Processor), the system shall provide a shared input/output (I/O) bus such that all peripheral devices can communicate directly with the computer

4.2 Speed
The I/O bus shall support I/O transfers at rates up to 30 kHz.

4.3 Input/Output Parity
I/O parity shall be provided. The system shall provide a hardware parity test for each I/O transfer and indicate all I/O parity errors by program interrupts

4.4 Input/Output Addressing
Capability for addressing a minimum of sixty-four (64) peripheral devices shall be provided. Each bidder shall indicate the standard I/O assignment by logical device number and hardware address number for all standard peripherals available for the computer

4.5 Digital Inputs

4.5.1 Capacity
The system shall provide for the input of at least two thousand (2000) binary signals. These signals take the following form

Type a 500 twelve (12)-bit voltage words.
Type b 1000 one-bit binary voltages.
Type c 500 one-bit contact closures.

4.5.2 Logic Definition
Voltage inputs shall be positive true (1 = positive voltage). The following voltage range is required

$$\text{Logic } 0 = 0.0 \text{ volt}^{+0.5 \text{ volt}}_{-0.0 \text{ volt}}$$

$$\text{Logic } 1 = 2.3 \text{ volts}^{+2.7 \text{ volts}}_{-0.0 \text{ volt}}$$

(The values specified are for conventional diode-transistor logic. It should be noted that high-level logic with improved noise immunity has recently become available from several sources. This high-level logic should be used whenever possible.)
Contact signals shall be input as closure true

4.5.3 Speed
The minimum transfer rates are as follows

50 type a inputs 1 kHz/channel	(50,000 channels/sec)
450 type a inputs 0 033 Hz/channel	(3 channels/sec)
48 type b inputs 30 kHz/channel (2 computer words)	(60,000 words/sec)
952 type b inputs 1 Hz/channel (40 computer words)	(40 words/sec)
500 type c inputs 0 5 Hz/channel (21 computer words)	(11 words/sec)

4.6 Analog Outputs

4 6.1 Number of Channels
Twenty (20) channels of digital-to-analog output shall be provided

4.6.2 Output Range
The output shall be ±10 volts full scale

4.6.3 Data Input
The data input shall be twelve (12) bits per channel fully buffered

4.6.4 Accuracy and Linearity
Accuracy and linearity shall be at least ±0 05% of full scale 5 mV

4.6 5 Monotonicity
The converter output shall be monotonic for each input bit change from negative (−) to positive (+) full scale.

4 6 6 Sag
The output sag shall be less than 1 mV/μsec

4.6 7 Slew Rate
The analog output rise time (10 to 90%) shall be 3 μsec or less for a full scale step change (digital) at the input.

4.6.8 Settling Time
The time required to settle to within 0.1% of the final value shall be less than 15 μsec for a full-scale step change (digital) at the input with 1000 pF capacitive load

4.6.9 Short-Circuit Capability
The output amplifier(s) shall be capable of sustaining a continuous short circuit to ground without damage.

4.7 Analog Inputs
The analog input system shall consist of a multiplexer(s), sample and hold amplifier(s), and an analog-to-digital converter It shall include all interface hardware required to make the analog system a functional part of the computer system.

4.7.1 Multiplexer

4.7.1.1 Input Switches
The input switches shall be field-effect transistors, either junction type (J-FET) or metal-oxide-semiconductor (MOSFET). If MOSFET devices are supplied, each gate shall be protected from oxide rupture due to overvoltage.

4.7.1.2 Number of Channels
A minimum of 1000 input channels shall be provided. At least 500 channels shall be low level, the balance shall be high level (as defined in Sec. 4.7.1.6).

4.7.1.3 Input Configuration
Each input shall be differential-guarded (three-wire). All three inputs shall be commutated. A minimum of two (2) levels of subcommutation shall be provided to isolate the input.

4.7.1.4 Sampling Rate
The following minimum sampling rates shall be provided

100 low-level channels, 5000 channels/sec
100 high-level channels, 2500 channels/sec
400 low-level channels, 10 channels/sec
400 high-level channels, 10 channels/sec

4.7.1.5 Input Impedance
The input impedance of an "off" channel shall be greater than ten (10) megohms when measured differentially or from either input to ground.

4.7.1.6 Full-Scale Input Voltage
The full-scale input range of the multiplexer shall be as follows
Low-level inputs, ±10 mV
High-level inputs, ±10 volts

4.7.1.7 Crosstalk
Crosstalk shall be less than ±0.01% of full scale on any channel when a 100% overload is present on an adjacent channel.

4.7.1.8 Scatter
Channel-to-channel scatter shall be less than ±0.1% of full scale for the same input on all channels.

4.7.1.9 Common-Mode Rejection
Common mode rejection shall be at least 120 db from direct current to 60 Hz with a balanced source impedance. It shall be at least 85 db from direct current to 60 Hz for a 500-ohm unbalanced source impedance.

4.7.1.10 Maximum Common-Mode Voltage
The multiplexer(s) shall be capable of sustaining ±20 volts direct current or peak alternating current on any input without damage to the input switches and without turning on deselected channels.

4.7.1.11 Full-Scale Output Voltage
The full-scale output voltage shall be ±5 volts or greater for both low- and high-level inputs.

4.7.1.12 Address Modes
Three separate address modes shall be provided random, sequential, and dwell. Each mode shall be program initiated. The random access mode shall permit an external binary word to select any address at random. The sequential mode shall provide a fixed sampling pattern and be capable of operating from an internal or external clock. The dwell mode preselects one channel for continuous duty.

4.7.2 Analog-to-Digital Converter

4.7.2.1 Number of Bits
The converter shall provide 12 bits of information with the most significant bit representing the sign of the input data.

4.7.2.2 Conversion Speed
The total conversion time shall not exceed 10 μsec including sample time and hold time.

4.7.2.3 Aperture Time—Sample and Hold
The converter shall incorporate a sample and hold amplifier. The aperture time shall be 100 nsec or less.

4.7.2.4 Acquisition Time—Sample and Hold
The acquisition time shall not exceed 6 μsec for a full-scale step input.

4.7.2.5 Sag—Sample and Hold
The permissible decay during hold shall be less than ½ of the least significant bit (lsb).

4.7.2.6 Accuracy
The transfer accuracy of the converter shall be at least ±0.05% ±½ lsb

4.7.2.7 Monotonicity
The converter output shall be monotonic increasing (or decreasing) for a change from plus (+) to minus (−) full scale and from minus (−) to plus (+) full scale.

4.7.2.8 Linearity
The deviation from a straight line through plus (+) and minus (−) full scale shall not exceed ±0.1% ±½ lsb

4.7.2.9 Overscale indicator
One bit shall be provided to indicate an overscale input.

4.7.2.10 Display
A front-panel display that indicates the output word status shall be provided for troubleshooting purposes.

8-6.4 Standard Peripherals

Whereas the input/output includes the peripherals that are peculiar to process control systems, the standard peripherals include those items and their interfaces which are common to most computer systems The characteristics of each item depend on the application and often are compromises between programming efficiency and hardware cost This is particularly true of punched-card units and line printers. Only by experience can one estimate accurately the tradeoff between the programmers' man-hours and the machine cost involved.

Although cathode-ray-tube (CRT) displays are becoming more common, they have been used in computers in so many different ways that no standard set of design criteria has yet been developed. It is therefore necessary, once the display content and formats have been decided on, to make a detailed analysis of the required data storage and transfer rates These are then related to the known capabilities of currently marketed hardware. Equipment to display both alphanumeric and graphic data should be studied carefully, a raster method may be required for one and beam steering for the other, with the result that two separate spares are needed if standby redundancy is a system requisite.

The standard-peripherals section of the sample specification is given below. The intermediate-speed bulk storage device may be either disk or drum, the specifications being quite similar. The disk was arbitrarily chosen for the example.

5.0 STANDARD PERIPHERALS

5.1 Disk Memory
A disk memory shall be interfaced to the computer. It shall utilize a fixed head per track design. The read/record heads shall not contact the disk surface.

5.1.1 Capacity
Disk capacity shall be a minimum of 12,000,000 bits.

5.1.2 Access Time
Worst case access time shall be less than or equal to 16 msec.

5.1.3 Error Control
Parity generation and error detection shall be provided for all transfers to and from the disk. The nominal error rate shall be no greater than 1 bit lost in 10^{10} data transfers.

5.1.4 Write Lock
Write lock shall be provided for at least 50% of the total storage capacity.

5.2 Line Printer
A line printer shall be interfaced to the computer. The printer will be used for on-line printing of alphabetic, numeric, and symbolic data.

5.2.1 Print Speed
Print speed shall be not less than 300 lines per minute.

5.2.2 Number of Columns
A minimum of 132 print positions (columns) across shall be provided.

5.2.3 Character Spacing
Character spacing shall be ten (10) characters to the inch (horizontally). The maximum cumulative error shall not exceed ±0.02 in. for the 132-column line.

5.2.4 Character Size
Nominal character size shall be 0.1 in. (vertically) by 0.066 in. (horizontally).

5.2.5 Character Registration
Vertical and horizontal registration shall be within a ±0 005-in tolerance.

5.2.6 Character Set
The following 64 characters shall be supplied A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z, 1, 2, 3, 4, 5, 6, 7, 8, 9, ϕ, (,), ′, „ , , ., /, -, +, &, ?, $, <, >, ↑, !, ″, =, #, @, , %, *, [,], \, ←

5.2.7 Character Replacement
It shall be possible to individually remove and replace characters.

5.2.8 Line Spacing
Line-to-line spacing shall be 6 lines per inch.

5.2.9 Line Registration
Line-to-line registration shall be within ±0.005 in. nonaccumulative.

5.2.10 Paper Handling
The printer shall accept paper widths ranging from 2.5 to 18.5 in. The paper used shall be standard Z-fold sprocket feed. It shall be possible to use 6-part paper (multiple copy).

5.2.11 Ribbon
The printer ribbon shall be equipped with an automatic reversal feature.

5.2.12 Printer-Cabinet Soundproofing
The printer cabinet shall contain sound-deadening material with a minimum thickness of ½ in.

5.2.13 Paper Storage
Both input and output paper storage shall be provided.

5.3 Paper-Tape Reader/Punch
A paper tape reader/punch shall be interfaced to the computer

5.3.1 Speed
The system shall read/punch at a minimum speed of 300/100 characters per second.

5.3.2 Code
The system shall read and punch the standard 7-level ASCII code as described in ASA Standard X3.18-1967.

5.3.3 Tape Take-Up and Supply
The system shall utilize fanfold paper tape. Both supply and take-up bins for fanfold tape shall be supplied.

5 4 Display—Alphanumeric and Graphic
Two independent displays shall be interfaced to the computer. Each display system consists of a cathode-ray-tube assembly, vector generator, character generator, light pen, keyboard, and interface electronics.

5.4.1 Display Area
The display screen shall be not less than 19 in. across the color cathode-ray tube (diagonal or diameter measurement). The usable viewing area shall be not less than 12 sq in. All specifications shall be met everywhere in this area.

5.4.2 Phosphor
The CRT shall utilize a P22 phosphor (or equivalent) The faceplate shall have a boned safety shield installed.

5.4.3 Spot Size
The display-spot size shall not exceed 0.020 in. at the half-light points.

5.4.4 Random-Positioning Time
It shall be possible to display points at random. The maximum time required to position the beam and settle to within one spot width of the final position shall not exceed 16 μsec.

5.4.5 Positioning Repeatability
The display-spot position repeatability shall not exceed ±0.3% of full scale independent of the previous position.

5.4.6 Jitter
The display-spot jitter shall not exceed ±0.2% of full scale over a time interval of 1 hr.

5.4.7 Resolution
The resolution in the x and y directions shall be ten (10) binary bits. The matrix defined is 1024 by 1024 points

5.4.8 Contrast Ratio
The contrast ratio for black and white shall be no less than 4 1 in an ambient light level of 20 ft-c.

5.4.9 Brightness
The brightness shall exceed 20 ft-lamberts in an ambient light level of 8 ft-c.

5.4.10 Vector Data Format
The display shall provide at least two (2) vector formats, one long and one short. Short vectors are defined as less than 1 in. The time required to display short vectors shall not exceed 5 μsec It shall be possible with the long-vector mode to specify either (inclusive) relative vector or absolute vector. In relative mode the x and y coordinates of the end point are given and the vector is drawn from the previous point. In absolute mode the x and y coordinates are specified and the vector is drawn relative to the origin of the position matrix.

5.4.11 Vector End-Point Registration
End-point registration shall be within ±0 035 in

5.4.12 Vector Writing Rate
The time required to write a vector shall be less than 50 μsec regardless of length. The display intensity shall be constant irrespective of the length of the vector.

5.4.13 Character Plot
The character generator shall contain at least sixty-four (64) alphanumeric and symbolic characters. The character set shall include those charac-

ters listed for the line printer in Sec. 5.2.6. The character generation time shall not exceed 10 μsec.

5.4.14 Character Sizes

At least two (2) programmable character sizes shall be provided.

5.4.15 Number of Characters Displayed

The display system shall be capable of displaying and refreshing not less than 1500 characters (50 Hz refresh rate)

5.4.16 Aspect Ratio

The character aspect ratio shall be not less than 4 3 (height to width) or greater than 3 2

5.4.17 Intensity

Three programmable intensity levels shall be supplied for each primary color (red, blue, and green).

5.4.18 Light Pen

A photoelectric light pen shall be supplied for each display. It shall transmit an interrupt signal to the computer whenever a point on the display screen, within view of the pen, is intensified

5.4.19 Keyboard

An alphanumeric and symbolic keyboard shall be supplied with each display such that all defined characters can be entered from the keyboard. In addition, a function keyboard with at least 16 keys shall be supplied. A keyboard overlay that permits the selection of at least eight (8) different function groups shall be provided for all function keys. A separate overlay shall be supplied for each of the eight groups. Overlay code names shall not be supplied

5.4.20 Memory

A local refresh memory capable of storing one frame of data shall be supplied with each display.

5.4.21 Enclosure

The display system shall be enclosed in a console cabinet. It shall have a table extending in the front below the cathode-ray tube. The cathode-ray tube shall be tilted slightly toward the back to facilitate operator viewing

8-6.5 Software

The software part of the specification is the most difficult to state in precise terms This is partly attributable to the prevalence of an imprecise vocabulary in which several words can mean the same thing (monitor, executive, organizer), a practice that compels the specification writer to describe programs by function. Some of the difficulty may also be credited to the existence of the two distinct kinds of software *systems programs* (sometimes called utility programs or operator routines), which implement programming, and *process programs,* which implement data handling and control Avoid confusion by specifying programs in terms of the tasks that each is to perform

The designer must be very firm about receiving the systems programs in working order Although many of the programs are fixed for all systems, those which require the operation of peripherals may never have been tried on the exact configuration being specified.

Several of the programs listed in the sample specification (below) are optional Many users will not make the compiler a firm requisite, although most U S manufacturers include some version of FORTRAN in the software package The editor program is very valuable when paper tape is the programmer's only high-speed communication with the computer, but the editor program loses value if punched-card equipment is available. The process programs are useful only to the extent to which they can be adapted to the application at hand. The current difficulty in this regard is simply that a compact and efficient software package cannot support a variety of applications, nor can a computer, properly sized for the application, support an oversized software package that has been designed to suit all occasions. It is hoped that in the future a truly modular approach to process software will allow the designer to specify a control system, equipment, and programs as easily as he has specified analog equipment in the past [19] The software section of the sample specification follows

6.0 SOFTWARE

Specific software requirements to be furnished with this equipment are listed in the following sections In addition, each bidder shall include a description of all software available (including extra price where applicable) for the specific configuration (core memory, peripherals, etc) described in this specification

A complete listing of the software documentation available for the specified configuration shall be supplied

6.1 Executive

An executive monitor oriented to on-line real-time processing shall be provided The monitor shall reside on the disk, along with the processor and library routines, and shall utilize the disk for scratch storage if necessary. Foreground–background processing shall be required Foreground operations shall include provision for both resident (in-core) and nonresident (core-disk swapping) real-time programs. Both the monitor and real-time programs shall be protected against inadvertent destruction by a background program.

The monitor shall provide automatic interrupt, context switching and storing, programmable priority-interrupt structure, nested-interrupt inquiries, program-priority queries, and linkages and facilities for handling all devices included in this specification. Device-independent I/O programming shall be provided. The monitor shall provide for reentrant subroutine execution The maximum time that the monitor disables interrupts shall be stated

6.2 Compiler

A FORTRAN compiler shall be provided to allow programming in English and mathematical-like statements The compiler shall be capable of operating in a real-time environment and, as a minimum, of meeting the following requirements

- Compliance with ASA Standard X3.9-1966 FORTRAN.
- Intermixing of FORTRAN statements and assembly-language statements by macros or other suitable means.
- Provision for reentrant subroutines.
- Provision for queuing and utilization of priority interrupts in real time

6.3 Assembler

A symbolic assembler program shall be provided which processes a machine-oriented language. The assembler

shall provide pseudo instructions for the purpose of defining symbols, reserving memory, linking subroutines, and controlling input/output options. The assembler shall provide macroinstruction capability.

6.4 Correction Program
A correction program shall be provided which shall enable corrections and additions to be made on source programs by inputting the source program into memory (limited by the capacity of the memory) and making corrections through the keyboard. The output shall be a new program taken from memory which includes the corrected statements.

6.5 Diagnostic and Utility Programs
Programs shall be provided to assist programmers during the debugging phase of program development. These programs shall include, but not be limited to, the following features

Clearing all or part of memory
Modifying memory from the keyboard.
Printing all or part of memory under specified conditions.
Inserting and deleting breakpoints.
Initiating a jump on condition to any part of memory.

Additional features shall be listed in the bid response.

6.6 Input/Output Programs
Input/output drivers shall be provided for all peripheral devices required in this specification. The drivers shall provide for testing device status and executing data transfers. The tests used for each device, the device address (logical and hardware), and the number of interrupts, by level, shall be indicated in the bid response

6.7 Maintenance Programs
Maintenance programs shall be provided which enable testing of the entire central processor and all peripheral equipment Testing shall include the memory instruction set, central control, arithmetic section, priority interrupts, and each peripheral 8

6.8 Delivery Form
All software shall be delivered as individual paper tapes. Where more than one program (e g., loader and monitor) resides on a tape, the individual tapes will also be supplied This requirement does not apply for the library decks for FORTRAN and assembly language

6.9 Documentation
Three sets of all software manuals shall be provided All paper tapes shall be accompanied by a source program listing.

8-6.6 Environmental and Miscellaneous Characteristics

The environmental and miscellaneous characteristics comprise the temperature and humidity ranges under which the system is to operate and such various items as power requirements, documentation, cabinets, and quality assurance

The hardships that have been caused by inadequate or erroneous circuit and schematic diagrams are well-known. The same pains can be experienced if the software is incorrect. Complete program descriptions and updated listings of all supplied software, as well as accurate as-built drawings of the hardware, must be required.

A subsection on the manufacturer's quality-assurance practices should be included in the specification It is usually a requirement of any large system The specification should require that all proposals describe the seller's current quality-control programs to an extent commensurate with the size of the system Incoming-materials inspection, manufacturing procedures, quality control, documentation control, and use of existing codes and standards should be covered. It should be made clear that response to this section will influence the selection of the supplier.

The environmental and miscellaneous characteristics section of the sample specification is as follows

7.0 ENVIRONMENTAL AND MISCELLANEOUS

7.1 Temperature
The computer and all peripheral devices shall meet the requirements of this specification over a temperature range of 50 to 90°F

7.2 Humidity
The computer and all peripheral devices shall meet the requirements of this specification over a humidity range of 50 ± 30%

7.3 Power
The computer shall operate from 120/208-volt, 60-Hz power, single or multiple phase Each manufacturer shall provide literature that describes the following items

1. Power required—by voltage, current, and phase
2. Power dissipation in British thermal units per hour and kilovolt-amperes separately stated for the central processor and each peripheral device plus the total power consumed by the system.
3. Connector wiring diagrams for every input power connector, cross labeled by manufacturer type

7.4 Enclosure
Each item specified is to be supplied in a fully enclosed cabinet with access doors for ease of maintenance Peripheral devices may be grouped to share a single cabinet Each manufacturer shall provide literature that describes the following items

1. Cabinet configuration and mechanical position assignment for each peripheral device and for each portion of the central processor. Unused rack space shall be identified and dimensioned.
2. Service clearances required for all racks and cabinets
3. Installation dimensions for assessing doorway, elevator, and loading-dock clearances
4. Total system weight and weight by cabinet (console or rack) Shipping weight.

7.5 Spare Parts
Standard spare parts package and terms for later exchange of faulty circuit boards shall be provided. Extender boards shall be provided for each type of printed-circuit connector supplied (where applicable).

7.6 Documentation
Four copies, unless otherwise noted, of the following documentation shall be supplied

1. Final as-built drawings.
2. System block diagram.
3. Instruction and maintenance manuals.
4. Parts list.

7.7 Reliability
Reliability data shall be provided, both calculated and tested. The method of calculation (MIL-METHOD etc) shall be specified. Where data are not available, so indicate.

7.8 Quality-Assurance Program
The vendors shall supply in the proposals evidence that a Quality-Assurance Program is maintained that will assure the purchaser that all articles procured from the vendors will satisfy the purchaser's requirements. This evidence shall consist of either the vendor's quality-control procedures manual or references to applicable public documents which constitute the procedures used in the vendor's quality program.

The vendor's quality program shall show evidence of an organized and documented approach to the attainment of quality both in inspection and manufacturing procedures and in document control as it pertains to the purchased system.

8-6.7 Other Sections of the Specification

There are several other items to consider when procuring a computer system for the automation of a nuclear power plant. The specification should provide for appropriate vendor action on each item

(a) Acceptance Tests. The complex nature of a computer control system demands a close and continuing check on its operability. A thorough set of checkout programs should be run at the factory and again after delivery to the site to disclose any faults that might have occurred in transit. These tests must encompass all the requirements of the specification and will be time consuming and tedious

(b) Installation. It is impractical in a full-size power plant to require the control-system manufacturer to install his equipment. He will, however, be expected to supervise the placement of cabinets, interconnecting cables, and the running of final acceptance tests

(c) Training. There has been, to date, no surplus of experienced process programmers. The quality of programming and maintenance training that the system manufacturer offers will depend on the availability of his personnel. It is advisable to leave the training schedule open to negotiation, within specified limits, to make best use of the teacher's time. However, the specification should include a request for outlines of the training courses.

(d) Appendixes. A list of control-system inputs and outputs can be appended to the specification to aid the bidder in sizing the equipment required. A rough layout of the control console will also help him visualize the display configuration and perhaps offer suggestions for improvement A floor plan will aid in placing components and in determining the lengths of interconnecting cables.

8-7 CURRENT PLANT DESIGNS

A few of the world's nuclear power plants are described briefly in this section to give the reader an idea of present computer applications These plants were selected because they are completed or soon will be, have some degree of computer control, and have been adequately discussed in meetings or publications. Pertinent data are summarized in Table 8.5. The dates listed are years during which the plant

Table 8.5—Computer-Controlled Power Plants

Plant	Country	Year on-line	Reactors	Computers	Computer control functions
Douglas Point	Canada	1967	1	1	Flux tilt control rods, power-level demand, and safety logic modification
Marviken	Sweden	1969	1	1	Start-up and shutdown sequence, refueling, and superheater throttle valves
Wylfa	United Kingdom	1969	1	1	Turbine run-up
Dungeness "B"	United Kingdom	1970	2	3	Reactor start up, reactor coolant outlet temperature, and turbine run up
Hinkley "B"	United Kingdom	1971	2	3	Reactor start-up, reactor-coolant outlet temperature, and turbine run-up
Prototype Fast Reactor	United Kingdom	1971	1	2	Start up sequence, fueling sequence, and power and temperature regulation
Pickering	Canada	1972	1*	2	Zone reactivity, reactor power, boiler pressure, and refueling
Gentilly	Canada	1972	1	2	Zone reactivity, reactor power, and coolant flow

*Initially

goes on-line as a power-generating station, in some cases these have been inferred from other planned milestones, such as plant completion and date critical

8-7.1 Douglas Point

The CANDU reactor[20] at Douglas Point, Ontario, is probably the earliest planned use of digital-computer control in a nuclear power plant At present the computer directly drives neutron absorber rods to control the reactor flux profile and indirectly adjusts power by providing the set point to the analog moderator level controller

As an assist to higher plant factor, the computer also modifies safety-circuit operation. The safety circuit alone will initiate scram if low coolant flow in any fuel channel is signaled, however, when the computer is operating, it inhibits the trip unless low flow is accompanied by high coolant outlet temperature.

8-7.2 Marviken

The Marviken Nuclear Power Plant,[18] a 200-MW(e) station, will have a comprehensive set of sequence programs for start-up, running, shutdown, and refueling These are largely automatic with interspersed stopping points that require a manual command to proceed The control system will also automatically adjust the throttle valves in 32 superheat channels in the reactor core, a difficult procedure because a high-channel temperature requires resetting not only the affected channel valve but also those in several surrounding channels This is a good example of applying computer control where other means are inadequate.

8-7.3 Wylfa

Wylfa,[21] a MAGNOX reactor station, is the first in a series of three plants in which computer-based data and display systems have been applied progressively more toward direct control as United Kingdom experience grows Wylfa has automatic turbine run-up

8-7.4 Dungeness "B"

In addition to automatic turbine run up, the Dungeness "B,"[22] an advanced gas-cooled reactor station, will have complete start-up, from subcritical to power, under computer control with manual intervention required if the system encounters abnormal conditions The computer will also control, by rod movement, the ratio of outlet gas temperatures among five reactor zones This is a difficult control problem under all conditions of coolant flow and reactor power level

8-7.5 Hinkley "B"

Except for a different array of inputs and outputs, the Hinkley "B"[13] is controlled similarly to the Dungeness "B " Both stations are examples of the "dual-plant three-computer" configuration discussed in Sec 8-5.

8-7.6 Prototype Fast Reactor

Automatic computer control of reactor flux, coolant outlet temperatures, and steam-generator outlet temperatures is being considered for the prototype fast reactor,[16] a 250-MW(e) sodium-cooled fast reactor facility This is the plant, cited before, in which a detailed economic and technical study resulted in a redundant computer system and a revision of principles to allow plant shutdown on complete control-system failure

8-7.7 Pickering

Nearly all the major reactor variables in the Pickering Nuclear Power Station,[23] as in other Canadian plants, will be computer controlled. This includes flux profile, overall reactivity, boiler pressure, and the fueling process

8-7.8 Gentilly

As in the Pickering, most control of the Gentilly Nuclear Power Station[24] will be by computer Of interest is the reactor's large positive void coefficient, which will be compensated by moving a set of booster rods according to changes in plant power level Primary-coolant flow valves will also be automatically controlled as a function of power

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Chapter 9

Power Supplies

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CHAPTER CONTENTS

9-1 INTRODUCTION

The safe operation of nuclear power reactors requires that many of the instrumentation and control systems have a high degree of reliability. One factor in reliability is the integrity of the power source for the instrumentation and control power buses. This chapter provides the designer of instrumentation and control systems with sufficient information to choose the power-source system best suited to his specific application and giving maximum support to the overall system reliability.

9-1.1 System Requirements

The power sources most commonly used are electrical. Accordingly, this chapter deals mainly with them and only briefly with nonelectrical systems. The common combinations of static, rotating, and stored-energy system components are discussed. Battery-supported static inverter systems, which are among the most frequently used electrical source systems, are emphasized.

The systems discussed differ with respect to their degree of noninterruptibility, i.e., their capability to continue operating under emergency conditions after normal source failure, the quality of their output, and their cost. The designer of instrumentation and control systems must first determine his requirements and establish the relative importance and criticality of each part of the system before choosing the most economical power-source systems to meet his needs. The various systems described offer phase changing, direct-current transformation, line-frequency and line-voltage transformation, isolation, and stabilization. Capability for short-time operation with stored-energy sources and long-time operation with engine-driven energy sources can also be included.

9-1.2 Design Objectives

To design the power-source system for nuclear-reactor instrumentation and control and to achieve maximum reliability requires, at the outset, a thorough evaluation of the load characteristics. A designer of electronic systems is painfully aware of the risks in having instrumentation and control systems depend on plant auxiliary-power sources.

Complete independence from outside power sources would provide ideal integrity. The best power system for a particular application cannot be designed by just selecting available components to obtain complete power-source independence. The designer must take into account, in his effort to satisfy the overall design objectives economically, such aspects as the allowable outage time of the power source, allowable transfer time between normal and standby power sources, initial cost, maintenance expense, and operating cost The system that provides the desired reliability with the minimum cost is usually based on a compromise between many design considerations

9-2 TYPES OF POWER SUPPLY

9-2.1 System Similarities

Each available power-source system provides a different degree of power continuity and independence, or isolation, from the plant auxiliary-power system In general, each system has a form of stored energy for providing power to the critical bus during an unacceptable frequency or voltage excursion and during the time interval when it becomes necessary to disconnect the normal source of power and transfer to the standby power source Each system has a means of isolating the unacceptable normal power source and initiating the alternate source (if one is provided) before the stored energy of the system is depleted Automatic reconnection to the normal source, after it has returned to a stable condition for a given period, is also a common feature

9-2.2 Energy Storage Methods

The five major ways to provide stored energy for a standby power system are

1 Pneumatic (stored air or gas) systems
2 Hydraulic accumulation systems
3. In-house or on-site steam-driven turbogenerator systems
4. Inertia, flywheel with and without eddy-current coupling systems
5. Storage-battery-supported systems

The first four systems are commonly used with rotating machinery, and the last is associated with static* systems

The last two methods are electrical in nature and have had the greatest acceptance Each of the last two methods is used to improve the quality of the power normally provided by the plant auxiliary-power source by acting as a filter or buffer When they are combined with a diesel-driven generator backup, they also provide reliable protection from prolonged power outages Storage-battery systems are normally combined with static battery charging rectifiers and either static inverters or d-c to a-c motor–generator sets to provide short-time power continuity Static inverters, with and without output transfer switching, have also gained wide acceptance as reliable sources of a-c power for critical loads

*"Static' as used here means "no moving parts "

9-3 REQUIREMENTS FOR POWER SUPPLY

9-3.1 General System Categories

Instrumentation and control power systems may be categorized as either interruptible or noninterruptible.

(a) **Interruptible Systems.** Interruptible systems are those in which power is obtained directly from the plant auxiliary-power system through suitable filters and regulating equipment, if they are required to improve the power quality. An interruption of plant auxiliary power results in total loss of instrumentation power This type of system is applicable only where the instrumentation and control loads are noncritical, i.e., absolute continuity of operation is not essential. Usually the total interruption time is a maximum of approximately 15 sec, i e., the time in which the plant standby auxiliary power source, several diesel-engine-driven generators, reestablishes power to the essential auxiliary buses

(b) **Noninterruptible Systems.** Noninterruptible systems are those in which any interruption of power results in loss in continuity of operation or in erroneous operation of critical instrumentation and control loads Since noninterruptible power systems are the type most commonly required for nuclear-reactor instrumentation and control applications, the remaining sections of this chapter concentrate on power-source systems that are noninterruptible for a discrete length of time after a plant auxiliary-power failure.

There are two categories of noninterruptible power systems, *nonisolated* and *isolated*

Nonisolated systems are those in which plant auxiliary power is imposed directly on the essential auxiliary-power buses Normally the noninterruptible power supply is also fed from these essential power buses and is storing up potential energy. If a plant auxiliary system fails or if there is a severe transient, the noninterruptible power supply releases the stored energy to the critical bus, thus affording a short-time carry-over of stable power

The more commonly used type of noninterruptible power supply is the *isolated* system This differs from the nonisolated system in that the instrumentation power buses do not receive power directly from the plant auxiliary power system but rather through the noninterruptible power supply. The noninterruptible isolated power supply thus acts as a filter or buffer separating the instrumentation power buses from the plant auxiliary-power system and any transients that appear on that system

9-3.2 Load Characteristics and Causes of Trouble

If, for economic reasons, the reactor instrumentation and control system is designed for use on a single d-c source, then the power-source system is simple If a single d-c power source is not satisfactory, the choices of power-source configurations increase greatly. Factors to be considered include alternating source voltage and frequency stability, harmonic distortion, plant auxiliary-power outage time and allowable transfer time, maximum allowable rate of change of voltage and frequency, and load power factor. A specification that is overly restrictive, just to be safe, results in an unnecessarily high cost for the power supply and should be avoided.

Momentary loss and surges and dips of voltage are relatively frequent in plant auxiliary-power systems Voltage dips and surges are caused by switching, failure of equipment remote from the critical bus, and starting large motors on the same power system The duration and intensity of the undesirable transient depend on its proximity and the clearing time of the protective equipment ahead of the faulted section. A single cycle can be severely distorted without a power interruption. (Such distortion might occur when heavy loads are placed or pulsed on a radial feeder remote from the critical bus) Wave-shape distortion can also result from momentary faults that, in fact, become equivalent phase shifts Large banks of capacitors and intermittent reactive loads can give rise to wave-shape distortion

The most widely accepted method of avoiding or minimizing these effects is to insert a noninterruptible power source to act as a filter between the plant auxiliary-power supply and the critical instrumentation load In addition, the system cable routing and installing must be designed to segregate the redundant systems and methods so that the clean output from the noninterruptible power source will not be contaminated by induced noise from cables in other noncritical systems The imposed static and dynamic seismic loading postulated for the specific area within the nuclear plant in which the noninterruptible power supply is to be located must be taken into account The seismic criteria should be incorporated within the equipment specification. In addition, proper seismic design of equipment foundations and anchors is essential, electric cables and conduit between all critical items of equipment must be flexible.

The reliability of a noninterruptible power system is only as good as the weakest part of the total installed system. This point should be emphasized not only during the design and installation phases but also throughout the life of the system. A continuous and conscientious maintenance and testing program is essential

9-4 COMPONENTS OF POWER-SUPPLY SYSTEMS

All the power-supply systems discussed in this chapter are comprised of individual components, or building blocks The degree of power continuity and overall system reliability and cost achieved in any system depends on how the basic building blocks are combined The following sections describe the building-block components of the system. Some necessary aspects of properly specifying the components as part of the overall system are also covered.

9-4.1 Static Inverters

Static inverters become an essential part of a high-reliability power system if short transfer time and an a-c output are required. These inverters are usually used in conjunction with batteries and a static rectifier to provide, on failure of the plant auxiliary-power source, instantaneous transfer of power from the plant auxiliary-power source to the battery system.

Static inverters consist of three basic parts a low-power oscillator, a power-switching section, and (usually) an output ferroresonant transformer. The low-power oscillator determines the operating frequency of the inverter and can be independent of or synchronized with the plant auxiliary-power system. Once the inverter has been running for several hours, an output-frequency stability within ±0.25% of the desired frequency is obtained The major factors tending to change the frequency are long-term drifts in components and variations in the ambient temperature

The power switching section is probably the most critical portion of the overall inverter and usually consists of bridge-connected silicon controlled rectifiers (SCR) The four main SCR's are alternately switched in pairs, which converts the input d-c source into a square-wave alternating voltage that is applied across the primary of the output transformer The peak amplitude of the alternating voltage is essentially equal to the direct input voltage At the end of each half cycle, the two conducting SCR's are shut off by momentarily providing a reverse voltage bias This process, called commutation, is an extremely critical function in the proper operation of the inverter If during any half cycle the commutation should fail, the system would be left with more than two SCR's in the conducting state This would result in an effective short circuit across the battery and would shut down the unit Ensuring proper commutation even under the most adverse conditions is essential in designing reliable inverters In addition to proper commutation, the associated circuit must limit the SCR rate of rise of current (di/dt) or voltage (dv/dt) and the peak forward and reverse voltages that appear across the SCR's

In most applications the desired output is a regulated low-distortion sine wave. Usually both regulation and filtering are provided by the ferroresonant output transformer, a passive magnetic system similar to the commonly used constant-voltage transformer. An important feature of the ferroresonant transformer is that, as the load current is increased, the output voltage remains essentially constant up to a point in excess of rated load. Above this point the characteristic becomes a very nearly constant current mode As a consequence of this, the inverter can be operated

continuously into any overload, up to and including a short circuit, without affecting the square-wave switching portion of the inverter A sine-wave inverter of this type can therefore satisfactorily handle load transients that might otherwise cause misoperation or lack of commutation in the square-wave section

The normal regulation that can be expected is ±3% for all conditions of input voltage and for loads between zero and rated maximum at unity power factor Loads at other than unity power factor have an additional effect on the output Generally, inductive loads reduce the output voltage whereas capacitive loads increase the output voltage. Loads with a power factor below 0 8 lagging increase the harmonic distortion in the output For these reasons it is preferable to operate with a load having a power factor as near unity as practical, unity power factor also corresponds to minimum d-c input drain. Where the load has an inherent low power factor, the designer must provide suitable correction either at the load or the inverter

In applications where other critical loads are also fed from the battery system, it is desirable to use a filter on the input to the inverter With a sine-wave output from the inverter, the input current resembles a half-wave rectified sine wave Superimposed on this direct current is a large a-c component that may modulate the battery voltage sufficiently to cause an undesirable hum in the input of other equipment fed from the battery. The filter eliminates this problem. A second and probably more important function of an input filter is the elimination of spikes that are generated across the battery by other equipment, such as d-c motors and solenoids. Such equipment, commonly used in nuclear power plants, is notorious in generating large voltage transients during operation. Inverter input protection should be provided for short-term transients, in the order of 100 μsec up to 4000 volts, when fed from large-station battery systems

Table 9.1—Input and Output Ratings of Typical Static Inverters

	Single-phase output	Three-phase output
Output voltage, volts (a-c)	120	208Y/120 230/399
Frequency, Hz	50 or 60	50 or 60
Output, kVA	2 5 to 28	9 to 150
Input voltage, volts (d-c)	48 or 125	125 or 250
Output voltage and frequency regulation, %	±1	±1 to ±2
Output harmonic distortion, %	<5	<5

Inverters are readily available in a variety of standard output and input ratings, the most common of which are listed in Table 9.1. The typical standard ratings in Table 9.1 do not, of course, represent the limits of the manufacturers' capabilities. Nonstandard inverters of different output and input voltage, kilovolt-ampere rating, and output quality are available for a premium price on request. The following is an outline of the major areas of importance which should receive attention when specifying a static inverter

The range of input voltage over which the required output must be maintained for a stated time during normal and emergency operation is most important In most cases the inverter supplier does not have control over the input source, which is usually the nuclear-power-plant station battery. It is not sufficient just to determine the normal long-term variations of input voltage. Transient input voltages are also important A common design error is to focus on the large-magnitude short-time transients and neglect the higher energy transients of low frequency (0 5 to several Hz). Input voltage transients due to starting motors may not show up on either a long-time source voltage recorder or an oscilloscope set up to detect switching transients Comprehensive knowledge of the characteristics of the input source is prerequisite to proper inverter application and protection

The precise definition of source impedance is not always necessary. However, it is relevant to note the length and size of conductors between the inverter and the d-c source and between the inverter and any switching or protective devices in the incoming lines Because of input-current pulsing during the SCR switching, an input filter may be desirable to remove unwanted modulation of the d-c source. This adds to the inverter cost, and, the actual need for it should be determined before specifying an input filter

The load characteristic should be carefully defined Of specific importance are the load power factor, the variation of load, and the maximum load to be switched at one time. Static inverters have definite limits to their momentary overload capacity, and the limits cannot be exceeded. This characteristic is different from the characteristic of a rotating inverter that has inertia and becomes very important where motor loads or other high inrush loads are present. The possibility of load short circuits should also be considered. It may be concluded that a current-limited output is desirable, and, if so, this should be specified

The efficiency of static inverters may be defined in two ways For the amount of heat to be removed due to losses in the inverter, efficiency may be expressed as the ratio (in percent) of output power losses to rated output power losses However, if the purpose is to determine the source current, efficiency is expressed as the ratio of rated output a-c power to rated input d-c power (in percent). It is important to indicate which definition is to be submitted by the manufacturer in his bid proposal This is particularly important for load power factors, which differ significantly from unity.

The output of the static inverter may be synchronized with another source or with a frequency standard. It is important to indicate the impedance, potential variation, and transient noise capability of the synchronizing signal to be used.

In most cases an extremely low harmonic output distortion level is not necessary. If the a-c output is to be rectified and filtered, a square-wave output would even be desirable. Should a square-wave inverter output be used in conjunction with external transformer loads, the transformers must be capable of handling the additional 11% swing in flux without overheating.* In general, a wider harmonic distortion tolerance in the specification results in reduced size, cost, and weight of the inverter.

9-4.2 Storage Batteries

Two principal types of lead–acid batteries are in use today: Plante and Fauré. Plante invented the lead–acid battery about 100 years ago using positive and negative plates of pure-lead sheets. Today batteries that have pure lead in their positive plates are called Plante types. The original Plante battery was expensive because the lead peroxide, which is the active material of the positive plate, was extremely difficult to form on the surface of the positive plate. Some time later, Fauré invented an economical method of pasting lead peroxide on the positive plates and lead oxide on the negative plates. This is the type of construction used today.

Fauré batteries can be either lead–antimony or lead–calcium alloy plate grid types. The names are derived from the hardening alloy material used in the manufacture of the plate grids. Of the many types of batteries available, the lead–antimony and lead–calcium Fauré types are the most common in noninterruptible power supplies. A lead–calcium battery costs up to 15% more than a lead–antimony battery; however, the lead–calcium battery offers several advantages over the lead–antimony battery. The lead–calcium battery requires much less water replacement and therefore generates a proportionately smaller amount of hydrogen gas during the recharge cycle. The floating voltage is less critical, 2.17 to 2.25 volts per cell (compared to 2.15 to 2.17 volts per cell for the lead–antimony battery). If the lead–calcium batteries are float-charged between 2.20 and 2.25 volts per cell, they are reported to never require an equalizing charge. These advantages must be balanced against the higher initial cost of the lead–calcium battery since satisfactory operation for equal lifetimes can be expected from both types of batteries when properly maintained.

The current produced by a lead–acid battery results from the chemical reaction of dilute sulfuric acid on the active materials in the plates. Lead dioxide reacts with the sulfuric acid at the anode to produce a positive charge. At the cathode, metallic lead reacts with the acid to produce a negative charge. During the discharge process, sulfuric acid is consumed and replaced by a corresponding amount of water. During charging the process is reversed, acid being formed at the plates with a corresponding consumption of water and generation of oxygen and hydrogen gas.

As the discharge of a lead–acid battery progresses, the water formed is absorbed into the electrolyte, resulting in a reduction of the specific gravity of the acid. The battery open-circuit voltage depends on the concentration of the acid in contact with the active plate materials. The voltage available for useful work is the voltage across the battery terminals during discharge. This latter voltage is equal to the sum of the internal cell voltages minus the drop due to the internal resistance of cells. The reduction of acid concentration as the cell discharges is accompanied by an increase in internal resistance; the increase is gradual at first and then rapid as the cell approaches full discharge. The internal resistance may increase by as much as a factor of 2 to 3 on approaching full discharge. The internal resistance of a fully charged battery is so small that it has little effect on the terminal voltage except when high discharge rates are encountered. During discharge lead sulfate accumulates on the plates. Lead sulfate is a nonconductor and has a tendency to block the pores of the plates, thereby impeding the chemical reaction. Sulfate is a contributing factor in the reduction of the terminal voltage during discharge.

When the battery is discharged at low rates, the formation of water and lead sulfate proceeds slowly, allowing the acid in the electrolyte to be readily absorbed into the pores of the plates and resulting in a gradual decrease of the terminal voltage. When the battery is discharged at a very high rate, the depletion of acid at the plates takes place so rapidly that the rate of acid replacement cannot keep pace, which causes a greater reduction in terminal voltage. The increased depletion of acid at the plates on high discharge is the primary reason that batteries have a lower ampere-hour capacity at high discharge current rates.

The capacity of the lead–acid battery is reduced as the ambient temperature decreases. The amount of reduction also depends on the rate of discharge and cell design. The major reasons for the reduction in capacity with decreasing temperature are the increased electrolyte viscosity, which impedes the diffusion of the acid at the plates, and the higher internal cell resistance caused by increased resistance of the electrolyte. The common practice is to refer to the capacity of a battery at reduced temperatures as a percentage of its capacity at 77°F.

Batteries are rated on the basis of ampere-hours, which means the amperes that the battery will deliver for a given time at a specified temperature to reach a specified "final" voltage. The standard battery terminal voltages commonly used are 24, 48, 120, and 240 volts. These correspond to 12, 24, 60, and 120 cells, respectively, at a nominal 2 volts per cell. Fauré batteries are float-charged at a cell voltage

*The maximum flux in a transformer is inversely proportional to the form factor (root mean square/average) for the input voltage. Since the form factors are 1.00 and 1.11 for square-wave and sinusoidal inputs (of the same frequency), respectively, there is an 11% additional swing in flux for the square-wave input. In view of the fact that this increase would increase the total core loss, it could lead to exceeding the rated temperature rise within the transformer at full load.

ranging from 2.15 to 2.25 volts, depending on the type of cell. Determining the size or ampere-hour capacity of a battery involves a detailed procedure that is beyond the scope of this test. (Details of the methods are given in the bibliography at the end of this chapter) Sizing of the battery can be done by the design engineer, who is aware of the battery limitations, or by the manufacturer or supplier of the noninterruptible supply package In general, the battery must have sufficient ampere-hour capacity to carry momentary loads plus continuous or basic loads for a specified length of time before reaching its final voltage, commonly referenced at 1.75 volts per cell

A lead–acid battery must receive the correct charge to give optimum performance and life. It is difficult and impractical to obtain this precisely on every charge or under floating operation. Lead–acid batteries do not need a full charge on every recharge to obtain satisfactory operation. For long life, however, they must be brought to the fully charged condition periodically, the period depending on the degree and frequency of discharge On daily or frequent recharges, it is common practice to charge slightly short of a fully charged condition, a complete charge must be made every 1 to 3 months This complete charge is commonly referred to as an "equalizing charge" Most modern battery-charging equipment is designed to effect a periodic equalizing charge.

The equalizing charge is intended to be sufficient to equalize any minor differences among the cells and should be continued until each cell of the battery reaches maximum voltage and specific gravity. To achieve this state requires manual attention and is, therefore, impractical However, the same effect is obtained by giving the entire battery an additional amount of charge for a limited period, which is not harmful to the battery. Most charging is controlled by an automatic timing switch incorporated in the charging equipment The most practical means of giving an equalizing charge is to set the time switch for an additional period of time For batteries in normal full-floating service, which is the most common service in standby power systems, a common practice is to raise the floating voltage above its normal value by about 5 to 10% for a period of 8 to 24 hr, depending on the type of battery and application. It is important to ensure that any noninterruptible loads on the battery during the equalizing charge are rated for operation at the higher voltage levels

The efficiency of a battery may be expressed as ampere-hour efficiency, voltage efficiency, or watt-hour efficiency. Ampere-hour efficiency is the ratio of the number of ampere-hours a battery yields on discharge to the number of ampere-hours required to fully recharge the battery. A typical lead–antimony battery requires a recharge in ampere-hours about 10% greater than the previous discharge, and the ampere-hour efficiency is 91%. Voltage efficiency is similarly defined as the ratio of discharge voltage to charge voltage. For the same typical lead–antimony battery, the average voltage on charge is approximately 17% higher than on discharge, the voltage efficiency is 85%. The product of ampere-hour and voltage efficiencies gives a watt-hour, or total, efficiency. For the lead–antimony battery, the watt-hour efficiency is 0.91 X 0.85, or 77% This is a representative value for such batteries. (The watt-hour efficiency is slightly higher for a typical lead–calcium battery.)

The Fauré battery is the most reliable single component used in noninterruptible power systems today. Properly designed, battery-supported systems afford the optimum in overall reliability.

9-4.3 Stored-Energy Eddy-Current Coupling

The systems described in Secs. 9-5 6 and 9-5 7 use an eddy-current magnetic coupling in combination with a stored-energy flywheel to obtain limited sustained operation (i.e., 10 sec to 2 min) after failure of the normal source of power. An eddy-current coupling consists of rotor and stator assemblies, quite similar in many aspects to the common squirrel-cage induction motor. The rotor assembly is an input shaft on which is mounted a field coil and pole pieces, the coil being energized from a d-c source through slip rings. The stator is simply a hollow soft-iron cylinder with the output shaft attached to one of the cylinder bases

The air gap between the rotor pole pieces and the inner surface of the stator is small. As a result, the magnetic field established by energizing the rotor coil is concentrated in the soft-iron cylinder As the energized rotor rotates within the iron cylinder, the magnetic flux of the rotor sweeps through the stator cylinder and induces eddy currents The eddy currents in the stator set up magnetic fields that interact with the rotor fields, and, as a result, torque is developed which tends to drag the stator along with the rotor. There must be relative motion between the rotor and stator to develop any torque If there is no relative motion, no eddy currents are produced and no torque is created. The amount of torque produced by the coupling is a function of the rotor field strength and the speed difference between rotor and stator The output torque (stator) increases with increased rotor excitation and also with increased slip.

The use of a rotating field coil and slip rings with brushes creates maintenance and reliability problems that can be eliminated by using a brushless stationary field coil In this type of eddy-current coupling, the excitation coil is rigidly mounted in a frame. The input shaft carries a smooth cylindrical drum designed so that there is a small air gap between the stationary field assembly and the drum The output shaft carries the rotor, which is fitted into the input shaft cylindrical drum and separated by a small air gap. The flux path is from the stationary field poles to the cylindrical drum on the input shaft to the rotor and then axially in the rotor back to the cylindrical drum and to the field poles. The flux actually traverses two air gaps, as opposed to only one when slip rings and brushes are used. The output torque is developed by the interaction of

eddy-current-induced magnetic fields on the inner surface of the cylindrical drum with the main field concentrated in the rotor. The main field flux is prevented from being short-circuited in the cylindrical drum by a nonmagnetic strip that separates the two halves of the drum. The stationary field design has increased reliability and reduced maintenance. The efficiency is less than that of a brush and slip-ring coupling because the double air gap requires more excitation for equal output torque

As noted earlier, the eddy-current coupling is similar to a squirrel-cage induction motor. In an induction motor a rotating magnetic field is established in the air gap by means of a polyphase winding on the stator. In the eddy-current coupling of the rotating field type, a rotating field is established by mechanical rotation of the energized rotor assembly by a prime mover The soft-iron cylindrical rotor of the coupling is analogous to the squirrel-cage rotor bars of an induction motor. In addition to these similarities, the slip-torque characteristic of an eddy current coupling is similar to that of a squirrel-cage induction motor. The slip-torque characteristic of an eddy-current coupling can be modified in the same manner as that of an induction motor. Use of high-resistance material for the soft-iron cylinder affects the slip-torque curve of an eddy-current coupling in the same manner as the use of high-resistance rotor bars affects the slip-torque curve of a squirrel-cage motor.

Eddy-current couplings are noted for their low efficiencies, especially for large differences between input and output shaft speeds. Whenever the output speed is different from the input speed, heat is generated. This loss, called slip loss, is essentially equal to the difference between input shaft power and output shaft power. Slip loss is the major source of heat in an eddy-current coupling, and the heat must be dissipated by cooling fluid or air. At rated torque and output speed, the slip loss of a typical eddy-current coupling will be about 2 to 4%. Considering other losses, such as friction, windage, magnetic drag, and excitation, the peak efficiency is about 92%. At reduced speeds the slip loss increases, and the efficiency becomes essentially equal to the ratio of output speed to input speed.

The application of an eddy-current coupling in a noninterruptible power supply with a drive motor, stored-energy flywheel, and output generator requires a large difference between the input and output eddy-current coupling shaft speeds. This results in a large coupling slip loss and hence poor efficiency, this can be relieved by operating normally without energizing the eddy-current coupling, see Sec 9-5 7

If the poor efficiency experienced when operating with the coupling normally energized is discounted, extremely close speed control and hence output frequency control can be attained with an eddy-current-coupled system. Upon coast-down, after losing the prime mover input power, the eddy-current coupling, used in conjunction with a flywheel, is able to dissipate the flywheel stored energy at a finely controlled rate just sufficient to maintain a constant output shaft speed (thereby providing an acceptable generator output) for intervals as long as several minutes.

9-4.4 Engine-Driven Alternators

The systems discussed in Secs. 9-5.4 to 9-5.7 use an a-c generator driven by an internal-combustion engine in combination with other components to provide a sustained power supply. Once operation is established with the engine as the prime mover, the time during which the alternator will operate is limited only by the available fuel supply.

The simple system shown in Fig. 9 8 is the basic configuration of a typical large standby auxiliary-power supply used in nuclear power plants. For a two-unit nuclear power station, a number of such large standby power sources sufficient to deliver as much as 20 MW when the normal auxiliary power is lost are required to maintain safe shutdown conditions or to provide power for the engineered safeguard auxiliaries during a loss-of-coolant accident.

The principles involved in the design and application of such power supplies are well known and are defined for nuclear power generating stations by standards* These principles or criteria are also applicable to the much smaller engine–generator units discussed elsewhere in this chapter.

9-4.5 A-C and D-C Drive Motors

The normal drive motor for a noninterruptible rotating power supply can be either induction or synchronous The choice is usually determined by the frequency requirement of the output generator. The standard a-c squirrel-cage induction motor is considered more reliable and can operate for a longer period with minimum maintenance. The slip rings and secondary excitation required by a synchronous motor require maintenance. However, brushless synchronous motors are available and approach the reliability of induction motors, although at a greater cost.

The a-c induction motor can accelerate a greater load from rest than a synchronous motor can accelerate. The induction motor can be designed to have a very low slip value and thus can provide an output speed as little as 1% below that of a synchronous motor.

Synchronous motors provide a constant output frequency with constant input frequency. If a brushless synchronous motor is used, it is necessary to furnish an external exciter with voltage control and an external out-of-step protective relay, these are not required by an induction motor. Usually a large synchronous motor, when used with a stored-energy flywheel, is required to accelerate the flywheel into step. Thus, when large flywheels are used for stored energy, a synchronous motor that has several times the horsepower needed to drive the load may be required. In addition to the higher initial cost of the larger motor, the motor would be running normally at light load with decreased efficiency

*See Vol 2, Chap 14

The emergency drive motor for a rotating noninterruptible power supply can be a standard d-c motor with the possible addition of auxiliary fields for speed control. Usually the motor can have an intermittent rating since its duration of operation is relatively short, being limited by the d-c battery source used. Because the characteristics of common loads and supply voltages vary, automatic speed-regulating equipment should be furnished as part of the motor control.

9-5 DESIGN OF POWER-SUPPLY SYSTEM

The following various combinations of the basic power-supply building blocks are representative of the power-supply systems in use. In any system different possibilities exist for improving one characteristic at the expense of others. However, the vast majority of practical systems incorporate the principles and characteristics represented by the power supplies described in this section.

9-5.1 Simple A-C/D-C System

The basic a-c/d-c system (Fig. 9.1) consists of a single voltage-regulating and harmonic-filtered stepdown transformer and a static rectifier This system is usually fed from the facility essential auxiliary-power buses and, of course, is subject to interruptions in the order of 15 sec before the large standby diesel generators can reestablish power to the essential buses At best the simple a-c/d-c system provides filtering and voltage regulation for noncritical instrumentation loads. When the system is required to supply only d-c power, the regulating transformer is usually incorporated within the static rectifier

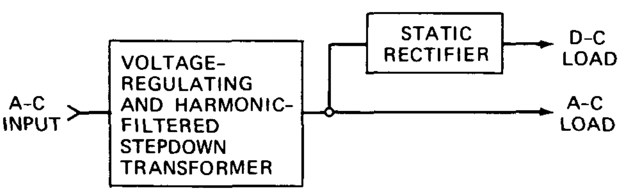

Fig 9.1—Simple a-c/d-c system

9-5.2 Rectifier–Battery System

The basic system (Fig. 9.2) consists of a static rectifier, a battery charger, and a battery. The normal d-c load is supplied from the rectifier. If the a-c line fails, the load is automatically transferred to the battery without interruption. Although the system is highly reliable, the capacity of the batteries limits the length of possible emergency operation. Of course, the system can only serve d-c loads

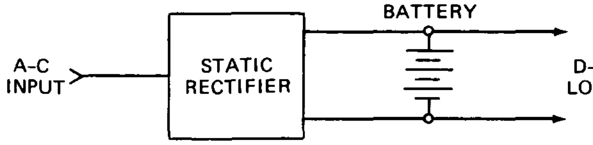

Fig. 9.2—System using static rectifier and battery.

9-5.3 Rectifier–Battery–Static Inverter Systems

(a) Basic Continuous-Inverter System. The basic continuous-inverter system (Fig 9.3) consists of a static rectifier, battery charger, battery, and static inverter The inverter carries the a-c load at all times Under normal

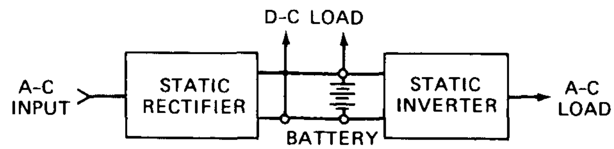

Fig. 9.3—Basic continuous-inverter system

circumstances the charger provides the d-c load plus the input to the inverter and floats the battery or recharges it as required. The charger in turn is fed from the plant auxiliary source of a-c power. If the plant auxiliary power fails, the inverter continues to run on the battery for a period of time dependent upon the reserve battery capacity. In this mode of operation, as long as the charger is functioning properly, there is no drain on the battery. Input current for the inverter is derived from the charger and does not pass through the battery. If the a-c line fails, the inverter drain is transferred to the battery without any interruption or disturbance in the inverter output Thus this simple system functions as a complete no-break backup power source Some capacitance is generally required in the input circuit of the inverter, and this provides a small amount of energy that, because there is a fast voltage regulator in the inverter, enables the system to handle the input transient from float voltage on the battery to discharge voltage without a significant transient in the output Loss of voltage on the input of the rectifier has no effect on the inverter output The advantages of this system are offset by the complete loss of power if the inverter fails. This disadvantage can be eliminated by using redundant equipment (see Fig 9 7)

(b) Continuous-Inverter System with Direct A-C Feed. The inverter system shown in Fig 9 4 is a more sophisticated version of the basic system shown in Fig 9 3 The normal a-c line feeds into the inverter directly at all times and is rectified. The resulting value of the d-c voltage is compared to the d-c voltage from the battery Solid-state circuitry within the inverter determines the highest d-c source, battery or rectified a-c line, and then inverts it to supply the a-c load. This is commonly referred to as

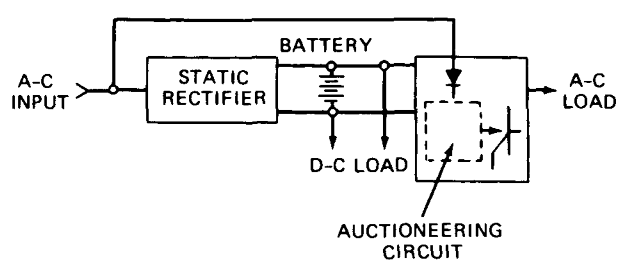

Fig. 9.4—Continuous-inverter system with direct a-c feed.

auctioneering. The internal transfer between the two sources of d-c power occurs instantaneously and is virtually undetectable. In this way the a-c load never sees the incoming a-c line, only the a-c output from the static inverter. Line synchronization problems, which are often a cause of difficulty (when external switching methods are used to effect the transfer between the inverter output and plant auxiliary a-c line), are avoided. Reliability is enhanced because there are no switching operations to cause transient voltages, and fewer critical components are needed The same result can be achieved by bringing the a-c line to the inverter through the battery charger (see Fig. 9.3), but then the battery charger must be large enough to handle the entire a-c load in addition to the d-c load and battery loads. This would necessarily increase system cost

Another inherent advantage of the system where the a-c line is fed into the inverter directly is built-in stabilization of line frequency and voltage Since the incoming a-c supply is rectified at once, input frequency is of little concern. The output oscillator of the inverter can have frequency stability to almost any accuracy desired, being only a function of inverter design The typical 60-Hz system maintains frequency to a tolerance of ±1.0%. The addition of an oscillator standard in the inverter can reduce the variation in output frequency to ±0.01%. The input frequency does not necessarily have to define the inverter output frequency, and therefore the same power supply can be used for frequency conversion. Similarly, phase changing can also be accomplished since the number of phases in does not determine the number of phases out

(c) Continuous-Inverter System with Electromechanical Transfer Switch. In certain applications it is desirable to feed the a-c load from a source other than the inverter This can be accomplished by switching from inverter to line (see Fig 9.5) or switching from line to inverter The two methods differ in the length of interruption of a-c power to the load and should be used where short-term interruptions can be tolerated. Conventional transfer switches are used and are generally supplied as electrically held, mechanically interlocked contactors. In the commoner mode of operation, the inverter is considered as the normal source The inverter carries the a-c load until it is manually transferred by an operator or until an inverter failure occurs The chief advantage of this arrangement is that the inverter failure rate is substantially lower than that of the plant auxiliary-power source. Thus transfers occur substantially less often than they would if the a-c line were considered the normal source. Since the inverter is operating continuously, there is assurance that both sources are available as long as the a-c line is present

A disadvantage of the inverter-to-line switching mode of operation is that the charger must have sufficient capacity not only to feed any d-c loads and recharge the battery but also to supply the input current to the inverter. In the alternate arrangement, where the plant auxiliary a-c line is considered the normal source and transfers are made to the inverter on-line failure, the charger capacity need only be sufficiently greater to recharge the battery and feed any d-c loads

In most transfer arrangements of this type, a delay is provided to prevent the emergency from transferring to the normal source after an outage until the normal source has been present for some period of time This time interval ranges from a few seconds to as much as several minutes, depending on the application

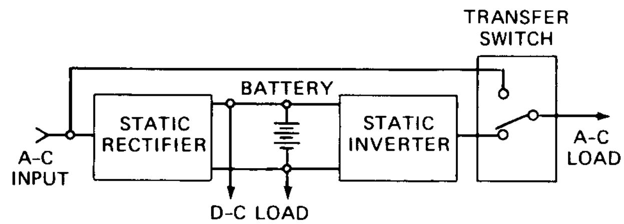

Fig 9 5—Continuous-inverter system with electromechanical transfer switch.

With standard contactors operated in a conventional manner, outage times on transfer are of the order of 0 1 sec. The outage time depends primarily on the time for failure sensing and transfer of the contactor In switching from line to inverter, however, an additional period of reduced output voltage is caused by the response of the inverter to a step-load change. For most commercially available inverters, the time to respond to a full-load step change is less than 0.04 sec Because of the relatively long transfer time, it is generally not necessary for the inverter to be synchronized in phase with the a-c power line Frequency synchronization may be desirable where the inverter carries the load continuously to keep certain classes of loads, such as clocks and chart drives, in step with local time.

In certain applications the transfer from normal to emergency a-c power source need not be automatic By substituting a make-before-break manual transfer switch for the automatic transfer switch indicated in Fig 9.5, the load can be successfully removed from the inverter without loss of potential The manual make-before-break transfer is an inexpensive concept of switching to the plant auxiliary source of power while still maintaining the continuity of power flow to the load. This system suffers the same problems as the system shown in Fig 9.5 The load experiences complete loss of power should the inverter fail (One could, however, manually transfer to the plant auxiliary a-c source after detection of the inverter failure)

(d) Continuous-Inverter System with High-Speed Transfer Switch. In certain cases extremely sensitive a-c instrumentation and control systems cannot tolerate the finite outage time given by the transfer arrangement of Fig. 9.5. The system shown in Fig. 9.6 uses special transfer-switch drive circuitry that allows transfer to be effected in less than 1 cycle, or 0.016 sec, in a standard 60-Hz system. Depending on the sensitivity of the sensing circuitry and

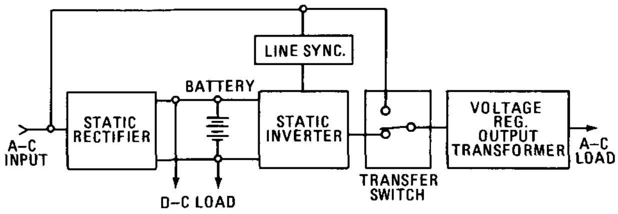

Fig. 9.6—Continuous-inverter system with high-speed transfer switch.

the size of the transfer switch, transfer times below 0.008 sec can be obtained. In all short-time transfer schemes, special attention must be given to line-phase synchronization and transformer saturations.

Because of the short transfer time, the inverter must be operated in phase synchronism with the commercial power line. It must also be recognized that the transfer time from line to inverter is increased by the load response time of the inverter. For these reasons it is generally preferable to use the inverter as the normal source of power and transfer to the line only if an inverter fails. Retransfer, after correction of the inverter failure, can be made either by allowing for the increased transfer time or by providing an auxiliary manual make-before-break switch which momentarily parallels the inverter output with the plant auxiliary-power system on retransfer.

To achieve a high-speed transfer, the sensing circuit must detect departure of the source from its standard value in periods as short as a millisecond. Most plant auxiliary-power systems experience short-term transients. It is extremely difficult to design transfer-sensing circuits that avoid transferring on a momentary line transient that is not necessarily followed by a complete line failure. The inverter output is relatively free of such spikes unless they are generated by the load, and therefore the likelihood of false transfer is avoided when operating with the inverter as the normal source. However, most inverters have a current-limited output characteristic; so any overload exceeding the output capability of the inverter is regarded as a failure and causes transfer to the plant auxiliary-power system.

In several available commercial systems of the type shown in Fig. 9.6, the high-speed electromechanical transfer switch is replaced by a solid-state silicon-controlled rectifier (SCR) a-c switch. The advantages gained include a decrease in transfer time down to 0.002 sec or less and, since the switch has no moving parts, a virtual elimination of maintenance requirements. A disadvantage is that the static transfer switch does not provide the same degree of positive isolation from the plant auxiliary system as does the mechanical transfer switch. Therefore, in a situation where a plant auxiliary-power-system failure is accompanied by a high-voltage transient, the static switch could fail and cause a complete system breakdown involving both a portion of the plant auxiliary power and the inverter. An important consideration when assessing the relative merits of a static vs. electromechanical transfer switch is that the inverter response time must be added to the transfer time when transferring from line to inverter.

The system shown in Fig. 9.6 uses the stored energy of the output transformer to overcome the relatively slow response of the inverter and provides improved transfer-time characteristics. By transferring on the primary of the ferroresonant output transformer with a high-speed transfer switch, one can achieve transfer times in the range of 0.008 to 0.016 sec. Because of the stored energy in the output transformer, there is no interruption of supply to the load during the transfer period. As previously mentioned, the inverter must be operated in phase synchronism with the plant auxiliary-power system to effect the desired uninterrupted transfer.

The system indicated in Fig. 9.6 requires the inverter to be the normal source of power. Several advantages result from this mode of operation. The frequency of transfer during operation is substantially reduced since the inverter output is comparatively clean. During plant-auxiliary-power-system fault conditions, when transfers from the line normally take place, the plant auxiliary power is characterized by erratic phase shifts and voltage excursions, and, if the transfer from source to inverter is to be successful at these times, the inverter must be maintained in phase with the faulted line. It is questionable if the inverter could respond properly to this mode of operation. Either the transfer would be made out of phase or the inverter would malfunction. In addition, the voltage transients characterized by the failing a-c line may make clearing of the transfer-switch contacts difficult. For example, a sufficiently large voltage transient on the line prior to switching could cause an arc to persist in the opening contact of the transfer switch for more than 0.008 sec. Since this would, in essence, short the inverter output to the failing line, an inverter malfunction would be likely. Using the inverter as the normal source avoids these undesirable possibilities.

(e) Continuous-Inverter System with Redundant Inverter and Transfer Switch. In the systems shown in Figs. 9.5 and 9.6, the switching is from the inverter back to the commercial a-c line to provide a backup source of power. The system shown in Fig. 9.7 represents a significant improvement with respect to isolation from the plant auxiliary a-c line. During normal operation both of the inverters are operated in parallel and are sized so that either could carry the entire a-c load. The two inverters are connected through normally closed transfer switches to the common a-c load. The logic and synchronizing circuits ensure that under all circumstances the inverters are operating in phase synchronism with each other and with the commercial a-c line if required. As long as both units are operating in phase with each other, the load is shared. Should either inverter fail, by either a reduction in output voltage or a shift in phase, the logic circuit disconnects the faulty inverter from the system, thereby transferring the entire load to the remaining inverter. The transfer switch

need not operate with extreme rapidity since the surviving inverter can drive the output transformer of the failing inverter without adverse effects. The failure of either inverter would cause some load disturbance attributable to

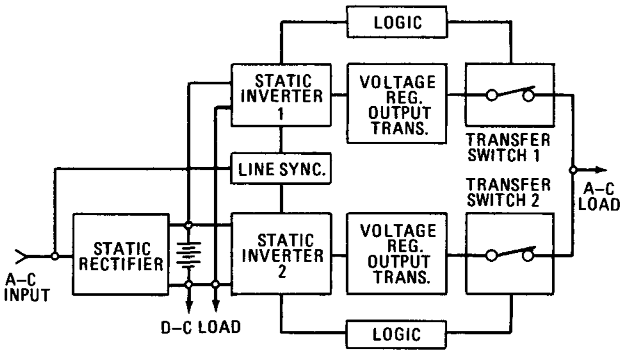

Fig. 9.7—Continuous-inverter system with redundant inverter and transfer switch.

the response of the surviving inverter to the 50% step-load increase (assuming each inverter to be normally 50% loaded). The overall output performance of this system is, therefore, essentially identical to that of the system represented by Fig. 9.6. The principal advantage is that both sources of power can be considered extremely reliable. Since there is no connection to the commercial power line except that provided by the charger, the possibility of introducing large voltage transients from external sources is minimal.

It is important to realize there is a substantial increase in cost as the complexity of the transfer circuits is increased. The transfer-circuit complexity increases as the permissible load-interruption time decreases. Usually the power source for the instrumentation and control system in a nuclear reactor facility is only one part of a larger system. In fact, because redundancy is necessary in the instrumentation and control system, several separate isolated power systems may be required. Therefore, in overall operation an inverter failure may be indistinguishable from a failure in a portion of the instrumentation and control system that the inverter feeds. In such circumstances justification of an elaborate (and expensive) power supply must take into account that the additional cost might better be used to improve some part of the system other than the power source.

9-5.4 Generator and Internal-Combustion-Engine System

In the system using a generator and an internal-combustion engine (Fig. 9.8), the normal flow of power is from the plant auxiliary a-c system. If the commercial power fails, the internal-combustion engine is started. As soon as the proper voltage and frequency are established at the generator terminals, the transfer switch connects the load to the generator. This system is widely used in nuclear power plants as the emergency auxiliary-power source. The main disadvantage of this system is that the load is interrupted for the time interval required to start the engine and transfer the load to the generator; typically this is 10 to 15 sec.

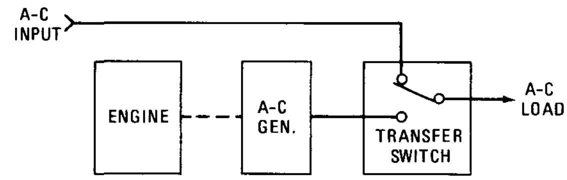

Fig. 9.8—System using generator and internal-combustion engine.

The system shown in Fig. 9.8 can be modified so that the generator will float across the line by being driven continuously by the engine. Whenever the normal a-c source failed, the generator would deliver power immediately without interruption. With this scheme the engine starting period is eliminated. However, the engine runs constantly, and transients are present on the line when switching. Power directional relays and synchronizing equipment are required for proper operation of the transfer switch. Since the engine is running continuously, increased maintenance and operating costs are involved. This is a distinct disadvantage.

9-5.5 Synchronous Motor-Generator–Flywheel–Clutch–Internal-Combustion-Engine Systems

(a) Nonisolated System. In the nonisolated system shown in Fig. 9.9, the critical load is normally fed directly from the plant auxiliary a-c power system in parallel with a synchronous machine operating as a motor driving a flywheel. Whenever normal plant auxiliary power is interrupted or a frequency or voltage anomaly in excess of preset tolerances is experienced, the synchronous motor

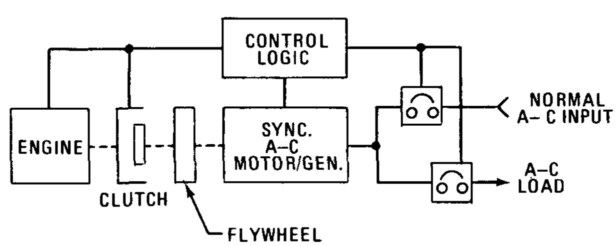

Fig. 9.9—Nonisolated system using synchronous a-c motor and generator, stored-energy flywheel, clutch, and internal-combustion engine.

and critical bus are disconnected from the system. The synchronous motor instantaneously converts to generator operation to supply the critical bus with interim power, with the stored energy of the flywheel being transferred to

drive the generator. The engine, when furnished, would simultaneously be started and then connected to the load when it is up to speed. The engine is recommended only for those systems requiring operating time, after plant auxiliary-power failure, in excess of the stored-energy capability of the flywheel.

Under fault conditions this type of system is subject to a power dip during the time required to isolate the critical a-c load from the plant auxiliary source In addition, since the critical load is normally fed from the plant auxiliary source, it is subjected to any transients occurring on that system. At best this system (with the engine) is justified only where the plant auxiliary source is very unreliable.

(b) Isolated System. The isolated system shown in Fig 9.10 offers a significant improvement over the nonisolated system (Fig. 9.9) in that complete isolation from the plant auxiliary source is obtained. The system consists of a synchronous motor with a stored-energy flywheel unit, which is fed from the plant auxiliary source and drives a synchronous generator that feeds the critical bus A standby engine is used whenever the duration of the outage exceeds the capability of the inertial unit. During normal operation voltage- and frequency-sensing devices monitor the incoming power line for variations beyond acceptable limits.

Should an unacceptably large voltage or frequency excursion occur, the synchronous motor is disconnected from the plant auxiliary-power source, and the stored energy in the flywheel is used to drive the synchronous generator. The standby engine, if furnished, is simultaneously started and brought up to synchronous speed in about 10 to 60 sec, depending on the stored-energy content of the flywheel, at which time the engine is connected to the generator shaft by the magnetic clutch. The frequency stability under engine operation is maintained by a highly sensitive load- and frequency-sensing governor that closely controls the speed of the engine. Should the voltage and frequency of the plant auxiliary power return to acceptable values and remain for a preset time period, the synchronous motor is synchronized to the source, the clutch is deenergized, and the engine is returned to standby condition.

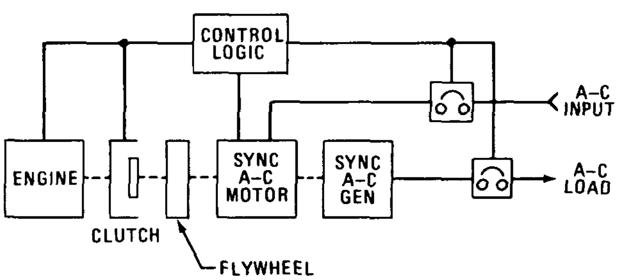

Fig. 9.10—Isolated system using synchronous a-c motor and generator, stored-energy flywheel, clutch, and internal-combustion engine.

On loss of plant auxiliary power, the system begins to draw energy from the flywheel and causes it to lose speed. Since the frequency is directly related to the speed of the flywheel-driven motor–generator unit, the frequency is soon reduced to a value below an acceptable limit to the critical bus.

The overall frequency regulation of this system is equal to that of the plant auxiliary-power system.

9-5.6 Induction Motor-Generator–Stored-Energy Eddy-Current-Coupling–Internal-Combustion-Engine System

In normal operation of the system (Fig 9.11), an induction motor drives a flywheel at a higher speed than the speed of the generator shaft. The induction motor–flywheel system is coupled to the generator shaft through an eddy-current coupling. The variable slip provided by the coupling allows the generator to be maintained at synchronous speed under all normal load conditions (see Sec. 9-4.3). When the frequency or voltage of the plant auxiliary-power system deviates from preset limits, it is interrupted. Through the use of speed sensing and slip control of the eddy-current coupling, the generator is maintained at synchronous speed as the flywheel speed drops to that approaching the generator synchronous speed. Simultaneously, the incoming plant auxiliary-power system voltage- and frequency-sensing relays determine whether a momentary transient or a complete loss of power has occurred. At a predetermined flywheel speed, the standby engine is started and brought up to speed, but it is not connected to the system at this time. If the speed of the flywheel continues to drop and reaches a preset minimum value prior to the return of the plant auxiliary-power system, the engine is connected to the system by energizing the magnetic clutch. The energy storage capability of this system varies between 10 sec and a maximum of approximately 2 min. If the allowable outage time for which protection is desired is less than 2 min, the engine standby unit can be eliminated.

This system gives excellent results in speed control, output voltage, and frequency regulation, and, when combined with the engine backup, it is able to operate for extended periods of time. However, eddy-current-coupling

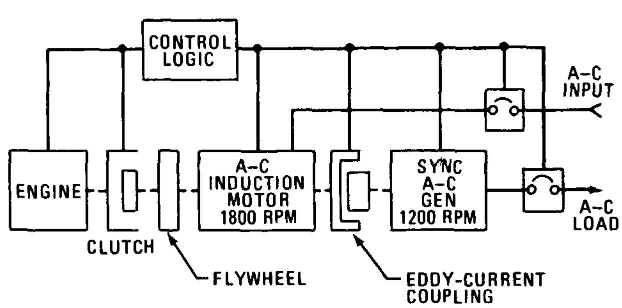

Fig. 9.11—System using induction motor, synchronous generator, stored-energy flywheel, eddy-current coupling, and internal-combustion engine.

systems are inefficient and generate considerable heat that has to be dissipated. Other disadvantages include high maintenance cost and, when combined with an engine backup, the requirement for fuel storage, exhaust ventilation, and scheduled exercising

9-5 7 Synchronous Motor-Generator—Stored-Energy Eddy-Current-Coupling—Internal-Combustion-Engine System

This system (Fig 9.12) consists of a synchronous motor, fed from the utility power system, which drives a synchronous generator, which, in turn, feeds the critical a-c load. Simultaneously, a small induction motor is driving a flywheel at a speed considerably in excess of the synchronous generator speed. The flywheel is not coupled to the generator under normal operation since the eddy current coupling between the generator and flywheel is not energized. When an unacceptable excursion in voltage or frequency occurs on the plant auxiliary-power system, the power-source feed is disconnected and the eddy-current coupling is energized, thereby coupling the flywheel to the generator. The stored energy of the flywheel then serves to drive the generator at synchronous speed in the same manner as described for the system shown in Fig 9 11 The present system (Fig 9 12), by excluding the eddy-current coupling from being energized during normal operation, operates at a much greater efficiency than the system shown in Fig. 9.11.

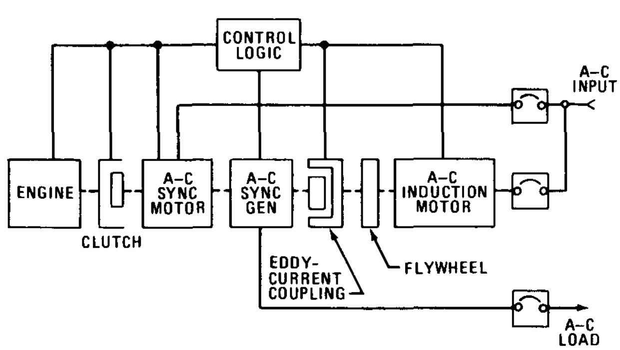

Fig. 9.12—System using synchronous motor-generator, induction motor, stored-energy flywheel, eddy-current coupling, and internal-combustion engine.

With the exception of improved efficiency, this system has the same characteristics as the system described in Sec 9-5 6, and, in addition, the frequency excursion of the generator output during transfer from normal utility supply to flywheel operation may exceed acceptable limits

9-5.8 Battery-Supported Motor-Generator Isolated Systems

(a) Motor-Generator—Motor-Battery System In the normal operation of the isolated system (Fig. 9.13), an a-c motor, fed from the plant auxiliary-power system, drives an a-c generator, which, in turn, feeds the critical a-c load. In addition, a second in-line d-c motor, normally floating on the battery system, is instantaneously available to drive the system if the plant auxiliary-power system fails This system suffers from the ills common to all systems with rotating equipment, including increased maintenance and wear, when compared to static systems In addition, the duration of operation after the failure of the utility source is limited by the battery capacity

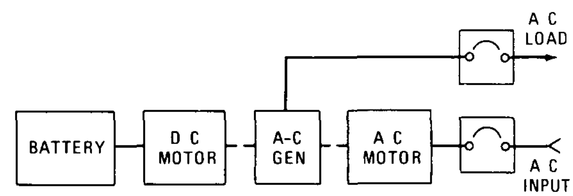

Fig. 9.13—System using motor-generator and motor and battery.

(b) Static Rectifier—Motor-Generator—Battery System. During normal operation of the system (Fig 9 14), utility-line power is rectified and applied to the d c motor that drives the a-c generator supplying power to the critical a-c load. The rectifier is sized to accommodate any normal d-c load in addition to the power required by the d-c motor and the power needed to maintain the battery at full charge. On failure of the plant auxiliary-power system, the d-c motor is supplied with power from the batteries, thereby maintaining the continuity of the a-c generator

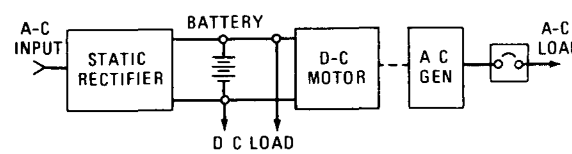

Fig. 9 14—System using static rectifier, motor, generator, and battery

prime mover. The length of emergency operation is limited by the capacity of the battery. Adding a backup internal-combustion engine to drive the generator directly would, of course, greatly extend the length of emergency operation.

The base system affords satisfactory operation during short-term transients because of the extremely effective filtering action of the battery and motor—generator combination.

9-6 CONCLUSIONS

The material of this chapter aids in selecting and specifying high-reliability power sources Only the major electrical systems have been discussed because they are the most commonly used in nuclear power reactor plants.

In determining which type of system is best, an important aspect is responsibility. A given system may be designed and specified and the component parts purchased

and assembled by the purchaser The purchaser thereby assumes the responsibility for satisfactory system operation.

An alternative procedure, and one that usually guarantees satisfactory results, is to specify the required parameters of the power source The system supplier then submits a quotation and assumes the responsibility for system operation to meet the specifications This latter procedure is recommended.

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Chapter 10

Installation of Instrumentation Systems

R. James Hall, Jerry J Engel, Gordon W. Young, and R. W. Madsen

CHAPTER CONTENTS

10-1 INTRODUCTION

The designers and constructors of the first nuclear power plants generally followed installation practices already established for conventional process and chemical

industries Adapting process instrumentation systems to nuclear power plants was reasonably successful However, nuclear radiation systems had no conventional counterparts During installation and preoperational tests in nuclear power plants, noise problems were found to be commonplace, and extensive modifications to the signal, control, power, and ground cables were required before nuclear radiation instrumentation systems could satisfy the established safety criteria

Since the nuclear power plants being built today involve many different geometric configurations and a number of different basic materials, it is impractical to recommend a standard installation for all plants However, the material presented here should provide engineers in the design and construction fields with a set of installation practices that will enable them to avoid many problems and pitfalls

10-2 REACTOR INSTRUMENTATION SYSTEMS

10-2.1 Control Room

The control room in a nuclear power plant has many features in common with fossil-fueled generating stations Many practices developed in fossil-fueled plants are directly applicable to nuclear plants

The control room should be designed and installed so that it can be safely operated and occupied under any external hazard condition, such as fire, smoke, contaminated atmosphere, flood, seismic disturbance, or major electrical fault

An acceptable nuclear power-plant control-room installation requires not only that equipment and components be integrated into a compatible system capable of the necessary overall performance but also that the human operator and his relation to this equipment be considered If the man—machine relation is to provide maximum efficiency in operation, human factors must be considered as part of the initial engineering criteria The control console and panel must be arranged so the reactor can be operated in a reliable manner with a minimum number of personnel

Good design and installation practices dictate that all important variables in the plant operation be available for display and control in the station control room Variables associated with reactor and heat transfer control are generally installed on the main control console Variables associated with the auxiliary equipment, such as the turbine and generator control, electric switchgear control, and several process-instrumentation control systems, are usually installed on the control panel

A representative control-room installation is shown in Fig 10 1 A plan view of this control room is shown in Fig 10 2

10-2.2 Control Console

The wraparound control console is widely accepted by the nuclear industry The console shown in Fig 10 1 is one example of good installation practices The accessibility to instruments, switches, controls, and terminal boards at the rear of the console is excellent The console is installed on a base structure that provides a step-down passageway behind the terminal boards and termination points at the rear of the control console Access to this passageway is through the rear doors of the console The passageway is wide enough to accommodate important test equipment, such as oscilloscopes

In some nuclear power plant installations the main control console is incorporated into and made an integral part of the vertical control board (see Sec 10-2 3) Accessibility to instruments, switches, and controls is made at the rear of the vertical control board

The following practices, based on observations of control consoles in several nuclear plants and on experience in nuclear-plant maintenance, are recommended

1 Accessibility to the rear of the console must be provided for maintenance and test

2 All field cabling coming into the control console and cabinets must be brought through a suitable dust seal, such as a penetration sealed by a compound This provision will help to maintain the control room at a slightly higher pressure than ambient to prevent such hazards as fire, smoke, and noxious fumes from spreading into the control center

3 Access must be provided to all components and electrical connections to facilitate maintenance (see also Sec 10 4)

10-2.3 Control and Monitoring Panels and Cabinets

The control panel is referred to as the "control board" or "vertical board" in the electric utility industry A variety of control instruments, recorders, indicators, meters, dials, and knobs are installed on the control panels The more familiar instrument systems include (1) switchgear and substation control, (2) turbine and generator control, (3) critical-temperature measuring recorders and scanners, (4) process instruments for controlling and monitoring critical pumps and valves in the auxiliary heat transfer loops, (5) emergency shutdown and monitoring for water reactors, (6) water treatment, and (7) annunciator alarm windows for all control panels involved The neutron-monitoring instrumentation cabinets and drawers and the radiation-monitoring system may be installed as part of the control panel or in separate cabinets

The depth of a control panel should be no more than required for easy access to all terminals and components at the rear Avoid stacking instruments and conduit boxes behind panel board instruments at the rear of the control panels It limits access to terminals and components at the rear of the panels and can adversely affect the safety of plant operation

Field cables entering the control panels either from floor conduits or from overhead trays should be bundled

Fig. 10.1—Control room of the San Onofre nuclear generating station.

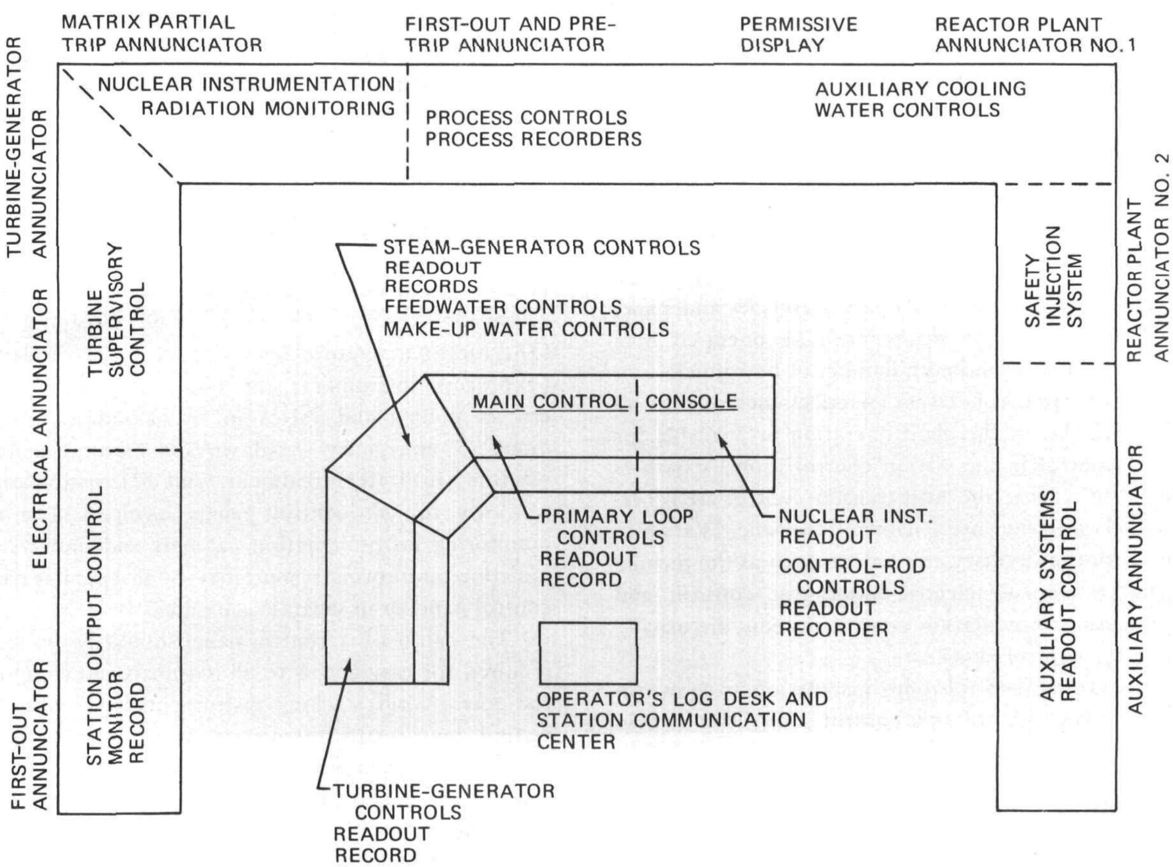


Fig. 10.2—Plan view of the control room at the San Onofre nuclear generating station.

and installed in a manner that will not inhibit access to any instruments, components, controls, or termination points at the rear of the control panel The installation of racks and cabinets is discussed in Sec 10-3

Graphic panel installations already generally accepted for control in fossil-fueled power plants are being used in nuclear power plants, particularly for generator output bus, switch gear, substations, and heat-transfer systems Opinions differ as to the effectiveness of graphic panels since the plant operator gets accustomed to the control knobs, lights, indicators, etc (see Sec 10-6) However, a survey of operating personnel in several generating plants revealed a decisive preference for graphic panels in the central control room

10-2.4 Nuclear-Instrument Systems

Slide out drawers containing electronic circuits which are housed in some modular arrangement have been accepted as a standard for nuclear industry Either a Nuclear Instrument Module System (NIMS) bin configuration is used or modules are removed from the top of the chassis The installation and interfacing of nuclear instruments with the control and signal cabling coming into the cabinet must be done properly

Very serious operating problems will affect the performance of the nuclear instrument channels if there is improper installation and bundling of critical coaxial, triaxial, and multiconductor cables Cables that are improperly installed frequently break off after they have been flexed a few times, causing open circuits Adherence to the following practices will reduce this problem

1 Avoid supporting a cable, wire, or bundle of wires by the terminal point Good engineering practice provides a solid support fastened to the cable, wire, or bundle such that there is no stress on the terminal Support as much of the cable length as possible by such mechanical means as cable retractors and springs

2 Avoid using a single-point support Distribute the support points over as wide an area as possible

3 Mount the cable, wire, or bundle so that kinks do not develop Use mechanical stiffening, such as nylon spiral wrap, wherever possible to prevent sharp bends

10-2.5 Plant-Protection-System Cabinets

Cabinets for the plant protection system contain relays, solid state devices, and other components that make up the logic circuits of the plant protection system The plant protection system should be totally enclosed, either the cabinets themselves or the area in which open cabinets are located

The equipment should be designed so that any component can be replaced or repaired without disturbing any other component Relays and other remotely operated equipment should be accessible for authorized maintenance and troubleshooting and protected against unauthorized access Each component should be clearly marked to prevent a mistake in identification

The cabinet terminal blocks, used to interface the field wiring to the cabinet wiring, should be accessible to the incoming cables as well as to the internal wiring The wiring on the terminal block should be arranged so that the internal wiring is terminated on one side of the terminal block and the field wiring on the other side

Terminal blocks that do not contain field wires may utilize both sides of the terminal block for internal wiring, particularly where it is convenient to install a series of shorting bars In installations where more than one row of terminal blocks is used, the internal wiring should be terminated on the terminals facing a common space between the terminal blocks, thereby leaving a space common to two rows of terminal blocks for the incoming cable terminations

All terminal blocks installed in the plant-protection-system cabinets should be clearly identified by both block and terminal point

10-3 INSTRUMENT RACKS AND CABINETS

10-3.1 Instrument-Rack Structure

The instrument-rack structure is defined, for the purposes of this chapter, as a structure in which the components of an instrument system are mounted This structure may be a completely enclosed cabinet with the components mounted inside the enclosure or a panel with the components mounted in a cutout in the face of the panel It may be a rack used to mount and support the equipment but which does not function as an enclosure for the components

(a) Structural Materials The structural materials used in an instrument-rack structure must have sufficient strength to support all equipment mounted in the structure Steel and aluminum, the materials most used for panel structures, are easily worked and readily available The thickness of the structural material used for the front panel depends on the type and weight of the instruments being installed, the structural material used, and the panel design Stiffening members may be required, however, they must not limit access to instruments and terminal points at the rear of the panels

Since instrument systems are generally assembled at a vendor's plant rather than at the location where the system is to be used, the instrument rack structure must have sufficient strength to allow the handling of the structure with all the equipment mounted Lifting eyes should be provided to permit moving completed rack assemblies

(b) Standard Modular Enclosures Modular enclosures are made by several manufacturers to meet the requirements of both stationary and mobile instrumentation systems They are designed to conform to an industry

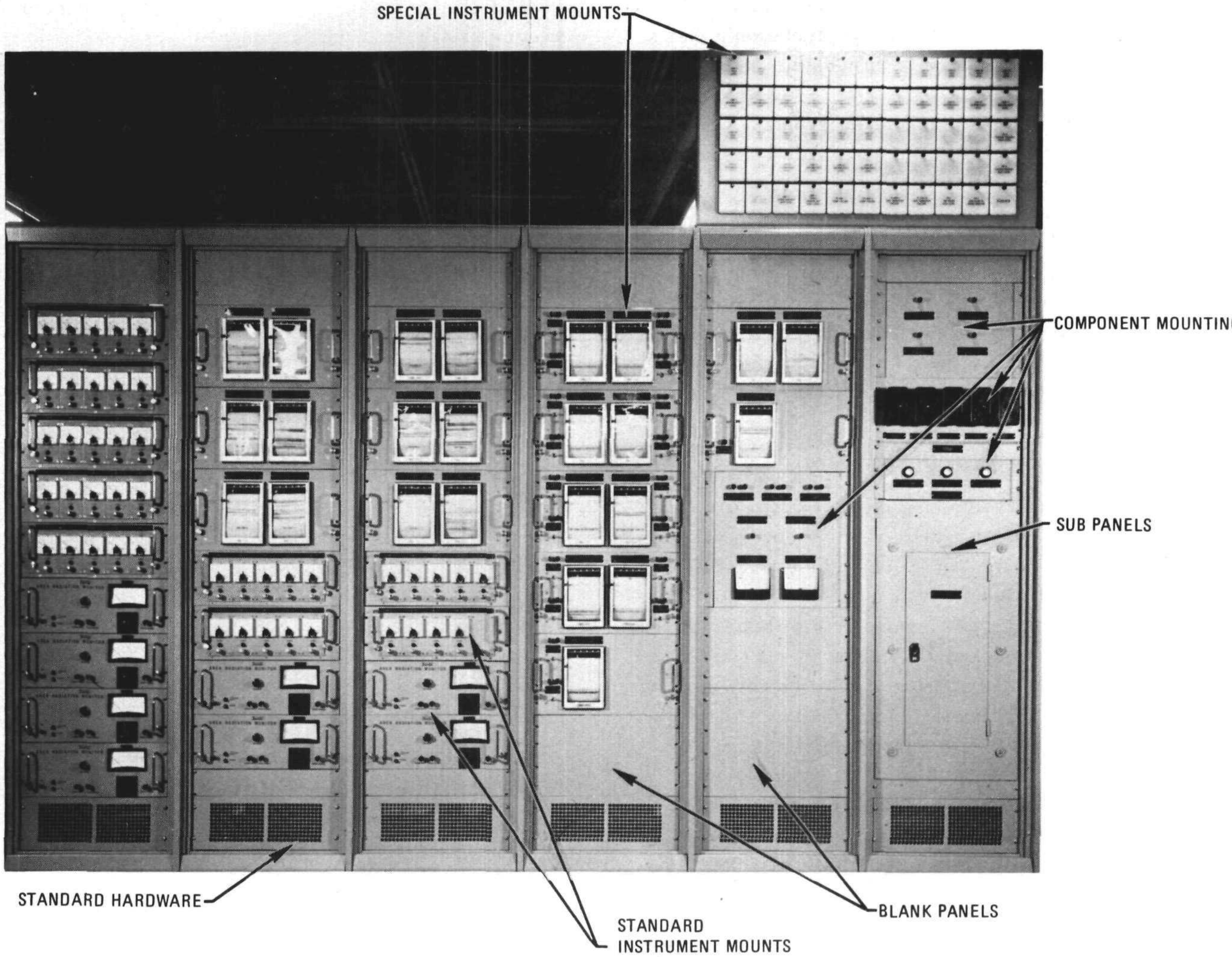


Fig. 10.3—Installation practices for standard modular enclosures. Note the flexibility of the panel configuration.

standard, such as the Electronic Industries Association* (EIA) Mounting Standards, thus eliminating by the standardization of parts the need for many special mounting devices. Because of the modular design, a series arrangement of almost any configuration can be developed. Manufacturers of modular enclosures also make many special features and accessories for the enclosures, such as radio-frequency interference (RFI) shielding, equipment-cooling blowers, and special enclosure trims.

Modular enclosures allow flexibility in panel configuration and equipment layout (see Fig. 10.3).

(c) Mounting Practices. Instrument cabinets are generally designed to be free-standing structures which may or may not be fully enclosed. Instrument cabinets that are stationary are mounted on bases or curbs. The bases or curbs are either steel or concrete and are designed so that the instrument structure with all the equipment installed can be placed on them and attached and held in place by bolts or clamps.

A general practice is to provide each rack group with a fabricated, 3- to 5-in. channel iron base. This allows for easy mounting to curbs with bolts and clamps sufficiently strong to withstand nominal seismic forces.

10-3.2 Fabrication and Assembly

(a) Mounting Major System Components. Each instrument and piece of equipment in the instrument-rack structure should be mounted, wired, or piped, where possible, so it can be removed without interruption of service to adjacent instruments and equipment. The instruments and equipment should be located and mounted so all wiring terminals and piping connections are readily accessible (see Fig. 10.4).

(b) Mounting Electrical Equipment and Hardware. The electrical equipment and hardware, as well as the installation of these items, should conform to some standard, such as the National Electrical Code. The ambient conditions at

*EIA headquarters are located at 2001 Eye St., N.W., Washington, D. C.

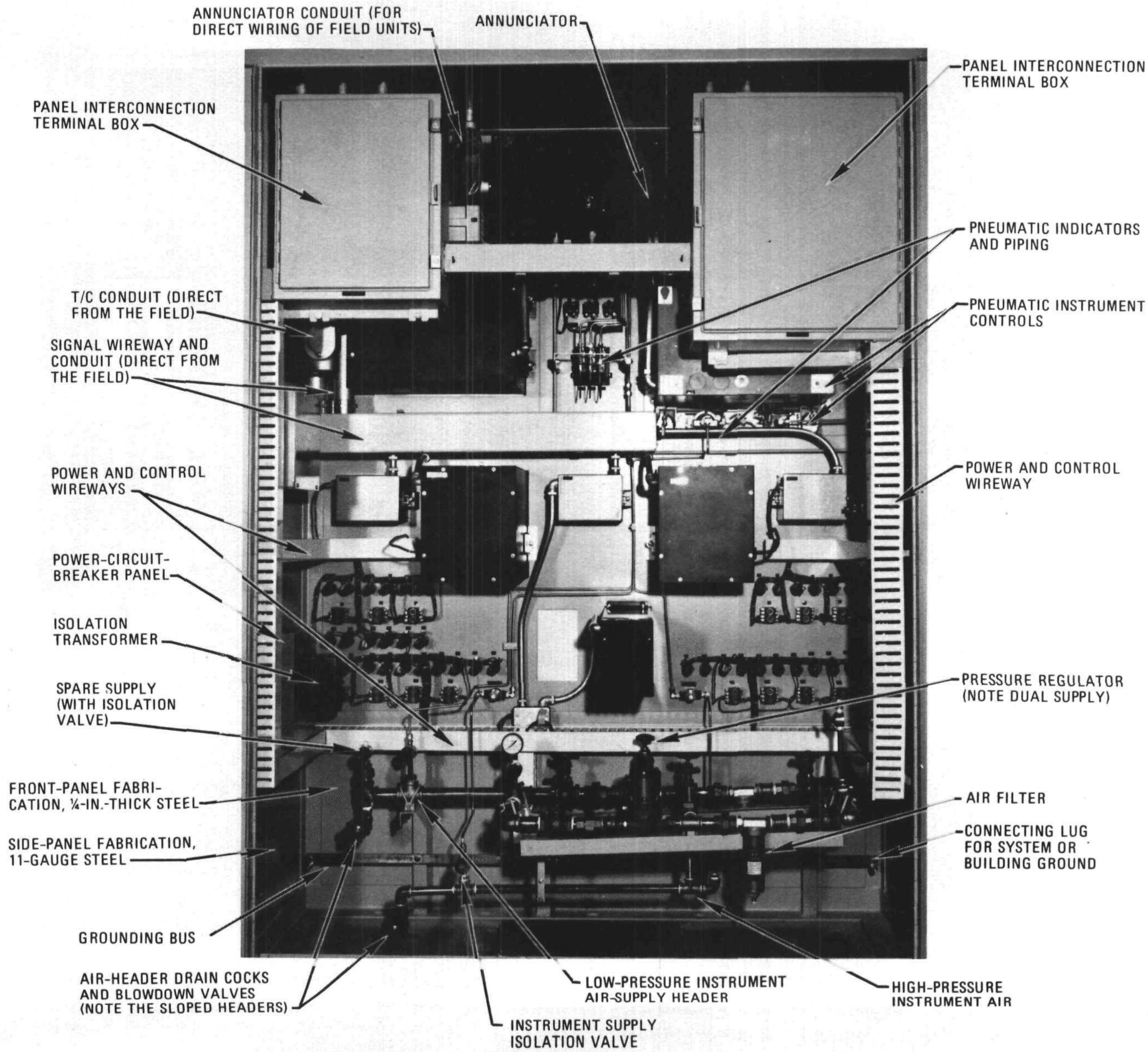


Fig. 10.4—Installation practices for major system components.

the location where the system is to operate and the type of system will determine which sections of the electrical code are applicable.

Terminal Blocks. Terminal blocks are arranged so that one side of each block is reserved for field connections (see Fig. 10.5). Spare terminals (10% minimum) should be provided for future use and should be distributed throughout the terminal blocks. Where a field cable may fill all the spaces on a terminal block, the spares requirement should be overruled to prevent the need for splitting the cable between two terminal blocks. Terminal blocks should be located in the panels and cabinets to facilitate maintenance and testing without impairing access to other equipment mounted in the structure. Terminal blocks and terminal points should be identified and labeled.

Wiring Installation in Panels and Cabinets. The wire used for power distribution in the instrument cabinets should be adequate to carry the current used by the circuit. Design and installation engineers must adhere to the National Electrical Code in sizing wire for power-distribution circuits. No wire smaller than No. 14 American Wire Gauge (AWG) should be used in power-distribution circuits. Control circuits with less than 5 amp of maximum operating current may use No. 16 AWG copper wire. Wire sizes smaller than No. 16 AWG could handle the current requirement of most control circuits; however, mechanical strength becomes an overriding consideration, and these wires are not recommended for installation in panels and cabinets.

Architect–engineers and reactor designers have specified both stranded and solid wires for instrumentation and

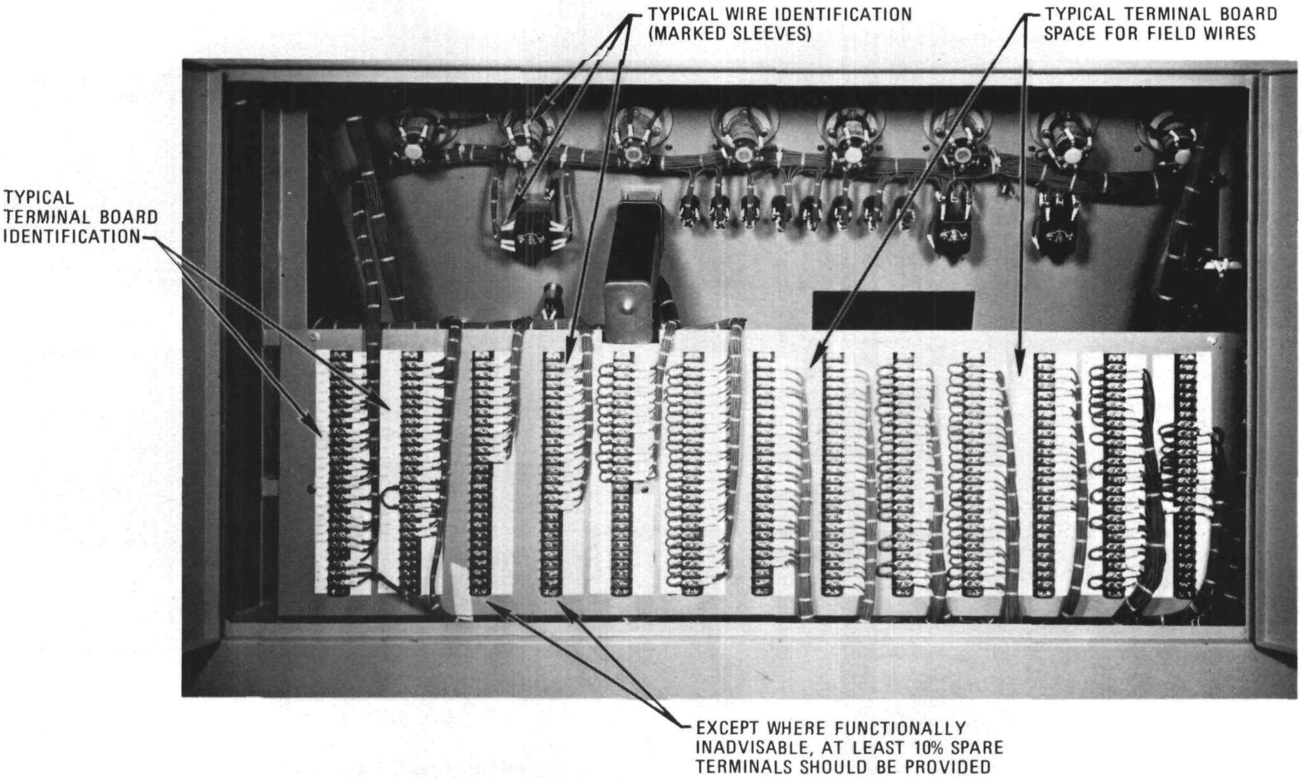


Fig. 10.5—Installation practices for terminal blocks.

control applications in nuclear plants. For power and control circuits, stranded wire is preferred and is much more widely used than solid wire. The flexibility of stranded wire facilitates installation and maintenance. Either stranded or solid wire can be used without affecting the electrical characteristics or performance of the circuit.

All wiring should have a minimum of 600-volt insulation and should be resistant to heat, oil, moisture, flame, and corrosive vapors. Insulation materials have been developed which meet the requirements for switchboard and control-panel wiring without requiring braid or fibrous coverings. This results in a smaller overall diameter with fewer stripping and terminating problems.

All wiring connections in the instrument panels and cabinets should be made with preinsulated compression-type terminals unless a solder connection is required. For solder connections, insulated sleeves should be used to snugly cover the finished solder joint.

Wires entering or leaving the instrument cabinet should be terminated in terminal boxes to facilitate maintenance. However, some wires, such as coaxial, triaxial, and thermocouple lead wires, should be terminated through appropriate connectors directly to the instruments or thermocouple junction boxes.

Multiconductor or twisted-pair shielded cable should be used for analog signals (low-level, millivolt or milliampere) in instrumentation circuits. Wire no smaller than No. 18 AWG is recommended to minimize wire breakage during installation. Each conductor and the outer jacket or sheath of the shielded cable should have a flame-resistant insulation. The shield is carried as a separate conductor at all cable junction points.

The signal wires are run in wireways separate from the control and power wiring to minimize noise pickup in signal wiring. Separate terminal boxes are recommended for the signal and the power wiring. Lacing of low-level signal cables into bundles with power or control wiring should be avoided. Wiring in the instrument racks should not be spliced; each wire should run unbroken from terminal to terminal.

Wiring between panel-mounted instruments and terminal boxes should be grouped in a neat and orderly manner and run in enclosed metal wireways. Exposed wiring should be laced or bundled together with lacing, tie straps, or similar means.

Each wire should be properly identified. There are several coding or identification methods, such as nonconductive markers, color-coding the wires, and providing label identifications on the terminal blocks. Proper identification facilitates testing and maintenance. Wiring identification should correspond to that shown on the elementary and connection diagrams.

Terminations. The termination of conductors, whether they carry low-current signals or high-current power, is an important part of installation. Whether the termination is made by a simple "crimp-on" lug or a complex triaxial connector, good workmanship is of the utmost importance. Careful adherence to the manufacturer's mounting instruc-

tions, including the use of proper tools, can save many hours of troubleshooting and wire tracing

Instructions and procedures for installing lugs and connectors on wire and signal cables are shown in Figs 10 6 to 10.9 The most widely used hardware for terminating

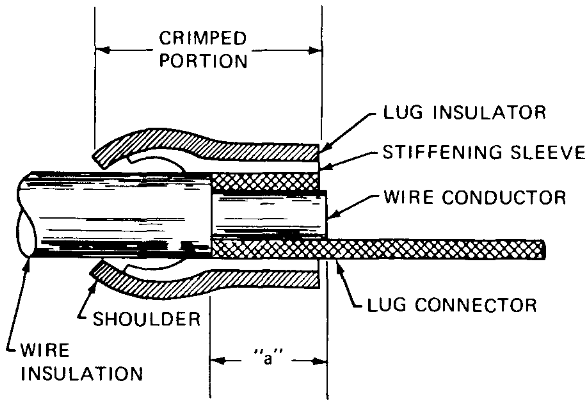


Fig. 10.6—Assembly of crimp on lugs

wiring and cabling is shown in these drawings Recommendations are included on how to avoid common problem areas in the installation of connectors

Crimp-on lugs Figure 10 6 shows the proper procedure for installing crimp-on lugs. To avoid installation problems, it is essential that

1 The proper type of lug (insulated or noninsulated, ring or spade, etc) be used.

2. The proper size lug for the wire and terminal be used

3. The insulation be stripped to the proper length (refer to "a" in Fig 10.6). The conductor should be inserted completely through the lug with the insulation butted up against the shoulder and the conductor cut so that it protrudes just past the crimped portion of the lug

4. The lug be properly crimped, using the proper crimping tool, with the wire conductor and insulator, where applicable, completely compressed to the lug It is recommended that a fixed-release crimping tool be used. This tool assures proper crimping of the lug every time by not allowing release of the lug until the full amount of crimping pressure has been applied

Standard Coaxial (BNC) Connector Figure 10.7 shows the proper procedure for installing standard coaxial (BNC) connectors. To avoid installation problems, it is essential that

1 All strands of the shield be free of the center conductor

2. All strands of the shield make a good contact with the connector shell.

3 All dimensions on the assembly drawing be followed precisely so that the connector will fit together properly.

4. A good solder connection be made between the contact tip and the center conductor

5. The connector and cable be cleaned properly with an appropriate cleaning agent

Crimp-On Coaxial (BNC) Connector Figure 10.8 shows the proper procedure for installing crimp-on coaxial (BNC) connectors To avoid installation problems, it is essential that

1. All strands of the shield make good contact with the connector shell

2 All assembly instructions and dimensions be followed precisely.

3. The connector and cable be cleaned properly with an appropriate cleaning agent

Triaxial Connector. Figure 10.9 shows the proper procedure for installing triaxial connectors To avoid installation problems, it is essential that

1 All strands of the two shields make good contact with their conductor Strands left out of the conductor have been a source of noise problems, particularly with pulse circuits having fast rise times in the microsecond and nanosecond range

2. None of the shield strands from either shield touch each other or the center conductor

3 All assembly instructions and dimensions be followed precisely.

4. The connector and cable be cleaned properly with an appropriate cleaning agent.

(c) Mounting Pneumatic Equipment and Hardware. The pneumatic instrumentation system uses compressed air for the operation of the measuring devices, indicators and controllers, and final control elements

Relatively trouble-free operation can be realized. In systems requiring 100% availability, a backup or dual system as shown in Figs. 10.4 and 10.12 should be used. The installation of an instrument air system should conform to a standard of the industry, such as the *American Standard Association Code for Pressure Piping,* A S A B31.1.*

Instrument Air Supply. In a pneumatic system the air is supplied by a compressor to a storage tank, and the system is supplied from the tank. The compressor and storage tank are sized so that the air usage of the system does not require continuous operation of the compressor. These items are generally located in a service equipment area The air is then piped to the instrumentation-rack structure.

Condensation in a compressed-air piping system must be limited because moisture can damage instruments and make the system inoperative Several air-drying techniques are available to remove the moisture from compressed air.

Desiccant dryer A desiccant dryer is located in the piping between the compressor storage tank and the filter—regulator station. The dryer consists of two identical units, each unit has a desiccant chamber, check valve with a reduced-area bypass, and a solenoid valve, connected as shown in Fig. 10.10. Part of the dried air from the chamber

*See Vol 2, Chap. 14, for a discussion of standards and the addresses of standards organizations.

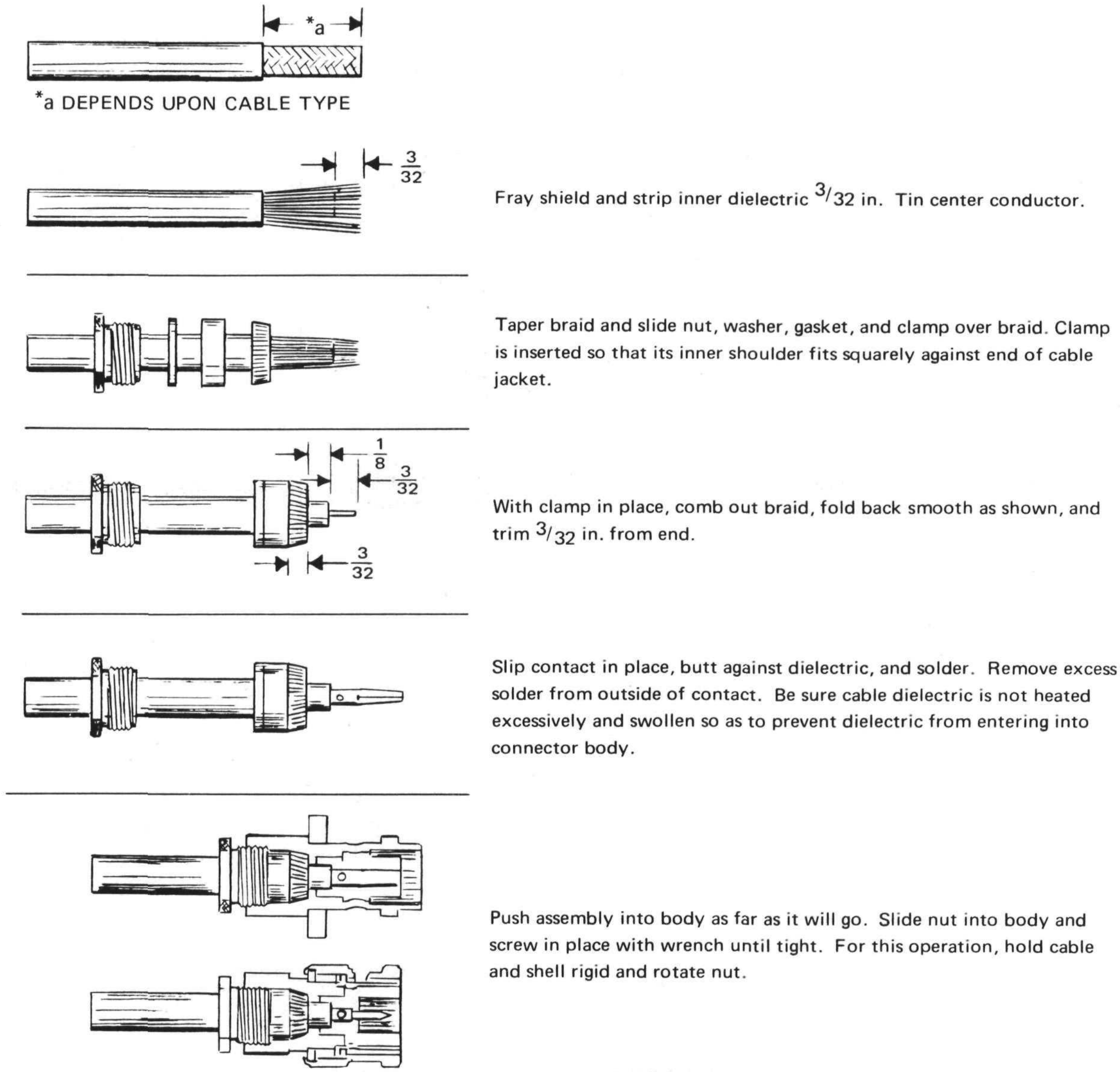


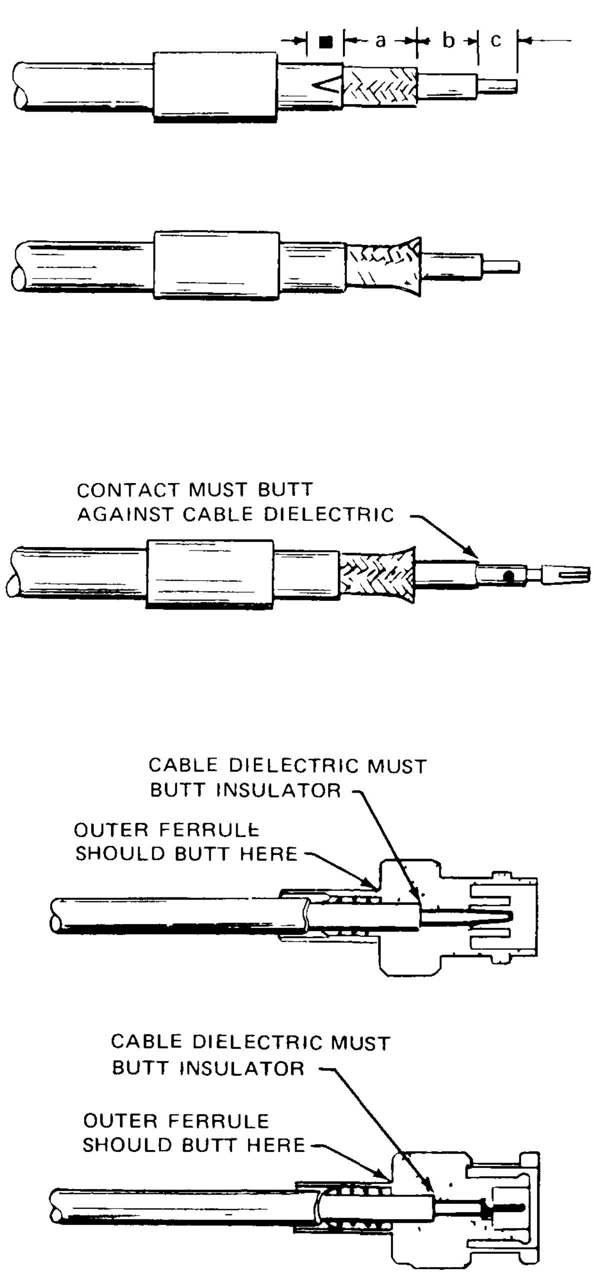
Fig. 10.7—Assembly of standard coaxial connector.

in service is used to regenerate the other chamber; this amounts to about one-third of the dried air produced. Because additional air is required for regeneration of the system, the compressors must be sized to supply the regeneration air in addition to the air required by the instrument system. As the chamber drying the air becomes saturated, the chamber on the regeneration cycle is dried out. An electric timer controls the solenoid valves and periodically switches them, reversing the operating cycle of the system.

After-condensers. After-condenser air dryers are also located in the air line between the compressor-storage tank and the filter–regulator station. The after-condenser consists of a heat exchanger that uses water as a cooling agent. Figure 10.11 is a simplified diagram of a water-cooled moisture condenser. The use of chilled water for cooling increases the capacity of the condenser.

Filter–Regulator Station. A filter is located upstream of the pressure regulator and is used to remove foreign matter or contaminants from the air stream. The pressure regulator reduces the air pressure to the level required by the instrument system.

Where instrument air must be available to the system 100% of the time, a dual filter–regulator station is used. A typical dual station is shown in Fig. 10.12 in schematic form, and an actual installation, in Fig. 10.4. Each of the parallel filter–regulator stations is sized to handle the total requirements of the system. Isolation valves in each of the parallel piping arrangements allow either of the filter–regulator stations to be isolated from the system for repair and maintenance without shutting down the entire system. Each instrument using air is connected to the instrument air header through an isolation valve. Each instrument air header should have spare air takeoff points (10% mini-



Strip cable jacket, braid, and dielectirc to dimensions shown in table All cuts are to be sharp and square Important Do not nick braid, dielectric, and center conductor Tinning of center conductor is not necessary if contact is to be crimped For solder method, tin center conductor avoiding excessive heat Slide outer ferrule onto cable as shown

Stripping dimensions (+ 1/64)

	MIL-Crimps			Quick-Crimps		
	a	b	c	a	b	c
Plugs and jacks	1/4	13/64	1/8	1/4	7/32	11/64
Right-angle plugs	1/4	13/64	1/8	1/4	3/16	11/64
Bulkhead jacks	1/4	13/64	1/8	1/4	1/4	11/64

Flare end of cable braid slightly as shown to facilitate insertion onto inner ferrule Important Do not comb out braid

Place contact on cable center conductor so that it butts against cable dielectric Center conductor should be visible through inspection hole in contact Crimp or solder the contact in place as follows

Crimp method

Crimp center contact using either of the following two tools Tool No 227-912-1000—To crimp the male contact (pin), insert the end of the nest bushing marked "P" into the tool To crimp the female contact (socket) insert the end of the nest bushing marked "S" into the tool Tool No 227-917 (MS-3191-A)—To crimp the male contact (pin), insert the positioner marked 227-918 into the tool To crimp the female contact (socket), insert the positioner marked 227 919 into the tool

Solder method

Soft solder contact to cable center conductor Do not get any solder on outside surfaces of contact Avoid excessive heat to prevent swelling of dielectric

Install cable assembly into body assembly so that inner ferrule portion slides under braid Push cable assembly forward until contact snaps into place in insulator Slide outer ferrule over braid and up against connector body Crimp outer ferrule with tool specified in table

Fig. 10.8—Assembly of crimp on coaxial connector

mum) The spare takeoff points should be equipped with isolation valves to allow the addition of new instruments to the system without requiring system shutdown. The header is sloped to the output, and so any condensation collects at the drain cock (see Fig 10.4)

Pneumatic Signal Lines The air supply and signal lines downstream of the instrument air header are plastic or copper tubing Runs of this tubing should be straight, parallel, accessible, and logical with vertical runs plumb and horizontal runs dropping away slightly from the instruments Tubing runs must be rigidly supported and fastened to the instrument structure or supporting braces These installation requirements ensure that the tubing installation will not only have a pleasing appearance but also will be easily maintained.

Each instrument signal input line should be equipped with an isolation valve and a test tee with a shutoff valve This arrangement allows maintenance or testing without shutting down the whole system.

Pneumatic Input–Output Terminal Panel The fact that instrumentation systems are generally assembled and tested at the vendor's plant and not at the location where the system will be used requires that provisions be made for terminating the pneumatic input–output lines One method of providing a terminal for both instrument structure lines and field-installed lines is to use a bulkhead tubing

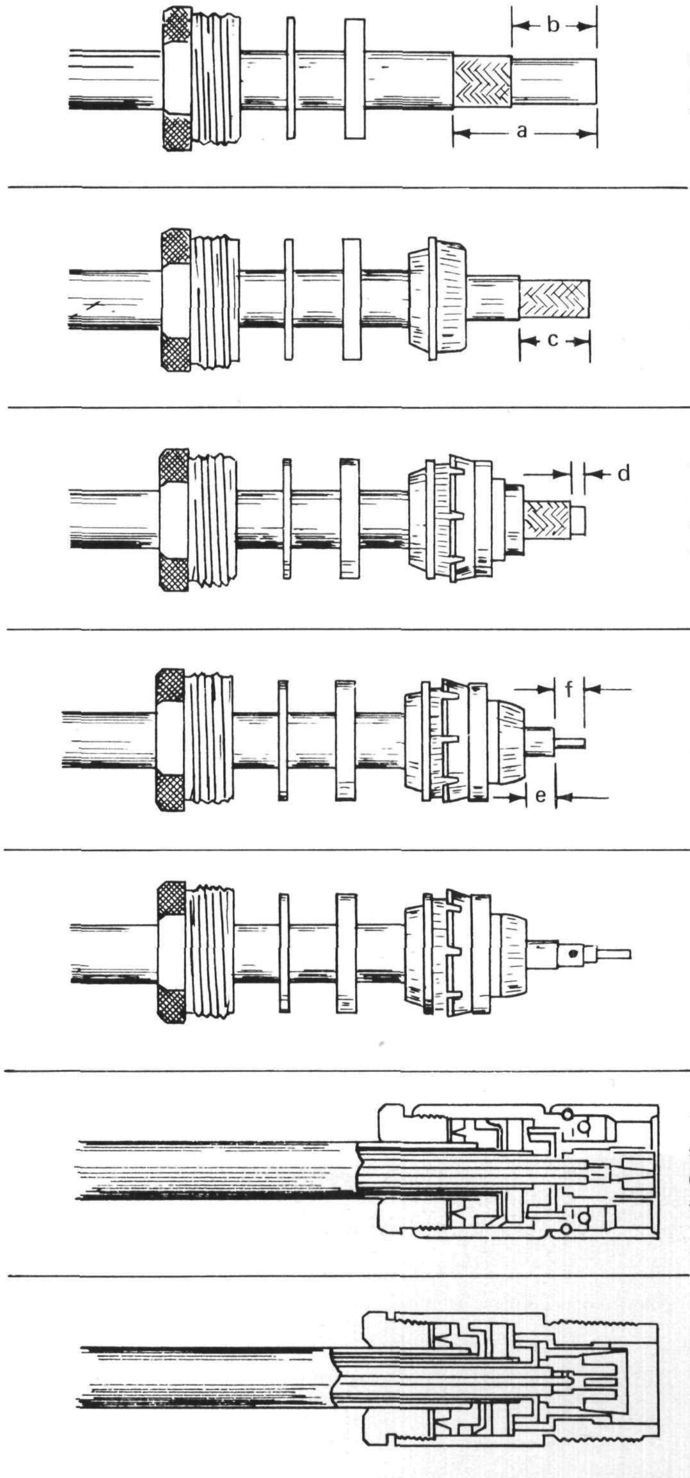


Fig. 10.9—Assembly of triaxial connector.

connector (see Fig. 10.13). The bulkhead connectors are mounted on the enclosure surface or on a mounting plate in a panel. The connectors are located in an area accessible to the field lines.

After the pneumatic systems have been installed, each system must be pressure-tested to be certain that leakage in the system does not affect the operation of the system. The Instrument Society of America (ISA) Pneu-

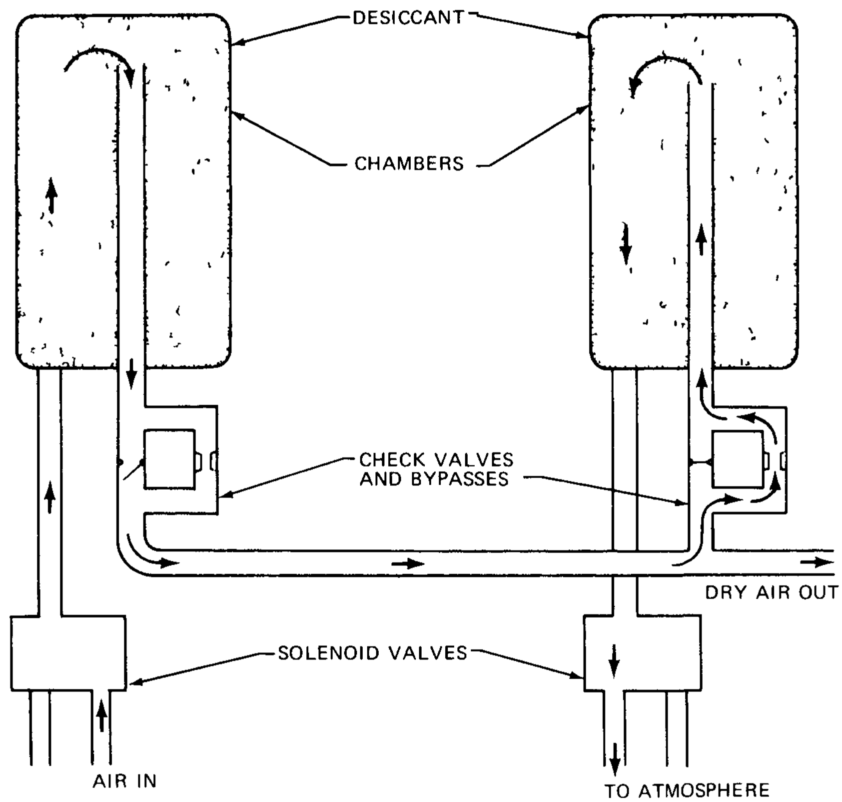


Fig 10 10—Air dryer desiccant type

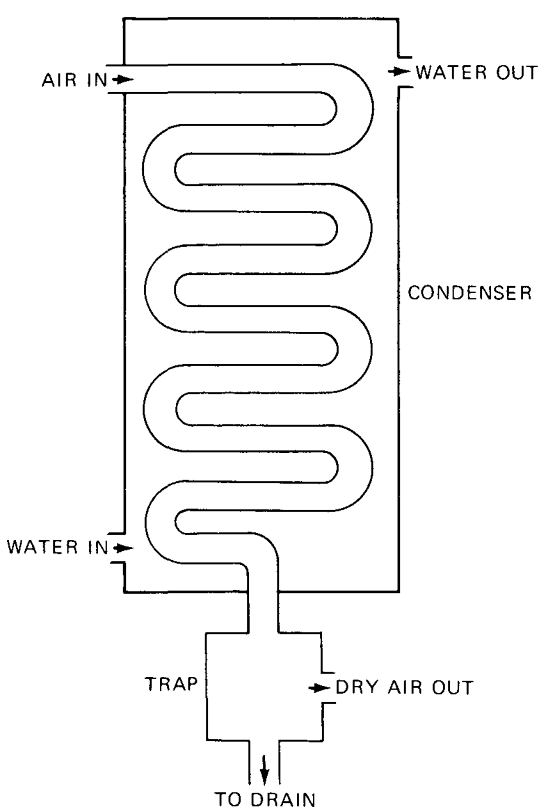


Fig 10 11—Air dryer after condenser type

matic Control Circuit Pressure Test, ISA RP7 1, is one test procedure for verifying the leakage in pneumatic systems and establishing the criteria for acceptance of the work

10-3.3 Installation for Environmental Control

(a) Temperature Control Temperature control of instrumentation systems is usually not given sufficient attention For example, although the overall average temperature of all components may not be excessive, many "hot spots" can develop through improper attention to cooling requirements Even though such hot spots may not cause immediate failure, they eventually show up in system failures and poor mean time before failure (MTBF), with resulting high maintenance costs Although temperature considerations are basically a design function, no designer's product can function effectively if operated in an environment in which it was never intended to operate For this reason those in charge of the installation must make certain that all equipment is operated within the designed environmental limits, whether thermal, vibrational, radiation, or any other

Since most instrumentation equipment is located in enclosed cabinets, proper ventilation must be provided to avoid convection cooling that may allow heat from a lower chassis in a cabinet to pile up in the top chassis, thereby effectively "baking" every component in the equipment Under these conditions some units that functioned well in a

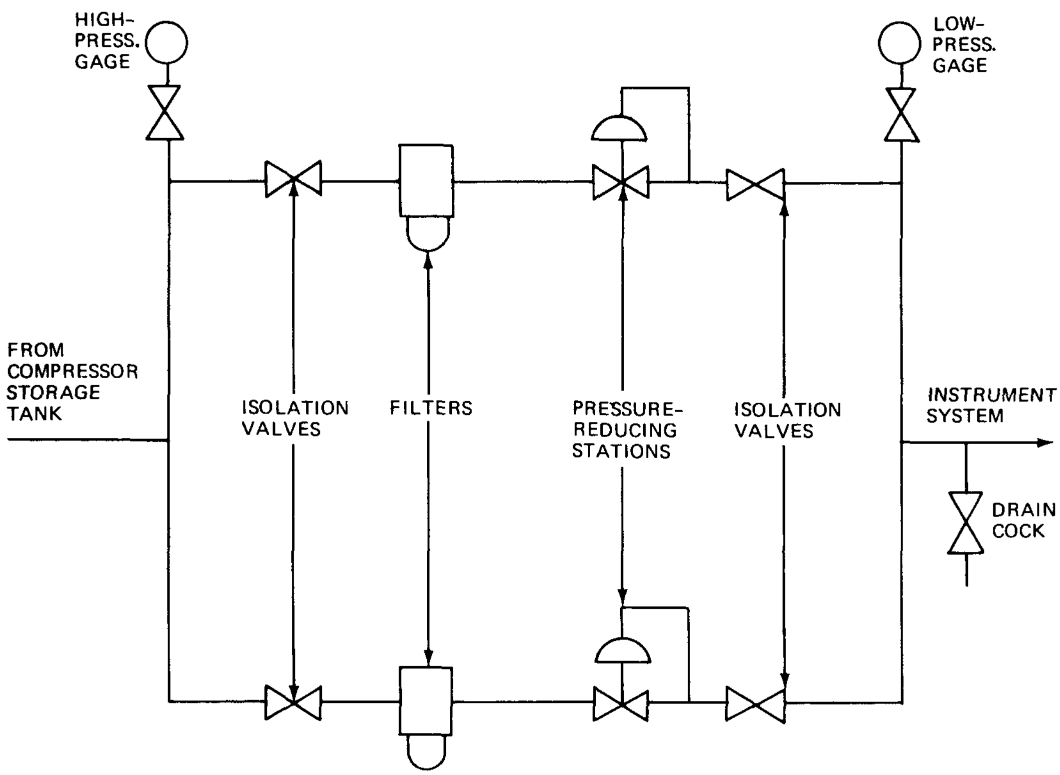


Fig. 10.12—Dual-filter regulator station For actual installation see Fig 10 4

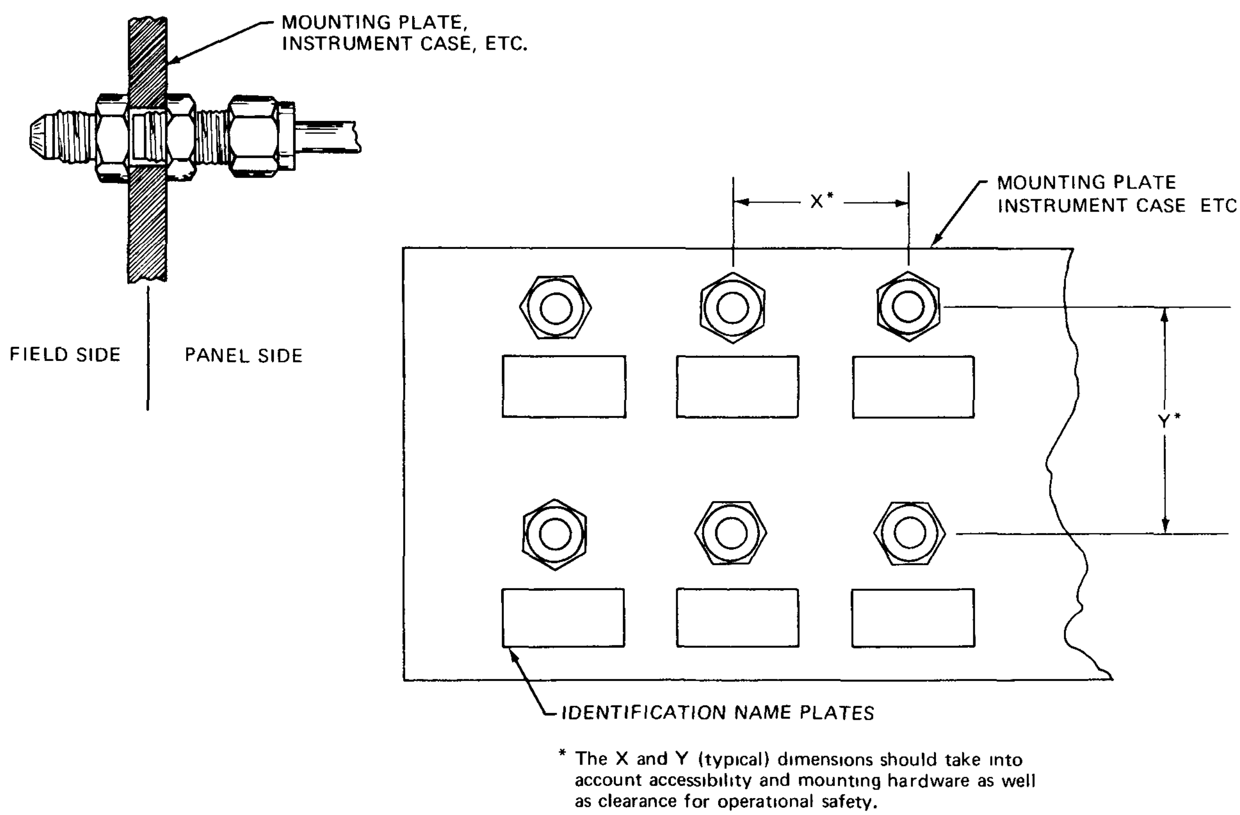


Fig. 10.13—Pneumatic terminal panel.

55°C test oven have been known to fail when operating in a "room-temperature" relay rack For this reason each chassis placed in a cabinet must be checked for power consumption before installation and provisions made for the total cooling load demanded per cabinet The type of equipment in the cabinet must also be considered, for example, a log amplifier requires closer temperature control than a relay

If temperature might be a problem (either high temperature for indoor installation or low temperature in winter at outdoor locations), provisions for correcting the problem should be made before the equipment is installed, not after Since the instruments in control rooms are usually a large source of heat, air may be drawn from the room through vents placed in the bottom of each cabinet and then drawn out of the top of the cabinet into the building's central air-conditioning return. Additional cooling capacity may be required in the air conditioning system at the time of plant construction to handle the load of the control room If proper size ducts are used from the cabinets to the air return, the airflow through the equipment and in the room will be silent, low speed, and unobtrusive If the air input to the room is filtered, the control room will stay clean as well as cool, providing a more pleasant and lower maintenance environment Each cabinet mav also be equipped with a thermometer so that the cabinet temperature can be monitored

During set up and testing of cabinet-mounted equipment, temperature-sensitive materials, such as tempilac, may be placed in areas of high-component densitv and low airflow or on components that require critical temperature control to be effective If after 8 hr of operation the temperature sensitive materials indicate proper operating temperatures, the airflow should be turned off or blocked, and the effect of the ensuring temperature rise on the equipment operation should be noted If any significant changes occur, an alarm annunciator should be installed to signal and warn of loss of system airflow

Other than the electronic package located in the control room, the most critical area regarding temperature regulation is around the reactor itself Energy dissipated in the reactor shielding material produces heat which raises the temperature of anv detectors or other sensors in close proximity to the core Those responsible for installations should be certain that the ambient temperatures of each sensor location do not exceed those recommended by the manufacturer and that any connecting cable is rated for the environment in which it must perform.

(b) Vibration Control. Every attempt should be made to mount instrumentation in vibration-free areas When it is necessarv to place instruments in high-vibration positions, it is most important that neither components, portions of the case, nor wires of any kind resonate at any of the vibrational frequencies involved since metal fatigue will most certainly cause ultimate failure

The easiest cure for vibrational problems is to shock mount the equipment and fasten securely all wiring harnesses by using anti wicking tools on connector solder points Anti-wicking tools prevent solder from flowing within stranded wire to a point beyond which the insulation has been stripped from the wire Other approaches mav also be required, including silicone rubber encapsulation of wires and connectors, special internal vibration dampening of equipment, etc For further information on vibration control, see Defense Department Wire Specification MIL-W-5088C or MIL W-9160D

(c) Selection of Insulation for Radiation Environment. Wiring insulation exposed to environmental extremes of radiation should be carefully selected It would be desirable to select wire that could withstand radiation exposures for the life of the plant (about 40 years) Extensive irradiation research programs have been conducted and numerous tables have been compiled on radiation damage to wire conductors and insulating materials

This chapter contains several tables on radiation effects on materials These tables are typical and may or may not agree with specific results obtained by other research organizations

There is no substitute for experience gained in operating nuclear plants It has been found that out-of-core detector wiring and some in-core wiring may be good for only 24 months or less Replacement of this wiring at refueling time is considered standard operating procedure

Table 10 1 shows the radiation stability of plastic insulating materials Klein and Mannal concluded that only inorganic insulation materials could function within the reactor primary shield since radiation dose rates up to 10^{12} rads/hr are often experienced * The same type of insulation will be required in the containment vessel of a fast breeder reactor, where levels are expected to reach 10^5 rads/hr Outside the primary shield but inside the containment vessel of a thermal reactor, the dose rates may range from 0 5 to 160 rads/hr, and temperatures up to 70°C may be expected

On the basis of the foregoing assumptions and a 40-year plant lifetime, wiring inside the containment vessel may be expected to absorb 5×10^7 rads under normal conditions, a power excursion or other nuclear accident may add another 4×10^6 rads Auxiliary structures, e g , residual heat removal compartments, outside the containment vessel mav be expected to receive dose rates 1/100 that of objects within the containment vessel, but, in the event of an accident, these areas must be able to withstand much higher levels

The temporary effects of radiation on elastomer based cables include thermoluminescence, decrease in electrical resistance, and gas generation Long term effects include either embrittlement or softening of the insulation Present theories tend to support the view that the cumulative

*P M. Klein and C Mannal The Effects of High Energy Gamma Radiation on Dielectric Solids in *AIEE Transactions on Communications and Electronics* Part 1 Vol 74, pp 723 731 American Institute of Electrical Engineers January 1956

Table 10 1—Radiation Stability of Plastics*

Material	Threshold dose for +5% change,† 10^3 rads
Polystyrene‡	40
Phenol formaldehyde (asbestos filler)‡	40
Polyester (mineral filler)‡	4
Polyvinyl chloride‡§	1
Polyethylene‡	0 9
Urea formaldehyde‡	0 5
Monochlorotrifluoroethylene§	0 2
Cellulose acetate§	0 2
Phenol formaldehyde (unfilled)‡	0 1
Methyl methacrylate§	0 01
Polyester (unfilled)‡	0 01
Polytetrafluoroethylene (Teflon)§	0 01

*From P M Klein and C Mannal The Effects of High Energy Gamma Radiation on Dielectric Solids, in *AIEE Transactions on Communications and Electronics* Part 1, Vol 74, p 723 January 1956

†Based on most sensitive property, usually tensile strength

‡Crosslinks

§Scissions

radiation damage to a substance in or near a nuclear reactor depends on the total energy absorbed by the material and is not a function of the type of radiation Accordingly, neutron damage to cables can be determined by referring to the tables for gamma-radiation damage and adjusting the total dose to account for the neutron energy Tables 10 2 to 10 6 show degradation as a function of absorbed dose caused by gamma radiation on various parameters of a cable and for various types of cable insulations From these findings, Blodgett and Fisher presented the data shown as Table 10 7. The table lists and rates materials that may be used successfully in various nuclear environments

10-3.4 Installation Symbols

The designers of nuclear power plants use different symbols on drawings for the installation of instrumentation and electrical systems Although there are some relevant electrical codes and standards, there still appears to be lack of uniformity throughout the industry

Table 10 8 lists symbols typical of those currently used in the nuclear industry.

10-4 INSTALLATION OF SIGNAL AND POWER CABLES

10-4.1 Installation Hardware

(a) Conduits. Two basic types of conduit are available, aluminum and steel, other types, such as plastic, are used occasionally. In addition, plastic-coated steel and aluminum are finding wide use where corrosion is a problem. Aluminum is light in weight, free from corrosion by moisture, and easy to install, whereas steel is a far better shield against magnetic fields and has greater strength

Where conduit is to be run through concrete (such as in biological shields), steel should be used since many concrete mixes eventually corrode aluminum, particularly with the presence of moisture If radiation levels and conduit temperatures permit, plastic coated steel conduits yield the best service in damp locations Drain holes should be drilled at low points in exposed conduits to permit any accumulated moisture to escape, and unexposed conduits, such as shield penetrations, should be arranged so that moisture cannot collect in interior points Conduit should be sized so that the installed wire cables, including allowances for expansion, fill no more than 40% of the conduit area to ensure ease of expansion and repair Information on conduit sizes and available fittings may be found in any equipment manufacturer's catalog

Particular attention should be paid to joints between aluminum and steel conduit, and, wherever possible, these should be avoided because of the possibility of electrolytic corrosion If such joints must be made, they should be located where they can be easily inspected and protected from moisture

(b) Wiring Trays and Supports. Wiring trays and supports are used wherever it is necessary to route a great number of large-diameter wires to a particular location and still allow easy access to the wiring Solid covered trays are used for instrumentation wiring and open mesh trays for power wiring

Care should be taken that heat buildup in enclosed power-cable trays does not lead to deterioration of insulation since power cables in enclosed trays should be operated at a lower rating than those in free air When trays are installed, they should be bonded together to ensure ground continuity and grounding to the main building ground This can be accomplished by several methods, such as welding and brazing the sections together, using bolted joints, or by running a ground wire along the tray sections and bonding each section to the wire with a suitable clamp (see Sec 10-5).

10-4.2 Signal and Control Cables

(a) Power-Distribution Cables. Since power cables for instrumentation do not normally carry high currents or high voltages, a reference, such as the latest National Electrical Code (NEC), should be used to determine minimum standards of conductor type, size, etc , and installers should be aware of signal cables in the vicinity of power lines so that proper shielding measures (as shown in Sec 10-5) can be taken. In addition to interequipment cabling, power lines in intrarack wiring should be enclosed in wireways wherever possible to improve shielding

(b) Unshielded Control Cables. The present practice in the electrical power industry of standardizing field wires to No 12 or No. 14 AWG with bulky insulation can cause

Table 10 2—Permanent Effect of Gamma Radiation on Physical Strengths of Cable Coverings*

	PVC	H D. Poly	SBR	C.B. CLPE	C.F. EPDM	Butyl	90°C oil base	N F. CLPE	C.F EPM	Sili-cone	PVC	Neo-prene	CSPE	CPE
Tensile Strength														
Original, psi	2114	2213	1520	2045	1455	798	804	2272	872	1191	2601	2544	2113	2170
Retention after irradiation, %														
5 x 10⁵ rads	110	96	98	122	104	96	121	102	101	76	80	104	106	112
5 x 10⁶ rads	104	98	100	112	97	58	103	97	106	100	88	98	113	98
5 x 10⁷ rads	79	123	82	101	93	†	98	70	119	100	61	77	124	135
1 x 10⁸ rads	83	118	40	95	79	†	71	59	90	‡				
200% Modulus														
Original, psi	2260	2000	588	1767	1033	520	335	1260	730	859	2415	930	884	626
Retention after irradiation, %														
5 x 10⁵ rads	94	95	106	125	100	103	121	96	116	75	81	107	116	108
5 x 10⁶ rads	90	98	121	115	94	69	126	102	127	112	95	103	156	152
5 x 10⁷ rads	§	§	150	§	120	†	121	108	§	98	§	160	203	§
1 x 10⁸ rads	§	§	§	§	§	†	103	§	§	‡				
Elongation														
Original %	260	640	460	270	470	450	870	480	300	290	250	550	560	670
Retention after irradiation, %														
5 x 10⁵ rads	115	103	93	104	111	93	97	90	96	107	100	96	89	99
5 x 10⁶ rads	115	103	96	96	102	87	90	96	81	90	80	93	86	63
5 x 10⁷ rads	31		70	48	47	†	71	58	41	34	40	46	59	18
1 x 10⁸ rads	19	2	33	37	32	†	53	25	26	‡	‡			

*From R B Blodgett and R G Fisher, Insulation and Jackets for Control and Power Cables in Thermal Reactor Nuclear Generating Stations, in *IEEE Summer Power Meeting* Chicago, Illinois, June 1968, Institute of Electrical and Electronics Engineers, New York †Degraded (scission) ‡Brittle §Elongated <200%

Note A description of the specific wires tested is given below

1 *PVC* Polyvinylchloride per IPCEA S 61-402, Sec 3 8, and UL types THW and MT, No 4 AWG (7 strand) copper 0 047 in wall

2 *H D Poly /PVC* High density polyethylene, type III, Class B grade 3 per ASTM D1248 63T, and polyvinylchloride per IPCEA S 61-402, Sec 3 7, and IPCEA S 19-81, Sec 4 13 5 No 12 AWG (7 strand) copper, 0 030 in insulation, and 0 015 in jacket

3 *SBR/Neoprene* Styrene–butadiene synthetic-rubber based insulation per IPCEA S 19 81, Sec 3 13 and polychloroprene-based jacket per ASTM D 752 and IPCEA S 19-81, Sec 3 13 3, and UL type RHW No 14 AWG (7 strand) copper, 0 047 in insulation and 0 0156 in jacket

4 *C B CLPE* Low voltage, carbon black-filled, chemically cross linked polyethylene per IPCEA S-66 524, Interim Standard No 2, and UL type RHW-RHH No 14 AWG (7 strand) copper, 0 047 in wall

5 *C F EPDM/Neoprene* Ozone resisting mineral-filled EPDM based low-voltage insulation exceeding the requirements of IPCEA S 19-81, Secs 3 15 and 3 16, and polychloroprene based jacket per ASTM D-752 and IPCEA S-19 81, Sec 4 13, UL type RHH No 14 AWG (7 strand) copper, 0 047 in insulation, and 0 0156 in jacket

6 *Butyl/Neoprene* Ozone resisting butyl based insulation per IPCEA S 19-81, Secs 3 15 and 3 16, and polychloroprene based jacket per ASTM D-752 and IPCEA S 19-81, Sec 4 13 3, and UL type RHW RHH No 14 AWG (7 strand) copper 0 047 in insulation and 0 0156 in jacket

7 *Oil Base/CSPE* Ozone-resisting 90°C oil-base high voltage insulation meeting the requirements of IPCEA S 19 81, Secs 3 14 and 3 15 UL type RHH, and chlorosulfonated polyethylene-(CSPE) based jacket per ASTM D 752 and IPCEA S 19-81, Sec 4 13 3, UL type RHH No 14 AWG (7 strand) copper, 0 047 in insulation, and 0 0156-in jacket

8 *N F CLPE* High-voltage, nonfilled, chemically cross-linked polyethylene (nonstaining antioxidant) per IPCEA S-66 524, Interim Standard No 1 No 14 AWG solid copper, 0 047-in wall

9 *C F EPM/CPE* Ozone-resisting clay-filled EPM-based high-voltage insulation per IPCEA S-19-81, Sec 3 16, and UL type RHW-RHH and chlorinated polyethylene-based jacket per ASTM D-752 and IPCEA S-19 81, Sec 4 13 3 No 14 AWG solid copper, 0.047-in insulation, and 0 0156-in jacket The insulation was discussed in IEEE paper 31 TP67 481

10 *Silicone* Ozone resisting silicone rubber insulation per IPCEA S 19 81, Sec 3 17, UL type SA No 14 AWG (7 strand) copper, 0 047-in insulation, and 0 010 in glass braid

11. *Neoprene* Polychloroprene-based jacket per ASTM D 752 and IPCEA S-19-81, Sec 4 13 3, UL type RHH No 14 AWG solid copper, 0 047-in wall

12 *CSPE* Chlorosulfonated polyethylene based jacket per ASTM D 752 and IPCEA S 19 81, Sec 4 13 3, UL type RHH No 14 AWG solid copper, 0.047-in wall

13. *CPE* Chlorinated polyethylene based jacket per ASTM D 752 and IPCEA S 19-81, Sec 4 13 3, No 14 AWG solid copper, 0 047-in wall

Table 10.3—Permanent Effect of Gamma Radiation on Dielectric Constant (k′) of Cable Coverings*†

Dose, rads	Measured after 2 hr, °C	PVC	H.D. Poly.	SBR	C.B. CLPE	C.F. EPDM	Butyl	90°C oil base	N.F. CLPE	C.F. EPM	Silicone
					k′ (S.I.C.), 40 volts/mil, 60 Hz						
None	23	4.90	2.58	3.32	3.58	3.37	4.35	3.44	2.25	3.47	3.11
	75	6.82	2.52	3.84	3.44	3.19	4.21	3.27	2.30	3.49	2.96
	90	7.32	2.51	‡	3.04	3.18	4.14	3.09	2.30	3.44	2.98
					% Change						
5×10^5	23	+3	−1	+5	−1	−4	−2	+5	+7	+8	0
	75	−4	−2	+10	−2	−4	−2	0	+3	0	−1
	90	+52	+1	‡	+4	+5	−2	+2	−4	+3	−1
5×10^6	23	+4	+39	+5	+3	−9	−20	+10	+3	+8	+29
	75	+6	+42	+6	−7	−6	0	−4	−7	+3	−8
	90	‡	+132	‡	+4	+5	0	+3	+4	+3	−8
5×10^7	23	+21	+36	+1	+3	−7	−20	+6	+3	+10	+2
	75	+41	+39	−9	−1	−8	§	+1	−1	+6	+1
	90	‡	+104	†	+9	+2	§	+10	+9	+9	0
1×10^8	23	+59	−6	+1	+2	+1	§	+7	+2	+7	+6

*See note Table 10.2.

†The high dielectric constants of the neoprene-, CSPE-, and CPE-based jacket materials were not significantly affected.

‡Loss higher than limit of bridge.

§No test, sample degraded.

Table 10.4—Permanent Effect of Gamma Radiation on d-c Resistivity of Cable Coverings*

Dose, rads	Measured after 2 hr, °C	PVC	H.D. Poly.	SBR	C.B. CLPE	C.F. EPDM	Butyl	90°C oil base	N.F. CLPE	C.F. EPM	Sili-cone	Neo-prene	CSPE	CPE
					D-C Resistivity, 100 Teraohms-cm, 500 volts D-C									
None	23	0.15	240	2.3	70	12	76	15	141	71	0.2	10^{-3}	0.2	10^{-2}
	75	10^{-4}	25	10^{-3}	40	0.3	0.2	1.2	68	1.3	10^{-2}	10^{-4}	10^{-3}	10^{-4}
	90	10^{-4}	20	10^{-4}	37	0.3	0.1	0.1	50	1.0	10^{-3}	10^{-6}	10^{-4}	10^{-3}
						% Change								
5×10^5	23	−28	−43	+50	+33	−20	0	−1	−4	+11	+57	−31	−14	−46
	75	−90	−32	+48	+50	+32	−14	+100	−3	+10	0	−34	−32	−55
	90	−23	−90	−6	−33	−29	−51	+100	−3	0	+52	−85	−54	+198
5×10^6	23	−48	−70	+13	−59	−4	0	−1	−4	+38	0	+15	−5	0
	75	+10	−99	+40	+17	−8	−84	+66	−3	−9	+25	+4	−17	0
	90	−47	−92	0	−43	−51	−98	+90	−3	0	+15	+415	−82	+19
5×10^7	23	−67	−81	+48	−68	+53	−82	−5	−4	+25	+60	0	0	−14
	75	+100	−80	+250	−52	−34	†	+33	−4	−7	+20	+11	−17	−92
	90	+27	−99	+100	−75	−79	†	+25	−3	−40	+64	+390	−75	−85
1×10^8	23	+120	−70	+58	−7	+60	†	+35	−8	0	+60			

*See note Table 10.2.

†No test, sample degraded.

Table 10.5—Permanent Effect of Gamma Radiation on Flame Resistance of Thin-Wall Wires in Underwriters Laboratories Flame Test*†

	PVC		H.D. Poly./ PVC		SBR/ neoprene		C.B. CLPE		C.F. EPDM/ neoprene		Butyl/ neoprene		90°C oil base/ CSPE		N.F. CLPE		C.F. EPM/ CPE		Silicone glass	
Dose, rads	0	10^8	0	10^8	0	10^8	0	10^8	0	10^8	0	10^8	0	10^8	0	10^8	0	10^8	0	10^8
Results	P	P	F	P	F	F	F	F	P	P	F	F	P	P	F	F	P	P	P	P
% flag destroyed	0	0	100	0	100	100	100	100	0	0	100	20	0	0	100	100	0	0	0	0
After burn, sec	0	0	180	0	52	60	180	100	0	0	50	80	0	0	180	180	0	0	0	0

*See note Table 10 2
†P, pass, F, failure

Table 10.6—Threshold (in rads) of Gamma Radiation Damage for Elastomer-Based Cable Coverings*

Property	PVC	H.D. Poly	SBR	C.B. CLPE	C.F. EPDM	Butyl	90°C oil base	N.F. CLPE	C.F. EPM	Sili-cone	PVC	Neo-prene	CSPE	CPE
Tensile strength	10^8	10^8	5×10^7	10^8	10^8	5×10^6	10^8	5×10^7	10^8	5×10^7	5×10^7	5×10^7	5×10^7	5×10^7
Elongation	5×10^7	5×10^6	5×10^7	5×10^7	5×10^7	5×10^6	10^8	5×10^7	5×10^7	5×10^7	5×10^7	5×10^7	5×10^7	5×10^6
Rate of oxidation	5×10^6		$>5 \times 10^7$	$>5 \times 10^7$	$>5 \times 10^7$	5×10^6	$>5 \times 10^7$	5×10^6	5×10^7	5×10^5	5×10^6	5×10^6	5×10^7	5×10^6
Dielectric loss	5×10^7	5×10^5	10^8	10^8	10^8	5×10^6	10^8	5×10^5	10^8	10^8	5×10^7	5×10^7	5×10^7	5×10^7
Electric stability	5×10^5	$>5 \times 10^7$	5×10^5	$>5 \times 10^7$	5×10^7	5×10^5	5×10^7	5×10^7	$>5 \times 10^7$	$>5 \times 10^7$	5×10^5	5×10^5	5×10^6	5×10^7
Dielectric strength	5×10^7	5×10^7	5×10^7	10^8	$>10^8$	5×10^6	10^8	$>10^8$	$>10^8$	$>10^8$	5×10^7	5×10^5	5×10^5	5×10^7
Overall threshold of damage	5×10^5	5×10^6	5×10^5	5×10^7	5×10^7	5×10^6	5×10^7	5×10^6	5×10^7	5×10^5	5×10^5	5×10^6	5×10^6	5×10^6
Highest dose still serviceable	5×10^6	5×10^7	5×10^7	10^8	10^8	5×10^6	10^8	10^8	10^8	5×10^7	5×10^6	5×10^6	5×10^7	5×10^7

*See note Table 10.2.

Table 10.7—Suggested IEEE Nuclear Environment Classification for Elastomer-Based Cable Coverings

Radiation class	Temperature Class		
	O(90°C)	A(105°C)	B(130°C)
1 (9×10^4 rads)	Silicone (see Note 1)	Silicone (see Note 1)	Silicone
2 (9×10^5 rads)	Butyl/neoprene, CSPE, CPE, and H D Poly	See below	None
3 ($8\ 8 \times 10^8$ rads)	EPDM, EPM, oil base, N.F CLPE, and C B CLPE	EPDM, C B CLPE, and EPM	None
4 ($8\ 8 \times 10^9$ rads)	None	None	None
5 (10^{10} rads)	None	None	None

Notes

1 Dimethylsilicone based insulations (IPCEA S-19 81, Par 3 17) are suitable at their usual 130°C temperature rating only in low-radiation environments because of their sensitivity to steam and poor resistance to oxidation after irradiation Blodgett and Fisher rate them only in classes O1, A1, and B1

2 Carbon-black (and probably clay-filled) cross-linked polyethylenes and clay-filled EPM- or EPDM based insulations are suitable at 105°C up to class 3 radiation levels when protected with suitable flame-resistant braids (such as the glass construction used in Blodgett and Fisher's study) or flame and water-resistant asbestos constructions Blodgett and Fisher rate these two materials for classes O1, O2, O3, and A1, A2, and A3

3 Butyl and high-density polyethylenes with neoprene, CSPE, or CPE jackets or the CPE as integral insulation jackets are suitable at their usual 90°C temperature rating only up to class 2 radiation levels Blodgett and Fisher rate these systems only for classes O1 and O2

4 Nonfilled cross linked polyethylenes and oil-base insulations, when protected by a neoprene, CSPE, or COE jacket, are suitable at their usual 90°C temperature rating up to class O3 Blodgett and Fisher rate these systems for classes O1, O2, and O3

5 SBR and PVC-based coverings are suitable only at relatively low temperatures and radiation levels In particular (IPCEA S 61-402, paragraphs 3 7 and 3 8), PVC's are sensitive to hot water and steam when exposed to more than 5×10^5 rads

serious installation problems if the instrument-cabinet terminal blocks are not properly sized The design engineer and instrument-cabinet manufacturer should allow ample space in the cabinet for terminal blocks, conduits, and wireways to accommodate the large-size field wires Single-conductor field wires with diameters of ¼ to 5⁄16 in are being used in power-station design

Several types of single conductor wire with small-diameter plastic insulation are durable and meet all the environmental requirements for power-station design

Where smaller (No 18 to No. 22 AWG) wires are used, they should normally be in the form of cables having a number of twisted pairs covered by an outer sheath, with one pair assigned to each circuit function Avoid having several circuits tied to a single ground conductor since, if this conductor fails, a number of circuits will be put out of commission instead of only one

It is evident that only power cables, switch commands, relay operating signals, and lines that can tolerate some cross-talk, such as communication lines, should be run in unshielded cables

If one of these lines is terminated in a terminal strip or block, solderless crimp connectors may be used, if the line terminates in a connector, solderless or solder-type terminations may be used. When wires are terminated in a connector, covering each wire with teflon tubing, shrink tubing, or other insulation will decrease the probability of shorts

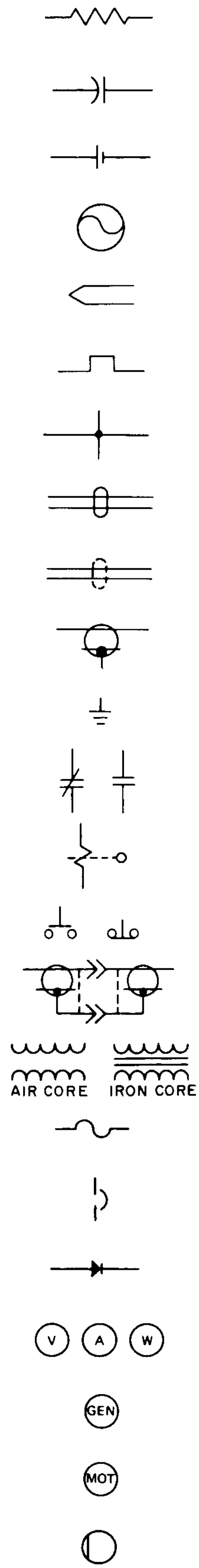
In general, unshielded wiring is much easier to install than shielded and, if standards such as those referenced in other sections of this chapter are followed, should create no problems

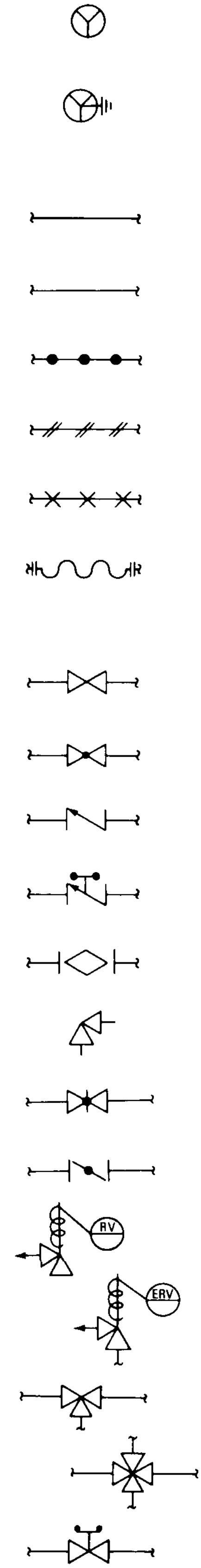
(c) Instrument Signal Cables (Multiconductor, Shielded). Because of cross talk, spike induction, and other interference problems, it is important to consider the routing of each cable with respect to its electromagnetic environment Mixing of low-level signals, relay commands servomotor control currents, and communication cables in the same conduit or raceway results in interference problems whether shielded cable is used or not Good practice dictates that instrumentation cables be separated physically according to signal level and function as well as electrically by shielding etc , wherever possible In critical circuits, such as reactor-control circuits, separate each channel's measurement and control function from all others This will result in at least three sets of separately run conduit, color coded or identified in some way If this policy of separation is followed along with coincidence safety logic in the control-instrumentation design as well as in wiring layout, any portion of the control system may be disconnected without causing a scram

Isolate wiring according to function Cables carrying high currents or voltages should be isolated from those carrying low currents or voltages, and cables carrying interference-producing signals should be isolated from those carrying direct current A designer should use a separate

Table 10.8—Installation Symbols Commonly Used in the Nuclear Power Industry

Resistor	Winding connection 3-phase ungrounded
Capacitor	Winding connection 3-phase grounded
Battery	**Piping**
Alternating-current source	Primary flow line
Thermocouple	Secondary flow line
Thermal element	ASME Boiler Code line
Conductor and junction	Control air line
2-conductor cable	Instrument capillary tubing
Shielded 2-conductor cable	Flexible hose
Coaxial cable	**Valves**
Ground	Gate
Basic contact assemblies	Globe
Electromagnetic actuator with mechanical linkage	Check
Push-button switch	Stop check
Coaxial connector	Plug
Transformer	Angle
Fuse	Manual flow controller
Circuit breaker	Butterfly
Semiconductor rectifier diode	Relief
Meter	Electromatic relief
Rotating generator	Three-way
Rotating motor	Four-way
Winding connection 1-phase	Throttle





(Table continues on next page)

Table 10 8—(Continued)

Bleeder trip	BTV	Local mounted transducer electric to pneumatic	E/P
Locked open	LO	Amplifier controller	AC
Locked closed	LC	**Miscellaneous Instruments**	
Self contained		Flow meter	FM
Control (opens on air failure)		Sight flow indicator	PG
Control (closes on air failure)		In line flow indicator	FI
Air lock	AL	Flow nozzle	FE
Operators		Flow orifice	FE
Diaphragm		Restricting orifice	RO
Electric motor	MOV	Thermocouple	TE
Nonelectric power	POV	Resistance bulb	RTO
Float		Sample cooler	SC
Manual trip and reset		Sample nozzle	SN
Solenoid	SV	Drain trap	DT
Damper with electric operator	MO	Manometer	M
Damper with air operator	PO	Basket strainer	BS
Instruments		Hose connection	
Local mounted	PI PS	Air relay	
Panel mounted	PI PS	Remote manual control	RMC
Annunciator alarm	H XX L BOARD SYMBOL	Air switch	
Local mounted transducer pneumatic to electric	P/E		

conduit for all low-level (detector, thermocouple, etc.) signals, a separate conduit for high-level control signals containing shielded wires, a separate conduit for relay and contact closure leads, and a separate conduit for a-c and d-c power distribution.

If every precaution is not followed, scrams may be caused by arc welders or other noise-producing devices, such as switching d-c circuits, when placed near the detector cables.

Concerning the signal and control cables, each cable should carry only signals of the same type and, for instrumentation purposes, should have at least an overall shield (either braid or metal foil) for each group of conductors In all instances the cable shielding should have an insulating layer over the shield to provide isolation from ground-loop currents likely to be circulating in the outer conduit. Each of the two most common types of shields (braided and foil) offers different degrees of shielding protection. The braided type of shield offers good protection for low-level signals. However, because of the effect of leakage capacity through the braided shield to ground, common-mode reflection suffers, and something better is needed for noise-free transmission of microvolt-level signals. Lapped foil shields have been developed for this purpose, and this type of solid-foil shield, plus a low-resistance drain wire, reduces the leakage capacity from about 0.1 to 0 01 pF/ft, typically. In addition, the foil shield improves shield-to-ground electrical leakage characteristics, rejection of magnetic pickup, and shield-resistance characteristics, and reduces termination problems

Conductor pairs within the cable should be of the twisted variety since this in itself reduces interference as much as 15 dB * The use of balanced, twisted pairs is even more effective, resulting in an interference reduction of up to 80 dB. The foregoing techniques were applied in the construction of the Ballistic Missile Early Warning System (BMEWS), where many different types of cables were located in close proximity to one another. In this system inherent shielding of the cableways provided 6-dB attenuation, twisting of power and other cables provided 26 dB, and the use of balanced, twisted pairs added another 80 dB

Because instrumentation cables must not be considered separately from the system in which they are to be used, the designer should consider terminating all cables carrying signals having frequencies greater than 10 kHz with their characteristic impedance to avoid end reflection. Termination of signal cables depends on the type of cable and the signal levels involved. In general, cables other than coaxial can be terminated using color-coded crimp connectors of the "ring" type and affixed to terminal strips Each end of a conductor should also be marked by attaching a piece of plastic sleeving bearing the wire designation number as shown on the system interconnection diagram.

*1 dB = 20 log A, where A is a voltage or current amplitude ratio.

Wires within a conduit should not exceed code limits to ensure easy cable pulling. No splices should be allowed except in appropriate junction boxes [see Sec 10-4.1(a)]. The conduit "fill" should not exceed 40%, including planned additional space reserved for system changes. When cable is pulled through conduit, excessive stress should not be placed on the cables since this may result in damage to insulation in regular wiring or changes of impedance in coaxial cables. Spare conductors should be installed in each cable to permit system expansion. As a rule, running 10 to 15% more conductors than required seems to work well This allows for additions without raising the cost excessively. However, the type of reactor installation (power, experimental, etc.) may alter this general rule.

Termination of thermocouple leads is a special case, and the manufacturer's instructions should be followed to ensure that there are no error currents produced by improper terminations In addition, thermocouples should be kept away from cables carrying high current or voltage signal levels Self-balancing temperature recorders respond too slowly to be affected by transients on thermocouple leads. However, electronic time-sequential multiplexing of large numbers of thermocouples into a device (such as a computer) requires that transients on the thermocouple leads be eliminated since sampling of a particular thermocouple may occur when the signal level is being influenced by a transient.

(d) Coaxial and Triaxial Cables. Coaxial and triaxial cables require care in selection and termination because signal levels are of the order of 1 mV or less Triaxial cables provide additional low-frequency (<100 kHz) shielding attenuation of 20 to 40 dB over coaxial cables, and additional benefits, such as low leakage, may be gained by appropriately driving the inner shield as explained in Sec. 10-5.5(a) Regarding installation of these cables, it is safe to use BNC type connectors of either the crimp or solder style up to 500 volts d-c. (The crimp type is popular.) Above 500 volts d-c, MHV series connectors may be used to voltages of 5000 volts d-c, except where high-frequency pulses are present At very high pulse rates (>1 MHz), the connector impedance must match the cable, and so other types of connectors must be chosen. When cable connectors are being installed, care must be used to ensure that there are no loose ends of the shield braid to cause shorts or lower the breakdown resistance of the connector After the cable has been assembled, the test procedure outlined in Table 10.9 is recommended

Table 10.9—Cable-Testing Procedure

Operating voltage	Test procedure
<600 volts d c	2 times rated voltage plus 1000 volts applied for 1 min.
>600 volts d-c	2 25 times rated voltage plus 2000 volts applied for 1 min

Since magnetic and electric fields are responsible for most interference problems below approximately 3 MHz, low-frequency (60 Hz) pickup should be guarded against by using steel conduit around low-level coaxial and triaxial cables The steel effectively attenuates both magnetic and electrostatic fields at all frequencies

At termination ends of coaxial or triaxial cables, each connector should be marked with its appropriate print number as well as the number of the mating connector for the particular cable An appropriate marking device is a plastic sleeve wrapped around the cable end and bearing the necessary information

When triaxial cable is used, connector assembly is more critical than when BNC is used, and greater care must be taken in testing the completed cable The tests in Table 10 9 should be applied in this case not only between center conductor and inner shield but also between the inner and the outer shield to ensure proper connector integrity For extra protection a quantity of silicone grease may be used inside the connector to provide additional insulation and to prevent accumulation of moisture within the connector

(e) Containment Penetrations. Penetrations for signal, control, and power cables in the reactor containment have been custom designed Custom designed penetrations, in many cases, required assembly at installation and disassembly for repair Many problems experienced with containment penetrations resulted from field-assembly conditions Although the problems experienced with field-assembled penetrations were often similar (e g , difficult installation, leaking seals, and poor wire termination), the variety of custom designs prevented universal solutions from being applied to similar problems

For greater reliability and ease of installation, several manufacturers have designed and now fabricate preassembled and pretested electrical penetrations These penetrations can be supplied with seals that are compatible with a variety of ambient environmental conditions (temperature, moisture, and nuclear-radiation level) Penetrations can be supplied with electrical conductors ranging from unshielded control and power wires to coaxial, triaxial, and other types of shielded cable Wire terminations are available that range from pigtails and pressure or crimp splice tubes to special high-voltage and shielded connectors The preassembled penetrations are tested at the factory for leak rate, conductor continuity, and insulation resistance The assembled and tested penetrations can be equipped with a leak-monitor pressure gauge and pressurized with inert gas, thus allowing the penetration to be monitored for leaks during shipment and installation as well as during operation. The preassembled penetration can be supplied for field installation with a welding ring or a bolted flange Figure 10 14 shows some of the features available in preassembled penetrations

10-5 GROUNDING AND SHIELDING

10-5.1 Electrical Noise Problem

Establishing a common ground may be the goal of electrical machinery design, but it creates problems in data measuring systems Ground-loop currents between pieces of equipment that are gounded at separate points to

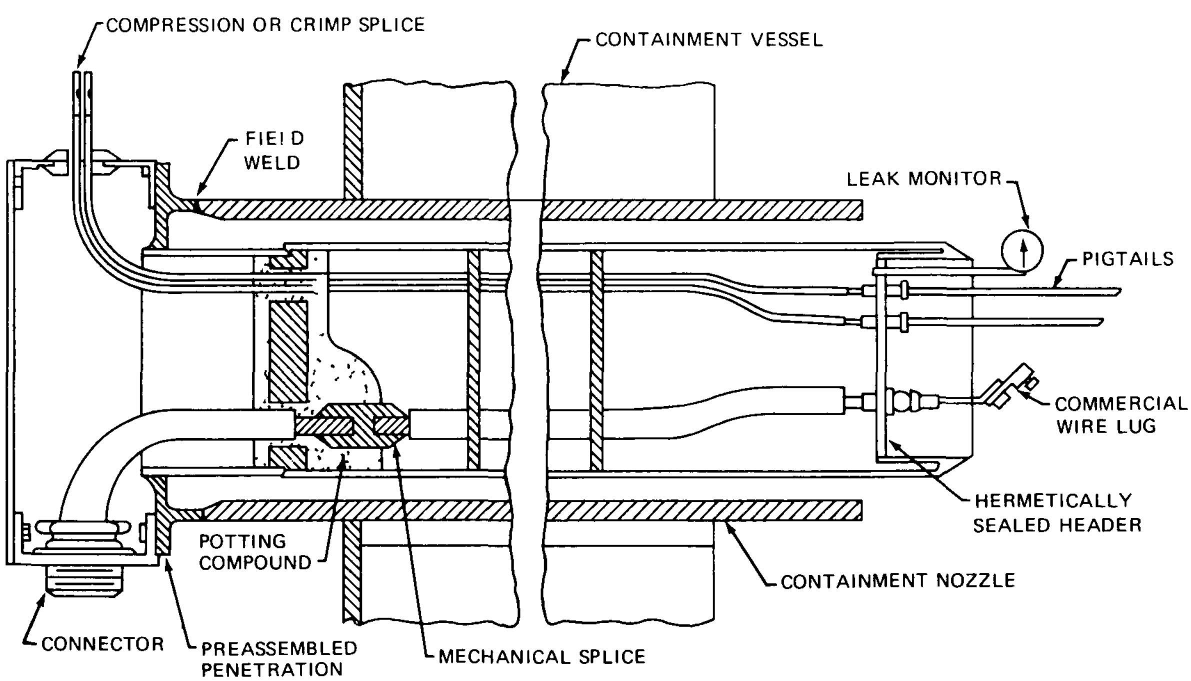


Fig. 10.14—Electrical penetration

a common ground introduce voltages that can affect measurements. Differences in potential between various points in a grounding system are not uncommon. These differences are caused by stray currents of any origin in the system, such as faults or transients on electric-power equipment If low-signal-level instrumentation has multiple connections to ground, either by intention or accident, these potential differences can result in ground-loop currents.

Difficulties attributable to grounding have been experienced in several nuclear-power-reactor installations and are difficult to locate For this reason a single-point grounding system is used in nuclear-power-plant reactor instrumentation systems An independent grounding system, isolated from the building grounds, has been installed The concept of an independent grounding system has advantages, however, it will not eliminate capacitive coupling or leakage resistance to ground, which also results in ground-loop currents.

The final design of instrumentation grounding depends on several factors, particularly the types of reactor instrumentation to be used and the nature of the reactor-building grounding system. Intricate reactor instrumentation systems almost always require some extensive modifications of grounding connections after the equipment is installed to obtain satisfactory operation

10-5.2 Grounding System for Reactor Building

The grounding system for a nuclear power station must provide for (1) instrumentation-system grounding, (2) ground connections for grounded neutral power systems, (3) a discharge path for lightning arrestors, (4) grounding of equipment frames and housings to protect equipment and personnel from dangerous electrical potentials caused by faults, and (5) communication and fire-alarm-system grounding

Figure 10.15 shows a system using a grounding grid for a nuclear power station. A properly installed grounding grid with its associated grounding rods or grounding wells should have a total resistance across the entire grid of less than 0.2 ohm. Some nuclear power stations may use means other than a grounding grid for grounding between buildings, containment spheres, and other major systems. The essential requirement is that all major systems, subsystems, and equipment be thoroughly grounded with ample size grounding conductors and proper grounding connections.

The grounding of a reactor building should be well established All grounding connections to stainless-steel equipment and piping should be made to stainless-steel stringers or saddles welded to the equipment with, if possible, thermite welds Grounding connections should be accessible Two or more grounding connections are recom-

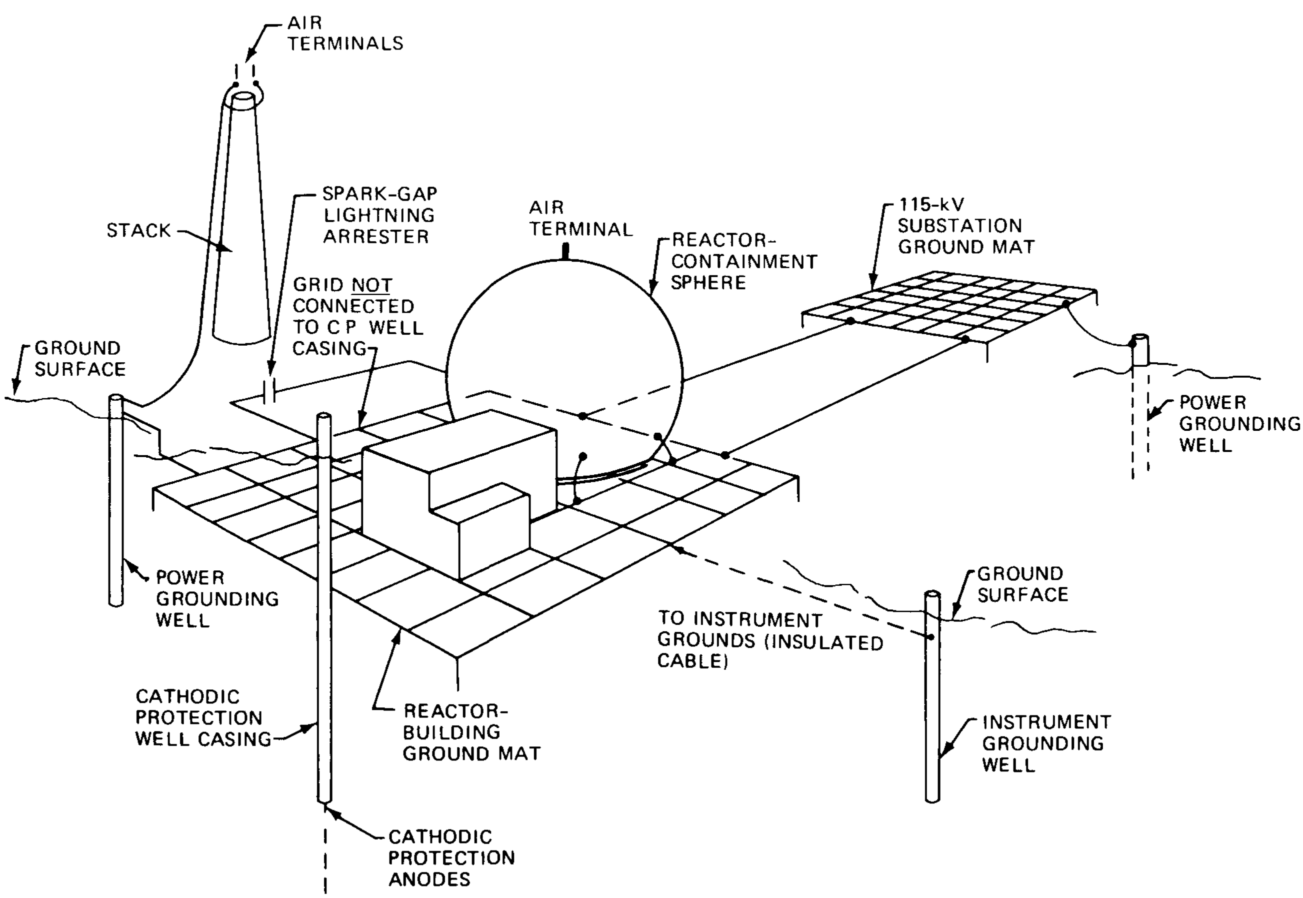


Fig. 10.15—Reactor-building grounding

mended for large equipment An equipment ground conductor should be included for all power circuits entering the containment. Penetrations of the independent instrumentation grounding conductors must be insulated from the containment

10-5.3 Grounding of Electrical Switchgear and Motor Control Centers

Improper grounding of the electrical switchgear, motor control centers, and machinery has been a source of electrical noise for reactor instrumentation A ground bus with a rating equal to the rating of the largest circuit breaker in the structure should extend throughout the largest of the switchgear assemblies. Each enclosure should be grounded directly to the ground bus The frame of each circuit-breaker unit should be connected to the ground bus through a separate ground contact device except when the primary disconnecting devices are separated a safe distance.

All other equipment requiring ground connections should be connected to the main ground bus by a copper bar or stranded copper cable The terminal fittings should be pressure-type solderless connections. All contact surfaces at splices should be silver-plated. The ground bus should have the same rating throughout the length of the cabinet and switchgear assemblies Tapered ground buses should not be used At each end of the switchgear assembly, cabinets and panels, and motor control centers, provisions should be made for connecting the ground bus to the station grounding system, these connections should consist of silvered sections of the bus

10-5.4 Grounding of Instrument Panels and Cabinets

Grounding the instrument panels and cabinets does not normally involve the massive amounts of metal required in grounding power systems. Nevertheless, the principles are the same, and all equipment cabinets, racks, etc., must be electrically bonded together and connected to a common ground point These connections should be either welded or brazed, particularly the connections to the ground bus from the equipment.

Each instrument-rack structure must be equipped with an electrical grounding bus This bus is generally a 1 25-in. copper bar (Fig. 10.4) mounted in the lower section of the structure. The bus is provided with a means for connecting it to the plant grounding system. Maximum resistance measured from the grounding bus to the building ground should be less than 1 ohm. Where electrical grounding of equipment is required, the structure frame must not be used as a ground path A conductor from the equipment to the ground bus must be provided.

So that electrical noise will not be induced in the instrument circuits, the circuit components must not use the equipment frame ground conductor as a ground. Currents in an equipment ground conductor can cause a voltage drop along the ground conductor, thus changing the point of reference for any circuit using the conductor.

Figure 10.16 shows the grounding system for a series of instrument racks and cabinets scattered throughout the reactor plant, including an instrument panel located in an adjacent building

The independent grounding system for reactor instrumentation shown in Figs 10 15 and 10.16 terminates at an instrument grounding well and is isolated from the building grounds. The most widely accepted method employs a single-point grounding system for reactor instrumentation that is terminated at one point to the building ground. This latter method provides a ground at the amplifier cabinets in the control room, however, in some nuclear stations the grounding may terminate at the reactor near the neutron detectors.

If an independent grounding system is used, it should be entirely separate from the power grounding system. Several separate areas or zones of instrumentation, divided as to type and location, should be provided with individual grounding buses or conductors that can be connected to the independent grounding system or left floating, as operating experience dictates

An independent ground system requires that all instrumentation be constructed with the signal grounds insulated from frames, chassis, power-supply grounds, etc. Separation of the two grounding systems involves some difficult practical problems For example, any sensor, amplifier, or other component normally grounded to its housing requires special construction, therefore the type of grounding system used must be decided in advance.

Because of inevitable ground-loop currents over any appreciable length of building ground bus and for added reliability, relays for control circuits should always be operated with one twisted pair of wires per relay. In addition, neither of the relay control wires should be grounded except at the controlling location since to do so may introduce circulating currents in the grounded wire as well as in the ground bus.

It is good engineering practice to install suppression devices on control relays to attenuate interference from relay operation. Such devices as diodes, thyristors, or capacitor–resistor networks can be used for this purpose.

10-5.5 Grounding of Neutron-Monitoring System

The neutron-monitoring system is a vital part of both the reactor control system and the plant protection system. The system must have proper grounding and shielding. Some factors involved in determining the proper grounding and shielding methods are

1 The length of the signal conductors between the detectors and amplifiers.

2 Methods used for internal grounding of detectors and amplifiers

3 Methods used for grounding the electrical distribution systems of the building

Several types of neutron sensors are widely used by the nuclear industry (see Chaps 2, 3, and 4) Some variation exists in the manufacture of nuclear-instrument circuits in regard to the method of providing internal signal grounding Some nuclear instruments have the signal ground on the chassis, whereas others have the signal ground insulated from the chassis ground.

The following discussion concerns the grounding systems currently accepted by the nuclear industry in operating power plants

(a) Grounding of Signal and Control Cables. The following must be kept in mind when considering the methods to be used for grounding neutron-monitoring systems

1 There is always some potential difference between two points on the earth's surface

2 Because a cable is connected to a ground bus, it is not necessarily a good ground

3 Ground connections are not always noise-free

Since it is virtually impossible to eliminate noise and induced current in ground connections, the proper procedure to follow in wiring practice consists of routing the inevitable currents around the equipment in such a manner that the signal input is not affected

Figure 10 17 shows a typical sensor—preamplifier—count rate-meter combination as often installed, along with some of the sources of error and interference due to potential differences generated by the system at various points Figure 10 18 shows the same system with different grounding connections to eliminate ground loops in sensitive circuitry If the ground loops shown in Fig 10 17 are not removed, a "battery" voltage composed of noise is impressed on the opposite ends of the cable shield, thus effectively causing a current in the shield that may add to or modulate the desired signal Ground loops are eliminated by isolating the system from ground except at the console This is only one of several noise-rejection grounding techniques available Others are electric differential input techniques and the use of balanced lines [see Sec 10-5 6(b)]

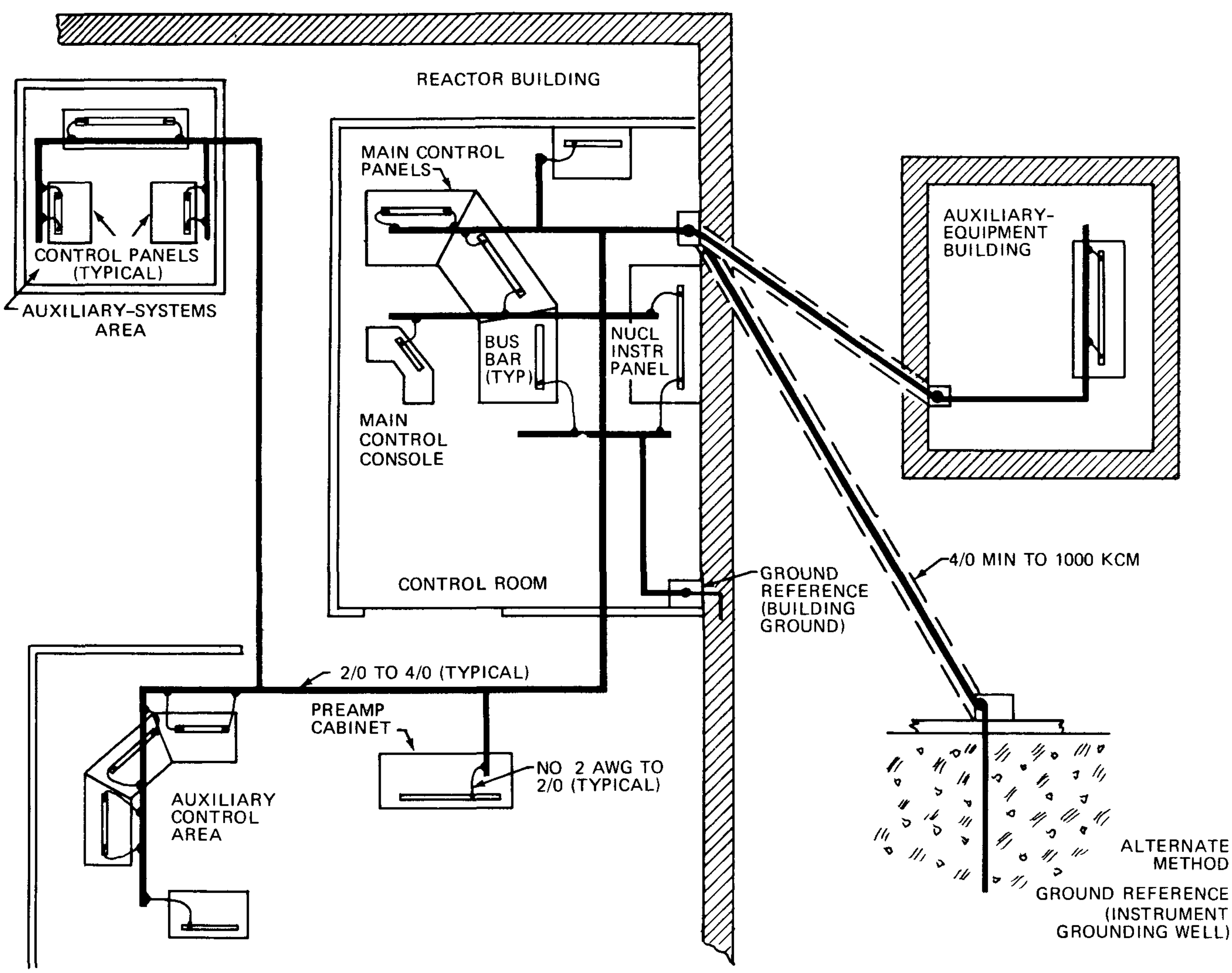


Fig 10.1o—Grounding instrument panels and cabinets

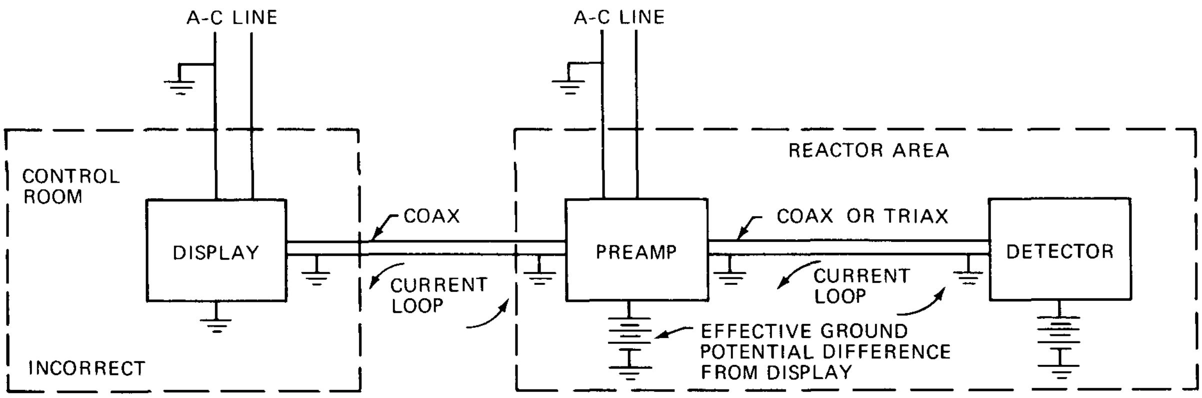


Fig. 10.17—Incorrect grounding system

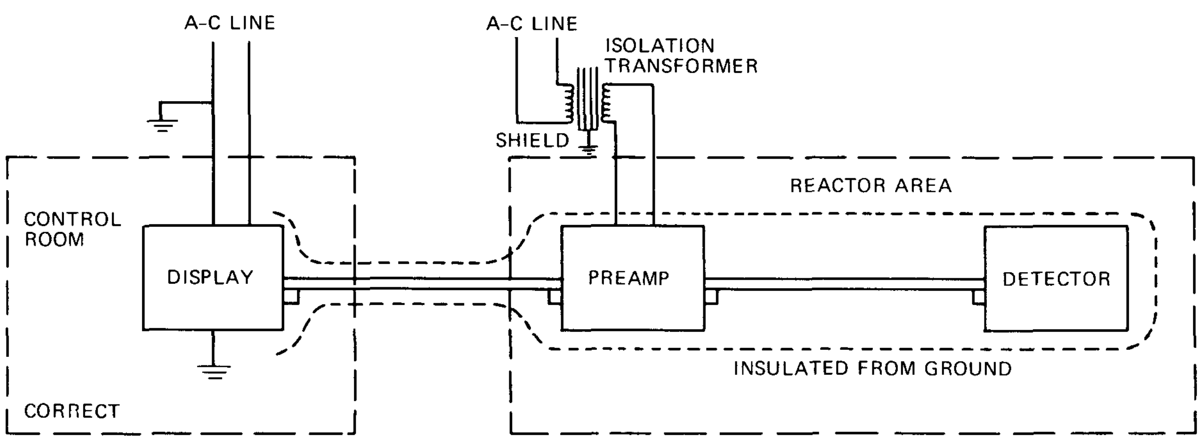


Fig. 10.18—Correct grounding system.

(b) **Grounding and Shielding Practice.*** We made a survey of 10 major nuclear power plants in the United States, including 4 of the largest operating plants, according to MW(e) output in service as of January 1969 The purpose was to collect and compile data on methods used in these plants for grounding and shielding the neutron-monitoring systems. Each had experienced noise problems in the neutron-monitoring channels

Figures 10.19 to 10.21 illustrate the grounding and shielding methods used by the nuclear power plants surveyed. Numerous modifications were made on the equipment after the plants were constructed. Such modifications as adding line filters, radio-frequency (r-f) grounds, and π filters were made to the equipment to suppress noise and interference In a majority of the plants surveyed, a single-point ground system was used either by grounding the system at the nuclear-instrument cabinet or at the neutron detector. Other nuclear power plants provided grounding at both the neutron detector and amplifier cabinet

*At the end of Sec. 10-5 5(c), the most widely used and preferred grounding system used in the nuclear industry is described.

Figure 10.19 illustrates a grounding method in which the neutron-monitoring-system ground is made at the amplifier cabinet The pulse amplifiers, counting circuits, and other associated circuits are grounded to the building ground. Generally instruments in the cabinet are grounded to the building ground by connecting all instruments to a bus bar in the cabinet The grounding bus bar is connected to the building ground through a grounding cable

The entire neutron-monitoring system from the pulse amplifiers to the neutron sensor is insulated and floated above ground. This method prevents circulating ground currents from causing noise and distortion in the electrical signal being transmitted to the control room.

Figure 10.20 illustrates a method where the single-system ground is made at the sensor or at the preamplifier The signal-cable shielding and ground side of the signals in the amplifier cabinet are all insulated and floated above ground.

Figure 10.21 illustrates a method where multiple-system grounds are used. Grounding takes place at both the amplifier cabinet and the preamplifier The neutron-detector cable may be grounded at the reactor or ungrounded the full distance to the preamplifier

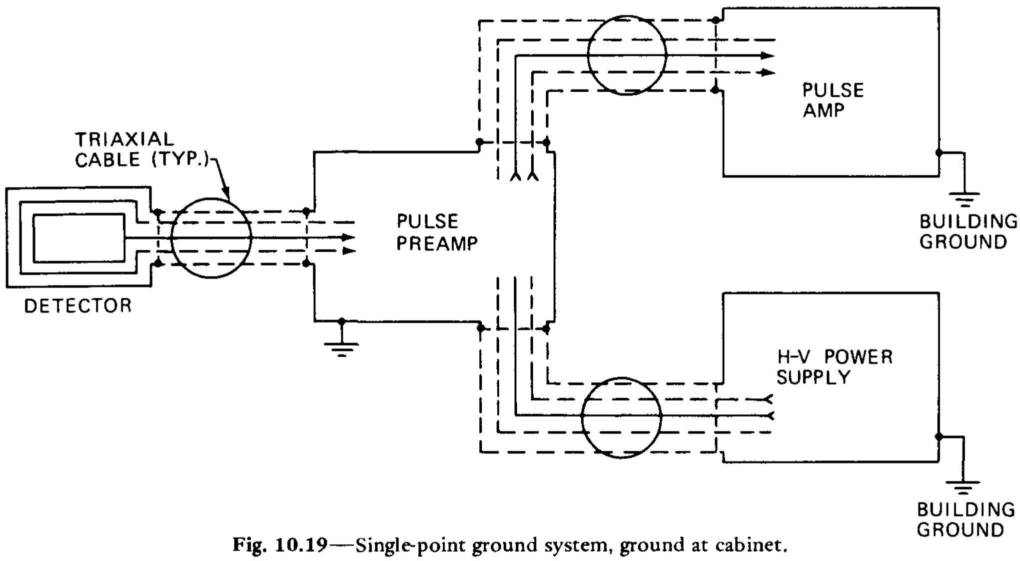


Fig. 10.19—Single-point ground system, ground at cabinet.

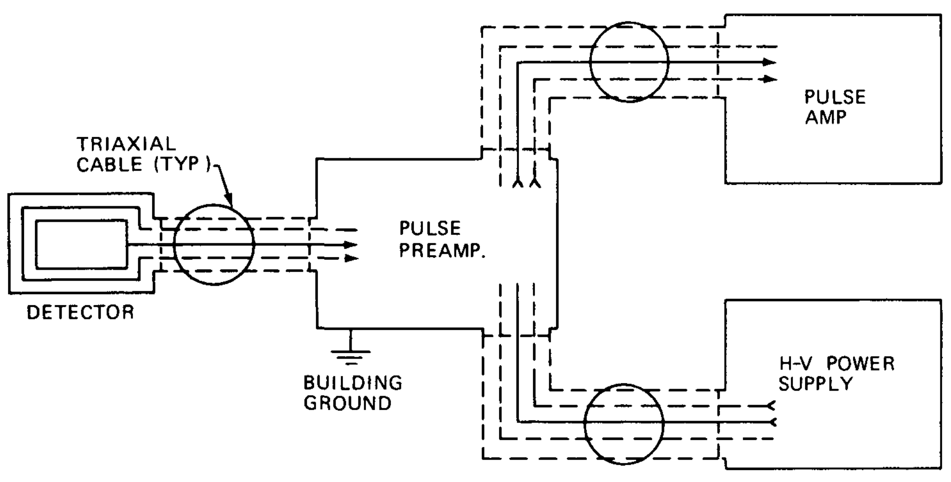


Fig. 10.20—Single-point ground system, ground at preamplifier.

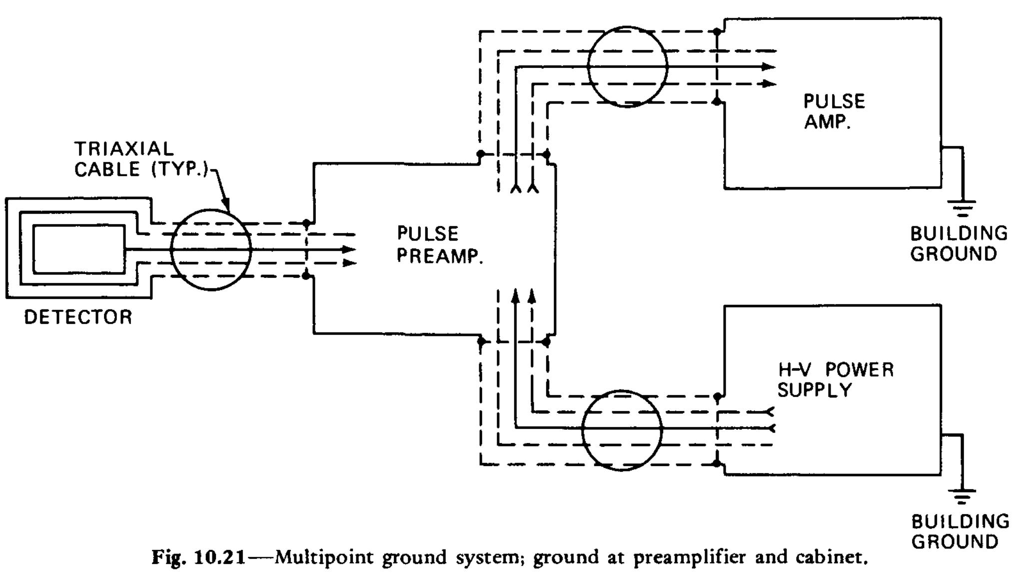


Fig. 10.21—Multipoint ground system; ground at preamplifier and cabinet.

(c) Engineering Data Sheets, Grounding and Shielding. Engineering data sheets, included as an appendix to this chapter, explain the methods used for grounding the start up channels at 10 major operating nuclear power plants in the United States Included with the system descriptions are comments on operating problems and modifications made to the equipment to prevent noise and interference. These data sheets should be used by both the design and construction engineer in selecting the best method of grounding an instrumentation system. Information is included on how to avoid pitfalls that have been encountered in nuclear power plants and, more important, how to avoid having to make extensive modifications after the plants have been constructed

Grounding and shielding problems in nuclear plants are often associated with the neutron-monitoring start-up channels A number of mechanisms in a nuclear plant generate r-f and low-frequency noise, which finds its way into the neutron-monitoring start-up channels This noise generates signals that must be cut off by a higher discriminator voltage setting, thereby materially reducing channel sensitivity If rate amplifiers and reactor trip circuits are used with the start up channels, inadvertent scrams result where noise increases As the reactor power is increased and current-measuring channels take over from the pulse count-rate channels, the effect of noise is much less important

The following conclusions can be drawn from the information contained in the engineering data sheets

1 A single-point grounding system, grounded to the building ground at the amplifier cabinet with the signal-cable shields and neutron sensors floated above ground, appears to be most widely used by the nuclear industry The entire system is grounded at one point

2 The use of triaxial cable in place of coaxial cable is becoming standard throughout the nuclear industry, thus improving the suppression and rejection of noise and interference in the neutron-monitoring channels

3 In the use of coaxial and triaxial cable, it appears that the required care is not used in the installation of cable connectors and terminations during the construction phase of the plant Rework of cables and connectors is often necessary after plant construction has been completed

4 Eliminating noise at the source is a task that is quite frequently done by operating and maintenance staffs at nuclear plants This task sometimes involves days of tedious work to isolate and eliminate the source of noise Faulty a-c and d-c machinery, relays, switches, motor starters, etc , are sources of noise

5 Techniques, such as the use of line filters, r-f filters, and other electronic means, are being used by some nuclear plants to reject and suppress noise in the neutron-monitoring channels

(d) Noise Filter Design. There are times when a rapid "fix" is needed on the signal input or power input of a piece of instrumentation to eliminate high-frequency noise present on the line Although the use of commercial radio-frequency interference (RFI) and line filters is recommended, there are times when a simple 18 dB/octave, low-pass π or T filter can solve a noise problem Figure 10 22 shows design details for networks of this type

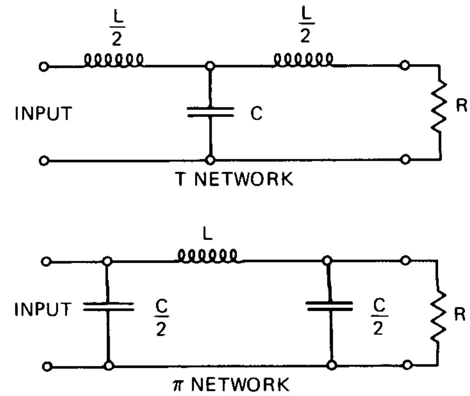


Fig 10 22—Typical π and T networks R, load resistance (ohms) $L = R/\pi f_c$ (henries) $C = 1/\pi f_c R$ (farads) f_c, frequency at cutoff (hertz)

When a filter of this type is installed, it should be placed in its own metal box where possible If not possible, at least the input and output leads should be separated Such a filter can be used either as a low-level-signal filter or as a high-level power-line filter if the components are suitably rated These filters may be placed in power input lines to any piece of equipment in a neutron-monitoring system and may also be used in signal input leads to equipment as long as the desired input-signal frequency is below f_c These filters are not used in pulse amplifier inputs

10-5.6 Process-Monitoring Instrumentation

Process monitoring instrumentation refers to those systems outside the neutron-monitoring group which indicate, record, and control all operational systems within a nuclear reactor facility A channel includes the primary sensor, the interconnecting conductors, the measuring circuit, and displays The primary sensors are located at a point in the process system The measuring-circuit instrumentation (amplifier, recorder, power supply, etc) is located in the main control room or in an auxiliary control area

Grounding and shielding of instrumentation systems accomplish two major purposes (1) proper operation of the instrumentation by reducing or eliminating erroneous signals and (2) personnel safety with respect to hazardous operating parameters

(a) Personnel Safety. Equipment grounding provides safety for personnel who might come in contact with the equipment As far as instrumentation is concerned, two main hazards exist for which protection must be provided electrical shock and heat All external surfaces should be at

ground potential and at a temperature less than 120°F Where this is not practical for the component itself, protection for personnel safety should be provided by completely surrounding the instrument or installation The National Electrical Code gives rules for grounding that have wide commercial application These same rules, with more details added by individual manufacturers or by special applications, can be used to ensure proper personnel protection for most types of installations and equipment

(b) System Problems (Involving Erroneous Signals) In instrument systems, good stable grounds are needed to provide a measurement reference, a solid base for the rejection of common-mode signals, and effective shielding for low-level circuits

A stable reference for measurement can be provided positively in only one way by referencing all measurements to a single-point ground However, this is not possible except through the use of a floating system (i e , all system components completely isolated) A floating system also provides a firm base for the rejection of common-mode signals Compared to single-point grounding, the instrumentation reference ground is inferior, however, it is more generally used The instrumentation reference ground uses a grid or bus that is maintained, as nearly as possible, at a consistent fixed electrical potential Circuits and systems using this type of a ground bus system must be grounded at one point only Grounding the system at more than one point will create ground loops, which will cause erroneous signals to be introduced into the equipment, either directly through one of the signal leads or induced through the shielding

Since in most instances the primary element is located some distance from the measuring circuit, there most certainly will be a difference in ground potential or reference Also, owing to the distances involved, sizeable differences in conductor impedance to ground could exist These conditions cause two of the main problems in low-level measuring circuits, ground loops and common-mode signals These two problems can be dealt with either by eliminating the conditions that cause the problem or by rejecting the erroneous signals that are produced as a result

Some elimination remedies follow. These remedies are usually difficult to implement [see Fig 10 23(a)]

1 Interrupt the continuity of the ground loop while preserving the path for the sensor signal [i e , increase the ground impedance (Z_g) ideally to infinity]

2 Reduce the resistance of the ground conductor (R_g) to zero [This effectively shorts the total ground potential (V_{AB})]

3 Break the ground-loop current path (I_g) by floating the system (i e , isolate the sensor or the amplifier and power supply grounding at a single point only) Note If the amplifier is used to feed signals to a recorder, analog-to-digital (A/D) converter, display, or other data handling device, the path of the ground-loop current may be reestablished through these devices

Generally, some method of rejecting the erroneous signals is more practical than the elimination remedies discussed above One of these rejection remedies is to interrupt both the signal and ground-loop currents and then transmit the signal while blocking the ground-loop current Two common methods to achieve this are

1 A transformer and a modulator—demodulator can be used [see Fig 10 23(b)] Some of the advantages of this method are (1) a wide voltage range of both signal to amplifier ground and signal to common mode can be handled and (2) error rejection is independent of closed-loop gain Some of the disadvantages are (1) the bandwidth is limited by the modulating frequency, (2) output errors are induced by intermodulation, and (3) error-reducing feedback cannot be used without reestablishing the ground-loop path

2 A switched capacitor can be used [see Fig 10 23(c)] This method has the same advantages and disadvantages as the transformer method with the added disadvantage of poor frequency response

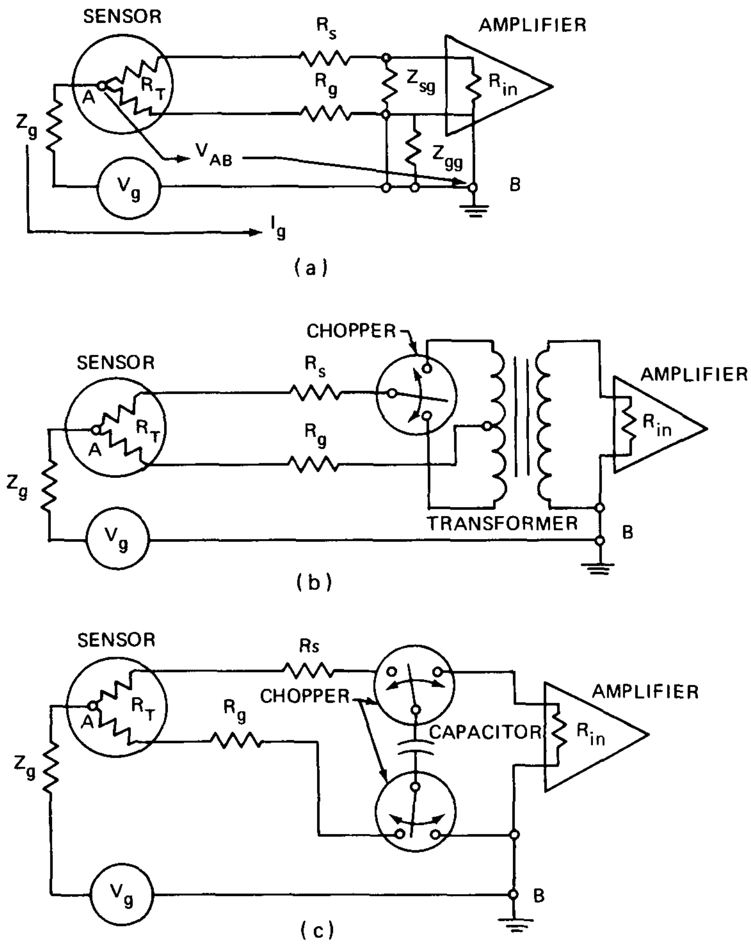
A popular method of curing ground-loop problems is by using a differential amplifier Identical fractions of the ground-loop voltage are applied to the inverting and noninverting inputs of the differential amplifier This causes the ground-loop voltages to be seen as a common mode voltage, and, as such, they are rejected (to a degree depending on the particular amplifier used) This method also becomes directly applicable to differential transducer signals that are imposed on relatively high levels of common-mode voltage Here using the differential amplifier allows extraction of these low-level signals from the high-level common-mode voltages

Although differential amplifiers in general have extremely good common-mode voltage rejection, they are not perfect Certain system parameters affect the level of these common-mode signals and can be manipulated to help reduce the problem Ideally, the common-mode signals can be eliminated by either of two methods [Fig 10 23(a)] reducing the conductor resistances of both the signal and ground (R_s and R_g) to zero or increasing the impedance to ground of both the signal and ground conductors (Z_{sg} and Z_{gg}) to infinity Practically, this same result can be attained by making the ground and signal conductor resistances (R_g and R_s) equal and the signal and ground impedances to ground (Z_{sg} and Z_{gg}) equal This can be accomplished by observing the following rules

1 Use a "balanced line" between the sensor and the amplifier (i e , equal resistance and impedance in both the signal and ground conductor between the sensor and amplifier and the conductor and ground) This can be done most easily by using a shielded twisted pair of conductors for transmission of the signal from the sensor to the amplifier

2 Keep signal cables as short as possible

3 Use a source with a center tap if possible



R_s	SIGNAL-CONDUCTOR RESISTANCE
R_g	GROUND-CONDUCTOR RESISTANCE
Z_g	GROUND IMPEDANCE
V_g	GROUND POTENTIAL
Z_{sg}	IMPEDANCE SIGNAL-CONDUCTOR GROUND
Z_{gg}	IMPEDANCE GROUND-CONDUCTOR GROUND
I_g	GROUND-LOOP CURRENT
R_{in}	AMP INPUT IMPEDANCE
R_T	SENSOR RESISTANCE (TWO COMPONENTS)
V_{AB}	TOTAL GROUND POTENTIAL $(I_g Z_g + V_g)$

Fig. 10.23—Ground loops and common-mode signals.

Both the signal source and the cable impedance have a shunting effect on the input signal to the amplifier. Having equal impedances at each end (sensor and amplifier) idealizes maximum power transfer; however, in transferring voltage signals, this is detrimental owing to line losses caused by system impedance. Therefore, if low-impedance sensors and high-input-impedance amplifiers are selected, the amount of signal current can be kept at a minimum, thus minimizing system error due to voltage drop. For systems where higher sensor impedance is required, correspondingly higher amplifier input impedance should be used. Good practice dictates that the input impedance of the amplifier should be at least 10 times the output impedance of the sensor.

The following general rules should be observed in the installation of low-level signal systems:

1. Avoid ground loops.
2. Provide a stable signal ground and a good signal-shield ground.
3. Ground the signal circuit and the signal shield at one common point.
4. Never use a signal-cable shield as a signal conductor.
5. Ensure that the minimum signal interconnection is a uniformly twisted pair of wires with all return current paths confined to the same signal cable.

(c) Primary Elements (Sensors and Transducers). Observance of the following basic rules with respect to

primary elements will eliminate or alleviate many of the problems associated with grounding and shielding of low-level-signal transmission systems

1 Use low signal-source impedance devices whenever possible This not only reduces system noise but also minimizes the shunting effect at the input of the measuring circuit

2 Use a center tap on the sensor output whenever possible This permits the signal-cable shield to be firmly fixed and operated at a minimum potential with respect to the signal pair, thus providing the most effective shielding

3 Use special configurations, such as the noninductive strain gage, to reduce or eliminate interference problems from electromagnetic fields, magnetic fields, and other types of induced noise

4 Ensure proper isolation from all mounting hardware for isolated sensors

(d) Interconnection. Observance of the following basic rules with respect to interconnection will eliminate or alleviate many of the problems associated with grounding and shielding of low-level-signal transmission systems

1 Use a "balanced line" between the sensor and the amplifier (i e , equal resistance and impedance in both the signal and ground conductor between the sensor and amplifier and the conductor and ground) Use twisted, shielded pair

2 Keep signal cables as short as possible

3 Never use splices in signal leads

4 When using connectors (multipin) (1) use adjacent pins for signal pairs, (2) carry shield through pins adjacent to signal pins, (3) use spare pins as a shield around signal pair by grounding them together and then to the signal shield

5 Separate low-level-signal cables and power cables by the maximum practical distance and cross them, where necessary, at right angles

6 Isolate signal cables with conductive conduits and wireways

7. Ensure that spare shielded conductors in signal cables are single-end grounded, with the shields grounded at the opposite end

(e) Measuring Circuit. Observance of the following basic rules with respect to the measuring circuit will eliminate or alleviate many of the problems associated with grounding and shielding of low-level-signal transmission systems

1 Ensure that the measuring circuit has (1) high common-mode signal-rejection ratio, (2) high input impedance, (3) good d-c stability, and (4) wide bandwidth

2 In terminating the signal cable to the measuring device, use twisted leads exposed for as short a distance as possible from the shielded cable

10-5.7 Radiation-Monitoring Instrumentation

Most radiation-monitoring equipment requires the use of remotely located detectors connected to the monitor and control section by a multiconductor cable Generally, these systems use a common ground for signal reference, power, and chassis A separate conductor as well as the shield for the signal leads should be used between the control unit and the detector unit The manufacturer's recommendation for grounding and shielding should be followed explicitly, and care should be taken to ensure that the mounting and assembly of components is proper Most of the problems and their solutions discussed earlier in this chapter are directly applicable to radiation-monitoring instrumentation

10-5.8 Grounding, Shielding, and Connection of Computers and Digital Data-Holding Systems*

The same general principles of isolation of signal leads and shielding of sensitive circuits apply to both analog and digital systems There are, however, distinct differences in the techniques of interference suppression in digital and analog systems

Because of the higher signal levels and the high-frequency signals used in digital devices, standing waves, stray inductances and capacitances, RFI, and line propagation delays may become problems if not carefully taken into consideration Many digital control signals have rise times in the nanosecond range, so there are frequency components in the hundreds of MHz range Connecting cables must be treated as transmission lines to pass this information from circuit to circuit

The points discussed in the following should be considered to provide suitable interconnections between units of high-speed digital systems

1 Cables carrying frequency components above 100 kHz should be terminated properly, i e , both ends having an impedance match between the cable and circuit input or output Ordinary wire has a characteristic impedance of about 150 ohms at frequencies where standing waves become a problem, so this is a good value to choose as a terminating resistor when an approximate first choice is called for If coaxial cable is used, the terminating resistor should match the cable impedance The output of the equipment must be able to supply the current to drive the characteristic impedance of the cable under continuous load conditions, if long-term, constant d-c signal levels are expected [Fig 10.24(a)]

2 Another method of terminating a data cable is shown in Fig 10 24(b) A Zener diode is used to clamp the reflected signal to ground and limit signal excursions above the desired input signal This circuit is useful in the control of standing waves where not enough continuous power is available to supply a low terminating impedance and a series of high-speed single-polarity pulses is to be sent along a line Figure 10 24(c) outlines the same technique except that the grounding diode is returned to a −0 7-volt line to

*See Chap. 9

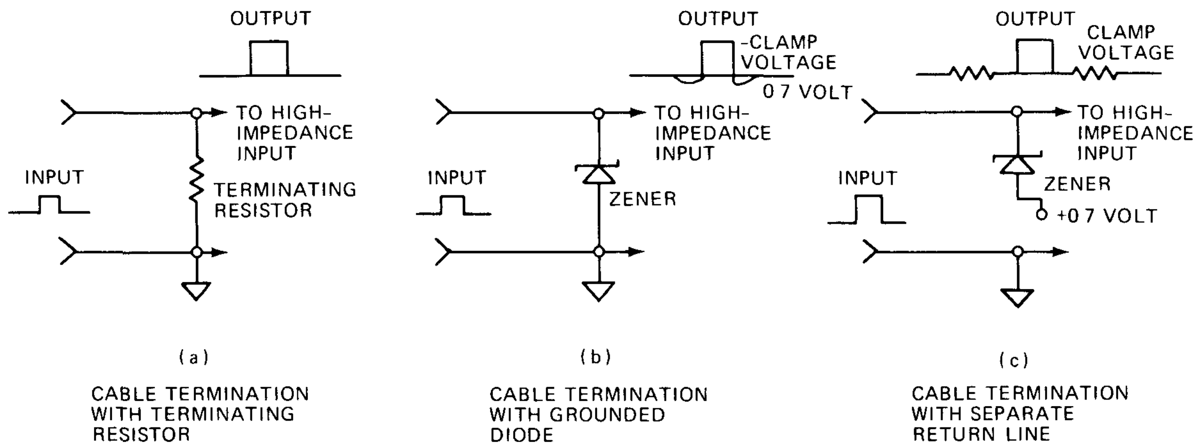


Fig 10 24—Data system terminations

ensure that the reflected wave on the line is clamped to a value approaching zero.

3. The usefulness of a digital approach to instrumentation derives partly from the fact that a signal is either off or on, and all modern digital systems have varying degrees of sensitivity to noise pulses in the circuit "Noise immunity" is usually defined as the minimum voltage difference between the higher O-voltage level and the lower 1 level, this typically ranges between 1 and 10 volts Because of this, millivolt or microvolt interference levels are of no consequence, so many of the elaborate shielding and guarding techniques described in this chapter are not needed for digital systems Inputs to pulse-sensitive devices, such as some flip-flops, should be protected by shielding or other means against spikes on the input lines, however, the rapid rise time of an induced noise spike may cause spurious triggering even though it is less than the specified d-c noise immunity level *

(a) Data-System Power and Ground Connection. In general, a small computer or other digital system may be connected to both power and ground by following standard electrical code procedures It is important, however, that the various cabinets of the system be connected together by a low-resistance bus, such as No 4 AWG copper wire, and the system be tied to a good earth ground The steel frame of the building in which the computer is housed is a good ground, or, if this is not convenient, a large water pipe is also a good ground. The ground wire should be run along with the signal cables when it is used to interconnect different portions of the system. A good a-c ground for a signal return is important As an example, the d-c resistance of a bond strap 0 002 to 0.003 in. thick, 1 in. wide, and 1 to 5 in. long would be negligible at direct current but would be about 0 1 ohm at 10 MHz and 15 ohms at 1000 MHz. This relatively large change in impedance with frequency indicates there is no substitute for a short grounding connection with a large cross section and low self-inductance

The quality of the ground depends on the type of system since a self-contained system (one having no remote transducers or A/D converters) is more immune to noise than, for example, a system accepting thermocouple signals directly. For this reason all the interference-reduction ideas mentioned in this chapter should be applied to any system that has many small signal circuits

10-5.9 RFI and Electromagnetic Shielding

An enclosure that has high conductivity and completely surrounds a piece of equipment forms an excellent shield against RFI radiation, provided it is grounded A useful rule of thumb, however, is that below 2 to 3 MHz interference from one component to the next in a system is primarily electromagnetic (i.e , the coupling is by magnetic and electric fields), whereas above this frequency radiated (r-f) energy is the primary carrier of interference This means that low-frequency shielding should be mostly composed of ferromagnetic materials to eliminate magnetic fields and high-frequency shielding should have high conductivity since magnetic fields are not significant Often, if magnetic materials, such as steel, are used at high frequencies, the ohmic resistance they have (compared to materials such as silver) causes potential differences and subsequent electric fields to be set up in shields around sensitive circuits, thereby nullifying some of the effectiveness of the shields In the gray area (a few megahertzs) composite shielding, such as copper-coated steel, is often used. These shields should be used wherever the adjacent equipment or components are sensitive to interference (e.g , coaxial shields applied on input leads and shields placed over any gaps in the case if either enclosed or external circuits are r-f radiation-sensitive).

Though shielding is effective in the elimination of interference, additional suppression is sometimes added by filtering inputs, outputs, and power connections to elimi-

*R. E. Matick, *Transmission Lines for Digital and Communication Networks,* McGraw-Hill Book Company, Inc , New York, 1969

nate noise riding in on those lines. This can be accomplished by placing feed-through capacitors or other filters on lines entering the shielded enclosure where the affected equipment is located and by using diode–capacitor isolation networks on power-supply leads where they enter the instrument circuit-board area within each individual piece of equipment This ensures decoupling of equipment

The power source for instrumentation equipment should be free from spikes, jitter, and poor regulation. Without proper filtering and regulation, any transients that occur will couple through power transformers in equipment (through interwinding capacitance) and cause difficulty in sensitive circuits This problem is usually eliminated by a power-line filter which may be no more than a 0.02-μF, 600-volt capacitor connected from each side of the line to ground.

In summary, interference can, and usually does, enter equipment wherever there is an unprotected entryway It is up to the equipment installer to make sure that no signals other than those desired by the circuit designer enter the equipment To accomplish this task, he must be aware of the many techniques available for suppression of interference.

10-6 INSTALLATION OF REACTOR CONTROL, DISPLAY, AND RECORDING EQUIPMENT

The control, display, and recording functions of any system constitute the major portion of the instrumentation Man is linked to the machine by the displays and controls, and he uses the recorded data to analyze and improve operation.

10-6.1 Control–Display Relation

Proper relation of the control function to the display is the basic purpose of the system. The function of the display system is to provide information to enable the operations personnel to make decisions regarding plant and system operation. The grouping of control–display components should always reflect the use of human factors engineering The maximum efficiency with which data can be perceived and the control action initiated indicates the effectiveness of the control–display design

10-6.2 Installation of Hand Controls

The installation of hand controls should utilize human-factors engineering Considerable thought must be given to aspects such as type and placement of controls as related to function Likewise, operator qualifications and limitations should be considered. All controls should be mounted to withstand the rigors of normal use and possible abuse Controls affecting plant or system safety should be protected from accidental actuation Controls that are subject to extreme environments should be protected, including the marking and identification of the control.

10-6.3 Installation of Specific Controls

Nuclear reactor instrumentation systems use some specific controls that are unique, not necessarily in the components used, but rather with application and interactions of the controls When components are being selected, the function of components being controlled as well as the function of the controlling component should be considered. Such components as push buttons, selector switches, and level switches have specific applications Factors such as speed of response and resolution of control should also be considered in selecting specific components. Control for such components as control and safety rods should be selected and installed in the prime control areas of the main control console, with primary and secondary loop and auxiliary controls being installed according to frequency of use and importance to the system.

10-6.4 Installation of Visual Display and Recording Equipment

The location of all equipment that must be visually monitored should be given priority consideration. The physical abilities and limitations, as well as the psychological characteristics, of the operating personnel should be taken into account Viewing distance and angle as well as illumination must be considered, along with character size, configuration, and background, to avoid eye strain, inaccurate perception, and glare Audible display should be considered in areas where there is a possibility of failure to give the necessary visual cognizance for critical and semicritical parameters

Compatibility with related controls and possible perceptual interaction with other displayed information are important factors in the installation of effective displays Recording equipment also used for displaying information should adhere to the criteria for any display equipment. In addition, recording equipment must be installed so that routine operational maintenance, such as inking and chart-paper replacement, can be accomplished with maximum efficiency

10-6.5 Installation Recommendations

The installation of an instrumentation system involves the use of a combination of practices to achieve the desired results, both from a functional and an aesthetic standpoint (see Fig 10.25) Instruments and components should be grouped and mounted so that they are aesthetically neat and orderly as well as logically functional. Instruments with varying front panel dimensions should be mounted so that the instrument case tops are level Switches and pilot lights should be mounted with the center lines even Instruments with hinged doors should be mounted so that there is no interference between adjacent instruments. In general,

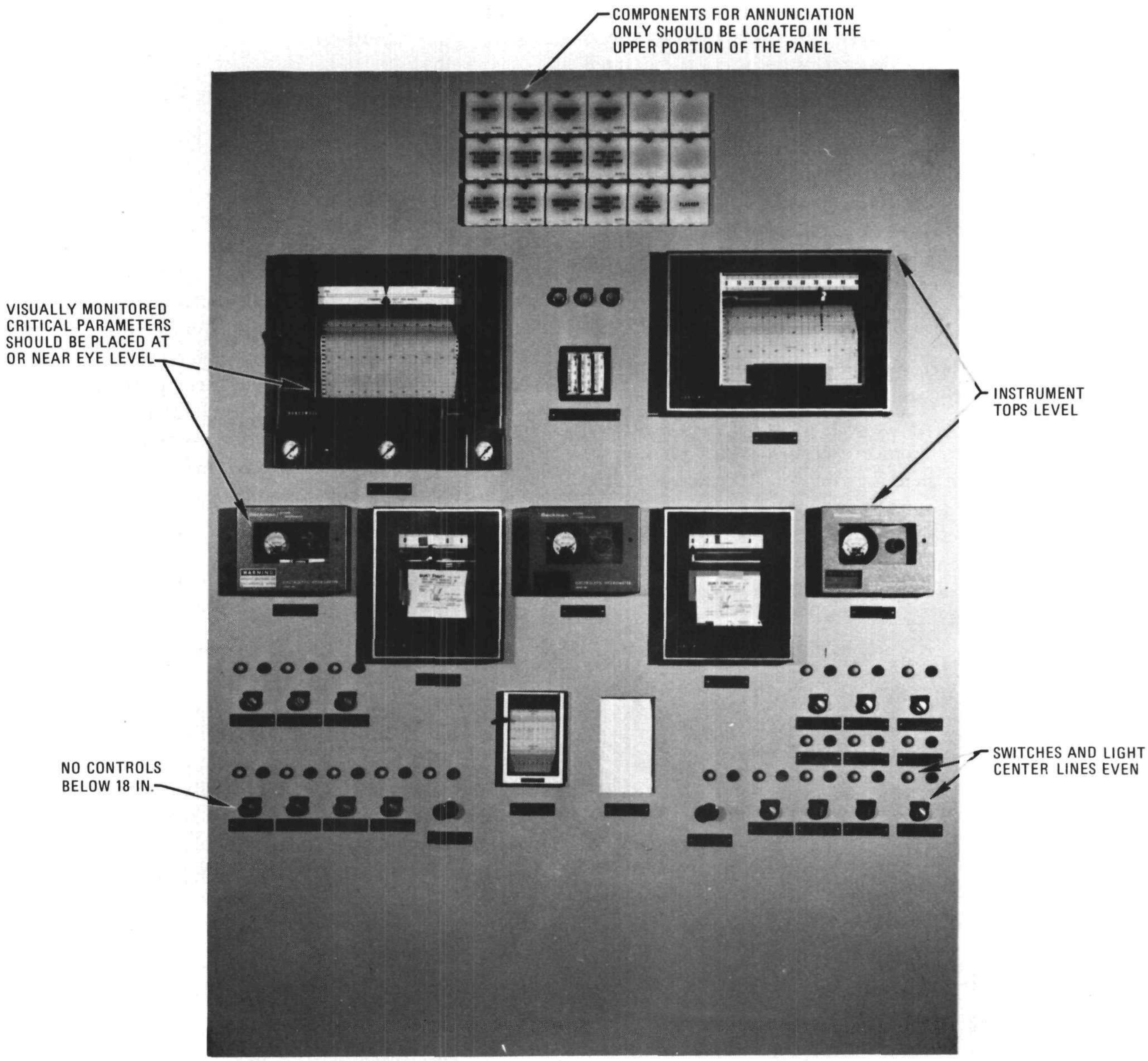


Fig. 10.25—Installation of layout for display and control.

controls, displays, and recorders should be placed in the prime functional areas of the panels in which they are mounted. Components that require visual readout should be as close as possible to eye level. All control actuation components should be kept within easy reach (at least 18 in. above floor level).

10-7 INSTALLATION FOR EASE OF MAINTENANCE

10-7.1 Reliability and Maintainability

The value of any instrumentation system is largely determined by its use factor, i.e., the amount of operating time compared to the amount of downtime attributable to instrument or component failure during normal operation of the system. The use factor is a function of both the reliability and maintainability of the instrumentation system. Reliability is concerned with the *frequency of failure*, whereas maintainability is concerned with the *duration of failure* (see Chap. 11).

Although in recent years gains have been made in component reliability, they have almost always been exceeded by increases in system complexity. With the certain evolution of MSI and LSI (medium-scale and large-scale integrated circuits), which will increase complexity on a component level without reducing reliability, systems reliability in the areas of total plant control and monitoring will begin to improve. Presently, the day of totally reliable, maintenance-free systems appears to be still

in the future This condition has forced the electronics industry to develop the technology of instrument and system maintainability. Although instrument manufacturers have always considered easy maintenance as a desirable feature, the complexities of today's systems have dictated renewed interest and analysis. Achieving the shortest possible problem analysis and repair time (maintainability) should be considered one of the most important goals in equipment design and installation.

10-7.2 Reliability

Reliability is primarily a function of instrument and system design However, two aspects of installation can affect reliability the quality of materials and of workmanship (particularly in system and component interfacing and interconnection) and the operating environment

Problems in the quality of installation can be minimized by the employment of highly qualified, competent labor and the use of highly reliable installation hardware Using crimp-type terminals and connectors with the proper tooling greatly reduces termination problems Installation plans with step checkoff sheets or diagrams can improve installation efficiency and accuracy

Many reliability problems associated with installation are created by unsuitable environmental conditions. In determining how instruments, components, and systems are to be applied, the environmental parameters must be carefully considered during installation. The manufacturer's recommendations concerning installation and operating conditions, such as temperature, humidity, cleanliness, electrostatic and magnetic fields, vibration, and nuclear radiation fields, must be given close attention. Where conditions exist that are contrary to those recommended, special packaging, cooling, etc , should be provided as required.

10-7.3 Installation for Maintainability

Assuming that all the equipment in the system is installed in accordance with the manufacturer's recommendations, system performance now becomes a function of system maintainability.

(a) Unit Design and Equipment Spacing. Several factors must be considered in the design of the system installation. The type and location of the plant determines the availability of maintenance personnel. Space and access considerations for the physical layout of the plant are influenced by the number and type of operating personnel on site during operation and also the type of test equipment required for maintenance Unit design is also affected by the general maintenance philosophy for each instrument or system, such as repair vs replacement, components vs modules, and on-line vs. off-line maintenance. This, in turn, is governed to a large extent by the availability of replacement parts

(b) Cables and Connectors. When maintenance requires removal of the equipment from its operating configuration, the ease with which the removal is accomplished is a prime factor in successful maintenance. All cables and connectors should be installed for easy removal without the use of special tools. It should always be possible to remove equipment without disturbing the operation of adjacent equipment Likewise, cables and connectors of the operating equipment should not interfere with the removal of the defective equipment Connectors should be indexed and coded so that incorrect interconnection is virtually impossible.

(c) Displays for Maintenance. One of the quickest ways to determine maintenance requirements is through the use of a self-annunciating or display system. Where practical, this type of failure alarm system should be used In instrumentation systems where self-checking is used, the installation of the display unit should blend as far as possible with the operational configuration of the system and should become conspicuous only when an alarm is actuated

10-8 SUMMARY OF INSTALLATION PRACTICES

Table 10.10 has been prepared as a summary of the material presented in this chapter It is intended to furnish the reader with an easy reference on sound installation practices and problem areas in the installation of reactor instrumentation systems Opinions on sound installation practices are diverse in the nuclear industry, however, the opinions expressed in Table 10 10 are shared by a majority of the people operating and maintaining nuclear power plants

Table 10.10—Installation Practices for Reactor Instrumentation Systems

Do's	Don'ts
Make certain the insulation is thoroughly stripped off wire before crimping on lug	Don't leave wire strands out of lug when crimping
Give installed connector a resistance and voltage test to assure proper operation	
Reserve one side of terminal blocks for terminating field wiring	
Use large-enough conductor to ensure proper grounding	Don't use panel structural member as a ground conductor
Bond all racks and chassis together and to ground	Don't use a common ground return wire for several relays
Support cables and wires at several points	Don't support cables and wires by terminations
Install coaxial and triaxial signal cables in metal conduits	Don't install power cables in the same conduit as signal cables
Keep switching command cables, such as those for relays etc , isolated from low level signals for detectors	Don't think that all signal levels in instrumentation are the same and lump all the cables together
Carefully inspect coaxial and triaxial cable installations and procedures to ensure work is properly done	Don't make coaxial cable out of triaxial cable by connecting both shields together
Allow extra conductors in cables wherever practical for future expansion (10 to 15%)	Don't let cable "fill" in a conduit exceed 40% in initial installations
Single-end ground spare shielded signal leads in a cable with the shield grounded at the opposite end	Don't ground circuits at random places or allow them to become grounded unless a ground is called for
Provide terminal blocks with terminals adequately sized to handle the physical as well as the electrical requirements of both the interior and field wiring	Don't forget to mark each wire and cable with appropriate identification to assist in circuit tracing
Keep signal lead as short as possible	Don't use splices in signal leads
Use line filters and shielded transformers wherever necessary	Don't think interference won't occur, it will
Segregate loads on power lines so that motors, welders, and other machinery are not on the same line as instrumentation	Don't neglect to put interference suppressors on any sort of device that may generate interference, i e , relays, motors, fluorescent lights, welders, and heaters
Consider radiation environment as well as temperature, moisture, etc , when choosing cables	Don't apply higher than rated voltages to coaxial and triaxial connectors

Do's	Don'ts
Use triaxial cables with a floating shield operated at a fixed potential	Don't ground the shield of a cable at both ends to avoid ground loops
Use triaxial cable for low-level signals, such as from neutron detectors and ionization chambers	
Provide easy access to the back of instruments behind the instrument panels	Don't install instrumentation, conduit, or electrical boxes behind instruments mounted in panels
Mount all visually monitored instruments at or near eye level	Don't mount hand controls below 18 in above the floor level
Protect critical controls from accidental actuation	
Ground all conduits to the main building ground bus	Don't use aluminum conduit in concrete unless care is taken to prevent corrosion
Drill drain holes in conduits at low points to allow water condensing inside to escape	Don't form bends in conduit in such a manner that water can collect in them
Use covered wiring trays for power leads, and band all tray sections together	Don't join aluminum and steel conduit to each other
Provide adequate temperature-sensitive circuitry	Don't stack instruments in racks without regard to ventilation or temperature rise
Be sure that radiation detectors are not overheated by neutron heating, etc	Don't mount instrumentation in areas of vibration unless precautions are taken
Pull cables by hand when possible to ensure that no problems exist which will cause the cable to stick	
Terminate high frequency cables properly to avoid end reflections and standing waves	
Shield all noise-sensitive circuits from electrostatic as well as magnetic fields if magnetic fields are a problem	Don't use adjacent pins in a multipin connector for signal and power circuits
Use differential amplifiers to eliminate common mode voltages and ground loop problems	
Use a sensor with a center tap where possible	
Use a balanced-line shielded twisted pair of conductors for low level signal transmission	
Use high-impedance measuring circuits	Don't use high-impedance sensors, if possible

Appendix

ENGINEERING DATA SHEETS ON NEUTRON-MONITORING START-UP-CHANNEL GROUNDING AND SHIELDING PRACTICES AND EXPERIENCE IN SELECTED U. S. NUCLEAR POWER PLANTS*

Nuclear Power Plant A

Type of neutron detector Fission counter

Type of signal cable RG-71/U double shielded

Location of pulse preamplifier Near loading-face shield at top of detector wells

Location of pulse amplifier In amplifier cabinet at control room

Distance between pulse amplifier and preamplifier Approximately 120 ft

Distance between neutron detector and preamplifier Approximately 28 ft

Method of grounding Multiple-point grounding system Both the preamplifier and amplifier are grounded to the building ground at the point of their installation The signal-cable shield is grounded at the preamplifier and the amplifier The neutron detector is grounded through the signal-cable shield back at the preamplifier

Operating problems and modifications During the first year of operation, it was noted that the excessive noise was eliminated by adjustment of the discriminator threshold bias control on the pulse amplifier Toward the end of the first year of operation, the noise became so excessive other methods were required to correct the problem. Examination disclosed that a No 8 conductor was installed between the preamplifier and amplifier cabinets to establish building grounds between these units The conductor resistance measured greater than 3 ohms Ground circulation currents caused by an excessive pickup of r-f noise from a-c and d-c machinery throughout the reactor building produced an emf across the grounding conductor The emf modulated the signal to the amplifier cabinet, causing excessive noise in the neutron-monitoring channels This source of noise was eliminated by removing the No 8 conductor and installing two No 2/0 grounding conductors in its place

Other shielding problems Noise showed up in the automatic servo-control system during the first year of operation. Examination disclosed that a shield on a multiconductor shielded cable had not been terminated to ground by the construction contractor The problem was corrected by properly terminating the shield to the reactor building ground

Nuclear Power Plant B

Type of neutron detector BF_3

Type of signal cable Triaxial

Location of pulse preamplifier At top of detector instrument well

Location of pulse amplifier In amplifier cabinet at control room

Distance between pulse amplifier and preamplifier 220 ft

Distance between neutron detector and preamplifier 35 ft

Method of grounding A single-point grounding system is used The neutron detector is grounded to the building ground at its point of installation The inner and outer shields of the triaxial cable are grounded at the neutron detector One electrode of the neutron detector is connected to the inner shield The inner shield to the preamplifier is connected to the preamplifier signal ground The outer conductor is insulated and floated above ground back to the amplifier cabinet The signal ground of the preamplifier and amplifier are likewise insulated and floated above building ground, being grounded at the detector

Operating problems and modifications During the initial installation and preoperational testing, it was discovered that the start-up channels were excessively noisy, which prevented further operation of the plant These problems were corrected by installing LR filters in the signal lead at the preamplifier output Other noise problems were isolated and corrected at the source, such as faulty switches, relays, and motor starters

*See Secs 10 5 5(b) and 10 5 5(c)

Nuclear Power Plant C

Type of neutron detector Fission counter
Type of signal cable Triaxial
Location of pulse preamplifier Preamplifier cabinet at reactor
Location of pulse amplifier Control-room cabinet
Distance between pulse amplifier and preamplifier 600 ft
Distance between neutron detector and preamplifier 60 ft
Method of grounding The system uses a single-point ground The system is floated above building ground and is grounded to a special instrument ground in a 700-ft deep well A shield around the detector and detector thimble is connected to building ground

Nuclear Power Plant D

Type of neutron detector Fission counter
Type of signal cable Coaxial
Location of pulse preamplifier Top of counter tube at reactor
Location of pulse amplifier Control room
Distance between pulse amplifier and preamplifier 250 ft
Distance between neutron detector and preamplifier 50 ft
Method of grounding This system uses a single-point ground at the pulse amplifier The detector and preamplifier chassis are also equipped with r-f paths to building ground at the counter tube
Operating problems and modifications After the system was installed, the preamplifier gain was increased to give a better signal-to-noise ratio for the signal between the preamplifier and pulse amplifier A filter was installed in the signal output lead of the preamplifier, this filter eliminated the disturbance on the system caused by the interaction of the ground system in the pulse-amplifier cabinet and the building ground at the counter tubes To protect against any ground loops, the shield on the high-voltage coaxial cable to the preamplifier was lifted from the preamplifier chassis and terminated into a high-valued bleeder resistance Low-pass filters were installed on the power leads to the nuclear instrumentation to eliminate the signal induced by having high- and low-power leads running together

Nuclear Power Plant E

Type of neutron detector BF_3
Type of signal cable RG-59/U coaxial
Location of pulse preamplifier Instrument pit at edge of loading-face shield
Location of pulse amplifier Control room
Distance between pulse amplifier and preamplifier 200 ft
Distance between neutron detector and preamplifier 75 ft
Method of grounding Single-point grounding system The detector and the preamplifier are isolated from ground. The coaxial-cable shields and all external chassis are grounded to the pulse-amplifier chassis The pulse amplifier is grounded to the nuclear instrument panel
Operating problems and modifications When placed in operation, the system was plagued by noise bursts, high-level background noise, cable ringing, and electromagnetic pickup so large in magnitude that neutron pulses were not distinguished by the system Many multiple grounds in the system were found and eliminated. The system was converted to a single grounded system by insulating the detector and preamplifier from ground and tying the system to ground at the pulse amplifier The system was improved greatly, however, some disturbances were still present in the system These disturbances, although not large enough to prevent operation, were annoying, and it was felt that the use of triaxial cable in the system would eliminate the disturbances altogether

Nuclear Power Plant F

Type of neutron detector BF_3
Type of signal cable Triaxial
Location of pulse preamplifier In amplifier cabinet at control room
Location of pulse amplifier In amplifier cabinet at control room
Distance between pulse amplifier and preamplifier 2 ft
Distance between neutron detector and preamplifier Approximately 140 ft
Method of grounding A single-point grounding system is used System ground is made at the amplifier cabinet The signal cable and neutron detector are insulated and floated above ground The two shields in the triaxial cable are connected together to one electrode of the neutron detector The two shields are grounded at the amplifier cabinet The signal ground in the preamplifier and the amplifier are grounded at the amplifier cabinet The amplifier cabinet is grounded to the building ground through grounding cable and buses

Nuclear Power Plant G

Type of neutron detector BF_3 and fission counters
Type of signal cable Coaxial between detector and preamplifier, triaxial between preamplifier and amplifier
Location of pulse preamplifier Top of neutron-detector instrument well
Location of pulse amplifier In amplifier cabinet at control room
Distance between pulse amplifier and preamplifier 185 ft
Distance between neutron detector and preamplifier 25 ft
Method of grounding A single point grounding system is used System ground is made at the amplifier cabinet The signal cabling, preamplifier, and neutron detector are insulated and floated above ground, being grounded at the amplifier cabinet The two shields in the triaxial cable are connected Coaxial fittings are used for both triaxial and coaxial cables The two shields are grounded at the amplifier cabinet The signal ground in the amplifier is grounded at the amplifier cabinet The amplifier cabinet is grounded to building ground through grounding cable and buses
Operating problems and modifications During the initial installation and preoperational testing, it was discovered that the start-up channels were subject to transient noise problems from several systems throughout the reactor plant These noise problems were corrected at the source by replacing faulty relays and switches and by providing better shielding for fluorescent lighting After several years of operation, an unusual noise problem showed up at this power reactor site The reactor was shut down in preparation for refueling Just prior to the start of the second fuel-loading program, r-f noise showed up on all the signal buses coming out of the containment sphere The noise was of such magnitude that all operations were suspended After several days of attempting to isolate the source of r f noise, the breakers at the 2180 kv substation were opened and closed by a planned operation The noise all but disappeared By readjusting the discriminator threshold bias control on the pulse amplifier, the start-up channels were brought within safe operating condition again A technical explanation has not been given as to what caused the severe r-f noise problem

Nuclear Power Plant H

Type of neutron detector Proportional counter
Type of signal cable Coaxial
Location of pulse preamplifier Source range detector thimble junction box
Location of pulse amplifier Nuclear instrument cabinet
Distance between pulse amplifier and preamplifier 1210 ft
Distance between neutron detector and preamplifier 19 ft
Method of grounding A single point grounding system is used The grounding point is at the pulse-amplifier chassis. The pulse-amplifier chassis is grounded to the station grounding grid by bus bar and cable

Operating problems and modifications During preoperational checkout of the system, it was discovered that the majority of the coaxial connectors in the nuclear instrument system were assembled with poor workmanship The main problems were the preparation of the cable, the soldering of the pins, and the assembly of the connectors Many hours of rework were required to correct the problems When the system was put in operation, the source-range channels were very noisy, a check of the system revealed that induced voltage was causing ripple on the +15-volt power supply to the preamplifier The leads carrying the +15-volt power supply were changed from nonshielded to shielded conductors, which improved the condition but did not eliminate ripple sufficiently to not affect the operation of the source-range channels A RL filter was designed and installed at the preamplifier in the +15-volt supply This filter removed the ripple and corrected the noise problem

Nuclear Power Plant I

Type of neutron detector Fission counter

Type of signal cable Single and double shielded coaxial

Location of pulse preamplifier At top of detector instrument well

Location of pulse amplifier In amplifier cabinet at control room

Distance between pulse amplifier and preamplifier 90 ft

Distance between neutron detector and preamplifier 24 ft

Method of grounding Multiple-point grounding system Both the preamplifier and the amplifier are grounded to the building ground at the point of their installation The signal-cable shield is grounded at the preamplifier and the amplifier The neutron detector is grounded through the signal-cable shield back at the preamplifier

Operating problems and modifications During the initial installation period and preoperational testing of the neutron-monitoring system, noise in the start-up channels was prohibitive Noise was reduced by replacing the RG-8/U single shield coaxial cable with RG-71/U double-shield coaxial cable Other noise problems caused by the operation of relays, motor starters, and switches were eliminated at the source The switches and motor starters for the fission-chamber carts were a source of noise causing large transients in the start-up channels Some problems were eliminated by installing filter capacitors across switches

Nuclear Power Plant J

Type of neutron detector BF_3

Type of signal cable Triaxial

Location of pulse preamplifier In amplifier cabinet at control room

Location of pulse amplifier In amplifier cabinet at control room

Distance between pulse amplifier and preamplifier 2 ft

Distance between neutron detector and preamplifier 225 ft

Method of grounding A single-point grounding system is used System ground is made at the amplifier cabinet The signal cabling and neutron detector are insulated and floated above ground, being grounded at the amplifier cabinet The inner shield of the triaxial cable is connected to one electrode of the neutron detector The outer shield is connected to the case of the neutron detector The two shields are grounded at the amplifier cabinet The signal grounds in the preamplifier and amplifier are grounded at the amplifier cabinet The amplifier cabinet is grounded to building ground through grounding cable and buses

Operating problems and modifications During the initial installation, it was discovered that the start-up channels were subject to transient noise problems from several systems throughout the reactor plant The starting and stopping of cranes were a major source of noise The noise problems were eliminated by installing capacitor filters across motor starters, relays, and switches Some noise still remains in the system, but the level is not great enough to affect operation of the system

Chapter 11

Quality Assurance and Reliability

Leland G. Marquis and Ivan M. Jacobs

CHAPTER CONTENTS

11-1 INTRODUCTION

11-1.1 Definition of Terms

Quality assurance comprises all those planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service. Quality assurance includes quality control, which comprises those quality assurance actions related to the physical characteristics of materials, structures, or systems which provide a means to control their quality to predetermined requirements.

Reliability is the probability that a system, channel, or component will perform a specified function under given conditions for a specified period of time without failure. For instrument channels this probability is normally a function of time because few one-shot measurements are considered in nuclear power plants.

A product may meet all design specifications when first tested, but, if components of the product are overstressed, they will fail sooner than expected. As a result, a product that passes stringent quality-control requirements may not necessarily be reliable. This relation between the two terms should be kept in mind even though they are treated separately here.

11-1.2 Quality and Reliability Requirements in Reactor Instrumentation

In the past few years a great deal of effort has gone into the generation of definitive specifications, standards, and regulatory requirements concerning all aspects of quality for the purpose of establishing universal guidelines for all nuclear-reactor systems and components manufacturers and their vendors, as well as nuclear-reactor architect–engineers and owner/operators.

Those organizations and personnel concerned with design, construction, and operation of systems and components for domestic power plants are bound by the 18 quality-assurance criteria in Appendix B of Title 10, Part 50, in the *Code of Federal Regulations*. This document, which was promulgated by the AEC, has created an atmosphere within the nuclear energy industry of extreme concern for the quality of systems and components that are important to safety.

Another document, also issued by the AEC, but much more comprehensive, is the standard used by organizations and personnel concerned with reactor development and test facility projects. The objective of this document, RDT-F2 2T, Quality Assurance Program Requirements, "is to assure that structures, components, systems, and facilities are designed, developed, manufactured, constructed, operated, and maintained in compliance with established engineering criteria."

Certain instrumentation devices, such as in-core detectors and penetration seals, which when placed into service become an integral part of a pressure boundary, are required to meet Sec III of the *ASME Boiler and Pressure Vessel Code*, which addresses itself to Nuclear Power Plant Components. Article NA-4000 of this section, titled Quality Assurance, "sets forth the requirements for planning, managing, and conducting quality-assurance programs for controlling the quality of work performed under this section of the Code."

In addition to the above-mentioned documents, the American National Standard Institute (ANSI), under the sponsorship of the ASME, is issuing a whole series of standards (N45 2 series) for the purpose of guiding organizations and personnel involved in design, construction, and operation of nuclear-power-plant systems and components in proper performance of the quality-related aspects of each phase of the total scope of activities.

There has never been any question about the need for a high level of quality and reliability in nuclear instrumentation, especially since it represents such a visible segment of the nuclear safety system. These documents attempt to describe the contents of an acceptable quality-assurance program, and it is up to the industry to develop such a program and still remain competitive. The remainder of this chapter endeavors to deal with this theme.

11-2 QUALITY ASSURANCE OF REACTOR INSTRUMENTATION

11-2.1 Fundamentals of Quality Assurance

Industrial quality assurance has evolved from a policing function, consisting of final inspection and test, to a defect-prevention system that begins with product conception and ends only when that product has satisfactorily fulfilled its intended function.

At some quality level the balance between cost of failure and the cost of prevention and appraisal will be at a minimum. A successful quality system operates at or near that level. In the nuclear industry the quality level must be higher than in most industries, this tends to result in higher costs for quality assurance.

In specialized industries, such as those producing manned space vehicles and nuclear reactors, the level of quality has been set more by reliability requirements than by cost considerations. However, as competition in the nuclear industry increases and as competition between nuclear energy and other energy sources increases, quality systems in the nuclear industry will have to meet plant safety and performance requirements at reasonable cost.

(a) Modern Quality Systems. Modern quality systems prevent defects and substandard workmanship by exercising controls over design, materials, processes, and products at the appropriate place in the product cycle. All modern quality systems contain three basic elements: design control, materials control, and process and product control.

Design control consists in the preproduction efforts of Design Engineering, Manufacturing Engineering, and

Quality-Control Engineering* in developing a design and production and test methods that will ensure with a high degree of confidence that a quality product can be built and sold for reasonable profit to a customer who will accept the product and remain satisfied over its expected life Design control must be a joint effort of the three groups Properly conducted design reviews are essential during this phase

Materials control consists in the preproduction efforts of Quality Assurance, Materials, and Purchasing Quality Assurance must evaluate the vendor's capability to perform and must ensure that quality requirements are included with purchase orders In addition, incoming material must be tested or inspected on a statistically valid basis An objective in materials control is to establish a certification program that puts the burden of quality control on the vendor rather than on Receiving Inspection This is essential for products that will be shipped directly to a site Materials control becomes extremely important whenever Boiler Code materials are involved Such materials must be traceable to their original heat number regardless of the state of manufacture This is accomplished by such techniques as color coding, electroetching, and tagging or by the use of move tickets, depending on the state of completion of the part All materials, whether raw stock or finished goods, must be controlled by Materials, and these controls should be audited periodically to ensure that they are being followed

Process and product control consists in the evaluation and control of manufacturing facilities (whether skilled workers or production machines) and the inspection and test of the product to ensure that the product meets all engineering specifications and quality standards Once control of manufacturing facilities has been accomplished through planning and the development of manufacturing and inspection or test equipment, training of operators, etc , process and product control must be maintained by implementing the quality plan This plan may require audits, automatic test, continuous sampling, or roving inspection It will specify the points in the manufacturing cycle where certain inspection or tests, or both, are necessary, the records to be kept, control charts, calibration and maintenance schedules of critical equipment, special handling techniques, etc Finally, there will be final inspection or tests, or both, to be performed and possible special packaging instructions and inspections to be performed at the site in many cases

(b) Justification of the Quality System. Since about 1950 most companies have incorporated a quality system containing the basic elements Given the talent, quality costs have been significantly reduced following the initial costs of putting the system in operation Costs have been reduced because the production lines have produced less scrap and customers have returned fewer goods or demanded less service The savings have more than paid for increased staff Savings have also been realized by reducing the number of policing inspectors and testers This reduction has been made possible by detailed planning of inspection and testing and by using automated test equipment Cost savings have been experienced by large and small concerns, whether production-line or job-shop oriented

Positive side effects have been experienced following the institution of a well-planned quality system improved product design, better processes, and the development of quality mindedness in the production and engineering forces It is especially important that such systems be set up in the nuclear instrumentation industry and that the industry be organized in such a way as to foster the philosophy of *total quality control* The difficult, but not impossible, goal of increasing quality levels while reducing quality costs can be achieved when this happens

(c) Organization of the Quality System. The staffing of an organization to implement and operate a modern quality system depends on the size and resources of the company The number of engineers and test and inspection supervisors depends on three factors volume, variety, and complexity of product In brief, one or more quality control engineers, process-control engineers, test-equipment engineers, foremen, planners, inspectors, and testers are necessary In a small organization the process-control engineer can double as foreman, the quality-control engineer can do planning and specify commercially available test equipment, and inspector—testers can combine those two functions The quality-control engineer participates in design control, writes quality plans, including inspection and test instructions for a given product, evaluates vendor's performance data, analyzes process and product measurements and product service reports, and applies the results to prevent poor-quality material and products in future purchases and production The process-control engineer is responsible for implementing the quality-control engineer's quality plan (including control of incoming materials, processing equipment, and inspection or test equipment) He should be the leader in solving technical quality problems in the manufacturing area

Since this chapter is intended to detail quality assurance of nuclear instrumentation systems, the foregoing summary of a quality system and its staffing must suffice For additional information the reader is referred to Refs 1 to 3

(d) Special Aspects of Reactor Instrumentation Quality Control Nuclear sensors are used to detect the presence and amount (intensity and energy) of neutrons and gammas (see Chaps 2 and 3) Sensors that are located in the nuclear-reactor core are considered an integral part of the pressure vessel and therefore fall within the scope of the *ASME Boiler and Pressure Vessel Code* As a consequence, manufacturing procedures and quality control of these sensors are stringent Many of the processes used in the

*Initial capitals are used in referring to groups in the industrial organization that is designing and manufacturing the product

manufacture of in-core sensors are peculiar to that product (e.g., uranium and boron coating of electrodes, casting metal to ceramics, outgassing and backfilling with special mixtures, and pressures and purities of fill gases). In-process quality control procedures rely heavily on mechanical inspection techniques, especially where mechanical tolerances are critical. Helium mass-spectrometer leak testing is important after enclosure welds are made, and insulation-resistance checks are very important wherever parts are mechanically and electrically isolated from each other. Final test and inspection depends on the end use. Actual end-use operating conditions should be simulated as closely as is economically feasible.

Nuclear-reactor readout instruments can be classified as any electronic system that accepts a signal from a nuclear sensor and converts it to usable information. Formerly, this category was normally typified by rack-mounted equipment. However, recently the trend has been to integrate various instrumentation functions directly into panels and consoles; this has necessitated drastic changes in the in-process quality control. With rack-mounted instruments, there are usually printed wire boards to be checked out either as boards or as a part of a system. Obviously the quality of work by personnel who solder components or attach leads to the boards or to instrument chassis must be very high and should be monitored at carefully chosen points in the manufacturing cycle. Quality-control problems are different from those involved in sensor manufacturing.

Nuclear instrumentation systems can be classified as a group of instruments, including sensors, that together perform a specific function, such as the reactor protection system, the neutron monitoring system, the off-gas monitoring system, the rod control system, or the area monitoring system. Usually such systems are housed in one or two panels or a panel and a console so that systems check-out can be made without having to interconnect more than two panels. These panels may house a multitude of instruments, or they may house switches, relays, and meters. The degree to which in-process check-out (continuity, insulation, etc.) can be effected is determined by the configuration of the panel.

Peripheral equipment is a catch-all term for the essential equipment involved in interfacing sensors and reactors or instruments. It includes drive mechanisms, penetration seals, etc., and must be treated individually since each piece of equipment has its own peculiar problems.

11-2.2 Design Control

(a) Early Coordination Efforts. A typical engineering organization has a development group that is responsible for the design work involved in developing new products. If the new product is tied in with a production contract, quality-assurance coordination must be factored into the design cycle as early as possible. This can be accomplished by setting up a team of four or five key personnel to review periodically the progress of the design. Normally the team would consist of representatives from Marketing, Design, Manufacturing, and Quality Assurance. In this way individuals from all the important engineering groups are keyed in to developments on new designs and are in a position to contribute from their special backgrounds. They can feed back information to their respective organizations so that timely preparations can be made for manufacturing and testing the new design.

Another approach is for the design engineer to hold one or more design reviews, depending on the complexity of the design. The participants in the design review normally include the personnel noted above plus any other interested parties. The review should be chaired by the design engineer. So that the review will be successful, all parties involved must be given all the design particulars (drawings, specifications, prototype test results, design reports, etc.) before the actual review.

(b) Design and Performance Specifications. Design and performance specifications must be forwarded to Manufacturing and Quality Assurance as soon as possible so that process development and design and construction of special manufacturing or test equipment may proceed well in advance of the release of the design to Manufacturing. For the same reason, design reviews on new products should be held at critical stages of their development, and process reviews should be held on new processes as they are being developed. The quality-control engineer should be involved in the development of new processes since it is often possible to integrate test and/or inspection equipment right into the processing equipment, thus ensuring automatic feedback to keep the process within specification limits.

(c) Process Development. The quality-control engineer is responsible for ensuring that all manufacturing processes are maintained under control throughout the manufacturing cycle. He can best do this by being well informed about all these processes and by keeping in constant contact with the manufacturing engineer. The controls he institutes must be consistent with product costs and must be compatible with the associated manufacturing equipment.

Two basic types of process control are (1) operator, or open-loop, control, where the operator adjusts the process to keep it under control, and (2) automatic, or closed-loop, control, where the process is regulated by a feedback system. The objective of process control is to keep the process operating within predetermined operating limits.

Mechanization of measurements and process control may be accomplished in one or more stages of the manufacturing process, depending on the quality requirements placed on the product and the process itself. For example,

1. Preprocess measurement and control may be required for monitoring or controlling the materials or parts entering the process.

2 Measurement and control may be used during processing to regulate the process in response to a measured variable

3 Postprocess measurement and control may be desirable or necessary if it is difficult or impossible to measure or control the product during the manufacturing process

4 Features of two or more of the above techniques may be combined

(d) Prototype Construction and Testing. During prototype construction and testing, the quality-control engineer may have an opportunity to prove out inspection equipment and in-process testing equipment and procedures He should make every effort to have these developed in time to be used and evaluated during the phase

Although prototype testing is normally done by the design engineer, the quality control engineer can assist in these tests and thus gain (1) the product knowledge needed to develop a meaningful quality plan, (2) confidence in the special inspection and testing equipment that has been developed, and (3) the advance information needed to correct the quality information equipment if it does not work satisfactorily on the prototype Prototype testing should subject the prototype to essentially every environmental extreme in which the unit is intended to operate This may entail use of expensive equipment that may be used for qualification testing alone Even if the test work has to be farmed out, a quality-control engineer should be involved in the prototype testing along with the design engineer so he can become familiar with the new product

Sensor Prototype Testing The major problem with nuclear sensors is that the operating environment of a nuclear reactor is very difficult and expensive to simulate This is particularly the situation for in-core sensors, where meaningful tests (e g , response, burnup rate, saturation level, and signal-to-noise ratio) require accurate simulation Test reactors are available where, by using specially built thimbles and specially designed instrumentation, meaningful tests can be performed These should be used whenever possible

Circuit Prototype Testing Circuit designs start with tests of breadboards and subassemblies Each individual module must function within the limits of the environmental extremes for the complete assembly The design engineer must determine in advance at what stages in the development modules and subassemblies are to be tested to environmental extremes It may be that certain of these tests are only meaningful after the prototype instrument has been completed A test program must be carefully planned in advance so that all necessary tests are performed in a logical sequence and testing facilities are available when needed

System Prototype Testing More and more systems are being standardized, and it has become essential to perform environmental tests, such as temperature rise, on entire systems This can be accomplished by shrouding the entire operating system with a plastic hood and monitoring for hot spots with well-placed thermocouples Appropriate functional tests are performed on prototype systems

Peripheral Equipment Testing Peripheral equipment is normally mechanical and may be subject to wear and fatigue failures due to a hostile environment (heat and nuclear radiation) Life tests must be run to evaluate the reliability of the assembly before proceeding with production Weld integrity should be checked periodically in these tests

(e) Test Specifications. The results of prototype tests help the design engineer determine the test specifications for the product The test specification should be a formal communication to Quality Assurance which spells out the tests that Engineering believes are essential to prove out the product functionally and the limits of each test Test conditions need to be spelled out to preclude any misunderstanding A description of the test setup should be included

Although Quality Assurance must have the test specification, this document is not necessarily the only criterion for the determination of test limits on the quality-control test instruction The quality-control engineer may decide to tighten the limits set up by the test specifications if a particular manufacturing process is not as dependable as the quality-control engineer wants it to be or if the measuring capabilities of the test equipment are such that the credibility of the measurement is in doubt For example, as a rule of thumb, the measuring equipment should be capable of reading out to at least ten times the specification limits (This means that if a proportional counter is supposed to be capable of 10^6 counts/sec, then the count-rate meter must be capable of resolving to 10^{-7} sec or 100 nsec) All test equipment, whether being used for engineering prototype tests or for quality control final acceptance tests, must be periodically calibrated to standards that are traceable to the National Bureau of Standards

(f) Engineering-Document Control Since the test specification is an official engineering document, it must be controlled in the same manner as other engineering documents, such as engineering drawings The control of engineering drawings, often referred to as blueprint control, must be accomplished both at the place of origin (by Drafting or Engineering Services) and at the place of use (usually by the Production Control organization)

There are many techniques for maintaining blueprint control These will not be described here However, it should be pointed out that there are pitfalls that Quality Assurance personnel should be aware of Some of these are

1. Advanced manufacturing releases These drawings may or may not be identical with the final release, and any planning that is based on advanced releases must always be contingent on review of the final manufacturing release

2 Marked-up drawings Sometimes it is necessary for the engineer to mark up a drawing prior to the issuance of a formal engineering change There must be some system for maintaining control so that Quality Assurance can be certain the loop is closed One technique is to maintain a log with an open entry that can only be closed when a revised drawing, containing a change identical to that of the marked-up drawing, is issued

3 Engineering changes These should be reviewed by the cognizant quality-control engineer before issuance to ensure that any quality planning affected by the engineering change can be revised accordingly The only effective way this can be handled is to keep the quality-control engineer in series with the engineering change, i e , if his signature is necessary for issuance of any change that may affect (1) health or safety, (2) functional performance, effective use, or operation, (3) interchangeability, reliability, or maintainability of the item or its repair parts, and (4) weight or appearance (where these are important factors)

(g) Process Instructions Manufacturing process instructions are as important as engineering drawings and must be controlled, i e , Manufacturing Engineering would be responsible for generating such documents, but Engineering and Quality Control Engineering must have approval authority Any changes to process instructions should be controlled in the same way as engineering changes and should have the same approvals In this way any process-instruction changes that may affect process limits are reviewed to ensure that no product degradation results and that quality checks are appropriately changed

(h) Quality Planning Quality planning is developed throughout the design phase of a new product It consists in determining all the quality checkpoints that are necessary to ensure, with a high degree of confidence, that any rational customer will be satisfied with the product for the duration of its expected lifetime and that the product satisfies all other special requirements, such as applicable standards and codes

Quality planning must take into account software as well as hardware requirements For example, the quality plan must specify the material certification requirements necessary for inspection of raw materials as they are received, the marking and identification of material through its machining and processing, and the in process inspection and tests and documentation thereof, as well as the final acceptance tests and all necessary paperwork required, both internally and for customer submission Thorough quality planning provides for each of the following

1 Determination of control points
2 Classification of characteristics
3 Determination of quality levels
4 Determination of process capabilities
5 Determination of control procedures
6 Appropriate record forms
7 Disposition routines
8 Routing and handling procedures
9 Quality information equipment development
10 QIE calibration
11 QIE maintenance
12 In-process test and inspection
13 Final-product test, inspection, and acceptance
14 In-process audit (both procedure and product)
15 Outgoing product audit
16 Shipping inspection
17 Quality data feedback
18 Quality measurements

A good overall quality system may provide for a general quality plan, an area quality plan, a product quality plan, a contract quality plan, and a vendor quality plan

A general quality plan takes into account quality-control procedures that are common throughout all segments of the business and are followed regardless of what type product is being built or what manufacturing area is involved (e g , quality information equipment calibration)

An area quality plan integrates all the individual station control plans (A station control plan is the basic plan for each identifiable manufacturing station, such as a lathe or an electronic assembly bench This plan is usually an integral part of the manufacturing planning and should include provision for controlling all inputs to the station including direct and indirect materials, e g , stainless steel and cutting fluid or electronic components and solder, tooling, environment, and workmanship skills It should also include provisions for monitoring the station continuously and checking the outgoing part or assembly as necessary) It includes all controls and procedures that are common throughout a manufacturing area

In an area where there is a definite flow from one station to another, such as an assembly area (as opposed to a machine shop where each article is subject to a different sequence of operations), a flow chart should be constructed to indicate the relations of the various stations to each other and to show every important manufacturing process in its proper sequence with all quality checkpoints inserted Each manufacturing station and quality checkpoint (inspection or test) should be identified by legend and references to the applicable operating instruction or general inspection procedure

In an area where there is no particular flow pattern, a schedule of stations should be established which describes each manufacturing operation or station and all the controls of inputs to such stations as well as specific quality checks applicable to these stations

The area quality plan should describe the environmental conditions required in the area (such as temperature and humidity extremes and cleanliness) and the controls for maintaining such conditions It should describe any special materials handling or in-process storage requirements peculiar to the area And it should describe all quality-measuring tools needed for direct support of production as well as the requirements of the test and inspection

equipment for the quality checkpoints in the area. Special maintenance work should be delineated for manufacturing tooling, such as stamping dies and cutting tools. Calibration cycles on test and inspection equipment in the area should be reviewed and special exception made to the general quality plan whenever there is to be a deviation from standard practice.

The quality-data feedback system should be described in the area quality plan and should include applicable quality cost data necessary for analysis, how it is to be obtained, and how it is to be fed back to Quality Control Engineering.

A quality training and awareness program is an essential part of a good quality program for each manufacturing area and should provide for both operator training and continuous upgrading and verification of quality personnel. Every quality plan must provide for an audit that ensures adherence to the quality plan in its entirety.

A product quality plan is an integrating plan that ties together the individual quality plans for each of the various assemblies and subassemblies making up the final product and includes all the controls and procedures common throughout the manufacturing cycle of that particular product. The product quality plan should reference all applicable area quality plans and workmanship standards as required.

The number of individual quality plans for assemblies and subassemblies is dictated by the complexity of the final product; however, each quality plan must contain a flow chart indicating the relation between all lower-tier parts and subassemblies. These flow charts should show each important manufacturing process with all necessary quality checkpoints. Each manufacturing station and quality checkpoint (inspection or test) should be identified by legend and referenced to the applicable method sheet or inspection or test procedure. The manufacturing-operations sheets and inspection and test procedures should be an integral part of the product quality plan.

A contract quality plan is an integrating plan that ties together all applicable area quality plans plus the product quality plan and all special customer requirements resulting from the contract. It may modify standard quality plans to the extent necessary to meet all customer requirements. The contract quality plan must contain a schedule spelling out in detail the data requirements and identifying who is responsible for them along with a schedule of target dates for each submittal.

A vendor quality plan is a plan that describes in detail the requirements of the vendor's quality system, including any and all requirements for data submittal. The vendor quality plan should also spell out the special tests or receiving inspection steps that must be taken to ensure receipt of acceptable vendor material.

(i) Process Capability Studies In addition to making certain that the test and inspection equipment is adequate during the prototype stage, the quality control engineer must know whether or not the production equipment is capable of meeting the engineering tolerances and, accordingly, must determine the optimum sampling plan. This information can be obtained by performing process capability studies.

"Process capability" has been defined as "that which the process is capable of producing under normal, in-control conditions." The key phrases in this definition are "the process" and "normal, in-control conditions."

The process includes the entire manufacturing process and all that enters into it, such as the raw material, the machine or equipment, the measuring device, and the skill of the operator or inspector or both. The process is a single combination of these factors. One process is with a given raw material, a given machine, a certain operator, and the like, whereas another process may be different only in the raw material used. Practically speaking, many of the processes made up by these various combinations of factors are similar in output and can be considered as one. But only those combinations which will yield the same output under the second condition, "normal and in-control conditions," can be so considered as one.

Normal and in-control conditions are those which yield parts with measurements having a predictable and normal frequency distribution compatible with the target specified. Since the process capability is a forecasted distribution of the variability for a given process, this distribution needs to be predictable not only in the spread but also in the shape. Generally, most distributions that are not normal indicate a lack of control and nonnormal conditions.

Quantitatively, the process capability is defined in terms of six standard deviation units (6σ). Within $\pm 3\sigma$ from the mean lie 99.73% of all the readings for a normal distribution. For the majority of operations, this 6σ interval includes practically all the readings and represents the capability of the process. Thus, if the process capability is less than the drawing tolerances, a certain amount of sorting and scrap will result.

The process capability study is a powerful tool. Not only can it be computed easily but also its uses are many, including providing the following information:

1. To facilitate the design of a product.
2. For acceptance of a new or reconditioned piece of equipment.
3. For scheduling work to machines.
4. For setting up a machine for a production run.
5. For establishing control limits for equipment that has a narrow process capability in comparison to the allowable tolerance band.
6. For determining the economic nominal around which to operate when the process capability exceeds the tolerance.

The following points should be kept in mind when a process capability study is being performed:

1. The study should be taken under normal conditions of operation.

2 Factors in the manufacturing process that will introduce nonrandom variations should be held constant

3 Normally, at least 50 readings should be taken

4 The order of the readings should be preserved

5 The individual readings should be plotted over time

6 The measuring devices used should normally have an accuracy of at least 10 times the tolerance spread and 8 times the capability spread

Although computing the process capability from the range is usually the easiest and fastest method, it is also the one that is most affected by the requirement for a normal distribution The first step in computing the process capability through ranges is to compute the ranges, R, of subgroups of the total sample of 50 pieces If, for example, we assume a subgroup of 5, then the average range, $\overline{R}$, is the arithmetic average of each of the 10 values of R Using the relation $\sigma = \overline{R}/d_2$ (where d_2 can be determined from the readings, see any standard text on statistical quality control[3,4]), then we find the process capability is simply $6(\overline{R}/2\ 326) = 2\ 58\overline{R}$ for subgroups of 5

Process capability studies can produce savings by identifying losses due to inadequate processes, poor tool maintenance, unskilled operators, etc The process capability study can help ensure optimum programming of machines and operators in making the product to specification at a minimum cost

11-2.3 Qualification Testing

(a) Test Instruction Preparation Once prototype testing is completed and the design specifications and drawings are released to Manufacturing, the qualification test program must be developed The prototype testing phase establishes design feasibility and engineering specifications On the other hand, the qualification testing phase probes whether the product really does meet the engineering specifications when manufactured under normal production conditions Therefore, the qualification test instruction must be a comprehensive document covering all the environmental extremes considered necessary to verify product performance

Because some of the tests on such items as in-core sensors are unusual and expensive, the qualification test instruction should be developed jointly by Quality-Control Engineering and Design Engineering In tests of in-core sensors, where the unit being tested may become radioactive or even be destroyed during certain tests, the sequence of tests is vitally important and must be carefully considered It is advisable to perform certain reference tests before and after each environmental test and to perform the most severe tests (such as shock and vibration) near the end of the test phase, thereby accumulating as much reliable data as possible before risking mechanical failure of the product Tests of in-core sensors or other equipment in a neutron flux will render the tested units radioactive, these tests are normally performed last to avoid unnecessary exposure of personnel to nuclear radiation

Prototype testing must be performed under carefully controlled conditions, taking data by automatic means if possible, with well-designed test equipment that is appropriate for the intended purpose

(b) Pilot Production. The pilot production units must be monitored closely to ensure that quality plans are being followed and are adequate so that the cost of quality does not become exhorbitant Naturally, building the first few production units may involve problems, nevertheless, with sufficient preplanning these problems should be minimized It is advisable to include extra in-process inspections and tests as part of the plan for the first few production units until confidence is built up in production techniques Photographs taken at various critical assembly stages during this stage of production have been found useful, they can be used as samples for future production

(c) Extent of Testing and Equipment Selection One question that never seems to be adequately answered, because of cost and scheduling difficulties, is how many units should be tested If only one unit were to be tested, there would be little confidence in the value of the test results in determining specification limits Assuming a relatively expensive product, three units should be the minimum to be considered for testing However, using the results from tests on 10 units would naturally yield a higher confidence factor, and therefore using 10 units would be preferable

The equipment to be used in qualification testing should be as accurate and reliable as is economically feasible but not necessarily the same as that to be used for production testing Since many of the tests to be performed during the qualification testing phase may be unique, it is not unusual to have special testing equipment designed and built specifically for that purpose

(d) Environmental and Special Functional Tests *Nuclear Sensor Qualification Functional Testing* Some of the possible functional tests in qualifying nuclear sensors are

1 Radiographic To observe extremely tight fit up conditions, critical welds, etc

2 Dye penetrant To observe critical welds for possible cracks

3 High potential To observe corona or high-voltage breakdown that may indicate faulty assembly or an incorrect gas fill or improper gas pressure

4 Insulation resistance To determine the integrity of the weld joint and the condition of the insulating surfaces

5 Capacitance To indicate improper assembly or an open circuit in the center conductor

6 Mass spectrometer leak detection To test for seal integrity

7 Partial pressure gas analysis To investigate for gas contamination

8 Pulse-height gas analysis To check on proper gas mixture and pressure in neutron sensors

The choice of the test equipment to check the output of a nuclear sensor depends on what type it is, i e , pulse-counting, d-c measuring, or mean-square voltage (see Chaps 2, 3, and 5) If many checks on a quantity of sensors are to be made over any length of time, it will pay to automate the test equipment and have the test data automatically recorded

Nuclear Sensor Qualification Environmental Testing Environmental tests for nuclear sensor qualification include

1 Gamma sensitivity Up to 10^7 R/hr, depending on specification requirements

2 Neutron sensitivity Up to 10^{13} neutrons cm^{-2} sec^{-1}, depending on specification requirements

3 High temperature Other parameters would normally be tested simultaneously, such as insulation resistance or neutron sensitivity

4 Reactor environment This test should embody as many of the actual environmental conditions as possible

5 Shock This would be required for certain defense applications

6 Vibration The extent would be determined by end-use conditions, e g , in-core sensors should be subjected to vibrations simulating those expected in reactor core

7 Humidity Most out-of-core sensors are in high humidity environments and should therefore be tested accordingly

8 Autoclave This combination steam and high pressure test for in core sensors must be carefully controlled if used

9 Hydrostatic A required test for ASME Boiler Code applications, primarily for testing the integrity of weld joints and sheath

Electronics Instrumentation Qualification Functional Testing

1 Power supply input and output voltage, ripple, line, and load regulation

2 Rise time, linearity, pulse width, waveform, and dynamic range

3 Overall response time with simulated maximum-input cable capacitance

4 Trip-circuit accuracy, hysteresis, and range

5 Calibration checks to specified tolerances at all outputs

6 Full load test for a period of time sufficient to represent a significant fraction of the life expectancy

Electronics Instrumentation Qualification Environmental Testing

1 High-temperature tests at full load

2 Humidity tests

3. Vibration tests

(e) Error Correction The qualification test program will inevitably indicate that certain design or specification changes should be made Consequently the results should be analyzed promptly and fed back to Engineering for their use in correcting errors in, or improving, the design If the design engineer is performing or participating in the qualification test program, this is unnecessary This is, however, the last good place to make or recommend design changes It may be, for example, that the instrument works satisfactorily but is very difficult to assemble, test, or maintain, thereby indicating the need for a design change

(f) Final-Product Specifications Final-product specifications can now be firmed up and released by Engineering This event should trigger a review of all manufacturing and quality-control procedures as well as a review of tools, fixtures, methods, and equipment by Manufacturing and Quality-Control Engineering Hopefully, changes will be minor and any units built during the time of qualification testing will not have to be rebuilt in any way that would necessitate repetition of the qualification tests This decision should be made jointly by Design Engineering and Quality-Control Engineering Should it be necessary to repeat some of the qualification tests, the extent of the testing should be considered carefully since normally a complete redesign would be required before a complete rerun of the qualification tests would be necessary

The final-product specifications form a part of the manufacturing release from Engineering which also contains all drawings and parts lists Materials then procures all the various parts in accordance with the specifications

11-2.4 Purchased-Materials Quality Assurance

(a) Review and Coding of Material Requests Vendor quality can be controlled by having Quality Engineering review all requests for production materials and parts When the requests are reviewed, several aspects should be kept in mind the estimated cost of the purchased item, the functional criticality of the item, and the relation of the item to the production schedule There should be a quality plan for each purchased part The plan should detail each parameter or characteristic to be checked (and to what statistical plan), should dictate the equipment to be used, and should describe exactly how to perform any tests or inspections other than those considered standard or routine

Besides indicating to the vendor the relative importance of the various characteristics of the part, the classification category (see next subsection) gives the quality-control engineer a basis for determining the sample size for his receiving inspection plan For example, he may choose to have every critical parameter or characteristic checked or verified 100% of the time, then perhaps a 0 65% acceptable quality limit (AQL) would be assigned to major characteristics, a 4 0% AQL to minor characteristics, and perhaps a one-piece sampling of characteristics that are designated incidental

It is recommended that statistical sampling for attributes should be in accordance with MIL-STD-105

(b) Classification of Part Characteristics. A most important step in controlling the quality of the outgoing product is to control the quality of the incoming parts and materials The job of the vendor can be made easier (and therefore better quality assured) by classifying the various characteristics of the part or parts he is to supply If, for example, a part has several dimensions or characteristics, some are obviously going to be more critical to the function of the final product than others Accordingly, typical classifications used are "critical," "major," "minor," and "incidental " These are usually defined as follows

1 A critical classification means that, should a characteristic thus classified not be within specifications, it would likely result in hazardous or unsafe conditions for individuals using, maintaining, or depending on the product or it would be likely to prevent performance of an essential function of a major end item.

2. A major classification means that, should a characteristic thus classified not be within specifications, it would be likely to reduce materially the usability of the unit or product for its intended purpose and would most likely result in a customer complaint

3. A minor classification means that, should a characteristic thus classified not be within specifications, it would not likely reduce materially the usability of the unit or product for its intended purpose but would most likely still be found objectionable by the customer

4 An incidental classification means that, should a characteristic thus classified not be within specifications, it would not be found objectionable except by the most critical customer (e g , a blemish on the inside surface of an instrument housing).

(c) Test and Inspection Equipment Requirements. The test and inspection equipment needed to support a nuclear instrumentation receiving inspection area includes such items as an insulation-resistance tester (voltage variable to about 1000 volts d-c), an a-c high-potential tester (to about 3500 volts a-c), a helium mass-spectrometer leak detector (sensitive to 10^{-10} cm^3 He/sec), optical comparator (at least 14 in), dye-penetrant test set, precision bench centers, standard volt-ohm-milliammeter, transistor and capacitor checkers as well as integrated circuit testers, and other electronic component testers

Another possibility to be considered is source inspection, i e., inspecting the product at the vendor's plant This may be essential in cases where the vendor is either in trouble or is so new that he has not yet proved his ability to produce In other cases, where the cost of the product is very high or the function of the product is critical, the quality-control engineer may consider it important to institute vendor surveillance to ensure that the vendor understands exactly what is required of him.

(d) Material Verification. Whether raw material or completed parts, positive proof of material identity must be on file, particularly in the case of materials and parts for in-core sensors where the *ASME Boiler and Pressure Vessel Code* applies A practical way to handle this is to have the material certifications reviewed against the applicable specifications as soon as they are received If the paperwork is correct, it still may be considered appropriate to make certain chemical spot tests to verify that the material is properly marked or to send a sample to the laboratory for chemical or spectrographic analysis The next step is to file the "certs" by purchase-order number and have the material painted according to an identification system such as that described in Appendix A to this chapter The more critical materials, such as stainless-steel tubing and bar stock intended for use within a reactor, should be marked along their entire length with the purchase-order number, the material identification, and heat number for ready reference at any subsequent time

(e) Destructive Testing Procedures and Use of Laboratories. If there are any doubts concerning the validity of the certification or if the material requirements are critical, then it is sound practice to send a sample to a qualified materials-analysis laboratory for spectrographic or wet-chemistry analysis Where heat treatment is important, a hardness test should be performed to verify surface condition. Tensile strength would have to be verified by performing a pull test on a tensile specimen

(f) Nondestructive Testing Procedures There are several nondestructive testing procedures available Perhaps the least expensive is the use of a dye penetrant for locating minute cracks (e g , in aluminum insulators and welded tubing). Ultrasonic testing is the best technique for testing large quantities of welded tubing for cracks and flaws, once the equipment is set up, tubing can be tested rapidly Other nondestructive tests, such as radiography, are used more for in-process and final inspection than for receiving inspection

(g) Disposition of Defective Material. Any material found defective by Receiving Inspection, either by test or inspection or as part of a defective lot, should be so identified and segregated from good or unexamined material until it can be returned to the vendor Scheduling constraints may make it necessary to review the nature of the defect and take an alternative action, such as (1) use as is, (2) rework to drawing, (3) rework to an acceptable configuration not to drawing, (4) sort to screen out acceptable parts, (5) scrap, or (6) return to vendor

11-2.5 Production Inspection and Test

(a) Inspection and Test Instructions. *Machined Parts* Inspection instructions for machined parts are normally simple enough to be included as part of the production planning When special instructions are required, a separate inspection instruction may be written and referenced on the planning sheet.

Subassemblies Often it is necessary to ensure that subassemblies are correct before progressing to the next

assembly step, particularly where the next assembly step will obscure visual access or where the next assembly operation is expensive and would be wasted should previous operations prove to be faulty The quality engineer must assess the type of inspection or test that is needed after every production operation. He may have to design special test equipment (black boxes) or inspection fixtures, such as "go, no-go" gages. Again the complexity of the instruction determines whether it can be a part of the production planning or if a special instruction is required.

Test instructions for modules or boards containing active circuit elements should be derived from engineering test specifications Modules or boards with only passive elements may be inspected visually and tested later as part of a complete instrument. Functional tests are normally performed on each active element-containing module or board at ambient conditions. The functional tests may include the following

1. Zero, balance, and calibration adjustments to specification.
2. Load regulation to specified tolerances.
3. Linearity, pulse width, waveform, and dynamic range to specification.
4. Trip-circuit accuracy, hysteresis, load, and range to specification.

Electronic Assemblies Typically nuclear electronic assemblies include rack-mounted chassis-type equipment, such as power supplies, source-range monitors (count-rate meters), intermediate-range monitors (log N current amplifiers), and power-range monitors (flux amplifiers), as well as wide-range monitors (picoammeters) with their associated logic and trip circuits. Test instructions for this equipment should be derived from engineering test specifications For special-purpose instrumentation, test instructions may be derived from customer specifications as well as from engineering test specifications. Standard tests that may be included in the test procedures include the following

1 Mechanical zeroing of all meters
2 Power-supply input and output voltage, ripple, and line and load regulation checks to specified tolerances
3 Zero, balance, and calibration adjustments to specification.
4. Rise time, linearity, pulse width, waveform, and dynamic range checks to specification.
5. Overall response time to specification with simulated maximum-input cable capacitance
6. Trip-circuit accuracy, hysteresis, and range to specification.
7 Calibration checks to specified tolerances at all outputs.
8. A full-load run for 24 hr at maximum specified ambient temperature, followed by an operational recheck

Nuclear Sensors and Peripheral Equipment Test instructions for sensors should be derived from engineering test specifications and may include

1. Gamma and neutron sensitivity checks
2 Gamma compensation check.
3. Insulation-resistance and high-voltage (hi pot) checks
4. Mass-spectrometer leak test.
5. Cable-resistance test at room temperature and at maximum specified temperature.
6. Pressure test at room temperature.
7. Dye-penetrant and radiographic tests as specified
8. Continuity checks

Systems Test Instructions Systems test instructions may be derived from customer specifications or test specifications provided by Engineering Standard system tests normally include the following

1 Point-to-point wire check of all interconnections per connections diagram.
2 Tests at 1000 volts above normal control voltage and/or insulation-resistance tests at 500 volts on all power and control wiring. (Instruments, including meters and recorders, are disconnected and/or shorted during test.)
3. Functional electrical tests with interconnections to simulate field wiring, which may include
    a Simulated (including cable capacitance) current or pulse signals to all neutron- and gamma-monitoring channels through all ranges or decades.
    b Externally connected loads of specified impedance.
    c Operation as system elements of all switches, meters, relays, recorders, lamps, logic circuits, and other panel-mounted devices.
    d Recording of specified data, such as accuracy, response times, trip points, logic operation, stability, and repeatability
4 Functional checks on each panel-mounted process instrument, which may include the following
    a Rough accuracy checks at or near 10 and 90% of scale using pneumatic or electrical signals to simulate process variables
    b Interlocking, alarm, and trip contacts operation at panel terminal-board points.

Final Inspection of Systems To assure the quality of the completed system, the inspector should use a checklist A typical checklist is given in Appendix B to this chapter.

(b) Test and Inspection Equipment. *General* Test equipment may differ for factory or field use Factory test operations involving high production rates require automated or semiautomated devices Care must be taken that data obtained by such devices can be verified by equipment available to the field Factory test equipment used for development, design, and low-production-rate work should be selected from commercially available items Equipment used for production prototype final design and tests should have specifications that can be duplicated in all significant characteristics by factory and field equipment

Field test equipment, in addition to duplicating factory equipment characteristics, should be selected, insofar as

possible, from vendors who have nationwide service capabilities (or worldwide in the case of systems sold overseas) Some required field test equipment may not be commercially available, in which case instrument-system vendors must supply special portable test equipment using normal design and production methods plus issuance of complete operation and maintenance instructions

System manufacturers must issue formal listings of all test equipment required, including either catalog numbers or essential characteristics. If system manufacturers are responsible for field check-out, they should insist on the right to review customer-purchased test equipment for compatibility. Obviously factory training programs should use the same listed test equipment.

High-Production-Rate Test Equipment Although a hard and fast rule cannot be made, a continuing production rate of 500 relatively complex circuit boards of one type per year usually justifies automated testing and the associated investment in design and equipment A subsystem of interconnected assemblies comprising many circuit boards or modules of several types might justify automated tests at subsystem production rates of five per year

Automated equipment is usually designed and built by the instrument-system manufacturer There are also test-equipment vendors specializing in custom design and/or building of such devices The cost of such equipment must be weighed against expected product design life It should be recognized that the more highly automated the device, the less adaptable it is, in general, to changes in production design.

Semiautomated test equipment usually consists of specially designed devices that interface conventional signal sources, the production item under test, and conventional output readouts The interface device accepts a circuit board, a module, or an interconnected assembly directly by mating connectors. It may also contain signal conditioners, voltage, load, or other parameter-changing elements that can, when a few switches are operated and external input signals are varied, test the production item

Although no rigid distinction exists between semiautomated and fully automated devices, the latter would replace the manual switching and variation of input signals with electromechanical or electronic switching and stepping circuits Manual output logging is usually replaced by a digital tape printer The item under test is simply plugged in, a start button pushed, and the test is automatically completed with data printed out Large interconnected assemblies can be connected by mating connectors or terminal fanning strips. One type of automated test device used for circuit-board and module testing continuously compares production items with known good standard boards or modules on a go, no-go basis and alarms when defects are found. Some testers may even localize the failed circuit element or region.

Examples of nuclear-instrument circuit boards and modules lending themselves to semiautomated or fully automated testing are d-c amplifiers, trip circuits, voltage regulators, power supplies, and generally items used with uncommon signal-conditioning boards or modules in assemblies comprising an instrument entity, such as a count rate meter, a log N amplifier, or a mean-square-voltage neutron monitor Base-mounted multichannel in-core power-range monitor subsystems, flux-mapping systems, and control-rod-position information systems may contain "card files" of identical circuit boards, which, along with their systems, can profitably be tested with automated equipment.

The degree of customization required for this type of test equipment precludes any detailed description here

Field and Factory (Nonautomated) Test Equipment Field and factory test equipment should be selected, wherever possible, from commercially available items, preferably with availability as extensive as the market to be served by the instrument manufacturer In development work, where the circuits are not directly used in production equipment, relatively more sophisticated items can be justified, a greater variety of items can be used than would be appropriate in final design and quality-control work. Development extras include sampling oscilloscopes, spectrum analyzers, multichannel pulse-height analyzers, harmonic wave analyzers, noise generators, double-pulse generators, and similar equipment High accuracy is desirable but not mandatory

Test equipment used in design, quality-control, and field work need not be as sophisticated as that used in development, but it must yield accurate and reproducible results. National Bureau of Standards traceable devices to generate or measure alternating and direct voltage and current, time and frequency, resistance, inductance, capacitance, pressure, and temperature must be available, either owned or leased from a local calibration service, and used for calibration of design, quality-control, and development test equipment Test equipment used in the field at locations where local commercial calibration service is not available must be supplemented with minimal portable standards, such as current sources, which can be periodically sent out for calibration and recertified

As noted earlier, devices used for factory design, factory test, and field test should duplicate each other in all significant characteristics This is especially true of equipment used for pulse or complex wave-form generation and analysis As an example, if the designers use a 50-MHz response oscilloscope in the factory to obtain wave-form or response-time data (to be included in the instruction manual) on a fast preamplifier driven by 10-nanosecond rise-time input pulses and a 25-MHz oscilloscope in the field, the test pulses will display different wave forms and lead to unnecessary troubleshooting Interface devices, such as terminating elements, must also be specified in detail by designers so that results can be duplicated Considerable frustration can be experienced in reactor instrument-system

check-outs because of nonduplication and failure to properly interface

Special Test Equipment Special test equipment denotes equipment that is required for factory or field test of production equipment but is not commercially available Although this would include the automated test equipment previously discussed, here it shall be assumed to be portable equipment required for factory or field check-out of instruments or systems Examples are test fixtures used to simulate control-rod-position indicators or multiple current inputs or to generate squaring circuit calibration signals Test devices should also be provided for modules or circuit boards used in systems that do not permit bypassing during operation

The nuclear instrument manufacturer is responsible for reviewing the testability of his product and offering, as manufactured and documented items, all special test equipment needed in the field to calibrate the product and demonstrate its operability This includes jumpers for interconnecting items under test with test devices and power supplies as well as special input or output load simulators

Specific Test Equipment for Nuclear and Process Sensors and Instruments Nuclear sensors and channels, such as logarithmic and linear count-rate meters and logarithmic and linear current amplifiers, are used at most reactors Process sensors and instruments for measuring temperature, pressure, level, and flow are also used Mean-square-voltage monitors and power averaging instruments for both in core and out of-core applications are gaining popularity

The lists of equipment given here are intended to be typical rather than complete Except where noted, required test equipment is commercially available, usually from several vendors Overseas applications must specify proper line voltage and frequency Some available devices may combine listed functions

Table 11 1 lists the equipment required for testing and inspecting nuclear sensors Table 11 2 is a similar list for eight basic nuclear instruments log or linear count-rate meters, log N amplifiers, period meters, linear mean-square-voltage monitors, linear direct-current (often called d-c-current wide-range monitors, single-range d c (power-range) monitors, power-averaging instruments, and process and area radiation monitors Table 11 3 lists general-purpose equipment used in troubleshooting, instrument power supply voltage setting, and calibration of other test devices

Because of piping requirements, process primary sensors and associated transmitters are frequently calibrated or tested in place This requires portable test devices Control room indicators, controllers, signal conditioners, recorders, and similar items lend themselves more readily to instrument shop test or calibration A clean shop air supply must be provided for pneumatically operated instruments Interfaces, corresponding to dummy loads for nuclear instruments, are usually far more difficult to simulate for process

Table 11 1—Equipment Required for Testing and Inspecting Nuclear Sensors

1 *High resistance meter* (to measure cable or detector insulation or leakage resistance) Range, 1×10^{6} to 1×10^{14} ohms full scale switched accuracy, ±20% reading above 10% of full scale, d c test voltages, 10, 50, 250, and 1000 volts with 10^{5} amp limit

2 *Low current or voltage meter* (to measure background sensor current or cable to detector polarization current or voltage) Range (d c), 10^{5} to 10^{13} amp, switched or (d-c), 1 to 100 mV, switched input resistance, 10^{4} to 10^{11} ohms ±5%, depending on voltage or current range

3 *Current limited power supply* (to check detector element breakdown voltage) Range, 0 to 1500 volts d-c limited to 100 μA (or use a limiting resistor and microammeter to calculate resistor voltage drop)

4 *Test sources*

a *Gamma sources* to cover energy and intensity ranges speci fied for system. Sources of ^{137}Cs or ^{60}Co are adequate if the energy response of system is documented Intensity must be high enough to activate the highest range (or decade) response with acceptable geometry

b *Neutron sources* to provide low-range response on start up and wide range instruments For some intermediate- and all single-range power range monitors, the reactor is the test source, and initial activation and operation to full-scale ranges must be observed during start up

instruments Static check-out of components does not always predict dynamic operation in a system with control valves and piping Table 11 4 lists test equipment for temperature monitors, and Table 11.5 lists equipment for testing pressure and differential-pressure (flow or level) monitors As in the listing for nuclear sensors and instruments, the listed devices are typical for the types of the instruments or sensor combinations noted For most overseas applications, equivalent metric scales must be specified

(c) Special Environmental Test Requirements. The original design of a nuclear instrument must be qualified in the anticipated nuclear-reactor environment, and the instrument itself may have to be subjected to that environment during production testing An example of this is the *ASME Boiler and Pressure Vessel Code* testing of in-core detectors All in-core instrumentation must be subjected to minimum ASME Code requirements and certified by the authorized code examiner Obviously radiation-detection instruments must be exposed to nuclear radiations to determine whether they are working properly, nevertheless, there are practical limits of absorbed dose which should not be exceeded Instruments that are to be subjected to high temperature should be tested at a sufficiently high temperature to ensure that they will have adequate insulation resistance when used in a nuclear reactor The ability of the instrument to withstand low-frequency vibration, such as might be encountered during seismic disturbances, would normally be proved out during qualification testing, however, for certain sensitive equipment a vibration test may be included as a production test

Table 11.2—Equipment Required for Testing Nuclear Instruments

A. Count-Rate Meters, Log or Linear, Including Preamplifiers

1 *Pulse generator*
Internal repetition frequency 5 Hz to 1 MHz continuous with rough calibration only
Externally synchronized repetition frequency D-c to 2 MHz, output pulse duration, 100 nsec to 100 msec continuous
Output pulse rise time <10 nsec.
Output pulse amplitude 0 to 30 volts peak into 1000-ohm load, continuous, negative, and positive.

2 *Electronic counter* (to accurately set pulse-repetition frequency)
Range 5 Hz to 11 MHz.
Accuracy 1 part in 10^4 per year (cumulative) ±1 count with minimum 10 mV rms input
Internal standard 100 KHz or 1 MHz.
Gate time 0 1 to 10 sec.

3. *Step attenuator* (coaxial) (to match pulse generator to preamplifier)
Range 0 to 120 db in 10-db steps.
Impedance 50 ohms nominal
Power dissipation 0.5 watt average.

4 *Standard capacitor* (coaxial) (to generate simulated detector charge pulses)
Value 1, 10, or 100 pF, depending on charge range required, accuracy, ±0.1%.

5. *Oscilloscope* (dual-trace)
Bandwidth D-c to 50 MHz, above 20 mV per vertical division, D-c to 40 MHz, 5 to 20 mV per division.
Time base 0 1 μsec to 1 sec per horizontal division, calibrated deflection factor, 5 mV to 10 volts per division, calibrated accessories, 1 1 and 10 1 probes.
Delay to permit viewing leading edge of triggering wave form.

B. Log N Amplifiers

1 *Current source* (d-c) (self-contained or calibrated resistance box)
Range 5×10^{3} to 1×10^{13} amp
Accuracy ±1% at 5×10^{-3} to 1×10^{6} amp, ±2% at 1×10^{6} to 1×10^{-9} amp, ±3% at 1×10^{9} to 1×10^{11} amp, ±4% at 1×10^{11} to 1×10^{12} amp, and ±5% at 1×10^{-12} to 1×10^{13} amp (accuracy may be attained with aid of voltage and temperature corrections).
Source impedance at least a factor of 1000 greater than input impedance of device under test at test current level

2. *Voltage source* (for resistance box, if used)
Range As required for above current range.
Accuracy As required for above overall accuracies.

3. *Oscilloscope* (to observe response times, spurious signals, etc) See item 5 under section A of this table

C. Period Meters (Without Self-Contained Ramp Generator)

1. *Function generator* (triangular wave form)
Range 0.01 Hz to 1 KHz, switched by decade.
Accuracy ± one division for 92 dial divisions (9 to 101).
Linearity Less than 1% over full range.
Output 0 to 10 volts peak to peak into 600 ohms.

2 *10 turn potentiometer* with calibrated dial (to reduce generator output)
Resistance 600 ohms.
Linearity <1%.
Accuracy ±1%.

3. *Oscilloscope* (see item 5 under section A of this table)
Frequency response ±1% at 50 Hz to 1 MHz ±5% at 10 to 50 Hz, 1 to 10 MHz.
Input impedance 1 megohm shunted by 50 pF (maximum)

4. *Oscilloscope* (see item 5 under section A of this table).

D. Linear Mean-Square-Voltage Monitors (Including Preamplifier)

1. *Test oscillator* (sine wave)
Range 10 Hz to 10 MHz, decade switched
Accuracy ±3% of dial reading
Output 0 3 mV to 1 volt rms into 600 ohms.
Attenuator 70 db in 10-db steps over output range.

2. *Test attenuator* (to interface oscillator output with monitor or preamplifier)
Special test device to provide complementary output steps that are proportional to the square root of monitor range steps For example, if the monitor is switched to a 1-decade less-sensitive range, the attenuator must supply a signal greater by $\sqrt{10}$ or 3.16

3. *True rms voltmeter*
Range 1 mV to 10 volts full scale, $\sqrt{10}$ range switch factor

E. Linear Switched Direct-Current (Wide-Range) Monitors

See current and voltage source for log N amplifiers (items 1 and 2 under section B of this table) except that calibrator accuracy should be a factor of 4 better than specified monitor accuracy, range for range This implies that some potentiometric or standard ramp or capacitor calibrator checking system, not commercially available as a single device, would be required for accuracy below about 10^{-8} amp

F. Single-Range Direct-Current (Power-Range) Monitors

1 See current and voltage source for log N amplifiers (items 1 and 2 under section B of this table) except that calibrator accuracy should be a factor of 4 better than specified monitor accuracy. This can usually be accomplished with precision resistors and d-c current and/or voltage standards available to 0.1% or better accuracy over the current ranges involved (usually 10^{-6} to 5×10^{-3} amp).

2. *Oscilloscope* (see item 5 under section A of this table).

G. Power-Averaging Instruments

Test fixture (to simulate multiple sensors or flux amplifiers)
A special test device to supply constant currents or voltages to the number of channels averaged. Device must have both single channel and averaged output self-checking ability with an accuracy a factor of 4 better than averaging instrument or must possess interfacing switches to permit external current or voltage monitoring using test devices of that accuracy.
Oscilloscope (see item 5 under section A of this table).

H. Process and Area Radiation Monitors (Typically Gamma Monitoring)

These instruments are in principle and electronic test-equipment requirements either identical to sections A, B, and E of this table or are combinations of them (many area monitors are log count-rate meters at lower radiation levels and become log current amplifiers at higher levels). In addition to the test devices described, radioactive sources to cover specified energy responses and intensities are required (see item 4a of Table 11.1).

Table 11.3—General-Purpose Equipment Used in Calibrating Test Devices, Troubleshooting, Etc.

(Some or all of the items listed below, in addition to those listed in Tables 11.1 and 11.2, are widely used for troubleshooting, for setting instrument power-supply voltage, for calibrating test equipment, etc)

1. *D-c volt-ohm ammeter* (typical electronic type)
   Voltage range 1 mV to 1000 volts, $\sqrt{10}$ range switch factor
   Input resistance 10 megohms minimum
   Current range 1 μA to 1 amp, $\sqrt{10}$ range factor
   Ohmmeter range 1 ohm to 100 megohms, center scale
   Accuracy ±1% of full scale, all voltage ranges ±2% of full scale, all current ranges, and ±5% at center scale, all resistance ranges
2. *Multimeter*
   Voltage range 1 to 5000 volts a c or d-c at 20,000 ohms/volt d c and 5000 ohms/volt a c
   Current range 50 μA to 10 amps d c
   Ohmmeter range 1 ohm to 10 megohms
   Accuracy ±5% of full-scale voltage and current, all ranges and ±10% of center scale reading, all ohmmeter ranges
3. *D-c voltage standard*
   Null voltmeter and standard voltage source, range 1 to 1000 volts full scale, decade switched, 20 mA capability as source
   Accuracy ±0.02% of setting or reading.
4. *A c differential voltmeter*
   Range 1 to 1000 volts full scale, decade or $\sqrt{10}$ range factor.
   Accuracy ±0.15% of full scale at power-line frequency.
   (This may be used in conjunction with a regulated a-c voltage source for meter calibration.)
5. *D-c power supplies*
   Selected to match ranges of instruments' internal power supplies and also power sources if d-c powered. Supplies should have current-limiting capabilities, ±0.1% line or load regulation, and 1 mV or 0.1% of setting maximum rms noise (whichever is greater)
6. *Sinusoidal voltage regulator*
   To supply standard line voltage and specified line frequency at ±0 2% line or load regulation, 3% maximum harmonic distortion A 1-kW minimum rating is recommended.
7. *Cables, connectors, and adapters*
   Test cables with connectors to mate any instrument used with any test device, including inter type and tee adapters, as required
8. *Dummy loads*
   Test loads to simulate system input and output impedances

Table 11.4—Test Equipment for Temperature Monitoring

1. *Direct reading pyrometers* (one for each range) with 10-in arm, assorted heads, ranges 0 to 400°F and 0 to 1200°F, and ±1% of full scale as millivolt meter
2. *Portable potentiometers* (two at least) with assorted scales, such as 32 to 570°F (copper–constantan), 32 to 522°F (iron–constantan), 32 to 1700°F (iron–constantan), 32 to 2425°F (chromel–alumel), 0 to 14 8 mV, 0 to 53 5 mV, and 0 to 155 mV.
3. *Portable Kelvin double bridge* (for measuring system lead resistances) 8 ranges, 0.0001 to 0.0011 ohm to 2 to 22 ohms, ±0 1% accuracy, and ±0 1% repeatability
4. *Portable Wheatstone bridge* 4 ranges, 0.1 to 1 to 100 to 1000 ohms, ±0.1% accuracy, and ±0.1% repeatability.
5. *Decade resistance box* 0 to 1000 ohms in 0.1-ohm steps, ±0.1% accuracy

Table 11.5—Test Equipment for Pressure and Differential-Pressure (Flow or Level) Monitoring

1. *Pressure vacuum variator* (bellows for generating pressure to 30 psig or vacuum to −20 in. Hg) Effective volume, 12.5 in ^{3}.
2. *Dual-range deadweight tester* with pump (oil) 0 to 600 psi (5-lb increments) and 0 to 3000 psi (25-lb increments), accuracy, 0 1% at increments
3. *Test gage* (one per range) range, −30 to 15 psi, 0 to 30 psi, 0 to 60 psi, 0 to 100 psi, 0 to 300 psi, 0 to 600 psi, 0 to 1000 psi, 0 to 1500 psi, and 0 to 2000 psi, accuracy, ±0.25% of full scale or with movable tabs capable of ±0.1% of tab point when calibrated with deadweight tester.
4. *Dial manometers* (one per range) 0 to 30 in. Hg and 0 to 60 in. Hg, accuracy, ±0.1% of full scale.
5. *Slope tube manometer* 0.5 to 2.0 in. (Hg or water).
6. *Portable test pump* (water) 0 to 5000 psi, with test gages 0 to 160 psi, 0 to 600 psi, and 0 to 5000 psi, accuracy, ±0.25% of test gage full scale.
7. *Water-weight gage* 20 to 3000 psi in 0.2-psi increments, accuracy, ±0 1% at increment.
8. *Differential pressure indicator* 0 to 200 in. water, 0.5-in. divisions, accuracy, ±0.5% of full scale.

(d) In-Process Inspection. The variety of instruments and associated equipment involved in nuclear-reactor operation is so great that in this chapter it only is feasible to survey briefly the various in-process inspection and test techniques that are available and useful to the industry

Nuclear Radiation Sensors In-process control of coated electrodes, whether uranium or boron (see Chap 3), demands careful analytical techniques during the coating process Proof-testing with dummy ion chambers is an excellent technique after the coating process has been completed, but, once the process has been qualified, it need only be performed on a sample basis. Two of the most important tests performed on ion chambers are the mass-spectrometer helium leak test (after practically every welding or brazing operation) and the high-voltage insulation-resistance test (after practically every important assembly operation)

Electronic Control and Monitoring Equipment In-process inspection and test procedures vary according to the manufacturing techniques used Basically, visual examination is required after every major operation or series of minor operations. (Operations include hand soldering, wire wrapping, etc) A typical subassembly, such as a printed wire board, has all components mounted on it by one or several operators It is then checked as a first piece by an inspector and run through a solder machine The board is again inspected and then subjected to a performance test, after which (if all is well) the remainder of the production lot may be run Tests from this point on may be either on a sampling basis or 100%, depending on such factors as complexity, quantity, and adequacy of succeeding tests on the next level assembly

A common technique for verifying whether or not a board is correct is to use the first piece sample as an inspection aid against which succeeding boards are checked

The tester can be set up on the same principle a known good board and the board under test are electronically compared by subjecting both boards to identical signals and automatically comparing outputs across a bridge circuit Necessary adjustments can then be made by tuning for a null

A variety of automatic and semiautomatic testing devices are available or can be designed to meet specific objectives Such test devices can range from a simple black box to an elaborate computer arrangement that analyzes and prints out data automatically Each situation has to be evaluated and analyzed by a competent test engineer Computers can be effectively adapted to testing some of the more complex logic systems that are necessary in nuclear-reactor control systems

Peripheral Equipment Testing of peripheral equipment often presents a great challenge to the test-equipment designer because the equipment usually combines mechanical and electrical capabilities and often creates serious space problems (e g , a drive-mechanism test in conjunction with a traversing in-core probe)

In-process inspection and test of penetration seals is extremely critical since Boiler Code requirements must be met Records are important for such tests as leak tests under pressure High-potential and insulation-resistance testing offer real challenges because of the safety aspect and the sheer number of combinations and permutations on seals with multiple penetrations

(e) Serialization and Control Control of equipment by serialization is usually a function of production control A common technique is to maintain a notebook of consecutive serial numbers for each major subassembly This would normally be a component that could be provided as a spare part, it would have a functional specification that could be tested and might require a data sheet completed by quality-control test

The serial numbers can be assigned as a block when the work order is initiated Serial numbers can be physically affixed to subassemblies in any number of ways, such as by wired-on tags, etching, screwed-on plates, and silk screening

Test data are normally filed first by drawing number and then by serial number Copies of data from all indentured parts are usually filed together with the top assembly in the customer project file

Serialization of larger discrete assemblies, such as ion chambers and source-range monitors, is accomplished in the same manner as above except that it may be important to date code One way to do this without revealing the actual date (if this is desirable) is to establish a date code such as A to L for the months January to December and A to Z for the years 1961 to 1986, and use the date code as a prefix or suffix to the regular serial number Thus a serial number DF87432 would indicate the 87,432nd unit of a particular drawing number and that it was shipped in April 1966

(f) Final Inspection and Test Requirements *Radiation Detection Devices* Final inspection and test of radiation-detection devices is accomplished in about as many ways as there are different types of detectors However, some general principles apply For example, even though the best possible test for any item is to test it in its actual operating environment, this is usually impractical and often undesirable, particularly where the test causes the item to become radioactive Therefore it is often necessary to devise substitute tests that test only certain characteristics over a limited portion of the total operating range

Since many nuclear radiation-detection devices, such as in-core sensors, cannot be tested in their intended operating environments, the importance of in-process tests and inspections cannot be overemphasized For example, when a uranium coating has been checked and found to be correct through in-process testing, when the various parts and components have been found to be dimensionally correct, when the final fill-gas purity and pressure have been determined to be correct, and when the continuity of the center conductor is proven, about the only item left to verify is leaktightness of the final seal Since a high-temperature insulation-resistance test normally reveals problems of this nature, it may be this final test that gives a high degree of confidence that the unit is functionally operable

Electronic Control and Monitoring Equipment Final tests of electronic chassis, assemblies, and systems should simulate actual operating conditions as closely as possible Special test equipment must be devised to load individual units with simulated inputs, e g , pulses and ramp currents As noted in Sec 11 5(a), a variety of functional electrical tests can and should be performed whenever practicable The check list of Appendix B is also useful for inspection of systems

Peripheral Equipment Since final testing of peripheral equipment is usually only an extension of the in-process tests that have already been performed, it is not necessary to repeat, only to mention, that there is no substitute for a complete and thorough checklist when performing final inspection

(g) Disposition of Rejected Units Rejected units, regardless of whether they are small fabricated parts, large subassemblies, or completed instruments, must be properly labeled and physically separated from accepted units and the uninspected portion of the lot The label must be distinctive and must include the drawing number of the unit, serial number of the unit, reason for rejection, and specification limits of the rejected parameter There should also be space on the label for an inspection stamp and date

Most manufacturing organizations use a Material Review Board (MRB), normally made up of representatives from Design Engineering, Manufacturing Engineering, and Quality- or Process-Control Engineering, to review rejected

material The objective of the material review is to determine the best disposition of the rejected material An appropriate disposition may be to (1) scrap, (2) rework to drawing, (3) rework to MRB instructions, or (4) accept as is A decision by the MRB should be unanimous Obviously any decision to rework or accept must be made only after careful consideration. Sometimes special studies have to be made to determine the possible effects of accepting out-of-spec material The personnel comprising the MRB must be experienced and knowledgeable since the board must take into account all viewpoints (safety, quality, cost, and schedule)

(h) Reporting and Disposition of Error Correction. Any well-run quality assurance organization has a built-in feedback loop whereby errors or defects are reported and assimilated into a report that automatically exposes problem areas where attention is required Many subtle but expensive problems are never brought to light simply because the reporting system only reports significant problems requiring immediate action or, worse yet, there is no reporting system and problems are attacked only when they threaten shipments

A system to report defects, based on such items as total scrap and rework expense or impact on shippable sales so that reasonable priorities may be established automatically, is an excellent technique for operating the "Pareto" principle, i e , 10% of the problems account for 90% of the excess cost By implementing such a system, the process-control engineers or the quality-control engineers can apply their efforts where they will pay off most for the company.

11-2.6 Test- and Inspection-Equipment Engineering

Test equipment and measurement systems are generally sufficiently complex to require a special engineering group to provide measurement hardware The requirement for test equipment is set by the quality-control engineer. The test- and inspection-equipment engineers, who are basically design oriented, take the quality-control engineer's requirements and provide the hardware that will be used by the process-control engineer in implementing the quality-control engineer's plans The most comprehensive measurement expertise in an organization usually is in the test and inspection engineering group. Calibration to ensure correct functioning of test equipment is often a responsibility of this group as well.

Test equipment may be defined as that equipment used to measure or generate any of the various units of measure. This distinguishes between equipment that is part of the manufacturing process (and thus the responsibility of the manufacturing organization) and the test and inspection equipment. It is convenient to consider two categories of test equipment *commercial equipment* (equipment that is commercially available and may be purchased from a vendor) and *special equipment* (equipment that is designed, usually by the test and inspection-equipment engineering group, to solve a particular measurement problem) Since both categories involve intimate knowledge of measurement techniques (although no design skills are required in specifying commercial test equipment), both categories of test equipment are usually made the responsibility of the test- and inspection-equipment engineering group The two categories may be further broken into mechanical and electrical equipment

(a) Commercial Test Equipment. The availability of suitable commercial equipment should always be explored before the decision is made to design special equipment The cost of the commercial instrument will almost without exception be less than the cost of designing a piece of special equipment In addition to lower cost, there are a number of other advantages to using commercial equipment Commercial equipment is generally flexible, having been designed for the broadest possible market This flexibility reduces the chance of obsolescence when a measurement requirement changes or a new process must be measured An additional, and often major, advantage is that, when a particular commercial instrument breaks down, a substitute is available within the plant or from the vendor

There are many pitfalls to be avoided in purchasing commercial test equipment, and it is wise to let the responsibility rest with a group that specializes in measurement problems and test equipment The newest manufacturer with equipment having the latest innovations is not necessarily the best choice of vendor. Unfortunately, new companies frequently drop a product line or go out of business, leaving the purchaser with an unsolvable maintenance and parts problem. The purchaser must also be wary of "specmanship," where the manufacturer carefully selects his specification wording to make his product appear better than his competitor's An example of this might be a digital voltmeter that operates within its temperature specification on a hot day but does not meet its accuracy specification unless it is operating at the low end of its line-voltage specification and (in addition) unless it has been calibrated and adjusted during the preceding 48 hr. The final choice of manufacturer and model should be based on

1. The ability of the equipment to perform the required task and any reasonable variations of the task.
2 The stability of the manufacturer and the proven reliability of his products
3 The compatibility of the equipment with existing test equipment (in terms of interfacing with other equipment and maintenance and calibration).
4 Price and delivery Price should be considered after the first three considerations since problems with any of the first three usually result in losses far exceeding any price differential in competitive products.

(b) Special Test Equipment. *Justification* The decision to design and build special test equipment is usually

made when it has been determined that there is no commercial test equipment to perform the particular measurement. Less frequently, the decision is made when commercial equipment is so general purpose and the particular measurement is so specialized that it is cheaper to design and build a special instrument than to purchase the general-purpose equipment. The most common pitfall in this latter situation is finding that, after the special test equipment has been built, a design change in the equipment being tested results in total and irreversible obsolescence of the special test equipment. Even where there is no choice but to design specialized test equipment, obsolescence through design change of the assembly under test presents a real hazard. The solution is to design all special test equipment to be as flexible as practical.

Design and Building. Special test equipment is produced in small quantities, typically only one of a kind being built. The labor costs for design and construction are the major items of expense, and material costs are not significant. This must be kept in mind. For instance, other considerations being equal, it is not profitable to devote 2 hr of design effort to avoid the use of an SCR that is $10 more expensive than another SCR. Similarly, incorporating available designs as elements in the special-equipment design can save time and money. Duplication of circuits in the unit under test is often necessary to ensure compatibility between the test equipment and the tested unit. Although the designer has greater freedom in some respects, he has some constraints that are more stringent than those imposed on the product design engineer. Accuracy of the equipment being used to measure or to generate quantities normally must be 10 times greater than the tolerance of the device under test, i.e., the test equipment itself can contribute no more than 10% to the error that is allowed for the unit under test. There are occasions when even 10% test-equipment error cannot be tolerated. There are other occasions when state-of-the-art measurements are made and a 10:1 accuracy ratio cannot be achieved. Although special test equipment involves construction of a single item or, at most, a limited quantity, workmanship cannot be compromised, and rugged construction is generally a must. Engineering breadboards and prototypes cannot be simply stuffed into a box and shipped out for use. Inadequate mechanical ruggedness as well as poor solder connections in breadboards and prototypes are certain to create problems in normal use. One technique, normally associated with production in quantity, can be applied to advantage in the production of special test equipment, namely, the use of printed circuit boards. These provide ruggedness and also have the short direct paths between discrete components needed in high-frequency and pulse circuits. Printed-circuit-board construction even on a single-unit basis can be as economical as a terminal-board layout. Definite cost savings can be realized if two or more units are built. Moreover, the printed circuit board ensures similar performance of the units.

The approach in designing special test equipment is similar to that in designing a commercial product. Initially the design goals are established in close cooperation with the quality-control engineer. Design alternatives are studied, and the best is selected for the particular measurement problem. In this choice a number of factors must be considered: the complexity or difficulty of the measurement, working environment, skill level of the operator, expected useful life of the test equipment, cost per measurement over the useful life, operator convenience or human engineering, ease of maintenance and calibration, cost of maintenance and calibration, accuracy, safety, and initial cost. Once the approach has been established, the design engineer develops the detailed design, including breadboards of critical circuits if the problem is electrical. Construction is best accomplished under the direction of the design engineer by people familiar with the peculiarities of test-equipment construction. The completed equipment or first item is evaluated by the design engineer and, with more-complex design problems, further evaluated by the quality control engineer. After his acceptance the equipment is then passed through the Calibration Laboratory for formal entry into the calibration cycle. Finally, the equipment is released to the process-control engineer for application.

Documentation. The documentation problem on special equipment is as complex as that for a new product to be marketed commercially. The first documentation takes place in the engineering notebook or similar document, where various design approaches are explored and details supporting the design logic are recorded. When problems arise as the result of measurements made by test equipment, whether special or commercial, the first area questioned is the adequacy of the test equipment. This is rightfully so, and it is only sound engineering practice to have the validity of the design well documented. In many cases the normal documentation associated with construction and calibration of test equipment is not adequate for this purpose. Documentation of the design details, with one exception, must be complete and under formal control. Because of the unique nature of test equipment and the importance of decisions that are based on its performance, the designer must clearly express all the details of his design to the group constructing the equipment and the group calibrating and maintaining the equipment. The exception to this would be the assembly details that are normally associated with the new product. Since special test-equipment production usually consists of only a few items and since they are constructed under the direct supervision of the test-equipment engineer, those assembly details not essential to the accuracy of the equipment need not be documented. Calibration instructions and specifications must be provided for the Calibration Laboratory. The equipment must not only perform correctly when initially released but also must continue to perform within specification, be periodically recalibrated, and be successfully

repaired when necessary, all without the direct and continuing direction of the test-equipment engineer. When more complex test-equipment designs are involved, the quality-control engineer's test or inspection instructions may not be adequate. Then a detailed instruction manual, similar to the manual for any commercial piece of test equipment, must also be provided by the test-equipment design engineer. This manual would provide the same type information customarily put into instruction manuals for commercial equipment, such as oscilloscopes, frequency counters, and spectrum analyzers.

Follow up and Feedback. Performance and continuing evaluation of special equipment is monitored in two ways. The maintenance record maintained by the Calibration Laboratory provides an accurate record of long-term performance. The process-control engineer provides rapid feedback of any critical problems. During the first months of use, he must be particularly alert to spot problems not readily apparent in an engineering evaluation. One of the common weaknesses of test equipment that is not always found in an engineering evaluation is its response to certain modes of failure in the unit under test. Under some conditions destruction of the test equipment is possible, and protection must be designed into it. The long-term performance information from the Calibration Laboratory maintenance record can be used to revise calibration recall intervals, i.e., to base them on actual performance In addition, this record may also indicate more subtle reliability problems

(c) The Calibration Laboratory. Both commercial and special test and inspection equipment must perform as intended by the original design engineer so that the test technician will feel confident of the results he obtains The Calibration Laboratory ensures this performance through its various activities and provides the basis for his confidence

The fundamental responsibility of the Calibration Laboratory is to ensure that the units of measure at a particular facility have the same dimensions as those defined and maintained at the National Bureau of Standards There are four basic areas of responsibility

1 Traceability of all units of measure to the National Bureau of Standards (NBS). Traceability implies both derivation of the local unit from the national unit and a known accuracy relation between the local and national units.

2. Maintenance, both preventive and corrective, must be performed to ensure continued performance of equipment within its specifications.

3. Documentation must be initially validated and thereafter maintained to ensure that the equipment can be calibrated and restored, if necessary, to the required level of performance.

4. Recall control must be established to ensure that the equipment can be relied on throughout its life to be within its specifications with a reasonable degree of confidence

Organization and Staffing. The Calibration Laboratory can take many forms from a single person who performs all the basic functions to individual departments for each of the various tasks. In a medium- or large-scale operation, the first logical division of effort should be between the maintenance function and the standards function Meaningful results in standards work can only be obtained when meticulous care is taken in making measurements by someone who is not only familiar with the techniques involved but also takes great pride in his work. The maintenance function also requires special talents, but not to the same degree as standards work. In either case the individual must live by the rule that the quality of work, not quantity, is of prime importance. Where there are a number of people on the Calibration Laboratory staff, there must be technically competent leadership. In small organizations this is provided by the supervisor or manager. In large organizations engineers who are specialists in the areas of electrical and mechanical measurements provide the leadership.

New Equipment Control All new equipment, commercial or special, should pass through the Calibration Laboratory before it is released to the end user An initial calibration is performed to ensure that the equipment is indeed within its specification. At the same time the documentation is being checked out to make certain that it is adequate for future calibration and maintenance. The performance and repair record, discussed later in this section, is initiated at this time, and the equipment is placed on a recall schedule. These steps are taken to establish a firm base for all future control of the equipment.

Calibration Standards The traceability of any unit of measure, including a known accuracy relation to the unit as defined by the National Bureau of Standards, is the fundamental responsibility of the Calibration Laboratory The number of intermediate steps between the end user and the NBS depends on the accuracy requirements. Traceability does not imply direct comparison of the local standards against the NBS standard A valid traceable standard can exist even though the measurement has been passed from NBS through many intermediate laboratories provided the accuracy degeneration is correctly defined.

In each calibration laboratory some instrument or piece of equipment represents the most accurate repository at that local level for a particular unit of measure This then becomes the primary standard for that unit in that laboratory. Several echelons of measure may still exist between this local primary standard and the end user of test equipment. In some cases the local primary standard must be used directly to calibrate test equipment, more often it is used to calibrate other standards called "secondary standards" or "working standards." Depending on the accuracy required of the local primary standard, it may be calibrated either by an independent laboratory or directly by the NBS Every measurement made degrades the

transferred value of the standard involved in that measurement to some extent. This then becomes the disadvantage of using intermediate laboratories in establishing calibration standards. In very accurate measurements, this degeneration often cannot be tolerated. Despite this basic disadvantage, all local primary standards should not, and often cannot, be calibrated directly with the NBS. Calibration at NBS is usually much more expensive than traceable calibration through an independent laboratory, and it usually involves delays that may not be tolerable where alternate equipment is not available. In addition, NBS will not work with the less-accurate standards that are often all that are required for a particular local primary standard.

One word of caution on standards of any type no device, either mechanical or electrical, remains indefinitely stable, regardless of the ultimate source of the instability. For this reason all test equipment is placed on a calibration recall cycle. Standards, too, are subject to instability. The shiny new standard is not nearly as valuable as the old standard that has a proven record of stability. The standards of any calibration laboratory increase in value with time as their history of stability is documented

Use of Outside Laboratories. The integrity of traceable calibration is not jeopardized in the least by using outside laboratories for calibration of either the local primary standards or the user's test equipment In the case of standards calibration, the first consideration needs to be that the required level of accuracy for that standard can be achieved by a laboratory other than the NBS. Each intermediate step between the user and the ultimate reference at NBS degrades the transferred value of the unit. The particular outside laboratory chosen to perform the calibration must be selected with care, especially if a local primary standard is to be calibrated. There are a number of obvious things to look for good equipment, certificates establishing traceability, neat and well-organized laboratory areas, and available and well-used reference material. These are all items that may easily be checked. More difficult to determine is the level of competence of the personnel Regardless of the quality of the physical facilities, reliable results in precision measurements cannot be obtained without highly qualified personnel

The choice of an outside laboratory for routine calibration of standard test equipment is not as critical, although the selection should still be made with care The reason for using an outside laboratory instead of NBS for calibration of local primary standards is that the turnaround time is shorter than at NBS On the other hand, the decision to use an outside laboratory for calibrating test equipment is based on economics. If the number of calibrations per year of a particular type is limited, use of an outside laboratory that already has appropriate standards and trained personnel is more practical. When the cost of performing your own calibration is being compared with the cost of having an outside laboratory perform the work, the cost of calibrating local primary standards must also be included. It is not at all uncommon for the price of a single NBS calibration to exceed the cost of the equipment being calibrated.

Frequency of Calibration. A frequency of calibration is established to give the equipment user reasonable assurance that the equipment will remain within its specifications between calibrations. The frequency depends on the type of test equipment and its application. Because the severity of operating conditions can be so widely variable, calibration intervals for a class of instruments are usually based on their history of performance. This ensures an optimum recall interval for the particular conditions of environment, use, and abuse. Initially, intervals are established by reference to handbooks and manuals that describe normal recall intervals for typical applications. Too long a calibration interval is undesirable because it diminishes the possibility of the instrument's remaining within its specifications throughout the interval. The cost of repairs per call-in usually increases in this circumstance. On the other hand, too frequent call-in has disadvantages. Calibration costs per year on the instrument are higher than they should be. In addition, the instrument is out of service more frequently than is necessary, resulting in inconvenience to the user and the need for backup equipment that would not otherwise be required.

The significance of calibration stickers should be considered. Too frequently a current calibration sticker is considered proof that the instrument is functioning correctly, and, conversely, an expired sticker is proof that the instrument is no longer within specifications. Barring errors, the sticker is only proof that the instrument was within specifications at the time of calibration. It also signifies that, if the instrument is within the calibration interval, there is a reasonable probability that it is still within specifications. If the calibration interval has expired, there is a diminished probability that the instrument remains within its specifications. With both electrical and mechanical test equipment, there is always the chance of a subtle failure that is not readily detectable There is no substitute for intelligent use of test equipment by a user who is alert to subtle irregularities.

Call-in Techniques. It is often more difficult to break loose a piece of equipment from the user for a trip to the Calibration Laboratory than it is to repair and calibrate the instrument. Two direct approaches are generally used. When the instrument is calibrated, a sticker is put on it which gives, among other information, the date when the instrument is due for recalibration. The user himself can thus see when the equipment must be returned for recalibration, and he can schedule his use of the equipment to allow turn-in before the calibration has expired. The Calibration Laboratory keeps a record of the date the instrument is due for recalibration. Each month lists of equipment due for recalibration are circulated to alert the users so they can plan around the temporary loss of the equipment. Delinquent lists are also published by the Calibration Laboratory when equipment is not turned in as

required. The attitude of the supervisor or foreman in the area using the equipment can be helpful in ensuring the timely turn-in of the equipment. Another call-in technique that can be used in some special situations is the running-time meter Where equipment degeneration is based on running time rather than elapsed time since previous calibration, the running-time meter can be used.

Performance and Repair Records The Calibration Laboratory must generate at least two records the calibration sticker and the equipment-history card. The calibration sticker is placed on the instrument after calibration and contains, as a minimum, the date calibrated, the date due for recalibration, and the identification of the person who performed the calibration. Information such as equipment-use limitations and equipment accuracy may also be desirable. The equipment-history card contains all the basic data and history of the instrument. In small- to medium-size operations, this record is normally a maintenance or history record that is maintained on a one-card-per-instrument basis In large organizations the information may be entered into a computer. The basic information that must be maintained in this record includes the description of the equipment, the identifying serial number, the name of the person who performed the last calibration, the date of the last calibration, the date recalibration is due, and the condition the equipment was in when received for repair or calibration Besides providing the basic information for calibration recall, the history information is useful in troubleshooting, and the information on equipment condition is used to establish realistic calibration intervals.

Obsolescence Determination Most equipment eventually reaches the point where it becomes more economical to replace it than to continue it in service There is no problem in determining that new measurement requirements have exceeded the capabilities of existing instrumentation More difficult to determine is when equipment should be removed from service owing to lack of use or the high cost of repair. The history card is the basic tool for making this determination Data on the equipment condition when received and the extent of repairs necessary at each calibration can be used to decide when it is cheaper to invest in a new instrument with low maintenance cost When this judgment is being made, maintenance costs associated with equipment abuse should be excluded since, in most cases, these costs would continue even with new equipment. Disposal of equipment for lack of use is highly dependent on an organization's specific situation. The advantages of removing the equipment from an organization's capital assets should be considered, as well as the cost of storage, equipment deterioration, and the risk of equipment obsolescence with prolonged storage.

11-2.7 Quality Control at the Reactor Site

(a) Verification of Condition on Receipt. All nuclear instruments, associated panels, sensors, wire, and coaxial cable should be inspected by Receiving Inspection for signs of damage on receipt at a reactor site. Receiving documents should then be checked to verify that the requirements of the purchase requisition have been fulfilled. The purchase requisition will contain specifications or refer to specifications that are applicable to the purchased item and will also state if vendor quality-assurance inspection and certification was a requirement before shipment

(b) Quality Checks During Installation.* During installation, quality checks of nuclear instrumentation should be made as follows

1 Check and ensure that coaxial connectors are installed on cables per the manufacturer's specifications. Cleanliness is very important during connector installation to maintain a high insulation resistance.

2. Check and ensure that noncoaxial connectors are installed per the manufacturer's instructions. Items to watch for are wire size, insulation removal, crimping, and pin insertion tools.

3 Insulation resistance of coaxial cables should be measured after the coaxial connectors have been installed. A rule of thumb is that the numerical value of the insulation resistance (in ohms) should be 10 or more times the reciprocal of the lowest signal current (in amperes) that the cable will carry. Where coaxial cables are used to carry a-c signals (pulses, for example), insulation-resistance values of 10^{10} ohms are more than adequate and are easy to achieve.

4. High-voltage (hi pot) tests of coaxial cables should be performed

5 Check routing of field cables to ensure that there are no friction points where excessive wear could occur on cable or wire insulation.

6. Perform construction tests. These are functional tests performed with the equipment energized to verify that all field wiring is correctly installed. Any method for checking field wires, such as manual operation of relays and use of jumpers, is acceptable. However, care must be taken to identify and tag equipment, circuits, and systems that are to be energized and to isolate, as necessary, circuits that should not be energized.

Before installation, equipment (and even cables) may be assigned a quality-assurance number that can be used later as a quick guide to the applicable certification documents

(c) Preoperational Check-Out Procedures. Preoperational tests are functional operating tests that are performed before putting into operation a system (e.g., neutron-monitoring, control-rod-drive, reactor protection system) and its associated instrumentation where the system is actually monitoring a process or performing a safety function The purpose of these tests is to verify that instruments and systems function as designed and as specified in the applicable technical specifications.

*See also Chap 10.

Inputs to nuclear instruments that receive inputs from sensors when in actual operation may be simulated with a pulse generator, sine-wave generator, or current source as required. Trip points can be set, and the resultant functions initiated by trips (e.g., scram, rod block, and annunciation) can be checked with simulated inputs.

An acceptable preoperational check-out procedure must be detailed enough to check out every component, circuit, wire, and coaxial cable in the system covered by the procedure. It must also cover the check-out of any mechanical equipment associated with a system, e.g., in-core sensor retracting drives used with source- and intermediate-range instruments.

Field tests must also be made on in-core neutron sensors before they are put into service. The in-core sensors fall into three groups (see Chap. 3) pulse counting for source-range coverage, mean-square-voltage type for intermediate range, and direct-current type for power range. Field tests of neutron sensors are as follows

1. Insulation-resistance tests to verify that no damage has occurred to the insulation and seals. In general, the insulation resistance should be greater than 10^{10} ohms.

2. Voltage-breakdown tests to verify that the filling gas has not escaped owing to a cracked or broken seal Current in this test should be limited to approximately 10 μA to avoid possible damage to the insulating material

Source tests of "dunking" chambers (fission chamber or proportional counter) that are to be used during fuel loading should be made after the fuel-loading source is placed in the reactor core. Curves of background count vs. discriminator setting must be made before the loading source is placed in the core. After the loading source has been placed in the core, but before fuel loading, discriminator curves and voltage-plateau curves should be run to determine the optimum discriminator set point and chamber operating voltage for each source-range channel. After the discriminator and voltage settings have been determined and set, a final check should be made to verify that the chambers are indeed seeing the neutron source. This final check can be made by raising and lowering the dunking chambers above and below the level of the source and verifying that the count-rate readout of the source-range channels decreases and increases accordingly In addition, neutron pulses can be distinguished from background and gamma by monitoring the source-range instrument input signal with an oscilloscope.

Source-range in-core fission chambers should be source tested as the source-range instruments are changed from dunking chamber inputs to the permanent in-core chambers. This changeover and the tests required are made after fuel loading has been completed and the large start-up sources have been placed in the core. The same tests that were performed with the dunking chambers should be repeated. If the source-range fission chambers are retractable, positive verification that the source-range chambers are seeing neutrons can be made by retracting the chambers and noting the decrease in count rate.

The field instrument engineer is responsible for verifying that all neutron-monitoring instruments have been calibrated before fuel loading, that preoperational tests on neutron-monitoring systems have been completed satisfactorily, and that documentation exists for verification of all tests and results

(d) Field Feedback Reporting and Analysis. The field engineer must feed back information relative to the performance of instruments and systems for which he is responsible. The information should be included in reports to the home office.

Reports of equipment failure are particularly important. To help those who must evaluate the failure, the failure report should include

1. Catalog and serial number of failed part
2. Description of the failed part
3 Mode of failure.
4. Operating status at time of failure.
5. Effect on system or subsystem, if known.
6 Date of failure and approximate total operating time before failure.
7. Corrective action taken.

Field engineers' reports should be distributed to the responsible engineering groups for information and/or evaluation For instance, if repeated failure of a particular component is observed at one or more field locations, a redesign of circuits or system may be warranted In some systems, depending on the effect of a component failure in that system, a single failure could make it mandatory for redesign to prevent recurrence

In situations where corrective action is initiated by a field engineer and the action involves a redesign or a deviation from approved drawings, change information should be sent to the home office immediately for Engineering approval and drawing changes before the system is put back into operation (where it is performing its intended function) Approval by telephone may be adequate in some cases when followed up in writing

Changes initiated by Engineering and performed by the field engineer should be reported to the home office as being completed once the change has been made and the instrument or system has been retested.

Analysis of feedback from the field and determination of corrective action is the responsibility of the appropriate component of Engineering. Field Engineering is responsible for carrying out the corrective action and documenting changes.

11-2.8 Summary

A total quality system that embodies design control, materials control, process control, and product control

must be implemented to attain the reliability necessary for achieving design goals relative to the appropriate level of safe and trouble-free life while still maintaining competitive costs.

The requirements of the Atomic Energy Commission and the customer fix the minimum quality standards that must be incorporated into the design of nuclear instrumentation systems. The Quality Assurance organization must ensure that these standards are upheld throughout the procurement and manufacturing cycles by establishing appropriate controls at critical points, such as receiving inspection of raw materials, parts, and subassemblies, in-process inspection and subassembly testing, final systems test, and shipping inspection. Judicious selection of the points in the manufacturing cycle where tests or inspections are to be performed as well as the selection of the correct type of quality information equipment and the generation of inspection and test instructions is the job of the quality-control engineer.

The life cycle of a particular product can be thought of in terms of distinct phases the preproduction phase, which includes design and procurement, the production phase, which includes manufacturing, testing and packaging, and the postproduction phase, which includes shipping, customer installation, and acceptance testing and service life (particularly during the warranty period). A total quality-assurance program will ensure, with a high degree of confidence, that appropriate measures are implemented during each phase by all personnel involved with the product, from sales to customer installation and servicing. Therefore quality assurance should not be thought of as the inspection and testing operation that screens the good product from the bad, instead, it must be thought of as a company-wide program to ensure customer satisfaction with minimum cost to the company.

The quality-assurance program for a company involved in the design and manufacture of nuclear instrumentation must contain all the elements of a good total quality-assurance program. Criteria and standards promulgated by the AEC and ASME, such as Quality Assurance Criteria for Nuclear Power Plants (Appendix B to 10 CFR 50), or Quality Assurance Program Requirements (RDT F 2-2T), or Quality Assurance (NA4000 from Sec. III of the *ASME Boiler and Pressure Vessel Code*), or Quality Assurance Program Requirements for Nuclear Power Plants (ANSI-N45.2), all describe quality-assurance programs which if properly implemented will provide an excellent QA program for anyone in the nuclear industry

Nevertheless, it must be noted and emphasized that there is no substitute for a high degree of technical competence in the personnel involved in implementing such a system. For example, a competent quality-control engineer in this industry needs to be versatile not only in the quality-control and statistical field but also in the fields of electronics, nondestructive testing, and nuclear technology—four very specialized fields.

11-3 RELIABILITY OF REACTOR INSTRUMENTATION

11-3.1 Introduction

(a) Importance of Design Phase. Reliable instrumentation systems can only be created during the design phase. No amount of quality control, field testing, or maintenance can adequately compensate for a lack of careful planning during the conceptual design. A few designers seem to have an intuitive sense of good design, and their products enjoy a reputation for reliability Most designers can acquire the art of producing reliable designs by adhering to some of the disciplines of reliability engineering

A designer's most frequent failing is to be trapped into thinking only about how to design a system that will work and giving no thought as to how it might fail. Everyone is amused by the famous Rube Goldberg designs (Fig. 11 1) It is readily apparent how Rube's systems work and equally apparent how prone they are to fail. Modern reactor instrumentation systems have become so sophisticated that the designer, in concentrating his efforts on making the system work, forgets to look for ways in which it may fail By applying the techniques of reliability analysis, a good designer should consistently turn out a product that not only works but also has a low incidence of failure

The attitude of the designer is all important He must have the desire to create a reliable system. He must not be lulled into the attitude that the design is adequate because the system passed a design audit or was granted an operating license. A trained reliability engineer can probe deeply and learn much about a system, but, unless he has full cooperation from the designer, the effort will fall short of complete success

System reliability and system capability must not be confused. For example, the nameplate rating on a power supply tells the designer about the load capacity it may be expected to accommodate. Choice of a power supply with a rating in excess of the load requirements assures capability. A reliability study assumes system capability and goes on to make an assessment of the probability that the system will actually be successful in performing a given task within its capability The two terms, capability and reliability, are related through the term "design margin," and the designer should recognize the favorable influence excess capability may have on reliability through the application of appropriate derating factors.

Effort invested in systems reliability analysis is economically attractive The potential for cost saving lies in systematically selecting the higher reliability systems for detailed design, in choosing the simpler of two alternatives, in avoiding overdesign on portions of the system that do not contribute to reliability, in avoiding costly retrofits, and in gaining a reputation for a reliable product

(b) Reliability and Availability. The term "reliability" is frequently used in a qualitative sense to imply quality

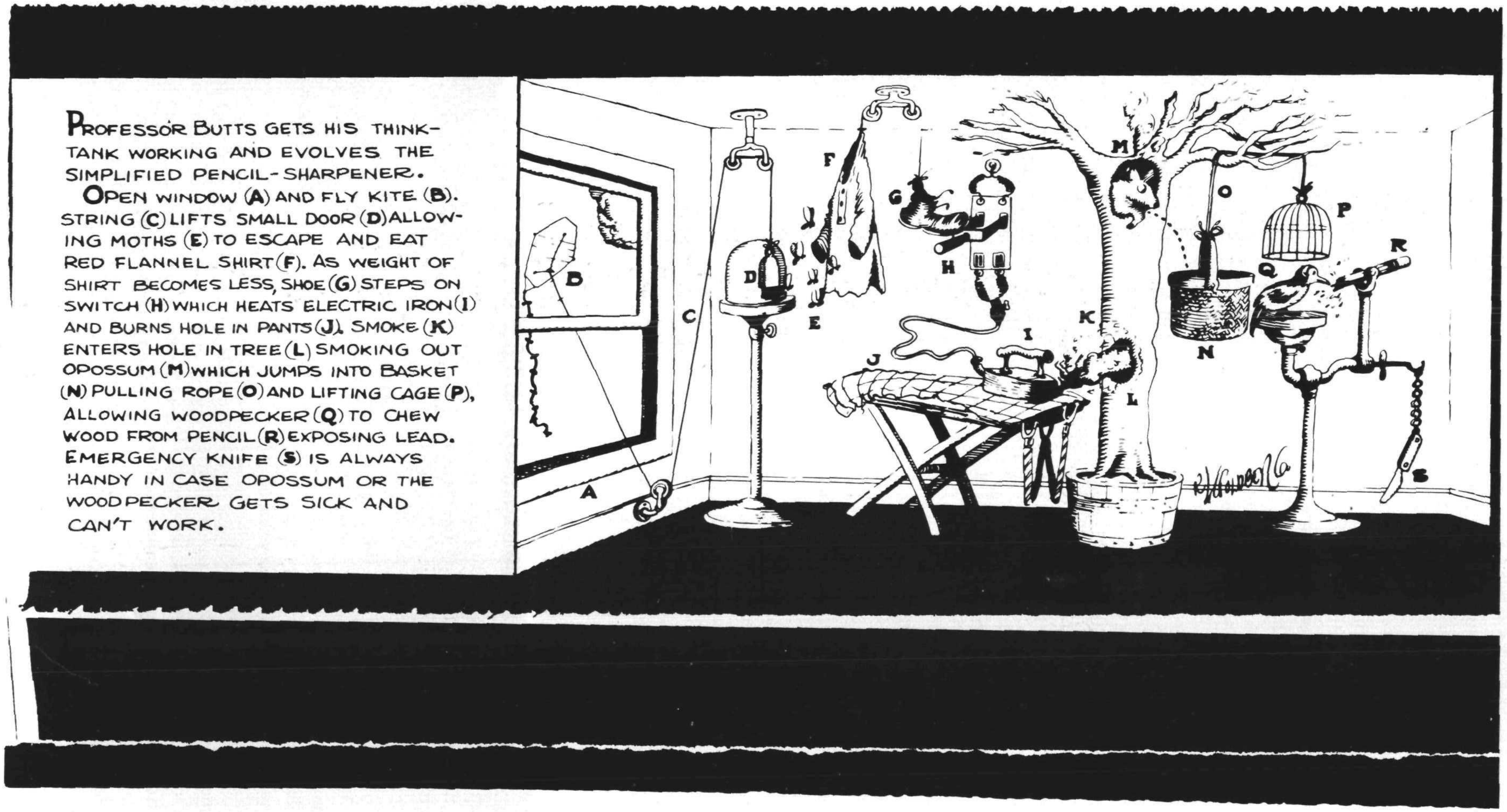


Fig. 11.1—Rube Goldberg's simplified pencil sharpener.

and integrity. As pointed out in Sec. 11.1 of this chapter, reliability is a measure of the time stability of a product's performance. This concept can be expressed in a quantitative sense in the definition of reliability approved by the IEEE:[4] "The characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time." In the general sense, this definition of reliability does not allow for failure and repair during the stated period of time. For example, consider a pressure switch monitoring the reactor pressure located where it is totally inaccessible during reactor operation. An assessment of the numerical reliability of the switch to survive one fuel cycle is a meaningful measure of its integrity.

In many other cases, inspection, test, and repair during operation are permitted, and this is, in fact, the preferred mode of operation. In this event, the most meaningful measure of integrity is called "availability" and is defined as[4] "The characteristic of an item expressed by the probability that it will be operational at a randomly selected future instant in time." Stated another way, availability is the fraction of the time the system is operational. In the long-term steady-state situation, availability is given by the equation

$$\text{Availability} = \frac{\text{Up time}}{\text{Up time} + \text{Down time}} \qquad (11.1)$$

where the up time is approximately equal to the average time between failures and the down time is the average time to repair and restore the system to service. Since the down time is the average time to repair the system, it must include the elapsed time between the failure and its discovery, a term that may be of primary significance especially in standby systems.

Availability, not reliability, is the term that is most applicable to the usual reactor instrumentation system, where redundancy, repair during operation, and a paramount concern for detecting and eliminating unsafe failures are prominent characteristics.

11-3.2 Preselection of a Basic System Configuration

The most effective reliability efforts are those expended during the preliminary design phase while the system configuration is being determined. During this period the reliability considerations can influence design decisions and ensure that the chosen configuration is one that can be developed to meet the reliability requirements. The process is an iterative one, with the designer continually looping back and trying different system configurations until all constraints are satisfied. At this time the principal effort is being expended at the drawing board. Errors of judgment may be corrected with an eraser instead of a jackhammer.

Reliability considerations are not the only constraints imposed on the design. Other constraints include capability, size, shape, weight, cost, schedule, and customer preference, all of which must be adequately satisfied. Reliability analysis provides a disciplined framework within which the interplay of these constraints can be viewed with sharper perspective. Frequently the result is not only a more reliable system but also a better system as judged by all other applicable criteria.

In the preselection of a basic system configuration, the designer should (1) define success for the system, (2) establish adequate reliability goals, (3) propose alternate designs, and (4) evaluate the reliability potential for each design. These four tasks are discussed in the following sections.

(a) Defining "Success" for the System. The designer must know exactly what his system is expected to do. This may sound trite, but many a design has been impaired because the designer either did not fully know or perhaps had lost track of the real reason for having the system. The definition of success should include the environmental constraints in force and the length of time or the number of cycles the system is expected to endure. There may be two or more valid success definitions for the same system, each requiring a separate analysis.

For example, assume an instrumentation system associated with a set of isolation valves. There may be two definitions of success imposed, one for safety reasons and the other for operational or economic reasons.

Success #1. Given that the pipeline downstream of the isolation valve is broken (complete severance), the instrumentation system shall detect the resultant leak within 10 sec and signal the isolation valve to close.

Success #2. Given that the pipeline downstream of the isolation valve is not broken, the instrumentation shall not signal the isolation valve to close.

Operating conditions. The cable and detector environment is 120°F and 50% relative humidity prior to the break and 212°F and 100% relative humidity following the break. The instrumentation system is tested every 3 months and calibrated annually.

In every case the boundaries of the system under consideration must be explicitly defined. In the above example, it is intended that the valve itself be excluded. For this reason a transition point from the instrumentation system to the valve must be chosen so that every component or potential point of failure is certain to be included within one system or the other, but never both.

(b) Establishing Goals. The designer must have some measure of achievement for the reliability of his system. One simple and effective goal that has been used on critical systems for many years is the so-called "single-failure" criterion, namely, that the system shall fulfill its success definition in the event of failure of a single active component. Basically, this criterion has served the nuclear industry rather well in spite of some limitations. One limitation is that it is not readily adjustable to match the whole range of consequences of system failure. If the

single-failure criterion were universally applied, a high-level warning instrument on a waste-water sump would need to be just as reliable as the reactor protection system, even though the consequences of failure are vastly different. In addition, the single-failure criterion does not adequately protect against multiple independent failures that are more probable than should be allowed. Despite its shortcomings, the single-failure criterion for all active components should be imposed as the minimum goal on all reactor instrumentation systems where safety and the potential for economic loss are important considerations

The techniques of reliability analysis, properly applied, yield a numerical measure of the expected system reliability or availability. For this reason a numerical goal serves an especially useful purpose Although such numerical goals are commonplace in the aerospace industry, they are only recently coming into use in the nuclear industry. A numerical goal can be established in any one of a number of ways.

1. Risk acceptance Ideally the goal should be a function of the highest risk the public will accept in return for the benefits derived from nuclear power. Risk is defined as the product of the probability of failure and the consequences of that failure. The consequences may be measured on any convenient scale, such as dollars, curies of ^{131}I, and injuries. Unfortunately this concept is not very far advanced and not universally accepted However, an examination of some of its precepts does yield some insight into the relative reliability required for various systems

2 Grandfather systems. Even though the nuclear industry is relatively young, there are some instrumentation systems that have gained wide acceptance for a given application and enjoy a reputation for being adequately reliable A reliability analysis of one or more of these systems will yield a numerical result that should prove useful in establishing a realistic numerical goal for new systems

3 Industry standard goals Industry committees concerned with the safety of nuclear plants (see Chap 12) are beginning to address themselves to the matter of goals On the international scene, a goal of 10^{-5} probability of failure has been proposed for the reactor-protection-system scram function The IEEE Nuclear Science Group Technical Committee on Standards (see Vol 2, Chap. 14) has considered goals, but it is currently recommending that each designer set a goal to meet the particular need.[4]

(c) Proposing Alternate Designs. Before any attempt is made at a detailed design, a wide range of design alternates should be blocked out for evaluation. The instrumentation system must be considered as an integral and essential part of the overall functional system. In other words, instrumentation systems perform an essential service for the functional systems in the plant, instrumentation does not exist for its own sake.

For example, assume that the functional system is an emergency cooling loop. The engineer designing the functional system and the instrumentation engineer must work together to propose alternates, such as the following

1. One loop, two 100% capacity pumps per loop
2. One loop, three 50% capacity pumps per loop.
3. Two loops, one 100% capacity pump per loop
4. Two loops, one 100% capacity pump per loop with a crosstie
5. Two loops, one 50% capacity pump per loop plus one 50% capacity pump shared by both loops

The list should be made as inclusive as possible so that no worthy configuration is omitted All proposed alternate designs should pass the capability test before being evaluated for reliability or availability. Obviously the probability for system success can vary widely, depending on the system configuration The instrumentation systems to start and stop the pumps and open and close valves are very different for the relatively few configurations cited.

(d) Evaluating the Reliability Potential for Each Design. It is not practical to perform a detailed design on each proposed system before making a selection that is based on, among other considerations, a detailed reliability analysis Therefore it is particularly important that the proposed designs be carefully screened to eliminate those which do not have the potential for development into a system with adequate reliability.

The foregoing may be accomplished by adhering to the following discipline

1 Construct a simple reliability model for each proposed design The blocks from which the models are constructed should encompass as much of the system's equipment as is reasonably possible For example, a block called "pump" could effectively include the pump, its driving motor, coupling, and circuit breaker.

2 Use a consistent set of failure data throughout the comparative evaluations Where failure-rate data have been reported, use them as a base, but do not hesitate to adjust them upward or downward to reflect best judgment, duty factors, or environmental conditions. Where failure-rate data do not exist, choose a value that reflects the best judgment of knowledgeable people in the field but use the same assumption consistently throughout the evaluation.

3. Reflect the expected operating conditions If in one design certain components are exposed to environmental conditions more severe than normal, that design should be properly penalized by adjusting the failure rates upward by an appropriate K factor to reflect the higher level of imposed stress

4 Allow each system proper credit for its compatibility with testing. In general, the unreliability of a component increases almost linearly with the interval between thorough tests (See Fig 11.4) Therefore a component that is physically inaccessible for test except during a refueling shutdown should be penalized in comparison to one that is readily accessible and frequently tested.

5. Solve the models for a numerical index of reliability If the model is really kept at its simplest level, the

probabilistic solution should not be difficult. If the solution is difficult, concentrate first on simplifying the model to get an approximate solution rather than straining at the mathematics for these preliminary design evaluations.

6. Conduct sensitivity studies to identify the dominant components contributing to the unreliability of each system. This may be done by making a significant change in the assumed failure rate of a particular component and noting the change in the overall probability of system failure. Figure 11-2 shows a plot on a log–log scale of component unreliability vs system unreliability. The reference or expected failure probability for component 1 is indicated by an arrow. Note that the arrow falls on the flat portion of the curve, indicating that this particular component does not contribute significantly to system unreliability. The reference value for component 2 is on the steep part of the curve, indicating that a change in failure rate here will have a dominant effect on system unreliability. Good safety design dictates that the overall system have a sufficiently low value of unreliability. Good economic design dictates that, in general, the least expensive components should not be dominant contributors to unreliability.

7. Redesign the proposed systems, as appropriate, to minimize the areas of apparent weakness revealed by the sensitivity analysis. This becomes an iterative process, but this is where the big payoff comes, in being able to bring quickly into focus the systems with the greatest potential for detailed design consideration.

8. Reexamine the final proposals to be sure that they satisfy all other operational and physical constraints that may be appropriate.

9. Select the one or two exploratory designs that show the greatest potential for maturing through a detailed design process and for adequately satisfying all constraints, including reliability.

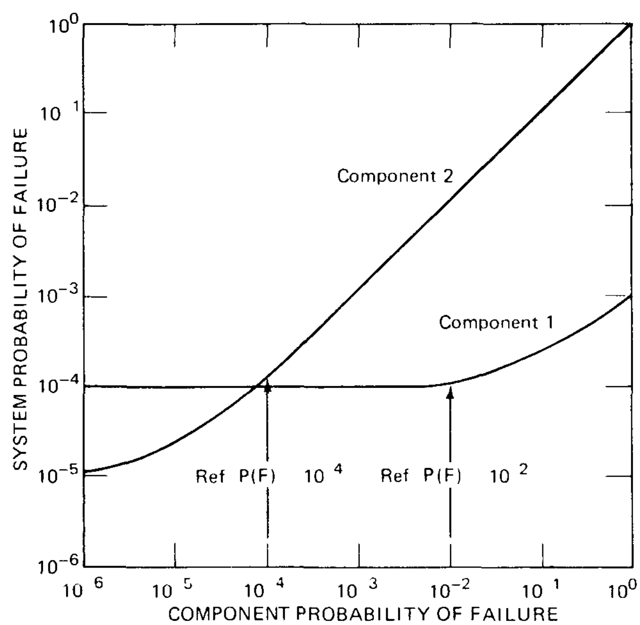


Fig. 11-2—Sensitivity study of system failure vs component failure.

11-3.3 Detailed System Design for Reliability

The proposed design or designs selected from the evaluations of reliability potential are subjected to detailed design. Components of known quality are selected and applied well within their rating for the expected environment. If a new component of unknown quality is to be applied, it may be appropriate to subject it to test, particularly if the assumed best-judgment failure rate indicates (through the sensitivity study) that the component has a dominant influence on reliability.

In every possible way the designer must endeavor to emulate the model and to be certain that the boundary assumptions are satisfied. If the model assumes that the failure of one component or group of components is statistically independent of other failures, the designer should try to ensure that this is true. For example, if two channels of instrumentation are assumed to be independent, they should be so located that only a highly improbable event could disable both. The routing of signal cables and the location of power sources must be carefully considered. Historically, localized overheating and fire have been the two most common single-event failures that can cause other failures to be interdependent. Careful judgment is required to develop a design that gives a reasonable assurance that a fire can be controlled without transgressing the independence of channels.

The designer should also recognize that interdependence can creep in by inconspicuous routes. If the required level of reliability is such that redundancy is necessary, it may be appropriate to make the redundant channel different just to increase the likelihood that an unknown deficiency or inadequacy in one channel will not be repeated in the other. Frequently this can be accomplished by functional diversity; for example, one channel can monitor temperature and another pressure, either signal containing the desired information. Where functional diversity is not possible, equipment diversity may be used to good advantage. For example, pressure can be monitored by two sets of equipment that operate on two entirely different principles. Functional diversity is to be preferred because it almost automatically includes equipment diversity.

If the model assumes that the component failure rates are constant, the designer should be sure that the maintenance and replacement practices will not allow worn-out components to remain in the system. If the model assumes that some of the components are to be tested while the plant is in operation, the designer should be sure that adequate testing facilities are provided. If the system or portions of the system perform functions in addition to a safety-related task, the designer must ensure that these additional functions do not interfere with the model of the safety-related function.

Simple straightforward systems are easy to understand, easy to model, and tend to have high reliability. If a system is allowed to develop without the benefit of a model to

emulate, the system can become complex and interwoven in such a way that modeling is extremely difficult and, intuitively, the whole system is suspect A safe rule, then, is never design a system that cannot be reduced to a tractable reliability model.

Of course, the instrumentation system must still meet all its normal objectives of performance The reliability discipline is simply superimposed on the usual detail design procedure. The concepts of reliable system design are not difficult nor are the associated mathematical relations. For this reason it is preferable that a designer with a good reputation for instrumentation design take on the disciplines of reliability engineering rather than interpose a reliability engineer as a series element in the design chain. A reliability engineer serves the highest purpose when used as a consultant and when he and the designer approach a problem with open minds and an honest desire to understand the system.

11-3.4 Evaluation of the Design

(a) The Failure Modes and Effects Analysis (FMEA). The detailed design is followed by a detailed reliability evaluation. As a minimum the system must be subjected to an FMEA. This is a subjective and nonnumerical analysis that exposes potential failure points The FMEA identifies every component in the system by component number and name It lists the various modes in which the particular component would fail (open, short, closed, stuck, etc.) and lists the failure mechanisms that can induce a particular failure mode. It further identifies the relation a failed component has to system failure and to the failure of other systems.

A sample page of an FMEA is shown in Fig. 11.3. There are many variations of this form, and there should be no hesitation in adapting the form to suit each analysis. The primary function of the FMEA is to provide an understanding in depth of how the system reacts to all modes of component failure. It is particularly valuable in serving as evidence of conformity with the single-failure criterion If only a minimum effort can be budgeted on reliability analysis, it is generally best spent on an FMEA.

The FMEA form also has space to develop information on failure rates, application factors, test intervals, and repair times in preparation for the more rigorous mathematical model of reliability or availability.

(b) Detailed Reliability Model. The designer now has the information at hand to conduct a more detailed reliability or availability analysis of the system. If the designer adheres closely to the framework of the original simple reliability model, the detailed model should generally be satisfied by the same skeletal block diagram, the exception being only in the number of blocks represented Thus the final model should be just as tractable mathematically as the exploratory model on which the design is based. If it is not, the designer should examine the original assumptions, particularly the one on component or channel independence, to see if they have been violated.

The main value in performing the detailed reliability analysis is in making certain that some trivial component does not make an unexpected and unwarranted contribution to unreliability. If such a discovery is made, the problem can usually be rectified by the choice of a better component, more frequent and more thorough testing, or by the judicious use of redundant components

When it has been determined that the contribution of a given component to unreliability is trivial, it may be eliminated from the model or lumped with associated components to simplify the computation.

FAILURE MODE AND EFFECTS ANALYSIS

(1)	(2)	(3)	(4)	(5)	(6)		(7)	(8)	(9)								
									Failure risk								
Item No.	Name	Failure mode	Failure mechanism	System effect of failure	Rate of failure effect		Failure class (consequence)	Remarks (compensating features etc.)	System state			System state			System state		
					Rapid	Slow			λ	t	λt	λ	t	λt	λ	t	λt

Fig. 11.3—Sample page for Failure Mode and Effects Analysis

11-3.5 Testing for Reliability

Instrumentation systems are characterized by two kinds of signals, analog and bistable The analog portion of the system can usually be depended on to annunciate its faults by causing either a zero output or an off-scale reading With the proper alarms, gross failures in the analog circuit can usually be detected immediately The bistable portion of the circuit can usually be designed so that the most probable modes of failure are to the "safe" state However, "fail-to-safe state" design is more of a design objective than an accomplished reality, and the only way one can be sure that a bistable device will successfully change state is to test it Accordingly the designer should address himself faithfully to the special problems of testing

(a) Thoroughness of Testing. The test should be thorough. The objective of the test is to ensure that the system still retains its original properties The test must reflect the conditions that will exist when the instrumentation system is called on to function For example, a bistable trip circuit should be tested by running the analog signal up to the trip level rather than dropping the trip level down to the normal operating point The former proves that the analog signal will not saturate before it reaches the trip level.

If possible, a complete channel should be tested end to end with the real input parameter as the variable For example, some designers arrange to squirt hot water on a temperature sensor to drive it past the alarm point, or, in other cases, there is a provision for removing a neutron shield from a neutron sensor to give it an up-scale signal If it is not possible, for safety or practical reasons, to vary the real input parameter, then a substitute should be used which bridges the gap For example, if it is not safe to reduce the flow down to the trip level, then a differential pressure signal may be substituted

Instrumentation systems that must function while the reactor is operating should be tested while the reactor is operating. If a system is repaired or maintained while the reactor is shut down, it should be tested using substitute inputs before start-up and retested after start-up in its operational mode.

(b) Testing Redundant Systems. Redundancy in a system presents special problems for testing The objective of redundancy is to provide a system that will continue to work in spite of the failure of a component. The redundancy tends to hide the failure, and, unless the test finds the first failure, the redundant system is not appreciably better than a nonredundant system.

The maximum benefit of redundancy is realized when the product of the failure rate λ and the test interval τ is kept small compared to unity. This principle is illustrated in Fig. 11.4, where the probability of failure is plotted as a function of $\lambda\tau$ for a single and a dual (redundant) device. Note that if $\lambda\tau$ is allowed to get too large, there is little advantage in redundancy.

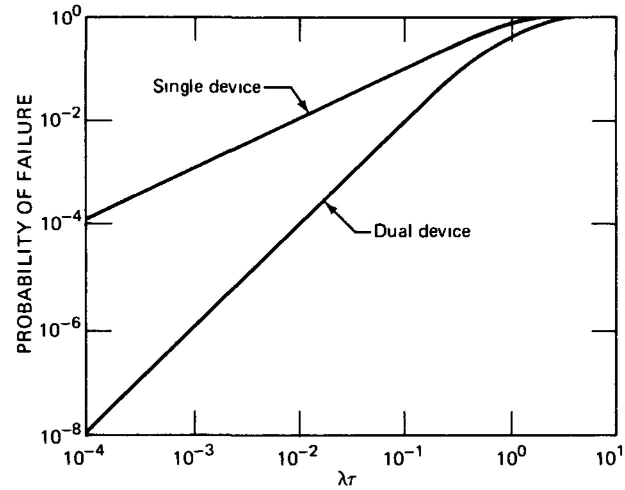


Fig. 11.4—Probability of failure of single and dual (redundant) devices as a function of λt [From I. M. Jacobs, Safety-System Design Technology, *Nucl Safety*, 6(9) 235 (Spring 1965).]

The ability to test should influence system design. In Fig 11.5(a) redundancy is applied on the component level, i e., each component is paralleled with a like component. If there is no opportunity to test or repair (e.g., in an unmanned satellite), component redundancy may have some advantages in higher reliability However, component redundancy is difficult to test because the function is performed if either of the parallel components perform. Also, few components work compatibly in parallel without some special provisions to get them to share the load, and there are likely to be single-failure modes that fail both components.

The system redundancy shown in Fig. 11.5(b) is amenable to test because each channel can be tested independently and the first failure can be found on test In addition, the two channels can be physically and electrically isolated from each other, and single-failure modes are minimized. System redundancy is the preferred design mode. Component redundancy should be used sparingly

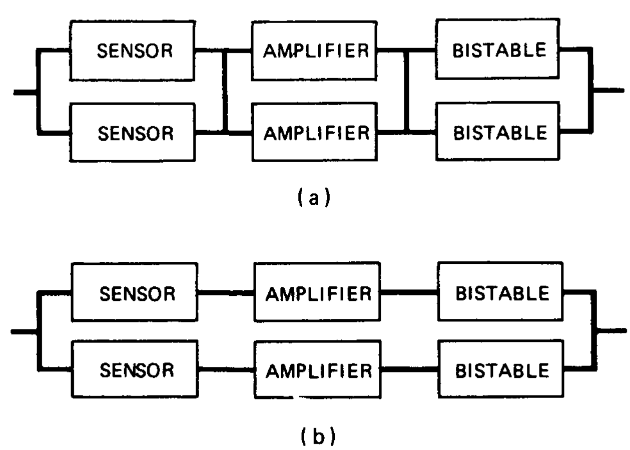


Fig. 11.5—Component (a) vs system (b) redundancy

and only to bolster the reliability of one component in an otherwise strong chain.

(c) Staggered Tests. If there are multiple channels of instrumentation performing the same function in a redundant manner, there is an advantage to be gained in staggering the tests For example, in a three-channel system scheduled for quarterly test, one channel should be tested each month. If the three channels comprise a one-out-of-three system, staggering the tests reduces the predicted unavailability to one-third that which would accrue for simultaneous testing. The higher the level of redundancy, the greater the benefits of staggered tests.

Table 11.6 shows the unannounced unavailability of various logic configurations for three different schedules of testing Note that random testing [calculated by the methods of Sec 11-3 6(f)] yields a result that is intermediate between simultaneous and perfectly staggered testing

Table 11.6—Unavailability as a Function of Logic Configuration and Testing Schedule

	Unannounced unavailability		
Logic	Simultaneous testing*	Random testing†	Perfectly staggered testing*
1/2	$\frac{1}{3}\lambda^2\tau^2$	$\frac{1}{4}\lambda^2\tau^2$	$\frac{5}{24}\lambda^2\tau^2$
2/2	$\lambda\tau$	$\lambda\tau$	$\lambda\tau$
1/3	$\frac{1}{4}\lambda^3\tau^3$	$\frac{1}{8}\lambda^3\tau^3$	$\frac{1}{12}\lambda^3\tau^3$
2/3	$\lambda^2\tau^2$	$\frac{3}{4}\lambda^2\tau^2$	$\frac{2}{3}\lambda^2\tau^2$
3/3	$\frac{3}{2}\lambda\tau$	$\frac{3}{2}\lambda\tau$	$\frac{3}{2}\lambda\tau$
1/4	$\frac{1}{5}\lambda^4\tau^4$	$\frac{1}{16}\lambda^4\tau^4$	$\frac{251}{7680}\lambda^4\tau^4$
2/4	$\lambda^3\tau^3$	$\frac{1}{2}\lambda^3\tau^3$	$\frac{3}{8}\lambda^3\tau^3$
3/4	$2\lambda^2\tau^2$	$\frac{3}{2}\lambda^2\tau^2$	$\frac{11}{8}\lambda^2\tau^2$

*Derived from A. E. Green and A J. Bourne, Safety Assessment with Reference to Automatic Protective Systems for Nuclear Reactors, British Report AHSB(S)R-117(Pt. 2).

†Derived from Sec. 11-3.6(f) of this chapter.

Another more subtle benefit of staggered testing should be noted. If all tests are run simultaneously, i e , one test immediately following another, there is increased opportunity for human error Suppose, for example, that the technician systematically reads the wrong scale on the calibration instrument and sets all channels to a low gain rendering them unsafe. If he proceeds directly from one test to the next, he is much more likely to repeat such an error on all channels than if the tests are spaced days apart

(d) Provisions for Testing. The designer should anticipate the needs for testing and make appropriate provisions If the test must be performed frequently, some built-in arrangements may be in order If the test is simple and is performed infrequently, it may be more appropriate for the one performing the test to implement the test provisions In any event the designer must be certain that the test can be run and that the test gear does not interfere with the ability of the system to perform its intended function.

If standard test-signal emitters are built into a channel, procedure should call for a regular cross calibration with another standard to ensure that the built-in standard remains within tolerance If switches are built in to facilitate testing, an alarm should be initiated if the switches are not restored to "normal" before returning the channel to operation.

Observing the response of the channel to normal process variability and cross comparing with other channels monitoring the same variable is a very convincing test for the analog portions of an instrumentation channel

Automatic testing provisions are sometimes used in reactor protection systems These have two primary advantages

1 The interval between tests can be reduced considerably with a corresponding reduction in system unavailability.

2 The automatic testing system can be designed to be a diagnostic help in troubleshooting

These benefits should be balanced carefully against the disadvantages

1 Extreme care must be exercised to ensure that a common-failure mode is not introduced in otherwise independent channels

2 It must be demonstrated conclusively that the automatic test signal (frequently a pulse train) has the same effect on the circuit output device as a bona fide trip signal, which may build up slowly and sustain itself much longer

3. The automatic test must encompass the whole channel, from sensor to channel output, and be thorough in discovering failures This presents some difficulty for the tester, especially if a portion of the channel is analog in nature.

(e) Setting the Test Interval. Several factors must be considered in setting the time interval between tests Tests spaced too far apart may allow unsafe failures to accumulate. On the other hand, tests conducted too frequently can become a burden on the plant operator if they do not truly enhance safety. The designer should consider the following factors in making the test interval a viable part of his design

1. The tests should be made frequently enough so that the system will meet its design goal. In fact, one way to increase or decrease the availability of a system is to alter the test interval.

2 The tests should not be scheduled as "busy" work at an unrealistically short interval lest the tester lose his respect for the test and become negligent

3. Only failure modes that are primarily time dependent need be considered in setting the test interval. For example, it is futile to test for a failure that occurs only as a result of the stress of initiating the test.

4 Wear-out due to testing should be a consideration, and, if it is necessary for the sake of safety to test so often that wear-out could be a problem, provisions must be made

to monitor the component failure rates carefully and renew the components before they deteriorate to too low a level.

5. If a channel must be bypassed while it undergoes test, then the interval between tests (τ) should not be so short that the unavailability due to being bypassed is higher than the expected unavailability due to unsafe failures For a single channel there is an optimum test interval. If the expected channel unsafe failure rate is λ and the time required to perform the test is t, the optimum test interval for highest availability is given by the expression[5]

$$\tau = \left(\frac{2t}{\lambda}\right)^{1/2} \tag{11.2}$$

In no case is it of benefit to test more often. The preceding expression does not hold for a redundant or majority logic system, there being no true optimum. However, negligible benefits are derived from testing the individual channels of a redundant system more often than is indicated by Eq. 11.2.

11-3.6 Probabilistic Manipulations

Systems are made of component parts, and the reliability of each component part is either known or can be predicted. The reliability of the overall system is what is desired. The reliability of the system can be predicted as a function of the reliabilities of its various component parts by applying the logic of success–failure events in the system.

The methods discussed in this section are "decision tree" logic, Boolean algebra, conditional probability, minimal cuts, binomial theorem, and availability analysis All the methods of probabilistic manipulation described here are suitable for hand calculation and some can be used as the basis for computer calculation.

(a) Decision Tree Logic. The "decision tree" is a systematic way of accounting for all the system paths to success and of giving each its proper probabilistic weight. The success diagram of Fig 11 6 represents a physical

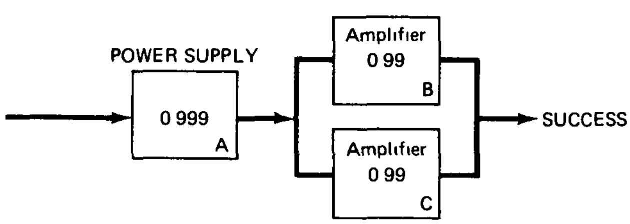


Fig. 11.6—Reliability block diagram for a series–parallel system.

system in which two amplifiers are dependent on one power supply. Success is assured if the power supply and at least one amplifier are operating

The decision tree used to calculate system success is shown in Fig 11.7. Each branch in the diagram, reading from left to right, represents a decision, go or no-go, on the success or failure of that particular component. By convention, good outcomes branch upward and bad outcomes branch downward. The components are considered in order A good outcome on A and a good outcome on B ensures success, so this branch terminates on the vertical bar labeled "success" Likewise, a good outcome on A followed by a good outcome on C ensures success. A good outcome on A followed by bad outcomes on both B and C ensures failure. Finally, a bad outcome on A ensures failure regardless of the state of B and C since the amplifiers cannot operate without power

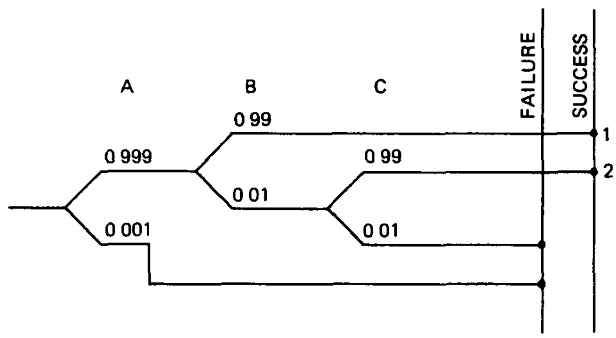


Fig. 11.7—Decision tree for predicting system success for the series–parallel system of Fig. 11.6.

A probability must be assigned to each branch based on the probability of success and failure of the components in that branch. Assume that the probabilities of success and failure for each component are as follows

Component A	Probability of success = 0 999, probability of failure = 0.001.
Component B	Probability of success = 0.99, probability of failure = 0.01
Component C	Probability of success = 0.99, probability of failure = 0 01

The probability of success may be computed by tracing each success path back to the origin, taking the product of the probabilities along each path and summing the result For success path 1, find the product of (0 99) X (0.999) = 0 98901 For success path 2, find the product of (0 99) X (0.01) X (0 999) = 0.0098901 The total probability of success is the sum of the two products, or 0.9989001.

These rules are essential

1 The sum of the probabilities at each branch must be unity.

2. The components of the system must be considered in order until success or failure is ensured without regard to the state of any of the remaining components

3. The various component-failure events must be statistically independent

The least redundant component should always start the first branch and the most redundant components should be considered last to reduce the number of branches on the tree.

The decision tree can handle events with more than two states. It can also accommodate certain physical interdependencies. Consider the success diagram of Fig. 11.8. This figure shows an amplifier driving an output transistor whose

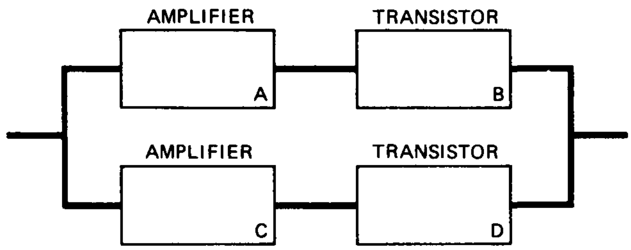


Fig. 11.8—System with multiple component failure states

output is connected in parallel with the output transistor from another amplifier One amplifier can fail without disturbing the other The output transistor can be good, fail open, or fail short. If it fails short, it voids the output of the parallel output transistor and failure is certain.

The decision tree for Fig. 11.8 is shown in Fig. 11.9. Note that three branches are shown for each output transistor decision good, open, short. Note also that any short causes failure whereas an open only leads to failure in combination with other failures. As in the previous example, a probability is assigned to each branch, summing to unity. The probability of success is the sum of the products of probabilities along each success path.

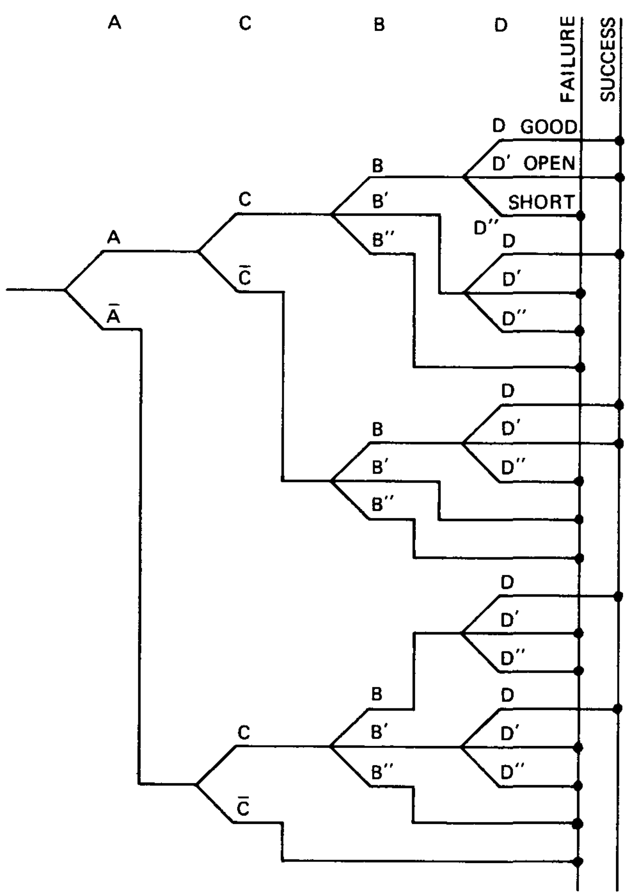


Fig. 11.9—Decision tree for the system with multiple component failure states shown in Fig. 11.8.

As numerical check, it is advisable to calculate the probability of system failure in the same manner and check to see that the sum of the success and failure probabilities is unity. Such a check does not guarantee against errors in the way the decision tree is branched to represent the problem. Consequently it is essential to exercise care in constructing the tree to be sure that it represents the physical system.

(b) Boolean Algebra. The techniques of using Boolean algebra as an adjunct to probabilistic calculations are documented in many sources.[6-8] For those not familiar with Boolean algebra, a simple, but often overlooked, technique will be described.

Consider a two-out-of-three, or majority, logic configuration as represented in the success diagram of Fig. 11.10.

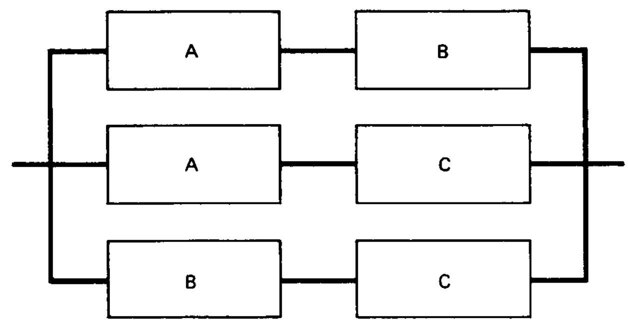


Fig. 11.10—Majority logic success model

If any two of the components are good, the system is good. In Boolean algebra, the event "success" is described symbolically as

$$S = AB + AC + BC \qquad (11.3)$$

where AB means A *and* B and + means *or* In words, Eq. 11.3 says, "The system is successful if A and B are good or if A and C are good or if B and C are good." The negation of A is denoted by the symbol $\bar{A}$, which means "not A" or, in this case, "A fails."

Equation 11.3 can be transformed into a form that is more useful in reliability calculations The following relations from Boolean algebra are used in the transformation

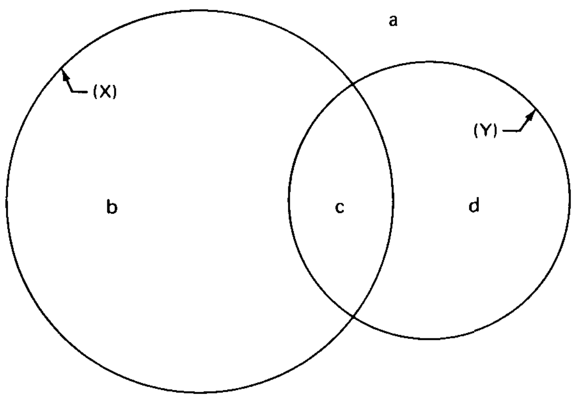
$$X + Y = X + \bar{X}Y \qquad (11.4)$$

$$\overline{XY} = \bar{X} + \bar{Y} = \bar{X} + X\bar{Y} \qquad (11.5)$$

$$XX = X \qquad (11.6)$$

$$X\bar{X} = 0 \qquad (11.7)$$

where X and Y are variables of the same kind as A, B, and C in Eq. 11.3. Figure 11.11 summarizes the basic equations of



X = area inside circle (X) = areas b and c
Y = area inside circle (Y) = areas c and d
$\bar{X}$ = area outside circle (X) = areas a and d
$\bar{Y}$ = area outside circle (Y) = areas a and b
XY = overlap of circles (X) and (Y) = area c
$X + Y$ = area covered by circles (X) and (Y) = areas b, c and d
$X\bar{X}$ = overlap of X and $\bar{X}$ = 0 (since there is no overlap)
$X + X$ = area covered by circle (X) and circle (X) = area covered by (X)
XX = overlap of X and X = X (since overlap is same as X)
$X + \bar{X}$ = area covered by X and $\bar{X}$ = total area (a, b, c, and d) = 1 by definition
$X\bar{Y}$ = area of overlap of X and $\bar{Y}$ = area b
$\bar{X}Y$ = area of overlap of $\bar{X}$ and Y = area d
$X + \bar{X}Y$ = area covered by X and $\bar{X}Y$ = areas b, c, and d

Fig 11.11—Venn diagram illustrating basic Boolean equations The diagram is a nonrigorous way to visualize the basic Boolean equations. From the above it can be seen that, e.g., $X\bar{X} = 0$, $Y\bar{Y} = 0$, $X + X = X$, $Y + Y = Y$, $X + \bar{X} = 1$, $Y + \bar{Y} = 1$, $XX = X$, $YY = Y$, and $X + \bar{X}Y = X + Y$ Multiplying corresponds to "overlapping" or "intersecting", addition corresponds to "covering" or "union" of the added elements. Multiplication can also be read as "and," i e , XY = X and Y, addition can be read as "or", i.e , X + Y = X

Boolean algebra and shows how they may be derived by a graphical representation (the Venn diagram)

Returning to Eq. 11.3, the expression is first broken into two terms

$$S = AB + [AC + BC]$$

and then, using Eq. 11.4, this is rewritten as

$$S = AB + \overline{AB}\,[AC + BC]$$

Similarly, the two terms inside the brackets are written according to the form of Eq. 11.4,

$$S = AB + \overline{AB}\,[AC + (\overline{AC})(BC)] \qquad (11\ 8)$$

From Eq. 11 5 the terms $\overline{AB}$ and $\overline{AC}$ can be written as $\bar{A} + A\bar{B}$ and $\bar{A} + A\bar{C}$, respectively. Substituting these into Eq. 11.8 yields

$$S = AB + (\bar{A} + A\bar{B})[AC + (\bar{A} + A\bar{C})\,BC]$$
$$= AB + \bar{A}AC + \bar{A}\bar{A}BC + \bar{A}A\bar{C}BC + A\bar{B}AC$$
$$+ A\bar{B}\bar{A}BC + A\bar{B}A\bar{C}BC$$
$$= AB + \bar{A}BC + A\bar{B}C \qquad (11.9)$$

In the final step the relations (from Eqs 11 6 and 11.7) $\bar{A}A = 0$, $\bar{A}\bar{A} = \bar{A}$, $C\bar{C} = 0$, and $AA = A$ have been used

In Fig 11.12, the result (Eq. 11.9) is shown graphically. The terms AB, $\bar{A}BC$, and $A\bar{B}C$ are seen to be mutually exclusive, i e , the areas wherein two events intersect are all shown on the Venn diagram, but the areas representing the three terms of Eq. 11.9 do not overlap. Therefore the probability of success is simply the sum of the joint probabilities

$$P(S) = P(AB) + P(\bar{A}BC) + P(A\bar{B}C)$$
$$= P(A)\,P(B) + P(\bar{A})\,P(B)\,P(C)$$
$$+ P(A)\,P(\bar{B})\,P(C) \qquad (11\ 10)$$

As a numerical example, assume P(A) = P(B) = P(C) = 0.99, then

$$P(S) = (0.99)(0.99) + (0.01)(0\ 99)(0.99)$$
$$+ (0.99)(0.01)(0\ 99)$$
$$= 0.999702$$

In summary, the foregoing method is as follows

1. Write the Boolean expression that is the union of all possible success paths.
2. Separate the first term and intersect the negation of that term with the rest of the terms Continue down to the last term.
3. Express each negated success path as the union of mutually exclusive events

$$\overline{AB.\ \ N} = \bar{A} + A\bar{B} + \ldots AB\bar{N}$$

4. Starting with the innermost enclosures, clear the expression using the Boolean relations $A\bar{A} = 0$, $A + A = A$, and $AA = A$.
5. The probability of success is equal to the sum of the probabilities of the mutually exclusive events

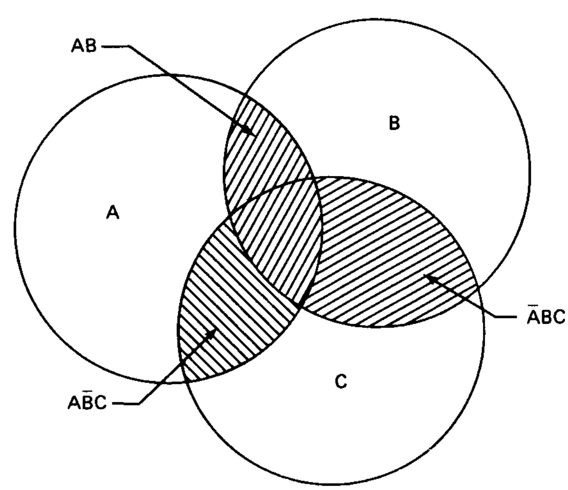


Fig. 11.12—Venn diagram for majority logic case Note that the regions AB, $\bar{A}BC$, and $A\bar{B}C$ are mutually exclusive, i e , they do not overlap each other

(c) Conditional Probability Frequently the complexity of a probabilistic calculation can be reduced by the use of conditional probability It is especially useful if a given component is repeated throughout many branches of the system success model or if the component occupies a key position in the model that makes it difficult to evaluate

Conditional probability may be expressed as

$$P(S) = P(S|A)\,P(A) + P(S|\bar{A})\,P(\bar{A}) \qquad (11\ 11)$$

where P(S) = the probability of system success
P(S|A) = the probability of system success, given that component A is good
P(A) = the probability that component A is good
$P(S|\bar{A})$ = the probability of system success, given that component A is bad
$P(\bar{A})$ = the probability that component A is bad

The method is illustrated by the solution to the reliability model resembling the bridge circuit of Fig 11 13(a) The probability of success can be expressed in the conditional sense as

$$P(S) = P(S|E)\,P(E) + P(S|\bar{E})\,P(\bar{E}) \qquad (11\ 12)$$

The P(S|E) may be obtained from the easily computed diagram of Fig 11 13(b), where component E is replaced by a solid line, indicating that E is perfect The $P(S|\bar{E})$ may be obtained from Fig 11 13(c), where the path normally provided by component E is missing, indicating that E has failed

This method is described fully in Ref 9

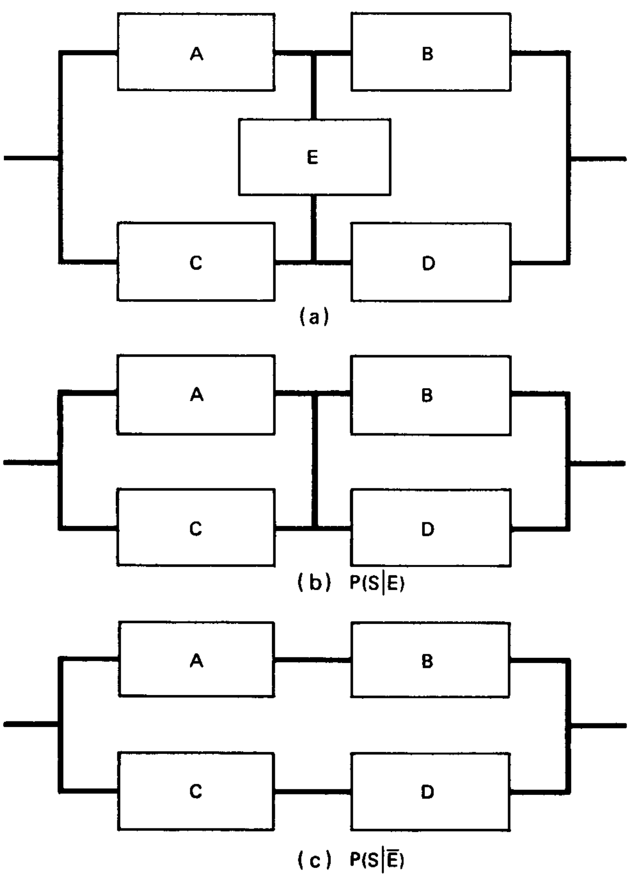


Fig 11 13—Bridge type reliability model

(d) Minimal Cuts A cut is a collection of equipments belonging to a model such that if all these equipments fail, then successful completion of the mission phase represented by that model is precluded[10] A minimal cut is a unique set of failed equipment such that the deletion of any one piece of equipment from the cut restores the system to success

Consider the reliability block diagram of Fig 11 14 The hand-calculation method is as follows Start by

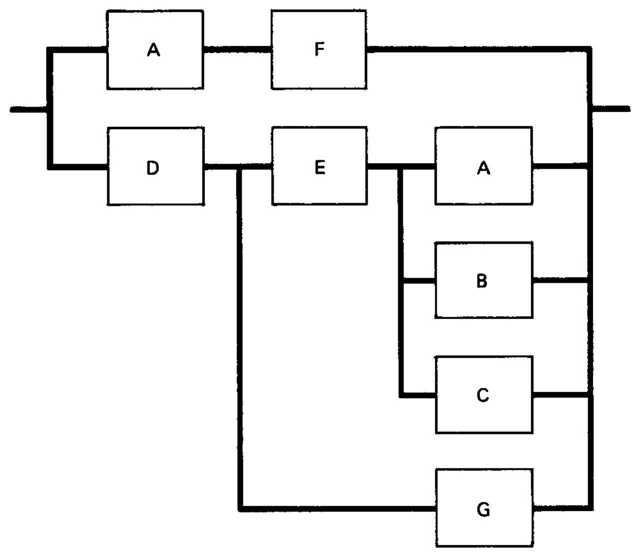


Fig 11 14—Reliability block diagram to illustrate minimal cuts method

considering component A as failed and write all the minimal cuts that must include A By inspection, they are $\overline{A}\overline{D}$, $\overline{A}\overline{E}\overline{G}$, and $\overline{A}\overline{B}\overline{C}\overline{G}$ Then restore A to operation, and write all the minimal cuts that do not include A In this it is obvious that, for the system to fail, all minimal cuts must either include $\bar{A}$ or $\bar{F}$, thus the remaining paths are $\overline{F}\overline{D}$, and $\overline{F}\overline{E}\overline{G}$ Adding together all the minimal cuts gives an approximate expression for the probability of failure

$$P(F) \simeq \overline{A}\overline{D} + \overline{A}\overline{E}\overline{G} + \overline{A}\overline{B}\overline{C}\overline{G} + \overline{F}\overline{D} + \overline{F}\overline{E}\overline{G} \qquad (11\ 13)$$

The approximation is very good provided the probability of failure of each individual component is $\ll 1$ For example, if all components have a probability of failure of 0 01, the system probability of failure is 0 000202 by the minimal-cuts method and 0 000201 by an exact method, an error of only 0 05%

In highly redundant systems, not all the minimal cuts need to be written if their total contribution to failure is small compared to the dominant paths For example, if

$\overline{ABCG}$ is known to be very small compared to $\overline{AD}$ or $\overline{FD}$, ignore it

(e) Binomial Expansion. The bionomial expansion is useful in solving models using redundant components Let p be the probability of success and q the probability of failure of an individual component By definition,

$$p + q = 1 \qquad (11\ 14)$$

Likewise,

$$(p + q)^n = 1$$

where n represents the level of redundancy For example, if n = 5,

$$(p + q)^5 = p^5 + 5p^4q + 10p^3q^2 + 10p^2q^3 + 5pq^4 + q^5 = 1$$

The terms represent the various ways success and failure can be achieved The first term, p^5, is the probability that all components succeed, there is only one way all of them can succeed The second term, $5p^4q$, is the probability that four components succeed and one fails, there are five combinations, including exactly four components succeeding and one failing There are ten combinations of three successes and two failures, or $10p^3q^2$, etc The terms thus account for all the possible combinations of success and failure of the five components

As an example, consider the system with five relief valves If three or more must function, then the probability of success is

$$P(S) = p^5 + 5p^4q + 10p^3q^2$$

that is, either all five can function, or four function and one fail, or three function and two fail If the probability of a single valve functioning is p = 0 95, then the probability of a single valve failing is q = 0 05 and the probability of system success is

$$P(S) = (0\ 95)^5 + 5(0\ 95)^4\ (0\ 05) + 10(0\ 95)^3\ (0\ 05)^2$$

$$= 0\ 9988$$

In general, the binomial expansion is

$$(p + q)^n = \sum_{k=0}^{n} \binom{n}{k} p^k q^{n-k} \qquad (11\ 15)$$

where

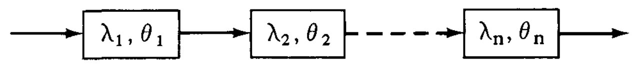
$$\binom{n}{k} = \frac{n!}{(n-k)!\,k!}$$

The coefficients of the binomial expansion can be generated by constructing Pascal's triangle, in which each number is the sum of the two numbers above it The procedure is shown in Fig 11 15

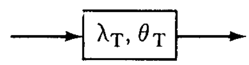
n	
0	1
1	1 1
2	1 2 1
3	1 3 3 1
4	1 4 6 4 1
5	1 5 10 10 5 1
6	1 6 15 20 15 6 1

Fig 11 15—Pascal's triangle for determining the coefficients of the binomial expansion

(f) Availability Analysis *Series Subsystems* If there are n subsystems in series with failure rates $\lambda_1, \lambda_2, \lambda_3, \quad , \lambda_n$ and mean repair times of $\theta_1, \theta_2, \theta_3, \quad , \theta_n$ and if repair is instituted on each subsystem as soon as failure occurs, then the series configuration



reduces to



where

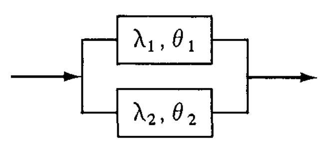
$$\lambda_T = \lambda_1 + \lambda_2 + \quad + \lambda_n$$

and

$$\theta_T = \frac{\lambda_1\theta_1 + \lambda_2\theta_2 + \quad + \lambda_n\theta_n}{\lambda_T}$$

The system parameters are
Mean time between failure for the system = $(1/\lambda_T)$
Mean down time for system = θ_T

Parallel Subsystems If there are two subsystems in parallel with failure rates λ_1 and λ_2 and mean repair times θ_1 and θ_2, if either one or both subsystems in operation constitute an operating system, and if repair is instituted on each subsystem as soon as failure occurs, then the parallel configuration



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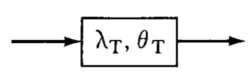


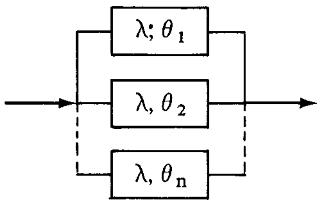
where

$$\lambda_T = (\lambda_1\lambda_2)\,(\theta_1 + \theta_2)$$

and

$$\theta_T = \frac{\theta_1\theta_2}{\theta_1 + \theta_2}$$

If there are n subsystems in parallel (partially redundant to each other), each having the same failure rate λ and mean repair time θ, and r out of n of these subsystems constitute an operating system, and if repair is instituted on each subsystem as soon as failure occurs, then this system



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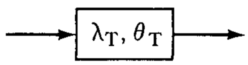

where

$$\lambda_T = \frac{n\binom{n-1}{r-1}}{\frac{1}{\lambda}\left(\frac{1}{\lambda\theta}\right)^{n-r}}$$

$$\binom{n-1}{r-1} = \frac{(n-1)!}{(r-1)!(n-r)!}$$

and

$$\theta_T = \frac{\theta}{n-r+1}$$

Example 1 Two out-of-three subsystems must operate, i.e., n = 3, r = 2.

$$\binom{n-1}{r-1} = \frac{2!}{1!\,(2-1)!} = 2$$

$$\lambda_T = \frac{3(2)}{\frac{1}{\lambda}\left(\frac{1}{\lambda\theta}\right)} = 6\lambda^2\theta$$

$$\theta_T = \frac{\theta}{1+1} = \frac{\theta}{2}$$

$$\text{Availability} = 1 - \lambda_T\theta_T = 1 - 3(\lambda\theta)^2$$

Example 2 Three-out-of-four subsystems must operate, i.e., n = 4, r = 3

$$\binom{n-1}{r-1} = \frac{3!}{2!\,(3-2)!} = 3$$

$$\lambda_T = \frac{4(3)}{\frac{1}{\lambda}\left(\frac{1}{\lambda\theta}\right)} = 12\lambda^2\theta$$

$$\theta_T = \frac{\theta}{1+1} = \frac{\theta}{2}$$

$$\text{Availability} = 1 - \lambda_T\theta_T = 1 - 6(\lambda\theta)^2$$

Note that the unavailability (= 1 − availability) of the three-out-of-four system is twice that of the two-out-of-three system.

The foregoing relations were derived from Ref 9. In the derivations it is assumed that failure rates and repair times are exponentially distributed and that all $\lambda\theta$ products are $\ll 1$

By these techniques any simple series-parallel availability model can be reduced to a single block with an equivalent failure rate and repair time. This technique is not applicable to a system with repeated components or components that bridge between series-parallel strings.

In many cases repair does not commence when failure occurs but rather when failure is discovered. This is particularly true of most of the failures of standby systems and of non-fail-safe failures on power-plant protection systems In these cases the mean repair time is equal to one-half the time interval between tests plus the actual repair time.

In the event that repair starts immediately on detection of the failure at a periodic test, the following substitution in the preceding formulas will yield useful results with little error

$$\theta^* = \frac{\tau}{2} + \theta$$

where θ^* is a new equivalent repair time including the time elapse between failure and discovery. Frequently the actual repair time is short compared to the time between tests, so the above can be approximated by $\theta^* \simeq \tau/2$

APPENDIX A RAW-STOCK IDENTIFICATION SYSTEM

Purpose To establish a method of identifying raw-material stock in terms of basic composition and thermal condition

Scope This procedure applies to raw metallic material that is to be used for production purposes in the Fabrication Department Specifically excluded are castings and extrusions or any other material that is produced in accordance with engineering drawings and is assigned a part number distinctly different from commercial part numbers

11-A.1 Identification System

The identification system used may be expanded to provide for materials that may be added to the listings (Table 11-A.2) by assigning striped colors, which are available within the system, or, if necessary, by using more than a single stripe.

11-A.2 System Description

All metals shall be identified by a color-coding system that uses the twelve basic colors listed in Table 11-A 1 A combination of at least two of these colors is required to identify a stocked item The use of the colors shall be according to the system described in the following paragraphs

(a) **Body Color.** One of the basic colors is assigned to each of the categories of materials given in Table 11-A 1

Table 11-A 1—Basic Body Colors

Color	Material category
Red	Aluminum alloys
Blue	Magnesium alloys
Pink	Brasses
Yellow	Beryllium coppers
Orange	Bronzes
Green	Carbon and free-cutting steels
Light green	Spring steels
Aquamarine	Alloy steels
Brown	Stainless steels
Gray	Magnetic metals
Black	Cast irons (bars and rods)
White	Coppers

This identifies the materials as falling within a specific category This color will be the background color or body color over which a stripe will be applied to identify the material according to the categories listed in Table 11-A 2

(b) **Body-Color Application**

1 Air-dry lacquer shall be used as the body color The colors shall match the stripe tape described below.

2 One end of bars, rods, and shapes shall be painted the body color (see Fig 11-A 1)

3 Sheet and strip and plate stock shall be stacked with one end in the same plane and the entire end painted with the body color

4 Coiled strip, wire, or tubing may be identified per item 3 above by a metal tag painted the body color and attached with a length of wire to the coil [Fig 11-A 1(c)]

(c) **Stripe Color** Strips of colored pressure-sensitive vinyl tape $\frac{1}{8}$ in wide shall be pressed across the body color painted on the ends of tags, bars, rods, or shapes Painted stripe is used on sheet stock Within any category of Table 11-A 1, the body color shall not be used for a stripe

Table 11-A 2—Stripe Colors

Alloy	Stripe color	Alloy	Stripe color
Aluminum		**Bronze**	
1100 0	Blue	Tobin SAL 73	Green
2011 T4	Black	SAE 660 QQB 691 Comp 12	Red
2017 T4	Pink	MIL N 994 QQB 636 SAE 63	Blue
2024 T4	Yellow	SAE type 1 class A MIL B 5687	Pink
3003 H14	White	**Carbon and Free-Cutting Steel**	
5050 H32	Orange	B 1113	Red
5052 0	White–orange	1018 (bar and rod)	Blue
6061 T4	Green	1010 to 1020 (sheet and strip)	White
6061 T6	Gray	MT 1015 (tube)	Yellow
6063 T5	Coppertone	**Magnetic Metal**	
7075 T6	Brown	Hi Mu 80	Red
Tool plate	Light green	Moly-perm	Blue
Brazing sheet	White–blue	Mu metal	Yellow
Magnesium		Conetic AA	Green
A731 B	Red	**Cast Iron**	
A731 B O	Pink	Meehanite	Red
A731 B H24	Yellow	**Stainless Steel**	
Tool plate	Orange	17 7 PH	Red–blue
Brass		301 AN	Red yellow
QQB 613	Red	301 FH	Red orange
QQB 626 SAE 72	Blue	$301\frac{1}{2}$ H	Red
WWT 791 SAE 74	Yellow	302 304	Blue
Spring Steel		302 FH	Blue–orange
1086	Red	303S 303SE	Pink
1095	Blue	316A	Yellow pink
Drill Rod		321	Light green
Drill rod	Orange	410	Orange
Alloy Steel		416	Green
52100	Green	430	Gray
4140	Red	440A	Light green–yellow
4620	Blue	440C	Yellow
4130	Yellow	440F	Gray–yellow
Beryllium Copper		Carpenter #10	Blue–yellow
25A	Red	MIL T 6845 ASTM 269	Black
$25\frac{1}{4}$ H	Blue		
$25\frac{1}{2}$ H	Pink		
25H	Orange		
10	Green		
Copper			
OFHC	Red		
Phosphor Bronze	Yellow		

(d) **Stripe Application.**

1 The striping tape shall be applied across the center of the body-colored ends of bars, rods, and shapes, except in cases where the diameter is so small or the configuration such that the body color is not clearly evident after the application, then the tape shall be wrapped around the material close to the painted end.

2 Stripes shall be painted over the body color on the ends of sheet, plate, or strip The stripes shall be placed so that when material is cut off a sheet, the color-code identification is not lost

3 Stripes shall be painted on coils of strip, wire, or tubing, or tape shall be applied across metal tags

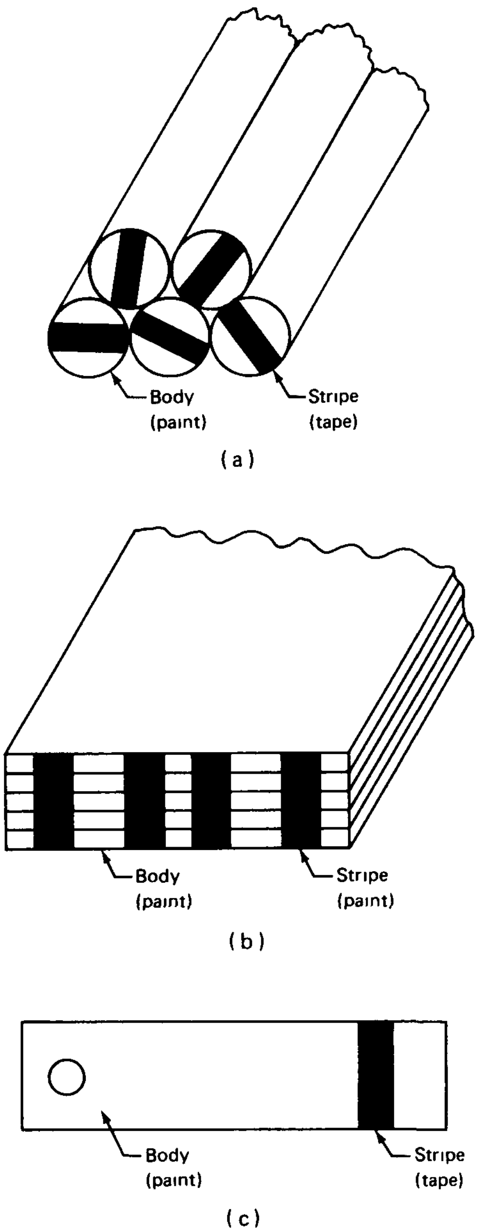

Fig. 11-A.1—Coding application (a) Bars, rods, and shapes (b) Sheet and strip and plate stock (c) Coiled strip, wire, and tubing

APPENDIX B QUALITY-CONTROL PANEL INSPECTION CHECKLIST

PROJECT ____________________ PANEL __________.

INSPECTION DETAILS

1 0 WIRE
- 1 1 Correct size and type ______
- 1 2 Insulation ______
  - 1 2 1 Correct type ______
  - 1 2 2 Correct color ______
  - 1 2 3 Nondefective ______

2 0 TERMINALS
- 2 1 Correct type and hole size ______
- 2 2 Staking ______
  - 2 2 1 Full staking impression ______
  - 2 2 2 Adequate insulation grip ______
- 2 3 No damage or distortion to grip or tongue ______
- 2 4 Correct wire insertion depth into barrel
  - 2 4 1 Wire insertion is within $^1/_{16}$ in of insulation stripback butt ______
- 2 5 Use of staking tools approved by the terminal manufacturer ______

3 0 CONNECTORS (disconnects or couplings)
- 3 1 Correct size and type ______
- 3 2 Correct clocking ______
- 3 3 Insulation sleeving over solder pots (where required) ______
- 3 4 Solder pots full of solder (no excessive overflow or peaks) ______
- 3 5 Wire insertion in solder pot is within $^1/_{16}$ in of insulation stripback butt ______
- 3 6 Connector shell mated and tight ______
- 3 7 Adapter ______
  - 3 7 1 Tight ______
  - 3 7 2 Lock washers under screwheads of saddle clamps ______
  - 3 7 3 Screws tightened evenly ______
  - 3 7 4 Ground return jumper tight (if used) ______
  - 3 7 5 Sufficient bushing or number of grommets under saddle straps to secure wires and relieve tension on solder pots ______
  - 3 7 6 Correct size and type of bushing ______
- 3 8 Hi pot test of connectors (where required) ______
- 3 9 Potted connectors ______
  - 3 9 1 Lack of voids ______
  - 3 9 2 Lack of sponginess ______
  - 3 9 3 Correct compound type ______
  - 3 9 4 Correct cure ______
  - 3 9 5 Proper clearance ______
  - 3 9 6 Complete fill ______
- 3 10 Crimp type pins
  - 3 10 1 Correct staking impression ______
  - 3 10 2 Correct wire insertion depth into barrel ______
  - 3 10 3 Insulation stripback is within $^1/_{32}$ in of barrel top ______
  - 3 10 4 Use of staking tools approved by the terminal manufacturer ______
- 3 11 Pins properly seated in connector ______

4 0 CLAMPS (support)
- 4 1 Correct size (snug fit but not tight) ______
- 4 2 Clamp "lip" closed ______
- 4 3 Hardware secure ______
- 4 4 Cushion closed ______
- 4 5 Plastic clamps free of distortion and pulling ______
- 4 6 Coaxial cable clamps are free of excessive tightness to prevent cable distortion ______

5 0 TERMINAL STRIPS
- 5 1 Correct size and type ______
- 5 2 Terminal lugs are staked back to back (if used in multiple) ______
- 5 3 No broken nodes (barriers) ______
- 5 4 Terminals are aligned in middle of nodes ______
- 5 5 Terminals are correctly and completely identified ______
- 5 6 Terminal screwhead slots free from burrs or twists ______

5 7 All wires in compression-type terminal secure and tight

6 0 COAXIAL CABLES
- 6 1 Correct type of cable and connector
- 6 2 Stripping
  - 6 2 1 Inner conductor for correct length, no nicks or cut strands
  - 6 2 2 Shielding and outer insulation for correct length
- 6 3 Correct assembly sequence
- 6 4 Contact pin soldered properly
- 6 5 Location of contact pin is correct after assembly
- 6 6 Hi-pot or megger test for insulation breakdown (where required)
- 6 7 Continuity check

7 0 SOLDER
- 7 1 Identity to type
- 7 2 Nonuse of acid core solder, fluxes, or paste
- 7 3 Bonding of wire to connector solder pots or eyelet by solder flow
- 7 4 No cold solder joints (frosty)
- 7 5 All wire strands in solder pot or eyelet
- 7 6 No excessive solder
- 7 7 No solder spill or splatter into receptacles, devices, components, or printed circuits
- 7 8 Excessive rosin flux removed
- 7 9 Soldered connections covered with insulation and secured (where required)
- 7 10 No overheating of terminals causing insulation scorch, barrier scorch, or component parts burn
- 7 11 Use of soldering tool with sufficient watt density to ensure acceptable solder joints
- 7 12 Equipment or hardware mounting to aid visual identification of part number or value of component after installation

8 0 GROUNDING
- 8 1 All control shafts and bushings grounded (unless otherwise specified)
- 8 2 Ground lugs are utilized in place of parts mounting facilities
- 8 3 Ground lugs mount on metal surface under screwhead

9 0 SPLICES (when permitted)
- 9 1 Inspect prior to covering or enclosing into wire bundles
- 9 2 Correct method and device used to make splice

10 0 PANELS, MODULES
- 10 1 Basic
  - 10 1 1 Bonding areas clean, free of primers of paint
  - 10 1 2 Equipment, devices, and operators for correct
    - 10 1 2 1 Part number
    - 10 1 2 2 Rating
    - 10 1 2 3 Location
    - 10 1 2 4 Model
    - 10 1 2 5 Type
    - 10 1 2 6 Size
  - 10 1 3 All parts mounted (when prac tical) so that values and identity are in full view
  - 10 1 4 Mounting security of parts
    - 10 1 4 1 Retaining nuts backed up with loc washers
    - 10 1 4 2 Correct length of screws and bolts
    - 10 1 4 3 Screwhead slots free from burrs or twists
    - 10 1 4 4 Bonding areas refinished after installation of jumpers or ground straps
    - 10 1 4 5 Unused mounting or terminal screws or nuts tightened
- 10 2 Wire bundles or harnesses secured
- 10 3 Wire bundles are routed to avoid interference with future terminations, components, moving mechanical parts, and stub-up locations
- 10 4 Slack loops are provided where needed to properly facilitate the movement of mechanical moving structures or allow access to components or sub-panel opening or removal
- 10 5 No twisting or entanglement of wire in harnesses or bundles
- 10 6 Bushings and barriers installed where required
- 10 7 Terminals correctly installed and tightened
- 10 8 Wire breakouts and wire entrances in or out of bundles are consistent Avoid "as the crow flies" or point-to-point wire routing in favor of main wire bundle flow pattern
- 10 9 Wire terminations at terminal blocks for customer "future tie in" or external connections are consistent either to the right or left of the terminal blocks
- 10 10 All disconnect plugs, receptacles, and connectors are suitably covered to prevent entrance of foreign material and moisture
- 10 11 Correct dimensions of
  - 10 11 1 Chassis
  - 10 11 2 Panel fronts
  - 10 11 3 Mounting hole layout
  - 10 11 4 Access door
  - 10 11 5 Clearance requirements
- 10 12 All wire bundles, harnesses, and wire runs are suitably protected from protruding surfaces, sharp edges, and abrasive surfaces
- 10 13 Controls
  - 10 13 1 Shafts clear panel cutout
  - 10 13 2 Shafts correct length
  - 10 13 3 Shafts are straight
  - 10 13 4 Knobs are secured to shaft
  - 10 13 5 Knobs clear front panel
  - 10 13 6 Locking devices on controls (where required)

11 0 FINISH
- 11 1 Paint
  - 11 1 1 Color
  - 11 1 2 Primer
  - 11 1 3 Dry (air or bake)
  - 11 1 4 Touch-up blended
  - 11 1 5 Free of ripples, sag, orange peel, over spray, pits, and voids

12 0 METERS
- 12 1 Correct range ______
- 12 2 Scale identification ______
- 12 3 Scale and index ______
- 12 4 Size, color, mount
  - 12 4 1 Flush, semiflush, front, back ______
- 12 5 Illumination ______
- 12 6 Dial or scale background color ______
- 12 7 Dial or scale numeral color ______

13 0 INDICATING LIGHTS
- 13 1 Illumination factor ______
- 13 2 Cover lens color correct ______
- 13 3 Engraving correct (where used) ______

14 0 NAMEPLATES
- 14 1 Correct etching or attachment ______
- 14 2 Drawing number—group number ______
- 14 3 Serial number ______

15 0 WORKMANSHIP

16 0 LAYOUT IDENTIFICATION OF PARTS

17 0 IDENTIFICATION OF COMPLETED COMPONENTS

18 0 IDENTIFICATION OF PANEL FACILITIES
All controls, indicators, lights, jacks, sockets, and fuse holders marked with suitable words, phrases, or abbreviations indicating the function or use of the part ______

19 0 IDENTIFICATION OF WIRE TERMINAL POINTS

20 0 CLEANLINESS

21 0 FINAL INSPECTION
- 21 1 Compliance to procedure, approved drawings, specifications, and all applicable data ______
- 21 2 Cleanliness continuity (if not part of test) ______
- 21 3 Function or operation (where required) ______
- 21 4 Rework completed and accepted ______
- 21 5 Accessory parts, instruction sheets, or books identified ______
- 21 6 All shortages documented ______
- 21 7 Applicable test and inspection stamps ______
- 21 8 Test data complete, reviewed, and approved ______

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