Radiation in Medicine and Industry
Nuclear Radiation Facts and Figures

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and

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FOREWORD

The public is presently seeking introductory information about radiation, especially radiation associated with nuclear-electric power plants. This booklet should help to meet that need. It will familiarize the reader with some of the more basic terms and concepts related to nuclear radiation.

Writing on a topic of this type is presently an extremely difficult task, in my opinion, due to the controversial nature of nuclear-electric power production, one of the sources of radioactive materials. Nevertheless, it is important that an uncomplicated, basic text on radiation be written to satisfy those who have a need for an introduction to the subject.

This booklet tells concisely what nuclear radiation is, where it comes from, its units of measurement, who regulates it, and how it may affect human health. The currently significant ideas on radiation effects on humans have been recorded, herein, recognizing that discussions and analyses of such effects will continue in the scientific field and that it is impossible to record in one brief presentation all points of view. The authors, however, have succeeded in preparing an orderly selection of introductory ideas, condensed out of a highly complex subject. They point out that radiation can be both beneficial and hazardous and that radiation of all types must be treated with respect.

In summary, you will find this presentation to be timely and to represent the generally recognized concepts in the field of nuclear radiation. It will, therefore, be most useful to those who have had little or no previous introduction to the basic ideas on radiation. Hopefully, this booklet will stimulate the reader to explore this subject further.

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October 31, 1979

I. PURPOSE

The purpose of this booklet is to introduce to a general audience the more significant basic facts and figures about radiation, particularly nuclear radiation. It is also designed to help inform those who may be unfamiliar with the various terms, benefits, and risks of radiation in medicine and industry. This information for the most part was derived from a large number of scientific studies and sources, a few of which are referenced on the last page.

Areas or containers where radiation or radioactive materials may be found must display prominently this three-bladed radioactive-caution symbol in magenta, or purple, on a yellow background as shown on the back cover.

Figure 1. Universal symbol indicating the presence of radiation or radioactive materials.

II. HISTORICAL PERSPECTIVE

Life on earth has evolved amid the constant exposure to naturally occurring radiations from beyond earth (cosmic radiation) and from radioactive material within the earth's crust. Humanity lives in a sea of radiation, and thrives on radiation from the sun. In 1895, Wilhelm Konrad Röntgen, a German physicist, discovered how to generate X-rays. In 1896, Antoine Henri Becquerel, a French physicist, discovered the natural radioactivity of certain ores like uranium. In the same time period, other scientists recognized that various types of radiation sources could be both harmful and useful. For roughly 85 years scientists, engineers and physicians have been using radiation beneficially and developing methods by which to protect society from radiation's injurious effects. By comparison, man has been using fire, beneficially, for some 500,000 years and has learned both to control and respect it.

Figure 2. Life on earth thrives amid naturally occurring radiation.

Radiation is of two types: **particulate** and **electromagnetic.** Particulate radiation is constituted of small particles which have mass and, in most cases, electric charge. By their motion from one point to another, such particles transfer energy in matter. The radiation particles of most interest are: **beta** (electrons with a negative charge); **protons** (with a positive charge); **neutrons** (neutral charge); and **alpha** (each particle contains two protons and two neutrons). Other radiation particles are deuterons (consisting of a proton and neutron), mesons (well-known as a constituent of cosmic radiation), positrons (electrons with a positive charge); and neutrinos (a tiny particle a few hundredths of the mass of an electron).

Electromagnetic radiation has both particulate and wavelike aspects. In its particulate mode, electromagnetic radiation consists of small bundles of energy called photons. In its wavelike mode, it is measured by its wavelength, in centimeters (cm), Angstrom units (Å), or nanometers (nm). Thus, electromagnetic radiations can be described in wavelengths and energies. In their order of decreasing energy and increasing wavelength, electromagnetic radiations are: **gamma rays; X-rays; ultraviolet** (from the sun, for example); **visible; infrared** (heat); **microwaves** and **radiowaves.** The family of electromagnetic radiations is illustrated in Figure 3.

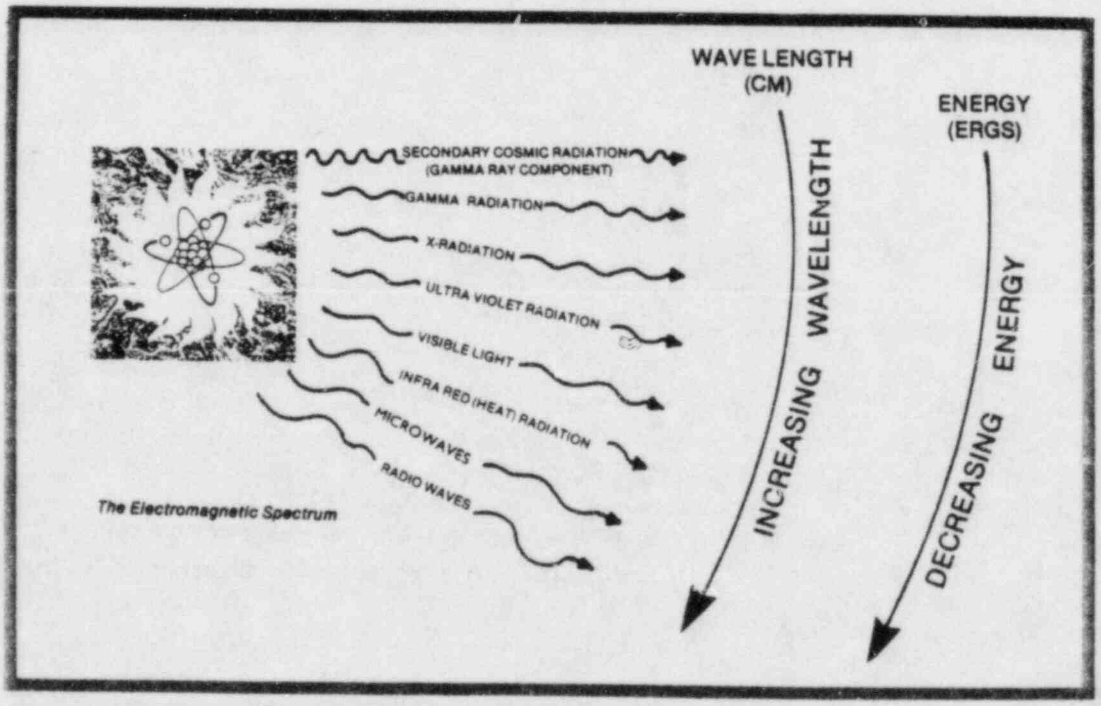


Figure 3. Electromagnetic radiations

One of the most biologically important aspects of particulate and electromagnetic radiations is **how much** energy they deposit in living matter. The deposited energy is referred to as the "dose." Various dose terms are used: the roentgen* (abbreviated R), the rad (radiation absorbed dose) and the rem (roentgen equivalent man). Some radiations cause more biological damage for each unit of dose than others. This difference is accounted for in the **rem** unit but not in the R or rad units. The rem unit is the most functional unit and the most biologically useful; therefore, it is used by physicians and health scientists in measurements referring to **radiation protection.** The R, rad, and rem are the accepted "units" of radiation dose (see Table I).

*German spelling — Röntgen

Table I. Radiation Dose Units

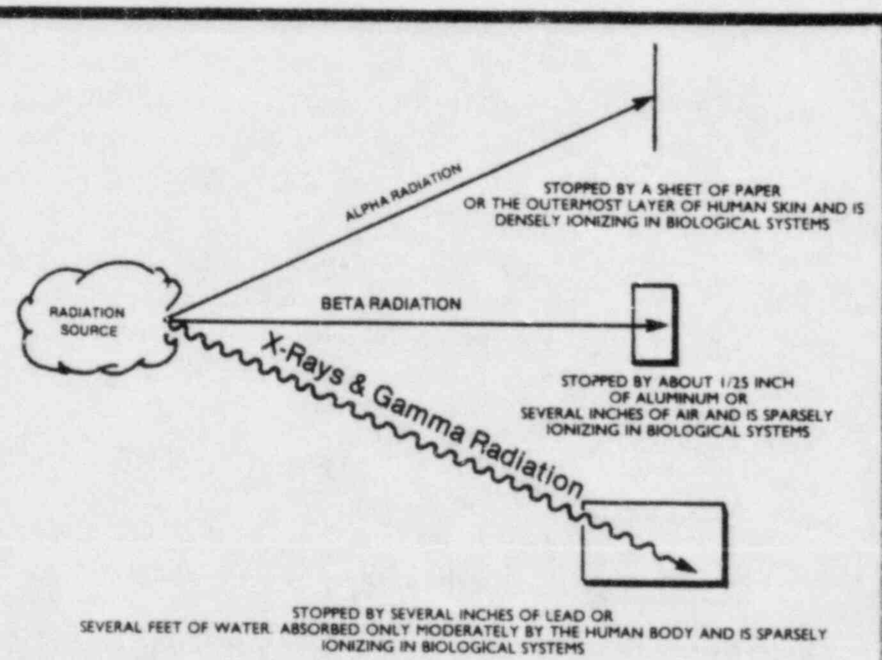
Unit	Abbrev.	Definition	Comment
roentgen or milliroentgen*	R (or mR)	represents the absorption of energy in air	for X-rays and gamma rays only
radiation absorbed dose, or millirad	rad (or mrad)	represents the absorption of 100 ergs of energy per gram of material	important unit because it represents how much energy is absorbed in the material of concern
roentgen equivalent man (or dose equivalent), or millirem	rem (or mrem)	this unit is the product of the amount of energy absorbed (rad) times the efficiency of radiation in producing damage (QF)** rem = rad x QF	this unit accounts for the different degrees of damage produced by equal doses of different radiations, for example: X-rays, gamma rays, and beta particles.....QF = 1; neutrons........QF = 2 to 10; alpha particles....QF = 10 to 20

* A **milli**roentgen is one thousandth of a roentgen.

** QF = Quality Factor. The rem **is not** defined for doses above the "protection level" and therefore **is not** an appropriate unit for quantifying effects at high-level exposures. Protection levels are generally considered to be **less than** 10 rad (ICRP-26; see Ref. 1). However, since the QF for beta, gamma and X-radiation is 1, **the rem and the rad are equivalent in this instance and are frequently used interchangeably.**

Since human exposure to radiation usually involves very small doses, it is convenient to use smaller units. For example, a radiation dose of one thousand millirem (mrem) is equivalent to one rem. The milliroentgen (mR) and the millirad (mrad) are small-dose terms frequently used by radiologists and health physicists.

Radiation deposition in matter depends on the type and energy of radiation and the material irradiated. The penetrating-ionizing power of various radiations is illustrated in Figure 4. Note that alpha radiation, although stopped by a sheet of paper, is densely ionizing and therefore will deposit more energy along its path in the human cell than will a beta particle.



Densely ionizing. Produces heavily concentrated numbers of ion pairs (which are pairs of free negative electrons and positive-charged atoms) at average specific ionization of about *1,000 to 5,000 ion pairs per micron* in water (as produced by alphas and neutrons).

Sparsely ionizing. Produces lightly concentrated numbers of ion pairs at average specific ionization of about *100 to 200 ion pairs per micron* in water (as produced by beta, gamma and X radiation).

Figure 4. The penetrating and ionizing power of various radiations.

When radiation exposure occurs over periods of time, it is convenient to refer to the **"dose rate."** Dose rates are usually measured with reference to one year of time (annually), and the appropriate unit is measured in millirem per year (mrem/yr). Equivalent doses spread over long periods of time are generally less harmful to living systems than those given over short periods. For example, a dose of 100,000 millirem delivered at 100,000 mrem/yr is much less harmful than 100,000 mrem delivered at 100,000 mrem/second. Generally, relative radiation injury increases with an increase in dose rate, as shown in Figure 5.

In a similar fashion, radiation injury is reduced when a given dose is delivered in fractions. This is called the **fractionated dose.** For example, if a total dose of 100,000 mrem is delivered instantaneously, a given level of injury is expected, depending on type of radiation and the tissue or organ that is exposed. If 100,000 mrem is fractionated into two or more smaller doses which are separated by a few days or more, considerably less injury is sustained. It is commonly accepted that the reduction of injury from fractionated doses is due to biological repair that occurs in the period of time between dose fractions. It is important to realize that many medical radiation exposures are, actually, fractionated doses.

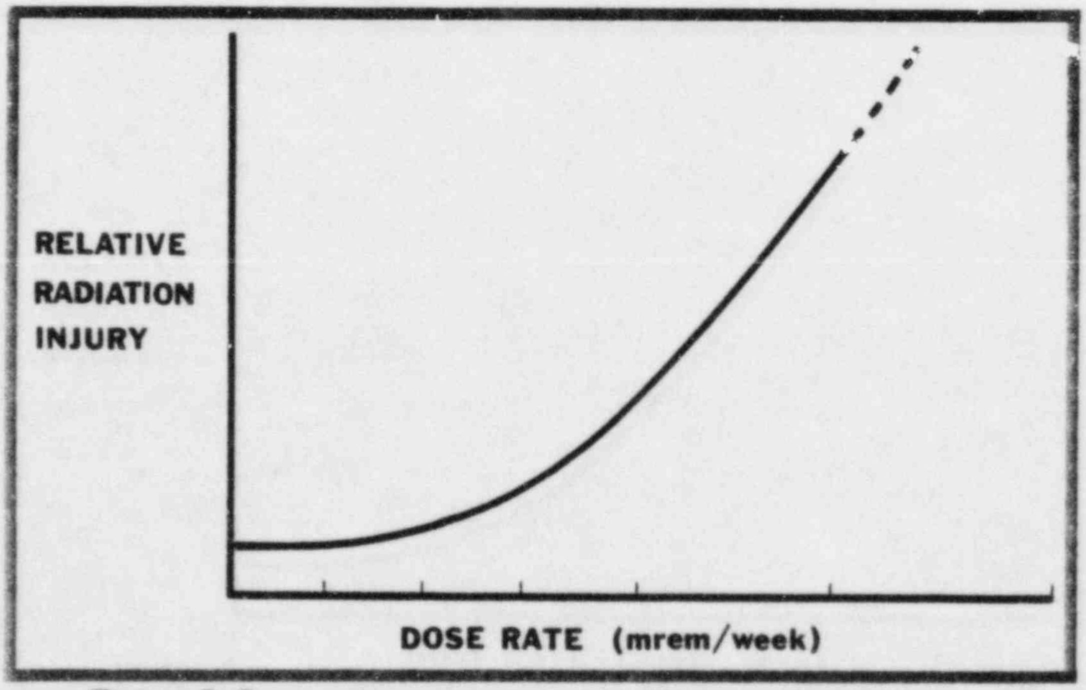


Figure 5. Dose rate compared with relative radiation injury.

VI. SOURCES OF RADIATION

Particulate and electromagnetic radiations which originate in outer space constantly bombard the earth and its living systems. Also, the earth's crust has always contained materials which emit radiations. These materials emitting tiny amounts of radiation become part of the components used in construction of homes and buildings and also enter the food chain for human consumption. Life on earth has been and continues to be exposed constantly to these natural radiations. In addition, humans, through technology, have managed to produce similar radiations artificially. X-rays are generated by high-voltage electronic devices (dental X-ray machines, for example), and materials can be made radioactive by splitting (fissioning) atoms inside a nuclear reactor, and these radioactive materials (fission products) emit radiation, predominantly beta and gamma (see Figure 6).

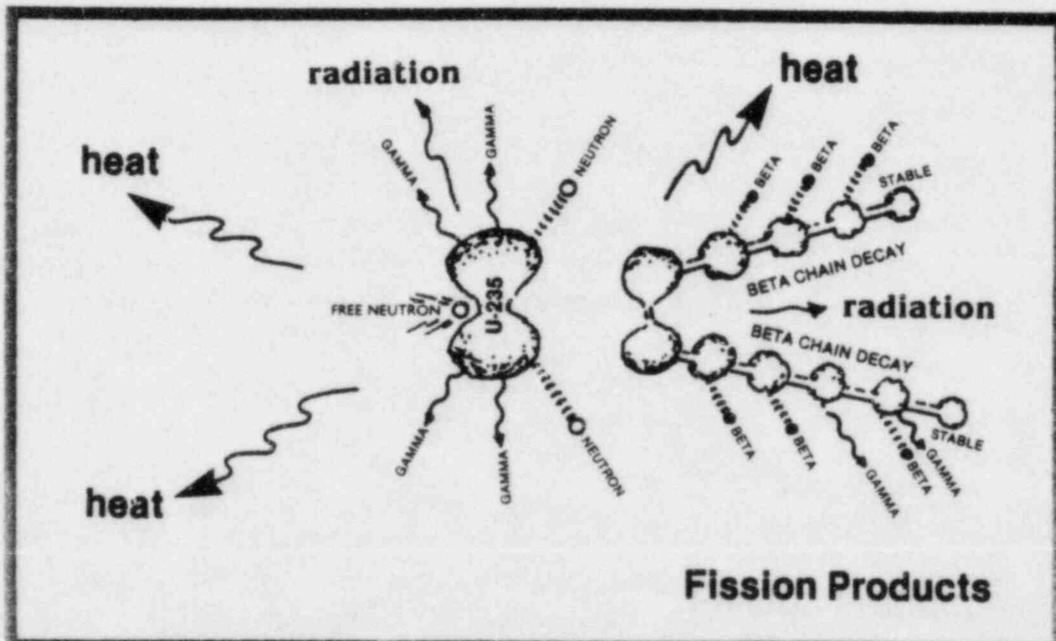


Figure 6. Uranium fission with resultant radiations, heat and fission products.

The fission process requires a particular fissionable type of heavy element, such as uranium-235 or plutonium-239. Natural uranium is a mixture of two uranium **isotopes**; 99.3% is uranium-238; the balance is principally uranium-235. Isotopes of a particular element vary in mass (by having different numbers of neutrons) but are physicochemically alike (by having the same number of protons). An atom of one of the uranium isotopes, uranium-235, can readily undergo fission when a free neutron strikes its heavy central nucleus. The nucleus (which contains neutrons and protons) breaks into two pieces (fission products) that fly apart at high speed; in addition, two or three new neutrons are released. The kinetic energy of the flying fission fragments is converted to heat when they collide with surrounding atoms. Also, considerable heat is released in the fissioning of the nucleus itself. The released neutrons can cause a chain reaction by initiating new fissions with other uranium-235 atoms. Sustaining the chain reaction is important in producing nuclear-electric power, for example, because more than 30 billion fissions must occur in one second to produce one watt of energy!

The uranium isotope, uranium-238, is extremely difficult to fission and is thus often called **nonfissionable** but converts to a **fissionable** plutonium isotope, plutonium-239, by absorbing neutrons from fissioning uranium-235. This conversion is known as the **breeding process**, and **breeder reactors** have been designed, built and operated to take advantage of the vast amounts of energy inherent in conversion of the plentiful supplies of uranium-238.

Fission-produced materials, fission products, emit various radiations at certain rates. These rates are referred to as "decay rates," which are described in units of curies (abbreviated Ci). **A curie represents a decay rate of 37 billion radiation emissions every second.** Because of the extremely small amounts of radioactive material in the environment, it is more convenient to use fractions of a curie; and, subunits like millicuries (one thousandth) or microcurie (one millionth of a curie) or even **picocuries** (one thousandth of a billionth of a curie) are frequently used.

Each different radioactive atom decays (emits radiation) at a characteristic rate. A term called **"half-life"** is used to describe how long it will take for one-half the number of atoms constituting a radioactive material to decay. Following decay of half a number of atoms, the remaining atoms do not all decay in the next time period but only half their number or only one-fourth the original number, and so on. Thus, radioactive atoms decay gradually over a period of time dependent on their characteristic half-life. For example, krypton-85 (Kr-85) has a half-life of 10.7 years (it takes that long for a number of Kr-85 atoms to decay to half the number); krypton-89 has a half-life of 3.2 minutes; plutonium-239 has a half-life of 24,300 years; potassium-40 (which exists naturally within and outside the human body) has a half-life of **1.3 billion years!**

Radiation sources may exist outside the body or inside. Examples of radioactive materials which can enter the body are iodine-131 (I-131), strontium-90 (Sr-90) and cesium-137 (Cs-137). Radioactive iodine tends to accumulate in the thyroid gland; radioactive strontium, on the other hand, resembles calcium and, like calcium, will accumulate in bone structure. These materials enter the body by inhalation or ingestion, primarily. In certain situations, radioactive materials may penetrate the skin. **All humans normally have small amounts of radioactive materials derived from the earth's crust within their bodies.**

The biological effects of radiation are the same whether the radiation source lies external or internal to the body. The important factor is how much of a dose the radiation source eventually deposits within body cells. **It is very important to realize that X-rays, gamma rays, alpha and beta particles do not cause the body to become radioactive.** Such radiations disappear promptly upon reacting with atoms or molecules. On the other hand, **neutrons can occasionally induce atoms of exposed material to become radioactive.** Upon exposure to neutrons, various materials in or on the body may become radioactive, such as the gold in gold fillings in teeth. Here, a neutron will convert stable, natural gold (Au-197) to radioactive gold (Au-198). Gold-198 emits beta particles and gamma rays and has a half-life of about 2.5 days. High dose neutron exposures to humans are rare, but can occur in some laboratories and during nuclear weapons explosions.

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External radiation sources are those which generate radiation outside the body and are typified by the **X-ray** unit used by dentists and physicians. A variety of electronic devices, such as radar units and CB radios, produce **microwaves** which are very low energy electromagnetic radiations. Because microwaves can produce heat deep within organic materials, they can be used for cooking food inside a microwave oven. Microwave radiation can produce harmful effects in human tissue through its heating phenomenon. Microwaves are not strong enough to be ionizing and therefore do not have the same biological effects as X-rays, gamma rays, beta or alpha particles. **Ultraviolet radiation**, especially that which originates in the sun and is filtered in part by the ozone layer in the upper atmosphere, is most commonly encountered on the external part of the human body and is absorbed by the top layer of skin. Ultraviolet radiation is beneficial to the human body in small amounts but can, after large exposures, induce skin cancer.

VII. DOSES FROM VARIOUS SOURCES

The annual dose rate to the average U.S. citizen from cosmic radiations and radioactive material in the earth is about **100 mrem per year** (60 mrem/year in Florida to 145 mrem/year in Colorado). Additionally, the average person receives about 75 mrem per year from medical X-ray diagnosis (see Table II). Specifically, an X-ray of the chest when properly administered gives a person a dose of approximately 10 millirem per X-ray film. A barium enema X-ray examination involves doses up to about 1,500 mrem to the skin of the midsection of the body.

Table II. Average Doses and Dose Rates
From Various Radiation Sources

Source	*Amount of Radiation
Natural Background	
Florida	60 mrem/yr
Michigan	80 mrem/yr
Colorado	145 mrem/yr
U.S. average	100 mrem/yr
Medical Diagnosis	
Average (US)	75 mrem/yr
Chest film	10 mrem/film
Dental X-ray	130 mrem/film
Nuclear Power	
Maximum dose to a member of the public who remains continuously for one year at the site boundary of a typical 1,000-megawatt, electric boiling water reactor (Ref. 2)	4.6 mrem
Maximum dose to a member of the public who remains continuously for one year at the site boundary of a typical 1,000-megawatt, electric pressurized water reactor (Ref. 2)	1.8 mrem
Code of Federal regulations, Title 10, Part 50, Appendix I specifies the **upper limit** allowable dose to a member of the public remaining continuously for one year at the site boundary of a typical 1,000-megawatt, electric boiling water reactor or pressurized water reactor	5.0 mrem
Three Mile Island accident (50-mile radius, average total dose per person)	1.4 mrem
Consumer Products	
High-voltage color television sets (dependent on age and type of set, distance of viewer, etc.); wrist watches; smoke detectors	0.03 mrem/yr
Air Flight	
Los Angeles - London, round trip	4 mrem/trip
Global Fallout	4 mrem/yr

*These numbers will vary slightly in different publications.

VIII. ELECTRIC POWER PRODUCTION AS A RADIATION SOURCE

A common method of producing commercial electric power is to burn (or fission) a fuel to produce heat, to make steam, to turn a turbine, to generate electricity. Of the U.S. commercial electric power plants generating electricity during the first nine months of 1979, about 47 percent were coal fired, 15 percent used natural gas, 14 percent used oil as fuel, 13 percent were hydro powered and 11 percent used uranium (nuclear fuel).

The nuclear-electric power plant produces commercial electric power in the usual heat-to-steam method (see Fig. 7), but the products of its heat generation are a significant source of radiation. To burn; i.e., fission, the fuel (uranium-235) to produce nuclear-electric power requires a **nuclear reactor.** The reactor serves as the furnace and provides an environment in which fission reactions can be initiated, sustained, controlled, and to make possible recovery of the released fission heat. The essential components of such a reactor are: nuclear **fuel** which fissions inside the reactor core to produce heat and neutrons; **control elements** which control the energy release rate; and **cooling fluid** which is essential to the fission process in a light (ordinary) water reactor and which removes the heat generated within the reactor and which converts to steam directly, as in a boiling water reactor, or indirectly, as in a pressurized water reactor (see below).

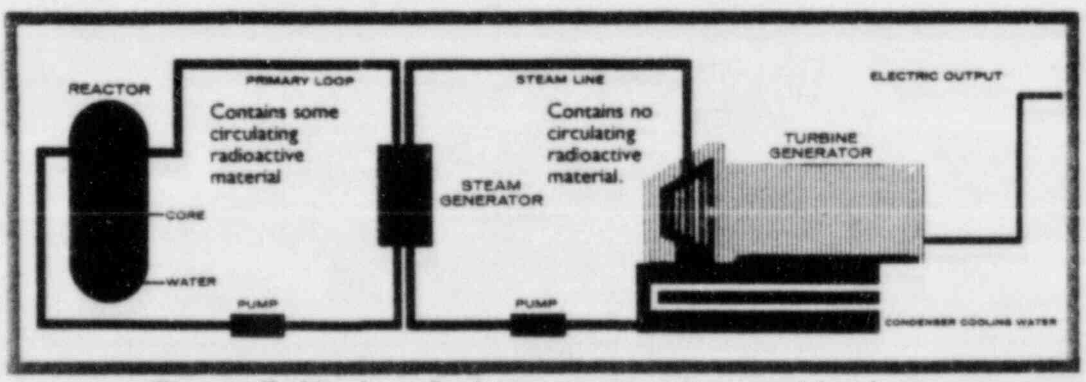

Figure 7. Nuclear fuel in reactor core provides heat to make steam that turns electric turbine generator

The reactor core. A large water-cooled reactor contains 50 to 100 tons of fuel. The fuel is slightly enriched uranium dioxide (UO_2) in the form of small cylindrical **pellets.** These pellets are placed in thin metal tubes to form fuel rods. A number of fuel rods bundled together make up the **fuel bundle,** or **fuel assembly.** A number of fuel bundles, or **fuel assemblies,** make up the reactor fuel **core.** The core is contained in a massive 8-inch thick steel tank, known as the **reactor vessel,** through which cooling water flows.

The coolant system. In the U.S., the two common types of nuclear reactors are the boiling water reactor (BWR) and the pressurized water reactor (PWR). In the BWR, the reactor cooling water is allowed to boil in the reactor vessel so that steam is generated. The steam is transferred by means of the steam line to the turbine, where it spins the turbine blades and is then condensed in the condenser, and the condensate is returned to the reactor vessel. In the PWR, the reactor cooling water (primary coolant, in the primary loop) is kept under pressure to prevent it from boiling in the reactor vessel (much like in a car's radiator). As the primary coolant passes through the heat exchanger it gives up its heat to a second stream of water (secondary coolant, in a secondary loop). Here the secondary water is converted to steam which is used to turn the turbine in the turbine-generator. The two types of reactors can be compared in Figure 8.

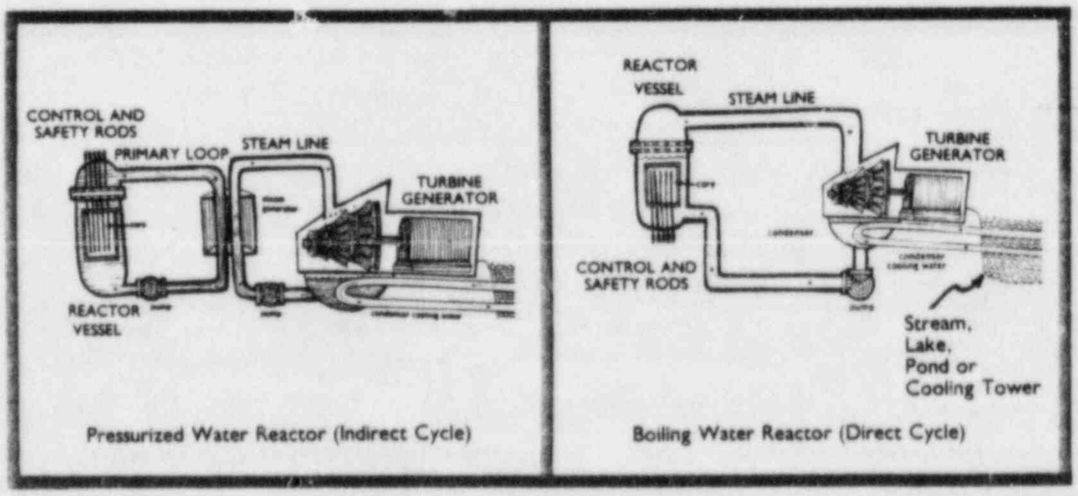

Figure 8. Comparison of boiling water reactor with pressurized water reactor.

As the nuclear plant operates, the reactor primary coolant picks up some radioactive material from the reactor core. One source of such material is leakage of tiny amounts of fission products through minute imperfections in the fuel element cladding. These fission products are mostly the gaseous and the more easily vaporized solid constituents of the fission product mixture. Another source of radiation in the reactor primary coolant is the neutron **activation products.** When elements in the reactor structure absorb neutrons, they can become radioactive. Most of such activation products have very short half-lives and enter the coolant through erosion and corrosion of the reactor core structural materials.

To maintain the purity of the water and to limit the amount of radioactivity in the primary coolant, the coolant is purified by one of several methods such as filtration, demineralization, or evaporation. All but a small fraction of the solid or liquid radioactive substances removed during purification are collected as waste concentrates. The balance is discharged in a dilute waste stream to the body of water serving the nuclear power plant, **in concentrations which must meet Federal guidelines for drinking water standards.**

The radioactive gases removed during purification average a few hundred thousandths of a gram per day during routine operation. These gases are released to the atmosphere through a tall chimney on a controlled basis to assure sufficient dilution and atmospheric dispersion, **in concentrations which must meet Federal guidelines.** Radiation levels inside and outside the plant must be routinely monitored to ensure that proper conditions are being maintained. Radioactive materials released in controlled amounts from nuclear power plants include argon-41, krypton-85 and xenon-133, which are inert gases, and also iodine-131 and carbon-14.

Radioactive waste products. The radioactive waste concentrates, together with other miscellaneous wastes and spent fuel, require waste management procedures and facilities to contain and store them for long periods of time. These wastes are grouped for convenience as liquid, gaseous and solid, and are either high level (highly radioactive) or low level (slightly radioactive; e.g., the amount of natural radioactivity in the human body would classify it, in theory, as low-level waste). The

spent fuel elements, for example, with their highly concentrated radioactive material content, must be removed from the reactor core and placed in a fuel storage pool where they are cooled and stored on a temporary basis.(Ninety-eight percent of the radioactive material in the elements decays away in the first 180 days of storage.)These elements ultimately must either be sent to a reprocessing plant to salvage the unused fuel or be stored in a waste repository. The first 500 years of storage in the repository are the most critical because the remaining two percent of the radioactive material in the elements is still quite radioactive during that period of time.

The volume of solidified, high-level radioactive waste of a large nuclear-electric reactor (1,000-megawatt, electric) operating for a full year is about 70 cubic feet, about the same as six standard filing cabinets. The majority of the radioactive waste, liquid and solid, stored since the early days of nuclear energy development came from the nuclear Navy and weapons programs. Much effort by scientists, Federal agencies, and industries has been devoted to developing a safe method of long-term storage of nuclear waste. Many scientists and scientific and industrial organizations have determined that safe long-term storage can be accomplished, and, by the beginning of 1980, over fifty-six hundred governmental studies had been devoted to storage of high-level radioactive waste. Most of the technology needed to store nuclear waste is available and some additional testing may be done before the U.S. commits itself to any single method of storage. However, as of January 1, 1980, no legislative decision (a clear policy statement by the Federal Government) had yet been made to initiate and implement a comprehensive plan for the management of high-level radioactive waste.

The coal resource also creates waste products which contain radioactive materials such as uranium-238, uranium-235, thorium-232, radium-226, radon-222 and many other heavy isotopes. The range of released radioactivity ranges between millicuries to curies per year (Ref. 2).

In the waste material of coal, all but the smallest particles of fly ash can be removed from the smoke waste. A considerable amount of sulfur escapes as sulfur dioxide. The waste fly ash contains the radioactive material which can deposit in human bone. For comparison, theoretical maximum

doses to **human bone** from the airborne radioactive material from typical 1,000-megawatt power plants are: **18.2** mrem per year from **coal; 5.9** mrem per year from a **BWR;** and **2.7** mrem per year from a **PWR** (Ref. 2). Maximum doses to the **whole body at the site boundaries** of such power plants are: 1.9 mrem, coal; 4.6 mrem, BWR; and 1.8 mrem, PWR.

Among oil, coal and nuclear fuels for electric power production over the next 25 years, nuclear power is expected to have the lowest adverse impact on health, according to a report by the American Medical Association's Council on Scientific Affairs. The report was adopted by the AMA House of Delegates on June 21, 1978 (see Ref. 3 and 4).

Accidents. The main safety consideration in the operation of a nuclear power plant is control of the plant's inventory of radioactive material. As with any such complex operation, accidents can occur. One such accident is **overheating of the core.** One cause of such an accident is a loss or reduction of coolant flow to the core. The power level at which a reactor can safely operate is limited by the capacity of its cooling system. If heat were to be generated at a faster rate than it is carried away by the coolant, the fuel would overheat and could melt. The consequences might range from heavy radioactive contamination of the coolant (through release of fission products from molten fuel) to damage of reactor equipment and some release of radioactivity from the primary loop into the plant containment system.

Natural safeguards contribute to reactor core stability. For example, as the temperature of the fuel rises, the proportion of neutrons captured by non-fissioning atoms increases and the rate of fission therefore tends to slow down. This so-called "Doppler" effect is not only automatic but instantaneous. A second safeguard is that as the fuel becomes hotter its density decreases, which also acts to lower its reactivity. Third, in BWR and PWR systems, the water that flows through the reactor core, besides carrying away heat, serves to "moderate" (slow down) the neutrons and thus increase the fission chain reaction. Uranium-235 can readily absorb a slow neutron and this causes it to fission. However, if, in an emergency, the temperature of the water were to increase dramatically, the density of the water molecules would decrease which

would decrease the moderating capability of the water which would **decrease** the **fission chain reaction** (less water molecules would occupy a given space, and thus neutrons would undergo less reactions with these molecules and not be slowed down as much, which would decrease the number of fissions or the fission chain reaction).

It is a common error among many to believe that nuclear-electric power plants can explode like nuclear bombs. Because of design configurations and characteristic changes in the nuclear fuel, such as the above, which would occur during an accident, such explosions are impossible.

Design safeguards are built into nuclear reactors to complement the natural safeguards. In general, the reactor's cooling system is designed to shut down the reactor automatically at the first sign of an unsafe condition. Also, interspersed between individual fuel bundles are highly efficient neutron absorbers called **control rods.** By moving these rods into and out of the core, the neutron population can be decreased or increased, thereby slowing down or speeding up the chain reaction. Extra control rods are held in reserve for emergency shutdown of the reactor. Also, in many reactors, solutions containing neutron absorbers are added to the primary coolant, either for routine control or for use during shutdown periods. Should a power failure occur, many "fail-safe" mechanisms automatically trigger into operation. For example, during an emergency, control rods held in standby position by power-operated electrical or mechanical devices drop, by gravity, automatically into the core and shut down the reactor. There are also multiple physical barriers in a nuclear power plant to guard against escape of radioactive substances into the environment: **the fuel element cladding, the walls of the reactor vessel, and the containment structure.**

However, accidents have occurred at nuclear power plants where radioactive substances escaped. In 1957, the **Windscale Reactor No. 1** in the United Kingdom, an air-cooled reactor (now obsolete), caught fire. About 20,000 curies of iodine-131 were released to the atmosphere. The **U.S. Army Experimental Low Power Reactor (SL-1),** a noncommercial type of reactor, in shutdown condition in 1961, was partially destroyed when one of the crew, by hand, withdrew a

control rod beyond a set position. This caused the coolant water to flash into steam from the fission heat. The resultant pressure destroyed part of the nuclear core and killed three men. Even though this experimental reactor had no containment system, less than 10 curies of iodine-131 escaped. The **Enrico Fermi Reactor** in Monroe, Michigan, a breeder reactor, experienced a partially blocked flow of coolant in 1961. Portions of the core overheated and melted. The reactor was promptly shut down. No radiation escaped the containment system. This reactor was rebuilt and operation resumed four years later. The plant has since been decommissioned.

On March 28, 1979, the U.S. experienced the worst accident in the history of commercial nuclear-electric power generation. The accident occurred at Unit No. 2 of the **Three Mile Island** nuclear power plant near Middletown, Pennsylvania. According to the President's Commission on the accident (the Kemeny Report, see Ref. 5), the accident was initiated by mechanical malfunctions in the plant and made much worse by a combination of human misjudgments in responding to them. Regarding radiation releases, the Commission concluded that the radiation doses as a result of the accident were low. The Commission also concluded that resultant health effects will be minimal. That is, there will be either no case of cancer or the number of cases will be so small that it never will be possible to detect them. The same conclusion applies to other possible health effects. According to the Commission, the TMI accident was the result of a serious down-playing of the importance of the human element in nuclear power generation.

As a result of TMI, the utility industry has undertaken a massive effort to improve reactor operations and has created an industry-sponsored **Institute of Nuclear Power Operations** (INPO) to upgrade the qualifications and performance of U.S. reactor operators. The industry has also formed the **Nuclear Safety Analysis Center** (NSAC) to investigate ways to improve plant safety and has begun a special public communications program under a new organization called the **Committee for Energy Awareness** (CEA).

The utility industry has reported that nuclear generating stations in commercial service, as of January 1, 1980, have accumulated more than 500 reactor-years of operating experience as well as compiling a record of safety unparalleled by any other major industry in the U.S.

IX. NUCLEAR RADIATION STANDARDS

Standards for protecting the public against radiation have been under study and development primarily by two organizations: the **International Commission on Radiological Protection** (ICRP) and the **National Council on Radiation Protection and Measurements** (NCRP). A number of scientific committees and international organizations also engage in analyses and reviews relating to use and control of radiation, such as the **Committee on the Biological Effects of Ionizing Radiation** (BEIR) and the **United Nations Scientific Committee on the Effects of Atomic Radiation.** (UNSCEAR).

Radiation guidelines have evolved from decades of study and recommendations by national and international groups, many established long before the arrival of nuclear power: the International Commission on Radiological Protection; the National Council on Radiation Protection and Measurements; the National Academy of Sciences; the National Research Council; United Nations Scientific Committee on the Effects of Atomic Radiation. These groups include hundreds of the world's leading authorities on radiation, its effects and control. Standards for radiation protection, then, have been studied continuously for half a century and represent the collective experience and judgment of many of the world's experts meeting nationally and internationally (see Figure 9) to present technical papers on and discuss the results of radiation research. For a good general reference on the science and the determination of radiation risks, see Ref. 6.

Many regulatory agencies in the U.S. enforce the radiation standards: the **Environmental Protection Agency** (EPA); the **Nuclear Regulatory Commission** (NRC); the **Department of Health, Education and Welfare** (HEW) or, to be called, the **Department of Health and Human Services** (HHS); the **Food and Drug Administration** (FDA). Also, many of the states, through various state departments, have established and enforce their own radiation protection guidelines.

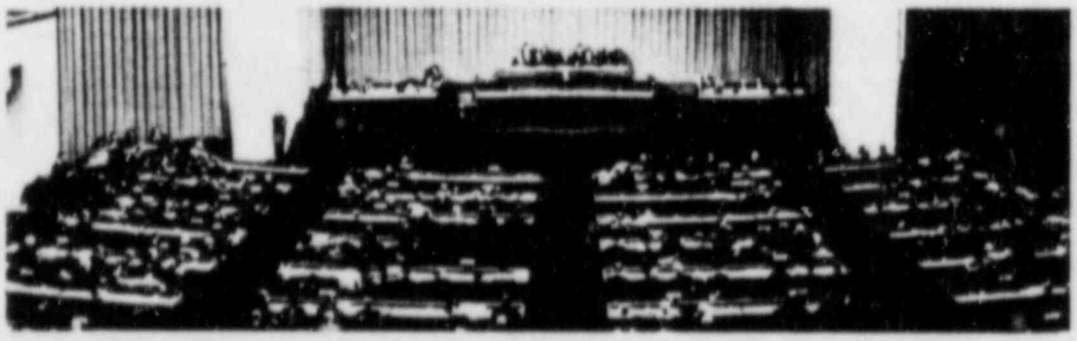

Figure 9. The Third United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1964
(Represented: 77 nations, 4,000 international participants and observers)

X. MAXIMUM PERMISSIBLE DOSES, DOSE LIMITS, AND RADIOSENSITIVITY

Regulatory control is applied to potential exposures associated with radiation workers in industry and in medical and research facilities, radiation workers at nuclear power plants, and the general public. All workers occupationally exposed to ionizing radiation in the course of their normal duties as an occupational risk are regulated under a **maximum permissible dose,** not to exceed **3,000 mrem per quarter year, whole body** (includes both internal and external organs). The maximum permissible dose as defined by the National Council on Radiation Protection and Measurements (NCRP) is the highest dose of ionizing radiation (from external and internal sources) that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his or her lifetime. Maximum permissible dose for occupational exposure of the skin of the whole body is 7,500 mrem/quarter year, while permissible exposure for hands, forearms, feet and ankles is 18,750 mrem/quarter year (see Ref. 7).

A worker's long-term accumulated maximum permissible whole body dose is further governed by the formula 5,000(n-18), where "n" equals the age of the worker in years. This means first that no person 18 years or younger is allowed to be occupationally exposed. A person of 19 years of age can receive 5,000 mrem as long as the dose rate does not exceed 3,000 mrem per quarter year. At age 20, a person can legally receive an **accumulated dose** of 10,000 mrem over his or her two years of employment. According to the formula, depending on age over 20, a radiation worker may receive as high as 12,000 mrem/yr during one year, as long as he or she **does not exceed** 3,000 mrem/quarter year and does not exceed 5,000(n-18). **Accordingly, at age 40, a person can legally accumulate up to 110,000 mrem over a 22-year period 5,000(40-18) provided that the basic constraint of 3,000/mrem/quarter year is followed. Average doses to such workers, however, are considerably less and actually range between 600 and 800 mrem/yr.**

U.S. citizens (the general public) are not on the other hand, by Federal regulation, to be exposed to more than **25 millirem per year** from the total nuclear fuel cycle (uranium mining, milling, fuel fabrication, power plant operation, and waste disposal). Of this 25 mrem/yr, nuclear power facilities are designed to meet a dose limit of **5 millirem per year**, i.e., the upper limit allowable dose to a member of the public remaining continuously at the property boundary of a typical 1,000-Mw nuclear power plant is 5 mrem/yr.

In contrast to the regulatory limit for the uranium fuel cycle, the NCRP recommends that the total radiation dose limit from **all** radiation sources to a single maximally exposed individual member of the **general public** be no more than **500 millirem per year.** Because the general public includes the very young, the very old, and some who are pregnant, who are more radiosensitive, the **recommended average** dose rate limit is **170 mrem/yr.**

More stringent recommendations are directed at pregnant women who are occupationally exposed to ionizing radiation to be reasonably protective of the fetus **during pregnancy**, and to meet the currently accepted standards for protection, the regulation is as follows: the total permissible dose to a pregnant woman occupationally exposed to radiation should be no more than 500 millirem for the entire gestation period (see Ref. 8).

Such strict protection is given during pregnancy due to the fact that certain tissues or organs are especially sensitive to radiation during the early stages of development of the fetus. In 1906, J. Bergonie' and L. Tribondeau concluded that germinal cells were more radiosensitive than interstitial cells because they have a greater reproductive activity. These were the first scientists to recognize that radiation may discriminate between different types of cells of the same organism based on degree of reproductive activity. The law of Bergonie' and Tribondeau states: **the radiosensitivity of cells is directly proportional to their reproductive activity and inversely proportional to their degree of differentiation** (specialization).

Less specialized, more primitive types of body cells having a high reproductive activity, such as epithelial and bone marrow cells, are more sensitive to radiation than specialized cells, such as neurons and muscle cells. Experiments show, however, that radiosensitivity is actually dependent on a large number of cellular characteristics; but, despite certain limitations and exceptions, the law of Bergonie' and Tribondeau is a valid and useful generalization (see Ref. 9). Some parts and tissues of the body are more radiosensitive or more radioresistant than others. Among those more radio**sensitive** are: breast tissue; bone marrow cells; the mucosa lining of the small intestine, especially the

duodenum; the hair follicles and sebaceous glands of the skin; antigen-antibody cells; the sperm and egg cells. The ovaries of the mammalian female are more radiosensitive than the testes of the same species. Among those more radio**resistant** are: the heart; large arteries; large veins; mature blood cells; neurons; muscle cells (see Ref. 9). Cancer cells are primitive, rapidly dividing, cells and thus are sometimes more sensitive to radiation than the nearby normal cells. This difference in sensitivity accounts for some of the success of radiation therapy in treating cancer.

XI. BIOLOGICAL EFFECTS

From a very large number of animal, plant and cell experiments, scientists have generated an enormous amount of knowledge about biological effects of radiation. Scientists have also studied radiation effects in several human groups exposed to radiation by accident, by warfare, or for medical purposes. The most important large group includes about 150,000 nuclear bomb survivors of Japan. Smaller groups of people have been inadvertently exposed to nuclear weapon test "fallout" and include about 240 Marshall Islanders and 23 Japanese fishermen. Many persons have been studied following radiation exposure given for medical diagnosis or therapy.

All radiobiological effects are initiated by the energy deposited in living systems by radiation. The nature and the extent of damage to the living organism depend on many factors such as the dose, dose rate, type of radiation, portion of body exposed, age, and health status. For all living systems, the energy deposition usually occurs within individual cells. Densely ionizing radiations, such as neutron and alpha, deposit relatively large concentrated amounts of energy in the cells through which they pass. These radiations are more damaging than the sparsely ionizing radiations, such as beta, X-ray and gamma, which deposit relatively less concentrated amounts of energy in cells. **The energy (dose) induces chemical reactions and molecular alterations within the cells. Of course, these reactions and alterations are not normal and, if imposed within a critical molecule of the cell, can lead to alteration of normal cellular structure and function.** This alteration precedes all the adverse biological and clinical effects seen later, such as those associated with cancer, birth defects, cataracts, or shortening of life span. Usually, a period of time is required between exposure and the manifestation of any damage (the **"latent"** period). There is a latent period of some 10 to 20 years between the initial disruption and the appearance of some forms of cancer. The minimum latent period for radiogenic leukemia is known to be as short as two years. The latent period is shorter for high doses and longer for lower doses.

Generally, the higher the dose, the more drastic are the effects and the sooner they appear. A thousand rem of acute whole-body exposure will kill any human within one or two weeks from blistering of the lining of

the small intestine. If a number of humans are exposed to 350 rem (350,000 millirem) of acute, whole-body X-rays, approximately one-half the number will die within the first 60 days of blood and bone marrow damage. The other, stronger, healthier half will recover.

Very large-dose radiation exposure also seems to accelerate the normal aging process. That is, persons exposed to very large-dose radiation may age more rapidly than those who are unexposed. Doses of between 50 rem (50,000 millirem) to 350 rem (350,000 millirem) and upward can produce a variety of subtle effects, including various degrees of nausea, vomiting, diarrhea, reddening of skin, loss of hair, blisters, a depression of the number of blood and bone-marrow cells and a decreased efficiency of immune response to infections. A summary of acute dose-response effects is given in Table III.

Table III. A Summary of Acute Dose-Response Effects in Humans

Dose (mrem)	Effect
10,000,000	Immediate prostration, coma, followed by death within 1 or 2 days from severe central nervous system damage.
1,000,000	Immediate nausea, vomiting, diarrhea. Death within 1 or 2 weeks from blistering of small intestine. Complications from depressed bone marrow activity.
100,000	No overt effects. Some depression of white cell count. Statistical increase in probability of radiogenic leukemia and life shortening (1 to 5 days/rem).
10,000	Effects are difficult to measure. In early embryo, developmental defects are possible. Subtle abnormalities of brain structure and perhaps also function may occur above 10 rem.
1,000	No measurable effects except a statistical increase of tumor incidence before age of 10 in infants exposed **in utero**.

Doses of between 25 and 50 rem (25,000 and 50,000 millirem) can produce measurable clinical (disease-related) effects in adult humans. In the human fetus, especially in the first trimester, injuries can be sustained from doses of from 1 to 10 rem (1,000 to 10,000 millirem). At later growth stages, the fetus is not as radiosensitive but is still quite vulnerable. At 4,000 to 12,000 mrem, following cardiac catheterization procedures, an increase in chromosome aberrations sometimes is observed within 30 minutes after exposure in humans. At 2,000 to 5,000 mrem, a reduction of as much as 35 percent in lymphocyte count can be observed in humans. At 1,000 to 3,000 mrem, the sensation of light can be produced in human subjects and is probably an effect on peripheral rod cells of the eye. Research on the meaning of these effects continues.

At doses below 1,000 millirem (1 rem) clinical effects are completely unmeasurable by current technology. These low doses, below 1,000 millirem, only increase the probability, not the certainty, of any clinical effect. Therefore, these doses and their small effects must be evaluated on the basis of the effects from large radiation doses and estimated by means of population studies involving complicated statistical techniques. This problem is dealt with by a unit of radiation exposure to populations termed the **"man-rem."** This unit is the product of the dose in rem and the number of people exposed. Thus, 2,000 man-rem (or person-rem, if you will) means that two thousand people each were exposed to 1 rem (2,000 person-rem) or that one person received 2,000 rem. A recent report by Roessler and others (see Ref. 10) shows that the collective person-rem dose from the Three Mile Island reactor accident in Pennsylvania was 3,300 person-rem. This involves the projected 1980 population within a 50-mile radius of the accident center (approximately **2 million people**).

XII. HEALTH EFFECTS FROM LOW DOSES OF RADIATION

As previously noted, as the dose of radiation becomes smaller, all clinical effects diminish. Radiation doses above 25,000 millirem can produce both subtle and obvious clinical effects. Between 25,000 and 1,000 millirem, clinical effects are extremely difficult to observe. Low doses, below 1,000 millirem, **appear** to be safe. However, research indicates that there probably is no totally risk-free dose and that, in certain instances, there could be a small impact on living systems even at the lowest doses. **However, this impact, or risk, statistically estimated to appear within the total population, is considered to be extremely small, especially when compared with other societal health risks such as the risks of improper diet, lack of exercise, uncontrolled consumption of alcohol and smoking of tobacco.**

The two general categories of serious health effects induced by radiation are **hereditary defects** and **cancer. Of the cancers, leukemia is considered to be the more serious because its incidence within a population can be affected more by low doses of radiation than the incidence of hereditary defects.** In Japan, no statistically significant hereditary defects related to the nuclear radiations of Hiroshima and Nagasaki were found in offspring of exposed parents even when either one or both parents received large radiation doses. Above 50,000 millirem, the induction of leukemia is statistically increased in large populations of exposed persons. There is considerable doubt that leukemia was increased at all in the Japanese who received less than 50,000 millirem. It is estimated that a population dose of 1,000,000 person-rem to 1,000,000 persons will result in one or two leukemia cases **per year** based on the best data.

What, then, is the risk of leukemia from low doses of radiation? To answer, scientists have to extrapolate from the reliable data at high doses and high dose rates down to low doses and low dose rates to assess the risk of leukemia. They know that at high doses the number of leukemia cases is increased over the number expected annually from all causes. They suggest this proportion may remain the same down to the lowest dose above zero. This is known as the **linear hypothesis.** If this is true, then suppose that one million people each receive 1,000 millirem of X-rays, acute and whole body. Then, this dose may increase the annual number of leukemia cases by one or two per year in a million

persons exposed. Moreover, in this same million persons exposed, other agents (environmental chemicals, viruses, bacteria, genetic accidents and natural background radiation) are expected to cause about 60 to 70 cases of leukemia annually. Thus, for example, if a million persons each receive 1,000 millirem of X-rays, the incidence of leukemia will increase about 1 to 3%. Such a risk is said to be 1 or 2 chances per million per rem per year. (The risk of other fatal cancers or other effects due to radiation is smaller than for leukemia.) Table IV illustrates how selected human activities bring about a one-in-a-million risk of death from various causes.

Table IV. Activities Which Increase Risk of Death by One in a Million Over a Period of One Year (See Ref. 11)

Activity	Nature of Risk
Smoking 3 cigarettes (U.S.)	Cancer, heart disease
Drinking ½ liter of wine	Cirrhosis of liver
Spending 1 hour in a coal mine	Black lung disease
Traveling 300 miles by car	Accident
Flying 6,000 miles by jet	Cancer caused by cosmic radiation
One chest X-ray	Cancer caused by radiation

A present consensus (see Ref.12) on a most likely value of a risk estimate for any radiation exposure is **100 additional cancer deaths of all kinds, including leukemia, per million persons, each receiving a dose of 1,000 millirem above natural background exposure.** This risk is assumed to remain constant throughout the exposed person's life. Based on 1976 actuarial data, 197,603 Americans are expected to die of cancer annually. If each of one million persons were exposed to 1,000 millirem, the risk estimate above would predict that the radiation could cause about 100 additional cancer deaths, or 197,**703** instead of 197,**603** deaths annually in the United States. If a million persons were exposed to only 100 millirem, the total number of cancers would be 197,605 instead of the normal 197,603. This is an increase of about 0.001%.

Those radiation effects which become evident in the descendents of the individual exposed are called **hereditary** or **genetic.** Such effects are the result of changes, **genetic mutations,** in the reproductive cells. Radiation-induced genetic mutations may not become manifest in the children of the affected individual, but may lie dormant for several generations and may eventually be eliminated completely from the genetic pool. Genetic mutations can also be produced by certain chemicals, high body temperatures, viruses, and other agents.

Concerning congenital deformations caused by radiation, geneticists agree on their estimates. In one million newborn children each of whose parents had received a radiation dose of 1,000 millirem (10 times background radiation), it is predicted from the best available data that between 5 and 75 of these children will show a congenital deformity. This should be compared with the fact that 10 percent of all children born today have some congenital deformity, that is, that out of one million births today as high as 100,000 children will show some congenital deformity.

In the Three Mile Island (TMI) accident in Pennsylvania, the average dose received by residents **within 50 miles of Three Mile Island** was estimated at **1.4 millirem** (see Table II). No person outside the plant received more than 100 millirem. In comparison, and to repeat, the **average American** receives about **100 millirem per year from natural sources.** The cumulative dose from radioactive materials released at TMI at the time of the accident was determined to be quite small and, interpreted in terms of total health impact, has the **potential of producing** no more than **one** extra case of fatal cancer or non-fatal cancer, and **one** congenital deformation in the two million people living within the 50-mile radius of TMI. An extra fatal cancer would add **one** fatality to the **normally expected** 197,603 cancer fatalities during the year in the United States.

XIII. SUMMARY OF RADIATION KNOWLEDGE

Intensive study has led many scientists to conclude that **no matter how small, any dose of radiation involves a risk to human health** The higher doses produce greater risk than the lower doses. The cancer risk compared with absorbed radiation dose is shown in Figure 10.

In Fig. 10 the heavy line, **which represents the best summary of knowledge about radiation - induced cancer risk,** rises in Area A even at the lowest possible dose and shows that there is some risk of cancer at the low doses, but this risk is considered small compared to other societal risks (refer to Table IV).

In Area B, the heavy line shows that the risk begins to rise more rapidly as the absorbed dose increases (the quadratic hypothesis). **This is the area where research has actually produced good, reliable data; and, unlike Area A, in Area B scientists do not have to guess at the actual risk.** In Area B, risks can be fairly well documented from existing data. The "best" data are symbolized by the heavy dots. In Area C, the heavy line levels off and begins to turn downward, because extensive radiation damage kills cells outright, and these cells, therefore, do not survive to produce cancer.

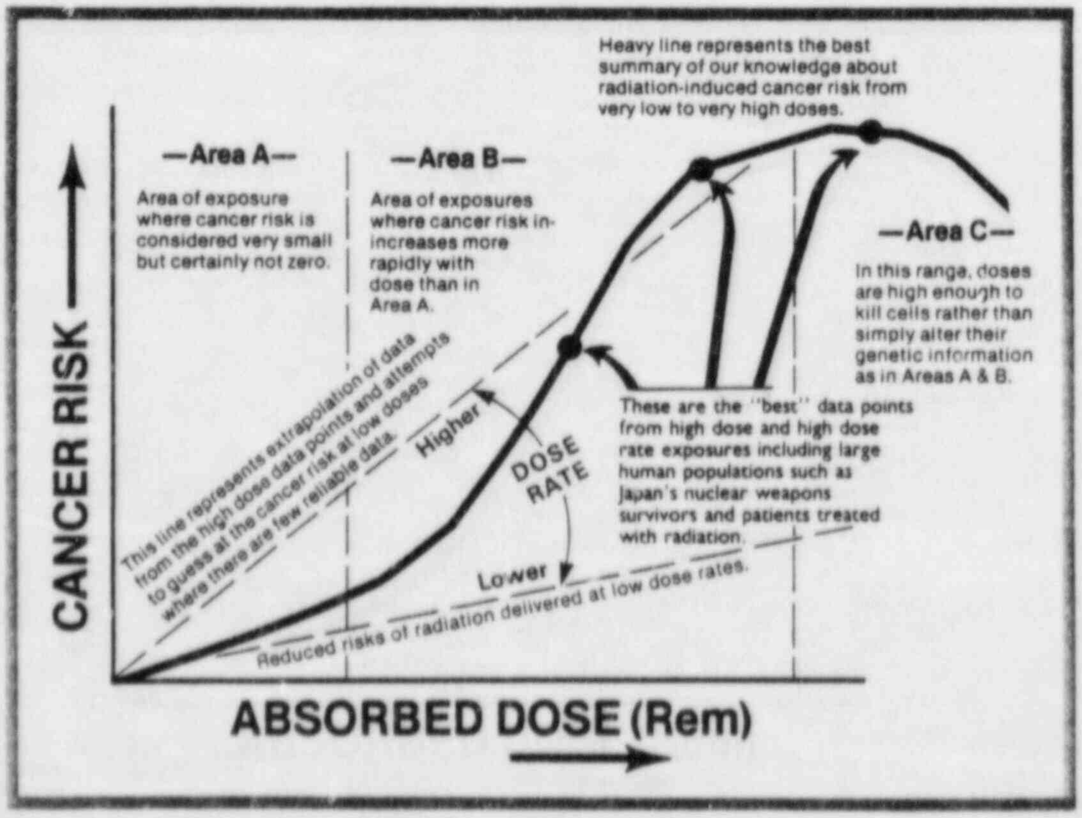

Figure 10. Cancer risk compared with absorbed radiation dose.

Today, scientists still have to guess at the risk of cancer from **low doses** of radiation. This is done by extrapolating or extending the best data points downward to low doses using a straight line (the linear hypothesis). This maneuver is shown by the uppermost dashed line (the extrapolated line extending between the best data points and zero dose risk in Figure 10). At low doses, the difference between the upper dashed and the heavy line means that by extrapolation, scientists probably **overestimate** the actual risk somewhat.

The lower dashed line is shown to illustrate that equal doses delivered at low-dose rates produce less damage than at high-dose rates.

Finally, Figure 10 shows that there is no risk-free dose of radiation. No matter how small, any dose carries a small risk of cancer or hereditary defects. Thus, to use radiation as a tool for humanity, **one must balance the risks against the benefits derived.**

XIV. CONCLUSION

It is proper to conclude that any dose of radiation, be it from an X-ray machine or a nuclear power plant, can cause some harm, even the very low doses. in other words, scientists expect some increase in the risk of all known radiation effects at all doses. However, at low doses of a few millirem, the associated risks such as cancer, life-shortening, and congenital defects are expected to be very small. As a matter of fact, the risk due to a low-dose exposure is so small that many studies have failed completely to show any change in the health status of persons exposed to different levels of natural background radiation -- 60 mrem/yr in Florida, 145 mrem/yr in Colorado. Of the higher doses of radiation, many of which are received through the activities of medicine and industry, the **benefits** must be weighed seriously against the **risks.**

Radiation is becoming less a mystery with each passing year. Its biological effects are known well enough so that it can be regulated and controlled with a degree of confidence, even though research on radiation effects **must** and **will** continue. Since the turn of the present century, scientists have been developing an understanding of this energy form. It is time, now, that all persons become knowledgeable about or at least familiar with, radiation and its effects on living systems. **Neither a person nor a society can hope to preserve or further the capacity for human achievement where there is ignorance or unreasoned fear.**

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