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UNITED STATES ATOMIC ENERGY COMMISSION

SUMMARY REPORT OF REACTOR SAFEGUARD COMMITTEE

Original with deletions to Hanford included

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For The Atomic Energy Commission
H. R. Carroll
Chief, Declassification Branch

Reactor Safeguard Committee

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SUMMARY REPORT OF THE REACTOR SAFEGUARD COMMITTEE

INTRODUCTION

Nuclear reactors are now used for research, for the production of radioisotopes, and for the production of fissionable material for atomic weapons. In the future, it is expected that nuclear reactors will also be used for power production, for propulsion of military vehicles, and, through breeding, for bringing about a great increase in our available supply of fissionable material.

It is unfortunate that our experience in the operation of nuclear reactors to date is small and the hazards to human life which may result from accident or faulty operation are believed to be great. The situation confronting the Atomic Energy Commission is one in which the danger of building and operating these devices must be weighed against the need for advancement of the technology of the field.

An illustration which seems apt is the case of the motor vehicle in the early days of its development. Considerable distrust of those early machines was felt and, indeed, the City of New York had a law, passed in the early days of motor traffic, which required that a motor vehicle be preceded by a man on foot waving a red flag before it would be permitted on the city streets. Today, after forty years' experience with motor vehicles, the laws are much less stringent; on the other hand, our automobile accident rate shows about 100,000 casualties per year.

With nuclear reactors, a device for which is predicted a future value to humanity of the same order as the present boon of the motor car, neither of the two extremes cited is desirable. It seems sensible to restrict the location of high power and potentially dangerous reactors to more isolated spots and to permit others of smaller power and more harmless characteristics to be built nearer to large cities and laboratories where their usefulness will be greater.

There is a good record of several years of safe operation of the reactors which are now in existence. As that experience is extended and designs are improved, it may be possible to relax considerably on the restrictions on location and operation which are now thought to be necessary. Constant review of the reactor safety problem from this standpoint should be contemplated.

HISTORY OF THE COMMITTEE

The Atomic Energy Commission has recognized that the future development of nuclear power opens up new and unexplored fields in which precedents of safe operation have not yet been fully established.

In considering what attitude it should take in evaluating the safety aspects and possible locations of new and untried reactors, the AEC requested the comments of the General Advisory Committee on the subject. In its fourth meeting on June 1, 1947, that Committee noted that no general answer to the problem could have value. Each reactor should be examined specifically in relation to its surroundings, mechanical construction, and proposed method of operation. The GAC recommended the creation of a panel to advise the Commission in matters of reactor safety and suggested the names of individuals who might appropriately perform this service for the Commission. In its next meeting, the GAC suggested additional names and at the time of the first meeting of the new Committee on November 7, 1947, its members were Dr. Richard P. Feynman, Dr. John A. Wheeler, Dr. Joseph W. Kennedy, and Dr. Edward Teller, Chairman.

In the letters of invitation to the members of the Committee, it was pointed out by the AEC that the group would have no legal responsibility in the event of disaster, but would rather serve the Commission as disinterested experts in various fields who would review reactor projects in some detail as they develop, reporting to the Commission on the hazards of each case. It was hoped that this Committee could also suggest methods by which the safety of the individual installations could be enhanced.

The first meeting of the Committee was held at Schenectady, New York, to consider the Knolls Intermediate Reactor and its possible location. After this first meeting, the group decided to ask Colonel Benjamin Holzman,

USAF, and Dr. Manson Benedict to serve as members of the Committee. At the same time, Dr. Feynman resigned because of the pressure of other duties. After the second meeting in Chicago at which the Argonne Fast Reactor was discussed, Dr. Abel Wolman was also invited to become a member of the Committee.

The membership of the Committee was then:

Dr. John A. Wheeler, physicist, Palmer Physical Laboratory, Princeton University.

Dr. Joseph W. Kennedy, chemist, Chairman of the Department of Chemistry, Washington University, St. Louis.

Dr. Manson Benedict, chemical engineer, Hydrocarbon Research, Inc.

Colonel Benjamin Holzman, meteorologist, Chief of the Geophysical Sciences Branch of Air Force Office of Research and Development.

Dr. Abel Wolman, sanitary engineer, Johns Hopkins University.

Dr. Edward Teller, physicist, Institute for Nuclear Studies, University of Chicago, Chairman.

An attempt was made in selecting the Committee members to include experts from the various fields of science and technology that have been found to be useful in the evaluation of reactor hazards.

In succeeding months, the Committee considered the Oak Ridge High Flux Reactor, the hazards associated with the Hanford reactors, the Brookhaven Air-Cooled Reactor, and finally, the Los Alamos Fast Reactor and Water Boiler. In addition, the Committee was presented with all pertinent data on seven possible locations for a reactor testing site, and was requested to make recommendations on the safety aspects involved.

In the course of its investigations over the period of some 15 months, the Committee has examined a number of types of reactors, considering them in relation to their widely dissimilar geographical locations. In each case, the Committee analyzed the individual situation on the basis of local conditions and developed at the same time general formulas and criteria which it considered were useful in evaluating hazards.

In the summary of the work of the Committee to the present time which is presented herein, it is intended to state the general philosophy of the Committee on reactor hazards, including sample calculations which were used in assessing the danger in various situations. It is expected that the

examination of future reactor proposals by the Committee will be facilitated in that, along with the reactor information, complete reports of surveys of the geographical location will be provided by the development laboratory making the proposal. Such reports would contain hydrological, climatological, and seismological studies of the area plus an analysis of conceivable hazards associated with the given reactor proposal. Appendix H contains a list of the more important items of information and investigations that should be compiled. Thus, the Committee will be of greatest use in the review of this data and the conclusions as to safety which are reached by the laboratory adding thereto comments and suggestions for changes or additions which might be in the interest of even greater safety.

DISCUSSIONS OF REACTOR HAZARDS

Introduction

Nuclear reactor operations were recognized from the very first days of the Manhattan Project as being potentially hazardous. Sites for the early reactors were chosen with remoteness from population centers as one of the requirements.

The principal hazards result from the operation of reactors, the operation of chemical separation plants, and the disposal of the wastes resulting both from the reactor and chemical separation plant operations. Some of these hazards have been reduced and controlled, others are on the way to control, but still others offer baffling resistance to final solution and control. The difficulties mentioned are inherent in the character of materials and emanations produced as the result of nuclear fission. The effects of those materials and radiations upon structure and apparatus add further difficulties not normally significant in the more familiar industrial chemical processes.

In the early discussions regarding nuclear reactors the fear was often expressed that the reaction, if uncontrolled, would cause the reactor to act like an atomic bomb. While it is indeed true that certain types of reactors may explode, in no case investigated so far has it been found that the blast from such an explosion would be a predominant factor in the hazard of such a casualty. [redacted]

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Studies to date have indicated that a nuclear reactor is a source of danger chiefly because of the great amounts of radioactive material that could be released in a single catastrophe. Such an accident could be self-induced, or be caused by fire, bombing, sabotage, or other reasons. The fission products and, in some cases, the plutonium content of the reactor may be vaporized and form a cloud; irradiation of individuals can result as the radioactive material passes overhead, or is deposited on clothing or on the ground. The activities so dispersed, whether in the form of gas, smoke, or small particles, may produce irradiation externally, or may cause a more localized internal effect if the activities are ingested or inhaled. Deposition on the ground of activities may be followed by wash-off of that material into streams that supply water for communities. The radioactive materials may also become concentrated in various farm products.

There is also a category of hazards which is associated with routine operation of the reactor and chemical processing plant. Stack gases may contain quantities of radioactive particles, gas, or smoke which are carried into air currents and, depending upon meteorological conditions, may appear in dangerous concentrations at some distance from the source. In like manner, radioactive cooling water or solutions leaking from the radioactive waste storage system may enter the ground water system and reappear in the water supply of downstream cities.

Each hazard in connection with reactor operation may be evaluated in a general way by considering first the allowable concentration or dosages from the standpoint of human tolerance, and then examining each proposed installation from the standpoint of the meteorological, hydrological, and topographical conditions existing in that location. The object is to determine the conditions which would control the possibility of reaching the tolerances in given situation. The human tolerances are not yet accurately determined and, unfortunately, the present practice is arbitrary and not uniform. For instance, the value of 0.05 per cent for retention of ingested plutonium in the body is often used. It is desirable to check the validity of this figure at low concentrations of plutonium. Other problems of a similar nature are the degree of retention and possible concentration in the lungs of radioactive fission products in the form of smoke or dust and the tolerance limits for radioactivity in drinking water. These problems have all been referred by the Reactor Safeguard Committee to the Division of Biology and Medicine for investigation. [redacted]

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Further, there is an incomplete understanding of the mechanics of atmospheric turbulence which is so important in estimating dilution of the active gases. Studies of air current behavior on the actual site are desirable in order to obtain information which is directly applicable. A less reliable alternative is to extrapolate data obtained from records kept at a point which may be nearby. However, the local topographical dissimilarities will significantly affect the results.

Using the best values of human tolerance obtainable, certain general conclusions can be reached as to the dangers associated with nuclear reactors. The application of these general criteria must be made to individual cases on the basis of the more detailed study which has been mentioned. It may be interesting to note that the conclusions reached by the Committee correspond very closely to conclusions reached in England by a committee which studied the problem of safety of the British reactors.

Discussion of reactor hazards from the standpoint of blast damage, release of radioactivity to the air, accidental release of stored fission product activity to water supply systems, and other reactor hazards, will be taken up in the following sections.

Blast Damage

In certain types of reactors, a species of explosion akin to that of the atomic bomb, although of a much smaller order of magnitude, may occur if the nuclear reaction gets out of control. Such explosions in reactors may approach one ton of TNT equivalent as compared to the 20,000 tons of TNT equivalent in the Hiroshima Bomb. The causes of such an occurrence may be many but, under proper operation of an adequately designed control rod and safety system, any such reaction would normally be prevented or stopped before it caused damage. The safety system may be called into play by the failure of the normal control system; such malfunctioning may be occasioned by material failure or human error. External causes such as earthquakes, bombing, or sabotage may also expose the reactor to danger of uncontrolled reaction through dislocation of reactor parts, loss of power

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for auxiliaries, or loss of reactor coolant. In every case the safety system which is incorporated into the reactor is expected to shut down the reactor in time to prevent a serious casualty. It is in the failure of the safety measures themselves that the real danger lies. If a combination of material failures can conceivably leave the reactor with no effective check on neutron multiplication, then the danger of explosion or at least reactor destruction certainly exists.

The magnitude of the blast that may be expected from a casualty such as just described will depend on the time rate of increase of the reactor power that results and the time that elapses before the reactor shuts itself off. The reaction will shut off because of the increase in size caused by the internal pressures that will be built up. The time needed for the number of neutrons in a nuclear reactor and, therefore, the power output of the reactor to increase by a factor of 2 depends on two factors: (1) the average life of a neutron in the reactor, and (2) the rate of reproduction of neutrons.

The average lifetime of the neutron in a reactor depends, in part, on the energy of the neutrons which cause the majority of the fissions in a reactor. In a fast reactor, the secondary neutrons are still fast when they multiply. In intermediate or thermal reactors, the majority of the neutrons must be slowed down to lower energies before the nuclear reaction takes place. In these latter reactors, the dangers of accidental increase in the reactivity are less because of the necessary delay in the multiplication process.

If the rate of reproduction in a reactor is unity, the neutrons do not multiply and the average power output is constant. If the rate of reproduction (denoted by ''k'') is greater than 1, the rate of neutron multiplication (increase of neutron population) is proportional to $k-1$. It is important to investigate what maximum value $k-1$ can attain in each reactor design.

The temperature stability of reactors must also be considered in assessing the dangers of uncontrolled reaction. If the reactivity or reproduction rate, k, of a nuclear assembly increases with increasing temperature, temperature instability exists and the reactor is less safe that if the opposite were the case. Temperature effects on reactivity are caused by changes in density and nuclear cross sections of reactor materials.

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The question of temperature stability is further complicated by the possibility of selective heating of the fissionable material. In fact, in the fast heating that accompanies a nuclear explosion, the fuel element will be heated to a considerably higher temperature than the surrounding coolant and moderator, provided the latter is not intimately mixed with the fissionable material. This heating of the fuel element influences the reactivity of the assembly in two ways: (1) by the action of thermal expansion of the fuel element which decreases the density, and (2) by the thermal agitation within the fuel element (Doppler effect). These two effects do not necessarily bear the same relation to each other in an explosion as they do in a static experiment. The effects of thermal agitation are of particular interest since they follow immediately upon release of energy and are not delayed by inertia. These effects are expected to arise because of the influence of temperature on nuclear resonances; they may cause either an increase or decrease in reactivity.

Physical dimensions of a reactor may also have a bearing on accidental changes in reactivity of the assembly and, therefore, on safety. If the reactor parts are arranged in a small volume, there will be a greater change in reactivity corresponding to a given accidental displacement of the parts than if the reactor were larger. Such displacements might arise for mechanical reasons or through the action of earthquakes or bombing.

There are further means by which the reproduction factor, k, may be affected. A well-informed saboteur may be able to cause large changes in this factor if special precautions are not taken. Much attention has been given in recent designs to limiting the speed with which the controls may be withdrawn by any means whatsoever and to the prevention of accidental or deliberate blocking of the control rod entrance holes and passages.

In connection with earthquakes, it is desirable to examine what changes in reactivity might result. For example, in the case of the Brookhaven Reactor, which is built in two halves with a 2 3/4-in. separation for center entrance of the cooling air, an earthquake might conceivably close the gap and add, in this case, $\frac{1}{2}$ per cent to the reactivity.

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Another factor of importance in determining explosiveness of reactors is the physical size of the reactor as it determines the heat capacity of the reactor parts. In a larger reactor, the time after the accident before the inner pressure increase will scatter the reactor assembly will be greater and a greater total heat release will result, as has already been noted. Furthermore, the parts which are scattered will have acquired a greater velocity in a large reactor because they will have moved farther from their original position before the reaction stops and the total impulse will be greater.

The behavior of a reactor when the flow of coolant is stopped is of interest since this is a casualty that is difficult to rule out of consideration completely. A reactor that continues its output without coolant flow will quickly overheat. If the coolant is subject to boiling as for instance water, the entire coolant is liable to be expelled from the reactor and this will have, in general, an effect on the reactivity of the assembly. This effect may be in either direction depending on the construction of the reactor but, obviously, the more dangerous possibility is an increase of reactivity. The Hanford reactors are an example of the latter possibility.

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In the case of the liquid metal coolants the problem of maintaining coolant flow is often of importance. The relatively high melting points of most liquid metals presents the possibility that the coolant will freeze in the passages. Sodium and bismuth, for example, are solid at room temperature and special auxiliary heating systems are necessary to keep the metal liquid at all points. Alloying sodium with potassium results in a lowering of the freezing point (as low as $-12°C$ for the eutectic alloy) but a decrease in the heat transfer properties of the coolant is entailed.

These various factors have been taken into account for the reactors which the Committee has considered and in no case which has been studied to date has a blast in excess of an equivalent of 30 tons of TNT been considered possible. This figure must, however, be interpreted as an upper limit which could not be reached even if all ingenuity were expended to cause a reactor to explode in the worst possible fashion. While such an explosion would be a great disaster and would be dangerous to the immediate operating personnel, it is not likely to be harmful

at distances which would involve nonparticipants. It is not believed, therefore, that blast will be a public hazard in any case that has been so far studied.

The Release of Activity into the Air

A more far reaching danger than that of blast is the release to the air of a substantial portion of the radioactivity contained in a reactor. Such an event will very probably accompany an explosion. Indeed, it is not necessary to postulate on explosion in this regard, for any uncontrolled reaction that leads to melting of the active portion of the reactor may result in such a release of activity in the form of a cloud.

Even if the safety system operates in the case of loss of coolant flow and the reactor is shut down, there remains a danger of damage to the reactor. The reason for this is the heat evolved from the fission products and action of delayed neutrons after shut-down. The temperature rise of a number of reactors, either existing or designed, have been calculated as a function of the time after shutdown, assuming that there is no coolant flow. Those curves (see Appendix "E") indicate that reactors of large volume such as Hanford and Brookhaven which operate at relatively great power and, therefore, contain very large quantities of radioactivity are nevertheless, from this point of view, quite safe since the large mass of the graphite moderator provides large heat capacity. This statement assumes the timely operation of some emergency cooling system. The newer designs of the Knolls Intermediate and the Oak Ridge High-Flux reactors have temperature rises of the order of 1000°C in the first 10 min after shutdown with no coolant and are the most dangerous studied in this respect by a considerable margin. This effect of temperature rise after shutdown is proportional to the power per unit volume of reactors.

An ordinary fire which might involve, say, the graphite moderator of a reactor, will also release radioactive gases or smokes. An even greater danger will arise if the fire is sufficient to vaporize or melt the main body of the reactor with the release of all its fission products. Sodium or sodium-potassium are also inflammable, particularly in the presence of water. Since sodium becomes radioactive under irradiation,

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the results of such a fire will be a cloud of smoke which may be dangerously radioactive.

Still another potential hazard lies in the chemical plants and radioactive waste storage areas associated with the reactor. Explosion from within the chemical plant due to maloperation or damage to both plant and storage areas may be caused by sabotage, bombing, or earthquakes. Some of those accidents may result in the release of active material to the air in the same manner as with a reactor. Since the quantities of active material may equal or exceed that stored in a reactor which has been running for any length of time, this hazard is considered to be of comparable magnitude to those previously mentioned.

It has already been mentioned that the dangers inherent in the cases which have just been discussed are the irradiation of individuals by the fission product cloud as it passes overhead or is deposited on clothing or on the ground. This latter possibility also involves the long term hazard of widespread plutonium ground contamination. The location of this contamination is difficult to predict but it might conceivably extend in very unfavorable circumstances over an area of more than 10 square miles.

Certainly, a study of meteorological conditions and hydrological information is necessary for the determination of the magnitude of the airborne problem in any specific case. Calculations based on arbitrary assumptions have been made of several of the present or proposed reactor sites to assess this hazard and a certain general method of approach has been evolved.

The radiation dosage due to the fission product cloud is calculated by estimating that practically the total fission product content of the pile might be in this cloud and then evaluating the total exposure received by an individual as the cloud passes over or by him. The worst probable case is assumed as the basis of the estimate. It has been taken that a most serious injury will result from the exposure of an individual to a total radiation of 300 r. At this level acute radiation sickness may be expected in each individual exposed; approximately 15 per cent will die within 2 or 3 months. The rest are expected to recover but the effects on the lifespan of the "recovered" individuals is not known. A sample calculation of the "control area" using a basic limiting figure for human irradiation of 300 r is set forth in Appendix "A" to this report.

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300 R.
upper limit dosage for expected acute radiation sickness.

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A factor which may markedly alter the conclusions as to the effect of a radioactive cloud is the possibility of precipitation (rain or snow). Precipitation may cause the greater part of a cloud of fission products and plutonium to be carried down and deposited on a restricted area with consequent danger to nearby populations. Certain wind directions may be accompanied by a high incidence of precipitation and these considerations should be examined before the selection of a reactor site is made.

On the basis of calculations such as those just cited, it has seemed necessary to recommend that the general public be excluded from a certain area in the vicinity of each reactor by bringing the area under complete control of the AEC. This area which would represent a region of maximum hazard would be a circle of radius in miles equal to one-hundredth of the square root of the normal operating level of the reactor in kilowatts ($0.01 \sqrt{kw}$). It will be observed that, according to this formula, the controlled area would be proportional to the reactor power in conformity with the simple idea of area contamination. Other lines of reasoning also lead to a proportionality of danger distance and the square root of the steady reactor power.

In the calculations of the area which should be controlled, no mention has been made of the effect on the calculation of other reactors at the same site. It is assumed that independence of reactors can be achieved from the standpoint of the effect of a catastrophe at one reactor on the safety of all other reactors in the vicinity. If reactors are in the same area and cannot be considered absolutely independent, then the control area must be considered to be the area obtained by calculations using the sum of the operating powers. It is believed that the condition of reactor independence can be met by proper design and reasonable separation of the reactors. In such a case the area to be controlled will be the composite area obtained by considering each reactor separately.

Outside the controlled area is a region of real but considerably smaller hazard — hazard so small as to be considered tolerable for any individual resident because of the combined effect of safety afforded by the isolation distance and the low probability of a major reactor accident

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with good design and careful operation. It would seem reasonable that this area be inhabited but desirable that it should not contain any large or industrially important center of population.

It is not possible to set the limits of the hazard area by any formula because not only are the type and power of reactor significant but also the local meteorological, topographical, hydrological and seismological conditions lead to different evaluation of hazards in different directions. In this area, concentration or imperfect dilution of the fission products and plutonium carried by the cloud and deposited on the ground may occur. Such concentration may come about by the action of precipitation carrying down activities which had previously been dispersed over thousands of feet in the vertical direction. Another and less probable but more dangerous form would be in the case of a thundercloud in which air is sucked in sidewise and brings down the activity on a small area. The percentage of the activity which will be carried down in this fashion depends on the particle size and physico-chemical nature of the radioactive particles.

The concentration may also occur by biological processes in vegetation or in the living organisms in water pools or streams even though the normal processes of dilution are in operation. If the active material is then gradually transferred to individuals by ingestion over an appreciable period of time, the dangers of the reactor accident may extend to a considerable distance.

Even normal dilution may be insufficient in the case of plutonium contamination since the limit of concentration of that element in drinking water of downstream communities has been given as about 5×10^{-5} μg of plutonium per cc. This latter figure comes about by virtue of the assumed retention of plutonium in humans from normal consumption of drinking water over the period of thirty years. This consideration would make a reactor site located on a main drainage system in the United States less acceptable from the standpoint of safety than if another site were selected. Sample calculations of this effect appear in Appendix "C."

Release of Stored Fission Products

In the present method of storing fission products from reactors large underground storage containers are used. The inventory of long-lived radioactive fission products may become, after an extended period of operation, a much greater potential hazard from the point of view of underground water contamination than the reactor itself. To cite an extreme example, it is noted that the total activity of long-lived fission products now in storage at Hanford is greater than 10^7 curies. If the containers in which that material is stored develop leaks, it would be possible for almost all of the contents to find their way into underground waters or perhaps into a large river during the course of, say, one year. A leak in such a storage system might be caused by corrosion, earthquake, bombing, or sabotage. A possible aggravation of the corrosion danger may result from the chemical effects of the radioactivity of the stored wastes. As an example, the decomposition of water molecules may conceivably accelerate corrosion.

Using a figure of tolerance of drinking water between 10^{-5} and 10^{-6} curies/cu ft, a substantial dilution of that leakage material would be necessary to bring it below tolerance for drinking purposes downstream (see Appendix "C"). It should be noted that a large majority of the possible locations for the present type of waste storage site in this country are open to criticism from this point of view.

Hazards Associated with Normal Operation

In connection with the day-to-day operation of a reactor and the associated chemical chemical separations plant, hazards also exist. Principal among these is the activity from the off-gas stacks. If air is used in the reactor cooling system, radioactive argon will be produced and unless recirculated must be discharged into the atmosphere.

Equally important is the off-gas system of the dissolver of the chemical plant from which a variety of fission products may issue, of which the notable offender is iodine. Along with the argon or the iodine may appear radioactive particulate matter of one kind or another. Recently there has been a thorough examination of the reactors and chemical plants at Oak

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Ridge and Hanford in this regard by the Stack Gas Committee.*

The particulate matter is of greater concern since it has been found that strongly radioactive particles have been emitted without the activity having shown up in the general atmospheric measurements. Such particles may escape detection and yet be breathed or ingested by individuals. So far there have been no reports of injury to health attributable to these particles, although they have been detected. One effective way of combating this hazard is in the use of appropriate filters in the off-gas stacks.

In the operation of the Brookhaven reactor where meteorological conditions may at times make discharge inadvisable, a continuous check must be maintained on those conditions and reactor operations modified in accordance. It should be noted that the regulation of reactor power level to prevent dangerous dissemination of stack gas as is mentioned here cannot be considered as a completely satisfactory solution. This is an admission of a problem left unsolved and one which must receive continuing efforts for solution. In assessing reactor hazards of areas other than Brookhaven Reactor, the Reactor Safeguard Committee has assumed that special systems to prevent or adequately control the radioactive stack gas emission will ultimately be developed and employed.

A similar problem exists in the case of water when used as a portion of the reactor cooling system. Continuous checks on the quantity and types of activities released in the cooling water must be maintained.

MEASURES DESIGNED TO MITIGATE REACTOR HAZARDS

Control Devices

It has been mentioned that explosion or rapid melting of a reactor may

*The Stack Gas Committee was formed by the Atomic Energy Commission to survey the problem of radioactive emissions from the stacks at AEC facilities, and to advise the Commission on ways and means of reducing this problem.

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occur if the normal safety measured designed to prevent such casualties fail to operate. An ideal control system would operate in such a manner that no conceivable circumstance or combination of circumstances could cause a runaway reaction. It is desirable in designing such devices to place reliance upon the minimum number of intermediary components and mechanisms, a failure of any one of which may render the system inoperative. As an example, the electron tubes associated with many such systems are liable to failure in operation. It would be desirable to have safety devices actuated directly and inevitably by, say, the rising temperature or by the increasing neutron flux and driven by some natural force such as gravity or thermal effects. Restriction of the operation of even such a device may occur in the case of earthquake or bombing. Liquid neutron absorbing solutions would be preferable in this respect to rigid rods or assemblies capable of mechanical binding; the liquid must not vaporize, however, under temperatures that might be encountered.

These dangers have sometimes been met in the past by the duplication or pyramiding of the safety devices, all of which may be rendered inoperative by the same cause, (e.g., power failure will take out all electrical devices without a standby local power system).

When one considers the desirability of making the reactor sabotage-proof, the ideal safety mechanism would be one which is built into the reactor or placed therein in such a manner that it cannot be removed except by the conspicuous and prolonged work of several people. Such a device could be arranged to release a neutron absorbing gas or powder when a special low-melting point plug fails as a result of the heat generated by the neutron flux.

Another type of device may serve to shut down the pile in case of an earthquake. Indeed, in case of an earthquake with a center not too close to the pile the first P-wave from the earthquake will possibly precede the destructive earth motion by sufficient time to give the normal safety device a chance to operate. Thus, it would be reasonable to install a crude seismograph, action of which would release the safety rods. Thus, the pile could be effectively shut down before the destructive phase of the earthquake arrives.

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Some or all of the foregoing examples may prove impracticable. They should, however, stimulate thought and discussion on novel or more effective types of safety devices.

Reducing Spread of Fission Products

Since the major hazard associated with reactor operation is the danger of the spread of plutonium and fission to the air and ground as a result of an accident, attention should be given to measures designed to reduce the dissemination of radioactive materials. Perhaps the simplest is to enclose the reactor in a gas-tight housing; then gases released in any explosion or accident which does not destroy the building will be contained and will not constitute a widespread hazard. No tests of the effectiveness of this type of construction have been made and the matter should be the subject of early investigation. Favorable reports on this scheme as a method of restricting the spread of fission products in the event of an accident would do much toward removing the restrictions which are now necessary in planning the location and operation of future reactors.

In the same interest, the plutonium which is built up in the fertile material of breeder piles should not be allowed to reach large amounts before removal from the reactor. Just what amounts are permissible must be determined in the light of isolation of the reactor, probable maximum contamination, and considerations of material losses in processing. Plutonium is not the only alpha-emitter which is to be feared. U^{233} is a similar but less dangerous long-lived contaminant. There is, in addition, a short-lived alpha-emitter produced in certain reactors which may become dangerous, namely polonium.

Reactor Design

The influence of temperature stability and loss of coolant on reactor safety has been mentioned. Reactor designs should be made where possible with decreasing reactivity for increased temperatures. The coolant system should have duplicate sets of pumping and other machinery as well as provision for stand-by gravity cooling. Note that maximum separation of alternate piping systems and gravity tanks, which is a

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routine precaution in designing for protection from the effects of bombing and the like, is equally desirable here. It is most advantageous to lose rather than gain reactivity when the coolant is lost from the reactor.

In the special case of inflammable coolants, additional precautions are necessary, such as inert gas blanketing of all areas through which coolant passes and the selection of alloys of sufficiently low melting point or methods of maintaining elevated temperature around the entire cooling system to prevent freezing at any point.

It is important that disaster plans be worked out at each reactor site to control and limit the damage as much as possible. This is particularly important where reactors are located close to each other and a disaster at one may affect the personnel or machinery at the other.

Fission Product Storage

Since the waste storage facilities of a reactor installation will contain, after extended operation, much more activity of long half-life than the reactor itself, extreme care in the layout and design of storage systems is desirable. The present methods of storing dilute solutions of fission products in tanks should be examined to the end of developing improved methods which will involve smaller volumes. Converting the material to solid form, as by evaporation, precipitation, filtration, or combining the waste solution with other materials into a solid cement are methods which seem worth investigating in this regard.

The general problem of the utilization of fission products seem to warrant particular attention. One of the present difficulties with fission product storage which causes concern is the fact that the great activity of the waste makes handling expensive. Changes in the handling methods for greater safety will probably increase the cost. On the other hand, if the wastes are made useful in some manner the problem of disposal of radioactive wastes may be largely solved.

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SUMMARY OF INDIVIDUAL INVESTIGATIONS

The comments set down here are those which were found by the Committee at the time of the investigation of individual reactors. Subsequent improvements or changes which may have been made in these reactors have not been taken into account in the following.

The Knolls Intermediate Reactor

The Knolls Intermediate Reactor is distinguished by the following features:

1. Operates in the intermediate neutron energy range — a hitherto unexplored field.
2. Substantial heat output — 10,000 kw.
3. Liquid metal (sodium) coolant.
4. Total U^{235} about 40 kg and maximum build-up of plutonium about 4,000 g.
5. Chemical and metallurgical plants associated with the reactor located in the same general area.
6. Reactor building will be of gas-enclosing type.

The hazards associated with the reactor are:

1. Nuclear Explosion. The temperature instability which may result from the Doppler broadening of resonance lines in U^{235} is one mechanism by which such an explosion could be set off. With an increase in "k" of 4 per cent, which is the maximum to be expected, an explosion of 6 kg TNT equivalent would result. This would be a sufficiently small explosion to leave the gas-enclosing function of the reactor building intact. The Doppler effect is susceptible of study in advance and should be better understood before the reactor is started.
2. Fire in the Sodium Coolant. This would release great quantities of radioactive smoke and might be as serious from the point of view of contamination as the nuclear explosion. Inert gas blanketing systems and the total exclusion of water supply to the reactor building would minimize this danger.

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3. Airborne Fission Products or Plutonium. The controlled area defined by the formula R = 0.01 /kw has a radius of one mile. Under very unfavorable conditions, the hazard may reach beyond this limit for a distance of several miles. The site location of the reactor places it within 20 to 30 miles of cities of the size of Schenectady, Troy and Albany. Although the prevailing wind is not in the direction of any of these cities, the possibility of hazard is not completely to be excluded, particularly if activity is deposited in the form of smoke or precipitated as rain on one of those centers of population.

4. Small Scale Accidents. Although the probability of small accidents primarily connected with handling hot materials is higher than that of a major catastrophe, the effects are not likely to cause damage outside the immediate reactor area.

5. Sabotage Objective. It was thought that the attractiveness of the reactor as a sabotage objective has been diminished by its removal from the vicinity of Schenectady and other war plants.

Argonne Fast Reactor

The Argonne Fast Reactor has the following special characteristics:

1. Operates in the fast neutron range where multiplication times are short.
2. Small size which will magnify effects on reactivity of small displacements of internal parts.
3. Low power output (1000 kw).
4. Sodium-potassium alloy coolant.
5. Proposed site at Argonne Laboratory in DuPage county, Illinois.
6. Chemical and metallurgical plant may be proposed for location near the reactor.

The hazards investigated were as follows:

1. Nuclear Explosion. The short lifetime of the neutrons in a fast reactor coupled with the unknown contribution to the temperature instability of the Doppler effect on U^{235} resonances renders this reactor relatively dangerous from the standpoint of nuclear explosion. Also, the scale of the reactor is so small that relatively minor changes in the fissionable material can produce relatively large changes in reactivity. Such a change might be caused by violent shock from outside,

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unequal thermal expansion of the nickel jacket of the rods, or other causes.

The Doppler effect may become dangerous if the reactor becomes critical by more than a small percentage. Such an occurrence is unlikely but not impossible under the cumulative action of a number of accidents. Under those circumstances, the explosive effect of the reaction is not likely to be greater than 10 kg of TNT and is exceedingly unlikely to be greater than one ton of TNT. The Doppler effect should be studied to determine its potential danger prior to startup of the reactor.

A violent shock from outside the reactor could conceivably cause an explosion in excess of 100 kg of TNT if the reactor were running. The same shock administered when the pile is idle and contains no neutron source will cause a reaction which occurs later and greater compression is built up causing a greater explosion. In such a case, explosions up to 30 tons of TNT cannot be excluded definitely. This latter would, however, require a carefully laid out and extremely difficult plan of sabotage.

2. Coolant Fire. The cooling system may freeze up causing the reactor to overheat and melt down, or the coolant may catch fire itself. In the first case, an improvement may be effected by selecting the alloy having the lowest possible melting point. The melting point of the 44 per cent potassium, 56 per cent sodium, alloy is +15°C but the eutectic alloy has a melting point of −12°C.

A coolant fire will not be excessively dangerous because of the low activity to be expected in the sodium. Blanketing with nitrogen is suggested for all areas through which sodium-potassium flows.

3. Airborne Fission Products. If the reactor had been in full operation prior to a catastrophe which released the activity to the air, the dosage received by an individual at 10 miles under very unfavorable wind conditions (1 mph) is 10 r, somewhat below a dangerous dose. On the other hand, a wind velocity of 10 mph is normal and the danger would be much less (1 r). Precipitation would increase the danger substantially, particularly because W and SW winds are often accompanied by rain and, in this case, large population centers lie in the down wind direction.

4. Plutonium Ground Contamination. Consideration of the danger of ground contamination by plutonium deposited from a cloud shows that the danger from drinking water contamination will occur only if 100 g of plutonium are spread over an area of less than 0.1 sq mi. It seems very

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unlikely that a deposition higher than that could occur in any place more than 2 or 3 miles from the reactor location. In this connection, it is noted that a limit should be set on the amount of plutonium which is allowed to build up in the reactor. A reasonable figure is 250 g.

Not considered here is the possible danger from introduction of plutonium and long-lived fission products into the nearby waterway although a small but finite danger to downstream water supplies will exist.

5. Population Concentrations. The presence of large concentrations of populations and important industrial centers in the vicinity of the proposed site for this reactor will aggravate the hazard of the reactor.

6. Power Output. The small power output of the reactor limits the maximum possible disaster which may occur in connection with its operation.

7. Storage of Wastes. Waste solution storage of the present type is not recommended near the present site.

Oak Ridge High Flux Reactor

The Oak Ridge High Flux Reactor is characterized by the following:

1. High power output (30,000 kw).
2. Low critical mass and high neutron flux (2×10^{14} neutrons/cm^2/sec).
3. Operates on neutrons of thermal energy.
4. The reactor construction places the active portion at the bottom of a well of water which acts as the moderator and the coolant.
5. Very little plutonium will be manufactured in the reactor.
6. Fission product activity in the reactor will be very high after operation for any time.
7. This reactor was considered specifically in relation to its possible location at DuPage site.

The hazards studied in connection with this reactor were as follows:

1. Nuclear Explosion. The danger of blast is thought to be very slight, since the characteristically long multiplication time of a thermal reactor will prevent explosions greater in effect than about 1 kg of TNT. This is not meant to imply that fission heat or the heat from fission products cannot melt the reactor if the water supply is stopped, with a

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consequent release of fission products.

2. Failure of Cooling Water. This is considered to be a very serious hazard, since it is not clear that the reactor would be safe, even if it were shut down immediately when the coolant supply stops. It is true that a loss of water from the reactor itself would automatically shut down the reactor since the reactor depends on the water to moderate the neutrons to thermal energies. However, the fission product heat would certainly melt the reactor down and release a large part of the very great quantities of radioactivity to the air. Thus, every precaution must be taken to prevent the loss of water in the reactor from any cause whatever. It is estimated that of the 35 million curies of activity which will be in the reactor 1 hr after shutdown, approximately one quarter or 9 million curies may be considered gaseous and may escape into the air.

3. Long-lived Alpha Emission. The hazard from long-lived alpha emitters, which is encountered in most reactors, is low in this reactor. In this case, the activity of the U^{233} in the breeder blanket is the greatest hazard. The maximum amount of this isotope which is expected to be built up is 700 g. When this fact is considered with the lower specific activity of U^{233} it is seen that the hazard is lower than existed in the case of the Argonne Fast Reactor with 250 g of Pu. In the case of that latter reactor it was estimated that no dangerous concentrations of alpha activity could be expected to occur at distances of greater than 2 or 3 miles from the reactor as a result of a catastrophe.

4. Hazards from Cooling Water. Radioactive content of cooling water will cause no significant health hazard, even in the immediate vicinity of the reactor, provided adequate precautions are taken. Such precautions include shielding the cooling lines and provision of retention basins of sufficient capacity to hold the entire contents of the cooling water system in the event of rupture of the active elements of the pile and contamination of the cooling water by fission products.

5. Stack Gas Activity. It has been estimated that about 5,000 curies of argon will be discharged in 24 hr by the stack gas which carries cooling air through the shield of the reactor. Insufficient information is available to the Committee to estimate the hazard which is created thereby and a further study on this point is considered necessary.

6. Chemical Processing and Storage of Wastes. Since the chemical plants that will be associated with this reactor will contain several million curies and the storage tanks for the spent waste might contain even an order of magnitude more fission products of rather long lifetime, another hazard would certainly exist. A leak in the storage system into the surface water is one mechanism by which the safety of individuals at large distances from the reactor site could be jeopardized.

7. Handling Spent Fuel Assemblies. Spent fuel assemblies will individually contain large amounts of radioactive fission products and when removed from the reactor must be adequately cooled for a certain period. These assemblies must be so handled as to prevent trouble in that sense and also that a critical mass is not accumulated at any point in the storage channels.

8. Power Output. In evaluating the hazard of this reactor the comparatively high steady power output and high activity in the reactor has been particularly stressed.

9. Maximum Power. As to the maximum power which the Committee thought appropriate for DuPage site, even with safest reactors and best safety precautions now known, a steady power level in excess of 1000 kw could not be recommended.

Hanford Reactors

The safety aspect of the Hanford installation was examined by the Committee in connection with the proposed irrigation of Wahluke Slope which is the territory just across the Columbia river from these reactors. The following features of the Hanford installation were found to be of interest in that regard.

1. There are three reactors presently in operation at Hanford and more are planned. The reactors are widely separated (3 to 4 miles).

2. The power level of the reactors is high.

3. The reactors are of the thermal type with consequent long multiplication time.

4. The reactivity decreases with an overall temperature rise of the reactor but, for situations in which the heating is accomplished in a short time and is confined largely to the fuel elements, the reactivity initially increases with temperature.

5. The Hanford reactors become more reactive with loss of coolant (an increase of 2 per cent in k).

6. As a result of the prolonged neutron bombardment to which the graphite moderator has been subjected, there is now a significant amount of stored energy in that material. There is a danger that a sudden heating of the graphite will set off an auto-catalytic reaction which will result in the sudden release of the major portion of that energy in the form of a thermal wave.

7. There is a long record of safe operation of these reactors.

8. There is associated with the reactors chemical plants and radioactive waste storage areas.

The Committee found that the main hazards at Hanford are due to (a) the piles, (b) the chemical separation plants, and (c) the waste disposal areas.

1. Explosion. For reasons already discussed in connection with thermal reactors, the blast from the explosion of one of these reactors is not likely to be serious outside the immediate area.

2. Discharge of radioactivity to the Atmosphere. Although the long successful operation of these reactors, the care in operation, and the high quality of personnel give some insurance against major malfunctioning of the reactors, there still exists a continuing danger in their operation. A loss of cooling water would have a good chance of resulting in melting down of the reactor, since such a casualty might make the reactor critical for prompt neutrons alone. Earthquake, sabotage, or bombing may produce a similar result. Finally, the thermal instability of the graphite which has been subject to prolonged irradiation and the expansion of the reactor and displacement of the shield which follows it may each have an effect on the continuity of cooling water supply.

3. Stack Gas Activity. The gaseous fission products and particles of different sizes which are emitted from the stacks of the chemical plants have been a source of contamination over a wide area. Measures are being taken to reduce this contamination and it is assumed that it will be successfully brought under control to the extent that the isolation of the area demanded from other considerations will be sufficient for this purpose.

4. Storage of Wastes. Radioactive waste storage areas are a hazard in that there is a possibility of the slow leakage of the stored material into the Columbia river with hazard to downstream water supplies. Special measures to safeguard against this danger seem advisable.

5. Reactor Instability. The installation of some inherently infallible device to overcome the danger from instability of these reactors to loss of water and other factors that have been cited might permit relaxation of restrictions which are now placed on their operation. This would free substantial parts of the Wahluke Slope from AEC control.

6. Effect on Wahluke Slope. No concrete safety recommendations were requested of the Committee, which did not have a bearing on the pile operations as they affect the irrigation and cultivation of the Wahluke Slope.

Brookhaven Reactor

In the investigation of the Brookhaven Reactor, the following characteristics of that reactor were brought out:

1. This reactor is modeled after the Oak Ridge air-cooled pile which has run for several years without disaster.

2. It is a thermal neutron reactor and, therefore, not capable of violent nuclear explosion.

3. The reactor has a sufficient heat capacity that failure of the coolant system should not lead to a catastrophe.

4. This reactor has a negative temperature coefficient of reactivity.

5. Power level is relatively high compared with existing piles.

6. The reactor is constructed in such a manner that a gap of 2 3/4 in. is left in the center of the active portion through which the cooling air enters the reactor. The reactivity of the pile would be increased by any action such as an earthquake would tend to push the two halves of the pile together.

7. The reactor loses a slight amount of reactivity with loss of coolant flow.

8. The system of fuel slug canning which is proposed involves fewer cans than is the case with the Oak Ridge pile. This fact is believed to lead to a more safe condition from the standpoint of slug failure.

9. There is to be a helium system installed for the early detection of failures of the fuel cans.

10. The reactivity, which can be taken up by the various safety devices that are to be installed, is not great when compared to the various reasons for possible changes in reactivity and their effects on reactivity.

11. Irregular and unexpected changes in k may be experienced when it is used as designed for an experimental reactor.

12. Stack gases discharge 6,600 curies per day of radioactive argon into the atmosphere.

13. Reactor operation is to be governed by the local meteorological conditions which may render inadvisable the discharge of large amounts of stack gas activity to the atmosphere.

14. No chemical plants are planned for this reactor.

Taking the foregoing reactor characteristics into account, the Committee concluded that no great hazard is involved in the operation of this reactor provided the following safety measures are adopted:

1. Additional, manually operated, gravity actuated, shutdown facilities should be provided which will reduce k by at least 1.5 per cent and which will remain operative even in the event of earthquakes, fire, or other major disaster.

2. The area surrounding the reactor site which is considered to be hazardous enough to require complete control is 1.7 miles radius for 25,000 kw.

3. In accordance with statement 13 regarding reactor characteristics, the program of continuously observing the concentration of radioactive argon from pile stack gases and of forecasting meteorological conditions affecting stack gas dilution should be fully implemented, and reactor operation should be curtailed or suspended whenever either radiological surveys of the area or meteorological information indicates that tolerance levels of radioactive contamination may be exceeded.

4. Studies of the earthquake history and recent observations are pertinent to the safety considerations of this reactor.

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Los Alamos Fast Neutron Reactor

The Los Alamos Fast Neutron Reactor has the following characteristics:

1. Low power output (20 kw max) and, therefore, low fission product activity.
2. Plutonium used as fuel (18 kg).
3. Negative overall temperature coefficient.
4. Reactivity decreases with loss of coolant.
5. Reactivity increases by about $2.00 with melting of fuel elements.*
6. With loss of coolant at full power, ample time is afforded to shut down the reactor and temperature rise thereafter is low.

The hazards noted in the case of this reactor were:

1. Reactor Explosion. Apparently, an explosive condition in the reactor can be obtained only through gross negligence or sabotage. If $1.00 excess reactivity can be obtained in a short period of time, the fuel may melt and a further $2.00 would ensue. The resultant explosion would probably be of the order of a few kg of TNT equivalent. If TNT were exploded in an experimental hole the action of forcing the core together might give rise to an explosion equivalent to a ton of TNT. The blast of such an explosion would have a direct effect which would be confined to the immediate area.

2. Plutonium Contamination. The danger from the reactor lies principally in the spreading of plutonium to Los Alamos as a result of explosion. The danger would come from individuals breathing an airborne cloud of plutonium dust or smoke as well as from ground contamination. The town would have to be evacuated in whole or in part and many individuals might receive lethal doses.

3. River Contamination. It is not expected that the plutonium content of the reactor could be introduced into the Rio Grande River

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* The percentage of reactivity represented by the contribution of the delayed neutrons is a significant quantity in reactor kinetics. That fraction of reactivity is here assigned a value of $1.00 and changes in reactivity are discussed in terms of dollars and cents using the foregoing definition as a basis. One dollar in this plutonium reactor equals 0.25 per cent k.

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in such a manner as to give a lethal dose of plutonium to an individual taking all his water from the river.* The question as to the contamination of Los Alamos water supply cannot be determined until earth permeability studies now underway are complete.

4. Santa Fe. The community of Santa Fe is 24 airline miles from Los Alamos. The hazard area includes this town but no greater hazard to Santa Fe is expected than has been considered for neighboring towns in the cases of the Knolls, Argonne, and Brookhaven laboratories.

Los Alamos Water Boiler

The Los Alamos Water Boiler has the following characteristics:

1. Low power (5.5 kw).
2. Slow neutrons cause the reaction.
3. Reactivity drops with loss of coolant and with temperature rise.
4. Activity in stack gas is normally at background level.
5. Location is a few hundred feet from the Los Alamos Fast Reactor.
6. Very little excess reactivity is available in the reactor.

The hazards of this reactor were:

1. A dangerous explosion is not at all likely because the expected total energy release under the most rapid power rise possible is only sufficient to vaporize the solution.

2. The contained fission products, if spread to Los Alamos, would constitute a small but not negligible danger.

3. A rapid change in power level could conceivably be caused by the careful placement of fissionable material around the reactor.

4. This reactor is near the Los Alamos Fast Reactor and some danger to the latter may be said to exist for that reason.

* This conclusion is based on data concerning the retention of plutonium by the human body and the tolerance of the body to that substance. Further information on these subjects may change the foregoing conclusion.

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5. After reviewing the hazards of the Water Boiler, the Committee concluded that it is the safest reactor which has been studied to the present time.

The Reactor Experiment Station

The Committee was presented with a report of the pertinent information on six possible sites for a reactor experimental station with a request for its comments in regard to the safety of the areas and a seventh site was added at the meeting of February 1-2, 1949. The seven sites were reviewed from the standpoint of the following casualties:

1. Disruption of a reactor with the consequent release to the atmosphere of large quantities of radioactive gas or smoke. Gas so dispersed was considered as it produces irradiation externally or internally.
2. The deposition of the activity dispersed as above on the ground and the subsequent washoff of the material into streams that supply water for downstream cities.
3. Accidental release of radioactive end products of the chemical processing plants and from other sources to the watershed of downstream cities.

The conclusions of the Committee were as follows:

1. The Wilmington, North Carolina, site would seem to be undesirable because with its location within 25 miles of the city of Wilmington, North Carolina, an important city of 33,000, a remote but still conceivable combination of circumstances would expose this city to a windborne radiation sufficient to kill a number of people and to require evacuation.
2. The isolation of the remaining six sites seems adequate for installations up to 1 million kw per independent unit. The safety of reactors on these six sites is a very substantial improvement on any of the reactor sites which have yet been examined by the Committee with the possible exception of Hanford. Consideration should be given however, to the possible developments which might significantly change the degree of isolation in future years.

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3. In the consideration of adequacy of isolation, the independence of the units on the station is assumed. This is to say, the failure of one reactor should not affect the safety of another reactor on the station.

4. Special concern was felt for the protection of downstream communities from the hazard that the drinking water of those communities may be contaminated by slow leakage from the fission-product storage areas on the reactor experiment station. The Committee felt that the waste product storage system of the station should be carefully studied with the object of significantly reducing this hazard. It is to be noted here that the ideal solution to the problem of waste disposal would be one by which the waste products would not only be rendered harmless from the standpoint of contamination of public streams but would be made useful to the government or to science or industry.

5. Climatic extremes are considered inadvisable from the standpoint of the added difficulties of operation and the possibility of failure of cooling and other systems in freezing weather.

6. In general, the Committee notes that no site on a main watershed will ever be completely free from the possibility of the hazards associated with the contamination of downstream water.

APPENDIX "A"

ESTIMATE OF RADIATION FROM CLOUD CONTAINING ALL OF A REACTOR'S FISSION PRODUCTS

An example of the methods of calculation of the radiation hazard presented by the vaporization of all a reactor's fission products is presented here. These methods are given in detail ~~for a Hanford reactor but~~ and the principles may be applied with suitable changes and corrections, to the discussion of reactors of ~~comparable~~ several designs. In each case, the worst one of probable events is assumed. No safety factors are included.

Radiation hazard is calculated from the basis of a ~~Hanford production unit~~ reactor in normal operation. It is assumed that for one of the several reasons which have been discussed in the main body of this report, the chain reaction gets out of control, the "k" of the pile is increased about 2 per cent above the critical value and, the power level increases by a factor of 2.718 in each period of about 0.1 sec. The temperatures of the reactor parts will rise rapidly until factors such as negative temperature coefficient or mechanical disruption of the pile stops the reaction. In any case, it is assumed that a considerable part of the fission activity of the reactor will have been carried into the air in the form of a cloud before the reaction stops.

We estimate that radiation dosage due to this cloud by first calculating the total power output of the fission products in this cloud and then evaluating the total exposure received by an individual as the cloud passes by or over him. The level of fission product activity after the disruption of a pile which had been operating at a steady level before the accident, is given approximately by the empirical formula:

$$\text{fission product activity in kilowatts} = 0.1\,\frac{\text{previous steady power in kilowatts}}{(\text{time in seconds after accident})^{0.2}}$$

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We assume that of this activity 50 per cent is present in the radioactive cloud. Thus we get:

$$)0.05 \frac{\text{previous steady power in kilowatts}}{(\text{time in seconds after accident})^{0.2}}$$

Negligible for the present purpose is the activity of the additional fission products produced during the period of run-away pile operation.

We have to multiply the formula for fission product activity by the following factors in order to calculate the level of radiation hazard attained:

(1) $\text{Concentration factor} = \frac{1}{\text{volume of cloud}} = \frac{1}{\text{cloud thickness x length x width}}$

According to meteorological evidence, the spread of a smoke cloud is roughly one seventh the distance of downstream travel, under a wide variety of wind conditions. Thus we have:

$$\text{Concentration factor} = \frac{7}{\text{distance from pile x cloud thickness x length}}$$

(2) The time of exposure, which is given by the formula:

$$\text{time} = \frac{\text{cloud length}}{\text{wind velocity}}$$

The product of expressions (1) and (2) is evidently independent of the cloud length. In other words, the integrated radiation dosage at a given position will be the same — granted constant wind direction — whether the uranium burns up and goes into the air in 1 min or 1 hr.

(3) The conversion factor between integrated radioactive power in kilowatt seconds per cm^3 (the product of (1) and (2)), and accumulated radiation in roentgen units. This factor is

$$\frac{10^3 \text{ volt ampere seconds x } 3\text{x}10^9 \text{ franklins/coulomb}}{30 \text{ volts per ion pair}} = 10^{11}$$

The factor just given will apply to a cloud so large that as much energy is delivered up per cm^3 and per sec in the form of ionization as is produced by radioactive decay per cm^3 and per sec. This condition will be satisfied if the thickness of the cloud is great compared to the range

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of the radioactive radiations and if, furthermore, the receptor is in the cloud.

We take as a rough average range for the beta particles, 5 ft, and 1,000 ft for the gamma rays, and note that roughly equal fractions of the energy discussed above go off as beta and as gamma radiation. If the receptor is on the ground, if the cloud extends to the ground and is greater in thickness than the range of the beta and gamma rays, and if finally none of the radioactive substances are deposited on the ground, then the dosage obtained by the receptor is roughly 0.6 times the dosage within the cloud. The factor 0.6 is obtained by considering that the receptor is exposed to gamma rays only from one-half of all directions (i.e., from above) and to beta rays of a 5-ft range from somewhat more than one-half of all directions.

We find for the accumulated radiation, by taking account of factors just discussed, the result:

$$\text{Accumulated radiation in roentgens} = 2\times10^{10}\,\frac{\text{previous steady power in kilowatts}}{\underset{\text{(in cm)}}{\text{(cloud thickness)}} \times \underset{\text{(in cm/sec)}}{\text{(wind velocity)}^{0.8}} \times \underset{\text{(pile in cm)}}{\text{(distance from)}^{1.2}}}$$

The result just obtained can be applied in the form in which it stands, but may be put into a more reasonable form by a little further analysis. From the present formula it follows that a receptor at a given distance, say 10 miles, from the pile, subject to radiation from a cloud of fission products of a given thickness, will receive an integrated radiation almost inversely proportioned to the speed with which the cloud passes by him. He will get about twice as great a dosage from a cloud which moves at $\frac{1}{2}$ mile an hour as from one traveling at 1 mile an hour. By admitting the possibility of a cloud of arbitrarily low velocity we should, therefore, admit an irradiation of arbitrarily great intensity. This result is unreasonable, as: (a) from a meteorological standpoint it is extremely unlikely that at the time of the accident a wind velocity will occur as low as $\frac{1}{2}$ mile per hour, and (b) if, contrary to all reasonable expectation, the cloud should actually move with such a low velocity,

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it would reach the 10-mile distant receptor only after the lapse of 20 hr. A time so long would seem adequate to notify individuals to evacuate. On both accounts we exclude irradiation at a 10-mile distance from a cloud moving so slowly.

On the other hand, a 3-mile an hour wind is not improbable in view of the meteorological conditions observed at Hanford. The 3.3 hr required in this case for the cloud to travel 10 miles will only barely allow notification of hazard.

In the light of this discussion we adopt the following point of view. We accept 3 hr as a critical time. We consider a receptor at a given distance from the pile catastrophe:

(a) If the wind is so slow that more than 3 hr are required for the cloud to reach the receptor then indeed the possible accumulated exposure will be greater than we are about to calculate. It is, however, possible to notify and move the people out of the way of the cloud. It is recognized that this evacuation itself will be difficult and hazardous.

(b) If the wind is so fast that much less than 3 hr are required for the cloud to reach the receptor, then the exposure time is short and the dosage is reduced. Consequently the worst case will be that in which a time just in the neighborhood of 3 hr is required to reach the receptor:

$$\text{Wind velocity in miles per hour} = \frac{\text{miles from pile to receptor}}{3\text{ hr}}$$

On this basis, our formula for exposure takes the form:

$$\text{Accumulated irradiation in roentgens} = 43\,\frac{\text{operating level in kilowatts}}{\text{cloud thickness in feet} \times (\text{distance from pile in miles})^2}$$

At an exposure to 300 r units, it is to be expected that acute sickness will follow in each individual. Approximately 15 per cent are expected to die within the next 2 or 3 months. The rest are expected to recover. It is unknown to what extent the life-span of the "recovered" individuals will be shortened. We have taken as the basic figure of our calculations 300 r. This evidently corresponds to most serious danger. Setting the

left-hand side of the last expression equal to 300, we get

$$\text{exclusion distance in miles from pile} = \left(0.144\,\frac{\text{operating level in kilowatts}}{\text{cloud thickness in feet}}\right)^{\frac{1}{2}}$$

For a more specific estimate of the exclusion distance some value is required for the possible minimum thickness of the cloud. For the Hanford site, where meteorological conditions are unfavorable, this thickness is set by the conditions of thermal inversions. Stagnant conditions not infrequently occur in the Hanford bowl. The air in this bowl up to an elevation of about 2,000 ft does not then significantly mix with the air above it. Smoke rises to the boundary layer. An altitude of 1,500 ft for the boundary layer is not an improbable occurrence and we use 1,500 ft for the thickness of the cloud. We are thus led to the formula:

$$\text{exclusion distance from pile} = 0.01\ (\text{operating level in kilowatts})^{\frac{1}{2}}$$

The foregoing argument shows that in our present state of knowledge we cannot possibly recommend settlement of population closer to a pile than this distance.

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APPENDIX "B"

RADIOACTIVE CONTAMINATION BY PRECIPITATION

In the following an estimate is given of the probable upper limit of ground contamination by β and γ active substances following dispersal of the active content of a reactor in the atmosphere.

ASSUMPTIONS

It will be assumed that the whole active content of a reactor is carried up in the atmosphere and that all of this active content will be deposited on the ground at a distance of M miles. In traveling the distance of M miles it is assumed that the radioactive cloud will have been widened out by the turbulence of the air currents to cover a circle of radius of M/14 miles. This gives an angular spread of the radioactive cloud of 1/7 of a radian, which seems to be a reasonable lower limit of observed angular spreads.

The assumption that the radioactive material in the cloud is deposited in a circle as described will definitely give an upper limit of the possible contamination. This, however, is not the case in a thunderstorm, where masses may be sucked in from the side and deposited in the active region of the thunderstorm. Thus during such a storm activity may be concentrated on a smaller area than the one over which the radioactive cloud was originally dispersed.

We assume that prior to the explosion the reactor has been steadily operating at a power of k kilowatts. Under these conditions there will occur in the reactor 3×10^{13} k fissions per second. We consider the radioactivity of the fission products at a time t after the explosion. This radioactivity has been expressed in The Rate of Decay of Fission Products ((MDDC-1194) by Way and Wigner), on page 22, by various formulae for various times. We select the time interval between 20 min and 3 days, because this time interval is most relevant for the acute effects of the radioactivity. For this time interval one finds that each fission releases $15t^{-0.28}$ Mev γ radiation per second if the reactor had been running at one fission per second. It also releases $9t^{-0.26}$ Mev of β radiation per second.

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The total activity of the reactor will be deposited over an area of $\pi \frac{(M)^2}{(14)}$ miles^2, or 4.15×10^8 M^2 cm^2. Thus one finds that per cm^2 there is

$$\frac{15t^{-0.28} \times 3 \times 10^{13}\ k}{4.15 \times 10^8\ M^2} = \frac{1.1 \times 10^6\ t^{-0.28}\ k}{M^2}$$

Mev γ radiation released per second at a time t after the explosion. Similarly, one finds that

$$\frac{9t^{-0.26} \times 3 \times 10^{13}\ k}{4.15 \times 10^8\ M^2} = \frac{6 \times 10^5 \times t^{-0.26}\ k}{M^2}$$

Mev of β radiation released per cm^2-sec.

It is of interest to compare the assumption of total deposition of radiation to events following explosion of atomic bombs. One of the bomb tests on Eniwetok was followed by a rainstorm on Kwajalein. The actual path that the air took in going from Eniwetok to Kwajalein was 840 miles. The radioactive products, however, were quite dispersed by the time they arrived at Kwajalein. In fact, the course of events was probably that the top of the cloud above an altitude of 20 miles was carried westward, then some of the radioactivity fell to lower levels and was carried by northeasterly winds to Kwajalein. A great dilution under such conditions may well be expected. One actually finds that in the heavy rainstorm at Kwajalein only 1/500 as much activity was deposited as could have been expected if all activity had been deposited at the distance of 840 miles, in accordance with the formulas* given above.

IRRADIATION PRODUCED

One Mev of β or γ radiation produces approximately 30,000 ion pairs. If the radioactive material is deposited on the ground, only $\frac{1}{2}$ of this activity will go in the upward direction and cause ionization of the air. Taking this factor into account, as well as the obliquity of the radiation, and assuming that the average range of γ rays in air is approximately 200 meters, one finds that near the ground approximately 10^{-4} of the radiation

* Converted to the case of instantaneous irradiation.

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[redacted]

will be deposited in the air for each one cm height. For the β rays one may assume that approximately 10^{-2} of the radiation will be dispersed per one cm height. Thus, if one has on the ground one γ disintegration/ cm^2-sec of one Mev energy, one finds that in the air 3 ion pairs/cm^3-sec are formed. Furthermore, under these conditions one β ray/cm^2-sec with one Mev energy gives rise to 300 ion pairs/cm^3-sec. Since an r unit corresponds to 2×10^9 ion pairs/cm^3, one finds that one Mev γ radiation/ cm^2-sec (on the ground) will give rise to 1.3×10^{-4} r units per day, and a similar amount of β radiation to 1.3×10^{-2} r units per day.

Converting the time unit into days and taking into account all the above factors, one finds the following situations for the explosion of a reactor which has been operating at k kilowatts: At M miles distance and after the elapse of d days we find that the γ radiation on the ground gives rise to $5.9d^{-0.28}$ k/M^2 r units per day, whereas the β radiation gives rise to $420d^{-0.26}$ k/M^2 r units per day.

Since most of the β radiation does not penetrate clothing and since one should not reasonably assume that more than 1/10 of the body will be exposed to the β radiation, one might reduce the effects of the β radiation by a factor of 10. Thus, one finds the effective radiation to be $42d^{-0.26}$ k/M^2 r units per day.

Example

In order to illustrate the above formulae we assume for

d	1 day
k	1000 kw
M	10 miles

This gives 59 units per day γ radiation. This γ radiation will constitute an immediate hazard, which can effectively be reduced by prompt decontamination. The effective β radiation on the other hand will amount to 420 r units per day. Thus, a full day's radiation would amount to a most dangerous dose. In evaluating the effects of the β rays one must bear in mind that covering of free body surfaces by gloves, masks, and goggles will effectively eliminate this danger. One, nevertheless, must count on damage to health and probably on some casualties as well if the activity described above is deposited in a densely populated area.

[redacted]

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APPENDIX "C"

PLUTONIUM LIMITS IN DRINKING WATER

ASSUMPTIONS

(a) Average individual consumes 2 liters/day = 2000 cc/day.

(b) Retention in body — 0.05 per cent. This figure obtained from experiments on animals at higher concentrations than those considered here and is open to question until further experimentation at low concentration is performed.

(c) Tolerance limit of retained plutonium in the body is 0.5 μg.

(d) Assumed length of time individual drinks the water — 30 years = 10,000 days.

$$\text{Allowed concentration in drinking water} = \frac{\text{Allowed grams in body}}{\text{cc ingested per day x per cent retention x days}}$$

$$= \frac{5 \times 10^{-7}}{2000 \times .0005 \times 10000} = 5 \times 10^{-11} \text{ g/cc}$$

$$= 5 \times 10^{-5}\ \mu\text{g/cc in drinking water}$$

If, further, the assumptions are made:

(a) That plutonium is spread over an area of 0.1 square miles = 2.5×10^9 cm^2.

(b) That annual rainfall = 1 meter/year.

Then, the amount of Pu which, when deposited on ground and washed off over 30 years, will give tolerance in drinking water = $1000 \times 2.5 \times 10^9 \times 5 \times 10^{-11}$

= 75 g Pu.

[redacted]

APPENDIX "D"

RADIOACTIVE LIMITS IN DRINKING WATER DOWNSTREAM

ASSUMPTION

(a) Average flow of a watershed is 27,000 cu ft/sec. (This is the case of the Missouri River at Sioux City, Iowa — taken from records of U. S. Geological Survey.)

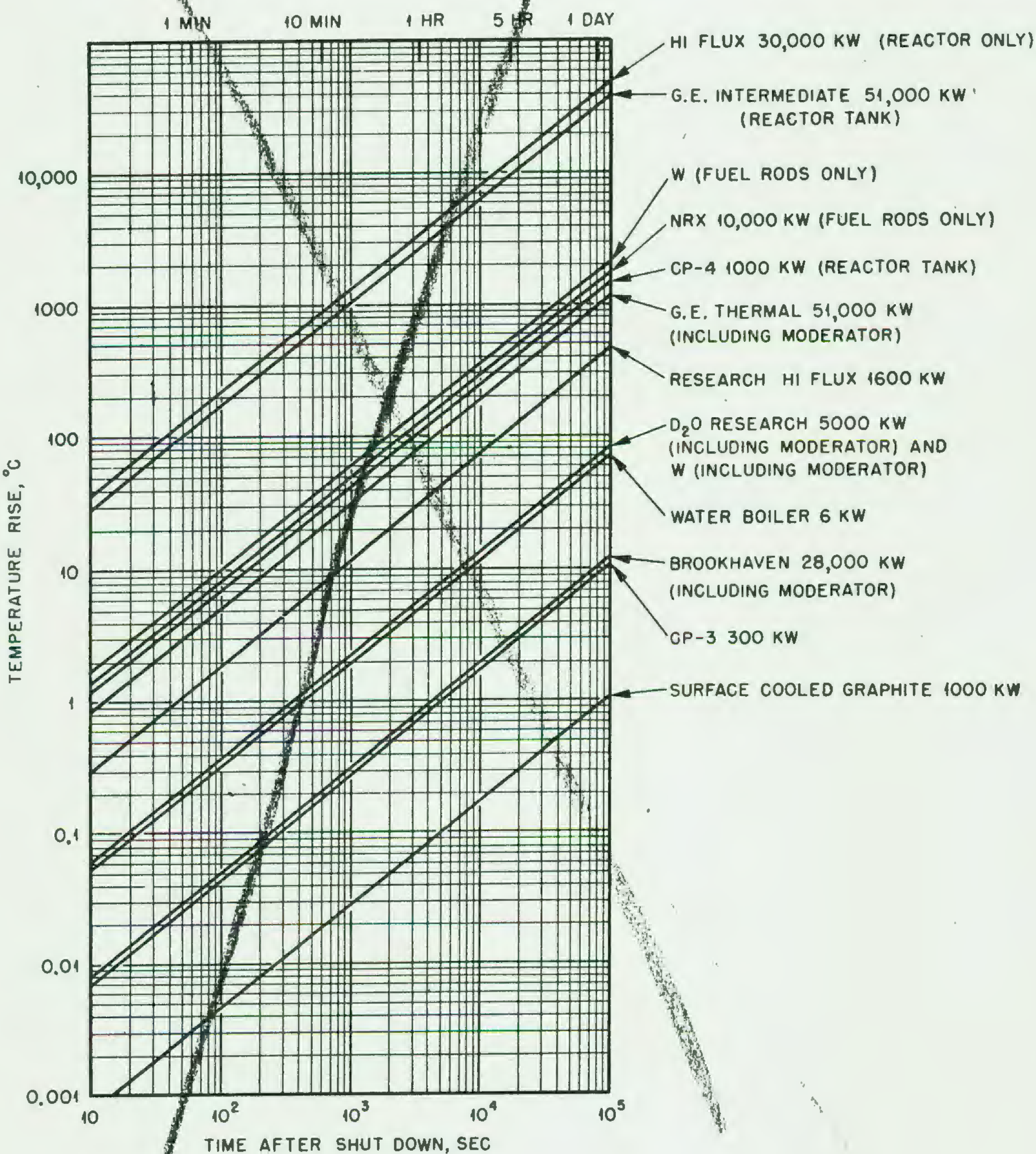
(b) Stored fission product activity in tanks equals 10^7 curies.

(c) Release of stored activity to stream is 100 per cent.

Based on the foregoing premises, the average radioactivity of water is

$$\frac{10^7}{27000 \times 86400 \times 365} = 12 \times 10^{-6} \text{ curies/cu ft}$$

This figure should be compared to a tolerance figure of the order of 10^{-6} curies/cu ft, which is calculated from data and formulae given by K. Z. Morgan in a report No. CH2801, entitled "Tolerance Concentrations of Radioactive Substances," dated January 31, 1945.



1 MIN
10 MIN
1 HR
5 HR
1 DAY
10,000
1000
100
10
1
0.1
0.01
0.001
TEMPERATURE RISE, °C
10
10^2
10^3
10^4
10^5
TIME AFTER SHUT DOWN, SEC
HI FLUX 30,000 KW (REACTOR ONLY)
G.E. INTERMEDIATE 51,000 KW (REACTOR TANK)
W (FUEL RODS ONLY)
NRX 10,000 KW (FUEL RODS ONLY)
CP-4 1000 KW (REACTOR TANK)
G.E. THERMAL 51,000 KW (INCLUDING MODERATOR)
RESEARCH HI FLUX 1600 KW
D_2O RESEARCH 5000 KW (INCLUDING MODERATOR) AND W (INCLUDING MODERATOR)
WATER BOILER 6 KW
BROOKHAVEN 28,000 KW (INCLUDING MODERATOR)
CP-3 300 KW
SURFACE COOLED GRAPHITE 1000 KW

Figure 1.

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APPENDIX "F"

THE ENERGY DEVELOPED IN AN EXPLODING REACTOR*

Numerous discussions on the effects of a possible reactor explosion have resulted in estimates of the energy yields. These estimates vary from case to case according to the nature and structure of the reactor. In the following discussion a few points of view and a few simple formulae are summarized which may prove useful as a guide for crude calculations in which the energy developed in reactor explosions is estimated. No attempts at a refined analysis can be made here. It must, furthermore, be remembered that the nuclear explosion may be followed by a chemical reaction which may release considerably more energy than the nuclear explosion itself.

We assume that a reactor has by some means become supercritical, and that after this its energy content increases as $e^{t/\tau}$, where τ is a multiplication period. It is useful to distinguish two cases: (1) $R/\tau \ll c$; and (2) $R/\tau \gg c$. Here R is the radius of the active core of the reactor (in all of the subsequent discussion we assume for simplicity that the core is spherical), and c is the average sound velocity within the material of the reactor.

(1) $R/\tau \ll c$. If this condition holds, one may consider the reactor in a first approximation as a system in equilibrium in which the pressure developed by the reactor is contained by the stresses set up in the reflector that surrounds the reactor. We introduce $\delta \Delta R/R$, where ΔR is defined by the assumption that the multiplication stops when the core radius expands to $R + \Delta R$. In all of the discussions we shall assume that δ is very small compared to unity. If our condition $R/\tau \gg c$ holds, δ will be given by the approximate expression $\delta = \kappa p$; where κ is the coefficient of compressibility of the reflector, defined as

$$-\rho \frac{d\frac{1}{\rho}}{dp}$$

and p is the pressure developed in the reactor. This expression is approximate, mostly because it assumes elastic behavior of the reactor. From p one can calculate the energy from a knowledge of the equation of state of the core

* This appendix was written in cooperation with Dr. Carson Mark.

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materials. This assumption of elasticity will seem reasonable at least in most cases in which the core materials are not vaporized. Under this condition the energy content per unit volume is quite small (of the order of 0.1 of the pressure), and the energy can promptly be estimated from the pressure.

We shall not discuss the case of an inelastic container, but we shall briefly consider a case where the reflector containing the reactor breaks. In this case (still assuming $R/\tau \ll c$) one will expect that the expansion of the reactor will occur sufficiently rapidly to counter-balance further increase in pressure due to the progress of the general reaction. Both in this case and in the case where the reflector does not completely confine the reactor, one may assume that only as much energy will be developed as is necessary to disassemble at least part of the reactor. In many reactors this will mean the boiling off of a few per cent of the reactor material. In the slowest reactors disassembly may occur through melting.

(2) $R/\tau \gg c$. In this case the energy liberation is regulated by an entirely different mechanism. Under these conditions a shock wave will move from the reactor into the surrounding reflector. The velocity of the shock wave will increase exponentially with time and most of the expansion required for disassembly will take place during a single period. From this condition one finds that the pressure p built up in the reactor is equal to

$$P = \frac{R^5 \delta}{V \tau^2} (\rho_c \rho_r)^{1/2}$$

where V is the volume of the core and c and r are the average densities of the core and of the reflector. From this formula one obtains the total energy E developed

$$E = \frac{R^5 \delta}{\tau^2} (\rho_c \rho_r)^{1/2} \frac{\epsilon}{p}$$

where the dimensionless quantity ϵ/p is the energy per unit volume divided by the pressure within the core. It has been mentioned above that for the condensed phase ϵ/p is considerably less than unity. If the core materials have been vaporized, ϵ/p lies roughly in the region between 2 and 5. As long as vaporization has not taken place, the total energy evolved is relatively small, not only because p is small but also because ϵ/p is small.

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Vaporization is connected with a great increase in energy. In order to estimate the energy developed in a very rapid manner it is well to remember that this energy is roughly equal to that developed by a TNT explosion of a mass equal to the core mass, provided the energy developed in the general reactor is just sufficient to vaporize the core material.

The approximate formula given above needs modification if the core is not homogeneous and if the distance between fuel elements in the core, which we call r, is large enough so that $r/\tau < c$. In this case, the initial expansion of the fuel elements will not decrease the reactivity and effective expansion takes place only after the shocks emitted from the various fuel elements collide. Thus the effective expansion of the core is slower and a greater energy liberation is to be expected than is indicated by the above equations. The condition $r/\tau > c$ is not satisfied in any reactor that has been built or designed. Furthermore, in the case of rodlike fuel elements, expansion along the axis of the rod tends immediately to reduce the activity of the reactor even before the shocks moving perpendicular to the axis of the fuel rods collide.

In some cases, the initial reaction will actually enhance the reactivity. Such reactors are called autocatalytic. Autocatalytic reactors are inherently more dangerous than such reactors which do not possess this feature, and the possibility of an autocatalytic process must be particularly carefully investigated. Autocatalytic action may be due to motion of materials (e.g., ejection of absorbers), or to a change in the behavior of materials with temperature (e.g., broadening of resonance lines), or to increase of thermal-neutron energies (e.g., heating of neutrons to a temperature slightly above an absorption resonance).

EXAMPLES

In the following we shall give two examples to illustrate the energy production in cases in which the simple considerations of elasticity or rupture of the reflector are not the governing factors.

The following characteristics of the reactor are assumed:

$$\text{Radius } R = 8 \text{ cm}$$
$$(\rho_c \rho_r)^{\frac{1}{2}} = 15$$
$$\delta = .005$$
$$\tau = 10^{-6} \text{ sec}$$

These figures refer to a fast reactor in which the condition $R/\tau > c$ is satisfied, and which is approximately 2 per cent prompt supercritical. Substitution into the above formulae gives

$$\frac{R^5 \delta}{\tau^2} (\rho_c \rho_r)^{\frac{1}{2}} = 2 \times 10^{15} \text{ ergs}$$

and we obtain $E = (\epsilon/p) \times 2 \times 10^{15}$ ergs.

The energy developed is sufficient to vaporize the substance. The values of ϵ/p for dense vapors are not well known. Setting $\epsilon/p = 5$ is likely to be an overestimate. This leads to an energy value of 10^{16} ergs. For purposes of comparison we note that 4×10^{16} ergs is one ton of TNT equivalent. Thus, the energy which we obtain for the reactor is equivalent to 1/4 ton of TNT.

As the second example we shall consider the behavior of a Hanford pile under runaway conditions. This reactor is autocatalytic because evaporation of the water will increase the multiplication factor by approximately 2 per cent. Even under these conditions it remains true, however, that $R/\tau > c$. The reactor is likely to disassemble by melting and partial vaporization of the slugs. This may result in dispersion of some U in the graphite and also in the movement of some slug material from the center toward the periphery of the reactor. The greatest energy release is likely to be connected with the partial vaporization of the slugs. Even so, an immediate energy release of several tons of TNT is quite likely. Burning of slug materials and possibly of the graphite may increase this energy release to a very considerable extent. This burning, however, will not take place in an explosionlike fashion.

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APPENDIX "G"

CHANCE OF DISASTER DUE TO SABOTAGE

The Reactor Safeguard Committee has in the past attempted to analyze the magnitude of conceivable disasters, but has so far found it much more difficult to estimate their probability. Yet probability is the usual measure of safety of such operations as airline travel, as described for example in fatalities per hundred million passenger miles. Similarly for each reactor, it would of course be most helpful to be able to give the probability that a major accident would take place in the course of a year of operation. If a certain reactor were estimated to have a chance of one in a hundred of blowing up in the course of a year, certainly much thought, energy, and money would quickly be devoted to decreasing this evidently great hazard. On the other hand, a probability of disaster as low as one chance in a million per year might be considered to impose on population outside the control area a potential hazard small compared to that due to flood, earthquake, and fire. Where the actual accident probability lies in relation to these two extreme figures is thus an important question, with definite practical consequences.

Conclusions reached to date about the hazard probability are extremely tentative and indefinite; nevertheless it seems to this Committee quite possible that the likelihood of disaster from some existing reactors may be substantially greater than the low figure of one chance in a million per year. The basis for this tentative conclusion may be briefly reported.

A nuclear reactor can be disrupted and its radioactive content spread over the project city if sufficient excess reactivity is suddenly made available, either by a malfunctioning of the controls, or by disturbances from outside — sudden introduction of external active material into several experimental holes, or a TNT explosion within the structure which suddenly brings into closer proximity the active material which is already present.

Either accident or sabotage may bring about this sudden increase of reactivity. An accident will occur only if by chance and at the same time a number of the independent safety features of the design become inoperative.

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The probability of such an accident is, therefore, given by the product of several numbers, each of which is evidently small. Thus, the product is still smaller. However, a reasonable way to estimate the actual values of the individual numbers or of the overall proability of such a multiple unlikely accident has not occurred to the Committee. Consequently, it cannot be stated with certainty that the probability of such an accident is less than the chance of successful sabotage. Nevertheless, it is obviously legitimate to take the estimated chance of sabotage as a lower limit of the probability of disaster.

In sabotage it is clear that the probabilities of failure of the individual safety devices cease to be independent. The same man who blocks one of them can block all of them. Moreover, he can wreak on the pile internal violence and give to it a sudden stimulus, of a kind which could never be counted under the heading of an accident.

Two bits of history may give some impression of the possibility for pile sabotage. First, Alan Nunn May, an able physicist with an honorable record, abstemious, liked and trusted by his associates, without telling them and on the basis of privately held convictions of his own, deliberately violated his oaths and the law and revealed important atomic secrets to foreign agents. His colleagues have since said, "If we had been told we had a spy in our laboratory, we would have suspected each other before we suspected May." Evidently the man on a nuclear installation who is going to betray the confidence reposed in him may well appear on all customary tests to be as reliable as his fellow workers. If he runs the great risks which he must face to set off an explosive chain reaction, he presumably has the strength of character not to reveal beforehand his messiah complex, his aim perhaps "to save the world from atomic warfare."

Second, sabotage is not an extremely rare phenomenon. In the period January 1, 1940, to February 1, 1943, the U. S. Federal Bureau of Investigation received reports of 7,400 cases of supposed sabotage, 558 cases of which were found to be real.* Only a handful of these acts were directly guided from outside the United States. The sabotage of the wiring systems of 24 bombers by the skilled Glenn Martin workman Etzel was done on his own initiative, as retribution for what he considered wrongs done to the German people. In some other cases the saboteur was driven on by grudges

* From the book of Irwin and Johnson on sabotage published by Norton in 1943.

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against the management or against fellow workmen, and in still other cases drunkeness or plain vicious character was behind the damage. Whatever the cause of these acts, their frequency provides the only starting point known to this Committee for estimating the chance of pile sabotage.

Without reporting any actual estimate of this probability, it is possible to name some of the more important factors which must necessarily enter into such a calculation. First, acts of deliberate damage are generally associated with differences between individuals, groups, or nations. Consequently, the probability of sabotage will not maintain from year to year the rough constancy of the highway fatality rate, for example, but will rise in periods of tension. After all, sabotage is one branch of warfare. In a period when neither an actual war nor a "cold war" is underway, it can, therefore, be supposed that the probability of intentional damage is less than it was during the past war. On the other hand, that war was a special case. Hundreds of German sympathizers and German agents were arrested immediately after Pearl Harbor. No significant organization was left to promote sabotage. Moreover, the number of dissidents in this country is generally believed to have been less in the past war than in any previous major conflict in American history. Thus, it is hardly reasonable to expect the sabotage rate of the last war to be an adequate index to the frequency of such occurrences in a future war. Especially, would this be unreasonable if that war were to involve a nation which makes a policy of stirring up discontent in other countries and takes pride in the sabotage which it has inspired.

Second, the recognized importance of the atomic bomb in a future war, the moral flavor of the campaign carried on by many individuals and some governments against its use, and the concentration of atomic bomb work in a few well known centers, would all seem to make these installations magnets for saboteurs.

Third, to set off a nuclear reactor requires a familiarity with its design and a level of specialized knowledge most unlikely to be found outside a few score specialists connected with AEC installations. The background and character of those men have been investigated carefully. Therefore, damage wrought out of viciousness of character or drunkeness appears most improbable. Instead the finger of probability points to a man of exceptional individuality of character, a second Alan Nunn May. But such a man is

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presumably to be found with greater likelihood in a group of experimental men at a laboratory site rather than in a routine operating shift of a production plant. This circumstance must influence the relative probabilities for premeditated disasters in experimental and manufacturing areas.

In conclusion, sabotage appears to be an important factor in determining the safety of reactor installations, and perhaps even the dominating factor. Moreover, the type of saboteur indicated by the foregoing discussion will operate in a twilight zone controlled neither by nuclear physics nor by security agencies. His specialized knowledge enables him to circumvent all known safety devices of a purely physical character. His independence of character and devotion to principle, if they have any influence at all on his chances to pass security checks, presumably help him.

Until some means is found to extend control over this twilight zone, it is conceivable to this Committee that other and more conventional measures will have relatively little effect in reducing the probability of reactor disasters.

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APPENDIX "H"

LIST OF ITEMS OF INFORMATION NECESSARY TO THE SAFETY EVALUATION OF A PROPOSED REACTOR INSTALLATION

Following is a list of the items of information which must be set down and the investigations which must be reported in order to permit an adequate safety appraisal of a proposed reactor or chemical plant installation:

1. Description of the reactor.
2. Detailed plan of the normal reactor operation.
3. Plan of the experiments which will be performed on the reactor including the limitations which will be placed on experiments.
4. The normal schedule of chemical processing and disposal of reactor products.
5. The description of the safety mechanisms of the reactor.
6. A discussion of the special hazards connected with the reactor, including the evaluation of the possibility of a major catastrophe.
7. The distribution of population near the proposed site.
8. A list of the vital industrial or war installations near the proposed location.
9. Frequency of occurrence of wind directions and velocities both at the surface and aloft; frequency of precipitation and its correlation with wind directions; and information as to the frequency of stable and turbulent wind conditions.
10. The occurrence of inversion layers and precipitation and their correlation with wind directions.
11. The methods proposed for the control of stack gases and the possibilities of the correlation of reactor operation with meteorological conditions.
12. The normal methods of disposal of aqueous coolant or other solutions.
13. Hydrological data on the area, the expected drainage of liquids in the case of a major accident, and the distribution of activities in the drainage system under such conditions.

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14. The evaluation of the probability of earthquakes and their intensities.

15. The evaluation of the probability of an ordinary fire.

16. Discussion of hazards and risks to surrounding population as influenced by meteorological, geological, and hydrological conditions.

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APPENDIX "I"

REACTOR CHARACTERIS

Reactor	Neutron energy	Power	Fissionable material	Physical size	Safety system	Long-lived alpha content	Coolant	Dep va
Knolls Intermediate	Intermediate	10,000 kw	40 kg U-235 95% enriched U-238 blanket	Small		4 kg (max) Pu	Sodium-primary Sodium-potassium in secondary circuit	1. S mech 2. U 3. U
Argonne Fast	Fast	1,000 kw	40 kg U-235 95% enriched U-238 blanket	Small		Pu (max amounts not fixed in design)	Sodium-potassium (44% potass.) m p + 15°C	1. S smal 2. U
Oak Ridge High-Flux	Thermal	30,000 kw	3 kg U-235 95% enriched Thorium or Bi Blanket	Small		700 g (max U-233) (others small)	Ordinary water (becomes radio-active)	1. " loss. 3. H avail
Hanford	Thermal			Large	Vulnerable to sabotage	Very large (Pu in fuel)	Ordinary water	1. I by 2' ener 4. V
Brookhaven	Thermal	28,000 kw	70 tons natural U contains 500 kg U-235	Large	Disaster shut down facilities of 1.7% k	Large (Pu in fuel) Also a max of 10^4 curies Po in Bismuth	Air	1. Va ment 2. H clos 3. N
Los Alamos Fast	Fast	10 kw to possibly 20 kw	18 kg plutonium normal uranium tamper	Small	No dangerous excess "k" is available under normal circum-stances	Very large 18-kg Pu	Mercury	1. N 2. k Pu. 3. k
Water Boiler	Thermal	5.5 kw	0.875 kg U-235 in in form of solution of 14.5% enriched uranyl nitrate	Small		None of consequence	Ordinary Water	1. N 2. k

APPENDIX "I"

REACTOR CHARACTERISTICS

ety tem	Long-lived alpha content	Coolant	Dependence of k on various factors	Stack gas activity	Location	River drainage	Chem. plants
	4 kg (max) Pu	Sodium-primary Sodium-potassium in secondary circuit	1. Small size, sensitive to mechanical changes. 2. Unknown Doppler effect. 3. Unknown temp. dependence.	Chemical plant only if installed	20-30 miles from Albany, Troy, Schenectady	Mohawk River nearby	Maybe
	Pu (max amounts not fixed in design)	Sodium-potassium (44% potass.) m p + 15°C	1. Small size, sensitive to small mechanical movements. 2. Unknown Doppler effect.	Chemical plant and metallurgical plant only if installed	DuPage county 30 miles from Chicago	Nearby waterway exists	Maybe
	700 g (max U-233) (others small)	Ordinary water (becomes radio-active)	1. "k" decreases with coolant loss. 2. Neg. temp. coeff. 3. High excess reactivity available.	5000 curies of Argon from shield cooling air discharged per 24 hr	Considered in relation to DuPage county, Ill. site	Surface leakage to waterway and under-ground waters possible at DuPage county	Yes
rable botage	Very large (Pu in fuel)	Ordinary water	1. Loss of coolant incr. "k" by 2%. 2. Graphite has stored energy. 3. Graphite expansion. 4. Vulnerable to sabotage.	Chem. plant activity high (iodine and particles)	Hanford, Washington (well isolated)	Columbia River nearby Large waste tanks buried	Yes
ter shut facilities % k	Large (Pu in fuel) Also a max of 10^4 curies Po in Bismuth	Air	1. Varying effect of experi-ments on k. 2. Has gap in center, which, if closed could increase k. 3. Neg. temp. coeff.	6600 curies of Argon discharged from stack in 24 hr	Long Island, N. Y. Large population centers 25 miles distant	None	No
ngerous s "k" is able under l circum- es	Very large 18-kg Pu	Mercury	1. Neg. temp. coeff. 2. k increases with melting of Pu. 3. k decreases with coolant loss.	None	Los Alamos, N. M. (near vital installation) (also near water boiler)	Drains to Rio Grande	No
	None of consequence	Ordinary Water	1. Neg. temp. coeff. 2. k decreases with coolant loss.	Outlet activity at level of background	Los Alamos, N. M. (near vital installation) (also near Fast Reactor)	Drains to Rio Grande	No

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APPENDIX "J"

REACTOR HAZARDS

Reactor	Danger of runaway reaction	Fire	Coolant stoppage or loss	Airborne contamination	F
Knolls Intermediate	Unknown thermal stability. Details of reactor not fixed so all dangers not known.	Coolant (sodium) is inflammable. Exclude water and use inert gas blanketing. Coolant will be radioactive.	Coolant can freeze in pipes. Need infallible system of auxillary heating of pipes.	Gas enclosing building should reduce danger. Control area 1 mile radius. Hazard area 20-30 miles radius. Rain is a hazard to cities nearby.	C a 1
Argonne Fast	1. Unknown Doppler effect. 2. Sensitive to small distortions in fuel elements from unequal thermal expansion or external shock.	Sodium-potass. coolant inflammable. Not very radioactive.	Coolant can freeze. Use lower melting point alloy and gas blanketing.	Hazard will not extend beyond 10 miles unless precipitation occurs.	I n t o
Oak Ridge High Flux	Long neutron lifetime will prevent abrupt explosion. Runaway reaction not probable but melting from loss of coolant is serious.	No danger noted.	Reaction stops with loss of water but active portion almost sure to melt.	Fission product activity is very great and could possibly give rise to 9 x 10 curies in the cloud. Hazard is particularly great.	U a A
Hanford	1. Reactivity increase with coolant loss and sabatoge vulnerability make for real danger. 2. Fire, sabotage, bombing may readily cause release of fission products to atmosphere. 3. Expansion of reactor may cause trouble.	Fire in graphite may release activity and may melt pile allowing release of even greater activity.	Stoppage or loss of coolant could easily occur and would cause dangerous increase in reactivity.	Hazard area will include Wahluke slope. Meteorological conditions not too favorable in Hanford bowl.	D ar R
Brookhaven	1. Earthquake may move pile halves together. 2. Irregular changes in k may occur. 3. Safeties not large in respect to possible hazards.	Possible in graphite.	Not serious.	Control area 1.7 miles at 28,000 kev. Low density population within 25 miles makes hazard not serious beyond 1.7 miles.	
Los Alamos	1. Very difficult under ordinary circumstances to cause runaway reaction. 2. Could be caused by careful sabotage plan. 3. Melting of Pu causes $2.00 prompt excess reactivity.	No danger noted.	Not serious. Will not overheat reactor.	Very serious plutonium hazard to Los Alamos residents either from breathing or ingestion.	Ve Ar
Water Boiler	Possible only if extensive changes or additions of fissionable material are made and then is held down by temperature effect.	None	Lowers reactivity, not serious.	If all contained active material spreads over Los Alamos there could be some danger.	Ve
Reactor Proving Ground	Separation of reactors and independence must be maintained. Climate and other factors which may cause interruption of power and coolant must be given careful thought.			Requires at least 400,000 acres controlled by AEC. Also separation from large cities or vital installations by many miles. Need gas-enclosed buildings, etc. reduce spread of fission products.	Ma ne

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APPENDIX "J"
REACTOR HAZARDS

Coolant stoppage or loss	Airborne contamination	Pu ground contamination	River contamination	Stack activity	Blast effect	Small accidents
Coolant can freeze in pipes. Need infallible system of auxillary heating of pipes.	Gas enclosing building should reduce danger. Control area 1 mile radius Hazard area 20-30 miles radius. Rain is a hazard to cities nearby.	Can be a hazard over an area greater than 10 square miles.	Mohawk River contamination not known		6 kg TNT with excess k = 4%	Not dangerous at distances of 1 mile or so.
Coolant can freeze. Use lower melting point alloy and gas blanketing.	Hazard will not extend beyond 10 miles unless precipitation occurs.	100 g of Pu would not not dangerously contaminate unless deposited on area less than 0.1 mile.	Not thoroughly investigated		30 tons TNT max under well organized sabotage. 1 ton max under normal conditions.	
Reaction stops with loss of water but active portion almost sure to melt.	Fission product activity is very great and could possibly give rise to 9 x 10 curies in the cloud. Hazard is particularly great.	U-233 contam. not more serious than Pu from Argonne Fast Reactor.	1. Cooling water should be held in basins. 2. Storage wastes large after long operation.	Could not evaluate hazard of 2,500 c stack activities without more data on winds, etc.	Less than 1 kg TNT	Individual assemblies need constant cooling and care to prevent critical mas in storage canal
Stoppage or loss of coolant could easily occur and would cause dangerous increase in reactivity.	Hazard area will include Wahluke slope. Meteorological conditions not too favorable in Hanford bowl.	Dangerous to hazard area and to Columbia River.	Columbia River contamination possible from storage tanks or reactor accident.	Iodine and particulate matter from chem. plant as yet not adequately safe.	Low	Explosion in chem. plant could happen but would be less dangerous than reactor accident.
Not serious.	Control area 1.7 miles at 28,000 kev. Low density population within 25 miles makes hazard not serious beyond 1.7 miles.		None	Operations controlled by meteorological conditions measured continuously.	Low	
Not serious. Will not overheat reactor.	Very serious plutonium hazard to Los Alamos residents either from breathing or ingestion.	Very serious in Los Alamos Area.	Not serious in Rio Grande. Unknown effect on Los Alamos water supply.	None	Low. A few kg or at most one ton of TNT.	
Lowers reactivity, not serious.	If all contained active material spreads over Los Alamos there could be some danger.	Very small.	No significant danger.	No hazard because of filters and discharge at distant point.	Very small. Total possible heat release just able to vaporize contained water.	
	Requires at least 400,000 acres controlled by AEC Also separation from large cities or vital installations by many miles. Need gas-enclosed buildings, etc reduce spread of fission products.	May be serious if location is near main waterway.	Great hazard in case of locations on streams serving cities drinking water.	Must be controlled.	Not serious to nonparticipants.	Not serious to nonparticipants.

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