McCullough

# The Safety of Nuclear Reactors

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## REACTOR TECHNOLOGY

In any new field of technology, it is important to investigate, quantitatively if possible, as many features of the field as seem pertinent for human welfare. Nuclear reactor technology is such a field, and no one looks to it with hope for many material benefits for mankind. Among these benefits are the possibility of electric power generation, propulsion by nuclear energy, and the utilization of reactors as research tools in many branches of science and medicine.

Along with a long list of possible attractive features of reactors, there are, unfortunately, certain dangerous characteristics. The Advisory Committee on Reactor Safeguards (see Appendix) has the responsibility of looking at the hazards connected with nuclear reactors. The members of this committee are exceedingly anxious to see rapid and fruitful development of reactor technology, but because of the nature of the hazards involved, and because they have been specifically requested to look at hazard problems, they feel it important that no undue risks be taken in the development of nuclear reactors.

## REACTOR SAFETY

Immediately, when one attempts to evaluate reactor hazards, there is encountered the necessity for attempting to define the notion of reactor safety, and what this notion shall include. Of course, absolute safety is not possible and what is really meant in connection with reactor hazards is the minimization of hazards until one has an acceptable calculated risk.

The operation of nuclear reactors appears safe and it is, in fact, deceptively safe. A nuclear reactor will not run away unless a number of serious mistakes of planning and operation should be committed. It is, however, impossible to conduct extensive operations over a long time without occasional occurrences of such mistakes. We have been exceedingly lucky so far that nobody has as yet been killed by a runaway reactor. It is not possible to count on indefinite continuation of such good luck.

One of the current difficulties in evaluating reactor hazards is this lack of experience with reactor accidents. So far, there have been essentially no reactor accidents leading to serious consequences. For this reason, statistical information about reactor accidents, although all favorable, does not suffice to give useful statistical information of the type needed by insurance companies, for example, in evaluating the nature of hazards. In other words, to determine what is an acceptable risk, a certain amount of judgment, detailed technical evaluation of a given reactor, and caution must be employed.

With all the inherent safeguards that can be put into a reactor, there is still no fool-proof system. Any system can be defeated by a great enough fool. The real danger occurs when a false sense of security causes a relaxation of caution.[1]

Problems of reliability, adequate control, adequate supervision, must all be included. It is convenient to look upon the concepts of reactor safety in the following ways:

One important concept is the division of safety problems into on-site and off-site problems. The on-site problems have to do with the protection of reactor operating personnel and other people who may be at the reactor site in order to make use of it, and the protection of the economic investment in the reactor facility. Off-site problems have to do with the protection of the general public, or persons who are not more or less directly connected with the operation of the reactor. One way to minimize off-site hazards is simply to locate the reactor at a remote and unpopulated place. In terms of reactor utilization and economics, this solution is often unsatisfactory. The economic utilization of electric power generated by reactors, for example, nearly always requires that the reactor be located reasonably close to potential users of this power. This means that for economic reasons the reactor should be located near populous, industrial areas.

Substantial moral and ethical problems are involved in connection with reactor hazards. On-site personnel, like persons working in other industries, knowingly and willingly submit themselves to whatever hazards are associated with working near a reactor because of salary requirements, special working conditions, or personal interest.

For off-site people, on the other hand, who have no knowledge or interest in the operation of the reactor, it seems that prevention of danger to their persons or damage to their property is a mandatory

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B5-1-21

moral obligation in the operation of a reactor. This problem is more severe than in the case of dangerous chemical or explosives plants, because the radioactivity contained in a reactor can constitute a hazard to a wide area if it escapes from a machine and becomes dispersed.[2] This public hazard has been one of the main concerns of the Advisory Committee on Reactor Safeguards.

From another point of view, the safety of a nuclear reactor can be said to depend upon two things: The intrinsic built-in stability and reliability of the machine, and administrative control of the machine and its operation. For example, the reactivity may decrease rapidly with increasing temperature. In this case, it may be practically impossible to exceed some safe limit in temperature. This intrinsic stability is very desirable. In fact, one may say that a machine with large intrinsic stability can be so stable, because of fundamental physical characteristics, that only a Maxwell demon can make it misbehave. An ordinary machine, which depends on the operation of the control system to set its power level, can be upset by a mere gremlin! One would like to minimize the dependence upon administrative control for safe operation of a reactor. However, as a matter of practical fact, most reactors will nearly always require a certain dependence upon administrative control for safe and reliable operation. This means that problems arise connected with the loading and unloading of fuel, the startup and shutdown of the reactor, proper manipulation of controls, and adequate accounting for all materials made radioactive by the reactor, including both intentionally irradiated material and any radioactive effluent associated with the operation. Thus the normal, as well as the abnormal operation and behavior of the reactor must be carefully considered. It is clear that a reactor which in normal operation is well run and under complete and precise control is much less likely to behave in an abnormal fashion leading to a serious accident.

## THE CONTAINED RADIOACTIVITY

The most serious continuing hazard associated with nuclear reactors is due to the large amount of radioactivity which they contain. Large reactors may contain hundreds of pounds of radioactive fission products which correspond to many tons of radium in conventional radioactive measure. Not all of these fission products are as hazardous as radium, but nearly all of them contribute substantially to the hazard.[3] There are two ways in which the hazard of contained fission products may be minimized: One is to remove fission products during the operation of the reactor in such a way as to maintain a minimum concentration of such material in the machine. This continuous removal of fission products requires some type of fluid fuel, either liquid or gaseous, in order to continue cleanup operations on the fuel during the operation of the machine. The other way to minimize the hazard is to minimize the possibility of the escape of these fission products from the machine. The potential ability of a reactor to run away makes it possible for this radioactive material to escape to the surrounding areas. The hazard is crudely analogous to conducting both explosive and virulent poison production under the same roof.[4]

Until really safe nuclear machines of the future become available, we have to construct our reactors with extreme circumspection and we must continue to operate them with the same caution after ten years of safe running as on the very first day when they were started up.[4]

In order to emphasize the characteristic of the special hazard due to radioactive materials in the reactor, a list of tolerances is presented in Table I.[5] Although there has been a substantial effort in the assessment of the effects of radiation on biological systems, particularly systems resembling people, there is still a great deal to be learned.[3] However, even allowing for considerable error in the quantitative assessment of this problem, it is still evident from Table I that radioactive poisons are more hazardous than chemical poisons by a factor of something like $10^6$ to $10^9$. This is such an enormous factor that radioactive poisons essentially must be considered a qualitative new kind of problem. Furthermore, this implies

Table I.[5] Comparison of Toxic Substances in Air*
(concentration in mg/m³)

| *Substance* | *Tolerance*† | *"Fatal dose"*‡ | *Ratio fatal to tolerance* |
|---|---|---|---|
| | | **Chemical Poisons** | |
| Chlorine | 2.9 ¶ | 290 § | 100 |
| Arsine | 0.16 ¶ | 800 § | 5000 |
| Beryllium | $1.5 \times 10^{-6}$ | ? | ? |
| | | **Radioactive Poisons**** | |
| $U^{233}$ (insol) | $1690 \times 10^{-9}$ | $1690 \times 10^{-5}$ | 10,000 |
| $Pu^{239}$ | $32 \times 10^{-9}$ | $32 \times 10^{-5}$ | 10,000 |
| $Sr^{90}$ | $1.3 \times 10^{-9}$ | $1.3 \times 10^{-5}$ | 10,000 |

* It should be remembered that industrial poisons are usually in many ton quantities, whereas radioactive poisons are in 100-kilogram quantities.

† "Tolerance" for chemical poisons is defined as the maximum tolerable level for 8 hours per day exposure. In the case of radioactive poisons tolerance is the maximum level which can be tolerated every day for 8 hours equivalent to 0.043 rem per day.

‡ "Fatal Dose" in the case of chemical poisons is defined as the "rapidly fatal" dose when the given concentration in air is inhaled for 30 minutes to one hour. In the case of radioactive material this means about 50% survival if the dose is acquired quite rapidly, for example, over a minute or perhaps during an 8-hour day. This is equivalent to about 400 rem.††

¶ Adopted at meeting of the American Conference of Governmental and Industrial Hygienists in Atlantic City, N. J., in April 1951.

§ Industrial Hygiene and Toxicology, Frank H. Patty, Editor, Interscience Publishers, Inc., 1949.

** Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water, Handbook 52, National Bureau of Standards, March 20, 1953.

†† The Effects of Atomic Weapons, US Government Printing Office, Revised September 1950.

that the problem of keeping radioactive materials within the reactor and preventing the spread of radioactive materials over populous areas is very serious.

In Table II there is a summary of delayed heat production and the corresponding radioactivity from fission products. For a machine of 250,000-kw heat power (60,000-kw electric power), something like 300 million curies of activity remains at the end of one day after shutdown. This corresponds to 300 tons of radium in terms of radioactivity. The sheer quantity of radioactivity is enormous.

Operation of this reactor for one year produces about 100 kilograms of fission products. On the basis of $10^{-7}$ mg/cm$^3$ this can contaminate $10^6$ cubic kilometers of air to tolerance. Said another way, a layer of air one km deep covering an area 1000 km on a side could be brought to tolerance level.

Another feature of radioactive poisons is that a lethal level is not detectable by human senses. Furthermore, very serious injury may not be detected for some years after exposure.[2]

## ESCAPE OF RADIOACTIVITY

The way in which reactors can malfunction and lead to the escape of fission products may be classified as follows: (1) a super-critical nuclear excursion or nuclear runaway; (2) melt-down of reactor components, even with the chain reaction shut down, because of the delayed heat produced by the radioactive fission products; and (3) possible exothermic chemical reactions among the components of the reactor itself. The latter, although it is clearly not present if the machine is operating normally, may be initiated by a runaway nuclear chain reaction or by delayed heat melting.

These problems will be discussed in more detail below. The first two are unique to nuclear reactors as compared to other power sources, and have no true analogue in other areas of technology. They are discussed in some detail, for research reactors,[6] and nuclear power plants[7] elsewhere.

## THE PROBLEM OF NUCLEAR RUNAWAY

An outstanding characteristic of nuclear reactors is their potential ability to achieve extremely high power levels in a short time if adequate control of the machine is lost. A typical nuclear runaway accident may start and be over in times appreciably less than a second. In this respect they are different from any other large-scale machines, and it is this extremely short time that makes it quite important that automatic control and safety systems be available, be reliable, and be relatively rapid in their operation.

Another feature of a possible nuclear runaway is that it does not seem to be very violent. A comparison between a nuclear reactor and an atomic bomb is very misleading and certainly not to the point. From a number of studies of possible reactor accidents of this type, it must be concluded that even though reactor accidents could happen quite rapidly in terms of human reaction times and conventional external emergency human actions, nevertheless, a nuclear reactor is a very sluggish device and does not produce a nuclear explosion even remotely approximating that of an atomic bomb. Indeed, for the large thermal reactors, nothing like an explosion really occurs. For very fast reactors with a non-thermal neutron spectrum and heavily loaded with enriched uranium, it does appear possible to have an accident which is fast enough so that portions of the machine may be propelled with velocities of a few meters per second. This again does not resemble an atomic bomb explosion, or even the explosion of ordinary chemical explosives; rather it is similar to the events that might occur in an automobile accident. Therefore a nuclear runaway, in itself, does not represent a serious hazard to off-site people.

Table II. Delayed Heat Power and Radioactivity* after Normal Shutdown

| *Time after shutdown* | | *Activity level from a previous steady heat power of:* | | | |
|---|---|---|---|---|---|
| | | *300 kw activity as:* | | *250,000 kw activity as:* | |
| *sec* | | *kw* | *curies* | *kw* | *curies* |
| 10 | 10 sec | 12.9 | $2.1 \times 10^6$ | 11,000 | $1.8 \times 10^9$ |
| $10^2$ | 1.7 min | 8.0 | $1.3 \times 10^6$ | 6800 | $1.1 \times 10^9$ |
| $10^3$ | 16.7 min | 5.2 | $8.4 \times 10^5$ | 4300 | $7.0 \times 10^8$ |
| $10^4$ | 2.8 hr | 3.3 | $5.3 \times 10^5$ | 2700 | $4.4 \times 10^8$ |
| $10^5$ | 28 hr | 2.0 | $3.3 \times 10^5$ | 1700 | $2.8 \times 10^8$ |

* The radioactivity figures are for fission products only (do not include radioactive fuels or components). It is assumed that the mean decay event corresponds to 1.0 Mev in converting from kw to curies.

However, as pointed out above, a nuclear runaway can serve to do two things: It may disrupt the structure of the reactor sufficiently so that radioactive poisons may escape, or it may lead to exothermic chemical reactions between different components of the reactor core, and a chemical explosion of considerable violence. Indeed, for certain types of reactor structures, it would appear that the chemical reaction that might follow a nuclear runaway would produce substantially greater energy and violence than the runaway which preceded it.

In order to make some of these notions more quantitative, it is convenient to talk about the rising period of a nuclear reactor. A nuclear reactor which is supercritical increases in power level by a factor of $e$ at each interval of time corresponding to the so-called $e$-folding time. In turn, the $e$-folding time is related to the intrinsic neutron generation time of the reactor, and the degree of supercriticality, by the so-called in-hour equation. In Fig. 1, a number of curves are shown connecting the rising period of the reactor with its excess reactivity, i.e., the fraction of excess neutrons produced in one generation. The $e$-folding times shown in the figure are relatively long. This is due to the delayed neutrons. As you all know, the fission event produces certain fission products which, in turn, after periods ranging up to 80 seconds,

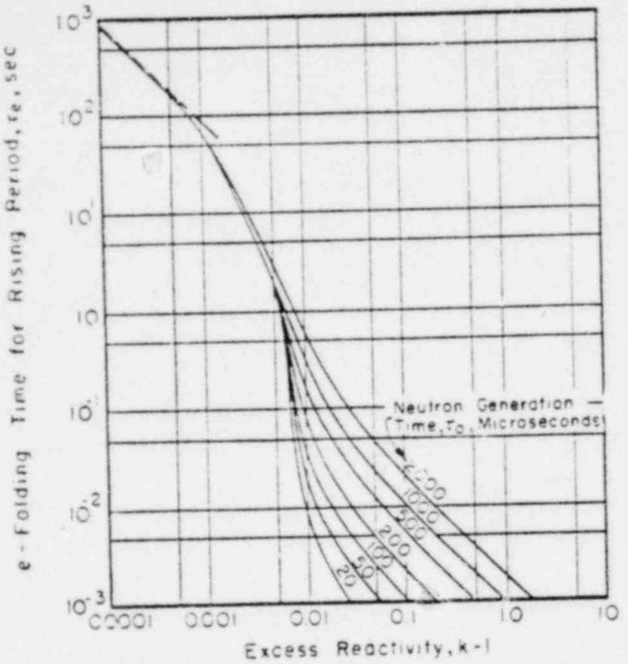

Figure 1. Variation of rising period with excess reactivity from the inhour equation:

$$k - 1 = \frac{\tau_0}{\tau_e} + k \sum_i \frac{\beta_i \tau_i}{\tau_e + \tau_i}$$

emit delayed neutrons. The fraction of these delayed neutrons produced in $U^{235}$ fission amounts to something like ¾% of all neutrons produced. If one makes the excess reactivity of the reactor so great that the chain can proceed without the delayed neutrons, then the reactor is said to be in a prompt critical condition, that is it is critical or even supercritical on prompt neutrons alone. In this condition the *e*-folding time becomes short and one may estimate it by means of the equation:

$$\frac{1}{\tau_e} = \frac{k_{ex}}{\tau_0}$$

In this equation, $\tau_e$ is the *e*-folding time, $\tau_0$ is the intrinsic neutron generation time which depends on the type of reactor, and $k_{ex}$ is the excess reactivity above prompt criticality.

Typically, neutron generation times are about one millisecond for large thermal reactors, something like 1/10 millisecond for water boilers and small thermal reactors, and may be as short as a microsecond or less for fast-spectrum epithermal machines. The value that one may assign to $k_{ex}$ depends on the type of machine and its requirements for excess reactivity in order to conduct experiments, overcome temperature effects, allow for burnup of the fissionable material, or override fission-product poisons. However, it seems reasonable to assume an excess *k*-value of about 0.01 fraction for terms of discussion. If this is done, then an *e*-folding time for the large thermal machines of 1/10 second is obtained. Only seven *e*-folding times, that is 7/10 second, are required in order to increase the power level of the machine by a factor of 1000. For machines with shorter neutron generation times, the *e*-folding times are correspondingly reduced. Here one may say that nuclear reactors represent a genuine departure from conventional power sources in that enormous power level increases are possible in the event of mal-operation in remarkably short times.

The Safeguard Committee has urged the development of automatic fuses which would prevent a nuclear runaway in case the reactor gets out of control. These fuses are expected to have two characteristics. First of all, they should be self-contained and wholly automatic so that they are not subject to error of adjustment or maintenance and are not subject to intentional tampering. Second, these fuses are to be activated by changes in the power level, essentially changes in the flux level of the nuclear reactor, and have rapid enough response so that they will introduce a substantial negative reactivity in the reactor in a time of the order of one second or less. One of the continuing difficulties in the development of these fuses is this latter requirement for short-time operation. It appears that successful development of such a fuse will soon be achieved, but because of the short-time requirement this development is neither easy nor simple.

As a matter of practical fact, one must consider how a large excess reactivity might be achieved in a nuclear reactor.[6] First of all, it is clear that it can not really be achieved instantaneously although something analogous to instantaneous excess reactivity can be obtained on startup of a reactor if only a weak source of neutrons is used during the startup procedure. It is then conceivable that through some error, rapid removal of control rods would allow the reactor to be highly supercritical before the power level had risen to something approaching the normal power range. For this reason, startup accidents are particularly to be avoided.

In any event, one must consider not only the possible degree of excess reactivity but also the rate at which reactivity may be added to the machine. For this reason, one would like safety rods and shim rods that move out rather slowly but which could be re-inserted rapidly at any point during withdrawal.[§]

One would also like the degree of control residing in the control and safety system to have a graded weight so that as the reactor becomes nearly critical, only smaller amounts of reactivity are introduced by the withdrawal of control rods. Safety rods which must be completely withdrawn and cocked before they may be re-inserted are particularly undesirable.

There is another point which is quite pertinent in the serious consideration of how rapidly excess reactivity might really be added to a given nuclear reactor. Extremely fast reactors, for example, look

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[§] In order to avoid circumlocution, all remarks concerning control and safety systems will be made as though these were conventional absorber systems. Of course it is entirely possible to increase the reactivity of a reactor by inserting fissionable material instead of withdrawing an absorber or by changing the characteristics of a reflector. Our discussion will assume that all controls are of an absorbing type.

particularly dangerous because of the very short *e*-folding time that one can achieve with modest excess reactivity. However, part of this danger is spurious because the reactor will become supercritical enough to run through a complete runaway accident before very much excess reactivity can be added by ordinary methods of operation of controls. Only very sudden motion of the control rods, motion so rapid that it would have to be induced by special pneumatic systems could lead to a rapid, explosive type of accident with these fast reactors. For this reason, a careful study of the possible rate of reactivity increase, rather than the total potential excess reactivity available, should be carried out when the nuclear runaway problem is considered.

It seems that the prevention of nuclear runaway accidents is very closely associated with the problem of excess reactivity and the rate at which excess reactivity might be added to a given machine. This in turn depends on the technical details of any given machine, both in its neutronic behavior and in the operation of control devices and possible other ways of changing the reactivity, perhaps because of the presence of experimental irradiation facilities. This is not a problem that can be generally solved for all machines, but each machine must be studied on its own merits.

We will now turn to the characteristics of a nuclear runaway, assuming that it is actually underway. As pointed out above, a nuclear runaway is not particularly violent but it does take place in a remarkably short time. The runaway will proceed according to the following steps. First of all, excess reactivity is inserted, the reactor then rises exponentially in power level with a nearly constant *e*-folding time until enough energy is accumulated in the structure to affect the behavior of neutrons. These early effects are characterized by the term, temperature coefficients of the reactivity. These may be either positive, that is making the reactor more reactive, or negative, making the reactor less reactive and tending to shut it down. If an increase in power level tends to make the reactor more reactive and increase the power level not only further but make the further increase more rapid, one sometimes says that this is an autocatalytic reactor. Such a reactor appears to be particularly dangerous, and can possibly achieve really short *e*-folding times. A few strongly autocatalytic reactors are known. For most reactors, negative reactivity coefficients will take effect and lead to a lengthening in the *e*-folding time.

Finally, a third phase of the runaway will occur when enough of the reactor structure is actually melted, vaporized or otherwise affected (in most cases reactivity coefficients will not be adequate to shut the reactor down without destructive effects, although for some reactors this will indeed be the case), and these destructive effects will shut down the nuclear chain reaction and stop the runaway.

Since the negative reactivity coefficients can lead to shutting off the nuclear accident without destructive effects, a few words about these coefficients may be desirable. First of all, large negative reactivity coefficients are clearly wanted. However, these coefficients must be quick acting, able to take effect and shut down the reactor during the transient conditions of a runaway. Primary changes in temperature are caused by the generation of fission heat in the fuel elements. Heating of the fuel elements may change the reactivity of the machine negatively if the fuel elements contain large quantities of $U^{238}$. This negative change is due to the increased absorption of resonance energy neutrons by Doppler broadening of the $U^{238}$ absorption resonances. For large lumped thermal reactors, this effect amounts to about $10^{-5}$ fraction of reactivity per degree C temperature rise.

A secondary reason for the temperature coefficient is the heating of the moderator. In many reactors, this will beneficially reduce reactivity. However, the time for heat to flow from the hot fuel elements to the moderated portion may be sufficiently long, several seconds to a minute in some cases, so that although the moderated temperature coefficient is favorable, it does not have time to come into play during a nuclear runaway. For example, the thermal diffusion time across a four-inch thickness of graphite-moderator in a large lumped thermal machine is nearly a minute. This time is so long that the coefficient associated with moderator heating plays no part during the runaway.

One of the important technical areas associated with understanding nuclear runaway behavior of a reactor is that of heat transfer under transient conditions. Relatively little knowledge in this area has been available because most heat transfer studies are conducted under steady-state conditions.

It appears likely that a nuclear runaway will cause enough disruption of the reactor structure so that fission products will start to leak out of the reactor into the surrounding area. How fast this escape of fission products will be depends upon the type of reactor and type of reactor accident. It may be possible to show that there will be very little mechanical violence outside the reactor shield, so that if the building which houses the reactor can be made gas-tight, then escape of fission products to areas outside the reactor building can be greatly reduced. We wish to emphasize that in most cases the building need only be gas-tight and not explosion-proof.

## DELAYED ENERGY PRODUCTION

Nuclear reactors have another somewhat unfavorable characteristic. Because of the accumulated fission products, and the accompanying exothermic radioactive transformation of these fission products, a nuclear reactor will continue to produce heat even when the nuclear chain reaction is shut down. The energy produced by the fission products has been studied, and the result for power production in the reactor which has been operating for a long time may be summarized in the following equation:

$$P_{delayed} = 0.07\, P_{normal}\, [t(\text{sec})]^{-0.2},\ t > 1 \text{ sec}$$

Here $P_{normal}$ is the normal operating power level of the reactor, $P_{delayed}$ is the delayed heat power level of the reactor in the same units as the normal power level, $t$ is the time in seconds, and the 0.07 is an experimentally determined coefficient. Although the fission products individually decay exponentially, the result of their statistical production is to make this delayed heat decay with the relatively weak power law indicated. For about one second after the reactor is shut down the delayed power level is approximately 7% of the normal power level.

The delayed heat problem is clearly a serious one. If some failure in the cooling system should occur, breakdown of pumps loss of pumping power, mechanical failure of cooling piping, then even if the nuclear chain reaction is immediately shut down by inserting control or safety rods, there will still be left a substantial heat load which must somehow be disposed of.

For example, if the fuel elements from the Materials Testing Reactor were suddenly removed from the reactor and left standing in the open air, they would melt down by themselves by delayed heat production. If they were suddenly immersed in water, probably this melting would not take place.

One may consider the delayed heat problem from the point of view of suddenly stopping forced cooling in the reactor and also suddenly stopping the chain reaction. The fuel elements, and other materials in the reactor in close thermal contact with the fuel elements will then start to increase in temperature. The rate of temperature rise will be proportional to the preceding steady power level of the machine, and the rate of temperature rise will be reduced if there is a large heat capacity in intimate thermal contact with the fuel elements. In fact, since the rule of du Long and Petit indicates that the heat capacity of solid materials is proportional to the number of atoms they contain, a crude rule of thumb would state that the rate of temperature rise is proportional to the power of the reactor per atom of material in good thermal contact with the fuel elements. The simple expression we have given for the delayed power indicates that the time rate of temperature rise should be proportional to the 0.8 power of the time. In Fig. 2 are curves showing the rate of temperature rise following uncooled shutdown from normal operation for a few reactors.[9] One concludes that this temperature rise, although not so rapid as to constitute a sudden event in terms of human reaction times, is nevertheless rapid enough to be quite troublesome. In Table II are summarized some delayed heat power levels.

Three types of preventive designs are suggested. One is to have a standby emergency cooling system which works either by gravity flow of coolant or by natural convection. Another is to have standby emergency arrangements of some sort which might be rather analogous to fire-fighting equipment. The "fire-fighters" would then approach the reactor and make suitable connections and force through emergency cooling. A third possibility is to have standby forced convection cooling similar to the main cooling system but connected to a special power supply and with special separate piping.

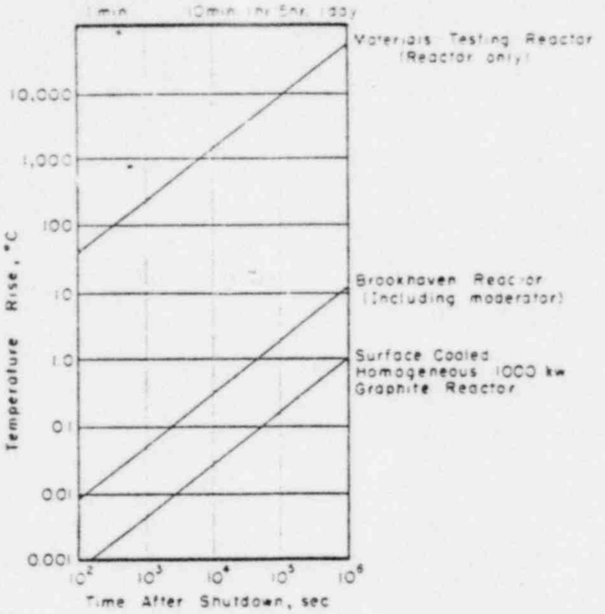

Figure 2. Calculated temperature rise after shutdown of the chain reaction. (Heat capacity assumptions are indicated.) (Courtesy of W. H. Zinn, Argonne National Laboratory)

It is clear that a delayed accident, if it could not be brought under control, might very well lead to sufficient disruption of the reactor core to allow fission products to escape. It is also clear that this again will not be of itself a very violent event, and again as in the case of the nuclear runaway it is probable that an accident of this kind can be minimized a good deal by providing a gas-tight building around the reactor.

## CHEMICAL REACTIONS

Either a nuclear runaway or a delayed heat accident may cause considerable melting and mixing of reactor components and lead to exothermic chemical reactions between these components. A simple example of this type is that of an air-cooled graphite reactor. A sudden temperature rise in the uranium fuel may be sufficient to cause it to melt and heat the adjacent graphite so that both the uranium and graphite can burn in the cooling air. If the air supply is not turned off, it is likely that a substantial portion of the reactor could be consumed in this way. This would then disperse radioactive fission products into the surrounding area through the exhaust portion of the cooling system.

Another example is that of a heavy-water-moderated-and-cooled natural uranium reactor. In a machine of this sort a runaway accident could melt the uranium and allow it to mix intimately with the water. In this case the thermodynamic potential indicates that an exothermic chemical reaction can take place. Whether or not such a reaction would be rapid and violent is not clearly known. In this case one has to deal with the chemical kinetics of a heterogeneously reacting chemical system (among other things the probable degree of dispersion of the uranium into the water is not known). Presumably, the rate will depend upon the intrinsic molecular kinetic process in the conventional chemical sense, but it will also depend upon the degree of dispersion of the uranium into the water, the rate at which reacting molecules can diffuse through the uranium oxide layer that would be formed between the uranium and the water, and the degree of turbulent mixing and scrubbing of the two reactants against each other. This latter effect might be generated by the reaction itself. This is clearly a complex problem and a great deal more needs to be learned. However, one can say this: If an exothermic reaction of this type goes to completion, the resulting energy release will nearly always be substantially greater than the energy generated in a preceding nuclear runaway. Thus it is important to determine the possible chemical reactions. A substantial increase in reactor safety can be achieved by the elimination of possible reacting components in the reactor structure.

## SAFE DESIGNS

It seems worth while to summarize the preceding discussion with a few remarks concerning the approach to safe reactor designs. First of all, it is desirable to provide a large negative reactivity coefficient. This can usually be achieved by thermal coupling of the fuel elements to those portions of the reactor which give a substantial reduction to the neutron multiplication when heated. For example, in the case of enriched, water-moderated reactors, close thermal contact between the fuel elements and the moderated water can lead to enough heating and vaporization of the water to reduce the water density in the event of a nuclear runaway, and shut down the reactor before serious damage is done. Successful tests of this sort have been made.[10] A design of this sort must be thought through carefully in order to make sure that enough heat transfer surface is available and rapid enough heat flow will take place to shut down a machine during an accident.

The control system must be carefully designed so that in the event of too high a power level, too high a rate of rise of power level, a serious reduction in coolant flow, or any major failure of fuel elements, the reactor will shut down in a time interval small enough to minimize damage. All potentially dangerous failures should be monitored by instruments and control channels leading to shut-down or "scram." These monitors and channels should be at least in duplicate, independent of each other, and preferably of different types. In addition, particular care should be taken that a failure cannot put the controls out of operation.

In order to prevent a delayed heat accident, it is important that enough natural convection heat transfer can take place in the overheated core to dispose of the delayed heat, perhaps just into the ground. Even if the structure is damaged, one must try to keep the temperature lower than that temperature which would start a substantial pressure rise in the reactor structure. In that case, the fission products may be kept inside the reactor shield. This means that some coolant contained in the core should have a large surface to which it can transfer heat by natural convection or by boiling convection, and that this degree of cooling should be sufficient to keep the bulk of all volatile materials below their boiling points. It may be remarked that boiling heat transfer is known to be especially efficient, so that in any event there will tend to be a ceiling put on the temperature rise at about the boiling temperature of the original coolant employed. This in turn implies that by appropriate construction one may limit the pressure inside the shield to a few atmospheres. Thus it may be rather easy to make sure that the fission products are kept inside the shield.

Finally, the problem of chemical reaction among reactor components can often be minimized. For example, already-reacted components might be used in some cases. Uranium oxide rather than uranium metal in an air- or water-cooled reactor may serve as an example.

The other general conclusion that the Safeguard Committee has come to is that explosive hazard in reactor accidents is minor, at least for people not at the reactor site. Indeed, for many reactors, it appears unlikely that there will be much mechanical violence external to the reactor shield. For this reason, a gas-tight building, or a moderately gas-tight building which may confine the fission products during a cooling period and from which the fission products are exhausted into scrubbers and out a high stack, may serve to prevent the spread of fission products following a reactor accident. For some reactors the confining building will have to be a gas-tight pressure vessel. Safe-design procedures represent an important field of nuclear reactor development.

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## ADMINISTRATIVE CONTROL

Although good administrative control of the reactor does not lead to the same degree of confidence in the good behavior of the machine that intrinsic gremlin-free built-in stability does, nevertheless, good administrative control does enhance the safety and reliability of reactor operation. Indeed, good administrative control is mandatory for those people who have an economic stake in the reactor. From the point of view of public hazard, careful reactor operation and maintenance makes it very much less likely that there will be a reactor accident.

However, this administrative control should not start just when the reactor is put into operation. Throughout the design and construction of the reactor, thorough supervision, careful design for reliability, and thorough testing of all reactor components including coolant system, off-gas systems, shims, safety and control mechanisms, and all control and operating instrumentation should be carried through. All these components should be given systematic and thorough shakedown testing before the reactor is put into operation and before it becomes radioactive so that modification, correction, and maintenance can be done with less difficulty. Indeed, it is extremely difficult to emphasize how important it is to have complete, thorough, systematic shakedown of all portions of reactor control and instrumentation.

In the design of the reactor, careful attention should be given to the problem of maintenance after it is placed in operation. It should be possible to enter all instrument areas, most of the control areas, and obviously the central control room, after the machine has started up and been operating for some time. Fuel-element failure, a continuing problem, may allow radioactivity to enter portions of the reactor structure which normally would be expected to be radiation-free. This should be taken into account in the original design.

Once the reactor is placed into operation, continuing close supervision is essential. Maintenance procedures should be carefully followed and maintenance checks should be scheduled in an appropriate way. The period of reactor startup is a particularly critical one, and should be followed very closely. Reactor loading and unloading are delicate operations, particularly the unloading of now-radioactive fuel elements. Startup of a reloaded reactor must be carefully considered since the reactivity may have been affected by a new fuel loading. The normal, or routine, day-to-day operation requires close supervision so that troubles may be detected at an early date and corrective measures taken. Clearly, careless operation of the controls may lead to a supercriticality accident and the manipulation of the controls should be carried out only by people who are thoroughly familiar with the characteristics of the reactor and its associated equipment.

If a reactor is employed as an irradiation facility, it is possible for experiments to give rise to sudden changes of reactivity. Experiments should be planned, the plan reviewed by the administrative staff, and suitable emergency procedures decided upon, before inserting experiments into the reactor.

Finally, there is one phase of the administratively controlled reactor which is usually taken for granted but may require a word or so: The careful accounting for all materials which have been irradiated in the machine. There is usually available a number of test holes in which experimental irradiations may be carried out. The samples so irradiated can be highly radioactive and should not be allowed to accumulate unduly, or to be lost, or to be handled in an irresponsible manner.

## CONSEQUENCES OF AN ACCIDENT

We believe the following discussion outlines the main features which can make a nuclear incident dangerous. In the event of a reactor accident, there will probably result a release of radioactive material from the reactor. Operating personnel may be seriously injured or perhaps even killed. The reactor itself may be damaged beyond repair or recovery. The reactor building and its associated equipment are very likely to be heavily contaminated and indeed, it may not be possible to clean up the building sufficiently to put it into operation again. Design of the building so that possible cleanup operations are as easy as possible is desirable.[11] Smooth, clean surfaces, perhaps clad in stainless steel, would make cleanup operations easier. Finally, radioactive materials can escape from the reactor site altogether. Fission products may be carried in the wind and spread over adjacent populated areas and constitute an acute hazard. Radioactive material may escape into the ground and be carried by the percolating ground water to adjacent rivers or other water supplies. Although a great deal needs to be known about the character of radioactive material that might escape from a reactor, whether it is in large or small particles, whether it is indeed gaseous, whether it would rise high into the air or seep slowly along and into the ground, nevertheless, some notion of the possible spread of the hazard could be obtained by study of the meteorology, and hydrology at the reactor site.[12,13,14] It is desirable, for example, to have the prevailing wind to blow from the reactor to uninhabited areas. It is also desirable to have the reactor site not be located on a main watershed. From the point of view of the hazard alone, it is of course desirable to have the reactor site far from populous or vital industrial areas. It will not always be possible to obtain this remote location and still obtain economic utility from the reactor. For this reason, the Safeguard Committee is continuing to emphasize the importance of safe reactor designs, the development of contained fuses to minimize the possibility of a runaway accident, and the use of gas-tight containing vessels and buildings.

Perhaps it is important again to emphasize the degree of public hazard that might follow a reactor accident. Assuming that good luck prevails and no one is killed, it may nevertheless be necessary to evacuate a large city, to abandon a major watershed, and very probably it would be necessary to make the reactor site itself a forbidden area for some years to come.

Despite all these possible dire consequences, it is the belief of the Advisory Committee on Reactor Safeguards that nuclear reactors will soon start to produce substantially increasing material benefits for humanity. We believe that useful electric power in large quantities can be generated by nuclear reactors. It is our concern that rapid progress shall be made but that enough caution be observed so that no catastrophic event will delay the fruition of reactor development.

## APPENDIX. THE ADVISORY COMMITTEE ON REACTOR SAFEGUARDS TO THE UNITED STATES ATOMIC ENERGY COMMISSION

The Advisory Committee on Reactor Safeguards was formed by combining the Reactor Safeguard Committee and the Industrial Committee on Reactor Location Problems. At this time members are: M. Benedict, Massachusetts Institute of Technology; H. Brooks, Harvard University; W. P. Conner, Jr., Hercules Powder Company; R. L. Doan, Phillips Petroleum Company; H. Friedell, Western Reserve University; I. B. Johns, Monsanto Chemical Company; C. R. McCullough, Chairman, ACRS; M. M. Mills, University of California Radiation Laboratory; K. R. Osborn, Allied Chemical and Dye Corporation; D. A. Rogers, Allied Chemical and Dye Corporation; C. R. Russell, Secretary, ACRS; R. C. Stratton, Travelers Insurance Company; E. Teller, Department of Physics, University of California; H. Wexler, United States Weather Bureau; and A. Wolman, The Johns Hopkins University.

The Reactor Safeguard Committee was formed in 1947, and the Industrial Committee on Reactor Location Problems was formed in 1949. The following were also associated with these committees for prolonged periods: Cmdr. J. Dunford, US Atomic Energy Commission; Col. B. Holzman, US Air Force; J. Kennedy, Washington University, St. Louis; F. Seitz, University of Illinois; G. Weil, formerly Division of Reactor Development, US AEC; and J. A. Wheeler, Princeton University.

## REFERENCES

1. Teller, E., testimony, *Atomic Power Development and Private Enterprise*, Hearings before the Joint Committee on Atomic Energy, 83rd Congress, 1st Session, June-July 1953 (Govt. Printing Office, Washington, D. C.).
2. Weil, G. L., *Hazards of Nuclear Power Plants*, Science *121*, No. 3140, 315 (1955).
3. Morgan, K. Z. and Ford, M. R., *Developments in Internal Dose Determinations*, Nucleonics 12, No. 6, 26 (1954).
4. Teller, E., *Reactor Hazards Predictable*, Nucleonics *11*, No. 11, 80 (1953).
5. McCullough, C. R., *General Criteria for Safe Reactor Design and Operation*, ASME Annual Meeting, Nov. 28–Dec. 3, 1954. ✓
6. Mills, M. M., *Hazards of Low Power Research Reactors*, Proc. 3rd Annual Oak Ridge Summer Symposium, TID 5031 (Technical Information Services, Oak Ridge, Tenn., 1951).
7. Hurwitz, H., Jr., *Safeguard Considerations for Nuclear Power Plants*, Nucleonics *11*, No. 11, 80 (1953). ✓
8. Way, K. and Wigner, E. P., *Radiation from Fission Products*, Phys. Rev. *70* 115 (1946).
9. Zinn, W. H., Private communication.
10. Dietrich, J., *Experimental Determination of the Self Regulation, and Safety of Water Reactors*, P/481, Vol. 13, International Conference on the Peaceful Uses of Atomic Energy, August 8–20, 1955.
11. Gilbert, F. W., *Decontamination of the Canadian Reactor*, Chem. Eng. Progr. *50*, 267, (1954).
12. Fitzgerald, J. J., Hurwitz, H., Jr., and Tonks, L., *Method for Evaluating Radiation Hazards from a Nuclear Incident*, KAPL-1045 (Knolls Atomic Power Laboratory, Schenectady, N. Y., 1954). Available from the Office of Technical Services, U. S. Dept. of Commerce, Washington, D. C.
13. Fitzgerald, J. J., Hurwitz, H., Jr. and Tonks, L., *Reactor Exclusion Areas*, Nucleonics *12*, No. 3, 75 (1954) and *12*, No. 4, 78 (1954).
14. Mesler, R. B., and Widdoes, L. C., *Evaluating Reactor Hazards from Airborne Fission Products*, Nucleonics *12*, No. 9, 39 (1954).

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# Proceedings of the International Conference
## on the
# Peaceful Uses of Atomic Energy

Held in Geneva
8 August - 20 August 1955

## Volume 13
## Legal, Administrative, Health and Safety Aspects of Large-Scale Use of Nuclear Energy

UNITED NATIONS
New York
1956