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INTEGRAL SAFETY DEVICES FOR REACTORS

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The impetus for development of an integral type, self-actuating reactor safety device derives from the fact that conventional safety mechanisms, in which a mechanically rigid neutron absorber is stored outside the active region, can become inoperable through any of several events such as core shift or failure of external circuitry. The ideal device should be independent of external circuitry and mechanical linkage. Triggering should be effected more or less directly by any dangerous increase in the rate of fissioning, perhaps also by loss of reactor coolant or other conditions detrimental to the reactor.

An integral safety device for a low-temperature, water-cooled, graphite-moderated thermal reactor has been designed and tested. This safety device operates on the principle of changing the geometry of a stored poison - gaseous BF_3 - in such a way as to increase its reactivity effect. The gas is stored in a relatively small high-pressure chamber; after triggering, it expands into a much larger chamber. The trigger is a fission-heated section of a gas-release tube in which is placed a tin-silver eutectic solder plug. At normal reactor power level, the fission heat is transferred to the coolant by a path of a chosen thermal resistance such that the solder plug is maintained at a temperature well below its melting point.

The response time of the device, defined as the time interval between reactor power and fuse temperature reaching trip level, was found to be a function of reactor period and of the same order of magnitude as the reactor period. Additional time for release of the gas, between fuse melting and the instant when the reactivity effect is 90% of maximum, was measured at 150 milliseconds. Reactivity change for a single unit is about 1.5 inhours. The device is specifically designed for a particular reactor type characterized by large size and slow response due to long prompt neutron lifetime; therefore, a large number of units would be needed.

As a program growing out of the above work, integral safety devices for both research reactors (or critical-assembly facilities) and power reactors are under development. The principal problems are, in the former, fast response and, in the latter, operability over a large range of ambient temperature. A first approach for research reactors uses an electronic signal from a reactor instrumentation channel to fire an explosive that releases boron trifluoride, stored in the reflector region, into the core region. This device has been demonstrated to shut down a super-critical reactor within 7 milliseconds after the trip point was reached, a time short enough to preclude damaging excursions for almost any research reactor.

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A device for high-power research reactors uses the first concept mentioned, that of a fission-heated solder plug to release poison. This device, which has a gas-release time of less than three milliseconds, has not yet been tested for total response time. If fast enough, it will offer the additional advantage of being completely self-contained.

These concepts, and the test results to date, give promise that integral, self-actuating safety devices can be developed which will ensure almost any type of research or power reactor against dangerous or seriously damaging excursions.

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INTEGRAL SAFETY DEVICES FOR REACTORS

by S.H. Fitch, N.E. Huston, N.C. Miller, and A.J. Saur*

I INTRODUCTION

It is envisioned that nuclear energy will be a boon to mankind, representing a potentially enormous source of power for his ever increasing demands. Nuclear reactors are powerful tools in industry, education, research, medicine, and other fields, in addition to their utility as a source of power. However, the fullest potential of nuclear energy will not be realized unless it is made and proved safe. A serious accident could conceivably delay the utilization of this power source by causing adverse public opinion and overly cautious restrictions with regard to design, siting and operation of nuclear reactors. Although the possibility of a serious incident is considered to be rather small for present reactors, as long as the probability does exist, the question of reactor safety will be of considerable importance.¹

Of primary concern is the safety of the general public, reactor operating personnel, and the reactors themselves. The greatest hazard to personnel is the accidental escape of fission products from the fuel material. Power reactors in particular may have large quantities of these radioactive isotopes contained in the core. The accidental release of these fission products as a radioactive cloud could cause death or injury to a great number of persons.² The likelihood of accidents of this type must be made extremely small.

The greatest hazard to the reactor itself is a destructive explosion, caused either by the heat released in a power excursion or by a chemical reaction between the fuel material and the reactor coolant. Accidents of this nature present a radiation hazard in addition to a costly cleanup and repair operation. With capital investments of millions of dollars, reactor "down time" alone represents a considerable expense.

An important goal of nuclear reactor design is the achievement of an inherently safe reactor. There are a number of reactor designs that do have inherent safety features such as a negative temperature or power coefficient of reactivity. In solution type reactors, radiolytic dissociation produces gas and decreases the system reactivity as the power level rises.³ It is also possible to use excess heat to cause boiling in the moderator⁴ or in melting fusible links⁵ in fuel elements to cause core separation. However, in any case where a quantity of material must be heated or a quantity of heat must be conducted to a shutdown mechanism, the system may be too slow to prevent serious damage.⁶

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The primary aspects of safe reactor operation which must be considered are excessively high values of neutron flux, excessively short period of flux increase, and diminishing flow of the reactor coolant. Ordinarily the safety of a reactor is provided by a control and safety system in which the control elements are returned to their least reactive positions when adverse conditions prevail. A high degree of safety can be attained by having any possible malfunctioning of equipment cause a scram, i.e. make the system completely "fail safe". Such systems can become extremely complicated, however, and result in an extensive loss of reactor operating time due to component failure. A system that is too complex can lead to the bypassing of safety interlocks, a procedure that has led to reactor accidents.

The response time of a scram system can be a critical parameter, particularly in reactors having very short prompt neutron lifetimes. Reduction of the response time represents a design complication, because the degree of complexity and consequent loss of reliability increase rapidly with decreasing response times.

Assuming proper operation, a control and safety system affords adequate protection. However, consideration must be given to the possibility of the simultaneous occurrence of system failure and a hazardous reactor condition. If the system were caused to be inoperative by earthquake or some other disastrous condition, the reactor would be without any protection from destructive transients.

There is a need to supplement conventional safety mechanisms and control systems to provide the ultimate safety. Independent, integral, self-actuated safety devices offer the possibility of providing this kind of reactor protection. Although no such devices have been completely tested and proved as yet, recent development work indicates that they do offer the promise of greater reactor safety. There is a program at Atomics International to develop integral safety devices for reactor protection. This paper is concerned with the history of this program and its accomplishments to date.

II SAFETY DEVICE DESIGN CONSIDERATIONS

Reactor safety devices should have two major characteristics. First, they should be self-contained and completely automatic so that they are not subject to error of adjustment or maintenance nor to intentional tampering. Second, they should be actuated by changes in reactor power level and introduce a substantial amount of reactivity in a short time. Some other general requirements are that the safety devices must be fail safe, reliable, and bomb and earthquake proof. If the ultimate safety of a reactor is to be provided by a safety device, it must cause reactor shutdown if it fails, i.e., it must be "fail safe". It must operate in a reliable manner, trip quickly at the proper time and yet be insensitive to small changes in power level. It should cause reactor shutdown under the most adverse conditions and yet cause little "stored state" reactivity loss.

There are two types of dangerous situations for which safety devices should afford protection. Reactor shutdown should be initiated when a preset flux, power, or temperature level is exceeded and also when an excessive rate of change of one of these variables occurs.

Safety devices ordinarily comprise the following group of components: a neutron sensor, a trip mechanism, a stored energy source, and a stored poison. The sensor detects the dangerous situation and converts the measured quantity into a form of energy that will actuate the trip mechanism. The trip mechanism is the means of releasing the stored energy which propels the poison from its stored state location to a location where it is more effective in absorbing neutrons.

A number of self-actuated reactor safety devices have been reported in the literature,^{7,8} but study has revealed failings in most. Analysis indicated that metallic differential expansion elements would be unsatisfactory because of the long response times involved. The solder-joint type of trigger element seemed feasible where the ambient neutron flux level was greater than $5 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$. Gas expansion elements appeared feasible for mechanisms with small energy requirements, such as for making electrical contacts. Consideration was also given to the use of momentum transfer of fission fragments, thermopiles using fission heat, radiation-damage elements, and ionization-sensitive devices. These ideas were set aside for a variety of reasons. The magnitude of the effect of momentum transfer required too delicate a design. Thermopiles were thought to be not easily adaptable to fail-safe designs. The use of radiation damage did not look promising because of long response times and ionization-sensitive devices seemed to suffer from inconsistent breakdown points.

III SAFETY DEVICES FOR PRODUCTION REACTORS⁹

The Hanford production reactors¹⁰ are large thermal reactors that are natural uranium fueled, graphite moderated, and water cooled. The core consists of a large parallelepiped of graphite, penetrated by many horizontal process tubes containing the fuel. The fuel is in the form of cylinders clad with aluminum, many of which occupy each process tube. There is a small annulus between the fuel slugs and the process tube through which the coolant flows.

The primary requirement of any safety device is that it protects against excessive neutron flux or power levels. However, in these reactors, another accident to be considered is the loss of coolant, either to a single channel or to the whole reactor. Loss of coolant, in addition to providing positive reactivity change, would result in a rapid increase in fuel temperature, which could result in damage to the channel or to the reactor and its environs.

A. POISON COATING SAFETY DEVICE

At the start of the safety program an investigation was made into various means of introducing poison into the reactor. It would be desirable to have this poison located outside the high flux region until after tripping occurred to minimize the "stored state" production loss. A method which would satisfy these conditions was to inject into the coolant passages a poison material that would coat out upon the coolant tube with coolant either present or absent.

The use of a fission heater as a sensor in connection with a fusible alloy as trip mechanism or "fuse" lent itself to actuation either by excess neutron flux or loss of coolant. Other components were a pressurized gas as the stored energy source, and a poison-bearing coating material as the

neutron poison. The solder plug in the trigger was to fail at some predetermined trip point, allowing the high-pressure gas to expand into the poison-storage chamber. Here the increased pressure would rupture a retaining diaphragm and force the poison material into the coolant passages where its neutron absorption would be more effective in shutting down the reactor. Approximately 500 elements would be required in a reactor loading because of the small reactivity effect of a single element.

The two major problems of this system were those of creep in the solder trigger and of obtaining a satisfactory coating material. Accordingly, an experimental program was undertaken to investigate these two phenomena.

Solder plug tests consisted of lifetime determination as a function of temperature, load, plug diameter, plug length, and plug material. Lifetime was shown to increase approximately exponentially with length and to decrease approximately exponentially with diameter. Short term shear-strength tests were run at elevated temperatures with pure tin, tin-silver eutectic, tin-antimony eutectic, and tin-lead eutectic solders. The selection of tin-silver eutectic solder to be used in the safety device was based on these tests. Lifetime tests with 0.25-inch long, 0.035-inch diameter tin-silver plugs pressurized to 1500 psi and held at 210°C (only 11°C below the melting point) showed no evidence of creep after a test period of six months.

Experiments were performed to determine the feasibility of plating the inside of the aluminum process tube with poison-metal coatings and with poison pigments in an organic carrier. Although good coats were obtained with cadmium fluoroborate, a solution which dissolves aluminum oxide and plates cadmium metal simultaneously, the process was too slow. Also, under dynamic conditions of plating from a high velocity water stream, satisfactory coats were not obtained.

More success was achieved with the use of organic coating in which the poison pigment was transported by the organic. Satisfactory coatings were obtained, but only when the coating, water, and surface to be coated were all at the same temperature. It was found that the temperature was a rather critical parameter, and the small useful range precluded application to production reactors. Consequently, emphasis was shifted from the poison-coating approach to designs which required a less extensive developmental program.

B. BORON TRIFLUORIDE SAFETY DEVICES

The designs reviewed were based on achieving a reactivity loss by a redistribution of poison from a small area configuration to a large area configuration. Poisons considered were cadmium metal redistributed by vaporization, cadmium amalgam, boron carbide or gadolinium oxide in powder form, and enriched boron trifluoride or gaseous helium-three. Since the use of gaseous poison appeared to require the least amount of development, work was directed toward a gaseous-poison device. Boron trifluoride was chosen over helium-three because of the unavailability of the rare isotope of helium.

An enriched-uranium-powered solder plug fuse was incorporated in some form in all designs considered. The melting point of a substance is not appreciably affected by irradiation so the trip level remains constant. Further-

more, such a trip mechanism can be part of a completely self-contained, inherent type safety device for it requires no electrical circuit nor mechanical parts.

The use of high-pressure boron trifluoride gas, serving as stored energy source and neutron poison, also has a number of advantages. The stored energy of the gas will not deteriorate under irradiation; redistribution of the poison is optimum and automatic. In addition, since the poison is stored in a "compact" geometry until released into the large chamber, the device must fail safe, for all leaks will be into the larger chamber.

The Mark II Safety Device, illustrated in Fig. 1, consists of a stainless-steel receiver chamber clad with a standard aluminum Hanford fuel slug can. Enriched boron trifluoride is stored at about 1200 psi in a small cadmium-lined storage chamber located at one end. The purpose of the cadmium is to minimize dissociation and heat production in the boron trifluoride by reducing the neutron flux in the chamber. A release tube leads to the fuse element which consists of an enriched uranium dioxide-copper matrix heater tube sealed with a half-inch-long tin-silver eutectic solder plug. A stainless-steel pad serves as a thermal resistance and provides a predictable temperature difference between coolant stream and fuse.

The device functions in the following manner. The loading of enriched uranium is chosen so that with the reactor operating at full power, the fuse is maintained below the melting point of the solder. However, when the power is excessive or the cooling is interrupted, the solder plug melts. The boron trifluoride is released from the storage chamber into the receiver. Here it presents a much greater surface to the neutron flux and therefore causes more absorption and a consequent decrease in the reactivity of the reactor.

The response time of a safety device is one of its most important properties. For the Mark II device there is the time required for the solder to reach its melting point in addition to the time required for gas redistribution. This lag of solder temperature behind reactor power is a function of the fuse geometry and the rate of change of the reactor power. There was no reactor facility readily available in which the fuse could be subjected to an actual neutron flux excursion. Consequently an experiment¹¹ was designed utilizing excursion simulation by transportation of the trigger assemblies through the exponentially-decreasing flux region of the reflector region of the Materials Testing Reactor.¹²

A truly exponential shape was assumed for the flux in the region, and consequently the test fuses were driven at constant speed toward the core. A flux increase of 15-fold was obtained for effective excursion periods of 0.08 to 3.4 seconds. Temperature of the fuses was monitored throughout the transient by means of thermocouples.

It was found, as expected, that the time delay (defined as the interval between the instants of reactor power achieving trip level and fuse temperature achieving trip level) was a function of reactor period. For tenth-second transients, the delay was of the order of 1 to 2 periods, while for long periods the maximum time was the thermal relaxation time of the fuse experimentally determined to be 2.5 seconds.

The time for gas expansion must be included in the response time of the safety device. Tests were conducted to determine the rate of gas expansion from the storage chamber to the receiver chamber.¹³ Experimental data were obtained by means of thermocouples and strain gages for temperature and pressure, respectively, in each chamber.

Calculations based on the experimental data showed that the safety device would be 90 percent effective within 150 milliseconds after the solder plug failed. Thus, for example, the overall response time would be 0.35 second ($0.2 + 0.150$ second) for reactor period of 0.1 second.

A production pile test of the safety device was run to determine empirically the enriched uranium loading for the fuse to provide the required operating temperature.¹⁴ Other objectives were to observe the behavior of boron trifluoride under irradiation with regard to pressure build-up, and to determine the effect on reactor operation of the triggering of a single element. The loading was to be determined from temperatures measured in the fuses. The effect of radiation on the boron trifluoride was to be obtained from pressure measurement by a transducer. The effect of the tripping of a single device on reactor operation was to be determined by existing reactor instrumentation.

The fission heater in the first assembly to be placed in-pile generated more heat than was expected, making it necessary to conclude the experiment before the reactor reached full power. After establishment of the fuse temperature for a given power level, the fuse was triggered by applying power to a heater mounted on the fuse. The poisoning effect on the reactor was not detected.

A second assembly installed in the reactor tripped prematurely while the reactor power was being increased. The fuse and pad thermocouples indicated correct design of the fuse assembly, but excessive pressure was generated in the high-pressure system caused presumably by excessive heat generation in the boron trifluoride. Further work on this test was precluded by termination of the production reactor safety device program.

The Mark II Safety Device was a laboratory model designed to test the feasibility of the system as a safety device. Each assembly was individually fabricated using complicated and expensive techniques. Before such safety devices would be useful they would have to be simplified for ease of fabrication and assembly.

A double-length element having a single storage chamber containing twice the poison of a Mark II element was considered. Such an element would have the advantage of reducing considerably the surface of the stored poison and therefore produce less stored state reactivity loss. There was also the possibility of a considerable reduction in unit cost. The characteristics of operation of the Mark IV double-length element, shown in Fig. 2, are the same as those of the Mark II. Some of the improved features are as follows: 1) The high pressure container was a cadmium liner, within a beryllium copper chamber that would provide only mechanical support. 2) The fuse was to be integral with a straight release tube which was made of monel to reduce axial heat conduction. 3) The annular shape of the pad provided simplified assembly and eliminated fuse hot spots.

IV SAFETY DEVICE FOR RESEARCH REACTORS

There is a wide variety in types of research reactor with regard to size, fuel, moderator, power, etc. Because of this great variety, it is virtually impossible to design a safety device compatible with all or even most of them. Devices must be individually designed for specific reactor types. Some reactors, such as the water boilers, have been demonstrated to be so inherently safe that they have little need for supplementary devices. Others have been shown to be unsafe under some conditions.¹⁵

At the present time there are a number of reactors of the swimming pool type whose operating power is limited by safety considerations. It would be most advantageous to use safety devices in these reactors to provide the additional margin of safety required for higher operating power levels. This type of reactor is exceedingly popular because of its flexibility and high specific neutron flux. Consequently, from a primary consideration of relative usefulness, a safety device has been designed for these reactors. The great majority of these high flux research reactors utilize regular or modified MTR fuel elements. These elements consist of a number of parallel fuel plates which are made of uranium-aluminum alloy clad with aluminum. The plates are fastened to side plates making a box three inches square and about thirty inches long. The fuel elements are supported side by side on a bottom grid into which the fuel element ends are inserted. On many of these reactors, reflector pieces of the same shape are placed around the core.

The safety device was designed to fit into an unused fuel element or reflector position. The system, shown in Fig. 3, is completely self-contained and has the same outside dimensions as a standard fuel element. The device consists of a sealed tube which is divided into two chambers, a storage chamber and a receiver chamber. Between these two chambers is an intermediate chamber whose walls contain rupturable diaphragms. A release tube leads from the intermediate chamber into the receiver to an enriched-uranium-loaded fuse. The tube is sealed by the cap portion of the fuse which is soldered in place.

In the "ready" state, air at atmospheric pressure is in the receiver, helium at 625 psi is in the intermediate chamber, and boron trifluoride at 1,250 psi is in the storage chamber. In the event of a reactor excursion, the excessive heat generation in the uranium causes the solder to melt. The cap blows off and relieves the helium pressure in the intermediate chamber. The rupturable diaphragms are coined to burst at 750 psi; as the helium pressure decreases, an excessive pressure difference is produced across the first diaphragm. After the first diaphragm bursts, a shock wave is formed which ruptures the second diaphragm. The poison gas expands into the receiver and produces a large absorption area in the core which causes the desired reduction in reactivity of the reactor.

One of the most important advantages of this system is that it is a completely unitized, self-contained system. There are no exterior connections and nothing is required to actuate the device except an excessive neutron flux level. The system is fail safe in that the only

place into which the boron trifluoride can escape is the receiver where it will cause a reactivity loss. Also, a helium leak would actuate the device, and any malfunction of the fuse cooling path would cause the fuse temperature to rise, which in turn would produce a lower flux trip level.

The principal time delay in the system occurs in the operation of the fuse. This delay is a function both of the intrinsic thermal relaxation time of the fuse, determined by the thermal properties and geometrical configuration of the fuse components, and of the period or e- folding time of the reactor transient. For transient periods in the range of five to twenty milliseconds, the fuse time delay is of the order of two to three periods. Other delay times in the system are much smaller. Insertion of poison into the core starts within three milliseconds after the solder reaches its melting temperature. In a specific case, the total delay time of the system is about twenty milliseconds for a reactor transient having a period of seven milliseconds.

Further advantages of this system are that it utilizes standard, simple techniques and only a very small amount of special material. A disadvantage of the system is that it requires a high flux level to actuate. Therefore, it is not applicable to low flux reactors or to zero power critical assemblies.

The empirical determination of the thermal transient behavior of the fuse component of the safety device was considered essential to the establishment of the feasibility of the system. Consequently, a series of tests¹⁶ were conducted in the KEWB-I transient facility.¹⁷ This reactor offered a convenient means for a limited investigation of fuse transient behavior. The tests were considered to be preliminary to higher power tests to be conducted in the SPERT-I reactor.¹⁸

The fuse behavior was determined by observing temperature in various parts of the fuse for the series of transients. The total energy generation in even the fastest KEWB-I transients was found to be insufficient to raise the solder to its melting point. However, the temperature-time curves agreed well with one-dimensional heat flow calculations. On the faster transients the results were obscured somewhat by spurious effects in the thermocouples during those intervals when the radiation levels were high.

In view of the favorable results of the KEWB-I tests of the fuse component, the safety device is considered ready for more extensive testing in the SPERT-I facility. The SPERT-I reactor, since it is very similar in both structure and behavior to a pool-type reactor, offers a more representative higher-power test of the safety device than does the KEWB-I reactor.

The SPERT-I tests are planned to investigate fuse transient behavior and to demonstrate the feasibility of the safety device by producing reactor shutdown. The first series will be similar to tests run in KEWB-I. The fuse transient behavior will be studied for a wide range of transients, starting with a transient which would yield just enough heat generation

in the fuse to trip the device. The range will extend to the most energetic transients that can be run without endangering the reactor. The reactor periods will range from approximately 100 to 10 milliseconds.

In addition, an attempt will be made to shut the reactor down while it is in a supercritical condition. Since reactor behavior will give the information needed, these test assemblies will not be instrumented. There will be eight assemblies to be tested in eight different transients. They will be prototype safety devices, completely unitized, and completely self-contained.

V SAFETY DEVICE FOR LOW POWER RESEARCH REACTORS AND ZERO POWER CRITICAL ASSEMBLIES

To date, the majority of serious accidents in atomic energy operations has been with zero power critical assemblies. The experimental nature of these assemblies probably makes them the most unsafe of all reactors. Critical assemblies are put together to determine the criticality of a system with regards to geometry, poisoning, moderation, fuel, and so forth. They do not have any cooling provided because they are operated at very low power levels.

These operating characteristics of critical assemblies make it difficult to utilize a direct neutron-sensing element in a safety device. Of the reactions of neutrons with matter, that involving nuclear fission releases the greatest amount of energy; but even so, the flux required to produce a practical energy release is at least 10^{12} neutrons/cm²-sec. Consequently, some means of amplification of the effects must be employed in order to provide a sufficiently low trip point. A number of schemes for low power reactor safety devices have been proposed and limited tests have been run with them.

In-pile tests have been conducted using a reactor safety device specifically designed for critical facilities but which is also useful on other low-temperature reactors. This safety device utilizes any electronic neutron detector as the sensor, an electronic trigger circuit as the trip mechanism, an explosive as the stored energy source, and gas as the poison.¹⁹ The system as designed for testing in the KEWB-I reactor is shown in Fig. 4.

The shell of this safety system is a receiver chamber that extends from within the core region of the reactor to, or beyond, the reflector region. A storage chamber is located at the end of the receiver farthest from the core, and contains the reactor poison, boron trifluoride, under high pressure. A detonation chamber containing an explosive is located at the same end. The geometry of the system is exceedingly flexible, for the detonation and storage chambers can be completely outside of the reactor, if desired, and the receiver chamber can be made in any shape convenient to the reactor core configuration. The storage chamber contains rupturable diaphragms which retain the poison until they are ruptured by the detonation of the explosive. When a signal of the proper magnitude, taken from any convenient neutron-sensing device, is applied to the electronic trigger, the explosive is fired. The diaphragms rupture and poison gas is released into the core region and produces the desired decrease in reactivity.

The safety system was tested in a series of KEWB-I excursions having reactor periods from 0.15 to 4 seconds. Approximately 1.5 percent negative reactivity was inserted into the core region, producing shut-down. The system response time, i.e., that time interval between trip and insertion times, was found to be 4.2 milliseconds. The response of the reactor to the insertion of the poison was quite rapid. The maximum value of reactor power occurred within 7 milliseconds after trip, and decreased to 50 percent of peak value within about 15 milliseconds.

VI SUMMARY

Since an "inherently" safe reactor or a "fool proof" reactor control system has yet to be designed, there is a need for supplementary safety provisions. Independent, integral type safety devices can provide some measure of the additional safety that is required if they can be shown to be reliable.

Safety devices for low-temperature, water-cooled, graphite-moderated production reactors have been designed and tested. The safety devices operate on the principle of changing the geometry of a stored poison gaseous boron trifluoride in such a way as to increase its reactivity effect. The gas is stored in a relatively small, high-pressure chamber; after release, it expands into a much larger chamber. The "fuse" for the system is a fission-heated section of a gas release tube sealed by a solder plug. Under excessive neutron flux level conditions the solder plug melts, releases the gas and produces the desired reactivity change.

Safety devices have also been designed for high-power research reactors and low-power critical assemblies. The device for high-power research reactors also uses the concept of a fission-heated solder plug except that the design has been optimized for fast response. The fuse component has been tested satisfactorily in reactor transients and test devices are at present being readied for demonstration in a high-flux transient facility.

The safety device designed for use with zero power critical assemblies uses an electronic signal from a reactor instrumentation channel to fire an explosive that releases boron trifluoride, stored in the reflector region, into the core region. This device has been demonstrated to shut down a supercritical reactor within 7 milliseconds after the trip point was reached, a time short enough to preclude damaging excursions for almost any research reactor.

These concepts, and the test results to date, offer the promise that integral safety devices can be developed which will provide the needed additional safety against dangerous reactor excursions.

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Fig. 1. Production Reactor Safety Device, Mark II

Fig. 2. Production Reactor Safety Device, Mark IV

Fig. 3. Research Reactor Safety Device

Fig. 4. Low Power Research Reactor Safety Device