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FAST-PERIOD REACTOR SAFETY FUSE TESTS

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GENERAL ELECTRIC

ATOMIC PRODUCTS DIVISION

AIRCRAFT NUCLEAR PROPULSION DEPARTMENT

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Nuclear Development Laboratories Sub-Section

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ABSTRACT

The combination of an effective fuse with a sensitive trigger is investigated. Tests conducted with two types of fuse, the annular-passage and the control-rod-type fuse, are described and analyzed.

Appendixes present the methods of analysis and calculation, an analysis of fuse performance, and a summary of alternative fuse trigger and fuse system designs, with methods for adaption of fuses to power reactors.

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INTRODUCTION

Analysis of data obtained from the Boiling Reactor Experiment (BORAX) fuse tests and the Special Power Excursion Reactor Tests (SPERT) fuse-trigger tests indicated the importance of investigating the combination of an effective fuse with a sensitive trigger. This report describes tests conducted with such a combination of components and the results obtained.

Two fuses, operating on the same principle but having different geometries, were tested in the SPERT I reactor. Each fuse was triggered by a bimetallic disk thermostat that completed a circuit through an electric primer. The detonation of the primer propelled boron powder along an evacuated passage into the reactor core. The powder was then retained in the core by layers of aluminum wire screen. The rapid insertion of boron-powder poison caused a fast reactor shutdown before excessive temperatures were reached, even though the power level and temperature were rising at a rapid rate.

This report describes the facility, the fuses, equipment and instrumentation, test procedures, and test results. Appendixes present the method of analysis and calculation, an analysis of fuse performance, and a summary of alternative fuse trigger and fuse system designs, with methods for adaptation of fuses to power reactors.

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FACILITY AND TESTS

SPERT FACILITY

Location of the Site

The Special Power Excursion Reactor Test (SPERT), facility is located at the National Reactor Testing Station west of Idaho Falls, Idaho. The reactor facility is remotely controlled from the central control room through connections made in the instrument bunker room adjacent to the reactor pit building.

SPERT I Reactor

The SPERT I Reactor is very similar to the BORAX Reactor.* The reactor tank is contained in a large cylindrical shield pit 10 feet in diameter and 16 feet deep; the top edge of the shield pit is flush with the floor of the reactor building. Valves for filling and draining water from the reactor tank are located between the walls of the pit and the reactor tank at the base of the tank. The reactor is shown in Figure 1.

The reactor tank, which contains the reactor core, is 4 feet in diameter and 10-1/2 feet deep. The core consists of a number of modified Materials Testing Reactor (MTR) fuel elements held at the bottom by a supporting grid 2 feet above the bottom of the tank and at the top by a removable cover or hold-down grid. The core grid can accommodate 80 fuel elements, but for these tests only 28 elements were used. The core loading diagram is shown in Figure 2.

In operation the reactor tank is filled with de-ionized water to a level 2 feet above the top of the core. This water constitutes the reflector, moderator, and coolant for the core.

Each fuel element assembly consists of two notched side plates and two notched central stiffeners that support 14 fuel plates or sheets (each consisting of three sections) and three plates with no fuel (each in three sections) along their entire length. The fuel plates are 60 mils thick and contain 20 mils of enriched uranium-aluminum alloy, covered by a 20-mil aluminum cladding on each side. Pure aluminum is used in the uranium-aluminum alloy; the cladding material is 6061-T6 aluminum.

The uranium-aluminum alloy forms a center strip 20 mils thick, 0.7 inch wide, and 23.6 inches long. The fuel plates are 60 mils thick, 0.923 inch wide, and 24.6 inches long. The complete fuel element fits into the 3-inch-square grid hole and contains 168 grams of enriched uranium.

The reactor contains five control rods; the central rod is wider than the four shim rods that operate in the channels separating the four quadrants of the reactor core. All rods are made of cadmium in aluminum casings. These control rods are attached by extension rods to drive mechanisms situated above the top of the reactor tank on a bridge. All rods are electromagnetically connected to their respective operating mechanisms, which,

*S. N. Stilwell and R. L. Waterfield, "Borax Fuse Tests," GE-ANPD APEX-441, December 1958.

Fig. 1 - SPERT reactor

Fig. 2 - Core-loading diagram

when released, allow the rods to be ejected downward. Rod ejection is completed early in the excursion so that the reactor power can go through several decades at a constant period.*

TEST EQUIPMENT AND FUSES

Large Annular-Passage Fuse

The large annular-passage fuse is similar to the type tested in the BORAX Reactor. The design of this fuse is based on two general requirements: first, the fuse must fit the space occupied by a fuel element in the BORAX or SPERT reactor; second, it must occupy an absolute minimum of space. For analysis the fuse will be considered to consist of three sections: the top section, which extends down to the top of the reactor core; the center section, which extends the length of the core and a little beyond; and the bottom section, which extends a short distance through the bottom fuel support grid. A shoulder of the bottom section collar rests on the grid, and an end cap extends beyond the grid. The fuse, excluding the end cap, fits exactly between the upper and lower fuel support grids of the reactor.

The top section consists of a round aluminum plate with an O-ring seal around the edge, a 45-degree watertight conduit fitting in the center, and an instrumentation cable that extends out of the reactor pit. The fuse is held in place at the top of the plate by a handle assembly that mates with the top fuel element hold-down grid.

The center section of the fuse is made of two concentric aluminum tubes separated by a 1/16-inch space that contains the poison-retention material. A hollow, partially tapered cylinder is welded to the bottom end of the inner tube. This cylinder is closed on the bottom by a cone having a 90-degree included angle. A single terminal hermetic seal is soldered in the side of the cone. The "hot" wire to the explosive primer is passed through this seal. Three pins project from the convex surface of the cone to maintain the proper spacing between it and a mating cone, which holds the explosive charge, in the bottom section.

Three layers of poison-retention material are wrapped around the inner tube of the center fuse section, with only one common edge near the top of the tube. The first layer is a piece of Refrasil glass cloth 18 inches wide; the second is a piece of aluminum wire screen 12 inches wide; the third is another piece of Refrasil 8 inches wide. These three layers form a staggered obstruction to the flow of the boron powder. They prevent the powder from packing into the top of the annular passage and from falling back to the bottom after it has been inserted.

The poison cartridge containing the boron powder is placed over the untapered part of the bottom cylinder. This cartridge consists of two very thin aluminum cylinders separated by four flat spacers to which the cylinders are spot welded. The space between the cylinders holds approximately 8 grams of boron powder enriched in boron¹⁰. The enriched boron is held in place by tissue paper cemented to the ends of the cylinders. Loading of the poison cartridge during testing was facilitated by placing a conical plug inside the cartridge and placing this assembly inside a close-fitting cylinder. The loading jig is shown in Figure 3.

The lower section of the fuse consists principally of two parts, the end cap and the lower cone. The end cap screws into a thick-walled section welded to the outer tube in the center section and makes a seal by means of an O-ring. The side of the end cap contains

*T. R. Wilson, "An Engineering Description of the SPERT I Reactor Facility," Phillips Petroleum Co., IDO16318, June 1957.

Fig. 3 - Expanded view of loading jig for poison cartridge

an evacuation port and a vacuum seal for pumping air out of the fuse. The lower cone, made of steel, has an included angle of 85 degrees and forms one wall of a tapered passage along the mating cone to provide good flow characteristics. A cavity in the center of the lower cone contains the explosive and directs the force of the detonation upward. A small hole in the bottom cone allows the "hot" wire from the hermetic seal to pass through to the explosive primer, whose leads come out the bottom end of the cone. Three other small holes form a vent between the space in the end cap and the annular passage in the center section so that the entire fuse can be evacuated. A small slot in the side of the cone piece aligns the hole for the wire with the hermetic seal by means of an indexing pin inside the sleeve, welded to the outer tube. The ground wire of the explosive primer is soldered to a lug screwed to the inside of the end cap.

To position the fuse properly in the reactor, a split square collar is clamped into a groove around the end cap so that when the fuse is placed in the bottom fuel support grid the handle on top will be properly aligned to receive the upper fuel support grid. A previous series of tests demonstrated that it was difficult to align this handle accurately by using only the fuel lifting hook and visual inspection. An expanded view of the annular-passage fuse is shown in Figure 4.

Moderator Rod

Calculations were made on various methods of increasing the reactivity value of the fuse by adding materials inside the inner tube. In the order of the reactivity value determined, these materials were: fuel and water, acrylic plastic, fuel only, and void.

Fig. 4A - Expanded view of annular-passage fuse

Fig. 4B - Inner aluminum tube with poison retention screen

On the basis of these calculations it was decided to place a piece of acrylic plastic inside the fuses to increase their reactivity value. As mentioned earlier, the space occupied by the acrylic plastic would contain a reactor fuel element when the fuse is installed in a specific core. An additional benefit of using the plastic during testing was that it provided a means of locating and supporting the temperature and flux instrumentation that was placed inside the fuse.

The plastic, 2-1/4 inches in diameter, fitted loosely inside the fuse and had a network of slots leading to holes where the sensory instrumentation was placed as shown in the assembly illustrated in Figure 5. The slots held wires that carried the signals from the sensors out of the fuse to amplifiers in the nearby instrument bunker. Holes spaced at intervals in the plastic rod contained a small flux sensor, two thermocouple assemblies, the fuse trigger (a nuclear thermostat), and a cable connector attached to the large flux sensor that goes around the bottom end of the moderator rod. The thermocouple positions were chosen so that the top thermocouple would receive about the same flux as the fuse trigger thermostat and would reach the same temperature, as shown in Figure 6.

Sensory Instrumentation

The large flux sensor on the bottom of the moderator rod consists of two cylindrical electrodes of enriched uranium foil with a single copper collector electrode between them. The two enriched uranium electrodes are connected to a brass cap that forms part of the enclosure for the sensor. Wires are brought from the brass cap and the collector electrode to a BNC cable connector in a hole near the end of the moderator rod.

A small flux sensor, shown in Figure 7, is built on the end of a type UG-657/U coaxial receptacle and located near the top end of the moderator rod. The sensor consists of a short length of aluminum, 0.575 inch in diameter, bored out and threaded onto the connector. The wall of the hole below the thread is lined with 1-mil enriched uranium foil. The solder lug in the center of the connector is covered with a brass sleeve to increase its diameter and provide a smooth contour. The O-ring built in the flange on the receptacle completes the seal when the sensor is assembled. Both flux sensors feed their signals into RG-58/U or RG-59/U coaxial cables, which are part of a special multiconductor cable attached to the fuses. (Belden No. 8282 TV Eye Cable.)

The area of exposed uranium in the large sensor is 34.67 square centimeters and its sensitive volume is 12.06 cubic centimeters, a ratio of 2.875. In the small sensor the area of the uranium is 2.72 square centimeters and the sensitive volume is 0.678 cubic centimeter, a ratio of 4.01. These ratios indicate the relative gamma response of the sensors.

The thermocouples were designed to incorporate ruggedness and ease of connection. The latter was achieved by using a sandwich arrangement in which the thermocouple wires were laid across the fuel piece and held in place by pieces of Bakelite. This assembly was fastened by screws to the bottom of a BNC chassis connector. The thermocouple assembly is shown in Figure 8. Any kind of fuel piece that is at least 0.010 inch thick can be accommodated. Four kinds of fuel pieces were used: enriched uranium foil, 0.010 inch thick; Teflon-uranium sheet, 0.012 inch thick; and two types of steel-clad fuel plates, 0.013 inch and 0.021 inch thick. These materials were used to obtain actual data on the final temperature that these representative types of fuel elements would reach in a fused reactor excursion, rather than calculating the data from measurements on a single fuel type.

Nuclear Thermostats - The triggering element for the fuses is a zirconium-uranium nuclear thermostat made by Metals and Controls Corporation of Attleboro, Massachusetts.

Fig. 5 - Fuse, moderator, and instrumentation system assembly

Fig. 6 - Thermocouple and thermostat locations with respect to flux curve

Fig. 7 - Small flux sensor

Fig. 8 - Thermocouple assembly

The thermal expansion coefficient of uranium is about 14×10^{-6} , while that for zirconium is about 5×10^{-6} . Thus a combination of the two metals has sufficient thermal activity to give a good action. A circular disk of this bimetal was mounted in a standard thermostat housing with standard switch contacts and screw terminals. The bimetal disk consisted of 8 mils of enriched uranium roll bonded to 4 mils of zirconium and was formed and mounted so that the switch contacts closed at temperatures between 115°F and 140°F . This temperature range was chosen to prevent false scrams and at the same time keep the reactor temperature increase small enough to prevent fuel element damage. The differences in thermal expansion of the two metals in the disk cause the disk to snap and reverse its curvature in approximately 0.3 millisecond. This action closes an electrical contact that completes a circuit from a battery to the explosive primer. Detonation, caused by completion of the circuit, is accomplished less than 1 millisecond after the disk gets ready to snap.

Explosives and Batteries

An electric squib was tested that had the right amount of explosive to produce minimum insertion time and had a vacuum-tight breach closure built in. The squib consists of a primer mounted on wires moulded in a piece of Neoprene, which is roll-crimped into the end of a copper primer cartridge. The primer utilizes a 0.0006-inch-diameter bridge wire having a resistance of 14 to 16 ohms and a No. 5 bead of lead stibnate and fires in less than 0.3 millisecond when a current of 1 ampere is passed through them. This in turn sets off the charge of 1 gram of SR 4990 pistol powder that propels the boron powder into the fuse. The entire squib is 0.270 inch in diameter and about 1.5 inches long.

The second type of electric squib tested, similar to the first, employs an explosive that is contained in a steel cylinder 1 inch long and 9/16 inch in diameter. The breach end is closed by a Neoprene sealant held in place by a threaded retaining ring; this arrangement makes the end vacuum tight. The steel cylinder threads into the fuse and seats on an O-ring to make a seal. The main charge consists of 170 milligrams of diazodinitrophenol (DDNP), and the firing time with 1 ampere of current is less than 0.1 millisecond.

A battery pack consisting of 30 small-size penlite dry cells (Eveready No. 912) connected in series and enclosed in a thin steel tube was designed and built for this test series. The battery pack is shown in Figure 9. The open-circuit voltage was 45 volts, which dropped to about 22 volts when connected across a squib, so that the battery pack delivered in excess of 1 ampere while the explosive was being detonated. The battery pack was designed to fit on the end of the moderator rod and slide down inside the fuse so that the battery pack was inside the poison cartridge holder. However, the first tests were run with the control-rod-type fuse, which required an external battery that was kept in use for testing the annular-passage fuse.

Control-Rod-Type Fuse

The control-rod-type fuse embodies a basically new geometry, but utilizes the same basic operating principles as the annular-passage fuse. Since it is smooth on the outside and can be made as small as 1/2 inch in diameter (the test fuse was 1 inch in diameter), the fuse is similar in appearance to a reactor control rod. The control-rod-type fuse is shown in Figure 10.

The four main structural parts are the outer tube, the upper and lower end plugs, and the poison retainer. Two O-rings on each end plug seal the tube and are held in place by screws through the tube. An O-ring surrounds the explosive primer, and the poison load

Fig. 9 - Battery pack

of boron¹⁰ is sealed with tissue paper. In the tests conducted, the nuclear thermostat was located outside the fuse tube, but a smaller model thermostat could be used. This thermostat could fit inside the fuse so that only the batteries would be outside the fuse.

The poison retainer in the experimental model consisted of aluminum wire screen with a tapering hole through the center and a constant diameter on the outside. This installation was accomplished by winding four strips of aluminum wire screen, about 4-1/2 inches wide, on a tapered mandrel. Four layers were wrapped on the small end and one layer on the large end of the mandrel. The poison retainer is shown in Figure 10. The screen was then inserted into the fuse tube and the mandrel withdrawn. It was expected that the tapered hole would offer free passage of the boron powder, but that the decreasing diameter would gradually stop the powder as it passed along and that the poison would be distributed uniformly. In view of the fact that the measured reactivity value of the fuse was about one-fourth that expected for the annular-passage fuse, even though the smaller fuse had much smaller areas and volumes, it seems likely that a good poison distribution was obtained in the smaller fuse.

Fig. 10 - Expanded view of control-rod-type fuse

The bottom end plug was bored out to contain the explosive and the poison charge. A small hole in the end permitted passage of the wires from the first explosive to the thermostat and battery; for the second explosive the explosive housing was screwed into a large threaded hole.

The top end plug contained a vacuum valve and evacuation port like those used in the annular-passage fuse but arranged in a different manner. The evacuation port was at an angle on the side of the fuse, and the vacuum valve screw extended out the end of the plug and slightly off center. This arrangement was necessary because of the extremely limited volume of material in which to bore the required holes for the vacuum screw and the 1/4-inch tubing fitting that connected to the vacuum line.

The outer tube was 1-inch-OD stock-size aluminum tubing with 1/16-inch walls. The inside was polished at the ends to improve the seal on the O-rings, and appropriate holes were drilled to fit the screws that hold the end plugs in place and permit attachment of the vacuum line. A diagram of the control-rod-type fuse is shown in Figure 11.

Fig. 11 - Diagram of control-rod-type fuse

Instrumentation System

Eight-Channel Log-N Amplifier - In order to test four fuses at a time and to measure the insertion speed of each one, it was necessary to employ an eight-channel amplifier for the signals from the eight flux sensors used to detect the passage of the boron powder in the fuse. It was expected that the lower sensor would detect a sudden decrease in flux by a factor of 2 when the boron passed it, and that a similar change occurring at the top sensor would be apparent even though the reactor flux was dropping rapidly at that time.

The log-N amplifier employs printed-circuit boards for all the circuitry; thus the amplifier is a very compact instrument, as shown in Figure 12. It was wired for operation from a d-c power supply and a 12-volt storage battery for a minimum of hum. An output hum of 2 millivolts was measured. The original design was made to connect to other circuits that required the output to vary from 30 to 96 volts for a change of six decades, from 10^{-11} to 10^{-5} ampere, in the input. The galvanometer drive amplifiers at the SPERT facility can accept a signal varying from 0 to 1 volt, so bucking batteries and a voltage divider were added to the output of the amplifier to provide this type of output. In this way it was possible to set up the log-N amplifier so that the output varied from 0 to 1 volt, while the input went from 5×10^{-12} to 5×10^{-10} ampere. The circuit diagram for the log-N amplifier is given in Figure 13.

Fig. 12 - Eight-channel log-N amplifier

Fig. 13 – Circuit diagram of eight-channel log-N amplifier

Each channel has five controls. With the selector switch in position 2, the output is adjusted to Zero on the log-N output meter by using the Ground Set control. With the selector in position 3, the Lo Calibrate control is adjusted for a noted deflection of the log-N meter corresponding to 2×10^{-11} ampere input. With the selector switch in position 4, the Hi Calibrate control is adjusted for a noted deflection of the log-N meter corresponding to 2×10^{-6} ampere input. These adjustments should be repeated once for each channel to assure good calibration of the instrument. If a calibrated input current is applied in decade steps with the selector switch in position 1, Signal, the log-N meter will indicate decade steps in output. With the selector in position 1, an input of 10^{-12} ampere is applied, and the Ground Set control is adjusted for zero output. With an input current of 10^{-10} ampere, the calibration pot is adjusted for 1-volt output. With these adjustments the amplifier is ready to use and will give 1 inch of deflection for each decade of input current. The instrument was operated at maximum sensitivity to insure that the output signal would be recorded if the sensors were working.

Connector Junction Box - For convenience in obtaining a watertight seal, a single multiconductor cable was brought out of the fuse to carry all electrical signals. The SPERT facility is equipped with numerous coax and twinax cables laid in conduits from the pit building to the instrument bunker. Hence it was desirable to have a junction box in the pit building to convert from one cable system to the other. On the side of this junction box were four large AN cable receptacles to accept the multiconductor cables from four fuses. The connector junction box is shown in Figure 14. Six BNC receptacles associated with each of the four larger connectors were situated on top of the junction box. These were labeled TC-1 and TC-2 for the two thermocouple signals, and F-1 and F-2 for the two flux signals that were sent over the coax cables from the fuses. The other two were marked Trig and Spare and could be used in any way desired. Provision was made inside the junction box for attaching cables without connectors to barrier terminal strips that were in turn connected to the four large AN input connectors. In actual usage, an 8-conductor cable, a 6-conductor cable, and a twinax cable were attached to the terminal strips to make up the 16 conductors required to send eight thermocouple signals to the instrument bunker. In addition, eight coax cables for flux and four for thermostat closure signals led from the BNC connectors on top of the box to the instrument bunker.

Battery Box - A battery box was constructed by utilizing a piece of apparatus previously constructed for use as a junction box during a series of fuse trigger tests.* This box had space for four batteries of 45 volts each that could be connected for two different purposes. One set of four connectors led directly to the battery terminals and was used for delivering the energy to the fuses to set off the explosives. A circuit diagram of the external battery box is shown in Figure 15. A second set of eight connectors was used during the last two tests when a large number of thermostats was tested simultaneously and their switching time was recorded. The connectors provided a connection into a voltage divider circuit so that approximately 0.8 volt was applied across a group of five thermostats, each of which had a different size resistor connected across its terminals. Thus a different size pulse was produced as each thermostat closed, and the pulse could be fed directly into the galvanometer driver amplifier. A diagram of the instrumentation assembly is shown in Figure 16.

Explosive Primer Test Box - The explosive primer test box contained a 1.5-volt battery and had a resistance of 285 ohms across two pairs of terminals. The explosive primer to be tested was connected across one pair of terminals and a 0 to 0.1 voltmeter

*R. J. Spera, S. N. Stilwell, and R. L. Waterfield, "SPERT I Fuse Trigger Tests," GE-ANPD APEX-446, January, 1959.

Fig. 14 - Connector junction box

Fig. 15 - Circuit diagram of external battery box

across the other, as shown in Figure 17. The resistance of the explosive primer bridge wire is 14 to 16 ohms, the current through it is about 5 milliamperes, and the voltage drop is 0.075 volt. If these values are doubled and the decimal point is moved, the resistance can be read directly in ohms. This box was used to test all the explosive primers before they were fired.

SPERT Instrumentation - The various cables that carried the signals to the instrument bunker were connected to permanently installed equipment supplied and operated by SPERT personnel (see Figure 16). The thermocouple signals were connected to suitable balanced-input amplifiers having a gain adjustable to about 1000. The outputs of these amplifiers were connected to galvanometer driver amplifiers in an adjacent relay rack. Two flux signals from SPERT flux sensors were amplified by their log-N and linear flux amplifiers and recorded. The linear flux amplifiers had three output connectors wired into a fixed attenuator so that signals with relative amplitudes of 0.2, 0.5, and 1.0 could be obtained. The four outputs from these two flux amplifiers were also connected to galvanometer drive amplifiers. The various signals indicating contact closures were connected directly to the galvanometer driver amplifiers, since they did not require amplification. Flux signals from the flux sensors located in the moderator rod were connected to the inputs of the 8-channel log-N amplifier described previously. The output signals of this amplifier were connected to eight galvanometer driver amplifiers. The galvanometer driver amplifiers were connected to the galvanometers in the 26-channel recorder in the control room by means of continuous-length coax cables 3000 feet long. The final zero position of the galvanometers just before the run was set mechanically by adjustments on the galvanometers. Shortly before this, the galvanometer driver amplifiers were set electrically to zero in the instrument bunker. Before any runs were made, the galvanometer deflections were calibrated according to two standards. The thermocouple amplifiers were adjusted so that a 1-millivolt input produced 1 inch of deflection, which corresponds to 33°F. Flux amplifiers were calibrated so that 1 volt was equal to 1 inch of deflection, or about 1 decade. The log-N signal at the SPERT facility had a permanent calibration so that 1 decade was equal to 1.6 centimeters or 0.63 inch. The full-scale deflection of the galvanometers was limited by saturation of the galvanometer driver amplifiers to about 3 inches and was produced by an input signal of about 0.9 volt.

EXPERIMENTAL PROCEDURES

Installation of Annular-Passage Fuses

Preparation of Instrumentation - The appropriate flux sensors and thermocouples were placed in their slots in the acrylic plastic moderator rod and connected to the signal cables. The nuclear thermostat was placed in its slot and the appropriate wires connected to its terminals. Tape was placed over all the wire slots to hold them in place and around

Fig. 16 - Diagram of instrumentation system

Fig. 17 - Circuit diagram of electric primer test box

the moderator rod to hold the sensors in their slots. The wire from the hermetic seal was drawn out of the top of the fuse through the hole in the brass cap on the moderator rod and connected to a terminal on the thermostat, as shown in Figure 5. Then the moderator rod and the sensors were placed inside the fuse and the top section fastened in place.

Installation of Explosives - The first type of explosive primer was inserted into the steel cone and the leads brought out the small hole in the rear. One lead was attached to the wire from the hermetic seal by soldering and covering the joint with plastic spaghetti tubing. The other lead was soldered to a ground lug installed on the shoulder inside the end cap. This lead was carefully wrapped counter clockwise around the neck of the cone so that it would not be twisted off when the end cap was screwed in place.

Final Checks - After the end cap was in place, the split square collar was placed around it. The collar was then aligned with the handle on the top section by resting both on metal blocks on the work bench. Next, an ohmeter check was made to determine that none of the leads in the signal cable was grounded in such a way as to prevent current from passing through the explosive. The explosive primer test box was used to determine that the explosive primer bridge wire carried a circuit of the proper resistance so that when the thermostat closed the primer would be set off. Next the fuse was connected to a vacuum pump through a short length of 1/4-inch copper tubing equipped with a vacuum gauge and a valve. The tubing was pumped out, valved off, and left a few minutes to ascertain that the connection to the fuse was leak-tight. Then the vacuum valve on the fuse was opened so that it could be pumped out and valved off to leak-check the fuse. It was specified that the fuses should lose vacuum at a rate no greater than 1 inch of mercury per hour to insure a reasonably good vacuum at the time of testing. Since closing the vacuum valve uses an O-ring in addition to those that prevent leaks during testing, a fuse could not leak faster after the valve was closed than it did before. Most of the fuses passed the leak test easily, since they were tested at Evendale with a helium leak detector before shipment to Idaho.

Installation in the Core - For each test two fuses were installed in the core diagonally opposite each other to minimize interference and obtain maximum reactivity value. The fuses were inserted into the selected locations in the lower fuel-support grid, and the cables were routed so that the upper fuel-support grid could be closed. The cables were then taped in place to prevent interference with the reactor control rods and brought to the edge of the reactor pit for connection to the junction box.

Installation of Control-Rod-Type Fuses

The installation of control-rod-type fuses was much the same as that described for the annular-passage fuses. However, since the control-rod-type fuses were designed to fit inside the annular-passage fuse can, which served as a container and support, no

moderator rod could be used. Therefore the instrument harness was removed from the moderator rod and placed on one side of the control-rod-type fuse so that flux sensors and thermocouples could be placed along its length in the same way as for the larger fuse. These sensors were taped to the side of the fuse, the fuse was evacuated, and the whole assembly was inserted into the large fuse can. The top section of the large fuse can was fastened in place, and an electrical check of all connections was made as before. The bottom end cap was installed with no explosive or steel cone, and the vacuum valve closed without evacuating. The square split collar was put in place and aligned, and the fuse was ready for installation in the core.

Instrument Connections and Adjustments

Cables were connected as described previously. Only two different cable arrangements were used, and these were left in place for several tests. In the instrument bunker the gains of the log-N and thermocouple amplifiers were checked and adjusted for electrical zero. Since the thermocouple amplifiers used a balanced ungrounded input, it was necessary to check the polarity of all the inputs to them. Once the polarities were established, no further checks were necessary, since polarity was fixed in all the instrumentation

RUN No's: 1 through 8

GROUP	SIGNAL	BUNKER CABLE NO.	AMP NO.	DRIVER NO.	LONG CABLE NO.	GALVO NO.	CALIB.
I	TC-1	YEL-BL	18	1	1	1	
	TC-2	OR-BR	15	2	2	2	
	F-1	1	LOG 1	5	5	5	✓
	F-2	2	LOG 2	6	6	6	✓
	SWITCH	9	-	15	15	15	
II	TC-1	RED-GR	16	3	3	3	
	TC-2	BL-WH	19	10	10	10	
	F-1	2	LOG 3	12	12	12	✓
	F-2	4	LOG 4	13	13	13	✓
	SWITCH	10	-	16	16	16	
III	TC-1	Ni-4	20	11	11	11	
	TC-2	RED-YEL	3	24	24	24	
	F-1	5	LOG 5	19	19	19	✓
	F-2	6	LOG 6	20	20	20	✓
	SWITCH	11	-	17	17	17	
IV	TC-1	BR-GR	2	25	25	25	
	TC-2	BL-WH	1	26	26	26	
	F-1	7	LOG 7	21	21	21	✓
	F-2	8	LOG 8	22	22	22	✓
	SWITCH	12	-	18	18	18	
LOG FLUX		-	LF-2	4	4	4	
LOW LINEAR FLUX		-	F-2	7	7	7	0.2
MED. LINEAR FLUX		-	F-2	8	8	8	0.5
HIGH LINEAR FLUX		-	F-2	9	9	9	1.0
ROD DROP		-	-	14	14	14	

Fig. 18 - Typical SPERT I Fuse Test Log

harnesses. In the control room the galvanometers were adjusted to selected zero positions immediately before the run to simplify trace identification and assure that none of the traces ran off the film.

Reactor Operation

Operation of the reactor for these transient tests is simple because of the inherent safety of the reactor and the absence of automatic scrams. The reactor is brought to a critical point at a power of approximately 200 watts on a period that is estimated by observing the linear power recorder. The central transient rod is then inserted to decrease the power level below 1 watt and set the amount of reactivity it will add when fired. The shim control rods are adjusted to make the reactor critical at this low level, and the transient button is actuated. This actuation expels the transient rod out the bottom of the core and starts to increase the reactor power on the desired period. When the power rises enough for measurable heat generation to begin, the thermocouples produce a signal. As soon as the temperature of the thermostat has risen sufficiently it snaps and closes the contacts; the explosive is set off, the poison is inserted into the fuse, and the reactor is shut down. The entire action of the fuse takes place in about 10 milliseconds, so that even on a 20-millisecond period the temperature rises less than a factor of 2 after the thermostat snaps. Since the snap action occurs only about 30 degrees above ambient temperature, the total temperature increase is small.

Data Recorded During Tests

During setup and installation of the fuses, the numbers, location, and connections of all the sensors and fuses were recorded, so that a complete record of all connections from the sensor to the galvanometer was made for each channel. Figure 18 is an example of one of the data pages for fuse tests. In addition, the date, time, run number, water

Run No. (ours) 4 (theirs) 1, time 1445 MST, date 26 Oct. 56, film no. 13130

Approximate period 20 (ms) water temperature 17.2 (°C)

First Critical Rod Position 1376 ½ Final Critical Rod Position 1510

ITEM	SIGNAL GROUP I POSITION 3-2	SIGNAL GROUP II POSITION 6-2	SIGNAL GROUP III POSITION 6-7	SIGNAL GROUP IV POSITION 3-7
FUSE NO.	A-35-1	A-5-6	A-11-9	A-12-2
MODERATOR NO.	—	—	—	—
POISON	B ¹⁰	B	B	B ¹⁰
TC-1 NO.	13-5	21-1	13-1	21-3
TC-2 NO.	13-6	21-2	13-2	21-4
F-1 NO.	4	8	—	5
F-2 NO.	6	3	—	1
SWITCH NO.	10	14	18	6
CABLE NO.	1	2	3	4
EXPLOSIVE	du PONT	du PONT	du PONT	CONAX

Remarks: Small fuses in large fuse cans.

All fuses pumped out and sealed by 4 PM 25 October

All fuses checked and repumped by 10 AM 26 October

Fuse reactivity value 0.6 percent

Fig. 19 — Typical SPERT I Data Sheet

temperature, approximate period, fuse location, sensors associated with each fuse, approximate reactivity value of the fuses after firing, and other miscellaneous information were recorded on another type of data sheet, shown in Figure 19. The oscillograph records all the flux and thermocouple signals, the closure of the thermostat contacts, and the time at 10-millisecond intervals. With this information it is possible to determine at what relative time each fuse fires, the temperature of the thermostat at that time, the insertion time, and the final temperature of the thermostat.

When numerous thermostats were tested simultaneously, a different type of data sheet was required. This data sheet is shown in Figure 20. The methods of determining the actuation temperatures of the thermostats are explained in the appendix.

DESCRIPTION OF TESTS

Reactivity Value of Fuses

To determine without doubt how many fuses would be required in each run, one small fuse was fired in the laboratory and inserted into the reactor. The critical position of the control rods was obtained with this arrangement. A similar unfired fuse was then placed in the same position and the new critical position obtained. The results of these tests

Run No's. 9, 10 Fuse Can No. A-10 Cable No. 2 Location 0-5

TRIGGER NO.	CLOSE SIGNAL	CONNECTIONS			DRIVER NO.	GALVO NO.
		JUNCTION BOX	BUNKER CABLE	BATTERY BOX		
10	1/2	TC-1	5	CHANNEL 7	19	19
14	1					
27	1-1/2					
31	2					
46	2-1/2					
41	1/2	SPARE	6	CHANNEL 8	20	20
38	1					
3	1-1/2					
37	2					
34	2-1/2					
43	1/2	TC-2	7	CHANNEL 9	21	21
36	1					
33	1-1/2					
26	2					
47	2-1/2					
13	1/2	F-2	8	CHANNEL 10	22	22
25	1					
24	1-1/2					
23	2					
7	2-1/2					

Remarks: Trigger No. 43 only one wired Active to fire fuses on Run 9. Triggers No. 43, 36, 33, 26 and 47 wired active to fire fuses on Run 10.

Fig. 20 - Typical SPERT I Trigger Test Log

Fig. 21 - Comparison of fused and unfused transient flux

Fig. 22 – Thermostat actuation temperatures, runs 9 and 10

indicated that two of the annular-passage fuses or four of the control-rod-type fuses would be sufficient to control a 10-millisecond period on the reactor.

Dynamic Test of Control-Rod-Type Fuse

Groups of four control-rod-type fuses were instrumented and placed in the four quadrants of the reactor core. After all connections were complete, the reactor was placed on a 20-millisecond period, and it was found that the fuses shut down the reactor much more quickly than would the usual action of the reactor moderator water. A comparison of fused and unfused transient flux curves is shown in Figure 21. After the test run, the reactor was again brought to critical to measure the reactivity value of the fuses.

Dynamic Test of the Annular-Passage Fuse

Groups of two annular-passage fuses were instrumented and placed in diagonally opposite quadrants of the reactor core as indicated in Figure 2. After all the connections were completed and checked, the reactor was placed on a 20-millisecond period to test the fuses.

Trigger Actuation Temperature

To provide statistical information on the behavior of the thermostats, 20 thermostats were placed in each of two fuse cans and the time at which each thermostat closed its contacts was determined. The thermostats were connected in a special circuit so that the pulse due to the closure of each thermostat could be identified. Since the excursions were run without the benefit of a fused shutdown, the cans were placed in two of the outermost positions in the fuel element support grid so that the thermostats would not get too hot. Even with the fuse cans in this outermost position the final temperatures were high enough to cause some damage to the thermostat disks, as evidenced by the fact that the operating temperature on the second excursion was much higher than on the first excursion. Thermostat actuation temperatures for runs 9 and 10 are shown in Figure 22.

ANALYSIS OF TESTS AND RESULTS

DYNAMIC BEHAVIOR OF FUSES

General Description

During a reactor excursion with a short period, many factors are acting simultaneously in a rapidly changing system. Since the excursion initially begins at a power level of approximately 1 watt, an insignificant amount of heat is generated in the thermostat at that time; the amount is given roughly by the ratio of the core fuel weight to the fuel weight of the thermostat, or about 1/2000. At a reactor power level of 2000 watts, the thermostat power is 1 watt, which will raise its temperature at the relatively slow rate of approximately 4.9°C per second. During the fuse tests the temperature was rising approximately 1000°C per second at the time the thermostat closed, indicating a thermostat power of 200 watts and a reactor power of 400 kilowatts. However, the poison was inserted so rapidly that the total power generation was rather small. The total temperature increase in the thermostat was only 40°C , and resulted from the generation of only 8 watt-seconds of energy.

During this rapid rise and fall of power, the flux undergoes an excursion that is similar except for the delayed neutrons. Since these delayed neutrons undergo a minimum delay on the order of 0.2 second, only a few are formed during the excursion. For this reason the flux levels off almost immediately after the insertion of poison has begun. As the poison passes along the length of the fuse, it causes a sudden local flux depression. Although it was expected that this depression could be sensed with the flux sensors that were placed inside the fuses to indicate how fast the poison was traveling, the chambers apparently were not sensitive enough to register the depression.

Analysis of Fuse Performance

A number of factors influence the dynamic behavior of fuses. These factors are outlined here and are discussed in detail, with graphs, in Appendix B, Fuse Performance Analysis.

1. Relative flux at the location of the trigger (thermostat).
 - a. Normal reactor flux distribution.
 - b. Perturbations due to materials in the vicinity of the trigger.
2. Energy generated in the trigger per unit average flux in the core.
 - a. Relative flux.
 - b. Total amount of uranium and the flux depression caused by it.
 - c. Transmission factor of the uranium.
 - d. Size and shape of the trigger.
 - e. Orientation of the trigger with respect to the core.
3. Flux required to operate a heat-sensitive trigger.
 - a. Energy generated in the trigger per unit flux in the core.
 - b. Total heat capacity of the non-generating material (zirconium).

- c. Temperature at which the trigger actuates.
- d. Heat losses from trigger during excursion (negligible).
- 4. Flux required to operate a radiation-sensitive trigger.
 - a. Ionization produced in the trigger per unit flux in the core.
 - b. Mode of operation of trigger (voltage or current sensitive).
 - c. Flux level at which trigger actuates.
- 5. Insertion time of the poison.
 - a. Force of the explosion moving the poison.
 - b. Straightness of the passage through which the poison travels.
 - c. Weight of the poison.
 - d. Initial air pressure in the passage.
- 6. Total reactivity value of the fuse.
 - a. Amount of poison material.
 - b. Neutron cross section of the poison.
 - c. Poison retention qualities of the fuse.
 - d. Total area over which poison is distributed.
 - e. Uniformity of its distribution within the fuse.
 - f. Transmission coefficient of the distributed material.
- 7. Rate of insertion of reactivity.
 - a. Number of fuses.
 - b. Insertion time of the poison.
 - c. Reactivity value of each fuse.
 - d. Flux level at which trigger actuates.
 - e. Time between trigger actuations.
- 8. Effectiveness of the fuse: limiting value of the total energy of an excursion.
 - a. Period of the excursion.
 - b. Flux level at which trigger is actuated.
 - c. Rate of insertion of reactivity.
 - d. Neutron lifetime of the reactor (limits rate flux can decrease).

RESULTS

Tests of Annular-Passage Fuse

Some of the annular-passage fuses were subjected to reactor excursions during which the firing mechanism was disconnected but the other recording channels were operating. The temperature and flux records obtained during these tests were used to obtain a good calibration so that temperature could be calculated from the flux curves obtained during the thermostat tests. These temperature records also demonstrated dramatically how hot insulated uranium fuel could get during an excursion even when limited by the reactor moderator. In run 6, the recorded temperature increase was 100°F (full scale) when the log-N flux indicated 8 units. The maximum value reached by the flux was 560 units. If a linear relationship between temperature and the area under the flux curve is assumed, the final temperature would be $14,000^{\circ}\text{F}$. Hence, it may be safely assumed that the black sooty deposit found on the acrylic plastic on run 6 and run 8 was formed by condensation of UO_2 vapor. Flux and temperature curves as a function of time are shown for run 8 in Figure 23.

Tests of Control-Rod-Type Fuses

Control-rod-type fuses were tested four at a time by placing them inside the annular-passage fuse cans and inserting these into the four inside corners of the core as shown in the core loading diagram, Figure 2. In run 4, the first thermostat closed after a temperature increase of 32°F , and subsequent fuses fired soon enough that the final

Fig. 23 - Flux and temperature versus time, run 8

temperature increase was only 72°F . The total reactivity value of the fuses was approximately 0.6 percent Δk , slightly less than that used to initiate the excursion. In run 5 the first thermostat closed after a temperature increase of 40°F , and the other fuses fired in such a manner that the final temperature increase was 145°F . The total reactivity value was 0.36 percent Δk , which accounts for the higher final temperature in this run. A theoretical investigation using the shape of the flux curve, the neutron lifetime, the reactivity value, the firing time, and the insertion time indicated the exact manner in which the individual fuses inserted negative reactivity into the core. Figure 24 presents the results of this investigation for run 4. It can be shown that the temperature of the thermostat rises from 10 to 50 times as fast as that of some well-known fuel elements; thus the protection that these fuses give such fuel elements is much more than the minimum. Material given in Appendix B demonstrates the effectiveness of the fuses under various other circumstances.

The amount of poison inserted in these tests was insufficient to keep the reactor subcritical. Since a limited number of fuses was available, the use of a below-minimum amount of reactivity for the tests gave an excellent basis for extrapolating the results to be expected for shorter periods when the proper amount of reactivity is available.

Tests on Statistical Behavior of Thermostats

On runs 9 and 10, the 40 thermostats placed in two annular-passages fuse cans were connected to an instrumentation system to determine the time at which the contacts closed. From the flux curve it was possible to deduce the relative temperature at any time (see "Methods of Analysis and Calculation"). If it is assumed that the first thermostat closed at about the same temperature as that of the first closure in run 4, which was somewhat below the minimum temperature of 115°F designated by the factory, the start-

Fig. 24 - Reactivity and flux versus time, run 4

ing point may be set on this temperature scale. Of the 40 thermostats tested, 16 closed below the requested upper limit of 140°F . This result is within reason for the first experimental lot of a new product, especially since the bonding technique for uranium and zirconium was still in the development stage at the time the tests were conducted. Ten thermostats closed at various temperatures up to 420°F , and the remainder did not close. On run 10 three thermostats closed near 220°F , and six others closed above this temperature, an indication that the temperature of approximately 2000°F to which they were subjected in run 9 caused some permanent damage, as could be expected.

CONCLUSIONS

The test results demonstrate that control-rod-type fuses can be developed to control any runaway that might reasonably be expected to be initiated by a reactor. This conclusion is supported by the data given in Figure 25, which presents the total increase in fuse

Fig. 25 – Total increase in trigger temperature versus temperature increase required for trigger actuation

trigger temperature versus the temperature increase required for trigger actuation. How this conclusion is reached on the basis of test results is further demonstrated in Appendix A, Methods of Analysis and Calculation.

For tests of the type performed in this fuse development program, the fuse assemblies must carry a heavy load of recording instrumentation to secure the required data. In actual use with a reactor the fuses would be unencumbered by this additional instrumentation and could be expected to perform much more effectively.

As compared with the annular-passage fuse, the control-rod-type fuse is a greatly simplified design that does not require such complex instrumentation. This fuse has the added advantage of being more economical to produce, by a factor of at least 100. The successful results of tests with the control-rod-type fuse strongly indicate the greater effectiveness and reliability of a simplified fuse design.

Following are two suggested methods by which the effectiveness of the fuses can be improved.

1. The thermostats could be designed to close after a temperature increase of as little as 5°F if the operating temperature of the reactor is sufficiently constant, as is usually the case in critical experiments and some experimental reactors.
2. The fuses can be interconnected so that closing the first thermostat will set off all the fuses at the same time. Run 5 gives evidence that the reactor was shut down by the first three fuses before the fourth one got warm enough to operate. Thus the first shutdown was not fully effective, and another might have been necessary a few seconds later.

The reduction in actuation temperature increase alone is enough to reduce the total temperature increase in the core by a factor of 4, and the simultaneous firing was demonstrated to reduce the temperature increase by an additional factor of 2.

APPENDIX A:

METHODS OF ANALYSIS AND CALCULATION

THERMOSTATS AND THERMOCOUPLE FUEL PLATES

Methods of Calculation and Physical Constants

Since the temperature measurements were made on thermocouple fuel plates rather than on the thermostats, a method is needed for calculating the thermostat temperatures from the thermocouple temperatures. Such a calculation involves corrections for the attenuation of neutrons by the uranium and for the different heat capacities of the materials. The enrichment of the uranium in all the samples is considered to have the same high value and will therefore be ignored.

The microscopic cross section of uranium is taken as 550 barns. With this value the absorption coefficient can be calculated:

$$\frac{18.7 \text{ g/cm}^3 \times 0.6023 \times 10^{24} \text{ atoms/mole} \times 550 \times 10^{-24} \text{ cm}^2/\text{atom}}{235 \text{ g/mole}} = 26.37 \text{ cm}^{-1}$$

This coefficient is used in calculating the transmission factor of the uranium by assuming that on the average the neutrons penetrate half the thickness of the uranium. It is realized that such an attenuation factor is not exact for a piece of material inside a reactor core, where neutrons come from all directions to the material. However, the thickness of the piece in each case is so slight when compared to its other dimensions that the error is small. Since the fuel pieces whose measured temperatures are used to calculate disk temperature are also thin and flat, the errors will be similar and the temperature ratios will be reasonably accurate so long as all transmission factors are calculated in the same manner. The temperature ratio is obtained by comparing the measured temperature increase of a piece of fuel with the calculated temperature increase experienced by a small piece of uranium of the same enrichment, insulated and having an insignificant attenuation factor, when subjected to the same neutron flux. The important factors that influence the temperature of the fuel piece are its heat capacity and attenuation factor, which are calculated as follows:

$$\text{Total heat capacity} = \sum_i (\text{mass of 'i'th material}) \times \text{specific heat of the 'i'th material}$$

$$\begin{aligned} (\text{cal } ^\circ\text{C}^{-1} \text{ cm}^{-2}) &= \text{thickness (in.)} \times 2.54 (\text{cm in.}^{-1}) \times \text{density (g cm}^{-3}) \times \text{specific heat} \\ (\text{cal g}^{-1} ^\circ\text{C}^{-1}) &= \text{total mass (g cm}^{-2}) \times \text{percentage composition} \times \text{specific heat} \\ (\text{cal g}^{-1} ^\circ\text{C}^{-1}) \end{aligned}$$

Summing the heat capacities of the constituent materials in the fuel plate gives the total heat capacity of the plate. All calculations are carried out for a unit area of 1 square centimeter. The transmission factor is calculated using the absorption coefficient of uranium, which is the only important absorber in the fuel plates, and half the equivalent uranium thickness (half the thickness that it would have in the absence of the structural materials):

$$\text{Transmission factor} = e^{-(\text{absorption coefficient} \times \text{half uranium thickness})} \\ = e^{-26.37 t}$$

where t is half the thickness of the uranium in the fuel plate. The temperature ratio for each of the fuel plates is calculated as follows:

$$\text{Temperature ratio} = \frac{\text{total heat capacity}}{\text{heat capacity of fuel}} \times \frac{1}{\text{transmission factor}}$$

The number obtained is the one by which the measured increase in fuel plate temperature is multiplied to obtain the maximum theoretical temperature increase obtainable in uranium due to the same neutron flux.

The fuel element samples tested or considered were composed of materials whose listed physical constants were used in the calculation of the respective temperature ratios. Properties of the fuel element test materials are shown in Table A1.

TABLE A1
FUEL ELEMENT TEST MATERIALS

Material	Density	Specific Heat
Uranium	18.7	0.028
Zirconium	6.44	0.068
UO ₂	10.9	0.07
Aluminum	2.8	0.214
Teflon	2.2	0.24

Temperature Ratios of the Thermostat and Thermocouple Fuel Plates

Thermostat Disk - The thermostat disk is 1 inch in diameter (5.066 cm²), and consists of a layer of zirconium 0.004 inch thick bonded to a layer of enriched uranium 0.008 inch thick. The heat capacity per unit area is:

$$0.004 \text{ in.} \times 2.54 \text{ cm in.}^{-1} \times 6.44 \text{ g cm}^{-3} \times 0.068 \text{ cal g}^{-1} \text{ }^{\circ}\text{C}^{-1} = 0.00445 \text{ cal }^{\circ}\text{C}^{-1} \text{ cm}^{-2} \text{ for Zr}$$

$$0.008 \text{ in.} \times 2.54 \text{ cm in.}^{-1} \times 18.7 \text{ g cm}^{-3} \times 0.028 \text{ cal g}^{-1} \text{ }^{\circ}\text{C}^{-1} = 0.01064 \text{ cal }^{\circ}\text{C}^{-1} \text{ cm}^{-2} \text{ for U}$$

$$\text{Total} = 0.01509 \text{ cal }^{\circ}\text{C}^{-1} \text{ cm}^{-2}$$

The transmission factor for the thermostat disk is:

$$e^{-26.37 \times 0.004 \text{ in.} \times 2.54 \text{ cm in.}^{-1}} = e^{-0.2679} = 0.765$$

The temperature ratio is:

$$\frac{0.01509}{0.01064} \times \frac{1}{0.765} = 1.854$$

Enriched Uranium Foil - The foil is 0.010 inch thick and 3/8 inch square. The heat capacity per unit area is:

$$0.010 \text{ in.} \times 2.54 \text{ cm in.}^{-1} \times 18.7 \text{ g cm}^{-3} \times 0.028 \text{ cal g}^{-1} \text{ }^{\circ}\text{C}^{-1} = 0.0133 \text{ cal }^{\circ}\text{C}^{-1} \text{ cm}^{-2}$$

The transmission factor for the uranium foil is:

$$e^{-26.37 \times 0.005 \text{ in.} \times 2.54 \text{ cm in.}^{-1}} = e^{-0.3349} = 0.7153, \text{ or approximately } 0.70$$

The temperature ratio needs no correction for heat capacity in this case:

$$\text{Temperature ratio} = \frac{1}{0.70} = 1.43$$

Teflon Fuel Element - This fuel element consisted of UO_2 powder suspended in solid Teflon in thin sheet form. The composition is as follows:

$$0.0549 \text{ g cm}^{-2} \text{ uranium, } 0.1611 \text{ g cm}^{-2} \text{ Teflon}$$

Since the uranium is in the form of UO_2 , its weight must be converted:

$$0.0549 \text{ g cm}^{-2} \times \frac{1}{0.88} = 0.0624 \text{ g cm}^{-2} \text{ UO}_2$$

The heat capacity per unit area may be computed:

$$0.0624 \text{ g cm}^{-2} \times 0.07 \text{ cal g}^{-1} \text{ } ^\circ\text{C}^{-1} = 0.004368 \text{ cal } ^\circ\text{C}^{-1} \text{ cm}^{-2} \text{ for UO}_2$$

$$0.1611 \text{ g cm}^{-2} \times 0.34 \text{ cal g}^{-1} \text{ } ^\circ\text{C}^{-1} = 0.03866 \text{ cal } ^\circ\text{C}^{-1} \text{ cm}^{-2} \text{ for Teflon}$$

$$\text{Total } 0.04303 \text{ cal } ^\circ\text{C}^{-1} \text{ cm}^{-2}$$

The heat capacity of the uranium alone in this plate, per unit area, is:

$$0.0549 \text{ g cm}^{-2} \times 0.028 \text{ cal g}^{-1} \text{ } ^\circ\text{C}^{-1} = 0.00154 \text{ cal } ^\circ\text{C}^{-1} \text{ cm}^{-2}$$

The transmission factor for the uranium in the fuel is:

$$e^{-26.37 \times 0.0549 \times \frac{0.5}{18.7}} = e^{-0.0387} = 0.9620$$

Since the transmission factor is nearly unity, the temperature ratio is:

$$\frac{0.04303}{0.004368} = 9.85$$

MTR-Type Fuel Elements - An assembly of these elements contains 130 grams of uranium. In the SPERT reactor this amount is distributed in 14 plates whose individual dimensions are 0.060 inch by 2.75 inches by 24.5 inches, a volume of 66.26 cm^3 per plate. From these data the fuel loading is found to be 0.0214 g cm^{-2} , which occupies 0.496 cm^3 in the fuel plate. The aluminum constitutes the remaining 65.76 cm^3 and has an area density of 0.423 g cm^{-2} . The heat capacity of this fuel plate is:

$$0.0214 \text{ g cm}^{-2} \times 0.028 \text{ cal g}^{-1} \text{ } ^\circ\text{C}^{-1} = 0.000599 \text{ cal } ^\circ\text{C}^{-1} \text{ cm}^{-2} \text{ for uranium}$$

$$0.423 \text{ g cm}^{-2} \times 0.214 \text{ cal g}^{-1} \text{ } ^\circ\text{C}^{-1} = 0.0906 \text{ cal } ^\circ\text{C}^{-1} \text{ cm}^{-2} \text{ for aluminum}$$

$$\text{Total} = 0.0912 \text{ cal } ^\circ\text{C}^{-1} \text{ cm}^{-2}$$

The transmission factor will be near unity because of the very low uranium loading; thus the temperature ratio is given by:

$$\frac{0.0912}{0.000599} = 152$$

Data on the fuel plates are summarized in Table A2.

TABLE A2

FUEL PLATE DATA

Fuel Element Type	Loading, g cm^{-2}	Heat Capacity, $\text{cal } ^\circ\text{C}^{-1} \text{ cm}^{-2}$	Temperature Ratio	Corrected Ratio
Uranium	~ 0	~ 0	1.000	0.54
Thermostat	0.380	0.01509	1.854	1.000
Uranium Foil	0.475	0.0133	1.43	0.771
Teflon	0.0549	0.04303	9.85	5.315
MTR Type	0.0214	0.0912	152	82

The corrected ratios are used to convert the measured temperatures to thermostat disk temperatures rather than to theoretical uranium temperatures.

REDUCTION OF TEMPERATURE DATA

Calibration and Reduction of the Thermocouple Records

All thermocouples were checked at Evendale before being shipped to assure consistent calibration. Previous tests in Idaho had indicated that placing an intermediate material between iron and constantan does not change the normal calibration of the thermocouples. The SPERT thermocouple amplifiers were adjusted so that when 1 millivolt was applied to the input terminals of the junction box in the pit building the galvanometer deflected 1 inch in the recorder. This calibration was originally selected because for the iron-constantan thermocouples it resulted in a scale of 100°F in the 3 inches that the galvanometers are allowed to deflect (33°F in $^{-1}$). To convert the deflections on the record to temperature, a Gerber Variable Scale was adjusted so that the amplitude of the deflection corresponded to 30 units on the spring scale. The index of this scale was then opposite the temperature on the fixed inch scale of the device. Readings were taken every 5 or 10 milliseconds along the record, and recorded on data sheets as original data. The type of fuel plate and its corresponding corrected ratio were also recorded for each column, along with the channel number of the oscillograph. The temperatures so recorded were then multiplied by the corrected ratio for the respective fuel plates, and these values were recorded on another data sheet as calculated data, representing the calculated temperature of the thermostat. These values were plotted against time, as shown in Figure A1, to obtain the temperature at which the thermostats closed.

Fig. A1 - Oscillograph traces, flux, and temperature, run 9

Correlation of Temperature with Flux

Since it was not possible to make a temperature measurement in addition to all the contact closure records taken in runs 9 and 10, calculations were made to test the correlation of temperature with flux, as mentioned earlier. This sort of correlation

also indicated the reliability of the calculated thermostat temperatures, since theoretically they have a linear relationship with the area under the curve when flux is plotted versus time. The flux curve used as the standard for the comparisons was channel 4, the log-N channel, since it was the only channel that always stayed on scale. This curve showed excellent correlation with the linear flux traces over the usable range. The flux was plotted against time on a linear scale, and the area under the curve was measured with a planimeter for time intervals of 10 to 20 milliseconds. When the sum of these areas was plotted against the corresponding calculated thermostat temperature, straight lines were obtained, an indication that the expected linear relationship between flux and temperature actually existed. These curves are given in Figure A2.

Fig. A2—Increase in trigger temperature versus area under flux curve

There is some difference in the slope of the curves, probably because the thermocouples were not oriented in the same manner with respect to the core on every run.

Since the data obtained in runs 4, 5, 6, and 8 have established that there is a linear relationship between the thermostat temperature and the area under the flux curve, the temperature curves for runs 9 and 10 may be sketched on the same graph with the flux curves, as shown in Figure A1. Because the thermostats tested in these runs were placed in an entirely different location in the core lattice, the previous ratio of temperature increase to area does not apply. The only way to establish a base point on these curves was to allow the first thermostat to close at about the same temperature as that observed in run 4, since this temperature value checked well with the manufacturer's specifications. This sort of approximation in run 9 led to the assumption that the temperature at the new core position was just 1/7 that measured in the fuse test positions. Inspection of the thermostats after run 9 revealed that the thermostats had probably been heated to a damaging temperature. Hence this method could not be used to establish a base point for run 10. Instead, the relationship established between the log-N flux channel and temperature in run 9 was used to establish the position of the temperature curve on the flux graph for run 10. Previous observation had established that there is a fairly constant relationship between these curves on the graphs. If the time at which the various thermostats closed their contacts is known, the corresponding temperature can be obtained by reference to the curves established by the methods just described. This temperature, of course, corresponds to the flux at the midplane of the reactor, which has a cosine-shaped flux distribution. The following correction was made for this effect.

It is assumed that the flux distribution is a cosine curve that falls to half of its maximum value at a point 12 inches from the reactor midplane. The general equation for such a distribution is:

$$\phi = \phi_0 \cos \frac{\pi x}{l}$$

where ϕ_0 is the flux at the midplane, x is the distance of the thermostat from the midplane, and l is the distance between nodes. Substitution of the required values of flux and distance into this equation shows that l is 36 inches. When 1 inch from the midplane is allowed for each additional thermostat in the stack of 20 that were tested in a single fuse can, the thermostats can be located. Substitution of these values into the flux equation gives the relative flux at each of these positions:

$$\frac{\phi}{\phi_0} = \cos \frac{\pi x}{36}$$

Multiplying this relative flux by the temperature T_0 determined from the graph gives the calculated temperature T at the position of the thermostat:

$$T = T_0 \left(\frac{\phi}{\phi_0} \right)$$

These data are tabulated in Table A3 for the thermostats in can A-34 in core position 0-6 on run 9, and a graphical presentation is given in Figure 22. Although the thermostat temperatures so obtained are subject to an error of 20 to 30 percent, the data indicate the relative behavior of the thermostats fairly accurately.

RELATIONSHIP OF POISON INSERTION TO REACTOR SHUTDOWN

Theory and Equations for Reactor Shutdown

Before this series of fuse tests was conducted, some preliminary analysis was done to ascertain whether the proposed method of measuring poison insertion time was

TABLE A3

DATA FOR THERMOSTATS IN CAN A-34 RUN 9

Channel No.	Time, ms	Step Size, mm	Standard Step, mm	Trigger Number	Distance from Center, in.	Flux Ratio	Graph Temperature Increase, °F	Calculated Temperature Increase, °F	Calculated Snap Temperature, °F
5	133.5	7	10	52	9	0.707	42.5	30.0	95
	145.3	13	25	40	6	0.866	69	59.8	125
	152.3	11	15	32	8	0.766	92	70.5	135.5
	170.7	4	5	30	10	0.643	200	129	194
	178.7	14	20	45	7	0.819	285	233	298
6	127.7	11	15	42	3	0.966	33	31.9	97
	133.0	13	25	51	1	0.996	41.3	41.1	106
	136.0	4	5	35	5	0.906	47	42.6	108
	165.0	14	20	44	2	0.985	158	156	221
	177.5	7	10	39	4	0.940	265	250	315
12	None--shorted								
13	143.0	13.5	25	12	-10	0.643	63	40.5	105.5
	146.0	14.5	20	20	-9	0.707	71	50.4	115
	190.3	11.5	15	22	-8	0.766	450	345	410
	-----	-----	10	1	-7	-----			
	-----	-----	5	17	-6	-----			

feasible. The question was whether, while the over-all reactor flux was dropping rapidly, an additional local drop could be seen at a sensor because of the curtain of boron powder passing it. Estimating the rate of decrease in flux seen by the sensor due to the boron alone was rather easy with simple mechanical considerations of its speed and proximity to the sensor. However, no really simple method was known for predicting how fast the over-all reactor flux level would be decreasing.

The method evolved is based on an equation from Glasstone and Edlund,* which gives the flux after a given amount of negative reactivity is inserted instantaneously into a reactor that has been operating at a constant power level for a long time. The equation has the form:

$$\frac{\phi}{\phi_0} = C_1 e^{a_1 t} - C_2 e^{-a_2 t}, \text{ where}$$

$$C_1 = B/(B-p) \quad a_1 = \lambda p/(B-p)$$

$$C_2 = p/(B-p) \quad a_2 = (B-p)/l$$

ϕ_0 = value of flux at peak power (reactor just critical)

ϕ = value of flux at any time t after peak power

p = value of reactivity at any time t (in this case always negative)

B = fraction of delayed neutrons

l = prompt neutron lifetime of the reactor

λ = decay constant of the delayed neutron group having the shortest half life

Substituting probable values for λ , B , and p into a_1 shows that the effect due to delayed neutrons is only about 5 percent at the end of 20 milliseconds after peak power; therefore this exponential will be neglected for the present. The equation then reduces to:

$$\frac{\phi}{\phi_0} = C_1 - C_2 e^{-a_2 t}$$

When fuses are tested in a reactor, the flux during the transient is recorded and the reactivity value of the fuses is measured after the transient has been completed.

On a semilog plot of the flux curve, the point at which it first reaches its maximum slope (and perhaps becomes a straight line for a short distance) is the time at which the poison insertion is completed. Measuring the slope at this point gives an experimental determination of a_2 ($a_2 = (B-p)/l$) from which B or l can be determined if the value of one is known. Some 20 or 30 milliseconds after the poison insertion is complete, the second term in the equation will be very small compared to C_1 , whose value can be determined as follows. Since C_1 is constant for several milliseconds after all the reactivity has been inserted, it is equal to the ratio of the flux level at some time when the delayed neutrons strongly take effect (the second term becomes insignificant) to the flux level at the time poison insertion has just been completed, and can therefore be measured from an experimental curve. When C_1 and a_2 are known, the remaining unknowns are the prompt neutron lifetime, the delay fraction, and the total reactivity inserted. If either neutron lifetime or reactivity value is known, the other two can be

*Samuel Glasstone and Milton C. Edlund, *The Elements of Nuclear Reactor Theory*, New York, D. Van Nostrand Company, Inc., 1952, p. 305.

determined from the two simultaneous equations for these two quantities. The final equation determined in this manner will fit experimental curves within 3 percent for about two decades down from the peak power of an excursion, as verified by fitting four BORAX reactor curves and two SPERT curves.

Fitting the Equation to Run 5

Figure A3 shows that all four fuses fired sometime during the excursion in run 5. The total reactivity value measured by means of the control rods was 0.36 percent Δk . Previous calculations indicated that a fuse containing boron 10 was worth twice as much as a fuse containing an equal amount of normal boron. On the basis of this ratio and the arbitrary assumption that a fuse that did not fire properly was worth only half its normal value, values were assigned to the four fuses that totaled 0.36 percent Δk :

Time, milliseconds	Poison	Reactivity Value, % Δk
48.5	B	0.07
51.3	B ¹⁰	0.15
57.0	B ¹⁰	0.06
69.5	B	0.08

Total Reactivity: 0.36

The final assumption for the first attempt to fit the recorded flux curve is that the poison in an individual fuse is inserted in 10 milliseconds at a constant rate.

With these data, the reactivity insertion curves of the individual fuses are plotted against time in Figure A3. Next, the sum of the reactivity values of the fuses is obtained as a function of time, and this value is plotted as the total reactivity versus time on the same graph. The value of this reactivity is determined at the moment the reactor reached peak power ($k = 1$), and this value is subtracted from all succeeding values on the graph to give a new curve, the net reactivity.

As a check to see that the assumptions thus far seem valid, the value of a_2 is obtained at several points along the experimental flux curve. The value of the neutron lifetime for this reactor was determined by SPERT personnel to be 5.5×10^{-5} second. The value of the delay fraction under these conditions is known from previous experience with this method to be less than 0.0008. Substitution of these values into the equation for a_2 provides the value of p , the total reactivity value of the fuses at any moment. This value is plotted on the same graph as the "experimental reactivity" curve. Since the resulting curve follows closely the "net reactivity" curve just obtained, the assumptions appear to have some validity. To simplify the calculations for the next step, a straight-line approximation is made to the net reactivity curve. This is called the linearized reactivity curve, also shown in Figure A3.

Values of reactivity are read off the linearized reactivity curve every millisecond and tabulated opposite the corresponding time, taking zero time when reactivity is zero. In the adjacent column the corresponding values of $(B - p)$ are tabulated. These quantities are used to tabulate values of C_1 and C_2 in the next two columns. The next column is a tabulation of $e^{-a_2 \Delta t}$, where Δt is the time interval between successive values of the variables being tabulated, 1 millisecond in this case. This function indicates how much the flux decayed during this time interval. The function is multiplied by C_2 and subtracted from C_1 (for the same time) to obtain the ratio of the values of

Fig. A3 - Reactivity versus time, run 5

the flux at the beginning and end of the time interval. This ratio is then multiplied by the value of the flux at the beginning of the time interval to obtain the value at the end of the time interval. In this manner values of flux are obtained at various times while the poison is being inserted. As soon as the poison insertion is complete, C_1 , C_2 , a_1 , and a_2 become constant, and the time interval must be measured from that instant. Thus the time interval continues to get longer, driving the exponential term to zero and dropping the flux ratio to the value of C_1 . By the time the delayed neutrons begin to govern the slope, the value of the flux has fallen to $C_1 \phi_f$, where ϕ_f is the value of the flux when the insertion of reactivity was completed. Figure A4 shows how well the calculated flux curve, based on the listed assumptions as to method of poison insertion, fits the experimental curve.

Use of the Empirical Equation in Run 4.

Obtaining data on poison insertion in run 4 was much more difficult because the more powerful explosives caused large spurious signals on all channels, including the flux. In addition, the reactivity insertion was somewhat greater because of the force of the explosives, so that the maximum power level was about 50 percent lower than in run 5, with less deflection of the recorder. First, a curve was drawn through all the points found for the flux curve, including the spurious oscillations of the galvanometer. From this curve a plot of reactivity versus time was obtained, as in run 5. On the same graph the reactivity insertion for each fuse was plotted; it was observed that the flux curve behaved as if the poison had been inserted about 10 milliseconds before the contact closures indicated. Alteration of the flux curve made very little improvement. A close re-examination of the contact closure traces revealed that the fuses had gone off sooner than originally thought. Changing the firing time of the fuses then caused their reactivity insertion as determined above for run 5 to correspond closely to that predicted from the slope of the flux curve. Values for C_1 and a_2 were determined from an examination of the flux curve, and a trial calculation of the flux curve was made. The resulting final flux curve is shown in Figure A5, and the reactivity insertion curve is shown in Figure 21.

Fig. A4—Normalized flux versus time, run 5

Fig. A5 - Flux and temperature versus time, run 4

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APPENDIX B:

FUSE PERFORMANCE ANALYSIS

Relative Flux at the Location of the Trigger

The primary factor influencing relative flux at the location of the trigger is the normal flux distribution in the reactor. To make the fuse more effective the trigger should be located in a region of maximum thermal neutron flux in the core. For this reason the thermostats used in these tests were located near the center of the core, which has a cosine distribution of flux. When the trigger is so placed, it naturally gets hot faster than if it were located in a low flux region, because more neutrons are available to cause fissions and produce heat.

Local perturbations produced by strong moderators or absorbers in the vicinity of the trigger also influence the flux seen by the trigger. Experiments indicate that if the trigger is located as close as 1 inch from the poison container, the flux seen by the trigger at that location with respect to the core is only half that which would have been available in the absence of the poison. The distance over which the poison can cause a flux depression depends upon the neutron diffusion properties of the materials present and the extent to which the arrangement is influenced by the proximity of uranium fuel. Moderating material tends to produce peaks in thermal flux, and in the presence of fuel the effect can increase the flux by as much as a factor of 2. This is one of the reasons for locating the thermostat in the acrylic plastic moderator rod for some of these tests. Hence, if the fuse trigger must be placed near the poison container because of reactor design considerations, the resulting flux depression can be offset, perhaps completely, by surrounding the trigger with a good moderator material. Calculated effects of such arrangements on local flux perturbations are shown in Figure B1. The magnitude of these effects depends strongly on geometrical factors that are very difficult to predict; only the easily obtainable maximum effects are discussed here. If it is intended that the moderator material should produce maximum effects on flux depression, measurements should be made on various geometries in a critical assembly before a final fuse design is chosen.

Energy Generated in the Trigger per Unit Average Flux in the Core

The primary factor here is the relative flux at the trigger location, as discussed in the foregoing paragraphs. Two other closely related factors are also important in determining how much energy is generated in the trigger when a given number of neutrons impinge on it. These are the total amount of uranium present in the trigger and a general effect that can be called the neutron utilization factor of the trigger. If the utilization factor could be neglected or held constant, the amount of energy generated would increase in direct proportion to the amount of enriched uranium incorporated in the trigger. This, however, is not the case.

The neutron utilization factor is influenced by many things, most important of which is the transmission factor of the uranium (discussed in Appendix A) for the specific triggers tested. A comparison of the data on the various fuel plates indicated that when

Fig. B1 - Calculated effects of moderator placement on local flux perturbations

more uranium is added per square centimeter, the outer layers stop some of the neutrons before they get to the inner layers, which therefore cannot generate their share of the heat. The transmission factor is greater for thinner pieces of uranium; thus the optimum value must be decided on the basis of both nuclear and mechanical properties. For the triggers described in this report, the thickness was made to correspond closely with that of other thermostat disks with whose properties the vendor was familiar. The resulting transmission factor was 76.5 percent, high enough to ensure acceptable utilization of the incoming neutrons.

Other factors that influence neutron utilization are the size, shape, location, and orientation of the trigger. These factors are less important in the center of the reactor, where equal numbers of neutrons arrive from all directions, than near the outside, where a decided current of neutrons may flow either into or out of the core. Whenever such a directional flow is suspected, the trigger should be oriented to present the shortest path for the neutrons to traverse. Care should be exercised in designing the shape of the trigger so that part of it does not unnecessarily shade another part from neutrons arriving from certain directions. Except for some locations near the outside of the core, a very thin flat sheet of uranium has the best shape.

Flux Required to Operate a Heat-Sensitive Trigger

An important factor here is the energy generated in the trigger per unit flux produced in the core, as discussed previously. Naturally, since more energy is produced in the trigger for a given amount produced in the core as a whole, the trigger has an advantage over the core with respect to relative temperature increase.

Another important factor is the total heat capacity of the other materials that make up the thermostat. The added heat capacity has two disadvantages: first, that these materials fail to contribute to the heat production; second, the materials also absorb heat produced in the uranium. The effect is significant since almost any material has a higher specific heat than uranium, as was shown in Table A1. The specific heat of uranium is 0.028, whereas iron, steel, and many other good structural materials have a specific heat of 0.11 or higher. Fortunately, the specific heat of the zirconium used in the thermostats was as low as 0.068, and its strength is high. Most materials having low specific heats, such as lead, bismuth, and tin, are poor structurally. The total heat capacity of a material depends on both its specific heat and its mass. For this reason the layer of zirconium was made thinner than that of the uranium. The only other method of reducing the total heat capacity of the disk is to insulate the structural material from the uranium. Tests of some experimental disks in which the two metals were separated by paper and held together with rivets or cement indicated that such a construction could be satisfactory. However, the advantage of this construction did not justify developing and perfecting the techniques required to form the thermostats accurately enough to operate at the designated temperature, when other units without this feature were commercially available.

A third factor that directly influences fuse performance is the temperature at which the fuse operates. During the time that the fuse temperature is rising, the temperature of the reactor core is rising at the same ratio. Thus when the temperature of the fuse doubles, that of the core does likewise. Since the reactor temperature will continue to rise for a short time after the fuse has fired, it is important that the fuse fire before the reactor reaches more than $1/3$ or $1/2$ the temperature that would cause damage. An advantage can be gained if the trigger can be designed with a composition that will heat faster than the fuel elements in the core for a given number of neutrons. As was shown earlier, the thermostat tested had a great advantage over all types of fuel elements tested, except the pure, unclad uranium.

Flux Required to Operate a Radiation-Sensitive Trigger

As with the heat-sensitive trigger, an important factor for the radiation-sensitive trigger is the energy generated in the trigger per unit flux produced in the core. However, the energy is utilized in a different manner in that it must produce a change in voltage or current, which can be used to set off the explosive. Preliminary investigations of both a voltage-sensitive and a current-sensitive trigger have been performed and both show more promise than a heat-sensitive trigger. Both have the advantages that they can act at a much lower flux level than the heat-sensitive device and that they do not lose any of the fission-produced energy to the other materials that make up the trigger.

Insertion Time of the Poison

Insertion time is greatly influenced by the force of the explosion. The time scale of the fuse action using various explosives shows that all of the slow-acting explosives may be eliminated from consideration. The explosion must be essentially instantaneous (completed in less than 1 millisecond); therefore the force as well as the total energy is important. In a series of tests, various amounts of the same explosive were used and the insertion time measured. These tests indicated that up to a certain point a greater amount of explosive increases the speed of insertion. Beyond this point, at which the speed is probably limited by the sonic velocity of the materials, more explosive is not beneficial. Other tests indicate that the straightness of the passage is very important in determining insertion speed. Since the relatively large boron particles have a much greater frictional effect than a gas, any turns are made at a great expense in speed. The design tested had no curves or obstructions to the path of the boron; thus the highest possible velocity was obtained.

The weight of the poison also determines its speed for a given amount of explosive propellant. The general effect is that, for a given configuration and propellant, velocity does not decrease as the amount of poison increases until a certain point is reached, beyond which the velocity falls off rapidly. The loading tested in this series was probably the maximum that could be used without a sacrifice of velocity.

Air pressure inside the passage into which the boron is inserted also slows down the boron travel. It is believed that the particles will move on the front of the blast wave at its sonic velocity if there is no air causing friction with the powder particles. As soon as some gas gets in front of the boron particles, they begin to slow down and suffer a considerable loss in velocity before they come to the end of the fuse chamber; hence the use of evacuated fuses. Experiments on the effects of air pressure were carried out using a compressed gas as a propellant.*

Total Reactivity Value of the Fuse

Two factors that directly influence reactivity value are the amount of poison and its neutron cross section. As discussed in the earlier section on the generation of energy in the trigger, the neutron utilization will be high as long as the transmission factor is high and more neutrons will be absorbed as more poison is inserted. By the same token, the higher the neutron absorption cross section of the poison, the more neutrons a given amount will absorb.

If all elements and isotopes with cross sections over 2000 barns are tabulated, together with boron, the list contains all of the really potent absorbers suitable for use as poisons in fuses. The list of poison materials is given in Table B1 with the atomic weight and density of these materials. The absorption coefficients can be calculated in cm^{-1} , which

*R. J. Spera, S. N. Stilwell, and W. Lamond Weiss, "Reactor Fuse Propellants and Configurations," GE-ANPD APEX-388, November 1958.

may be interpreted as $\text{cm}^2 \text{cm}^{-3}$, or cross section per unit volume. Dividing this quantity by the density in g cm^{-3} gives $\text{cm}^2 \text{g}^{-1}$, or cross section per unit mass. Since the mass of the poison required is important in fuses, this last factor is the primary one by which to judge gross poison effect. In Table B1 the poisons are arranged in the order of the values of this cross-section per unit mass, $\text{cm}^2 \text{g}^{-1}$.

TABLE B1
DATA FOR SELECTION OF REACTOR FUSE POISON

Element	Neutron Cross-Section (σ), barns	Absorption Coefficient (Σ), cm^{-1}	Absorption per gram (Σ/ρ), $\text{cm}^2 \text{g}^{-1}$
Gd ¹⁵⁷	180,000	5,480	690
Sm ¹⁴⁹	66,000	1,870	267
B ¹⁰	4,020	605	242
Gd	38,000	1,156	145.5
Cd ¹¹³	27,000	1,251	144.6
B	755	105	42.0
Sm	10,000	280	40.0
Eu ¹⁵¹	8,600	179	34.3
Cd	3,300	153	17.7
Eu	4,300	88.7	17.0
Hg ¹⁹⁹	2,000	82.3	6.05

After the poison is inserted, the next problem is to keep the poison in place if the fuse is in a vertical position. Testing showed that 1/16-inch mesh aluminum wire screen and a Refrasil glass cloth constituted a good distribution and retention system.* When these materials are arranged in staggered layers, some of the boron powder is stopped by each layer and tends to become uniformly distributed along the length of the fuse. The wire screen provides many small surfaces on which the boron can rest so that it will not fall back to the bottom of the fuse. One test showed that this retention system gave the fuse half the reactivity value that could be obtained from a check system in which the boron was manually distributed evenly before the fuse was assembled.

Another factor influencing the reactivity value of the fuse is the total area over which the poison is distributed. As the area increases, the layer of boron becomes thinner and the transmission factor is greater. As the transmission factor increases, the neutron utilization of the poison increases, and the optimum case is approached in which every atom of boron has an equal chance to absorb a neutron from the reactor. This effect was demonstrated in experiments that measured the value of the large annular-passage fuses in the BORAX reactor and in this series of SPERT reactor tests, which measured the reactivity value of the small control-rod-type fuses. The annular-passage fuse loaded with 10 grams of normal boron was worth about 0.7 percent Δk , whereas the small control-rod-type fuse with 8 grams of normal boron was worth only 0.15 percent Δk .

*R. J. Spera and S. N. Stilwell, "Poison Retention in Reactor Fuses," GE-ANPD APEX-358, June 1958.

The transmission coefficients of the boron distributions (assumed uniform) obtained in these two fuses may be calculated as follows. In the large fuse the boron is confined between a tube with an outside diameter of 2-1/2 inches and another tube with an inside diameter of 2-5/8 inches; thus the average diameter of the distribution is 2-9/16 inches, and the length is approximately 24 inches. The surface area of such a cylinder is 193.2 square inches, or 1246 square centimeters. In the smaller fuse the boron is confined inside a 7/8-inch-ID tube by a wire screen assembly varying from 1/16 inch to 1/4 inch in thickness. If the average thickness of the layer of poison is assumed to be 1/8 inch, the average diameter of the cylinder of poison is 3/4 inch. Such a cylinder 20 inches long has an area of 47.1 square inches, or 308 square centimeters. The 10 grams of boron in the large fuse has an area density of 8.02 milligrams per square centimeter, and the 8 grams in the small fuse has a density of 26 milligrams per square centimeter. The transmission factor for boron is calculated in much the same way as that for the uranium in the thermocouple fuel plates, with different constants. The thermal neutron cross section for normal boron is 750 barns, the density is 2.45 grams per cubic centimeter, and the chemical atomic weight is 10.82 grams per mole. The absorption coefficient is:

$$\frac{2.45 \text{ g cm}^{-3} \times 0.6023 \times 10^{24} \text{ atoms mole}^{-1} \times 750 \times 10^{-24} \text{ cm}^2 \text{ atom}^{-1}}{10.82 \text{ g mole}^{-1}} = 102.3 \text{ cm}^{-1}$$

The transmission factor for the distribution of boron in the fuses is calculated using the full computed thickness of the boron:

$$e^{-102.3 \times 0.00802/2.45} = e^{-0.335} = 0.7155$$

$$e^{-102.3 \times 0.0260/2.45} = e^{-1.086} = 0.3373$$

Thus the large fuse absorbs about 28 percent of the neutrons striking its surface, and the small fuse absorbs about 66 percent of the neutrons striking it.

A volume effect also contributes to the value of a fuse. The volume of the poison cylinder for the large fuse is 123.8 cubic inches or 2030 cubic centimeters; that for the small fuse is 8.84 cubic inches or 145 cubic centimeters. Calculation of an absorbing factor from volume and transmission coefficient provides the following results:

$$28\% \times 2030 \text{ cm}^3 = 577$$

$$66\% \times 145 \text{ cm}^3 = 96$$

The ratio of these two quantities (approximately 6) compares favorably with the ratio of the reactivity values (approximately 5) of the two fuses. Hence, this may be a good set of properties with which to compare the value of fuses in future designs.

Rate of Insertion of Reactivity

When several fuses act simultaneously in the same reactor during the same excursion, the number of fuses fired has a direct effect on the rate of insertion of reactivity. In such a method of firing, the insertion time of the poison in each fuse also has a direct effect on the over-all rate of inserting reactivity, as does the reactivity value of the poison in each fuse. When fuses are allowed to fire independently, as they were in these tests, the flux level at which each trigger actuates also has an important effect on the rate of insertion of reactivity. This effect was demonstrated in the analysis of the reactivity insertion in runs 4 and 5, in which differences in the local flux on the triggers caused considerable variation in the reactor flux level at which the triggers actuated. This spacing of the trigger actuations in time produces a lower rate of reactivity insertion, since the insertion is much more spread out (see figures 21 and A3.)

Effectiveness of the Fuse: Limiting the Total Energy of an Excursion

The period of the excursion becomes important only when it is less than one-half the insertion time for the poison, 10 milliseconds in this case. When the period is much shorter than this, the reactor power level can rise several factors of e before enough poison is inserted to stop the rise, and in this way may raise the final temperature of the fuel elements equally far above that which they had attained at the time the trigger actuated. Figure B2, which presents data derived from experiment, indicates that if the poison is inserted instantaneously the reactor flux ceases to increase about the time that the reactivity value of the poison equals the value of the delay fraction. High rates of poison insertion are sought since more poison is required as the insertion time increases. Other data obtained on the BORAX reactor strongly indicate that some additional factor not yet identified is also important. Peak reactor power in every case was reached less than 10 milliseconds after poison insertion was begun. Hence, for the purpose of estimating the effectiveness of future fuse installations, it was assumed the reactor power remained on the initial exponential rate of increase for 3 milliseconds (Δt) after the fuse trigger actuated.

Fig. B2 - Time interval versus reactivity increment

The variation of effectiveness with period may be calculated using empirical equations developed during these tests. As explained earlier, the part of the flux curve for an excursion from the peak down may be predicted by means of an iteration method that accounts for the rate of reactivity insertion and the neutron lifetime of the reactor while making an arbitrary assumption as to the delayed neutron fraction. A very simple and only slightly pessimistic assumption about the curve before the peak power is reached is that it continues on an exponential at the same period it had before poison insertion began (see Figure 21).

The two equations for these calculations are:

Before the peak: $\phi = \phi_0 e^{t/\tau}$, where τ is the reactor period

After the peak: $\phi = \phi_0 (C_1 e^{a_1 t} - C_2 e^{-a_2 t})$

The time t in the first equation starts at an arbitrary zero before the peak and continues to the peak. After the peak power is reached, the second equation is used and the value of time again starts at zero. Figure A4 illustrates how well this curve follows one obtained experimentally in run 5, and shows the change to be expected with a set of fuses giving maximum performance for a given period. Figure 22 was obtained by constructing a number of the previous flux curves and measuring the area under them to represent the total energy of the excursion. Here the strong influence of the shorter periods on fuse effectiveness is evident.

With this set of equations the effect of the flux level at which the trigger is actuated on the total energy of the excursion can be calculated (see Figure 22). The total energy is directly proportional to the temperature increase at which the trigger actuates. Thus the thermostat should be designed to operate a very few degrees above the normal reactor operating temperature for maximum effectiveness.

These equations can also be used to calculate the effect of rate of insertion of reactivity and reactor neutron lifetime on the total energy of an excursion at various periods. These effects, although not as pronounced as those just treated, are important and have been demonstrated experimentally in runs 4 and 5. The ratio of the trigger actuation temperature to the final temperature in these two runs changed more than a factor of 2; the change was due entirely to the rate and amount of poison insertion. Figure B3 shows the effect of insertion time on the shape of the expected flux curve; Figure B4 shows the effect of reactor neutron lifetime on this curve. Finding the area under a group of these curves makes it possible to express directly the effect of these factors on the total energy of a reactor excursion as indicated in Figures B5, B6, and B7. The effect of amount of reactivity and its rate of insertion are shown in Figures B8 and B9.

Integration of the Fuse with the Reactor Core

Reactor cores are sometimes designed for nuclear and thermodynamic characteristics before careful thought is given to integrating the control and safety systems into the design. Therefore, space may be a problem. The two fuse shapes described in this report were designed on the basis of possible space limitations. The large annular-passage fuse can surround one or more fuel elements, depending on their size, while occupying very little space itself. (The total wall thickness is 3/16 inch.) The small control-rod-type fuse will fit between fuel elements or assemblies. This fuse can be made as small as 3/4 inch outside diameter with the present arrangement, and can be reduced to 1/2 inch outside diameter if the thermostat or trigger are located elsewhere. If a radiation-sensitive trigger is used, relocation may be necessary to reduce its sensitivity sufficiently to prevent premature operation.

The fuse should be located at the particular point in the core in which it will be most effective. When less effective positions are chosen, the number of fuses must be increased in order to obtain the same reactivity value for the group. In a well-reflected reactor, location probably will not be a problem; critical experiments have shown that in such a reactor the fuse may be worth as much outside the core near the reflector as it would be if placed in the center of the core. In other types of reactors, locations within the core are required.

Fig. B3 – Normalized flux versus time as a function of various insertion times

Fig. B4 - Normalized flux versus time as a function of prompt neutron lifetime

Fig. B5 – Total increase in trigger temperature versus negative reactivity as a function of insertion time

Fig. B6 - Total increase in trigger temperature versus prompt neutron lifetime

Fig. B7 - Total increase in trigger temperature versus poison insertion time

Fig. B8—Total increase in trigger temperature versus negative reactivity as a function of insertion rate

Fig. B9 - Total increase in trigger temperature versus rate of insertion as a function of reactivity

In determining the required total reactivity value of the fuses a nuclear analysis of the core must be performed and the conceivable means of initiating an excursion must be carefully examined. When the maximum total value of reactivity that can conceivably be added to the core by any means (including implosion of the core by shaped charges) has been calculated, a number of fuses should be provided that will have approximately 1.5 to 2.0 times this value of reactivity. This amount of reactivity leaves an ample safety factor to insure that there will be at least enough negative reactivity available in the fuses to keep the reactor from starting up again following the initial fast shutdown. If the calculations are correct, this amount also insures that the shutdown will be very rapid because of the very high rate of poison insertion. Although a very rapid shutdown was obtained in run 4 of this test series, the total amount of reactivity inserted was still less than that which initiated the excursion; the reactor would therefore have started up again a few seconds later, as soon as the delayed fraction of the neutrons had built up to its normal value.

Integration of the Fuse with Reactor Controls and the Console

If fuses are to be relied upon, it is desirable that the control console of the reactor indicate their condition. Figure B10 shows that fuse indication on the console can readily be accomplished through the use of neon indicator lamps and current-limiting resistors connected in series with each explosive primer across 110 volts a. c. . Such lamps require a current of only 2 or 3 milliamperes, a current that has no effect whatever on the primers. When the resistance of the primer reaches some value much higher than normal, the lamp will be extinguished. While the lamp is lit, the primer is in good condition. If the contact in the trigger is closed, the primer will pass the high current required for rapid detonation, approximately 1 to 2 amperes. Manufacturers of such primers state that failure of the primer to operate is essentially impossible as long as there is an indication of continuity through the primer. A power failure is indicated by the lamp going out.

Fig. B10—Circuit diagram of primers and indicators across 110 volts a.c. with and without relay

The use of a low-voltage source and a low-resistance relay in series with the primer, as shown in Figure B11 is a more sensitive method of indicating fuse condition. The relay contacts remain closed and keep a pilot light on as long as the primer resistance is sufficiently low. If the contact of the bridge wire in the primer deteriorates in a way that increases the resistance of the primer by as much as a factor of 2, the current through the relay is reduced sufficiently to open its contacts and turn off the pilot

light on the console. In addition to increased sensitivity to primer resistance, this method offers the advantage that it operates a relay that can be used to scram the reactor, deactivate control rod actuators, or put them on automatic "all decrease." Such actions can also be obtained with the high-voltage source (110 volts a. c.) and a relay (see Figure B10), but will not occur until the resistance of the primer has reached several thousand ohms (nominal value 15 ohms).

Fig. B11 – Circuit diagram of primers and relays across a low-voltage source

Operator error is protected not only by the normal fuse action, but also by the ability of the electronic scram to set off the fuses at any power level or period that would normally actuate only scram rods in the reactor (see Figure B12). The power level at which the fuses would be triggered in this manner would undoubtedly be somewhat lower than that at which the normal trigger can operate, especially if the heat-sensitive type is used. The only purpose of such an arrangement would be the added protection of having the fuses fire sooner than they would as a result of the action of their own triggers. This arrangement should in no way interfere with the normal action of the fuse triggers.

Fuse Reliability

To improve further the reliability and effectiveness of fuses, wires should be connected from every trigger to every primer so that the first thermostat that acts will immediately detonate all the primers and insert all the reactivity at once. Such an arrangement also provides maximum reliability, since all the poison will be inserted if at least one trigger works. Figure B13 presents a circuit diagram for the interconnection of fuses and triggers. Performance of the primers is already insured by constant inspection but better protection would be given if two were installed in each fuse. In this way the reliability of the fuses individually is very high and a large number of multiple failures does not impair their effectiveness. Even more failures are permissible before the effectiveness of the group goes to zero. System reliability could be increased still further by connecting the fuses to the manual scram button after the initial startup operations have been completed, so that they can be set off manually

if all the triggers and scram system of the reactor fail. Complete failure of even one trigger is unlikely, since most have a stronger tendency to operate as the power level increases; at worst, trigger action should only be somewhat delayed.

Fig. B12 - Circuit diagram for connection of fuses to reactor control system

Fig. B13 - Circuit diagram for interconnection of fuses and triggers

APPENDIX C:

SUMMARY OF FUSE AND TRIGGER DESIGNS; ADAPTION TO POWER REACTORS

FUSE TRIGGER DESIGNS

In addition to triggers for the two principal types of fuses thus far discussed, other types of triggers were designed under the fuse development program. In order that this report may compile as much as possible of the currently available information on fuses, these fuse trigger designs are described in the following paragraphs.

The prime function of the fuse trigger is the detection and amplification of energy. A high degree of amplification is required to increase the heat or radiation energy of a relatively small number of fissions to the energy required to insert 10 grams of boron a distance of 25 or 30 inches in 10 milliseconds. Thus, more than one device or stage of amplification is necessary in most fuse arrangements.

Fusible-Metal Type Triggers

The fusible metal type of trigger employs the heat generated in the fissioning uranium to melt all or part of a trigger unit, which will initiate the release of poison into the reactor.

Fusible Disk or Diaphragm - In this trigger, powdered uranium oxide is mixed with the fusible metal to form a disk, which closes a relatively large opening to a compressed-gas chamber. When fission heat brings the disk sufficiently close to its melting point, it will yield under the stress of the compressed gas and release the gas rapidly. This is perhaps the slowest type of heat-sensitive trigger, since all the disk must be heated to a temperature near the melting point before a release of poison can be effected. This trigger also requires several grams of uranium and the use of materials that have a rather high creep rate (lead, bismuth, tin, etc.). This type of trigger was used in the BORAX fuse tests.

Fusible Solder Joints - The basic idea of this type of trigger is to join two parts with solder in such a way that enriched uranium is in direct contact with the solder. In this way only the surface of the material contacting the uranium need be melted to effect a release, and the total heat generation per unit mass of uranium is less than that with the fusible plug. If the specific heat or conductivity of the material in contact with the uranium is very low, the heat requirement is further reduced, an advantage in fusing low-power reactors where it is not necessary to remove heat from the trigger during continuous operation.

Dr. Walter H. Zinn developed a device consisting of two blocks soldered together with a piece of enriched uranium placed in the joint. Spring tension, which tended to pull the blocks apart during the test, was provided. The assembly was placed in the BORAX reactor, and the blocks were successfully melted apart during an excursion. This parting action could be used to operate a valve directly to release compressed gas, or it could close electrical contacts to produce some other action, such as setting off an explosive.

Thermal Expansion Trigger Devices

All of the thermal expansion trigger devices take advantage of the difference in rate of expansion of two different parts, whether caused by the difference in expansion coefficients of the materials or by the difference in temperatures reached.

Flat Bimetallic Strips - Basically, this type of device consists of two flat pieces of metal having different thermal expansion coefficients. The metal pieces are bonded together along their entire length to form a thermostat element. The bimetal may be mounted at one or both ends in either a rigid or an elastic support device. For the most sensitive construction requiring a minimum of fissions for actuation, one of the metals should be enriched uranium and the other some material having a smaller expansion coefficient. The motion of the bimetal can be used to close an electrical circuit or to release a spring-loaded actuating system. Closing the electrical circuit can detonate a solid or gaseous propellant or can operate a solenoid valve to release compressed gas. The spring-loaded actuation system can be used to drive a firing pin, which detonates solid or liquid propellant or releases a fast-operating release valve on a compressed-gas chamber.

Bourdon Tube Trigger - This device is similar to the bimetallic strip in that a differential expansion produces a small motion and a small force. The most promising design consists of a stainless steel tube, flattened, formed into a spiral, and filled with a liquid mixture of sodium and potassium containing some enriched uranium. Fissions produced in the uranium heat the NaK, causing it to expand and bend the tube.

Specially Shaped Uranium Strips ("Sine" and "W" Blade Switches) - Experiments have shown that the blades in some snap-action switches are in tension and that a very small linear motion that tends to change this tension is greatly magnified at the electrical contact. If such a switch blade is constructed of enriched uranium and mounted in tension on a support that does not expand appreciably, such as Invar, fission heating of the blade will cause it to expand, reduce the tension, and produce a much larger motion of the switch contact button. The action of such an arrangement is smooth, in contrast to snap action, but the device is sensitive enough that a 40° increase in temperature should easily close the contacts on a switch only 1 inch long.

Simulated Pulley-Block Motion Magnifier - This device is constructed in a manner similar to a block and tackle arrangement, with both pulley blocks fixed and the rope capable of expansion. The rope in this case consists of a length of enriched uranium wire held in tension by a spring. The pulleys consist only of short rigid members simulating pulley diameters pivoted about their transverse axis by short flat springs. Such an arrangement can be used because the total motion involved is very small, only enough to close electrical contacts or release a mechanical trigger mechanism. This device has the advantage of large motion combined with relatively large forces, and reduces the energy amplification required.

Uranium Rod and Glass Diaphragm - In this device, a short enriched uranium rod is held tightly against a glass diaphragm, which blocks a large passage connecting with a compressed-gas storage chamber. The support for the rod is constructed so that the structure is insensitive to ambient temperatures. When the rod is heated by fissions, it expands, breaks the glass, and releases the compressed gas.

Large Liquid Expansion Systems - These devices utilize enriched uranium dissolved in a container of liquid connected to a bellows system so that the motion can be greatly magnified. With such systems, magnifications as high as 1000 are possible. This magnified motion is used to close electrical contacts or release a mechanical trigger. The

system has the disadvantage that most liquids having a low specific heat and a high expansion coefficient are subject to radiation damage and release gas, which would cause false actuation. Such a system was constructed and laboratory tested. In these tests a bellows system was used to produce a large motion of a second liquid column, which simulated a poison rod. Such a system has some possibilities as an automatic control device for low-power reactors.

Detonation of Explosives by Direct Heating

Several systems of this type have been tested in the laboratory, and one was tested in a reactor. Solid explosive material was detonated in the SPERT reactor when it was packed tightly against a piece of uranium foil.* Liquid explosive could be detonated by the dissolved or suspended uranium. Explosive gaseous mixtures can be ignited by fine wires of uranium arranged in the enclosure. In all cases the temperature for detonation is considerably higher than the actuation temperature of a thermostat or some of the other expansion devices previously described. The device is very compact and direct acting.

Heat-Sensitive Electrical Triggers

One sensitive trigger of this type is constructed by loading thermistor material with enriched uranium and using the fission heating to change the resistance of the thermistor. As an alternative method an enriched uranium sheet or wire can be coated with a thin layer of thermistor material, if the coating can be made thin enough that heat conduction is not a problem. Regardless of how the thermistor is heated by the uranium, it can be used to produce several effects to initiate poison insertion:

1. The change in resistance of the thermistor could be used to raise the voltage on the grid of a cold-cathode thyatron above the firing potential. The current through the thyatron would be sufficient to close relay contacts, which would pass the large current required to detonate an explosive. Alternatively, firing the thyatron could directly actuate a fast solenoid valve that releases compressed gas into the system.
2. The decrease in resistance of the thermistor can be used to short across the scram rod magnets and cause them to drop. This does not initiate a fuse action, but is a separate scram system for the reactor.
3. The decrease in resistance of the thermistor when heated by fissioning uranium can be used to increase the current flow through a relay, operating it and firing fuses or releasing scram rods into the reactor core.

Radiation-Sensitive Triggers

Voltage-Type Triggers - Triggers of this type depend for their operation on the maintenance of a voltage just below their operating level. An increase in the radiation level to which the trigger is exposed causes the operating level to drop below the applied voltage, and the trigger operates to initiate the insertion of poison. One promising trigger of this type utilizes a corona-discharge voltage regulator tube that is coated inside with boron or uranium. Neutrons hitting these materials cause ionizing radiations, which have been demonstrated by the manufacturer to lower the initial firing voltage of the tube over 10 percent. When the tube conducts, the current can be used to operate a relay or perhaps to fire an explosive directly, depending upon the size of tube used. An operating circuit for a tube arrangement of this type is shown in Figure C1.

*R. J. Spera, S. N. Stilwell, and R. L. Waterfield, "SPERT I Fuse Trigger Tests," GE-ANPD APEX-446, January, 1959.

Fig. C1 - Operating circuit for voltage-sensitive corona-discharge regulator tube

Current-Type Triggers - Triggers of this type depend upon the generation of enough current from a very large ion or fission chamber to operate a current-sensitive relay. When the flux level rises sufficiently, the current from the chamber will be enough to operate the relay directly, without amplification. The contacts will close and pass the current required to set off the explosive and insert the poison. Probably the same battery can be used to operate both the chamber and the explosive. An operating circuit for a current-sensitive ion-chamber trigger is shown in Figure C2.

Fig. C2 - Operating circuit for current-sensitive ion-chamber trigger

It is believed that the voltage-type trigger will operate at a lower flux level than the current-type device, and it is known that the components are smaller and less expensive. The corona-discharge tube is a standard device that is much smaller and cheaper than a very large ion chamber. It will pass sufficient current to operate a low-cost relay rather than an expensive ultra-sensitive relay of the type required by the chamber-type detector.

FUSE SYSTEM DESIGNS

Integral Fuses

This group encompasses all fuse mechanisms that are an integral part of the core or fuel structure and are not an addition to them. Fuses of this type might better be described as special core designs to produce a very large negative temperature coefficient of reactivity. One example of such a design consists merely of a plastic fuel element placed in the center of the reactor core. The special fuel element has twice as much fuel per unit mass of plastic as does the remainder of the core. In case of an excursion, this section gets hottest, and foams first; the expansion separates the core to a less reactive

position. This arrangement involves no extra parts in the core, only a modification of one part. Such a modification could not be used in a power reactor, of course, because of the poor flux distribution.

Another possible integral-type fuse entails the use of hollow cylindrical fuel elements with special cladding. If the inside of the tube is clad with a material having a thermal expansion coefficient different from that of the material on the outside, the diameter of the tube will tend to change as its temperature changes. Such a change will produce some change in the reactivity of the core and will produce a fuse effect.

Stored-Mechanical-Energy Fuses

Fuses of this type may also be classed as special scram rods or scram devices. One type is actually a control rod but is not propelled by springs as are most other scram rods. The mechanical energy required for propulsion of this rod is stored in a heavy flywheel rotating about an extension on the end of the control rod. This extension has spiral grooves with a very steep pitch, so that when the flywheel is engaged to the grooves only two or three revolutions are required to drive the rod all the way into the reactor core. Simple calculations show that the energy stored per unit volume of space is much greater than anything obtainable with the usual coil springs. The flywheels are kept in motion by electric motors, and a power failure automatically engages the flywheels to the spiral to insert the rods. The rods can be cocked again by releasing the lugs engaging the flywheel to the spiral groove and withdrawing the rod by some small motor-driven mechanism.

A very similar fuse system that provides about the same speed uses two flywheels, a combination fuel-poison belt, and an idler pulley that actuates the system. The flywheels are kept rotating constantly, almost in contact with the poison belt. A trigger device releases the idler pulley, which forces the belt into contact with the flywheels and drives the poison part of the belt into the reactor core. To prevent slippage, a similar arrangement can be made using a chain.

Another method of storing energy in a flywheel provides even faster poison insertion. Steel balls containing poison are held in a tube around the periphery of a flywheel near the end of the reactor core. A trigger device releases a small trap door mechanically synchronized with the rotation of the wheel so that the poison balls, which already have a high velocity, are directed down a tangential tube into the reactor core. The insertion speed in this case is the full linear speed of the balls while on the flywheel, and can closely rival that of boron powder insertion. Some rather difficult mechanical problems may have to be solved before this device is perfected, but they are easily understood and do not seem insurmountable.

An energy-storage system mentioned several times in this report consists of a container of compressed gas that can be released quickly. Several variations of this concept are possible. In a fuse tested in the BORAX reactor, an exit tube was provided inside the compressed-air chamber for the poison, which was carried out with the compressed air. This arrangement was necessary because the trigger was a fusible disk, which must be located as close as possible to the edge of the core to receive high neutron flux. The disk formed the top limit of the compressed air chamber; hence if the poison were placed above the disk it would be situated within the limits of the core. For highest effectiveness the poison should be kept out of the core region to produce a maximum change in reactivity between the unfired and fired conditions of the fuse. By use of a remote trigger device, the poison can be placed in a cartridge outside of the compressed air container, and the insertion will be equally effective. This sort of geometry was used in the solid explosive propellant fuses tested in the SPERT reactor.

Although a problem is entailed in releasing the compressed gas quickly enough for effective fuse action, a trigger device, described in the previous section, performs the release satisfactorily. The compressed-gas storage method is much more compact than the mechanical devices; however, the capacity for energy storage is also less. Thus this method requires the use of a lighter poison, such as enriched boron powder, which has the highest poison value per gram of any substance except some separated isotopes of gadolinium or xenon.

FUSES FOR POWER REACTORS

The material presented thus far has been directed specifically toward the application of fuses to zero-power or very low-power reactors or critical assemblies. The maximum power of the reactor that is to be fused is limited by the nature of the heat-sensitive triggers, which are designed to prevent the dissipation of the heat generated in the disk. If energy were produced in the triggers continuously at any appreciable rate, the trigger temperature would eventually rise sufficiently to cause it to act and insert poison into the reactor core.

Triggers

One method of preventing unwanted trigger action would be to place the thermostat at a remote position in the shield. In this position it would receive fewer neutrons than if it were closer to the core and less heat would be produced in it. However, a large increase in power level in the core would be required to heat the fuse, and since the core is presumed to be operating near its maximum safe power level, such an excursion would be damaging.

An alternative method is to provide a conducting fin that will remove the heat from the trigger as it is formed. In such a system a careful balance must be achieved between the rate of heat conduction and the rate of response of the trigger to a fast rise in reactor power. If the cooling fin is too large, it will conduct heat so rapidly that a large power excursion will be necessary to increase the temperature of the trigger to its operating point. If the cooling fin is too small, the trigger will get hot and actuate before the reactor has stabilized at its full normal operating power level. For the optimum condition the fin should be just large enough to keep the trigger from actuating while the reactor is operating in a normal manner, so that a minimum power excursion is required to raise the trigger to the actuating temperature. The optimum arrangement for fusing a power reactor probably combines removal of the trigger a short distance from the core region and choice of the proper cooling fin.

The radiation-sensitive trigger can probably be adapted to a power reactor with less difficulty. The trigger can be placed in a remote position to prevent exposure to excessive flux. The actuation point can be set roughly 5 percent above the normal operating point, thus preventing large power excursions. How close to the actuation point the trigger can be operated depends on the stability of the firing voltage with respect to flux and time and on the stability of the voltage source.

Fuses

The remainder of the fuse can be placed within a power reactor with little difficulty as long as the ambient temperature of the fuse does not exceed approximately 500°F. At more elevated temperatures most metals become porous, and the vacuum inside the fuse could not be maintained without continuous pumping. Loss of the vacuum increases the time required to insert poison. The explosives may not withstand prolonged exposure to 500° temperatures or to large doses of radiation. Little data on heat and radiation resistance are currently available. However, temperature presents no

serious restriction since in water-cooled reactors, which at present are most popular for research work, temperature is generally limited to less than 200°F. The temperature difficulties may be compensated for more easily in the fuse than in the trigger, since special cooling may be provided without affecting fuse operation. All that is necessary is to provide a coolant channel into which the fuse will fit and to control the flow through the channel in such a way that the temperature stays within the limits required by the explosive material.

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NOTE

This is the sixth and final report in a series that describes the work performed by GE-ANPD in reactor fuse development during the period from November 1952 to February 1957. The reports are available from the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

Donaven, T. W., Stilwell, S. N., Stuart, J. G., "Internal Fuses for Low-Power Reactors," APEX-397, August 1958, 75 cents.

Spera, R. J., Stilwell, S. N., Weiss, W. Lamond, "Reactor Fuse Propellants and Configurations," APEX-388, November 1958, \$1.00.

Spera, R. J., Stilwell, S. N., "Poison Retention In Reactor Fuses," APEX-358, June 1958, 50 cents.

Stilwell, S. N., Waterfield, R. L., "Borax Fuse Tests," APEX-441, December 1958, \$1.25.

Spera, R. J., Stilwell, S. N., Waterfield, R. L. "SPERT I Fuse Trigger Tests," APEX-446, January 1959, \$1.50.

Stilwell, S. N., Waterfield, R. L., "Fast-Period Reactor Safety Fuse Tests," APEX-492, May 1959, \$2.25.