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Internal Fuses For Low-Power Reactors

GENERAL ELECTRIC

ATOMIC PRODUCTS DIVISION

AIRCRAFT NUCLEAR PROPULSION DEPARTMENT

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INTERNAL FUSES FOR LOW-POWER REACTORS

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Introduction

THE FUNCTION OF INTERNAL FUSES

In the event of a reactor excursion, some means of limiting the energy released is necessary. The most obvious means is to build a large negative temperature coefficient of reactivity into the reactor. However, not all reactors can be designed in this manner, and even a reactor having such a coefficient may be capable of liberating many megawatt-seconds of energy during a runaway. Thus it is apparent that some device is needed to shut down the reactor before a dangerous power level is reached. For maximum protection, the device should be sabotage-resistant and thus should have no external connections. Such a device is known as an internal fuse.

An internal fuse must prevent a hazardous release of energy and radioactive matter. For a reactor operating near its temperature limit, the fuse must act at a power level only a fraction above the normal operating power; on the other hand, a reactor operating at low power could conceivably sustain a power excursion to a level 10^4 or 10^6 times the operating level without causing hazardous conditions.

The specific interest of this study is an internal fuse that will prevent fuel element vaporization and thus radioactive cloud formation from reactors tested at low power. The internal fuses considered in this report are mainly of the type that will shut down a reactor after its power has risen by a factor of 10^4 to 10^7 from a low initial value. Some of the fuses considered can be adapted for other types of reactors.

The shortest reactor period considered possible during sabotage or accident is about 2 milliseconds. Under such conditions it would be desirable for a reactor to have an internal fuse that would stop a short-period excursion before the power level reached the range of 10^4 to 10^6 times normal power. The time requirements for operation of an internal fuse depend largely upon the power level at which the fuse starts to operate. It is evident that the time available for shutting down the reactor is much less for internal fuses that are activated only at a high power level than for fuses that are activated at a low power level. Therefore, it is desirable that an internal fuse operate in the shortest practical time and at a low power level. A practical fuse-reaction time would be of the order of magnitude of the shortest period that the reactor would have during a runaway. Therefore, work has been directed toward an internal fuse that will have a reaction time of 5 milliseconds or less.

TYPES OF INTERNAL FUSES

Internal fuses can be divided into two classes: those that derive all of their energy of action from nuclear fission, and those that use the energy caused by nuclear fission to trigger an auxiliary energy source to complete their action. In general, fuses of the first class have the advantage of maximum simplicity. Fuses of the second class have the advantage of operating at a considerably lower power level and in a much shorter time. The internal fuses that use an auxiliary energy source show the greatest promise, and

the work described in this report has been directed toward the development of fuses of this type.

One fuse of the second class utilizes the auxiliary energy to propel a poison into the reactor. A fuse of this type might be required to move a 4-ounce charge of poison at a velocity of 1000 feet per second in order to shut down the reactor in a sufficiently short time. The kinetic energy of such a charge is approximately 4000 foot-pounds.

There is an impressive resemblance between the problem of propelling a poison into the reactor and a problem of ballistics. A 12-gauge shotgun load consisting of 1-1/8 to 2 ounces of shot attains a velocity greater than 1300 feet per second. A 20-millimeter shell has a 4-1/2-ounce projectile that attains a velocity of about 3000 feet per second. The masses and velocities applying to poison insertion are quite similar. This similarity has led to the division of an internal fuse into the following parts:

1. Trigger: A sensing device that gives a signal when the flux or temperature exceed a given level.
2. Primer: A device that initiates the action of the main auxiliary energy source (propellant) when the trigger gives a signal.
3. Propellant: The auxiliary energy source that disperses the poison, or ejects fuel or moderator, to shut down the runaway reactor.

This cascading of energy offers great promise in increasing the speed of response of internal fuses and in decreasing the power level at which they operate. This division also allows considerable freedom in evaluating and combining ideas on various internal fuses. In some cases, of course, it is possible to omit one or more of these parts of an internal fuse, and its speed of response could be improved thereby. The total energy required to disperse poison in a reactor may be reduced by selecting the poison that makes the greatest change in reactivity per gram of poison. From this point of view, both natural boron and B^{10} are among the best poisons for thermal reactors. The poison must be finely dispersed to reduce self-shielding.

TRIGGERS FOR INTERNAL FUSES

A trigger for an internal fuse that is actuated only by a short reactor period may be constructed by using a bimetallic element made of plutonium and some other metal with the same thermal expansion coefficient. The heat developed in the plutonium by a short-period flux increase will not have time to diffuse into the other element; hence the element will bend and can be made to complete an electric circuit. The heat in the plutonium developed by a long-period flux change will, on the other hand, heat the whole element, and no action will occur. Such a trigger can be actuated by a temperature difference of less than 1° to 2°C .

Bimetallic elements can be built to buckle with a speed of about 300 feet per second, so that the time required to close the contacts is very short once the buckling temperature is reached. The wide temperature differential normal to snap-action bimetallic elements is not significant in this application, and heating not caused by neutrons will not actuate the trigger.

Developmental Program

EXPERIMENTS ON PENETRATION AND DISPERSION USING EXPLOSIVE PROPELLANTS

Experiments were designed to propel a powder at high velocity into water and other media by means of the shaped-charge technique. This method has the prime advantage that a jet of very high velocity, approximately 6 to 20 kilometers per second, emerges from the explosive.

Jet-forming hollow conical liners and hollow wedge-shaped liners* have proved very successful and have been thoroughly investigated. Both shapes were used in this work, and each showed different properties. The conical liners can penetrate farther into the absorbing medium than can the wedge-shaped or linear liners. However, self-absorption of boron in the conical jet renders it less effective in dispersion than the linear jet. The great advantage of the linear-shaped charge is that the poison is propelled into the receiving medium in sheet form and is thus projected over a plane-like surface for rapid dispersion.

The shaped charge is illustrated in Figure 1. When the booster is detonated, an explosive wave travels down the charge. When this wave reaches the apex of the thin-walled metal liner, very high pressures are suddenly produced on the side of the liner that is exposed to the wave. The forces are so great that the strength of the liner wall has a negligible effect on the process, and the metal can be treated as though it were a perfect fluid. The explosive pressure causes the thin walls of the liner to collapse and to move downward at extremely high velocities. Each of the walls is forced to a position nearly perpendicular to its original surface, as though the original angle were inverted. The metal in the liner then breaks into two parts. The metal at the apex of the liner forms a jet that travels downward at very high velocities, 2000 to 20,000 meters per second. The remaining metal forms a slug that travels downward at relatively low velocities, 500 to 1000 meters per second. The jet produces the cutting action of these charges and gives them a high power of penetration.

Preliminary firings were made using dynamite, which is known to be inferior for this use. The liners were made by mixing poison in powder form with grease and lining the cavity with the mixture. The dimension across the base of the hollow cone or wedge of the liners was limited to 1 inch. The height of the liner was determined by the apex angle, 45 degrees and 60 degrees. The weight of explosive was in each case 1/4 pound per linear inch of liner. A plastic model of the linear charge used is shown in Figure 2.

The first series of tests was designed to develop a linear jet or sheet to be fired into water. Since the penetration of a jet from a shaped charge is virtually independent of the physical strength of the material into which it is fired, jets were fired into paraffin as a

*Birkhoff, MacDougall, Pugh, and Taylor, "Explosives with Lined Cavities," Journal of Applied Physics, Volume 19, 1948, pp 563 ff.

Fig. 1—Diagram of shaped charge

Fig. 2—Plastic model of a typical linear-shaped charge

substitute for water. Figure 3 shows the results obtained when a 4-inch linear-shaped charge made of dynamite lined with a grease-boron mixture was fired into a 2- by 12- by 24-inch paraffin block. The photograph shows the two halves of the block after it was split by the shot. The powder dispersion exhibited is of a magnitude suitable for the specific fuse applications discussed earlier in the report. The 1/8-inch-thick jet penetrated about 18 inches into the paraffin.

Since the apexes of the wedge-shaped linear liners made on a sheet-metal brake were not sharp enough to give good penetration, it was decided that the liners should be machined. Figure 4 shows the very poor penetration produced by the broad apex of the bent liner. The better penetration shown in Figure 5 can be attributed to the sharper edge produced by machining. Figure 6 shows the good penetration produced using a 60-degree liner formed from machined steel rather than machined aluminum. The aluminum block shown in Figure 7 was spread rather than cut by the 45-degree machined-steel liner, probably because the liner was poorly aligned with the explosive charge. Comparison of this result with that shown in Figure 8, also produced by a 45-degree machined-steel liner, indicates that proper alignment probably accounted for the superior penetration shown in Figure 8. Figure 9 illustrates the mushroom effect produced by a 45-degree machined-aluminum liner. This spreading effect could have been caused, as in Figure 7, by off-center detonators, liners, or charge. In this series of tests, the liners were made of 0.030-inch aluminum, brass, or steel with 45-degree and 60-degree angles. The weight of the C-3 explosive charge, used in place of dynamite for the rest of the tests, was the same in all cases. The charges were fired into aluminum blocks 4 inches thick and 5 inches in diameter.

Other examples of the cutting action of linear-shaped charges are given in Figures 10 and 11. Figure 10 shows a 2-inch linear-shaped charge placed over an aluminum plate before being fired. Figure 11 shows the results of firings using several types of liners. It will be noted that very good linear jets were obtained using the 60-degree steel liners. The ceramic crucible and glass beaker fired into the plate gave less effective results because of the poor geometry.

In another test two 1-inch brass liners, one having a 60-degree angle and the other having a 45-degree angle, were fired by 1/4-pound charges into paraffin contained in a steel box. In the photographs of Figure 12, the 60-degree liner is on the left and the 45-degree liner is on the right of the steel box. Figures 12c and 12d show the penetration after removal of 2 inches and 4 inches of the paraffin, illustrating the difference in effects produced by the 60-degree and the 45-degree liner. The jet formation of the 60-degree liner gives deeper penetration and is thus more effective. In these tests the 1/4-pound charges with 1-inch liners penetrated 6 to 8 inches of paraffin. A conical liner fired in another test penetrated about 16 inches of paraffin.

The next test was made to investigate the effect of firing a poison into a reactor water channel by firing a charge with a brass liner into a tube of water. The charge was placed on a steel blast brake with a 3/4-inch by 2-inch slot over a 5-inch-diameter plastic tube full of water. Figure 13 shows photographs taken before, during, and after firing. A cloud of small brass particles may be seen in Figure 13c. The plastic tube was shattered for about 6 inches, and water was splashed out for another 5 inches. The dark cloud in the water is brass powder, which extended 19 inches into the plastic tube. Part of this powder was so finely dispersed that it took hours to settle out and had particle sizes in the 5- to 80-micron range. A micrograph of the larger brass particles found in the bottom of the tube is shown in Figure 13d.

In another test a 2-inch, 1/2-pound charge was fired upward into an 8- by 24- by 6-inch

Fig. 3 — Result of firing a linear-shaped charge into a paraffin block

◀ Fig. 4—Aluminum block into which a 60-degree aluminum liner, made on a sheet-metal brake, was fired

Fig. 5—Aluminum block into which a 60-degree machined-aluminum liner was fired ▶

◀ Fig. 6—Aluminum block split by a 60-degree machined-steel liner

◀ Fig. 7—Aluminum block into which a 45-degree machined-steel liner was fired

Fig. 8—Aluminum block split by a 45-degree machined-steel liner ▶

◀ Fig. 9—Example of mushroom effect produced by a 45-degree machined-aluminum liner

Fig. 10 - A 2-inch linear-shaped charge just before firing

Fig. 11 - Results of firings into an aluminum block

◀ a. Before firing 45-degree liner; blast produced by 60-degree liner is shown on left

b. Immediately after firing ▶

◀ c. After removal of 2 inches of paraffin

d. After removal of 4 inches of paraffin ▶

Fig. 12 – Results produced by 45-degree and 60-degree brass-lined 1-inch linear charges fired into paraffin block through a blast brake

a. Before firing

b. During firing

c. After firing

d. Micrograph of the larger particles found in the bottom of the tank

Fig. 13—Photographs taken before, during, and after firing a brass-lined linear charge into water

a. Before firing: closeup view showing position of C-3 explosive, liner, and slot in blast brake

b. Before firing: over-all view

c. After firing

Fig. 14 — Photographs taken before and after firing linear charge into a water tank. The heavy metal stand is a blast brake.

tank of water. The blast brake used in this firing had a slot $\frac{3}{4}$ inch wide by 12 inches long. When this shot was fired, the blast and water shock was sufficient to blow out the $\frac{3}{8}$ -inch-thick acrylic plastic sides, as shown in Figure 14.

Next a $\frac{1}{2}$ -pound shaped charge with a $1\frac{1}{2}$ -inch-diameter crucible liner was fired down a $\frac{1}{2}$ -inch pipe held in a blast brake. The pipe acted as a gun barrel to direct the jet from the liner. The movement of the jet and blast can be followed in the sequence of pictures taken at an estimated 5000 frames per second in Figure 15. The water in the tank was quickly displaced by the jet, after-jet, and blast. The $\frac{1}{16}$ -inch acrylic plastic sides of the tank were ruptured by the blast.

The possibility of using a "shotgun" to propel poison into the reactor was also investigated. A muzzle-loading 1-inch gun was made up and used to fire several charges of poison into the air. A fine boron carbide powder was propelled 10 to 30 feet into air with good dispersion. It should be possible to propel the powder at a speed of at least 1000 feet per second using such a "shotgun."

To test the directing ability of a pipe on a shaped-charge jet, a jet was fired down a $\frac{1}{2}$ -inch piece of water pipe. An aluminum block 9 feet from the charge was lined up visually with the center of the pipe. The jet collided several times with the wall of the tube before striking the aluminum block. The pipe aimed the jet very nicely, but the jet had very little penetration power by the time it reached the block.

Frame 1

Frame 2

Frame 3

Frame 4

Fig. 15—Sequence of pictures, taken at about 5000 frames per second, showing a conical-shaped charge fired down a pipe into a tank of water

RESULTS

A general survey of possible propellants for internal fuses indicated that the highest poison velocities could be developed by shaped-charge propellants. If the poison were used as the liner of a shaped charge, velocities of 6 to 20 kilometers per second would be possible. It was desired to simulate the projection of a "sheet" of poison into a water channel in the active core. Preliminary firings with dynamite indicated that this idea had possibilities as part of a very fast-acting internal fuse; further tests were then conducted using the explosive C-3. The tests gave convincing evidence that it would be possible to stop a runaway reactor using shaped charges as a poison propellant. However, the blast associated with the high explosive action is a great disadvantage. The blast may be reduced by using a blast brake or by firing the shaped-charge jet down an evacuated tube.

The tests with a "shotgun"-type propellant system showed that poison may be shot into a reactor in less than 5 milliseconds, and possibly in 1 millisecond. The blast from such a "shotgun" should not be great enough to do an objectional amount of damage.

Frame 6

Frame 7

Frame 8

Frame 15

Fig. 15 - Sequence of pictures, taken at about 5000 frames per second, showing a conical-shaped charge fired down a pipe into a tank of water

CONCLUSION

Internal fuses using shaped charges can be applied to fast reactors, since they produce ultrafast fuse reaction.

The blast effect resulting from explosive action is a problem that will require further investigation. Further studies must also be performed on fuse configurations to determine the optimum placement, size, shape, weight, and type of propellant and poison.

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