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REACTOR FUSE PROPELLANTS AND CONFIGURATIONS

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GENERAL ELECTRIC

ATOMIC PRODUCTS DIVISION

AIRCRAFT NUCLEAR PROPULSION DEPARTMENT

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ABSTRACT

This report is compiled from a series of reports made in conjunction with experimental tests of three types of propellants for reactor safety fuses and various configurations of the fuse.

Compressed gas, explosive gases, and solid chemical propellants are discussed; the latter proved to be the best.

A symmetrical annular fuse configuration was found to be best when compared with the offset type, the supported-rupture-disk type, and the GE-ANPD original developmental type fuse.

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INTRODUCTION

An investigation was made to determine the best way of dispersing a poison into a reactor in the shortest possible time in order to effect a shutdown of a reactor excursion before damage occurred.

This report sets forth the developmental work accomplished during the investigation of reactor fuse propellants and configurations from 1954 to 1956. The three types of propellants considered for investigation were: (1) compressed gas, (2) explosive gases, and (3) solid chemicals. The shape, size, and location of the propellant and poison storage area configurations as applied to annular-type reactor safety fuses were also considered.

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COMPRESSED - GAS PROPELLANT SYSTEMS AND CONFIGURATIONS

INTRODUCTION

The stored energy of compressed gas was thought to be a likely propellant for forcing boron powder, a reactor poison, into the fuse body located within a reactor. It was decided that the dispersion velocity and factors affecting it would have to be investigated.

EXPERIMENTAL DATA

A developmental reactor safety fuse with an annular passage was constructed. The annular chamber was 10 inches long and 1/8 inch wide with an outer diameter of 3.75 inches. A 30-degree-cone section, as measured from a plane normal to the axis of the annulus, joined the annulus to the tube containing the boron powder. Since the outer walls and cone of the test chamber were acrylic plastic and the removable inner-wall section was steel, it was possible to observe the passage of the boron powder in both the cone and annular sections (see Figure 1). High-speed motion pictures were taken to measure the boron powder velocity.

A rupture disk was placed between the annular chamber and the boron tube, which was separated from the compressed gas chamber by a quick-opening valve. The first runs were made with normal conditions, whereas succeeding runs determined the change in velocity resulting when one or more of the conditions was varied. The normal conditions were, in part, arbitrarily chosen, and, in part, made necessary by the structural design of the developmental reactor and the creep strength of the fusible alloy used as the trigger. The conditions considered as normal, the conditions that were varied, and the end results are listed in Table 1.

When normal conditions were used, the boron velocity was at the most 175 feet per second, which was much less than the desired 500 feet per second. The velocity through the cone section was found to be greater than the velocity in the annulus, indicating that a flow restriction existed in the turn from the cone to the annulus. Increased solids frictions, occurring when momentum forced the boron particles against the outside walls of the turn, is the probable reason for the loss in velocity. A similar loss probably occurred in the turn at the entrance to the cone section.

Decreasing the concentration of the boron powder in the gas stream by using a 1-gram boron charge increased the velocity considerably. Speeds of 315 feet per second were observed in both the cone and annular sections. This result was to be expected considering the work reported by Farbar in "Industrial and Engineering Chemistry," page 1184, June 1949. He showed that a pressure drop of a solid-gas mixture was almost directly proportional to the concentration of the solids present. If this is assumed to be true for the powder concentration ranges of interest, the pressure drop when a 14-gram charge of boron is dispersed is approximately 13 times greater than the pressure drop when 1 gram of boron is dispersed.

TABLE 1
DIFFUSION OF BORON IN ANNULAR FUSE CHAMBER

Condition of Test	Velocity Through Annulus, ft/sec	Remarks
Normal	135 ^a	Velocity through cone approximately 200 ft/sec.
Normal except: boron charge 1 gm	315	Velocity constant through cone and annulus.
Normal except: carbonyl iron powder used	315	Velocity through cone 100 ft/sec. Density of carbonyl iron 7.8.
Normal except: pressure of helium 150 psig	110	Velocity through cone approximately 225 ft/sec.
Normal except: annulus volume 33 in. ³	315 and 185	
Normal except: annulus volume 57 in. ³	264 and 244	
Normal except: annulus volume 80 in. ³	240 and 250	
Normal except: width of cone passage, 5/16 in.	50	
Normal except: boron charge 1-gm and annulus volume 80 in. ³	504	Velocity constant through cone and annulus.
Normal Conditions: Boron charge: 14 gm Helium pressure: 50 psig Annulus volume: 10 in. ³ Boron density: 1.73 Width of cone passage: 1/8 in.		

^aAverage of 5 runs given. Minimum: 40 ft/sec, Maximum: 175 ft/sec

Fig. 1—Modified annular test chamber

The powder concentration was also lessened by using carbonyl iron instead of boron. Carbonyl iron is much heavier than boron so that the number of iron particles needed to make up a 14-gram charge is considerably less. The iron particles attained the same velocity as the 1 gram of boron in the annulus of the receiving chamber, but their velocity in the cone section was much lower.

Undoubtedly the high momentum of the iron particles interfered with the flow of the particles in the turning sections. The similar annular velocities indicate that the time of particle acceleration is very short, and the average velocity of a small particle traveling in a straight line in a fast-moving gas stream can be considered independent of the particle density.

The effective volume of the annulus was increased by connecting it to an auxiliary chamber. Tests were made with apparent annular volumes of 33, 57, and 80 cubic inches,

and for all cases the velocity was greater than that measured for the 10-cubic-inch or normal annulus. This is attributed to the greater average gas velocity during the transitory flow period. When a compressed gas is released into a vacuum, the gas will attain its sonic velocity at the point of greatest constriction and will continue to flow at that velocity until the ratio of the receiver pressure to the compressed gas pressure reaches an approximate value of 0.5. The time required to reach this ratio depends only on the composition of the gas and the relative volumes of the compressed-gas and vacuum chambers. Enlarging the receiving chamber increases the volume of gas that will leave the pressure chamber at sonic speed. It would appear that increasing the compressed gas pressure would also increase the time that sonic speed was maintained by the gas at the constriction; but this is not true because the mass rate of flow is directly proportional to the compressed gas pressure. Hence, doubling the compressed gas pressure would double the mass flow rate through the constriction even though the throttling pressure is greater and double the rate of pressure increase in the receiver so that the relation between time and the pressure ratio would be unchanged for a constant receiver volume.

The increase in velocity concomitant with the increase in receiver volume was shown when a 1-gram charge of boron was dispersed into an 80-cubic-inch annulus. The velocity increased from 315 to 500 feet per second. This was the only test in which the desired velocity was obtained.

Widening the flow passage in the cone section or increasing the compressed gas pressure lowered the boron dispersion velocity to less than that obtained with normal conditions. The high-pressure gas may have packed the boron powder for the short time that the disk resisted rupture so that the boron did not flow as small particles but as agglomerate lumps. The tendency for boron to agglomerate was observed during attempts to grind it. Particles of less than 1-micron in diameter can be obtained by wet grinding in a ball mill, but, upon drying, the particles cling together and form lumps that average 10 microns in diameter. Compressing the powder before it is released into the vacuum chamber may form even larger lumps.

Another series of tests was run to determine the pressure and volume of compressed gas that would disperse 14 grams of boron powder in an arbitrarily chosen maximum dispersion time of 20 milliseconds.

The test apparatus consisted of an acrylic plastic chamber, which was easily disassembled and had the same internal dimensions as a reactor spacer tube, and modified pipe fittings that held the compressed gas and boron powder. A quick-opening valve was placed between the compressed gas chamber and the boron-holding tube, and a rupture disk separated the boron-holding tube from the spacer tube (see Figure 2). Cylinders of compressed gas and a vacuum pump were used to achieve the required pressure conditions. Initial pressures were set with gages, and transient pressures during the test were sensed by a Baldwin SR-4 strain-gage cell and recorded by a Brush recorder. Four 750-watt lamps were used to illuminate the plastic model for the taking of motion pictures with an Eastman Kodak high-speed camera.

One of the most important variables to be evaluated was the pressure of the compressed gas. In the reactor fuse the compressed gas and boron are sealed in their chambers by a low-melting alloy (Cerrotru) impregnated with enriched uranium. During a power excursion the alloy is melted by the heat generated in the uranium, and the compressed gas and boron are released. Since alloys that will melt with relatively small additions of heat have questionable, long-term creep properties, the reliability of the reactor fuse would be improved by using gas at the lowest pressure that will give satisfactory dispersion time. The pressures tested ranged between 20 and 150 pounds per square inch.

Fig. 2 - Test apparatus

Since limited space is available in the reactor for the nuclear fuse, tests were made to determine the effect of varying the compressed gas volume. The volumes of gas tested were 11.5, 19.7, and 31.2 cubic inches. The thermal neutron absorption coefficient of B-10 is approximately four times greater than that of natural boron, as mentioned previously; hence, three grams of B-10 would have about the same effect on a reactor run-away as 14 grams of natural boron. A number of tests were made with a 3-gram boron charge to see if the lower weight would result in greater dispersion velocities.

Other variables tested were the size of the tube opening and the effect of a vacuum in the spacer tube.

The acrylic plastic spacer tube was assembled and connected to the boron-holding tube which had previously been loaded with boron powder. The fuse chamber was pressurized, and, if required, the spacer tube was evacuated while the camera and lighting equipment were being adjusted. The test was performed by starting the camera, then opening the valve a second later when the camera had accelerated to the chosen speed. The compressed gas forced the boron powder against the rupture disk which resisted for a fraction of a second before rupturing.

The time for the dispersion of boron was obtained from the motion pictures. Examinations of succeeding exposures on a microfilm reader showed the distance traveled by the boron during the time interval between exposures. The elapsed time between exposures was calculated from marks placed on the films by an argon timing light in the camera. The product of the average elapsed time per exposure and the number of exposures gave

Fig. 3 - Dispersion of boron powder with compressed gas (volume = 19.7 in.³)

the dispersion time in the spacer tube. To estimate the boron travel time between the disk and the spacer tube, the distance traveled by the boron in the spacer tube was plotted against the elapsed time as shown in Figures 3 and 4. Extrapolating the curve to the rupture disk position gave an estimate of the elapsed time between the breaking of the disk and the entering of the spacer tube by the boron. The curve was also used to determine the velocity of the boron at any point by measuring the slope of the curve at the point. In order to compare the total elapsed times of different runs, the curves were replotted on a graph which had the rupture disk position at the origin. These curves are shown in Figures 5 and 6.

After these two series of tests were run, it was thought that the velocity might be increased further if the boron powder were placed directly below the annular receiving chamber so that the dispersion path is straight or if the boron powder were spread out beneath a large rupture disk.

Figure 7A shows the original fuse configuration, and Figures 7B, 7C, and 7D show the suggested alternatives.

Fig. 4 - Dispersion of boron powder with compressed gas (volume = 31.2 in.³)

The abrupt release of the compressed gas - boron powder fuse by the sudden application of gas pressure to the rupture disk is not practical when the boron powder is spread in a ring below an annular receiving chamber because the rupture plate would have to be annular in shape and, quite likely, would not rupture completely around its entire circumference. However, a number of small fuse units, each containing a small amount of boron powder, compressed gas, and a circular rupture disk, can be placed circumferentially beneath the annular receiving chamber.

Two receiving chambers were then fabricated of acrylic plastic and were 20 inches high, 0.1 inch thick, and 0.75 inch wide. The weight of boron powder was reduced for this small chamber to 1.8 grams and the compressed gas (helium) to 2 cubic inches.

The symmetrical device (Figure 7C) had the center of the rupture disk on the centerline of the receiving chamber, whereas the offset device (Figure 7B) had the edge of the rupture disk on the centerline of the receiving chamber. A fuse with the offset configuration would fit inside the original fuse configuration, but one with a symmetrical configuration would require larger tubes.

Fig. 5—Time for boron powder "front" to travel up the spacer tube (compressed gas volume = 19.7 in.³)

A number of tests were made before a suitable rupture material was found. The pressed Cerrotru disks used in the previous tests could not be made thin enough to give reliable operation. A double layer of 0.001-inch-thick tin foil was found to give the most satisfactory performance.

The method of test for this third series of tests was similar to that used in the previous two. Again, high-speed motion pictures were taken of the boron dispersion into the evacuated acrylic plastic receiving chamber to measure the boron velocity.

As shown in part D of Figure 7, the supported disk device had a large-diameter rupture disk placed approximately 1-1/2 inches below the annulus and was supported in the middle by a column extending down from the cone apex. The boron powder charge was spread in an even layer below the disk and was supported by a sheet of tissue paper.

This configuration was expected to have a higher dispersion velocity than the model used in the first series of tests because it eliminated the narrow flow passage along the cone surface.

The rupture disks were made by hot pressing Cerrotru alloy in a punch and die set. After the Cerrotru powder had been heated to its melting point in the die set, the die set was placed on its side and hand pressure applied to the punches. This allowed the entrapped air to escape and resulted in a solid cast disk between 0.040 and 0.050 inch mean thickness. One side of the disk was scored radially and circumferentially with a stylus to encourage complete disintegration of the disk into a number of small pieces.

It was also felt that a comparison should be made between the configuration of the device used in the first series of tests and a configuration designed with a serpentine gas-flow passage from the fusible disk trigger to the boron powder rest position.

Compressed gas released by the fusible disk is deflected back down around the helium chamber and turned a second time to the boron position. From that point it propels the boron into the evacuated receiving chamber. The S shape of the annular gas flow passage might induce sufficient turbulence to lessen considerably the velocity of the flowing gas, so it was necessary to check this possibility.

Some of the previous equipment was modified for this fourth series of test runs. An S-shaped tube was needed between the valve and boron tube. A smooth passageway was constructed from four socket-type copper elbows soldered together with short lengths of copper tubing. The over-all flow length was twice the design dimension, but this was considered minor compared to reproducing smooth 180° turns in copper tubing to exact design dimensions, since most of the turbulence and flow restriction would occur in the turns.

A pressure transducer was placed in the line between the S passage and the release valve. Opening the valve allowed the compressed gas to flow into the transducer section, and, a short time later, to break a foil diaphragm separating the transducer from the S passage. The rupture of the diaphragm resulted in an abrupt release of the compressed gas and showed up as a peak or plateau on the recorded pressure trace giving an excellent measure of the dispersion start.

Fig. 6—Time for boron powder "front" to travel up the spacer tube (compressed gas volume = 31.2 in.³)

Fig. 7A, B, C, D - Experimental fuse configurations

The pressure transducer used was a 0-100 - psi, Statham strain-gauge cell. The transducer output was amplified by a BL-320 Brush Universal Analyzer and indicated on a type 322-A Dumont oscillograph. A number 923 RCA photocell was used at the top of the acrylic plastic receiving chamber to sense the arrival of boron powder at that point. The photocell output was indicated by the second trace on the dual-beam oscillograph. The time between gas release and complete boron dispersion could be measured by photographing the two traces with a Polaroid Land camera and measuring the distance between pulses.

Continuous coupled sweep of the two beams were used which resulted in four heavy traces on the timed exposure photographs. The heavy lines represent, respectively, from top to bottom: (a) the initial photocell output, (b) the final photocell output, (c) the final pressure transducer output, and (d) the initial pressure transducer output. The faint line connecting the top two traces represents the arrival of the boron powder at the photocell. The wavy irregular lines between the bottom two traces represent the pressure fluctuations at the transducer during the dispersion. On the photograph the beams are sweeping from right to left at a speed of one major scale division per 2.5 milliseconds. The rising pressure trace from the bottom right corner indicates when the release valve was opened. The pressure increased at the transducer and suddenly decreased. This peak represents the rupture of the foil diaphragm and the start of the dispersion (see Figure 8).

Fig. 8 - Photograph of pressure trace and start of boron dispersion

The horizontal distance in the direction of beam sweep between the pressure peak and the vertical deflection of the photocell is found to be 2.8 major divisions. This distance represents several milliseconds or the total dispersion time.

RESULTS

The test results of this first series of experiments show that the velocity of the boron powder was observed to be a maximum of 170 feet per second with normal operating condi-

tions. Decreasing the concentration of the boron powder or increasing the volume of the annular chamber increased the dispersion velocity to approximately 300 feet per second. Only when both changes were incorporated on the same test was the desired velocity of 500 feet per second attained. Powder concentrations can be lessened by using the isotope B-10 instead of natural boron. Only one-fourth as much B-10 is needed. Increasing the number of fuses in the reactor would also lessen the weight of boron required per fuse. Lengthening the annular chamber to envelope the full height of the fuel element and/or attaching an auxiliary evacuated chamber to the annulus are two ways of increasing the annular volume. However, using an auxiliary chamber placed outside the active core would aggravate the problem of stopping and retaining the boron powder in the annulus.

A total of 46 test runs were made in the second series of tests of which 40 provided useful data. Although all of the test curves are not shown in Figures 5 and 6, the effect of the principal variables can be seen from the curves presented. The difference in elapsed time resulting when the pressure conditions were changed is shown in Figure 5. The volume of compressed gas was kept constant at 19.7 cubic inches while the compressed gas pressure was 75, 100, or 150 psi and the spacer tube pressure was either atmospheric pressure or a vacuum of approximately 28 inches of mercury. With atmospheric pressure in the spacer tube, increasing the pressure of the compressed gas from 75 to 150 psi decreased the dispersion time from 25 to 14 milliseconds. Dispersion times of 4 to 6 milliseconds resulted from the same compressed gas conditions and with a vacuum in the spacer tube.

The lighting used for the motion pictures resulted in a shadowgraph type of exposure. Hence, the dispersion times are based on the velocity of the advancing edge of the boron cloud which may or may not coincide with the average velocity of the boron particles. It appeared that only a small amount of the boron charge made up the initial cloud when an evacuated spacer tube was used, and the rest of the charge followed at a much slower velocity.

Many of the slower runs had curves in which the slope would suddenly change indicating a change in boron velocity at that point. This velocity change was probably caused by a reflected rarefaction shock wave catching up and imparting additional energy to the boron cloud.*

With compressed gas pressures of 100 psi or lower and with atmospheric pressure in the device, an increase in the compressed gas volume decreased the total dispersion time as shown in Figure 6. The dispersion time was lowered by 7 milliseconds when the volume was increased from 11.5 cubic inches to 31.2 cubic inches. The small time difference resulting when the pressure was 150 psi indicated that changing the volume affected the dispersion only at the lower pressures.

It was expected that higher velocities and lower dispersion times would result when the weight of the boron charge was decreased. However, the dispersion times for the 3-gram boron runs were much higher when all other conditions remained the same. It appeared that the compressed gas pierced the thin layer of boron powder rather than propelled it. The diameter of the tube opening was made smaller so that the thickness of the boron powder plug was increased. As a result, the dispersion time was lowered below that of the 14-gram runs. Results are listed in Table 2. No attempt was made to find the optimum opening size for a 3-gram charge.

Thirty-two test runs were made on the third series of tests of which the films of thirteen runs could be read and interpreted with the usual exactness of this method; seven others

*Courant and Friedrichs, "Supersonic Flow and Shock Waves," Interscience Publishers, New York, 1948.

TABLE 2
RESULTS OF BORON DISPERSION TESTS

Volume of Compressed Gas, cubic inches	Pressure of Compressed Gas, psig	Weight of Boron, grams	Number of Runs	Average Dispersion Time, milliseconds	Remarks
11.5	75	14	1	33.3	
11.5	100	14	1	26.6	
11.5	150	14	1	14.5	
19.7	75	14	1	25.8	
19.7	100	10	2	20.6	
19.7	150	14	2	15.7	
31.2	50	9	1	28	
31.2	100	14	2	17.1	
31.2	150	14	2	15.8	
19.7	50	3	1	70	
19.7	100	3	2	31	
19.7	50	3	1	26.5	Tube opening, 1/2 inch
19.7	100	3	1	20.7	Tube opening, 1/2 inch
19.7	150	3	1	12.2	Tube opening, 1/2 inch
31.2	75 (vacuum in spacer)	14	1	6.2	
31.2	100 (vacuum in spacer)	14	1	4.0	
31.2	150 (vacuum in spacer)	14	1	6.7	
31.2	60 (vacuum in spacer)	14	1	4.0	Tube opening, 5/8 inch
31.2	60 (vacuum in spacer)	14	1	6.0	Tube opening, 1/2 inch
31.2	20 (vacuum in spacer)	14	1	19.3	
31.2	60 (vacuum in spacer)	26	1	5.1	

Note: Except where noted, tube opening is 3/4 inch.

were not as clear, and the distance-time relationships interpreted from them may be subject to a small error. The remaining films could not be used or interpreted.

An average velocity of 795 feet per second was observed for nine runs with the symmetrical model using helium as the propellant gas. If two other runs, the results of which are not as clear as for these nine, are included, the average velocity is 858 feet per second. This velocity is attained in the lower 15 inches of the receiving chamber, which was chosen as the basis for comparing the different runs. The upper 5 inches of the test devices appeared hazy in most of the films, and in those which could be read the velocity of the boron was observed to decrease rapidly.

The observed average velocity of four runs with the offset model was 720 feet per second; including two runs with doubtful results raises the average velocity to 781 feet per second.

Three runs were made with the symmetrical device using hydrogen as the compressed gas. The results of all three may be subjected to a small interpretation error, but the average velocity was 975 feet per second.

Of the six test runs made on the supported-disk device, the average velocity on four of them was 450 feet per second. This is greater than the velocity obtained in the device used in the first series of tests, but only half as great as the annular boron powder configuration. The other two test films were ruined in processing.

The results of the fourth series of tests, in which the S-shaped gas passageway configuration was used, yielded a dispersion velocity of 400 feet per second, even though the passageway was twice the design length.

EXPLOSIVE - GAS PROPELLANT SYSTEM AND CONFIGURATIONS

INTRODUCTION

It was recommended that explosive gas mixtures be evaluated for rate and magnitude of pressure generation to determine their suitability as a power source in a nuclear fuse.

EXPERIMENTAL DATA

In the test setup (shown in Figure 9) used for the first series of these tests the cylindrical explosion chamber was made from a length of 2-inch stainless steel pipe, but the majority of the tests were run with an annular-shaped container having dimensions similar to the expected reactor fuse chamber. The annular chamber was formed by two concentric stainless steel tubes, each about 1/4 inch thick, clamped between blind flanges. Each of the cylindrical and annular chambers had ports for an igniter, a pressure pickup, a flame detector, and a connection for charging the gas mixture.

The igniter used in most of the runs was a "bridge wire" consisting of a short length of 1/2-mil tungsten wire soldered to copper leads. Discharging a capacitor through the bridge wire caused the tungsten to melt almost instantly, resulting in an electrical spark which ignited the gas mixture. A variation of this igniter was used in some of the tests. Photographic flash bulbs use a bridge wire coated with a combustible chemical. A number of these coated bridge wires were removed from flash bulbs and used as igniters. Other runs were made with a miniature spark plug connected to a Tesla coil which generates a high-voltage continuous spark. The type of igniter used had no appreciable effect on the exploding characteristics of the gas mixture.

The chamber was charged with the explosive mixture by first evacuating the entire system with a vacuum pump, then slowly introducing each gas of the mixture separately. The volume percent of a particular gas in a mixture is equal to its pressure percent; hence, the first gas, usually hydrogen or propane, was introduced until the rise in pressure divided by the intended total pressure equalled the desired volume percent for that gas. The second gas, usually oxygen or air, was allowed to enter the system until the desired total pressure, usually one atmosphere, was reached. Then, isolating the explosion chamber with a closed valve, the rest of the system was purged with flowing helium.

Twenty-eight runs were made with the cylindrical explosion chamber using various gas mixtures and changing such conditions as ignition energy and gas pressure with each run. The object at this point in the investigation was to determine the consistency of ignition and get some idea, if possible, of the amount of pressure generated. To achieve the latter, a pressure gage with a valve was connected to the chamber.

The test equipment and instrumentation were modified to measure the flame speeds occurring in the combustion chamber. This was one method of determining whether detonation was actually occurring. The annular combustion chamber was used for this and succeeding tests. The igniter was placed in a bottom port and a spark-plug flame detector was

Fig. 9—Schematic diagram of test equipment

placed in a top port on the opposite side of the chamber. The distance between the two was 10 inches.

A Berkeley counter or timer was used to measure the time taken for the flame to travel between the igniter and the spark plug. A capacitor connected to the igniter circuit provided a sharp pulse to the start channel of the Berkeley counter when the igniter capacitor was discharged. A stop pulse was obtained when the ionization within the flame front allowed another capacitor to discharge through the pointed tips of the spark plug. Details of this setup are shown in Figure 10.

An EP-500 Norwood pressure transducer, normally used to measure detonation pressures in internal combustion engines, was connected to the combustion chamber. The object was to measure the peak pressure and the pressure change with time and get a record of it by impressing the transducer output on an oscilloscope and photographing the trace. Originally, both the Berkeley counter and the transducer circuit were operating simultaneously, but the stop circuit of the Berkeley interfered with the sweep channel of the scope. The final arrangement used is shown in Figure 11. Discharging the igniter capacitor initiated the scope sweep through a connecting capacitor. The pressure transducer was connected to the Y-axis of the scope through a balancing bridge and a d-c amplifier. Thus, a curve was obtained with time along the X-axis and pressure along the Y-axis. The curve was photographed with a Polaroid camera attached to the scope face.

It was considered necessary to check the possibility that a short time period of elevated pressure might have an adverse effect on the dispersion of boron if the product gases condensed before the diaphragm separating the receiving chamber from the combustion chamber could be ruptured and the boron dispersed.

So, a previously used section of an annular receiving chamber made of acrylic plastic was modified to include a scaled-down combustion chamber, as shown in Figure 12. The exploded gas in the combustion chamber burst a 2-mil tin foil and forced the boron powder up into the acrylic plastic receiving chamber which was 20 inches long. When the boron reached the top of the plastic device, it cut off a beam of light to a photocell. The photocell output was connected to the Y-axis of the oscilloscope circuit previously described. The instrumentation setup is shown as modification A in Figure 11.

RESULTS

The first series of tests of 28 runs with the cylindrical explosion chamber showed that propane-oxygen and hydrogen-oxygen mixtures could be ignited with energies as low as 6 millijoules and voltage as low as 350 volts. The low energy is of interest because it means a capacitor of small volume could be used. The mixtures were also ignitable at total pressures of 1/2 atmosphere. The lower pressure could lessen the problem of sealing the explosive gases from the evacuated receiving chamber in the reactor fuse.

The second series of tests using the annular combustion chamber fitted with the flame detector consisted of 17 runs with a stoichiometric mixture of hydrogen-oxygen and five runs with a stoichiometric mixture of propane-oxygen. Two different velocities were observed for each mixture. Twelve of the runs with the hydrogen mixture had an elapsed time average of 0.94 milliseconds with an average deviation of 0.04 milliseconds, whereas the remaining five runs averaged 1.39 milliseconds with an average deviation of 0.06 millisecond. Three of the runs with the propane mixture averaged 0.85 millisecond with an average deviation of 0.06 millisecond, and the other two runs were measured as 1.24 and 1.23 milliseconds. Ignition energies, total pressure, and gas compositions were kept constant throughout this series of tests; the exact reason for the two sets of answers is not known.

Fig. 10—Instrumentation diagram for flame speed measurement

Fig. 11 - Instrumentation diagram for pressure measurement

Fig. 12—Boron dispersion with explosive gases

The above-average times represent velocities between 600 and 1000 feet per second. This shows that the burning of both the hydrogen and propane mixtures was primarily detonation since normal burning velocities are about 25 feet per second and detonation velocities are about 9000 feet per second for each gas. Apparently, ignition was followed by normal burning which compressed the unburned portion to a pressure that induced detonation.

Five runs with the Norwood pressure transducer attached to the chamber, made of a stoichiometric mixture of hydrogen-oxygen, gave consistent results. The peak pressure obtained averaged 165 psi and was achieved 1.7 milliseconds after ignition. The duration time of the pressure over 100 psi averaged only 1.9 milliseconds. Figure 13 is a photograph of one run. The trace was moving from right to left at a speed of 1 major division per millisecond. Each major division in the Y-direction represents 100 psi. The sharp pip at the start of the sweep was caused by interference from the igniter and indicates that the bridge wire arced about 0.2 millisecond after the circuit was closed.

Four runs were made with hydrogen-air mixtures. The peak pressure obtained was 80 psi for each run and was achieved 8.9 milliseconds after ignition. The pressure duration time averaged 6.75 milliseconds. The lower pressure and slower rate of generation makes the air mixture inferior to the oxygen mixtures, whereas the longer duration is more desirable.

Considerable variation in the results was obtained using propane-oxygen mixtures. Out of fourteen test runs only three peak pressure values were obtained. The average of the three runs was 450 psi. However, one additional run generated a pressure in excess of 520 psi and another exceeded 700 psi. On all the other runs the pressure was generated after completion of the scope sweep. The elapsed time to the peak pressure also varied a considerable amount. The average of the three runs providing definite information was 7.3 milliseconds with an average deviation of 2.9 milliseconds. Five others had peak pressures occurring after 8 milliseconds, and two runs had peak pressures occurring after 22 milliseconds. The average pressure duration time was 5 milliseconds.

These tests showed that a hydrogen-oxygen mixture was suitable as a propellant. Consistent ignition could be obtained with low ignition energies, sufficient but not excessive pressure could be developed in less than 2 milliseconds, and the product gases cooled and condensed rapidly so that the walls of the receiving chamber can be thin and thus occupy less space in the reactor core.

Figure 14 shows the results of a boron dispersion run using a hydrogen-oxygen explosion to provide propulsion. The trace was moving from right to left at a speed of 1 major division per 2.5 milliseconds. Since an increase in the Y-direction represents a decrease in the light intensity on the photocell, the start of the trace rise indicates the arrival of

Fig. 13—Photograph of pressure trace showing pressure generated from hydrogen-oxygen explosion. Sweep speed from right to left at 1 major division per millisecond. Vertical deflection represents 100 psi per major division.

Fig. 14 — Photograph of time trace showing measurement of boron dispersion time from hydrogen-oxygen explosion. Sweep speed from right to left at 1 major division per 2.5 milliseconds. Increasing vertical deflection represents decreasing light intensity at photocell.

the first boron particle at the photocell. The leveling off of the trace indicates sufficient boron has arrived to totally obscure the photocell. This photograph also shows that the boron reached the photocell in about 4.25 milliseconds and total obscurity was achieved in approximately 5.5 milliseconds. The average times for four runs were 3.8 milliseconds and 5.0 milliseconds, respectively. Two different sets of figures were again obtained when testing propane-oxygen mixtures. One set averaged 4.0 milliseconds for the first appearance of boron and 7.33 milliseconds for total obscurity. The second set averaged 11.25 and 16.0 milliseconds, respectively.

Three runs with hydrogen-oxygen were made with ignition energies lowered from 24.5 to 8.0 millijoules. The elapsed times averaged 4.06 and 7.5 milliseconds, respectively, which is a little longer than the times for the higher ignition energy runs.

SOLID CHEMICAL PROPELLANT SYSTEM AND CONFIGURATIONS

INTRODUCTION

Experimental tests using solid chemical propellants to insert boron into an annular chamber were made for comparison purposes with the other systems tested.

EXPERIMENTAL DATA

An annular chamber was constructed of steel with an acrylic plastic window inserted in the outer tube; the inner tube was polished (see Figure 15). A light beam was reflected off the polished inner tube to a photoelectric cell to measure the speed of insertion.

An electric primer cap (Olin Industries, Inc. mix 257W; charge 1.66 grains; resistance 0.8 to 1.5 ohms) is pressed into Part 1 (see Figure 15) and the smokeless powder (DuPont Pistol Powder No. 6) is then inserted and held in place by a wad of facial tissue paper approximately 1/16 inch thick. Approximately 20-25 pounds of pressure was used to tamp the smokeless powder. Results of the tests with solid chemical propellants are given in Table 3.

A 45-volt dry-cell battery energized the Hewlett Packard millisecond scaler or timer at the same instant that the primer was fired. The gas generated is deflected through two 180-degree turns to the boron position. From that point the boron is propelled into the annular chamber.

The distance from the powder charge to the center of the boron chamber is 5-5/16 inches and from the boron to the photoelectric cell is 3-3/16 inches. The distance from the powder charge to the center of the acrylic plastic window is 8.5 inches. The boron passing the window cuts off the light and causes a pulse from the photoelectric cell to stop the scaler.

It was necessary to amplify the pulse from the photoelectric cell to stop the scaler (see Figure 16).

RESULTS

The velocity of 700 feet per second is not exact because the boron traveled only 3-3/16 inches to the window. The gas developed by the powder charge traveled 5-5/16 inches. The gas was probably moving faster than the calculated velocity of 700 feet per second which is based on the time for 8.5 inches of travel in 1 millisecond. It was also shown that in the event that the vacuum was lost in the fuse, the primer will still have started the boron into the annular chamber in 8 milliseconds, as shown by the test at atmospheric pressure. Should this occur, the pressure in the chamber will increase to 15-20 psi, whereas an evacuated chamber gains no more than 5 psi after test.

Fig. 15 - Diagram of test fuse for solid chemical propellant

TABLE 3
EXPERIMENTAL TESTS WITH SOLID CHEMICAL PROPELLANTS

Test No. ^a	Amount of Boron, grams	Pressure After Test, psi	Amount of Power, grams	Time, milliseconds	Remarks
1	7	0	0	11	Primer cap only
2	7	0-5	1/2	1	
3	6	0-5	1/2	5	
4	6 to 6-1/2	0-5	1/2	5	Centered intertube was about 1/32 off
5	6	5-10	1/2	10	No vacuum
6	6	15-20	1	8	No vacuum
7	6-1/2	0-5	1	1	With vacuum
8	6-1/2	0-5	1	1	With vacuum

^aOn tests 1, 2, 3, 4, 7, and 8 the fuse was pumped down to a vacuum.

Fig. 16 - Instrumentation diagram for solid chemical propellant test

CONCLUSION

An analysis of the data obtained from the foregoing experiments indicates that a solid chemical propellant would constitute the best choice for inserting a poison into a nuclear reactor to achieve shutdown of the reactor excursion before damage occurred. It is fast acting and takes up the least space.

It was also demonstrated that a symmetrical annular-passage-type fuse gave the fastest dispersion velocity, especially if the poison location was directly adjacent to the annulus entrance.