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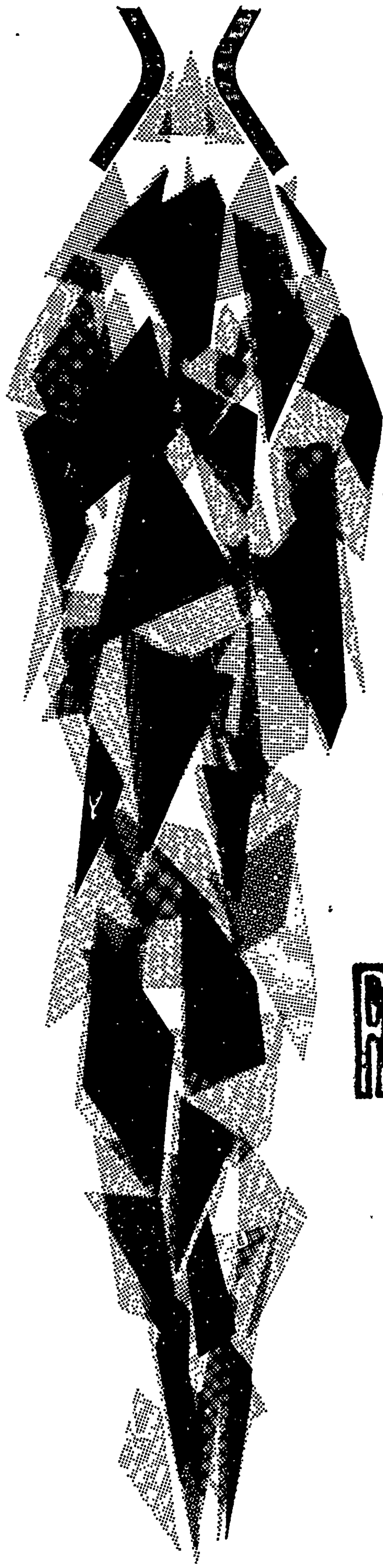

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REPORT NO. S-90

DEMONSTRATION OF SOLID-PROPELLANT SELECTABLE-IMPULSE MOTORS (U)

U. S. ARMY MISSILE COMMAND

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REDSTONE ARSENAL RESEARCH DIVISION
HUNTSVILLE, ALABAMA

Report No. S-90

DEMONSTRATION OF SOLID-PROPELLANT SELECTABLE-IMPULSE MOTORS

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February 28, 1966

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HUNTSVILLE, ALABAMA

DEMONSTRATION OF SOLID-PROPELLANT SELECTABLE-IMPULSE MOTORS

ABSTRACT

This report presents the results of a 10 months' program to demonstrate that solid-propellant boosters can be given zoning capability. The technique involves separating two grains with a thin inert combustion barrier so that all or only a fraction of the energy of the motor can be used as needed. A rocket-type igniter is used to remove the barrier and ignite the second increment.

Both tandem and concentric grain configurations were successfully demonstrated. With concentric grains the barrier thickness was nominally 0.010 inch but the tandem unit required a barrier eight times as thick.

Barrier and end restrictor materials were developed for a plastisol nitrocellulose composite propellant. The barrier can be applied by spraying which allows this technique to be used with virtually any grain configuration. Studies of barrier ablation under igniter gas flow made it possible to size a rocket-type igniter for a given barrier thickness. A sequencing system designed to trigger the second increment as the first reaches a given pressure integral was shown to be applicable to this type of unit.

The technology developed for concentric-cylindrical motors was successfully applied to a 6 X 33 motor having concentric star-perforated grains. The thrust level was 5800 lbf. Transition from first to second grain equilibrium operation was accomplished in 0.2 seconds or less. A nominal barrier thickness of 0.010 inch was adequate to prevent spontaneous ignition of the second grain. The total burning and action times were extended by about 10% by the inclusion of the barrier, but the duration of tailoff was not appreciably affected.

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DEMONSTRATION OF SOLID-PROPELLANT SELECTABLE-IMPULSE MOTORS

1. INTRODUCTION

The need for versatile and accurate artillery-type missiles requires that the propulsion system be capable of some type of energy management. For example, the technique of thrust reversal by opening forward-facing ports in the motor chamber has provided a satisfactory means of controlling total impulse in large missiles where a separable warhead is used. However, this is not practicable in small tactical missiles with integral warheads where a ten-fold variation in range is desired without a sacrifice in accuracy. What the user would like is the capability of programming a solid motor to deliver part of or all of the total impulse.

The present effort was undertaken to extend a technique that allows the total impulse of the solid-propellant motor to be "selected" before the missile is fired. Work done at the Propulsion Laboratory of the U. S. Army Missile Command had shown (1) that a propellant grain could be divided into two increments by a thin, inert barrier and that the protected grain would not burn as a result of firing the first increment; and (2) that hot gas could be used to burn the barrier away and ignite the second grain. A program was funded at these Laboratories to extend the knowledge of the mechanism of barrier removal by rocket-type igniters, to develop barrier application techniques which would be suitable for a wide variety of grain geometries, to investigate scaling effects, and to demonstrate that the technique would be practicable for tactical-type motors.

This last task required that the transition time from one increment to the other in quasi-continuous operation be less than 0.25 seconds with no thrust transients to cause significant deviations in the trajectory of a missile.

This report describes the details of the development program and the application of the technology to a tactical-type rocket motor.

2. EXPLORATORY FIRINGS OF SMALL MOTORS

2.1 Firings with Tandem Grains

2.1.1. Design Features

In order to demonstrate the concept, the first tests were run with two cylindrical-port grains in tandem using available 6-inch and 2-inch motor hardware. The grains were prepared separately in 6-inch-long cases which were coupled together for the firing. The forward grain was completely covered with a barrier material and thus protected during burning of the aft grain. A rocket-type igniter was installed in the head closure of the 6-inch motor to burn away the barrier and ignite the forward grain on command (Fig. 1).

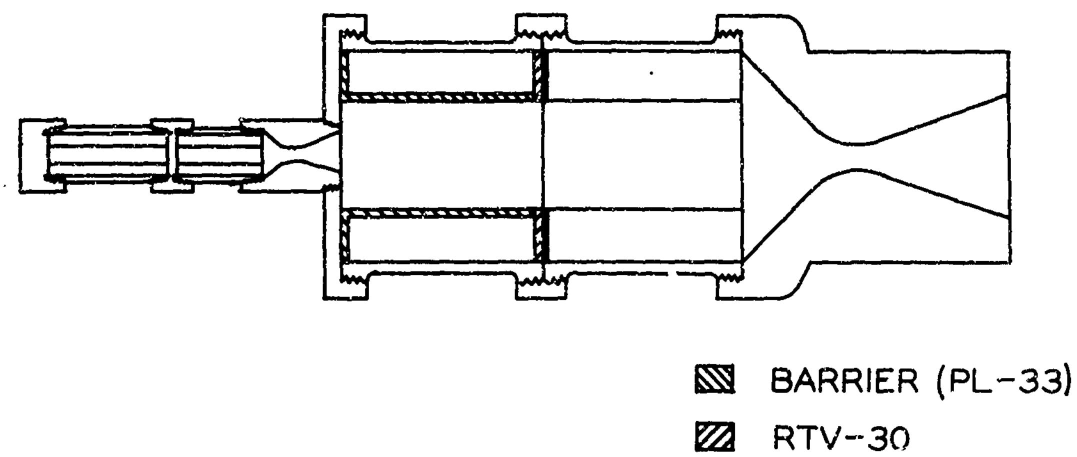


FIG. 1 CONFIGURATION OF THE TANDEM-GRAIN SELECTABLE IMPULSE MOTOR.

2.1.2 Preparation Techniques

Tests using inert grains[1] showed that 0.07 inch of restrictor would protect the grain during aft-increment burning, but a total thickness of 0.08 inch was used for the first two tests. A TEGDN-plasticized, epoxy-based liner, PL-33 (Table I), was applied to a 3-inch diameter, Teflon®[2]-coated mandrel assembly by using a sweep blade to smooth the material while the mandrel rotated slowly in a lathe. This material covered the cylindrical area and one end of the grain. The propellant was cast against this prepared mandrel and bonded to the PL-33 and the motor case. The barrier remained on the propellant surface when the mandrel was removed. RTV®[3]-30 was used to restrict the aft end of the forward grain. This material was expected to strip off at ignition so that the pressure trace of the 6C3-6 grain would be nearly neutral. No difficulty was experienced in any phase of the manufacture of these grains.

Table I

Composition of PL-33 Barrier Material

		Weight %
Hysol 2039[a] Resin	Epoxy Binder	20.4
Hysol 3579[a] Hardener	Epoxy Binder	26.6
TEGDN (Plasticizer)		23.0
Cellulose Acetate (Bonding Agent)		8.0
DMP-10[b] (Accelerator)		2.0
Asbestos[c] (Filler)		20.0

[a]Hysol Corporation, Olean, New York.
[b]Trademark for dimethylaminomethyl-substituted phenols, Rohm and Haas Company, Philadelphia, Pennsylvania.
[c]7TF-1 Johns-Manville, New York 16, New York.

[1]Detailed results of barrier ablation tests are presented in Appendix A.
[2]Trademark for tetrafluoroethylene (TFE) fluorocarbon resins, E. I. duPont de Nemours & Co., Inc., Wilmington 98, Delaware.
[3]Trade name for a family of silicone rubber compounds, General Electric Co., Schenectady 5, New York.

The rocket-type igniter was a slotted 2C1-7.5[1] test motor. Threaded hardware was used and a nozzle was modified to screw into the head of the 6-inch motor. The nozzle closure was designed to withstand the external pressure and heat from the first increment firing but to blow out easily under internal pressure. The composite sealing and support system is shown in Fig. 2.

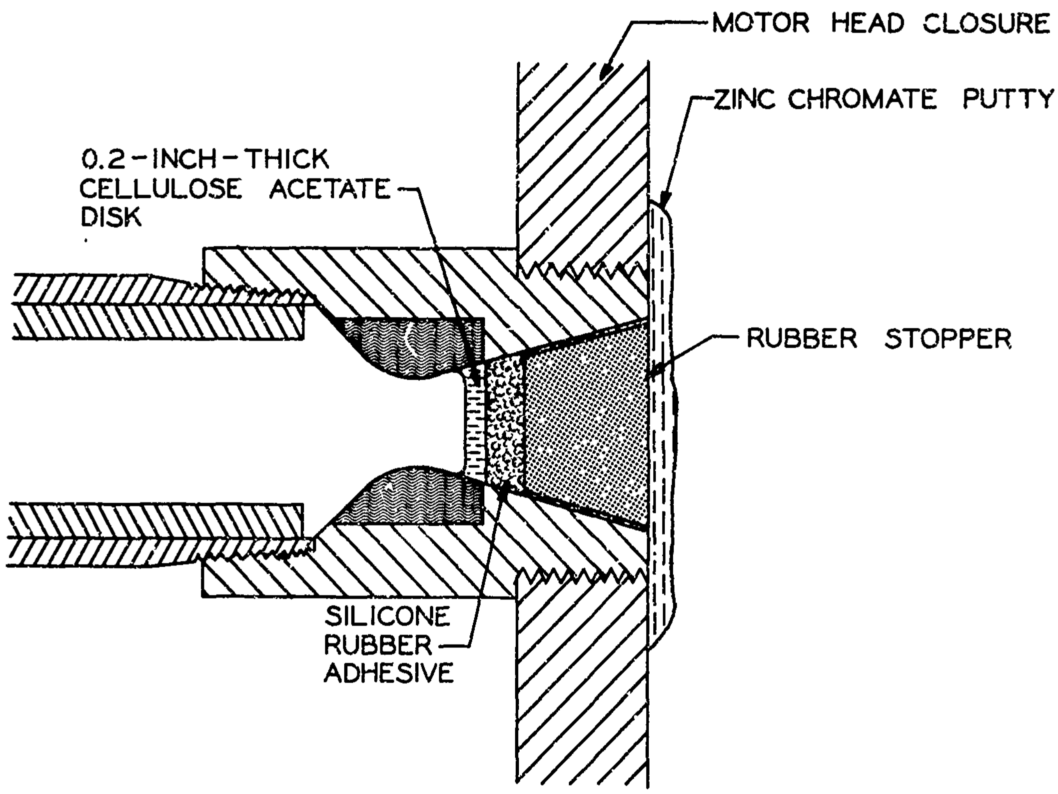


FIG. 2 NOZZLE CLOSURE AND SEAL FOR ROCKET-TYPE IGNITER MOTOR.

2.1.3 Results of Termination Test

The first firing showed that the barrier would protect the forward grain during burning of the aft grain. A 15-gm jellyroll igniter was used to ignite the aft grain; the firing was normal. Three minutes after aft-grain termination, the rocket-type igniter was fired. The igniter (a slotted 2C1-7.5 motor with an $\dot{m}$ = 2.0 lbm/sec) did not burn

[1]This designates a cylindrical port grain having a 2-inch O. D., a 1.0-inch I. D., and a 7.5-inch length.

long enough to remove the barrier completely and the silicone-rubber end restrictor did not strip off immediately; ignition was slow and the trace was progressive until the entire surface was ignited (Fig. 3). The test did show that adequate bonding was obtained between the PL-33 barrier and the propellant charge. Other details on the firing are presented in Appendix B.

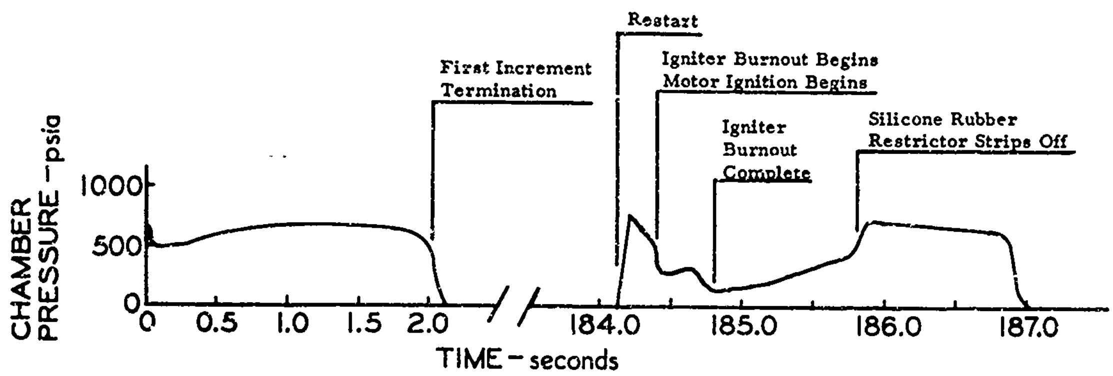


FIG. 3 PRESSURE TRACE FROM FIRING OF FIRST TANDEM-GRAIN MOTOR (ROUND 3970).

2.1.4 Results of Quasi-Continuous Firing Test

The second test used a larger, longer-burning igniter (a slotted 2C1-11.5 motor with an $\dot{m}$ = 2.7 lbm/sec) and the bond between the propellant and the silicone-rubber end restrictor was weakened before testing. A 10-gm. jellyroll igniter was used to ignite the aft grain, which burned normally. A timer was used to actuate the squib of the rocket-type igniter grain during tail-off of the first increment.

The changes made to correct the slow ignition in the first test produced a substantial pressure peak during ignition of the forward grain. The modified igniter burned too long and the end restrictor stripped away too easily. However, the shape of the pressure trace after igniter burnout indicates that the barrier burned away uniformly (Fig. 4). These results indicated that an ignition system and barrier material can be tailored to give either complete termination or a second increment of impulse on command. More complete details on this firing are given in Appendix B.

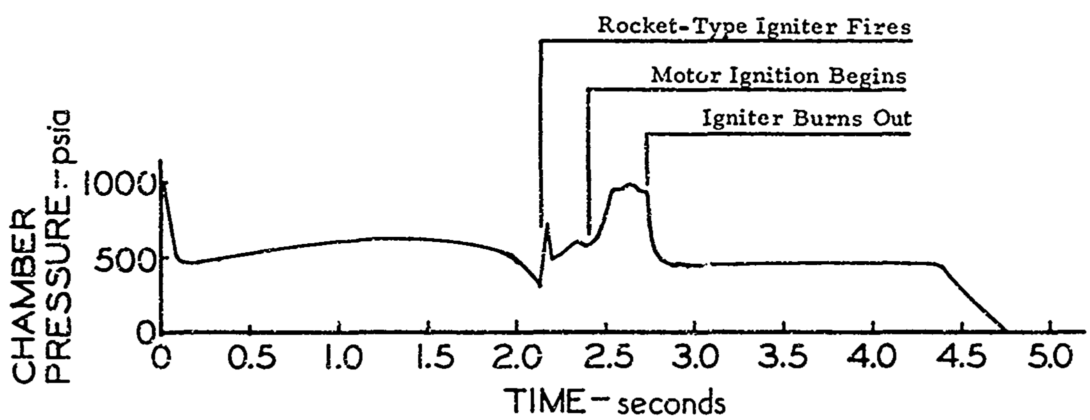


FIG. 4 PRESSURE TRACE FROM QUASI-CONTINUOUS FIRING OF TANDEM GRAIN MOTOR (ROUND 3971).

2.2 Firings with Concentric Grains

2.2.1 Design Features and Preparation Techniques

Although the tandem arrangement of grains was feasible, a more useful arrangement would result if the first grain were concentric with the second. In this case the barrier would be exposed to the flame of the first increment only during tail-off and could be much thinner. A reduced barrier thickness would, in turn make feasible a reduction in igniter size.

To check out this concept, concentric grains were cast into a 6 X 11.4 motor case. A standard Teflon-coated, 5-inch-diameter mandrel sprayed with a silicone release agent[1] was prepared by spreading a thin layer of barrier material over it. The motor was then cast with RH-P-112 propellant using this barrier-coated mandrel. The mandrel was withdrawn leaving the barrier on the surface of the propellant. Propellant for the inside grain was then cast into the same case using a Teflon-coated, 4-inch-diameter mandrel to form the cylindrical cavity. There were no problems in casting either grain or withdrawing the mandrels. The ends of the concentric grain were carefully trimmed and a non-strippable restrictor, SC-105[2], was spread over the surface to prevent burning in that area. Pliobond®[3] was used as an intermediate adhesive between the polysulfide rubber and the propellant. Fig. 5 shows the configuration. The barrier thickness was kept greater than 0.01 inch, which proved to be satisfactory for handling and fabrication.

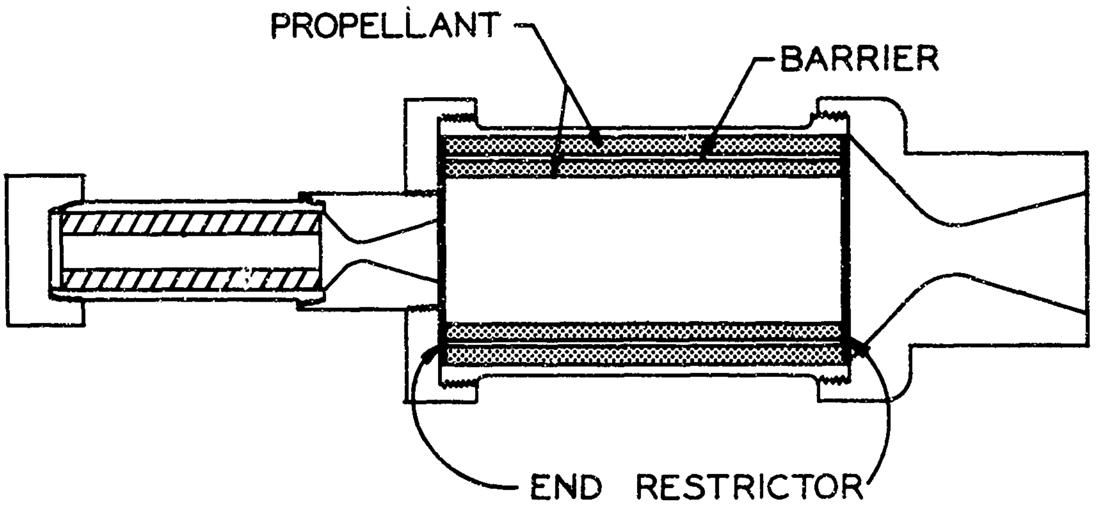


FIG. 5 CONFIGURATION OF THE CONCENTRIC-GRAIN SELECTABLE-IMPULSE MOTOR.

[1]Silicone spray parting agent, Injection Molders Supply Co., Cleveland 20, Ohio.
[2]Polysulfide Rubber, Thiokol Chemical Corp., Trenton, New Jersey.
[3]Trademark for a general purpose adhesive, The Goodyear Tire & Rubber Co., Akron 16, Ohio.

Reducing the thickness from 0.08 inch did create one problem in that PL-33 could no longer be used as the barrier. Since the barrier thickness was now less than the diameter of some of the cellulose acetate particles, the use of the sweep blade technique for barrier application had to be abandoned because bare spots were left when the particles lodged between the mandrel and the blade. PL-33 could not be sprayed because the cellulose acetate dissolved in the solvents used and formed a film on the surface of the sprayed material which interfered with solvent evaporation. For these reasons, a modification of PL-33 without cellulose acetate, designated PL-38 (Table II), was used in all of the later tests. This material could easily be spread "as is" or sprayed when thinned with acetone. The fact that this barrier material was sprayable was especially valuable in view of the plans to progress to more complex grain geometries in later tests. Removing the cellulose acetate apparently did not adversely affect the bond of propellant to the barrier.

The amount of igniter required for the barrier thickness used was determined on the basis of the ablation studies reported in Appendix A.

Table II

Composition of PL-38 Barrier Material

		Weight %
Hysol 2039 Resin	(Epoxy Binder)	22.0
Hysol 3579 Hardener	(Epoxy Binder)	29.0
TEGDN (Plasticizer)		24.0
DMP-10 (Accelerator)		3.0
Asbestos (Filler)		22.0

2.2.2 Results of Termination Tests

Eight concentric-grain motors were tested to determine termination characteristics; there were three failures. The barrier itself was not the cause of any of these failures. The first failure was caused by an inadequate interlock between the barrier and the end restriction which allowed hot gas to penetrate this weak point. The motor re-ignited slowly about 25 seconds after the first increment burned out, giving a haystack pressure trace. It is obvious that the 0.021-inch-thick barrier did not burn away immediately even though exposed to a hot gas environment (Fig. 6).

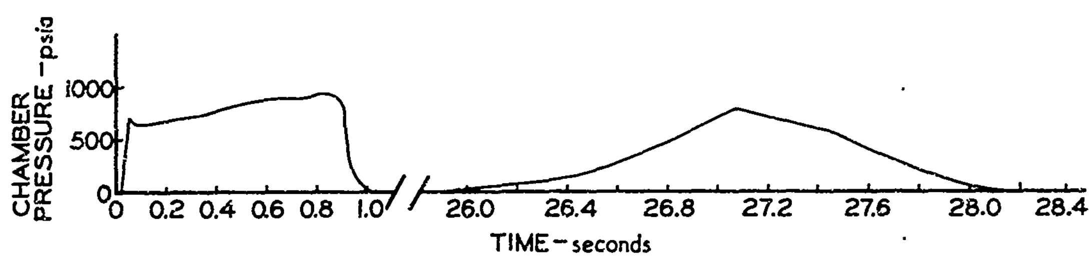
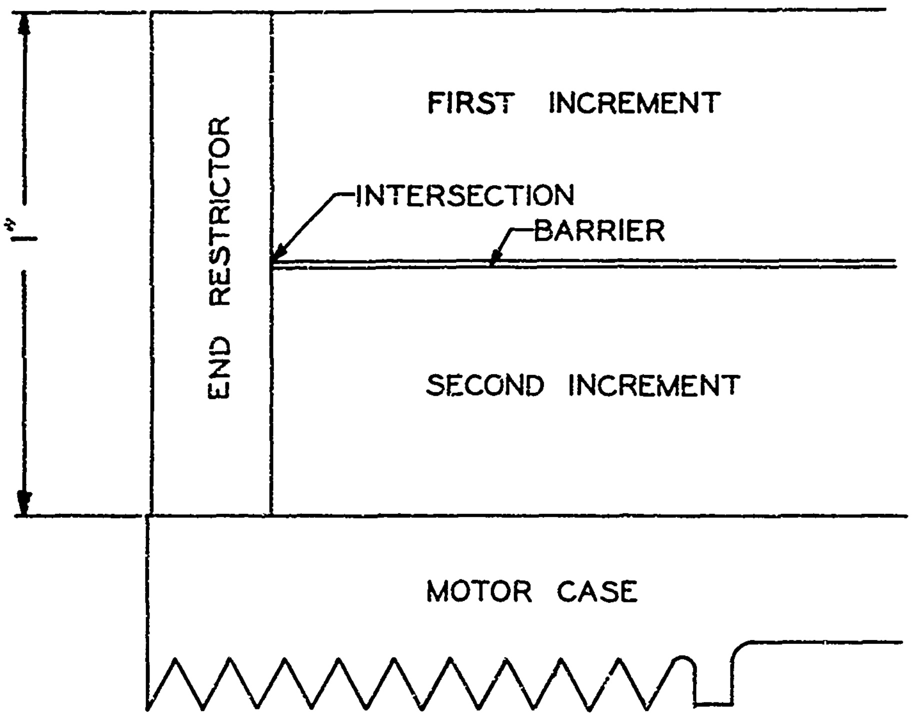
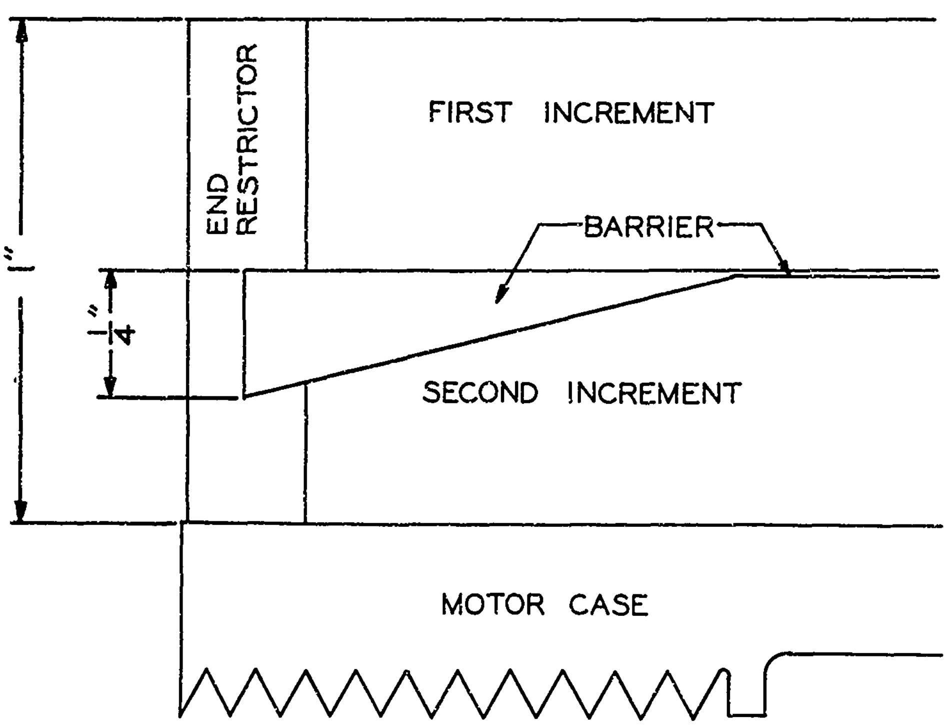


FIG. 6 PRESSURE TRACE RESULTING FROM FAILURE AT INTERSECTION OF BARRIER AND END RESTRICTION (ROUND 4147).

The joint was redesigned to eliminate this problem. Before spraying the mandrel the barrier thickness was built up to about 0.25 inch at each end to provide some mechanical strength and a larger surface for bonding. After both propellant grains were cast and cured, the propellant surface was cut back to expose the barrier layer. The end restriction was then placed on the end of the grains, interlocking with the barrier. The unsuccessful and redesigned intersections are shown in Fig. 7.



A. UNSUCCESSFUL INTERSECTION



B. RE-DESIGNED INTERSECTION

FIG. 7 COMPARISON OF UNSUCCESSFUL AND RE-DESIGNED BARRIER-TO-END-RESTRICTION INTERSECTION.

Two termination failures were caused by gas leaks through the nozzle seal of the rocket-type igniter. The resulting premature initiation increased the chamber pressure to 2000 psia, burned away of part of the propellant, caused uneven burnout of the first increment, and exposed part of the barrier prematurely. The heat absorbed by the barrier then soaked into the propellant and caused the second grain to cook-off. The resulting pressure trace is shown in Fig. 8. The high pressure of the second increment was caused by the small oxidizer particle size used in the propellant batch, and was not a cook-off phenomenon.

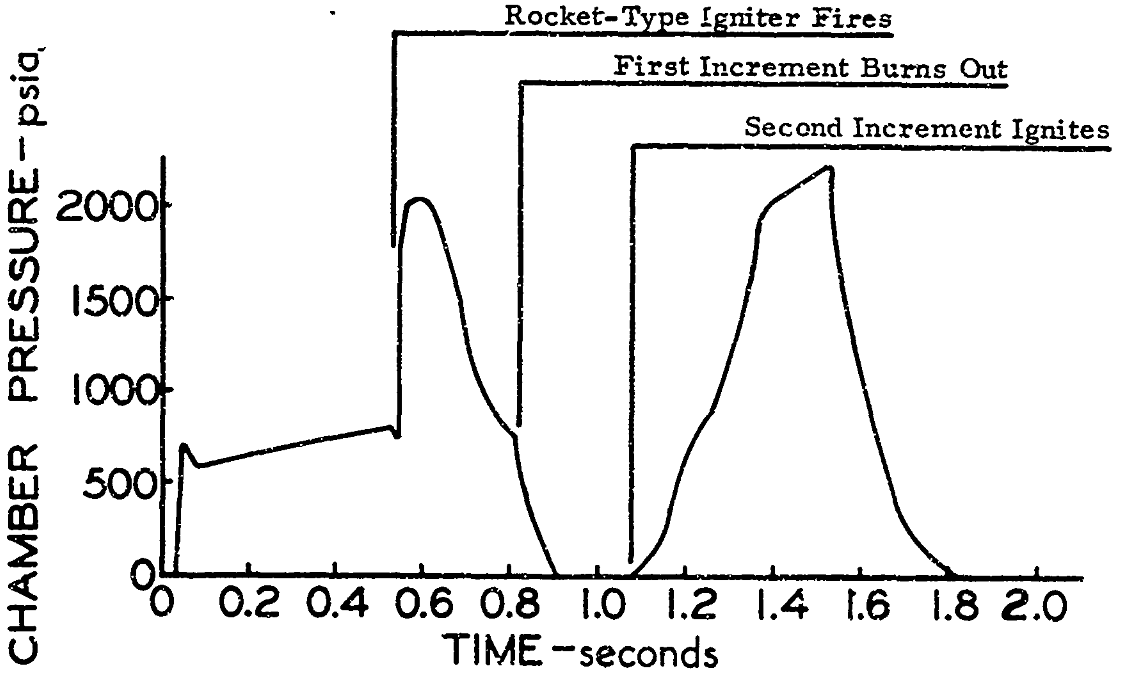


FIG. 8 PRESSURE TRACE RESULTING FROM PREMATURE INITIATION OF IGNITER (ROUND 4653).

The gas leakage was traced to an improper cure of the silicone-rubber adhesive that was used to bond the igniter nozzle closures in place. Increasing the cure time eliminated gas leakage and premature ignition of the rocket-type igniter.

There were five firings in which successful termination of concentric-grain motors was demonstrated. A three minute interval between burning of the first increment and firing of the igniter for the second increment was assumed to be sufficient time for a missile using such a motor to reach the target. However, one round was allowed to cool down several hours after the firing of the first increment and then removed from the stand; the second increment was successfully fired several weeks later.

The pressure trace for Round 4875 shows an excellent match between the barrier thickness (0.012 inch) and the rocket-type igniter. The first increment burned normally and was progressive; this is typical of an internal-burning cylindrical design. After a three minute delay the igniter was fired causing a rapid pressure rise and burning away the barrier. The massive nozzle seal of the igniter motor caused a pressure peak as it passed through the nozzle of the 6-inch motor and then normal burning continued until grain burnout (Fig. 9). A detailed description of all eight termination tests of the concentric grains, including propellant formulations and igniter sizes, is given in Appendix B.

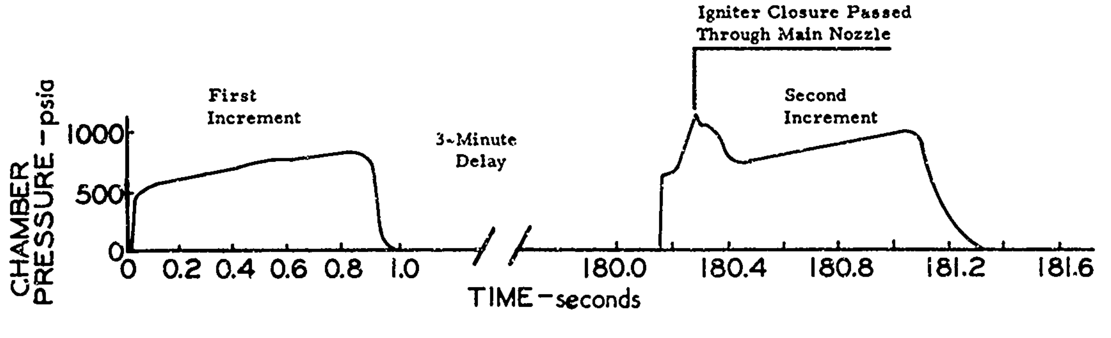


FIG. 9 PRESSURE TRACE FROM A SUCCESSFUL TERMINATION WITH GOOD IGNITION OF SECOND GRAIN (ROUND 4875).

2.2.3 Results of Quasi-Continuous Firing Tests

Nine concentric grains were tested in quasi-continuous operation, and all but one were reasonably successful. A wagonwheel geometry was used in the 2 X 8-inch igniter motor for most of these firings to provide a large mass flux (about 6 lbm/sec) in a reasonable length. The igniter work is discussed in detail in Section 2.2.4.1.

The rocket-type igniter for the second increment was actuated by a timer in the first few motors fired. However, a more sophisticated control, designed to trigger upon the accumulation of a given pressure integral (typical of the pressure integral of the given motor), became available, and was used to trigger all of the later tests. In one firing (Round 5076) the first increment burned out before reaching the given pressure integral and the squib to the rocket-type igniter was not actuated. The problems associated with the $\int Pdt$ switch system are discussed more fully in Section 2.2.4.3.

Fig. 10a shows a good match between the igniter operation and barrier thickness. The dip between grains was somewhat greater than desired but the overall effect was satisfactory. Increasing the barrier thickness to 0.015 inch produced a dip in pressure at 1.2 seconds, the result of incomplete barrier removal (Fig. 10b). If the igniter is actuated too early, a pressure peak results (Fig. 10c). The small dip in pressure indicates that the propellant remaining from the first increment provided some protection for the barrier so that complete removal was delayed.

2.2.4. Supporting Tests

2.2.4.1 Tailoring of the Rocket-Type Igniter

Ideally, the rocket-type igniter should generate mass at a rate equal to that of the main motor until the second grain begins to ignite; at that time the igniter mass flux should decrease as the mass

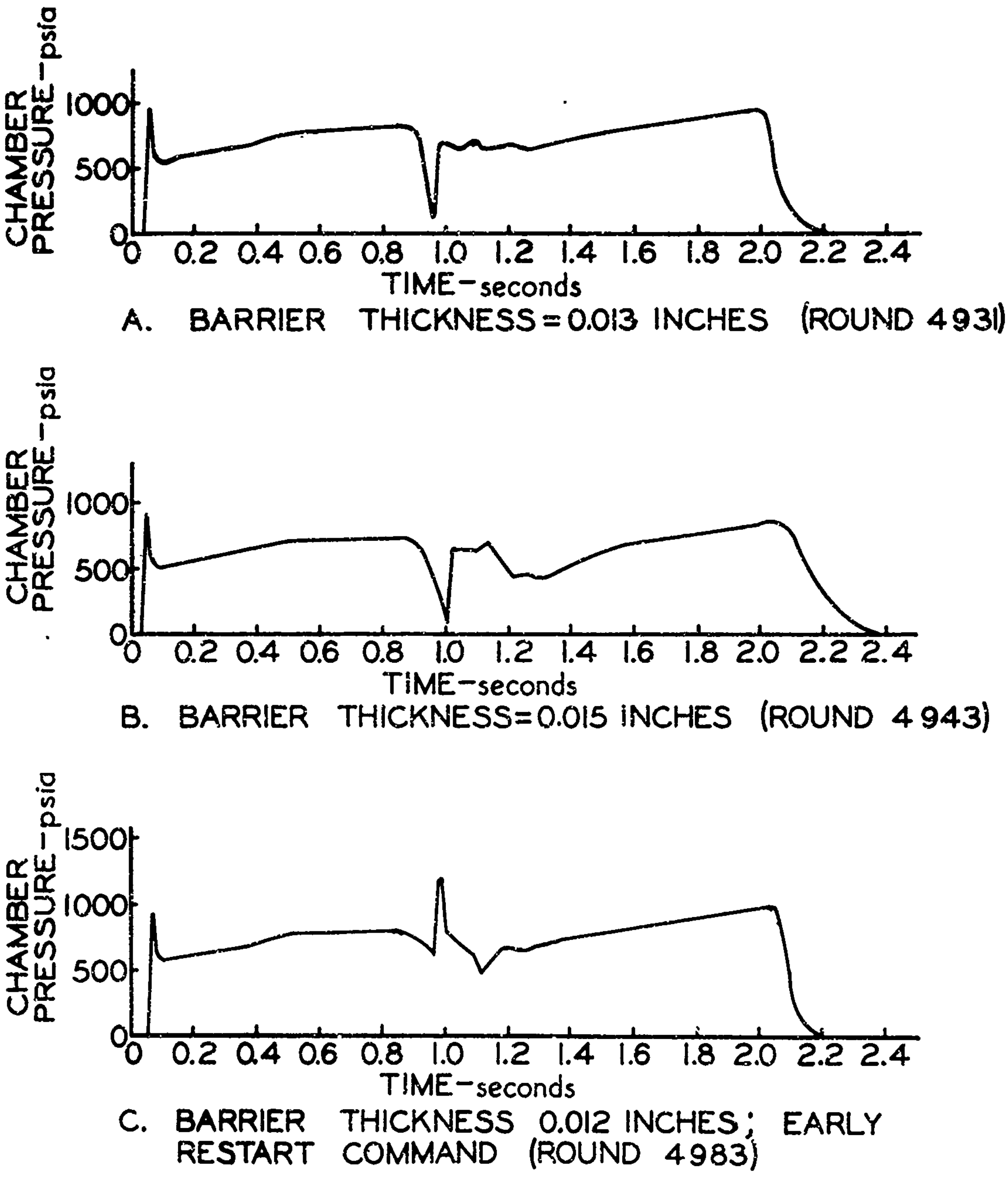


FIG. 10 PRESSURE TRACES FROM SUCCESSFUL QUASI-CONTINUOUS FIRINGS.

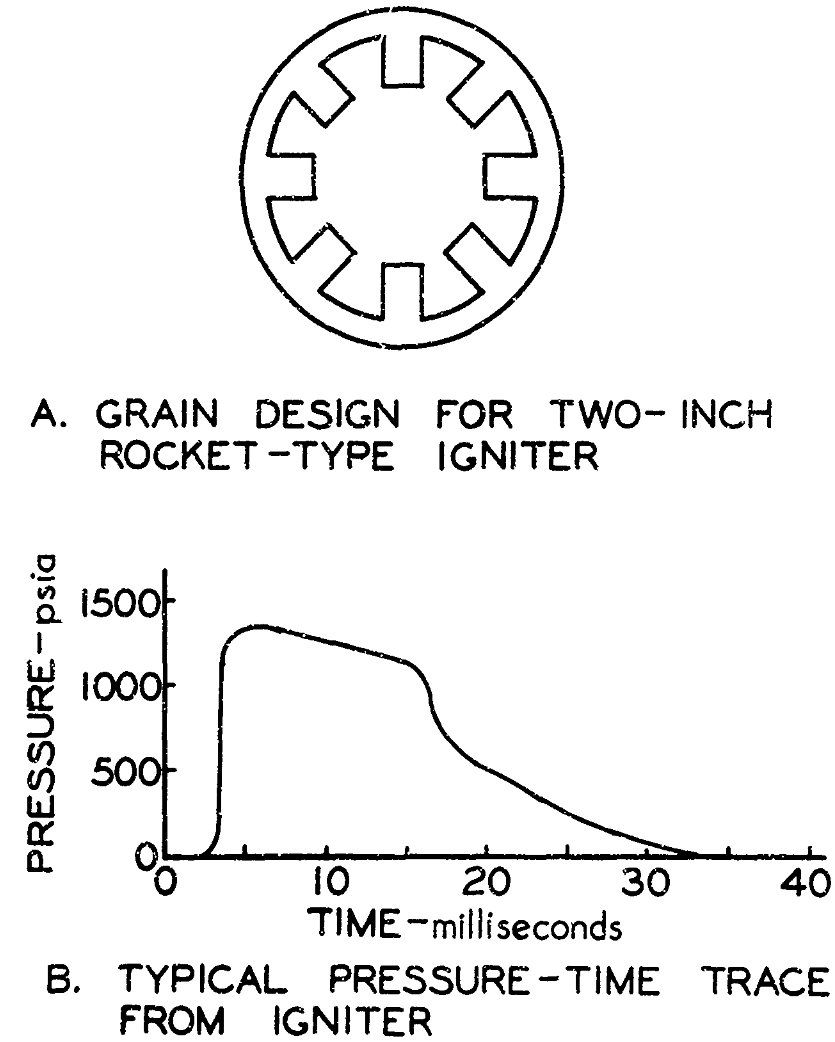


FIG. 12 GRAIN CONFIGURATION AND TYPICAL PRESSURE TRACE OF ROCKET-TYPE IGNITER.

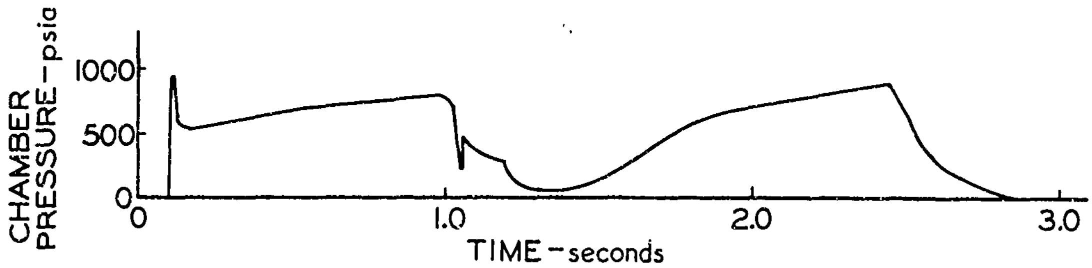


FIG. 13 PRESSURE TRACE WITH A HALF-LENGTH IGNITER (ROUND 5075).

2.2.4.2 Temperature Measurements on the Second-Increment Grain

One motor was prepared with thermocouples embedded in the second increment propellant, touching the outer surface of the barrier (Fig. 14). The purpose was to measure the temperature rise at the propellant surface and to assess the "safety factor" in the termination mode.

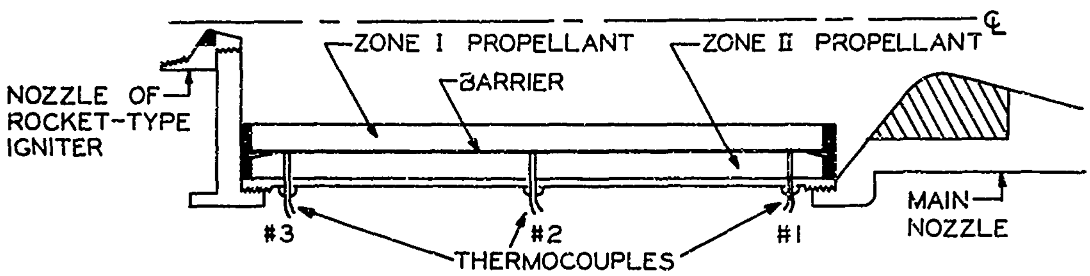


FIG. 14 LOCATION OF THERMOCOUPLES IN TEMPERATURE MEASUREMENT TEST.

Thermocouples No. 1 and No. 2 registered no temperature increase during the firing of the first increment but the temperature at thermocouple No. 3 began increasing just before tailoff and reached 540° F before the motor pressure reached zero (Fig. 15). The inside grain was evidently not concentric with the outer grain, and the barrier over thermocouple No. 3 was exposed prematurely. Even with the high temperature reached, the grain did not ignite and the thermocouple quickly returned to ambient temperature; this indicates that the grain would have remained extinguished for an indefinite period.

The second-increment igniter was fired after a 5-second wait. The thermocouple which had seen the high temperature during first-grain tailoff burned out immediately, and the other two burned out within 150 milliseconds (Fig. 15).

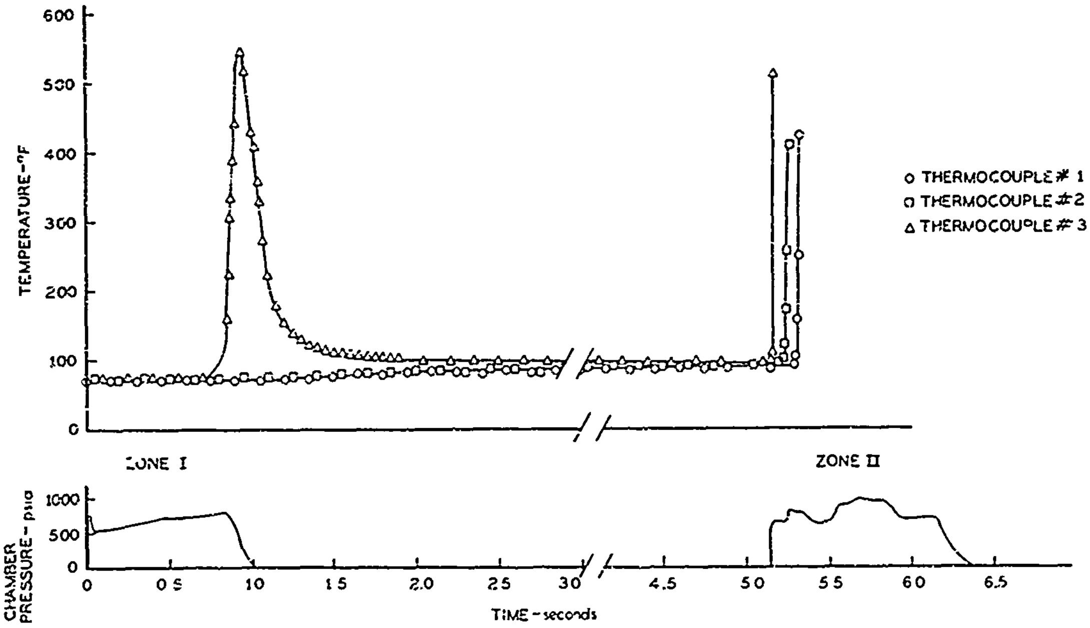


FIG. 15 TEMPERATURE MEASUREMENTS FROM A THERMOCOUPLE-INSTRUMENTED SELECTABLE-IMPULSE MOTOR (ROUND 5074).

Since the burning time of the igniter was 160 milliseconds, this experiment showed that the restrictor was completely burned away at the beginning of igniter tailoff. The immediate response of the head-end thermocouple (No. 3) indicates that essentially all of the barrier covering that point had been destroyed during exposure to the first-increment gases. The fact that thermocouples No. 2 and No. 1 burned out in sequence verifies the work with inert grains, i.e., the rate of barrier removal decreases toward the aft end of the grain. That the aft two thermocouples (No. 1, No. 2) did not indicate a temperature rise during first-stage tailoff could be taken to indicate an excessive barrier thickness. However, the behavior of thermocouple No. 3 did not confirm this. The presently-used thickness (about 0.012 inch) includes a factor of safety that takes care of the grain eccentricity and mal-alignment that can occur when normal production techniques and tolerances are employed. Thinner barriers could undoubtedly be made to work, but the additional effort was beyond the scope of this effort.

2.2.4.3 Sequencing Systems

For quasi-continuous operation of the selectable-impulse motor, a system to initiate the second increment at the end of first increment operation is required. Timers and pressure level sensors are possibilities, but both would require adjustments to compensate for changes in motor operating pressure and burning time as the ambient temperature changes. A system based on measuring the pressure integral would eliminate this problem if the pressure integral is reproducible and is not sensitive to temperatures.

The pressure integral may be expressed analytically as

$$\int P dt = \frac{m_p}{C_D A_t} \qquad (1)$$

where P = chamber pressure (psia)

t = time (seconds)

m_p = mass of propellant (lbm)

C_D = discharge coefficient (lbm/lbf-sec)

A_t = throat area (in^2)

Eq. (1) shows that the pressure integral should be reproducible and unaffected by firing temperature provided that the propellant mass, discharge coefficient, and throat area are constant. A series of motors fired at temperatures from -40 to +140°F showed that the discharge coefficient was not affected by firing temperature and that the pressure integral was fairly reproducible (Table III).

Table III

Reproducibility of Pressure-Time Integral of 2C1.5-4 Test Motors

Temperature (°F)	Pressure Integral Over Action Time (psia-sec)	Pressure Integral Over Burning Time (psia-sec)	Discharge Coefficient (lbm/lbf-sec)
-42[a]	186.1	179.1	0.00613
+8[a]	190.2	185.7	0.00606
+52[b]	188.2	184.7	0.00609
+79[c]	188.9	184.5	0.00610
+96[a]	186.0	181.0	0.00610
+144[b]	187.3	183.3	0.00613
Average	187.7	182.8	0.00610
% σ	1.4	1.9	

[a] Average of five shots.
[b] Average of four shots.
[c] Average of two shots.

Study of the data in the table reveals a possible problem area. The second-increment igniter should be fired during tailoff, i.e., in the interval between burning and action times. The difference between the largest burning-time integral and the smallest action-time integral is quite small; this indicates that under some circumstances the second igniter could be fired before the end of burning time, while in other cases the motor could burn out completely without reaching the triggering level. However, actual experience with nine tests shows that as long as the nozzle throat area is controlled, the system works very well. The two failures out of these nine tests were a result of (1) an oversize nozzle and (2) plugged pressure ports. In both cases the triggering integral was not reached.

The sequencing system used in this program used several components of the range instrumentation. The output of one of the digital integrating units was fed to a preset counter; when the number of counts accumulated in the counter reached the preset value (obtained from experience) the command to fire the second increment was given. This system worked well but could hardly be practical for tactical use in its present form.

Essentially the same function can be performed by a much simpler, more compact unit. The output of a potentiometer-type pressure gauge is fed through an amplifier into an adjustable integrating circuit. When the capacitor is charged to the selected value, second-increment ignition would be triggered. This type of unit is simple, compact, inexpensive, and rugged. Such a system has been used quite successfully in another program with similar requirements. The results of this work indicate that with close control over motor dimensions, the $\int Pdt$ system would be reliable and workable.

3. DEMONSTRATION FIRINGS OF LARGER MOTORS

While the above work showed that the concepts were sound and could be applied successfully to the 6 × 11.4 cylindrically-perforated motor, the grain design for a tactical missile would more likely use a star perforation to increase the surface area and loading fraction. Demonstration firings were made with longer 6-inch motors using an 8-point star geometry to investigate possible problem areas.

3.1 Design Features

Existing 6 × 33 hardware was used and an 8-point star grain was designed to give a loading fraction characteristic of artillery weapons (Fig. 16). The barrier, end restrictor, and the igniter motor were basically the same as used with the cylindrical grains. Motor characteristics are given in Table IV and the predicted pressure-time traces are shown in Fig. 17.

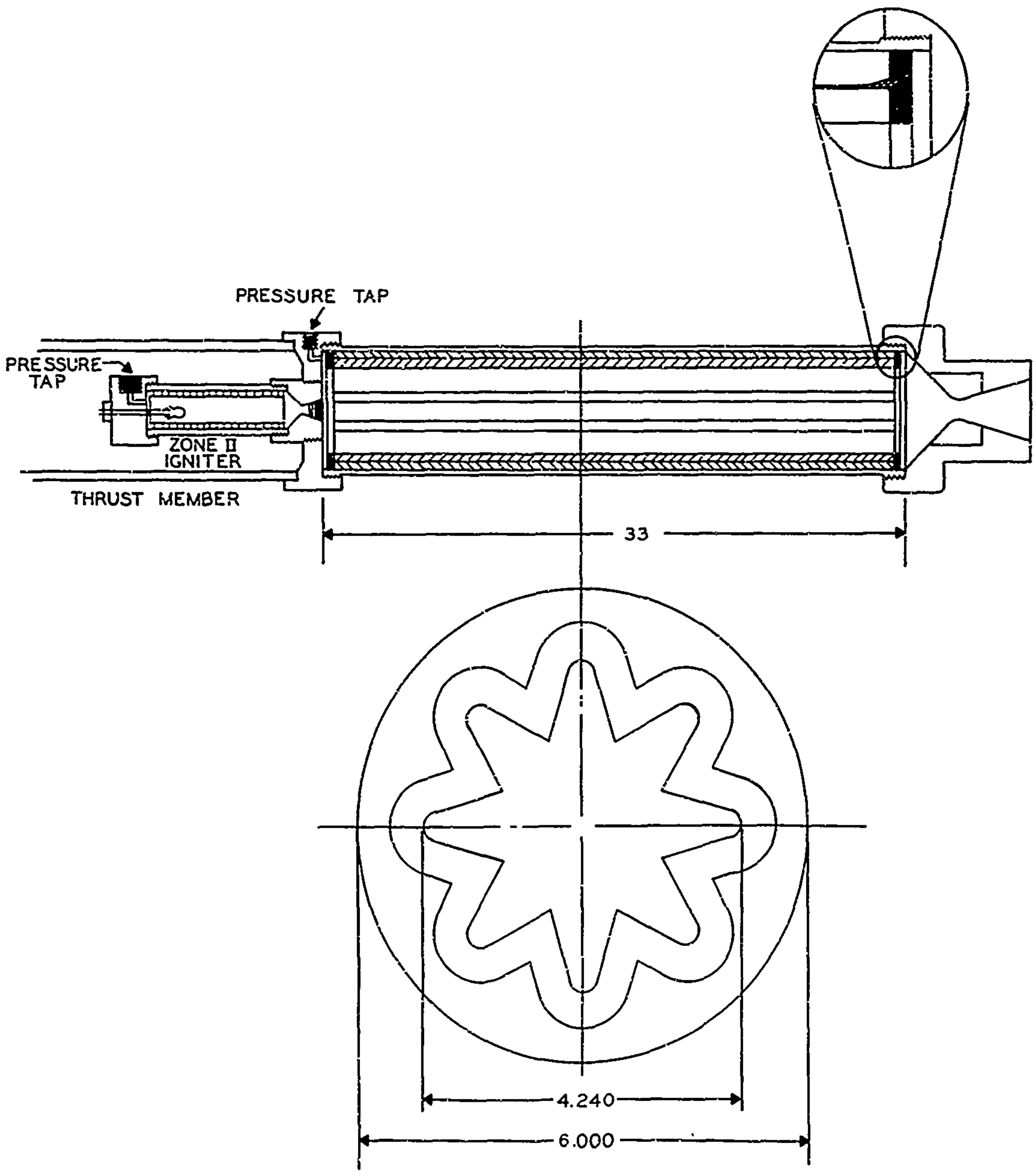


FIG. 16 FIRING CONFIGURATION AND MANDREL GEOMETRY FOR THE 6 X 33 SELECTABLE-IMPULSE MOTOR.

Table IV

Parameters of the 6 × 33 Selectable-Impulse Motor

		Zone I	Zone II	Total
A.	Dimensionless Calculated Quantities			
	Length-to-Diameter Ratio (L/D)			5.5
	Reduced Web (W*)			0.145
	Loading Fraction (ϵ), %	30.1	37.6	67.7
	Sliver Fraction (SF), %	0	7.5	7.5
	Useful Propellant Fraction (ϵ-SF), %	30.1	30.1	60.2
B.	Specific Motor Parameters			
	Length, in.	33.0	33.0	33.0
	Diameter, in.			6.0
	Web, in.	0.435	0.435	0.870
	Surface Area, in^2			641.5
	Port Area, in^2			9.1
	Throat Area, in^2			3.88
	J_o			0.42
	Propellant Composition		RH-P-112cf	
	Propellant Mass, lbm	16.8	22.1	38.9
	Igniter Propellant, lbm		1.4	1.4
C.	Predicted Performance Parameters			
	Burning Pressure, psia	1000	1000	1000
	Burning Time, sec	0.64	0.64	1.50
	Action Time, sec	0.75	1.30	2.20
	Average Thrust, lbf	5800	5800	5800

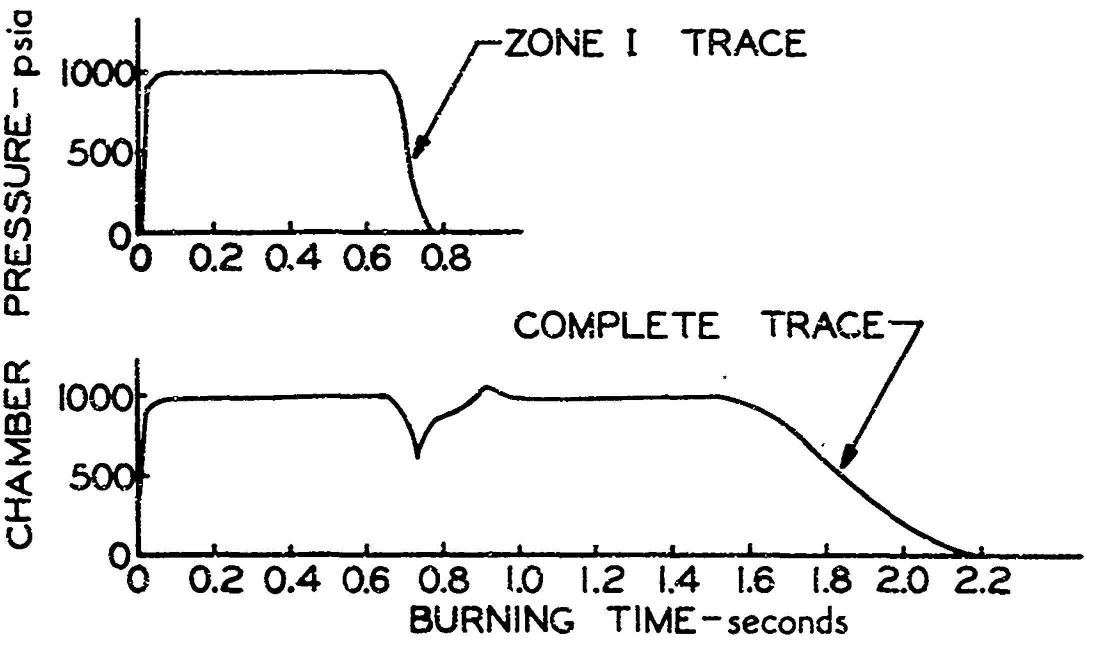


FIG. 17 PREDICTED PRESSURE TRACES FOR 6 x 33 (STAR-PERFORATED) SELECTABLE-IMPULSE MOTOR.

3.2 Preparation Techniques

The star geometry caused no complications in mandrel preparation; spray application of the barrier went smoothly and the barrier ends were easily built up to interlock with the end restrictor. Mandrel alignment was more critical because of the greater length, but good alignment was achieved in each motor. The thickened barrier ends were exposed by trimming back the propellant and the grain ends were restricted with polysulfide rubber.

3.3 Firing Results

3.3.1 Termination Tests

Three of the four termination tests were successful. In Round 5230 (barrier thickness = 0.015 inch) the first grain terminated well, but the second grain re-ignited after about 20 seconds and burned at low pressure for about 40 seconds. This failure was a result of a burnthrough of the SC-105 restrictor at the aft end of the grain and was not a result of a barrier failure. Rounds 5358 and 5472 (barrier thickness = 0.025- and 0.015-inch, respectively) both gave successful terminations, but neither re-ignition was successful. The 12-inch-long wagonwheel igniter ($\dot{m}$ = 10.8 lbm/sec) was not sufficient to burn through the barrier. A 34-second hangfire was experienced with the 25 mil barrier (Fig. 18) and a 2-second hangfire occurred with the 15-mil barrier (Fig. 19). These tests showed that for this size motor a larger igniter was necessary, that a 0.015-inch barrier thickness was excessive, and that the work done on ignition requirements in 6 X 11.4 hardware was not directly applicable to this motor.

Round 5547 was originally intended to be a quasi-continuous test, but the pressure ports plugged during first-increment operation, the $\int Pdt$ switch did not operate, and the second-increment igniter did not fire. That a successful termination occurred was especially significant because the barrier was only 0.011-inch thick and was also wrinkled by the shrinkage of the outer grain during cure. This test demonstrated that barriers thinner than 0.010-inch could probably be made to perform satisfactorily.

A 16-inch-long wagonwheel igniter was used for the second increment giving much better ignition than the three previous rounds (Fig. 20).

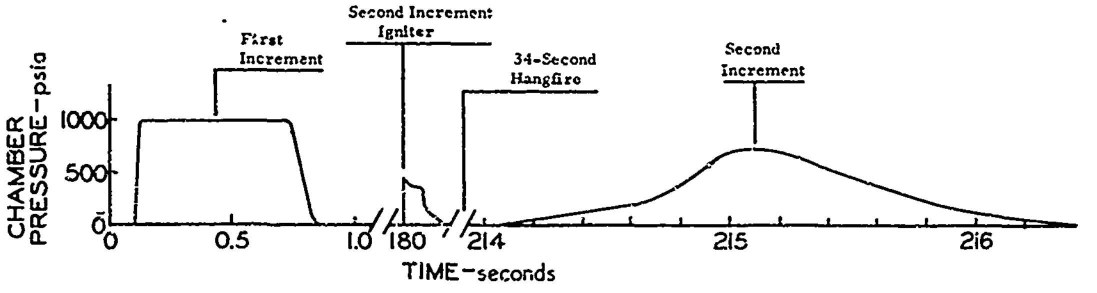


FIG. 18 PRESSURE TRACE SHOWING TERMINATION WITH A 0.025-INCH BARRIER AND UNSUCCESSFUL REIGNITION OF 6 X 33 MOTOR (ROUND 5358).

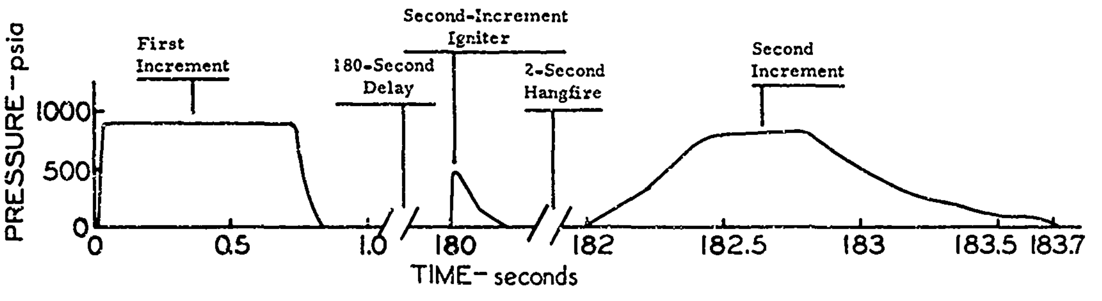


FIG. 19 PRESSURE TRACE SHOWING TERMINATION WITH A 0.015-INCH BARRIER AND POOR REIGNITION OF 6 X 33 MOTOR (ROUND 5547).

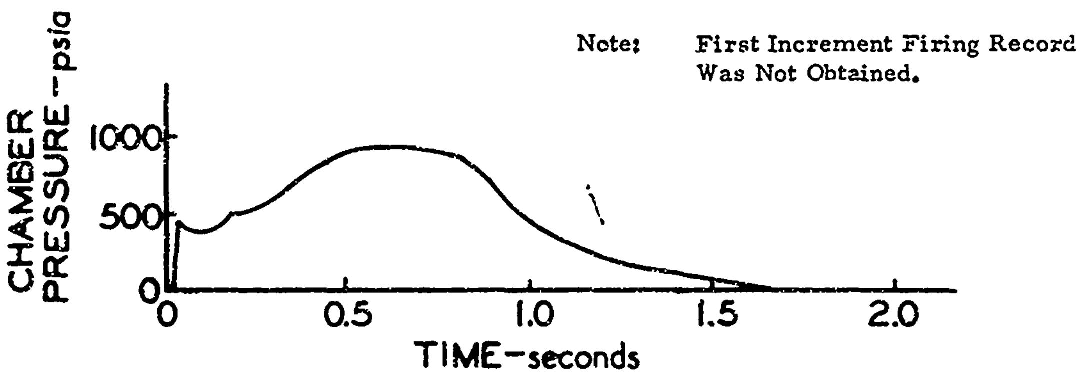


FIG. 20 IGNITION OF A STAR-PERFORATED GRAIN UNDER A 0.011-INCH BARRIER (ROUND 5547).

3.3.2 Quasi-Continuous Tests

Two quasi-continuous test firings of this motor were made. A 0.009-inch barrier thickness with a 2 X 16 wagonwheel igniter gave satisfactory performance and compared well with the prediction (Fig. 21). The smaller dip of Round 5695 resulted from firing the igniter earlier during the tailoff of the first increment. The quasi-continuous firings also compared well with a round having no barrier. A control round showed very little difference in the tailoff although the burning time was shorter, and the average pressure was higher (Fig. 22, Table V). A summary of all data obtained from the 6 X 33 firings is given in Appendix C.

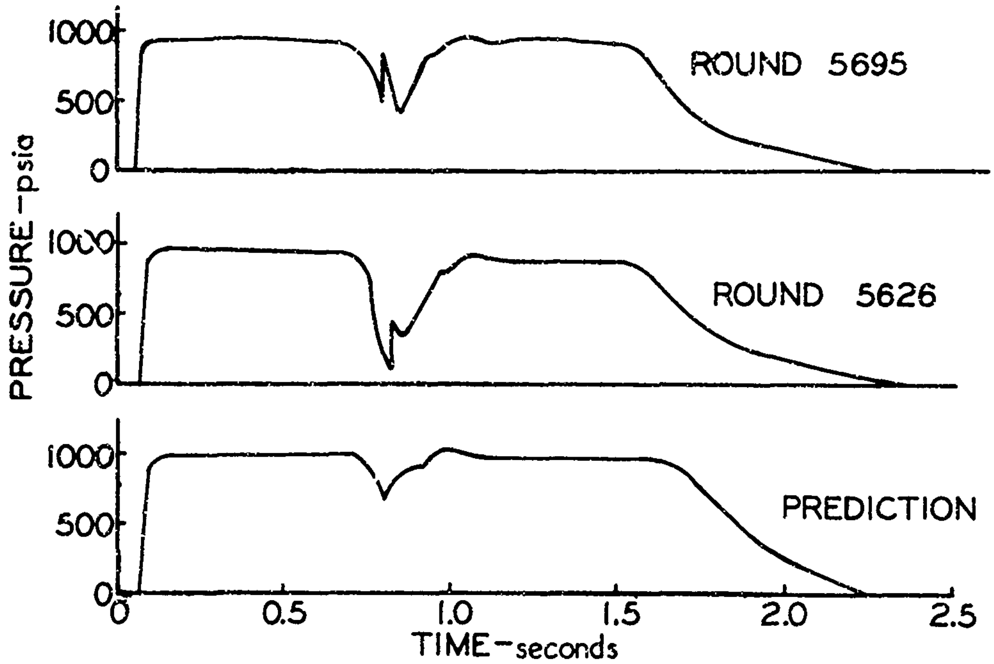


FIG. 21 COMPARISON OF PRESSURE TRACES FROM 6 X 33 SELECTABLE-IMPULSE MOTORS WITH PREDICTED TRACE.

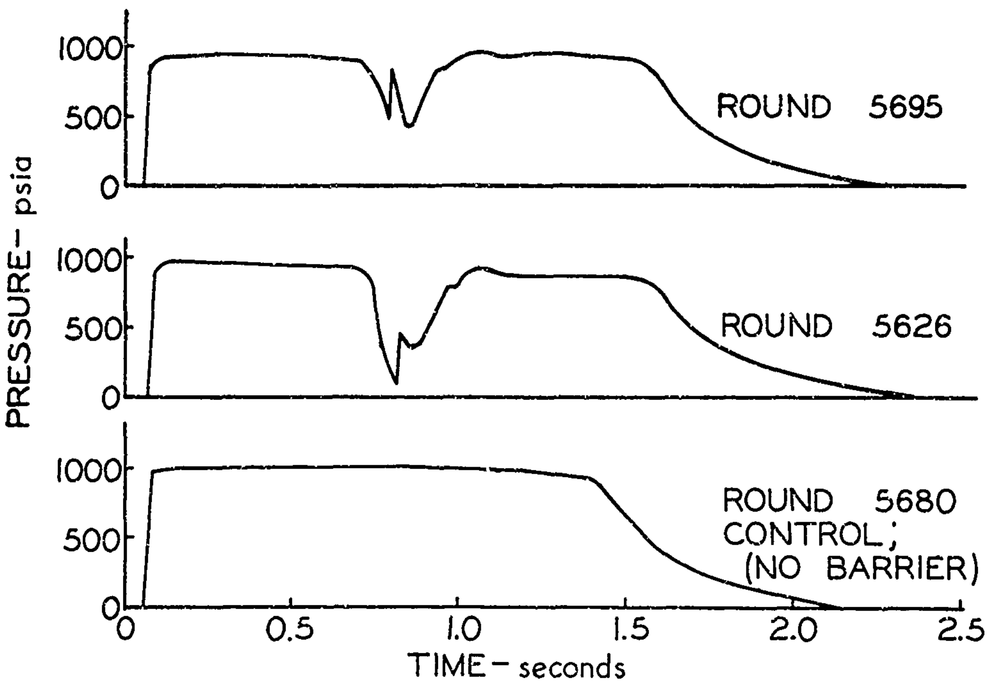


FIG. 22 PERFORMANCE OF 6 X 33 DEMONSTRATION MOTORS WITH AND WITHOUT BARRIERS.

Table V

Comparison of 6 X 33 Selectable-Impulse Motors with a Standard 6 X 33 Motor

Round No.	Type	Burning Time (sec)	$\overline{P}_b$ (psia)	Action Time (sec)	$\overline{P}_a$ (psia)	Transition Time (sec)	Transition Pressure (psia)
5626	S.I.	1.500	885	2.090	735	0.22	507
5695	S.I.	1.500	904	2.096	747	0.16	629
5680	No Barrier	1.36	1009	1.92	823	N/A	N/A

3.4 Future Work

This work will continue since it offers a promising technique for achieving selectable-impulse, high-thrust booster motors for tactical weapons. A few more firings are planned with plastisol nitrocellulose propellants. Future work will include a more thorough evaluation of materials for barriers, the use of other propellants, and application of this technique to other grain designs such as a wagonwheel.

4. CONCLUSIONS

A technique that allows the total impulse of a solid-propellant motor to be "selected" before firing has been characterized. A thin inert barrier was used to partition the propellant grain into two increments. The first increment was ignited and burned normally but the protected increment did not burn unless ignited by its own igniter.

The barrier material developed for plastisol nitrocellulose composite propellant can be applied to a mandrel before casting by a sweep blade or by spraying. Studies of barrier ablation under igniter gas flow made it possible to tailor a rocket-type igniter for a given barrier thickness. A sequencing system designed to trigger the second increment as the first reaches a given pressure integral was shown to be applicable to this type of unit.

A tandem arrangement of the propellant grains required barrier thicknesses up to 0.080 inch in a 6-inch motor, because the barrier was exposed to the high-pressure combustion gases during the entire burning time of the first increment. Long-burning rocket-type igniters were necessary to burn away the barrier.

A concentric arrangement of the grains permitted a much thinner barrier to be used. Thicknesses ranging from 0.009 inch to 0.015 inch successfully protected cylindrical-port and star-perforated grains in 6-inch test motors. Careful tailoring and sequencing of the rocket-type igniter minimized the dip in the pressure trace during quasi-continuous firings.

Demonstration firings with a 6 X 33 test motor confirmed that the technique would be useful in high-thrust motors with a practicable grain design. Both first increment and quasi-continuous firings were made.

APPENDIX A

ABLATION OF RESTRICTOR MATERIALS

The ablation rate of barrier materials under the flow of gases from a rocket-type igniter was determined under a number of test conditions. For these tests PL-33 barrier was cast into 6-inch hardware to simulate the outer surface of an encapsulated propellant grain. The igniter motor was located so that the gases leaving its nozzle flowed down the port of the grain. The effects of port size, igniter size, igniter propellant type (aluminum concentration) and motor length were studied.

The distance from the igniter had a significant effect on the barrier regression rate. The maximum rate usually occurred near the point at which the gases first impinged on the barrier surface. (The impingement point is at the intersection formed by extending the nozzle exit cone to the port diameter.) There was a uniform decrease in rate from the point of maximum to the aft end of the grain (Fig. A-1). The data shown are for Plexiglas®[1] but PL-33 will behave in the same manner.

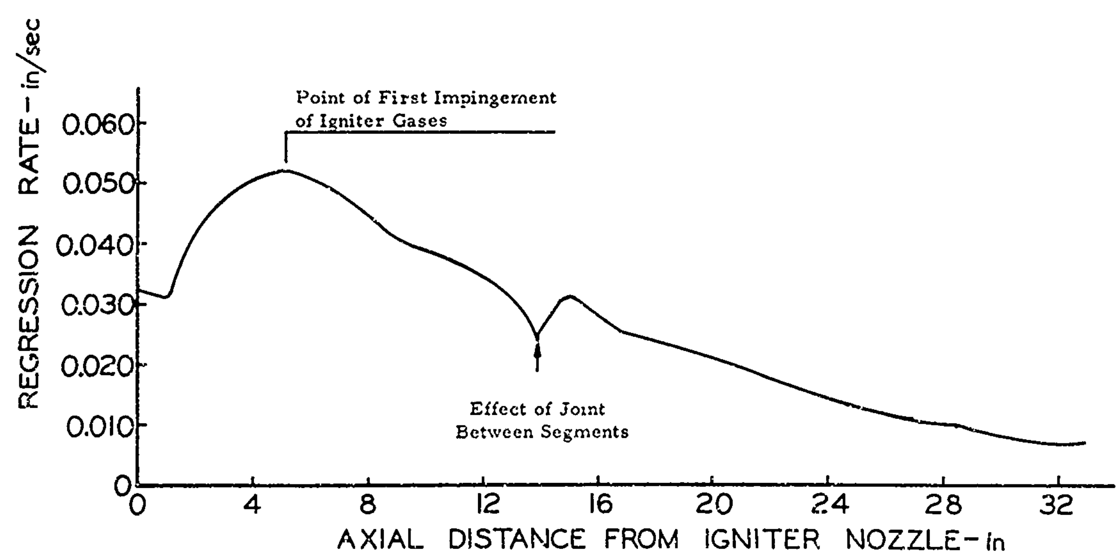


FIG. A-1 EFFECT OF DISTANCE FROM IGNITER NOZZLE ON ABLATION RATE OF PLEXIGLAS®.

[1]Trademark for thermoplastic poly(methyl methacrylate)-type polymers, Rohm and Haas Company, Philadelphia, Pennsylvania.

The port diameter and igniter size determine the specific mass rate of flow of gases in the port. As the specific mass flux increases, the barrier regression rate also increases. The maximum rate shown in Fig. A-2 corresponds to the point at which the igniter gases impinge on the barrier material in the port. The minimum rate was obtained from measurements made near the aft end of the grain. Maximum barrier regression rates estimated from actual 6 X 11.4 motor firings with live grains correlated fairly well with rates measured in the inert tests. It was interesting that the aluminum content of the igniter propellant had little effect on the barrier regression rate. (Compare test points for RH-P-178, RH-P-112, and RH-P-163 along the maximum and minimum lines in Fig. A-2.) A summary of the data from these test firings is given in Table A-I.

Table A-I

Ablation of PL-33 Restrictor Under Flow of Ignitor Gases

Round No.	Average Port Dia. (in)	Igniter: Size	Igniter: Propellant Composition	Igniter: Propellant Mass (lbm)	Igniter: D_t (in)	Igniter: $\overline{P}_b$ (psia)	Igniter: $\dot{m}$ (lbm/sec)	Motor: D_t Before/After (in) (in)	Motor: $\overline{P}_a$ (psia)	Motor: $\overline{t}_a$ (msec)	Motor: $\frac{\dot{m}_{ign}}{A_p}$ (lbm/sec-in²)	Ablation Rate: Maximum (in/sec)	Ablation Rate: Minimum (in/sec)
3913	4.25	2C1-7.5	178^{ce}_{cc}	1.04	0.493	2040	2.37	0.910/0.883[a]	603	439	0.596	0.435	0.172
3914	3.10	2C1-7.5	178^{ce}_{cc}	1.03	0.493	2116	2.43	0.909/0.880	648	433	0.322	0.281	0.029
3915	2.20	2C1-4.0	178^{ce}_{cc}	0.56	0.409	1361	1.05	0.911/0.880	284	531	0.276	0.194	0.064
3943	3.15	2C1-4.0	178^{ce}_{cc}	0.56	0.402	1323	1.03	0.909/0.864	263	520	0.132	0.134	0.017
4211	5.55	2C1-4.0	178^{ce}_{cc}	0.56	0.401	1360	1.05	1.023/0.970	225	517	0.043	0.100	0.008
4212	5.55	2C1-7.5	178^{ce}_{cc}	1.05	0.507	1790	2.22	1.011/0.976	486	471	0.092	0.132	0.004
4298	5.55	2C1-7.5	163^{ce}_{cc}	0.98	0.502	1409	1.66	1.09/0.981	354	587	0.069	0.100	0.012
4392	2.10	2C1-7.5	163^{ce}_{cc}	0.98	0.520	1214	1.56	1.023/1.026	340	627	0.450	0.240	0.063
4393	3.10	2C1-7.5	163^{ce}_{cc}	0.98	0.516	1247	1.59	1.011/1.025	332	610	0.210	0.154	0.038
4542	5.00	2 × 8[b]	112ce	0.72	0.833	1212	2.81	1.026/1.014	557	255	0.143	0.104	0.049
4543	5.00	2 × 4[b]	112ce	0.36	0.625	951	1.41	1.012/1.012	306	255	0.072	0.076	0.020
4754[c]	5.00	2C1-7.5	163^{ce}_{cc}	0.985	0.527	1139	1.40	1.011/1.012	302	705	0.071	0.058	0.010

[a] Indicates buildup in throat.
[b] Wagonwheel mandrel.
[c] Plexiglas grain.

The information contained in Figs. A-1 and A-2 can be used to design an igniter for a two-increment motor. The mass flux and duration of the igniter should be such that all of the barrier at the

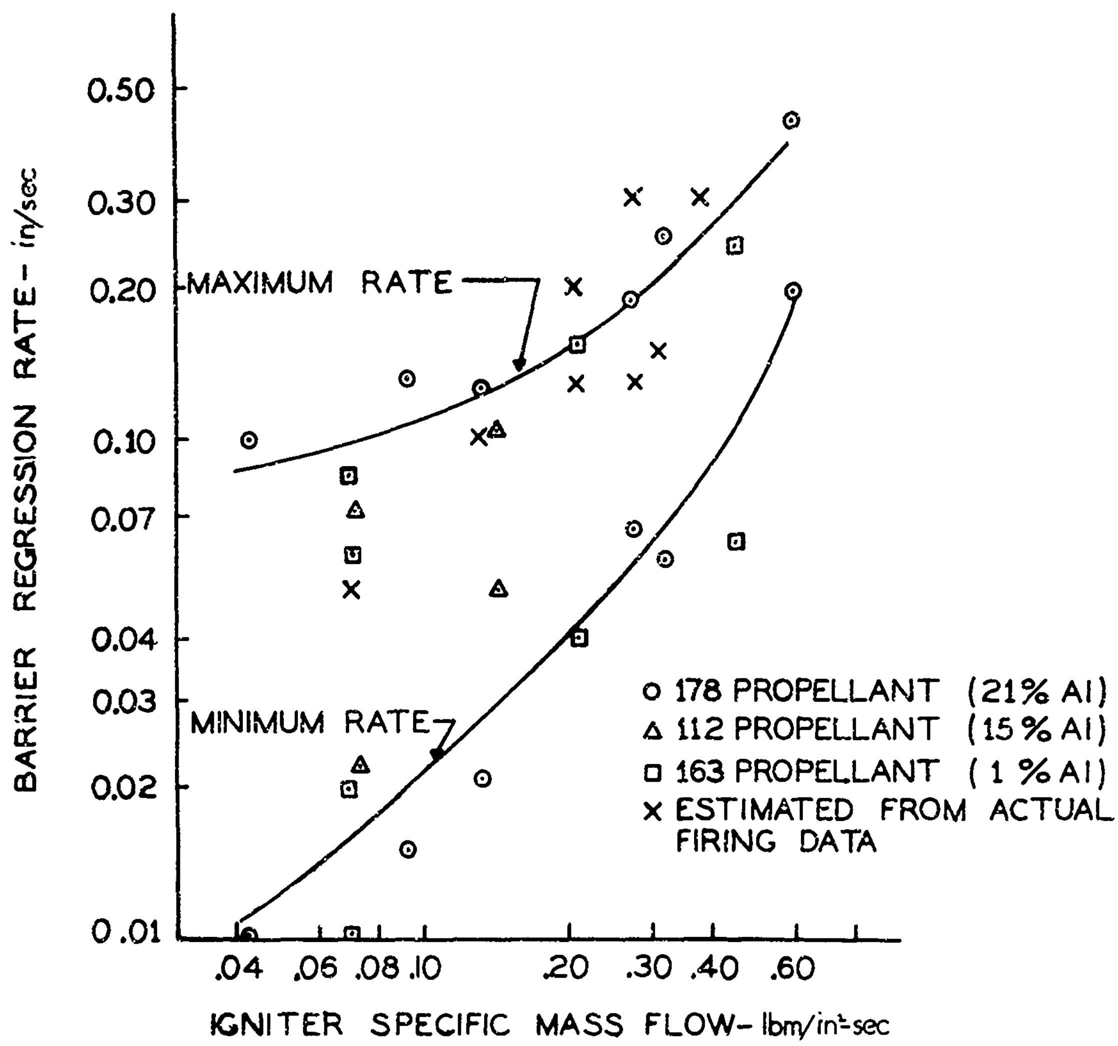


FIG. A-2 EFFECT OF IGNITER SPECIFIC MASS FLUX ON BARRIER REGRESSION RATE.

aft end (point of minimum regression rate) is gone at the instant of igniter burnout. At the same time, the initial mass flux should ideally be equal to that of the main motor, and the duration of this high mass flux would be fixed by the time necessary to penetrate the barrier in the fastest-burning area. With the time of burnout, initial mass flux, and average mass flux specified, the ideal igniter mass flux vs. time history can be drawn (Fig. A-3).

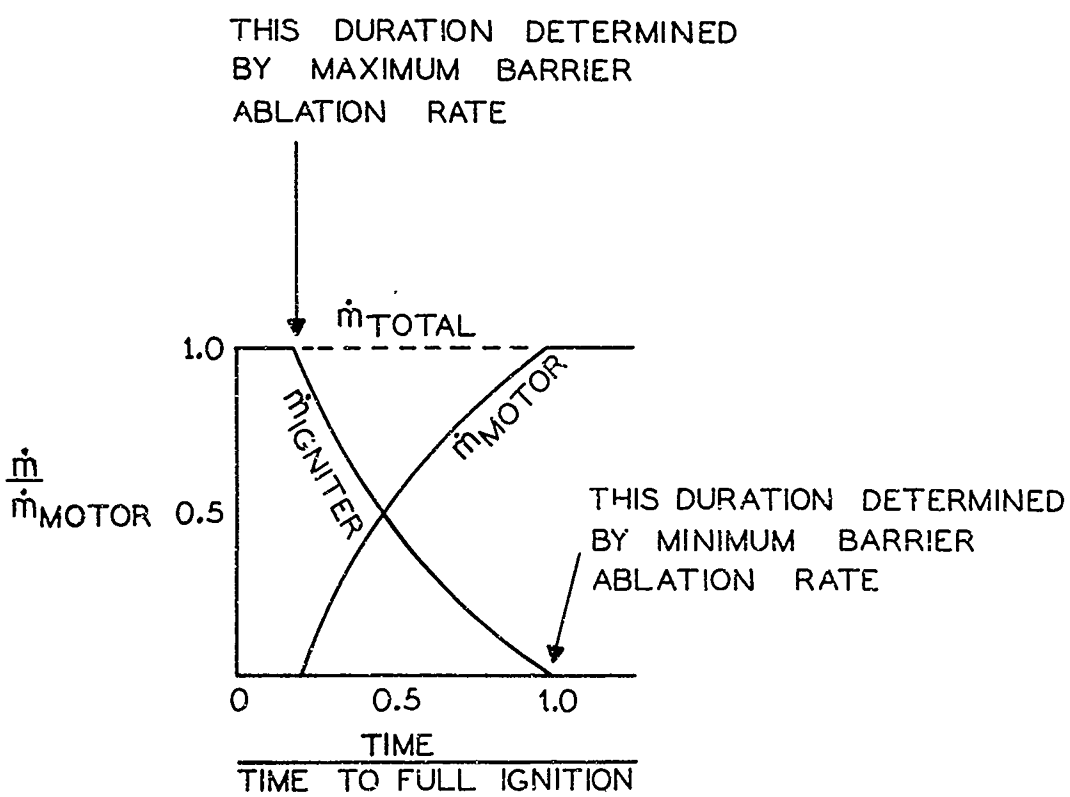


FIG. A-3 DESIGN OF A ROCKET-TYPE IGNITER MOTOR.

For the tandem grain arrangement, the ablation rate of the barrier at stagnation conditions (with aft grain operating) was determined in much the same way. Aft motors burning at different pressures for various times were fired with inert forward grains in place. The data indicated that the barrier ablation rate was a function of time and burning pressure (Table A-II). The maximum ablation rate was measured at the point nearest the burning grain. If more data were obtained, the average regression rate could be expressed analytically as a function of these two variables; however, these few tests yielded enough data for the first firings and the additional effort was not warranted.

Table A-II

Ablation of PL-33 Barrier in Tandem Configuration

(Ablating surface forward of burning grain)

Round No.	Port Diameter (in)	Motor Duration (sec)	Motor Pressure (psia)	Ablation Rate (in/sec) Average	Maximum	Minimum
3916	3.05	0.910	840	0.020	0.035	0.007
4041	3.05	2.150	590	0.010	0.012	0.008
4042	3.03	1.560	1090	0.016	0.021	0.011

APPENDIX B

SUMMARY OF FIRING RESULTS FROM SUBSCALE TESTS

The body of the report contains the major results and typical examples of firing records. This appendix presents a collection of all igniter and barrier parameters and a round-by-round review of the subscale firings with tandem-grain and concentric-grain motors.

The composition of the plastisol nitrocellulose composite propellants used in the main motors and the igniter grains is given in Table B-I.

Table B-I

Composition of Propellants for Test Program

Ingredient	RH-P-112 (Wt. %)	RH-P-163 (Wt. %)	RH-P-178 (Wt. %)
Double-base powder	16.67	16.67	10.92
TEGDN	37.33	37.33	31.83
Ammonium perchlorate[a]	30.00	44.00	35.25
Aluminum[b]	15.00	1.00	21.00
Resorcinol	1.00	1.00	1.00

[a] The nominal particle size (D^{50}_{M}) of the ammonium perchlorate is designated by a two-letter suffix: i.e., ce is 15μ; cf is 55μ; cc is 180μ.
[b] Alcoa 140, Aluminum Company of America, Pittsburgh, Pa.

Table B-II summarizes the important parameters and results of each test. The standard ballistic data, e.g., $\bar{r}_b$, I_{spd}, etc., are not reported because these numbers would add little to the results. Pages B-3 through B-20 show the trace shapes obtained from each firing, describe the test conditions, and summarize the results.

Table B-II

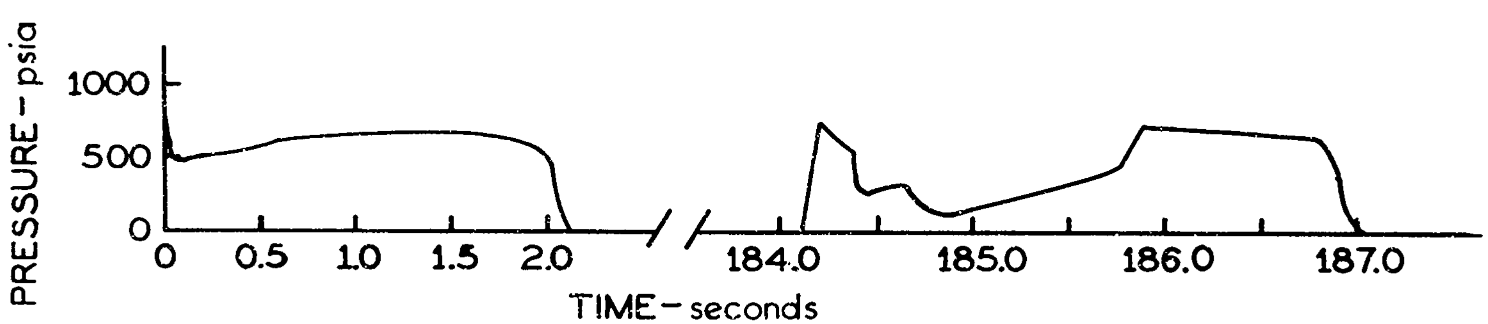
Summary of Firing Conditions and Results for Subscale Tests

Round No.	Barrier Thickness (in)	Delay Between Increments (sec)	Igniter: Type and Size	Igniter: Propellant	Igniter: Propellant Mass (lbm)	Igniter: Burning Time (sec)	Igniter: $\dot{m}$ (lbm/sec)	$\dot{m}/A_p$ (lbm/in^2 sec)	$r_{pred.}$[e] (in/sec)	Main Motor: Throat Diameter (in)	Main Motor: Mass Discharge Rate (lbm/sec)	t_{ign}[f] (sec)	r_{est}[g] (in/sec)
3970[a]	0.080	182	2Cst7.5[b]	178 ce/cc[d]	1.01	0.5	2.0	0.283	0.23	1.090	15.3	0.25	0.32
3971[a]	0.080	0	2Cst11.5	178 ce/cc	1.59	0.6	2.7	0.382	0.29	1.094	14.2	0.25	0.32
4147	0.021	25	2C1.5-4.0[c]	112 ce	0.29	---	---	----	---	1.124	10.2	---	---
4148	0.021	0	2C1.5-4.0	112 ce	0.29	0.2	1.45	0.074	0.10	1.142	10.3	1.30	<0.10
4342	0.020	181	2C1.0-7.5	178 ce	1.04	0.4	2.5	0.132	0.14	1.147	10.0	0.20	0.10
4343	0.012	0	2C1.0-7.5	178 ce	1.05	0.4	2.6	0.132	0.14	1.149	10.1	0.10	0.10
4652	0.011	0	Wagonwheel 2-2 x 4	112 ce	0.71	0.11	6.5	0.33	0.23	1.156	10.1	0.13	0.09
4653	0.017	7.1	Wagonwheel 2-2 x 4	112 ce	0.71	N/A	N/A	N/A	N/A	1.152	10.1	N/A	N/A
4875	0.012	160	Wagonwheel 2-2 X 4	112 ce	0.72	0.17	4.2	0.23	0.16	1.152	10.2	0.06	0.20
4876	0.014	7.2	Wagonwheel 2-2 X 4	112 ce	0.70	N/A	N/A	N/A	N/A	1.154	10.1	N/A	N/A
4930	0.013	0 ∫Pdt Switch	Wagonwheel 2-2 X 4	112 ce	0.72	0.17	4.2	0.21	0.16	1.165	9.9	0.10	0.13
4931	0.013	0 ∫Pdt Switch	Wagonwheel 2-2 X 4	112 ce	0.71	0.13	5.5	0.28	0.20	1.165	10.0	0.10	0.13
4943	0.015	0 ∫Pdt Switch	Wagonwheel 2-2 X 4	112 ce i	0.72	0.12	6.0	0.31	0.21	1.173	10.1	0.10	0.15
4963	0.012	0 ∫Pdt Switch	Wagonwheel 2-2 X 4	112 ce	0.72	0.12	6.0	0.31	0.21	1.158	10.0	0.16	0.08
5074	0.012	5 Timer	Wagonwheel 2-2 X 4	112 ce	0.72	0.13	5.5	0.28	0.18	1.173	10.1	0.10	0.12
5075	0.0125	0 ∫Pdt Switch	Wagonwheel 1-2 X 4	112 ce	0.36	0.13	2.8	0.14	0.10	1.175	10.1	0.25	0.05
5077	0.0145	180 Timer	Wagonwheel 2-2 X 4	112 ce	0.72	0.12	6.0	0.30	0.20	1.185	10.1	0.13	0.11
5076	0.013	None Planned ∫Pdt Switch	Wagonwheel 2-2 X 4	112 ce	0.72	0.12	6.0	0.30	0.20	1.187	10.1	0.12	0.11

[a] Rounds 3970 and 3971 had tandem grains. All others were concentric.
[b] This designates a cylindrical grain having a 2-in. O.D., a 1-in. I.D., and a 7.5-in. length with slots to give a regressive trace.
[c] This designates a grain having a 2-in. O.D., a 1.5-in. I.D., and a 4-in. length.
[d] 80% ce, 20% cc ammonium perchlorate.
[e] This is the predicted maximum barrier regression rate.
[f] This is time to first indication of grain ignition after igniter operates.
[g] This is the maximum barrier regression rate estimated from the firing.

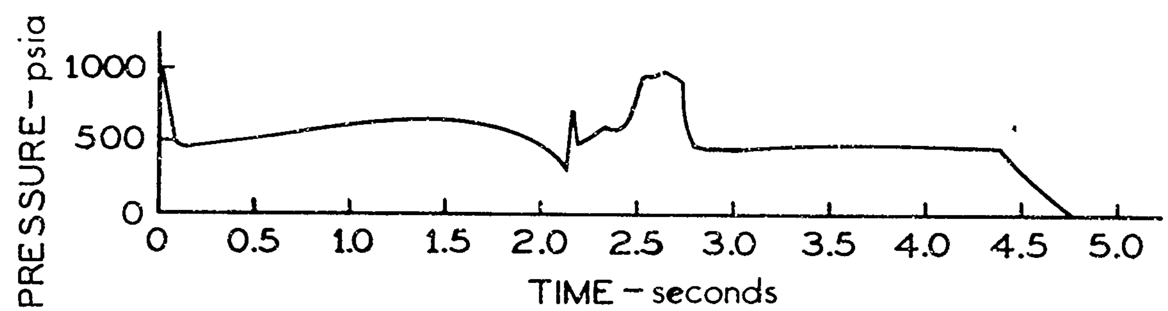
Round 3970

Type: Tandem, 180-sec delay.
Barrier Material: PL-33,. spread.
Barrier Thickness: 0.080 inch.
End Restrictor Materials: PL-33 (head), silicone rubber (aft).
Igniter Type: 2C1-7.5 with slots (regressive).
Igniter Propellant: RH-P-178cc. (ce)
Main Grain Propellant: RH-P-112ce.
Results: Successful termination but ignition of second increment was slow. The silicone rubber stripped late and the igniter action time was too short.



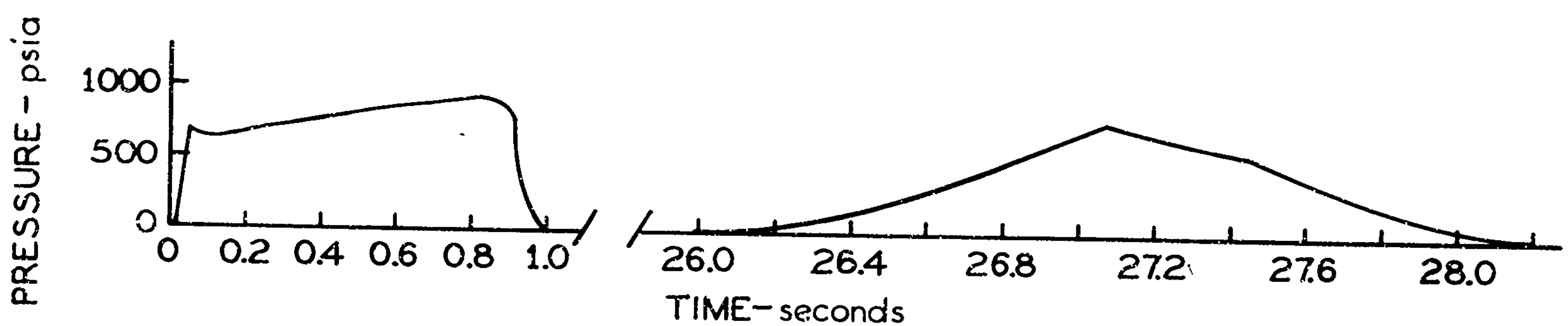
Round 3971

Type: Tandem, no delay, timer used for sequencing.
Barrier Material: PL-33, spread.
Barrier Thickness: 0.080 inch.
End Restrictor Materials: PL-33 (head), silicone rubber (aft).
Igniter Type: 2C1-11.2 with slots (neutral).
Igniter Propellant: RH-P-178cc. (ce)
Main Grain Propellant: RH-P-112ce.
Results: Successful re-ignition, but igniter action time was too long.



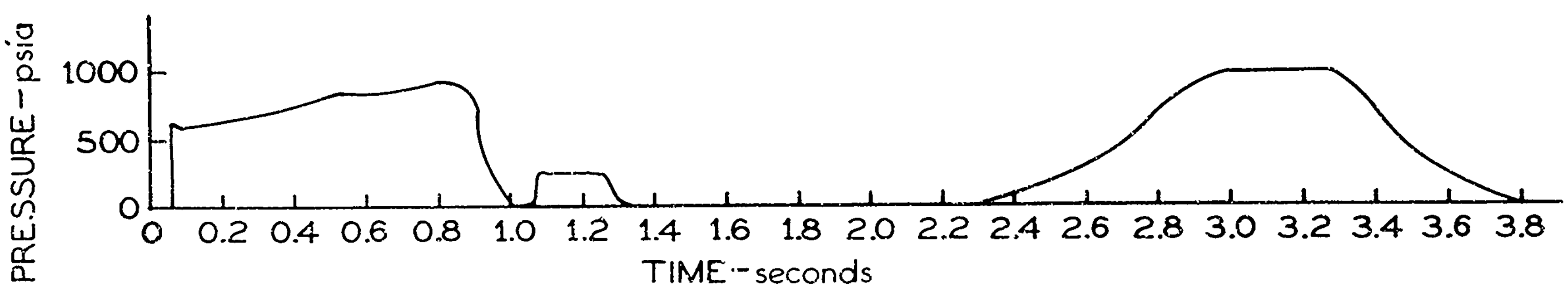
Round 4147

Type: Concentric, 180-sec delay planned.
Barrier Material: PL-33, spread.
Barrier Thickness: 0.021 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2C1.5-4.0 (not fired because motor ignited earlier than programmed).
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: Motor terminated but re-ignited spontaneously after 25 seconds. Failure apparently caused by a pinhole leak at the intersection between the barrier and end restrictor. The intersection was re-designed on the basis of this failure.



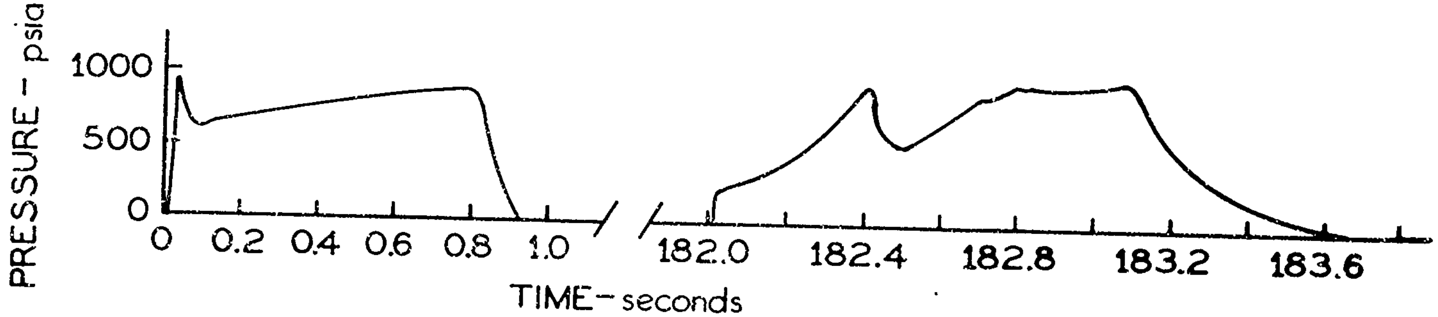
Round 4148

Type: Concentric, no delay, timer used for sequencing.
Barrier Material: PL-33, spread.
Barrier Thickness: 0.021 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2C1.5-4.0 (neutral).
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: The second-increment igniter was not sufficient for the barrier thickness; there was a long delay between igniter burnout and second-grain ignition. The barrier thickness and igniter were changed on the basis of this test.



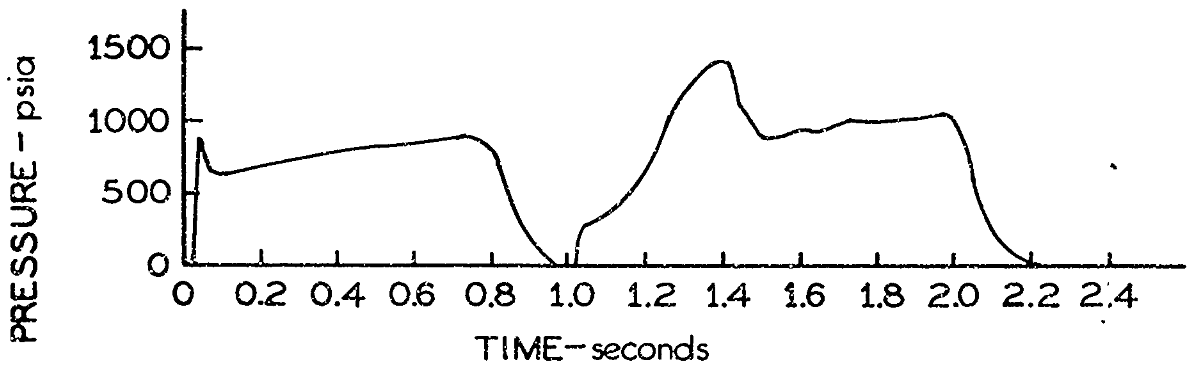
Round 4342

Type: Concentric, 180-sec delay.
Barrier Material: PL-33, spread.
Barrier Thickness: 0.020 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2C1-7.5 (progressive).
Igniter Propellant: RH-P-178ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: Successful termination, delay, and re-ignition. The barrier was not completely removed at igniter burnout.



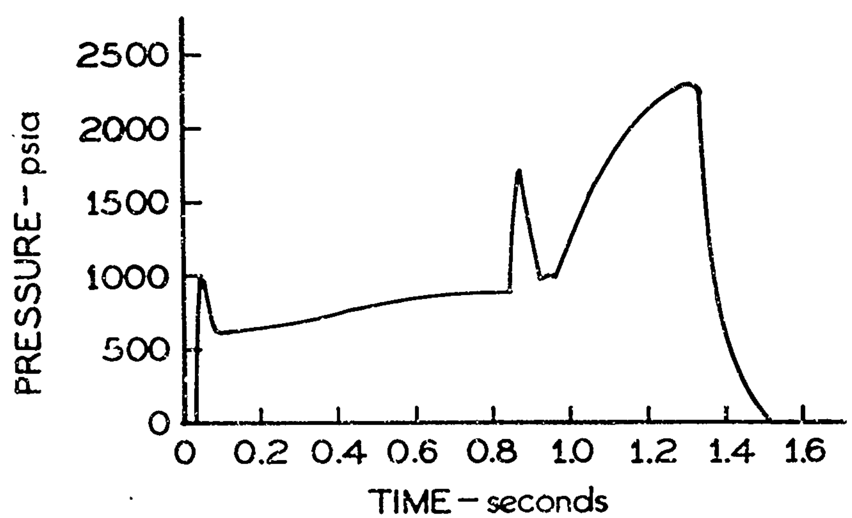
Round 4343

Type: Concentric, no delay, timer used for sequencing.
Barrier Material: PL-33, spread.
Barrier Thickness: 0.012 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2C1-7.5 (progressive).
Igniter Propellant: RH-P-178ce.
Main Grain Propellant: RH-P-112cf (first increment)and RH-P-112cf (second increment).
Results: Successful re-ignition. Barrier was gone before igniter burnout. Since the igniter was the same as in 4342, this clearly shows the difference between 20- and 12-mil barrier thickness.



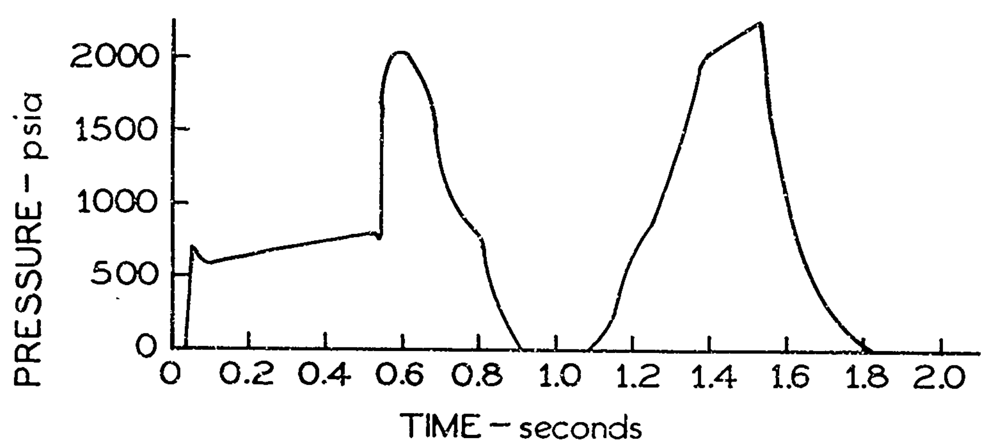
Round 4652

Type: Concentric, no delay, timer used for sequencing.
Barrier Material: PL-33, spread.
Barrier Thickness: 0.010 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 X 8 wagonwheel (regressive).
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ce (second increment).
Results: Successful re-ignition. Igniter fired early and caused spike, but second-grain ignition was rapid. Second grain propellant burned too fast and trace was not good.



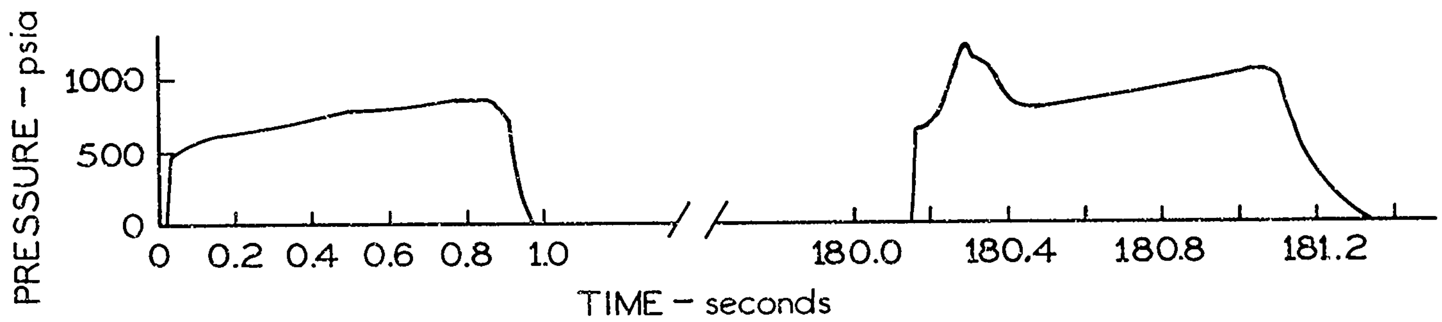
Round 4653

Type: Concentric, 180-sec delay planned.
Barrier Material: PL-33, spread.
Barrier Thickness: 0.017 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 X 8 wagonwheel (regressive).
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ce (second increment).
Results: Igniter nozzle closure failed; second-grain igniter fired during first-grain operation and eroded part of the propellant away. The barrier was therefore prematurely exposed in places and the motor re-ignited soon after first-grain burnout. The igniter protection was strengthened as a result of this test.



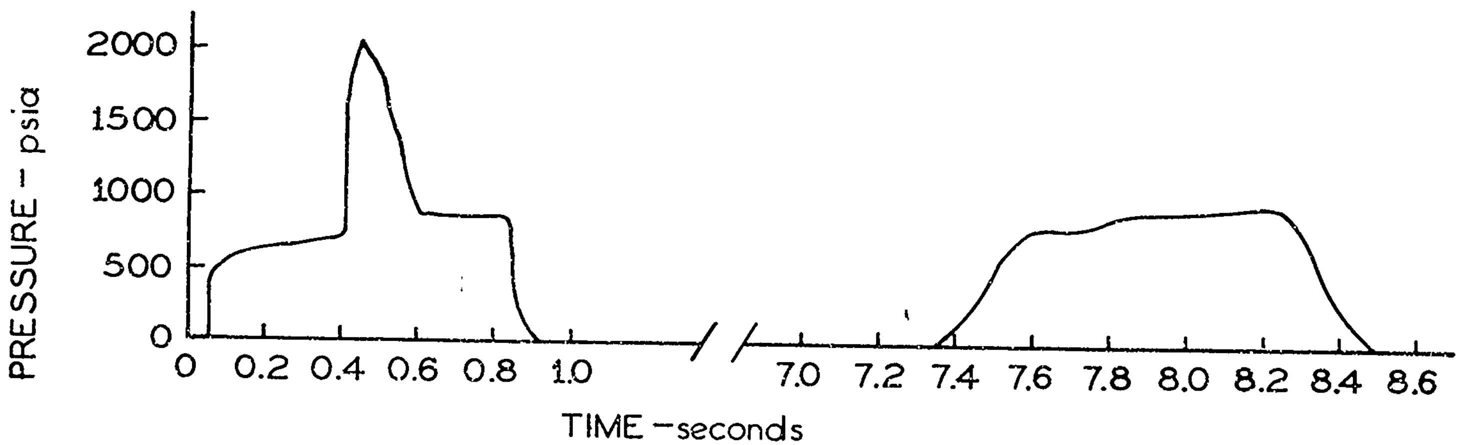
Round 4875

Type: Concentric, 180-sec delay.
Barrier Material: PL-38, spread.
Barrier Thickness: 0.012 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 X 8 wagonwheel.
Igniter Propellant RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: Very successful delay and re-ignition. The igniter nozzle seal momentarily plugged the main nozzle just after the second ignition.



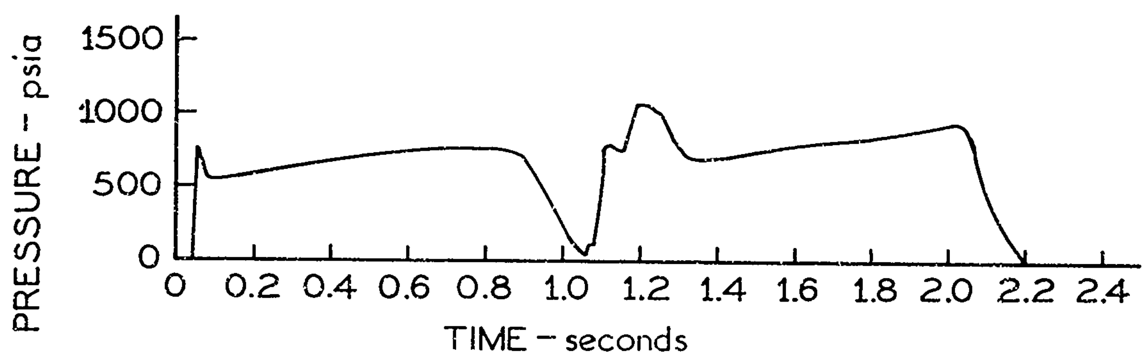
Round 4876

Type: Concentric, 180-sec delay planned.
Barrier Material: PL-38, spread.
Barrier Thickness: 0.014 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 X 8 wagonwheel.
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: Igniter nozzle seal failed due to poorly-cured adhesive/sealant. Grain erosion and consequent non-simultaneous burnout caused premature ignition of second increment after only 7 seconds of the delay period.



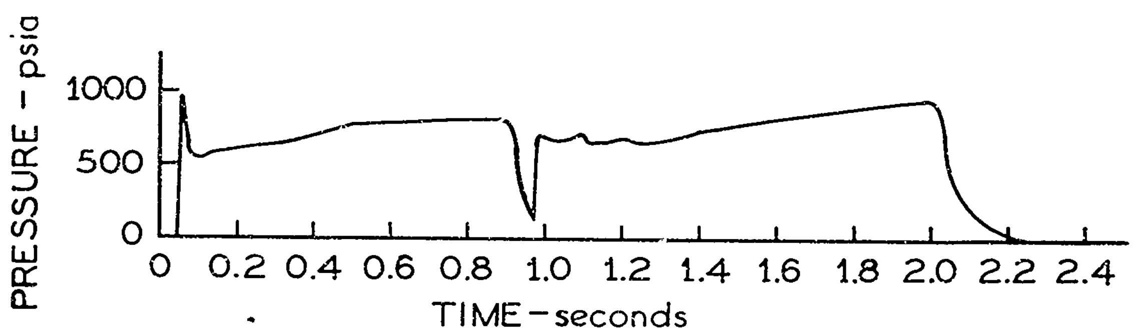
Round 4930

Type: Concentric, no delay, $\int Pdt$ switch used for sequencing.
Barrier Material: PL-38, spread.
Barrier Thickness: 0.013 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 × 8 wagonwheel.
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: The $\int Pdt$ switch was set to 2390 counts and the second increment fired just before the first increment tailoff was complete. The igniter nozzle seal again plugged the main nozzle momentarily.



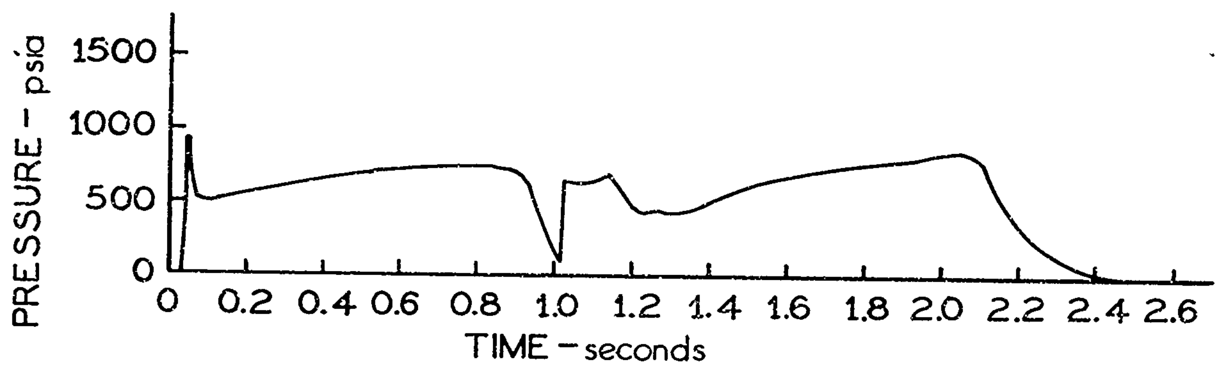
<u>Round 4931</u>

Type: Concentric, no delay, $\int Pdt$ switch used for sequencing.
Barrier Material: PL-38, spread.
Barrier Thickness: 0.013 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 × 8 wagonwheel.
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: The $\int Pdt$ switch was set for 2360 counts; the firing was the best to date. A smaller seal was used to protect the second igniter and no spike was observed.



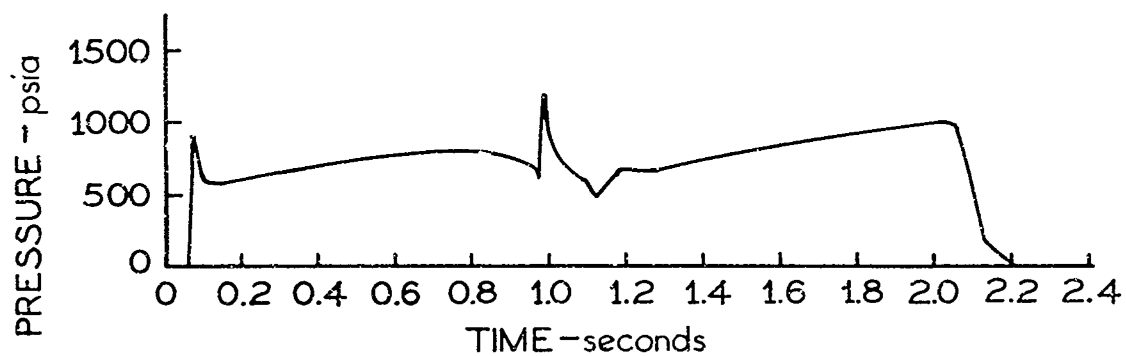
Round 4943

Type: Concentric, no delay, $\int Pdt$ switch used for sequencing.
Barrier Material: PL-38, sprayed.
Barrier Thickness: 0.015 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 × 8 wagonwheel.
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: The $\int Pdt$ switch was set for 2360 counts; the firing was satisfactory. The slightly thicker barrier caused a slight dip after the igniter burned out.



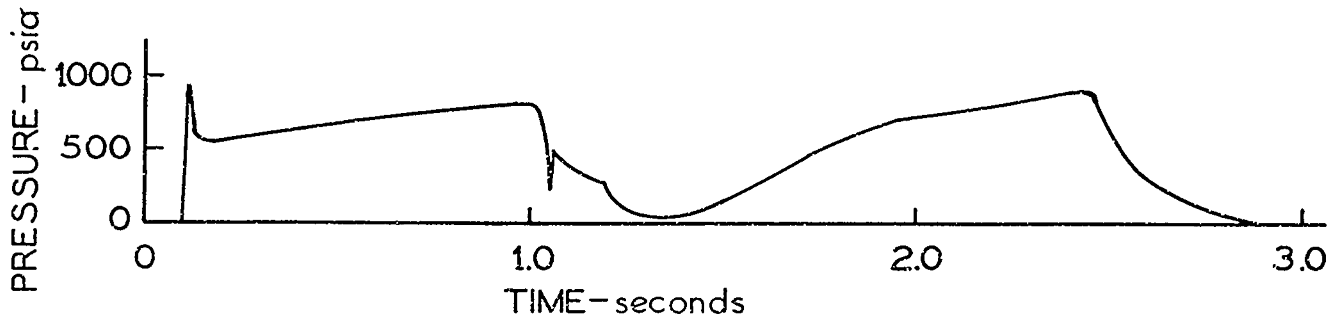
Round 4983

Type: Concentric, no delay, $\int Pdt$ switch used for sequencing.
Barrier Material: PL-38, sprayed.
Barrier Thickness: 0.012 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 × 8 wagonwheel.
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: The $\int Pdt$ switch was set for 2330 counts and the igniter fired slightly early; this caused a spike at tailoff of the first increment. Otherwise, the test was very successful.



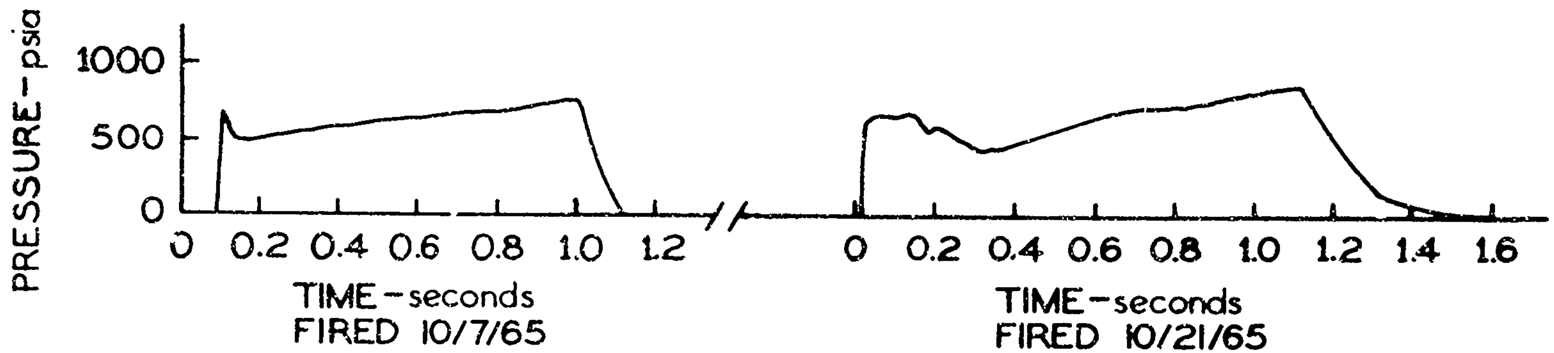
Round 5075

Type: Concentric, no delay, $\int Pdt$ switch used for sequencing.
Barrier Material: PL-38, sprayed.
Barrier Thickness: 0.013 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 × 4 wagonwheel.
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: The smaller igniter was not sufficient; the second increment almost did not ignite. This proved that the 2 × 8 igniter was necessary for rapid and reliable ignition with the thickness of barrier being used.



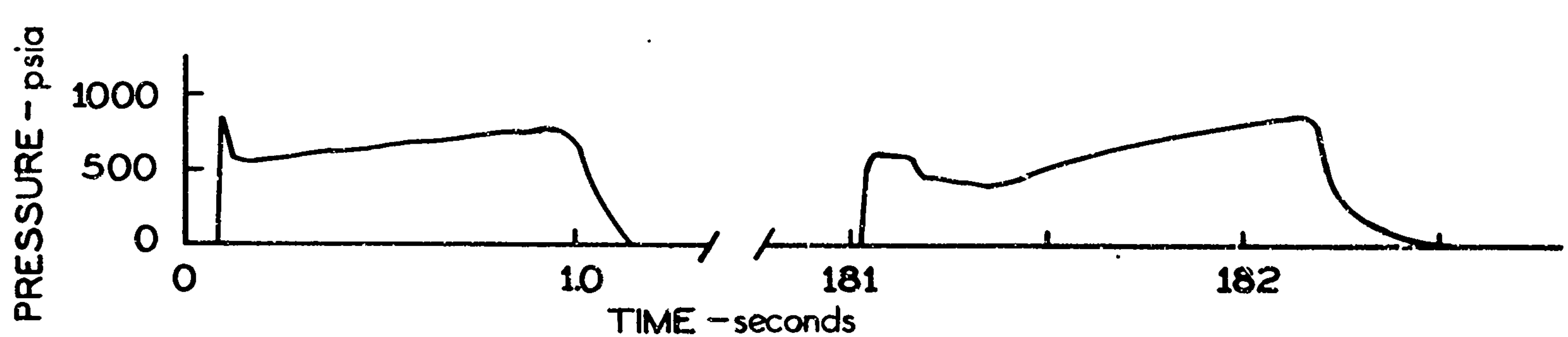
Round 5076

Type: Concentric, no delay planned, $\int Pdt$ switch used for sequencing.
Barrier Material: PL-38, sprayed.
Barrier Thickness: 0.013 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 × 8 wagonwheel.
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: The $\int Pdt$ switch was set for 2350 counts. The motor burned out before the necessary counts had accumulated so the second igniter did not trigger. The second increment was fired two weeks later and performed normally. This test again demonstrated that the barrier was adequate. The low pressure integral was caused by using a larger nozzle on the main motor than had been used on Rounds 4930-5075.



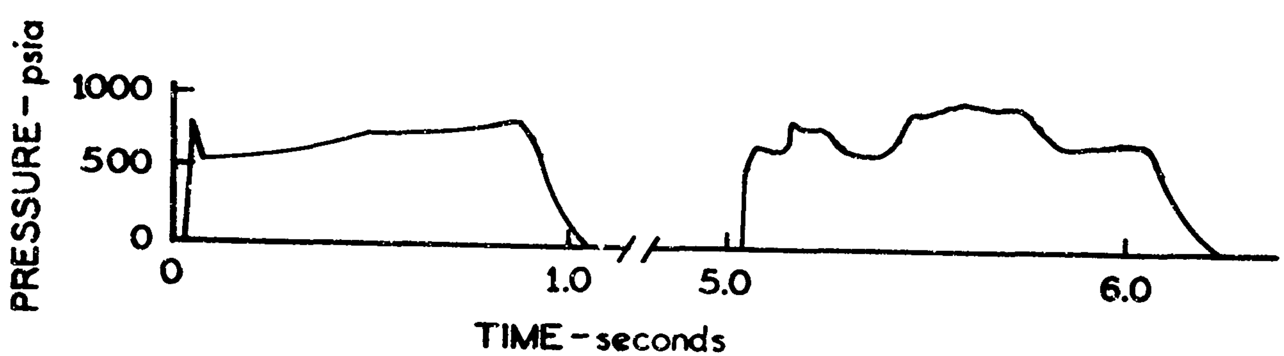
Round 5077

Type: Concentric, 180-sec delay.
Barrier Material: PL-38, sprayed.
Barrier Thickness: 0.015 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 × 8 wagonwheel.
Igniter Propellant: RH-P-112ce.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: The test went as planned, proving that the thickness of the sprayed barrier was adequate. The dip in the second increment was similar to Round 4943, which also had a 15-mil barrier.



Round 5074

Type: Concentric, 5-sec delay.
Barrier Material: PL-38, sprayed.
Barrier Thickness: 0.012 inch.
End Restrictor Material: Polysulfide rubber.
Igniter Type: 2 × 8 wagonwheel.
Igniter Propellant: RH-P-112ce.
Special Instrumentation: Thermocouples.
Main Grain Propellant: RH-P-112cf (first increment) and RH-P-112ca (second increment).
Results: This test demonstrated that the barrier had a safety factor that could take care of eccentricity that could occur because of normal tolerance buildup. The firing was normal. Irregularities in the second increment trace were caused by burning around the thermocouple sheaths.



APPENDIX C

SUMMARY OF FIRING RESULTS FROM 6 X 33 TESTS

Table C-I summarizes the important parameters of the firings with the 6 X 33 test motor.

Table C-I

Data from 6 X 33 Selectable-Impulse Motors

Round No.	Igniter Size (in)	Igniter Propellant Composition	Igniter Propellant Mass (lbm)	Igniter t_b (sec)	Igniter $\dot{m}$ (lbm/sec)	$\dot{m}/A_p$ (lbm/in^2-sec)	Barrier Thickness (in)	r_{pred}[a] (in/sec)	Motor Propellant Mass (lbm)	t_{ign}[b] (sec)	r_{est}[c] (in/sec)
5230	2 X 12WW	112ce	1.04	---	---	---	0.0135	---	38.9	---	---
5358	2 X 12WW	112ce	1.08	0.10	10.8	0.63	0.0240	0.30	38.6	---	<0.24
5472	2 X 12WW	112ce	1.09	0.10	10.9	0.64	0.0145	0.30	38.1	---	<0.14
5547	2 X 16WW	112cb	1.41	0.14	10.1	0.59	0.0115	0.30	38.1	0.12	0.096
5626	2 X 16WW	112cb	1.45	0.15	9.7	0.57	0.009	0.30	38.3	0.06	0.150
5695	2 X 16 WW	112cb	1.43	0.15	9.[illegible]	0.56	0.009	0.30	38.3	0.05	0.160
5680[d]	----	---	---	---	---	---	---	---	38.6	---	---

[a] This is the predicted maximum barrier regression rate.
[b] This is time to first indication of grain ignition after igniter operates.
[c] This is the maximum barrier regression rate estimated from the firing.
[d] Control round with no barrier.

Table C-II shows the reproducibility of the pressure data from the first increment of the 6 X 33 motor. The $\int P dt$ to 500 psia for Rounds 5230, 5358, and 5472 was used to set the counter for the quasi-continuous firings.

Table C-III shows that with good ignition the barrier does not greatly reduce the average pressure of the second increment from the predicted value of 1000 psia.

Table C-II

Pressure Data from First Increment of 6 X 33 Motor

Parameter	Round 5230	Round 5358	Round 5472	Round 5541[a]	Round 5626	Round 5695
Burning Time, sec	0.679	0.634	0.710	--	0.670	0.680
Action Time, sec	0.773	0.726	0.790	--	N/A[b]	N/A
Maximum Pressure, psia	995	1042	949	--	999	969
Burning Pressure, psia	959	1021	913	--	974	934
Action Pressure, psia	902	961	873	--	N/A	N/A
P_{max}/P_b	1.04	1.02	1.04	--	1.03	1.04
Integral Ratio	0.93	0.93	0.94	--	N/A	N/A
∫Pdt,[c] counts	2570	2591	2580	--	2550	2550

[a]Pressure ports were plugged.
[b]These values cannot be determined in a quasi-continuous firing.
[c]These values are the gross pressure-time integral from ignition to 500 psia at tailoff.

Table C-III

Pressure Data from Second Increment on 6 X 33 Motor

Parameter	Round 5230	Round 5358	Round 5472	Round 5541	Round 5626	Round 5695
Delay Between Increments, sec	20	180	180	1200	0	
Ignition Delay,[a] sec	b	34	2	0	0	0
Ignition Rise Time,[c] sec	20	0.9	0.4	0.5	0.2	0.2
Burning Time, sec	--	1.3	0.81	0.81	0.62	0.60
Maximum Pressure, psia	250	750	800	960	969	981
Burning Pressure, psia	--	450	600	738	916	949

[a]Time from initiation of rocket-type igniter to first indication of motor pressure.
[b]Ignited spontaneously.
[c]Time from first indication of motor pressure to equilibrium pressure.

Initial distribution of this report has been made in accordance with "Chemical Propulsion Mailing List," CPIA Publication 74, March 1965, and approved supplements.

Qualified users may obtain this report from the Defense Documentation Center.