AD-A279 904

(1)

ARMY RESEARCH LABORATORY

Investigation of Bulk-Loaded Liquid Propellant Gun Concepts

Robert L. Talley
John A. Owczarczak

ARL-CR-127

April 1994

prepared by

Veritay Technology, Inc.
4845 Millersport Highway
P.O. Box 305
East Amherst, NY 14051-0305

under contract

DAAA15-92-C-0018

NOTICES

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1994

3. REPORT TYPE AND DATES COVERED
Final, Jan 92 - Sep 92

4. TITLE AND SUBTITLE
Investigation of Bulk-Loaded Liquid Propellant Gun Concepts

5. FUNDING NUMBERS
C: DAAA15-92-C-0018

6. AUTHOR(S)
Robert L. Talley and John A. Owczarczak

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Veritay Technology, Inc.
4845 Millersport Highway, P.O. Box 305
East Amherst, NY 14051-0305

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-OP-AP-L
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARL-CR-127

11. SUPPLEMENTARY NOTES
The Point of Contact for this report is James De Spirito, U.S. Army Research Laboratory, ATTN: AMSRL-WT-PA, Aberdeen Proving Ground, MD 21005-5066.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The present study has formulated and explored experimentally the feasibility of two concepts for controlling the interior ballistic process in medium caliber, bulk-loaded liquid propellant guns (BLPG).

The general nature of ignition and combustion of liquid propellants (LP) in bulk-loaded LP guns—as currently understood—was reviewed to clearly indicate problems that need to be addressed in achieving successful combustion stability, progressivity, and reproducibility in such systems.

Accordingly, several features were identified with the potential for modifying undesirable characteristics and for achieving various degrees of control of the combustion process in BLPGs. Based on these features, two concepts were formulated to control the BLPG interior ballistics process by using gun chamber geometry to control the combustion. These concepts were evaluated in live gun test firings and found to be favorable in achieving a significant degree of combustion control.

The investigation recommends that further exploration and development of these concepts be undertaken to confirm feasibility, to demonstrate effective control and repeatability of the ballistic process and muzzle velocity, and to provide preliminary BLPG concepts for weaponization.

14. SUBJECT TERMS
bulk-loaded liquid propellant gun, liquid propellants, combustion stability, ignition, interior ballistics, combustion control concepts

15. NUMBER OF PAGES
58

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

		Page
	LIST OF FIGURES	v
1.	INTRODUCTION	1
2.	BALLISTIC PROCESS CONTROL CONCEPTS	3
2.1	BLPG Overview	3
2.2	Formulation Considerations	5
2.2.1	Chamber-Igniter Geometry	6
2.2.2	In-Barrel Effects	7
2.2.3	Type of Liquid Propellant	8
2.2.4	Miscellaneous Features	8
2.3	Concepts	9
3.	EXPERIMENTAL PROGRAM	13
3.1	20-mm Single-Shot Firing Text Fixture	13
3.3.1	Gun Test Fixture Assembly	13
3.3.2	Barrel	14
3.3.3	Chamber	15
3.3.4	Booster Retainer	16
3.3.5	Booster Housing	17
3.3.6	Breech	17
3.3.7	Projectile Spacer	17
3.3.8	Chamber Inserts	17
3.3.9	Ignition System	17
3.3.10	Projectile	19
3.2	Liquid Monopropellants	19
4.	INSTRUMENTATION	19
5.	EXPERIMENTAL RESULTS	20
5.1	In-Line Multi-Chamber Concept	23
5.2	Single Cylinder-Type Chamber Concepts	29
6.	CONCLUSIONS AND RECOMMENDATIONS	33
7.	REFERENCES	35
	APPENDIX - PRESSURE TIME TRACES	37
	DISTRIBUTION LIST	55

INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

Figure		Page
1.	Basic chamber concepts	10
2.	20-mm single-shot firing fixture	14
3.	20-mm Mann barrel	15
4.	20-mm chamber	16
5.	Short chamber booster retainer	16
6.	Booster housing	17
7.	Chamber insert configurations	18
8.	One-step chamber insert (chamber Type G)	23
9.	Comparison of pressure-time traces in current and past tests using Otto II	24
10.	In-line multi-chamber insert type 6.35 Multi G	25
11.	Pressure-time trace reproducibility in 6.35 Multi G chambers	26
12.	Comparison of pressure-time behavior in two different multi chambers	27
13.	Pressure-time effects from increasing first chamber section diameter	28
14.	Single cylinder chamber insert	29
15.	Comparison of pressure-time traces in current and past tests using different liquid propellants	30
A-1.	Booster and chamber pressure-time traces for Test No. 1 with chamber insert Type G	39
A-2.	Booster and chamber pressure time-traces for Test No. 3 with chamber insert Type 6.35 Multi G	40
A-3.	Booster and chamber pressure-time traces for Test No. 4 with chamber insert Type B	41
A-4.	Booster and chamber pressure-time traces for Test No. 5 with chamber insert Type 6.35 Multi G	42

LIST OF FIGURES

Figure		Page
A-5.	Booster and chamber pressure-time traces for Test No. 6 with chamber insert Type 9.52 Multi N	43
A-6.	Booster and chamber pressure-time traces for Test No. 7 with chamber insert Type 6.35 Multi G	44
A-7.	Booster and chamber pressure-time traces for Test No. 8 with chamber insert Type B	45
A-8.	Booster pressure-time trace for Test No. 9 with chamber insert Type O	46
A-9.	Booster and chamber pressure-time traces for Test No. 10 with chamber insert Type O	47
A-10.	Booster pressure-time trace for Test No. 11 with chamber insert Type A	48
A-11.	Booster and chamber pressure-time traces for Test No. 12 with chamber insert Type O	49
A-12.	Booster and chamber pressure-time traces for Test No. 13 with chamber insert Type A	50
A-13.	Booster and chamber pressure-time traces for Test No. 14 with chamber insert Type I	51
A-14.	Booster pressure-time trace for Test No. 15 with chamber insert Type I	52
A-15.	Booster and chamber pressure-time traces for Test No. 16 with chamber insert Type I	53
A-16.	Booster and chamber pressure-time traces for Test No. 17 with chamber insert Type 6.35 Multi P	54

1. INTRODUCTION

The objective of the Phase I Small Business Innovation Research (SBIR) program reported here involved advancing and investigating mechanical concepts to control the interior ballistic process in medium caliber bulk-loaded liquid propellant guns (BLPG).

The BLPG system is an attractive candidate for small and medium caliber weapons because the overall gun hardware is inherently simple and because the use of a liquid propellant (LP) in such guns offers potential advantages in logistics, cost, and vulnerability in comparison to comparable weapons that use solid propellants.

Successful completion of this technology development effort through both the Phase I and Phase II stages has the potential to provide the U.S. Army with a reliable technology base for application to achieve improved, direct fire BLPG gun systems. Such candidate systems might include secondary armament for the Advanced Field Artillery System (AFAS) (a 155-mm, regenerative-type LP howitzer), primary armament for infantry fighting vehicles, guns for air defense, armament for helicopters, and perhaps others. On a smaller scale, the technology could be used in various small arms applications.

Previous attempts to develop BLPG systems have been unsuccessful mainly because of the inability to control the combustion processes needed to achieve both satisfactory uniformity in ballistic performance and overall safety in gun operation. The main thrust of this current program has been directed toward resolving these combustion control issues.

The combustion process in a BLPG system is accompanied by several fluid dynamic and combustion instabilities. These include fluid motion to form a cavity within the body of LP in the gun chamber in response to both LP combustion and projectile motion, fluid turbulence and breakup resulting from liquid motion relative to the chamber walls, and liquid surface breakup arising from a velocity mismatch at the liquid-gas interface.

While a solid propellant propulsion system uses propellant grain geometry and deterrents to control the combustion rate, the instabilities just noted that exist in a BLPG system are developed as part of the combustion evolution and do not represent unique performance limiting constraints on which control of the process can be based. The instability characteristics can and do vary in response to the prior sequence of events, and small disturbances that arise early in the BLPG combustion cycle can become amplified in the absence of burn-rate limiting characteristics. The situation is aggravated by stiffness (low compressibility) of the LP charge, the presence of fluid dynamic waves, and the high pressure sensitivity of chemical reaction rates in LP combustion. These can sometimes lead to catastrophic results if not adequately controlled. The authors' first-hand experience gained during this and previous BLPG efforts has provided an understanding of some of these problems and has not diminished confidence that a solution exists for achieving acceptable performance.

The overall approach adopted here to achieve control of the interior ballistic processes in BLPGs concentrated on investigating concepts with the promise of achieving combustion stability, progressivity, and reproducibility. Combustion stability appears to be the key feature that must be obtained first. Progressivity of LP combustion within the gun can then be addressed by suitably increasing the burning surface area of the flame front as the burning progresses. Reproducibility of both the combustion pressure-time behavior and the resultant muzzle velocity should follow directly once combustion stability (with suitable progressivity) has been achieved.

This report documents the Phase I program investigations including the formulation and selection of control concepts for further examination, experimental exploration of their feasibility in controlling the ignition and combustion evolution in BLPG systems, and presentation of the associated findings.

The BLPG concepts advanced and explored under this program were configured with different interior chamber geometries and were explored experimentally as a means of achieving boundary-controlled combustion evolution within the chambers, which is both stable and reproducible. An attempt was made to retain much of the inherent simplicity of the BLPG concept.

A second feature investigated was the ignition and combustion stability of the LP XM46 in single cylinder-type chambers, as an extension of recent findings (Talley 1990) using the LP Otto II in a 20-mm BLPG test gun fixture, which has shown promise in achieving combustion control.

The preliminary results indicate that the two types of concepts investigated are favorable in exerting control of combustion evolution in BLPG systems. Further exploration will be necessary to confirm feasibility, demonstrate effective control and repeatability of the ballistic process and muzzle velocity, and provide preliminary BLPG concepts for weaponization.

2. BALLISTIC PROCESS CONTROL CONCEPTS

2.1 BLPG Overview. A typical BLPG system has often been characterized in the past as consisting of a near bore-diameter cylindrical combustion chamber, a projectile seated at the forward end just inside the barrel, and an igniter at the breech end. This classical BLPG system arrangement features the utmost in mechanical simplicity but offers few means to control and stabilize the ignition and combustion processes, or the fluid dynamics and combustion instabilities that often develop during combustion evolution.

The general nature of ignition and combustion of liquid gun propellants as currently understood is discussed in the following paragraphs to indicate associated problems encountered and to enable the significance of the unique features of the proposed concepts to be better understood.

Liquid or gel propellants may contain solid components, but all such propellants have a liquid as the continuous phase. The permeability of the LP to gas flow is zero. Since liquid combustion occurs in the vapor phase the igniter must vaporize a small quantity of propellant and heat the vapor to a temperature at which exothermic reactions occur. Several problems must be overcome to achieve successful initiation of LPs in the bulk-loaded configuration, including the following:

- Ignition and combustion gas cannot flow throughout the charge since the LP permeability is essentially zero; instead, the gas is confined.

- Gas from the igniter or from combustion of the LP can create radial and axial pressure waves and strong combustion interactions at liquid-gas interfaces.

- The ignition gas kernel (or bubble) must be sufficiently large and energetic to avoid being quenched by expansion cooling caused by projectile motion.

- The ignition-combustion burning surface is not well defined geometrically as it is in the case of solid propellants; rather, it is characterized initially by the growth and geometry of the ignition bubble and combustion gas (or Taylor) cavity. Once projectile motion becomes significant, the gas is expected to push through the LP to the projectile base, and gas-driven Helmholtz instabilities are expected to appear on the LP at the liquid-gas interface. These instabilities may grow and cause some of the liquid to break up and form droplets.

- The igniter output and early combustion must increase the chamber pressure to a level where reaction kinetics are rapid, where self-sustaining or controlled progressive combustion occurs, and where the ullage (sufficiently large pockets of gas [air or LP vapor]) is compressed to form a more rigid liquid charge—even with projectile motion.

- The amount and rate at which the LP is ignited is critical to control peak pressure in the chamber.

- Ullage can cause unwanted local ignition by adiabatic compression heating during the early time pressure rise.

These features indicate that the igniter must be tailored to the LP charge. Over-ignition or under-ignition can cause excessive pressures to occur. Pressure waves in the LP that impinge on liquid-gas-free surfaces may also enhance combustion rates and contribute to overpressures. Therefore, igniter and chamber designs should be configured to minimize pressure wave effects, while providing the sustained output required to achieve positive ignition without excessive delay. Because the entire initial gas cavity is generated by the igniter, overall combustion reproducibility depends to some extent on the inherent reproducibility of the ignition system itself, on the way this initial cavity develops, and on the tendency for combustion within this cavity to stabilize early during its development and growth within the chamber.

The interior ballistics characteristics of LPs are complicated by the way they burn. In the absence of the rather well-defined geometry of solid propellant burn surfaces, combustion in LPs occurs at exposed surfaces that are defined by a sequence of dynamic, physical events. In the classical BLPG system, these events may be separated into two segments: (1) before and (2) after the projectile has achieved significant velocity and travel.

Early, the projectile remains essentially stationary, and the main function of the igniter is to create a gas bubble within the liquid phase to achieve adequate pressure and gas volume to support initial projectile motion while maintaining combustion. The objective of most bulk-loaded liquid concepts is to minimize the ullage, to maximize the propellant load, and to minimize the potential for inadvertent ignition as a result of adiabatic compression. By the time the projectile velocity has become significant (i.e., about 200 m/s), a significant fraction of the ballistic cycle is finished; only a few percent of the propellant have burned and the gas pressure is unstable because of the relatively large (i.e., percentage-wise) volume changes and the stiff spring nature of the liquid. This early portion of the ballistic cycle is characterized by high amplitude dynamics and can be strongly influenced by the igniter. The shape of the gas bubble generated by the igniter, the bubble location (near the breech or projectile base), the bubble growth rate as influenced by primer flow rate, the change in bubble shape with evolutionary growth, and the interaction of the bubble surface with pressure waves within the chamber can all influence combustion during this period. Recent experimental results also indicate that ignition bubble contact with the chamber wall is an important factor that can reduce random variability substantially (Talley 1990).

Once the projectile has achieved significant velocity and displacement, the mode of combustion appears to change into one dominated by stripping of droplets from the liquid layer. While all the mechanisms are not well understood, it is believed that this mode may begin when the initial cavity penetrates the liquid to the projectile base as a result of projectile motion. The rate of surface generation and global combustion appears to increase for a period, corresponding to increases in the projectile velocity, then decreases as the projectile continues to move down the barrel. Combustion during this period is usually well behaved if the ignition is in a suitable range, but otherwise can present problems of developing high pressures unless some control of combustion progressivity is exercised. The latter is a key feature sought in concepts formulated under this program. Such control appears to be possible, in the sense of eliminating the occurrence of high pressure but may not enable suitably reproducible pressure-time behavior to be achieved in the latter portion of the ballistic cycle. This topic is addressed further, later in this report.

The transition between these two combustion modes has also shown the potential for variability. While the first mode is characterized by rapid pressure rise and rapid gas bubble growth, and the second mode by droplet stripping in high velocity flow, the transition period is characterized by constant or decreasing pressure and changing liquid geometries that can cause combustion to quench temporarily. Thus, during this transition period, additional energy from the igniter would help to stabilize the combustion process. This is the reasoning behind the electrothermal-chemical (ETC) concept. However, a goal of BLPG is to avoid the high electrical power requirements inherent with that concept.

2.2 Formulation Considerations. In accordance with the preceding overview and past BLPG technology features explored at the U.S. Army Research Laboratory (ARL), U.S. Army Armament Research, Development and Engineering Center (ARDEC), Veritay, and elsewhere (Liquid Propellant Gun Technology 1991), several features have been identified with the potential for modifying objectionable characteristics and for achieving a degree of control of the combustion process in BLPGs.

This synthesis of concepts has depended heavily on applying phenomena and system features that appeared to have a theoretical or experimental basis for controlling BLPG combustion. A number of these key items are noted in the following paragraphs.

2.2.1 Chamber-Igniter Geometry. Data obtained from firing tests and ignition diagnostics in a transparent chamber and presented in Talley (1990), indicated that a key factor in early time stability and control of bulk-loaded LP combustion is related to the degrees of freedom of ignition bubble expansion. Both ignition and combustion are relatively well behaved if the ignition bubble contacts the chamber wall during early growth. In contrast, if the bubble remains surrounded by liquid for a long period as a result of improper chamber geometry, the combustion performance will tend to show significant test-to-test variability. In the latter case, it appears that control of the combustion process can be adversely influenced by the multiple degrees of freedom associated with bubble growth and evolution. By maintaining contact with the chamber wall, the early radial growth, which exhibits a radius-squared burn surface for combustion, is eliminated, and only the near constant area flame front that moves along the chamber axis remains. Such axial burning will tend to occur even if the edge of the flame front does not maintain wall contact, but in such cases, random quantities of unburned liquid may be left adjacent to the wall (presumably as a result of turbulence) after the flame front passes. Subsequently, these random liquid quantities burn vigorously and cause significant pressure pulses and are believed to account for much of the test-to-test performance variability.

An important factor in establishing ignition bubble contact with the wall is the ratio of the diameter of the combustion chamber to the diameter of the output orifice, through which the hot booster gas of the axial pyrotechnic igniter passes. Tests in which this ratio was varied (Talley 1990) indicated that a ratio of about 15:1 or less resulted in much less pressure and muzzle velocity variability than greater values, for a test configuration featuring front ignition. Similar results were found for a breech-ignited BLPG. The optimum chamber/igniter orifice diameter ratio appears to exhibit some dependence on the booster type and mass, the chamber geometry and volume, and likely the projectile mass.

A second feature associated with the chamber-igniter geometry is that the observed peak chamber pressure is a function of the diameter of the first chamber section in which the ignition bubble forms. The peak pressure will increase as the chamber diameter increases.

A third feature related to this same igniter-chamber geometry is the nearly complete independence of peak chamber pressure from moderate increases in diameter after the first chamber section—provided the length of this first section exceeds some minimum.

A fourth feature becomes important after the third. Once the flame front passes a step change in chamber diameter, it will burn into the next chamber section, its burn surface area will expand, the mass burn rate will increase, and the front will restabilize.

A fifth feature arises from test firings that indicate that as the flame front moves beyond the position of a step, the combustion does not restabilize when inside a truncated cone rather than inside a cylindrical chamber section (where the same diameter change occurs for the same length following the step).

The restabilization of combustion and increased mass burn rate with diameter permits a sixth feature of geometrical progressivity of the LP combustion to be identified. Additional coaxial, cylindrical chambers with successively larger diameters can be added to the end of the first chamber section, thereby forming a composite chamber with stepped walls. The burn surface area will change as the combustion progresses through the bulk liquid, and the proper choice of chamber internal geometry will enable control of the progressivity of combustion to be achieved.

Finally, a seventh feature arises from the abrupt changes in chamber diameter at the steps. These annular type chamber surfaces will reflect portions of longitudinal pressure waves, which may develop in the chamber (both in the liquid and in the pressurized combustion gas). Such reflections help break up and diffuse these waves and thereby help reduce combustion "noise" in the chamber by reducing the wave-combustion interactions.

2.2.2 In-Barrel Effects. Data obtained from recent firing tests at Veritay (Talley and Bracuti 1990), and from an example repeated as Test No. 1 under this program (noted later in this report) indicate that combustion of LP can occur within the barrel. Some burning of this nature probably cannot be avoided when using breech ignition in a BLPG system, since some of the unburned LP near the front of the chamber is apt to be forced to follow behind the projectile during its early motion down the barrel. Subsequently, this LP will burn in the barrel. Depending on the quantity and surface area of the LP which burns in-barrel, a second, third, or more secondary pressure peaks may appear on the pressure-time trace within the gun. If these secondary peaks are sufficiently small, they may have negligible effect on the muzzle velocity of the projectile. Otherwise, they may influence the muzzle velocity adversely, since such pressure peaks are typically not very reproducible. As a result, it is desirable to minimize the presence of such secondary pressure peaks; this may be possible by choosing operating parameters within the BLPG system that will favor LP combustion in the chamber rather than in the barrel.

2.2.3 Type of Liquid Propellant. The type of LP to be used in a BLPG concept may have a significant bearing on the optimal configuration of the concept. Previous investigations of combustion evolution in BLPG test fixtures at Veritay have been conducted largely using the liquid propellant Otto II. In the present program, both Otto II and XM46 (formerly designated LGP 1846) were used for concept considerations and for testing.

2.2.4 Miscellaneous Features. A variety of miscellaneous features are known, which have been or may be used to achieve some contribution to controlling the combustion in BLPG systems. At present, these features are considered to be of secondary importance in this role of control, compared to the potential of the chamber-igniter geometry, in-barrel effects, and type of LP noted previously.

A brief list of some of these secondary features follows:

- soft breech—to increase the effective compliance of the LP charge by allowing the breech to move in response to increasing pressure
- compliant chamber walls—(same purpose as soft breech)
- soft or movable projectile base—(same purpose as soft breech)
- LP flow into a projectile base cavity—(same purpose as soft breech)
- programmed venting—(same purpose as soft breech)
- imbedded ullage in chamber—(same purpose as soft breech)
- mix air with LP—for ullage management

- swirling LP—to concentrate ullage

- wedges and buffers—to diffuse pressure waves in chamber.

2.3 Concepts. Two basic types of concepts (shown in Figure 1) were considered for controlling the interior ballistic process in a medium caliber BLPG and were advanced for further experimental investigation and evaluation under this SBIR program. Each of these concept types is based pr[illegible] on using chamber geometry to control the combustion process.

The first type, the in-line multi-chamber concept, consists of an overall gun chamber with two stages. A breech-initiated, first stage, cylindrical chamber is coupled to a cluster of two or more in-line cylindrical chambers which form the second stage. This concept is a new alternative to the step-chambers scheme, which has been explored at Veritay recently using Otto II.

A second concept consists of both single and one-step cylinder-type BLPG chambers (as two versions of the same basic concept) properly sized and breech ignited to achieve combustion stability and reproducibility using the liquid propellant XM46.

The reason for considering both the single and the one-step cylinder-type chambers as a single concept is that the principal portion of the LP combustion in each case occurs in only one main cylindrical section. In the one-step configuration, this main chamber section is the one after the step (towards the barrel). If the diameter (especially) of this main chamber section needs to be large to obtain a chamber of reasonable shape and volume to contain the LP required for ballistic reasons, this main chamber diameter may be too large to obtain effective geometrical control of the peak combustion pressure directly. It can be achieved indirectly, however, by igniting the LP in a small cylinder section chosen (together with the igniter) to give the desired peak pressure, and by coupling the output of this small chamber directly to the larger main chamber. This coupling introduces a step in the wall of the overall chamber configuration and yields a one-step cylinder-type chamber.

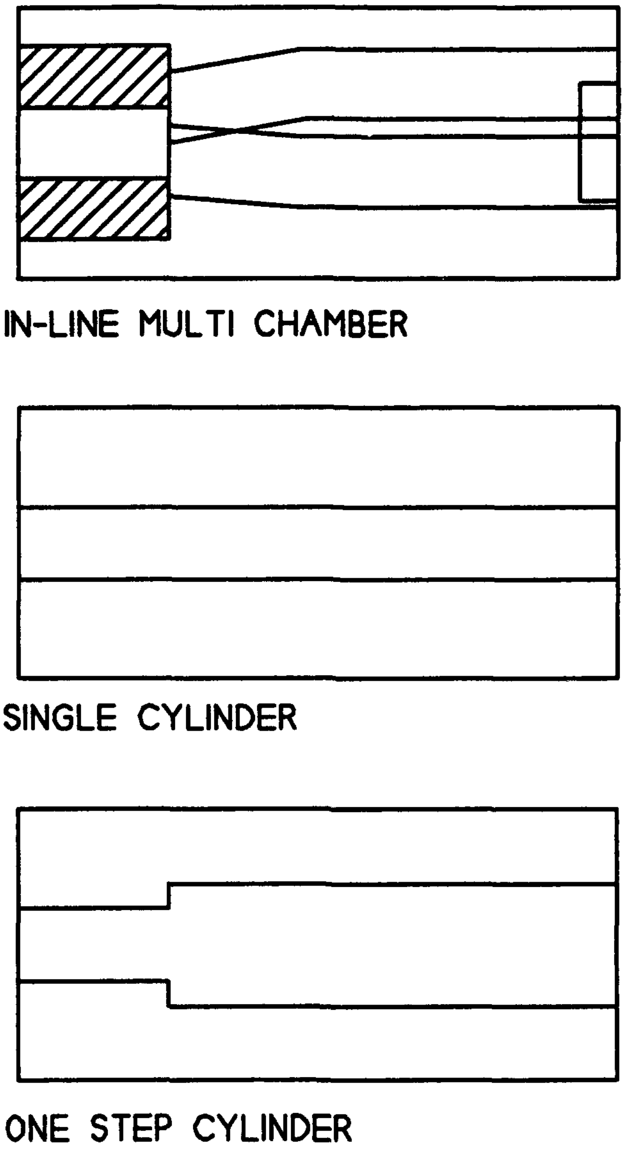

Figure 1. Basic chamber concepts.

The investigation of XM46 ignition and combustion performance in these chamber types is an extension of similar, previous investigations at Veritay with Otto II, which have yielded promising stable combustion results. These combined propellant-gun findings were, until recently, unknown for Otto II, and were also unknown for XM46 at the outset of this program. The innovative aspect of this investigation rests in using a different type of LP and characterizing and comparing its combustion performance with that of Otto II obtained in identical BLPG chambers. Favorable correlation of interior ballistic results between the two LPs could in effect enable a consistent BLPG database to be assembled from past tests using either or both LPs. This should also make future BLPG exploratory testing more efficient; confirmatory testing would not be altered. Such correlations would help form a base for modeling the BLPG interior ballistic process.

The in-line multi-chamber concept uses a pyrotechnic igniter located on axis at the breech end of the first stage cylindrical chamber section. The diameter of this first section is chosen to give an expected peak combustion pressure. The length of the first chamber section is chosen long enough to permit the early combustion to stabilize before undergoing a transition to the three-chamber configuration of Figure 1. The diameter ratio of this section to the igniter orifice is used to select the orifice size to ensure that initial combustion stability is achieved in this first chamber section. The pyrotechnic igniter parameters associated with the primer, booster type and mass, and orifice diameter are selected on the basis of what has performed successfully in past tests to ignite Otto II in the single and one-step chambers.

The geometry of the combustion transition region between the first chamber section and the three in-line cylinders is chosen for geometric simplicity, to cause limited generation of turbulence, and to maintain reasonably smooth combustion evolution. The initial configuration for investigation uses equal diameter cylinder sections for the first chamber, the three transition region cylinders, and the three in-line chamber cylinders. The sections in the transition region are splayed at 10° half angle and lie within a right, truncated cone-shaped envelope. The cross section of the small end of the envelope cone is circular and of the same diameter as the transition region cylinders. The cross section at the large end is also circular and just circumscribes the outer edges of the in-line cylinders at their breech end. The transition to the splayed cylinder trio at the front of the ignition section is not smooth, and some turbulence is likely to occur as well as a small increase in LP combustion rate. The transition from the splayed cylinder trio to the three in-line cylinders is not perfect, since the sections of the splayed cylinders on a plane perpendicular to the bore axis are elliptical with a small eccentricity. This should cause minimal turbulence at this forward end of the transition region.

In this concept, three in-line cylinder chamber sections, with their axes placed symmetrically about and parallel to the bore axis, were chosen for investigation. Other numbers of cylinders may be used as appropriate. The in-line cylinder chamber sections themselves can be chosen to be of a larger diameter than the previous ignition and transition sections, if combustion progressivity is desired which exceeds that provided by the number of chambers of the in-line section relative to the ignition section. For additional control of combustion evolution, it would probably be advantageous to replace the in-line cylinder chambers with in-line step-chambers. This prospect has not been investigated in this Phase I SBIR effort but is an obvious extension, which may have merit in both progressivity and scaling considerations. As a first approximation, it is expected that selection of candidate in-line chamber sections can be based on the combustion performance that each would exhibit when tested separately. Ideally, the combustion from a combination of such chamber sections will result in a properly behaved combustion process.

The diameter of the chamber sections must be chosen to restabilize combustion from the transition section, but this is not expected to be very critical. Perhaps a more important influence on this choice will be the amount of scaling required and the progressivity of combustion required to achieve proper pressure-time behavior for projectile acceleration. The flexibility of this multi-chamber approach is very great in this regard and offers the prospect of tailoring the combustion to meet the needs of a suitable ballistic cycle in BLPGs. This, together with the alternative of step-chambers, appear to be the BLPG counterparts of changing or controlling the burning rate of solid propellants as the size scale of the gun is changed.

Finally, the in-line multi-chamber concept involves a second transition region between the in-line chambers and the bore of the barrel. By the time the combustion reaches this region during the ballistic cycle, the projectile will have moved a short distance into the barrel and the region of the bore vacated by the projectile will have been filled with LP. The exact geometry required to maintain a smooth combustion transition in this region is currently unknown. A few candidate schemes involving geometric size reduction from the diameter of the circumscribing envelope of the chambers to the inside diameter of the bore are known, including conical and step reductions. Exploration and resolution of the combustion control concept in this forward region are expected to be deferred to the Phase II effort, since a number of tests will likely be required to determine the efficacy of particular candidate concepts.

The second concept of determining the combustion performance of LP XM46 in single and one-step BLPG chambers essentially consists of substituting XM46 in place of Otto II and determining the comparative behavior using the two LPs. More importantly, differences in configuration and operating parameters required to obtain suitable ballistic performance need to be determined. In this Phase I program, the goal has been to obtain indications of feasibility of using XM46 in this manner and of simultaneously achieving reasonable control of the ballistic process. More complete investigation will require the resources commensurate with a Phase II, SBIR program.

The single and one-step cylinder-type BLPG chambers use essentially the same ignition configuration features as outlined previously for the first chamber section of the in-line multi-chamber concept. One of the initial uncertainties in the use of XM46 resides in how easy or difficult it is to ignite, relative to Otto II, and what adjustments are required in the breech-positioned igniter to achieve suitable performance—even if this performance differs from that obtained with Otto II. The essential igniter parameters available for adjustment, as noted earlier, include the primer, booster type and mass, and output orifice diameter.

The use of both a straight cylindrical chamber and a chamber with a single step will allow the influence of the step on combustion evolution to be assessed with XM46—just as for the case using Otto II. Associated operating and geometric parameters of concern again include orifice and chamber diameters and diameter ratios, first chamber section lengths, peak pressures generated, sensitivity of combustion to generate and reinforce pressure waves, overall combustion stability, combustion progressivity indications resulting from the presence of the step change in chamber diameter, and so forth. Initial parameter selections are expected to be those used previously with Otto II so that direct comparisons can be made in at least the initial results.

3. EXPERIMENTAL PROGRAM

A brief series of live firing tests was conducted to explore the feasibility of the BLPG concepts formulated here for controlling ignition and combustion evolution in such a system. A 20-mm BLPG test gun fixture was used, which featured a steel chamber with an oversized cavity to accommodate plastic chamber inserts that could be individually configured to achieve different interior chamber geometries.

This section describes the test gun fixture, relevant details of its construction and component parts, and instrumentation used during the test-firing program.

3.1 20-mm Single-Shot Firing Test Fixture.

3.3.1 Gun Test Fixture Assembly. Figure 2 is a detailed drawing of the gun test fixture used in this program. The available chamber length is 97.87 mm (3.853 in). This length is 0.25 mm (0.010 in) longer than the plastic insert chamber, to accommodate the tape seals used on the ends of the plastic. The inside diameter of the chamber is 44.45 mm (1.750 in). This, too, is larger than the plastic insert by 0.18 mm (0.007 in) to permit easy assembly. A thin film of silicone grease is applied to the plastic insert to fill the void.

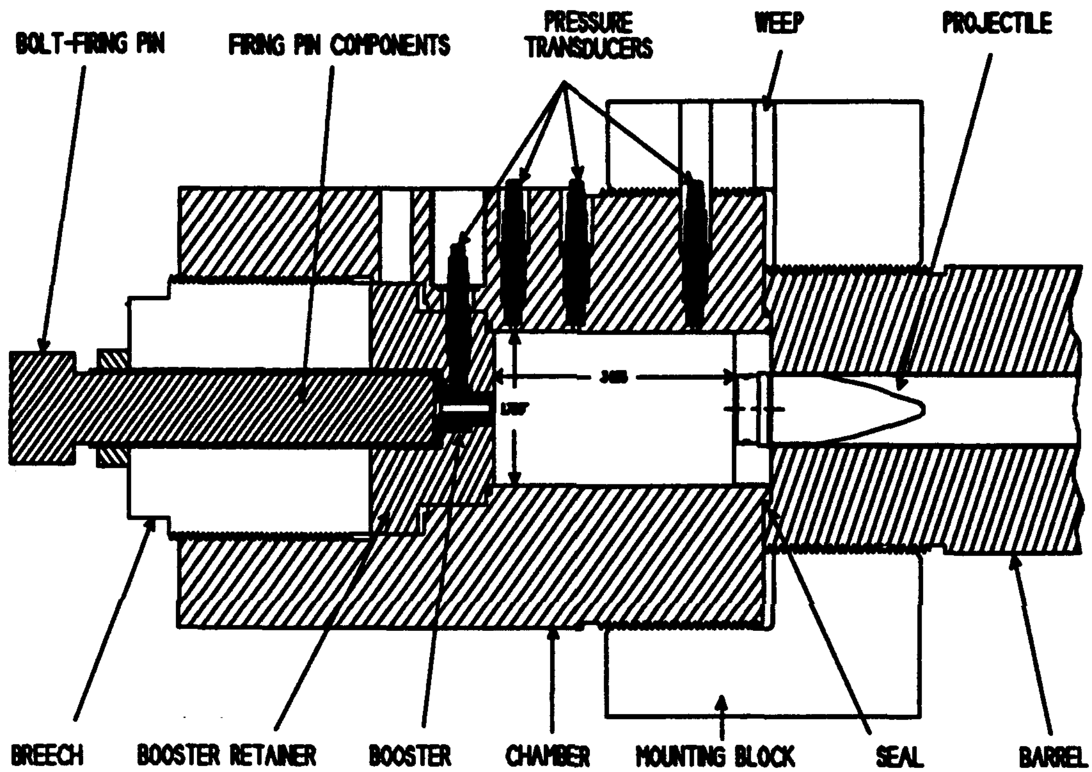

Figure 2. 20-mm single-shot firing fixture.

3.3.2 Barrel. A 20-mm, gain-twist rifled Mann barrel is used on this test gun fixture. It was manufactured from 4340 tool steel by Apex Rifle Co., formerly of Flagstaff, Arizona, and is heat treated to Rc 34-36. The rifling consists of nine, equally spaced, right-hand lead grooves, duplicating a standard 20-mm, gain-twist barrel.

As seen from Figure 3, the overall length of the barrel is 1.36 m (53.56 in). The external step-down section of the barrel, starting at 0.91 m (36 in) from the breech end, was incorporated to allow a simplification of the machining process. The barrel was instrumented at Veritay to incorporate a piezoelectric pressure transducer at the muzzle, 1.437 m (56.57 in) from the face of the booster orifice.

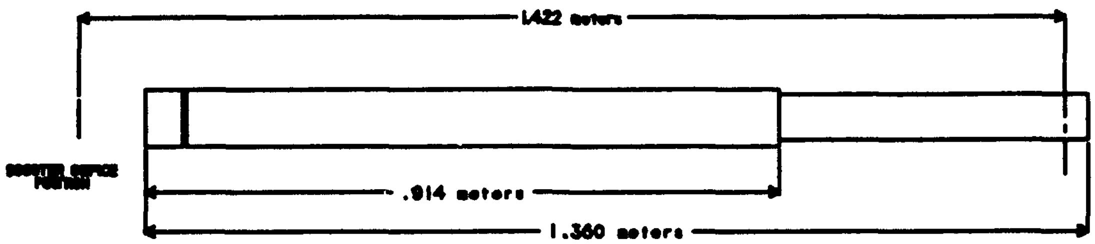

Figure 3. 20-mm Mann barrel.

3.3.3 Chamber. The chamber was built from 17-4 precipitation-hardened stainless steel, because of its high strength, availability, chemical resistivity, and reasonable cost. It is heat treated to a hardness of Rc 40-42.

The nominal outside diameter of the chamber is 127 mm (5 in), and the finished machined length is 239.6 mm (9.433 in). The breech end of the chamber is machined to accept a breech with a 3-8-2A thread.[1] As shown in Figure 4, two inner diameter levels have been cut into the breech end of the chamber. These two cylindrical sections enable the chamber length to be altered by using various booster retainers (see Figure 5). The outside diameter of the chamber is threaded at the barrel end, with a 5-8-2A thread, to allow the attachment of a barrel-chamber coupling block.

The chamber is currently machined to incorporate the use of four piezoelectric pressure transducers. The actual number of pressure transducers that can be used in the chamber is determined by the length of the booster retainer used. In the case of this test series, a short chamber booster retainer was employed; this allowed only three chamber pressure ports to be instrumented. The fourth pressure port was used as an access hole to insert a pressure transducer into the booster.

[1] All screw threads are indicated in English units; 3-8-2A indicates a thread of 3 in nominal diameter, 8 threads per in, with a class 2 fit.

To enable a pressure reading to be obtained in the booster housing, when the longer chamber booster retainer is used, a clearance hole through the chamber wall is available to allow easy access to the booster housing.

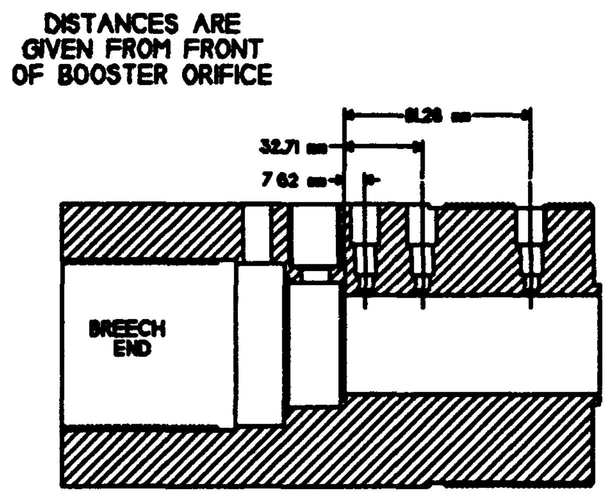

Figure 4. 20-mm chamber.

The pressure port locations are given in Figure 4. Chamber position 1 is located 7.62 mm (0.300 in) from the face of the booster orifice. Chamber positions 2 and 3 are located 32.71 mm (1.288 in) and 81.28 mm (3.200 in) from the booster, respectively.

3.3.4 Booster Retainer. The booster retainer is made from 17-4 stainless steel, heat treated to Rc 40-42. The short chamber booster retainer used in this program is shown in Figure 5. This retainer fits into the forward cylindrical position of the chamber fixture, and thereby forms a short chamber section in the fixture. The retainer is configured to accept a pressure transducer and a hexagonal key to achieve precise alignment of the pressure pathway in the booster housing. A slot cut into the large diameter section of the retainer is aligned during retainer installation with a locking bolt in the chamber. This ensures that the booster retainer does not rotate when the breech is assembled into the chamber. This also helps to assure that the chamber insert, used in conjunction with this chamber, does not rotate out of alignment with the pressure transducer ports in the chamber.

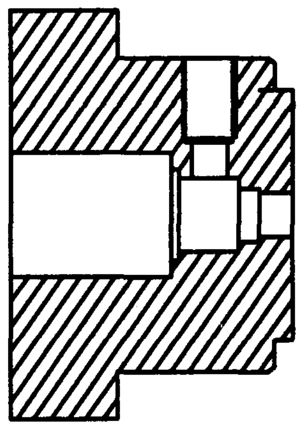

Figure 5. Short chamber booster retainer.

The booster retainer is designed to accept a wide range of booster housings, thereby enabling the effects of the quantity of booster powder used to be investigated.

3.3.5 Booster Housing. The booster housing, shown in Figure 6, fits inside the booster retainer. It is also made of 17-4 stainless and is heat treated to Rc 40-42. The booster shown here has a typical capacity of 0.57 cm^3 (0.035 in^3). The large opening, opposite the orifice, is incorporated in the design to permit the use of a small rifle primer. Because the outside diameter of the rifle primer may be smaller than the booster powder cavity, as it was in this test series, the primer is first pressed into a steel holder and then pressed into the booster housing.

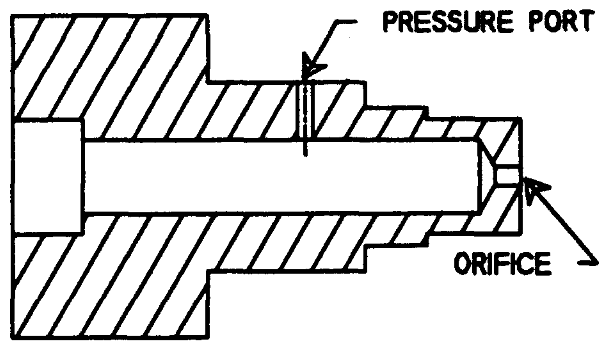

Figure 6. Booster housing.

3.3.6 Breech. The breech, made of hardened 17-4, was machined with 3-8-2A threads to mate with the chamber, with a hex to allow tightening, and with a tapped through-hole to allow the insertion of the firing pin mechanism.

3.3.7 Projectile Spacer. A 316 stainless steel spacer is used to position the base of the projectile in the high pressure chamber area and not in the barrel where the higher pressures may cause damage. This spacer positions the base of the projectile flush with the opening of the plastic chamber insert and with the rotating band resting on the origin of rifling.

3.3.8 Chamber Inserts. Plastic chamber inserts were used to facilitate study of the effects of the chamber geometry. They also enabled quicker turn-around time between tests. The inserts themselves are made of cast acrylic rod. The overall length of the finished plastic insert is 97.61 mm (3.843 in) and the outside diameter is 44.27 mm (1.743 in). The various geometrical configurations used for testing in this program are indicated in Figure 7. The chamber inside geometry was machined by reaming to the required depth, using metric reamers, and the finished product was measured for accuracy to ensure system reproducibility. In the case of the multichambers, the machining of the individual chambers was done with the help of a drilling fixture, which was designed and built at Veritay.

3.3.9 Ignition System. Ignition is started with a CCI 400 small rifle percussion primer, a product of Omark Industries. The primer ignites varying amounts of Hercules Canister Powder Unique, or Hercules 2400 Canister Powder. This combination, along with a 1.32-mm-diameter (0.052-in) orifice proved satisfactory to initiate combustion of the LPs.

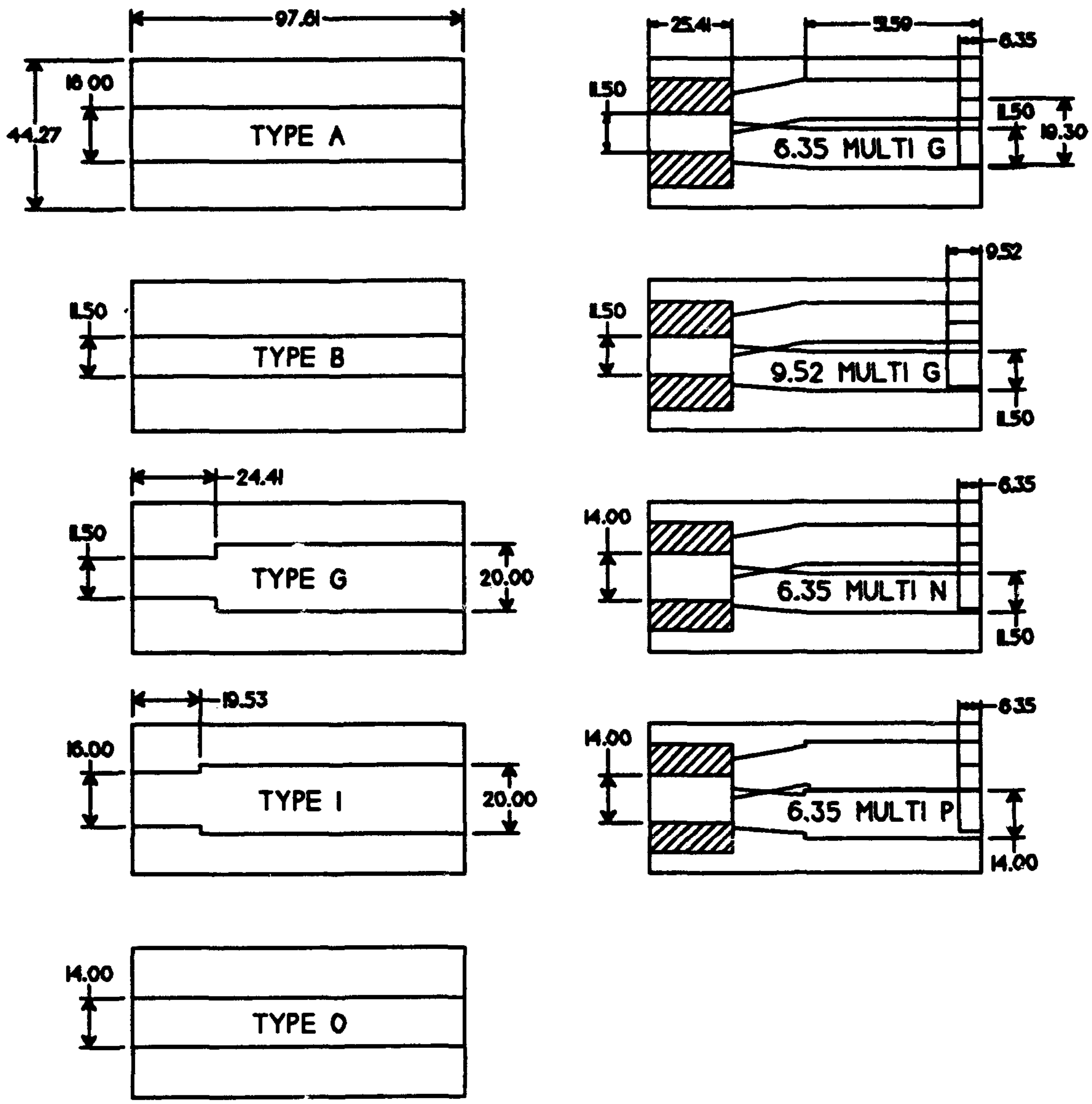

Figure 7. Chamber insert configurations.

3.3.10 Projectile. The projectile used is a 20-mm target practice bullet, obtained by de-bulleting an M55-A2 round, lot number LC-24-291. It is a steel bullet with an aluminum nose. The exact mass of each projectile is recorded for each test; the average mass is 99 g.

3.2 Liquid Monopropellants. Two types of liquid monopropellants were used in this test program, the nitrate ester propellant Otto II, and the hydroxylammonium nitrate (HAN) based monopropellant XM46 (formerly LGP 1846).

The thermo-chemical properties of these propellants have been extracted from Travis et al. (1986) and Knapton et al. (1988) and are given in Table 1.

Table 1. Properties of Selected Liquid Propellants[a]

LP	Fuel		HAN (wt%)	Water (wt%)	Density (g/cm^3)	Impetus (J/g)	Flame Temperature (K)	γ
	Name	wt%						
XM46	TEAN[c]	19.2	60.8	20.0	1.43	898	2,469	1.223
Otto II[b]					1.23	866	1,986	1.266

[a] Loading density = 0.2 g/cm^3.
[b] Composition of Otto II: 1, 2 dinitroxypropane 76%, di-N-butyl sebacate 22.5%, 2 nitrodiphenylamine 1.5%.
[c] Triethanolammonium nitrate (TEAN).

4. INSTRUMENTATION

For all the tests performed in this program, five PCB piezoelectric pressure transducers were used—one in the barrel, three in the chamber, and one in the booster. Two different model types of PCB transducers were used: Model 119A and Model 119A02. When used in combination with PCB's Model 462A charge amplifier, Model 119A is capable of measuring pressures up to 690 MPa (100 ksi), and Model 119A02 measures pressures up to 828 MPa (120 ksi). Although there is no difference in the pressure readings obtained by the different models their types and placements were recorded on the data sheets.

The primer strike, and pressure data obtained from each test firing are recorded, displayed and stored on magnetic diskettes using four-channel Nicolet Oscilloscopes, Model 2090. Sampling rates of 2 µs per point were used.

The projectile velocities were determined by measuring the time of flight between three break strips, located fixed distances apart. The time measurements were made using Global Model 5001 Universal digital timers.

5. EXPERIMENTAL RESULTS

Exploratory tests of the two basic types of BLPG concepts noted earlier and indicated in Figure 1 were conducted to obtain a preliminary indication of the feasibility of using chamber geometry to control the ignition and combustion process, when using either the liquid propellant Otto II or XM46.

The in-line multi-chamber tests were conducted solely using Otto II, because of the expected mild behavior of this LP and our experience and baseline information associated with its use. This choice of LP has permitted early exploratory tests, in this and in other programs, to be conducted during less than perfect conditions, without serious risk of incurring catastrophic gun fixture failure during testing. The single and one-step cylinder tests were conducted specifically using XM46, to determine its performance against a background of tests conducted using Otto II in these same chamber geometries. The catastrophic failure risk was minimal in this case. These safety concerns are appropriate and relevant inasmuch as the examination of test results obtained during both optimal and less than optimal conditions are considered essential for achieving the goals and objectives of this investigation.

A total of 17 tests were conducted under this program; 7 were concerned with the multi-chambers (one of those was a repeat with Otto II of an earlier test), and 10 with XM46.

A tabulation of the pressures, velocities, action times and ignition delays for the complete test series is given in Table 2. Configuration data for the 20-mm tests, including insert chamber type, booster orifice size, booster and propellant loading information, and projectile mass are given in Table 3. Complete sets of individual pressure-time (P-t) traces for the booster and chamber transducers are given in the appendix, and selected P-t traces are discussed briefly in this section. Complete data sets together with both pictorial and fabrication drawings of the 20-mm modular test gun with gain-twist rifled Mann barrel,[1] were transmitted under separate cover to BRL.

---

[1] This Government-owned test gun was designed and built under a non-SBIR Army contract with ARDEC (with Dr. Arthur Bracuti as COR), and was made available for use during this program on a shared basis with other on-going contract work for ARDEC.

Table 2. Performance Data From 20-mm BLPG Tests

Test No.	Insert Type	Booster Pressure (MPa)	Chamber Pressures (MPa)			Muzzle Pressure (MPa)	Action[a] Time (ms)	Ignition[b] Delay (ms)	Velocities (m/s)		
			C1	C2	C3				1.	2.	3.
1	G	436	346	302	425	33	—	0.160	899	892	896
2	6.35 Multi G	—	—	—	—	—	—	—	902	—	—
3	6.35 Multi G	515	355	316	324	24	2.116	0.138	925	—	—
4	B	540	331	349		9	3.300	0.092	—	—	—
5	6.35 Multi G	517	319	272	322	25	2.960	0.182	883	—	—
6	9.52 Multi N	491	386	316	310	26	2.100	0.186	908	914	912
7	6.35 Multi G	507	401	353	353	26	3.140	0.172	941	942	941
8	B	702	387	306	313	9	2.940	0.254	668	666	667
9	O	708	—	—	—	13	6.330	—	789	790	791
10	O	749	361	302	341	9	2.480	0.228	647	645	647
11	A	780	—	—	—	19	5.560	—	876	877	877
12	O	585	301	281	350	—	2.480	0.144	654	—	—
13	A	574	669	358	442	14	3.180	0.124	751	738	749
14	I	466	475	388	458	25	3.320	0.240	910	914	914
15	I	536	—	—	—	32	8.840	—	1,098	1,102	1,102
16	I	461	456	408	439	28	2.780	0.262	995	996	997
17	6.35 Multi P	385	513	465	573	36	3.060	0.356	1,006	993	1,001

[a]The action time is defined here as the interval between primer strike and the instant that the projectile leaves the barrel (approximated here by the instant the projectile base passes the muzzle pressure transducer).
[b]The ignition delay time is defined here as the interval between primer strike and the peak of the primer pressure pulse observed in the main chamber.

Table 3. Configuration Data for 20-mm BLPG Tests

Test No.	Chamber Type	Propellant		Calculated Volume (cm^3)	Booster		Orifice Diameter (mm)	Projectile		Average Velocity (m/s)
		Type	Mass (g)		Type	Mass (g)		Type	Mass (g)	
1	G	Otto II	32.6	26.5	Unique	0.335	1.32	M55A2	98.371	896
2	Multi G	Otto II	32.0	26.0	Unique	0.335	1.32	M55A2	98.934	902
3	6.35 Multi G	Otto II	31.0	25.2	Unique	0.336	1.32	M55A2	98.403	925
4	B	XM46	15.0	10.5	Unique	0.335	1.32	M55A2	99.415	—
5	6.35 Multi G	Otto II	32.0	26.0	Unique	0.336	1.32	M55A2	98.640	883
6	9.52 Multi G	Otto II	32.9	26.7	Unique	0.335	1.32	M55A2	98.977	912
7	6.35 Multi N	Otto II	33.1	26.9	Unique	0.335	1.32	M55A2	98.333	941
8	B	XM46	14.3	10.0	2400	0.325	1.32	M55A2	99.353	667
9	O	XM46	21.7	15.2	2400	0.338	1.32	M55A2	99.209	791
10	O	XM46	21.3	14.9	2400	0.338	1.32	M55A2	99.370	647
11	A	XM46	28.1	19.7	2400	0.336	1.32	M55A2	98.795	877
12	O	XM46	21.1	14.8	Unique	0.335	1.32	M55A2	98.802	654
13	A	XM46	28.0	19.6	Unique	0.335	1.32	M55A2	99.177	749
14	I	XM46	40.4	28.2	Unique	0.335	1.32	M55A2	97.967	914
15	I	XM46	40.8	28.2	Unique	0.325	1.17	M55A2	99.216	1,102
16	I	XM46	41.0	28.7	Unique	0.390	1.32	M55A2	98.316	997
17	6.35 Multi P	Otto II	43.0	34.9	Unique	0.330	1.32	M55A2	98.873	1,001

5.1 In-Line Multi-Chamber Concept. The tests associated with the in-line multi-chamber were conducted first. Test No. 1 was run as a baseline type of test for this initial series and actually used a one-step chamber (with chamber insert Type G) rather than a multi-chamber insert. The purpose of this test was to establish a baseline pressure-time result for the same LP volume as the three-chamber in a single chamber with the same 11.5-mm-diameter section in front of the step. This approach permitted comparison of results in these two cases and provided a P-t trace for comparison with one obtained using a nearly identical insert in an earlier program, to indicate consistency in test results. Further, this one-step chamber type was selected because the peak chamber pressures were relatively low and were expected to translate into corresponding peak pressures low enough in the multi-chamber case to allow the safe conduct of test operations.

Test No. 1 used a one-step G-type chamber insert (shown in Figure 8) and Otto II as the LP. The igniter configuration consisted of a CCI-400 small rifle primer and 335 mg of Hercules Canister Powder Unique.

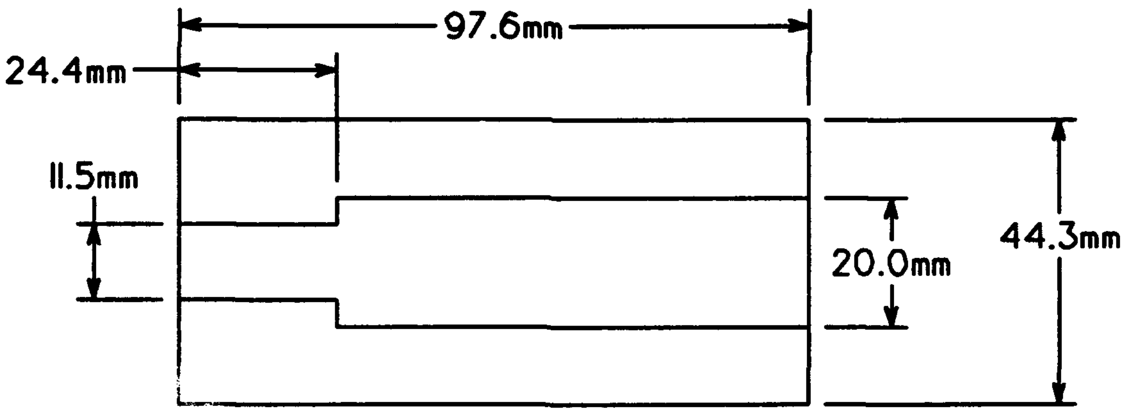

Figure 8. One-step chamber insert (chamber type G).

Figure 9 shows an overplot to show reproducibility of the G-type chamber pressure-time traces obtained in Test No. 1 and a test conducted in an earlier program. The figure shows only the pressures acquired at the No. 2 pressure transducer location, 32.72 mm (1.288 in) from the booster orifice.

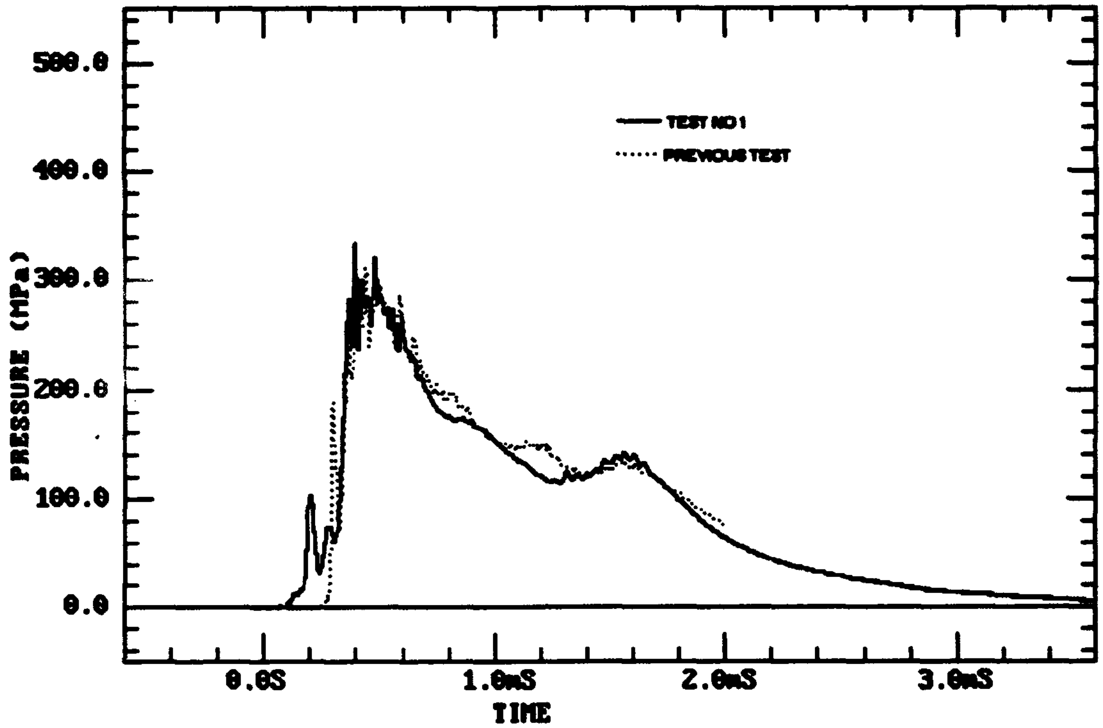

Figure 9. Comparison of pressure-time traces in current and past tests using Otto II.

The pressure trace labeled "previous test" baseline in Figure 9 was acquired from a previous test program using a chamber insert with slightly different sizes from those used in this test series. The differences are in the diameters of the smaller diameter cylindrical section, and of the larger diameter section. The smaller diameter for Test No. 1 is 11.5 mm (0.4528 in), while the small diameter in the earlier test is 11.7 mm (0.463 in). The large diameter in Test No. 1 is 20 mm (0.787 in), and the large diameter in the earlier test is 19.8 mm (0.781 in). Although there is a slight difference in sizes, it is apparent from Figure 9 that these small differences have not caused any significant change in the peak pressure or in the shape of the curve. This apparent insensitivity of the P-t trace to small changes in chamber diameters may not hold if the diameters are scaled to other sizes.

Test No. 2 was conducted using the in-line multi-chamber concept, but a malfunction in the instrumentation trigger mechanism resulted in the failure to record pressure data. Only one velocity measurement was obtained.

Test No. 3 used the in-line multi-chamber insert, designated 6.35 Multi G, which duplicated the area change in the single step chamber Type G used in Test No. 1. This multi-chamber configuration is shown in Figure 10. For this test, 31.0 g of the LP Otto II was used. The igniter consisted of a CCI 400 small rifle primer and a booster load of Hercules Canister Powder Unique.

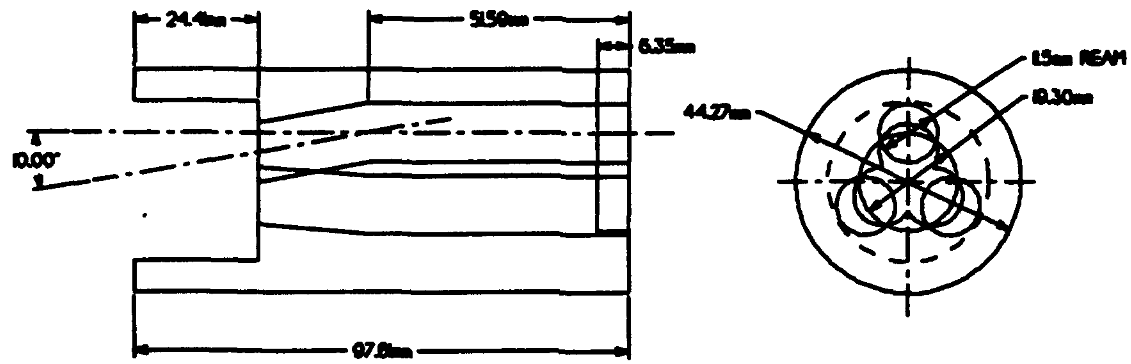

Figure 10. <u>In-line multi-chamber insert Type 6.35 Multi G</u>.

Experience with the combustion phenomena in a geometrically designed chamber configuration has indicated that the peak pressure is directly related to the diameter of the first cylindrical section, assuming the length of this section is adequate to allow the combustion of liquid propellant to stabilize before proceeding to the next section of increased area. Accordingly, a reasonable assurance against over-pressurization in the multi-chamber configuration was achieved by incorporating the use of the small 11.5-mm-diameter (0.453 in) first chamber, as used in Test No. 1, the baseline test. The change in area between the single chamber to the multi-chamber section of the G-type multi-chamber is 1:3, or 1.04 cm^2 to 3.12 cm^2. This area change is approximately the same as that in the previous test, where the change is 1.04 cm^2 to 3.14 cm^2. A second area change also occurs in the G-type multi-chamber at the projectile end. This change in area is 3.12 cm^2 to 2.93 cm^2. This area change is the result of a cut-out region that was introduced to reduce the amount of resistance to the gas flow from the chamber to the barrel. Other area changes that are incurred in the test fixture are the openings in the projectile holder and the rifled portion of the barrel. These area changes are relatively small and are close to the area change at the cut out region, but they do produce a turbulent effect which increases the burn surface area. At present, it is believed that the second hump in the pressure-time curve of Test No. 3, shown in the appendix, is the result of turbulence generated near the area changes in the cut-out region and the projectile-holder locations.

Test No. 4 was a single chamber insert type test conducted with LP XM46 and will be noted in the next section.

Test No. 5 was a repeat of Test No. 3, using the 6.35 Multi G chamber. A comparison of their pressure-time results is given in Figure 11. The reproducibility of P-t traces for these two tests tends to show some promise in the region of the primary pressure peak but is lacking at times, exceeding about 0.8 ms in the ballistic cycle. Development of this second major pressure peak is believed to be the result of a combination of effects possibly involving, first, a turbulence-enhanced combustion rate as the combustion from the in-line cylinders exits into the combined chamber region of enlarged cross-sectional area just behind the projectile, and second, an in-barrel burning of LP behind the moving projectile. Because of the apparent basis for this second pressure pulse, inherently it may not be very reproducible and will need further attention to ensure that its behavior can be controlled or circumvented.

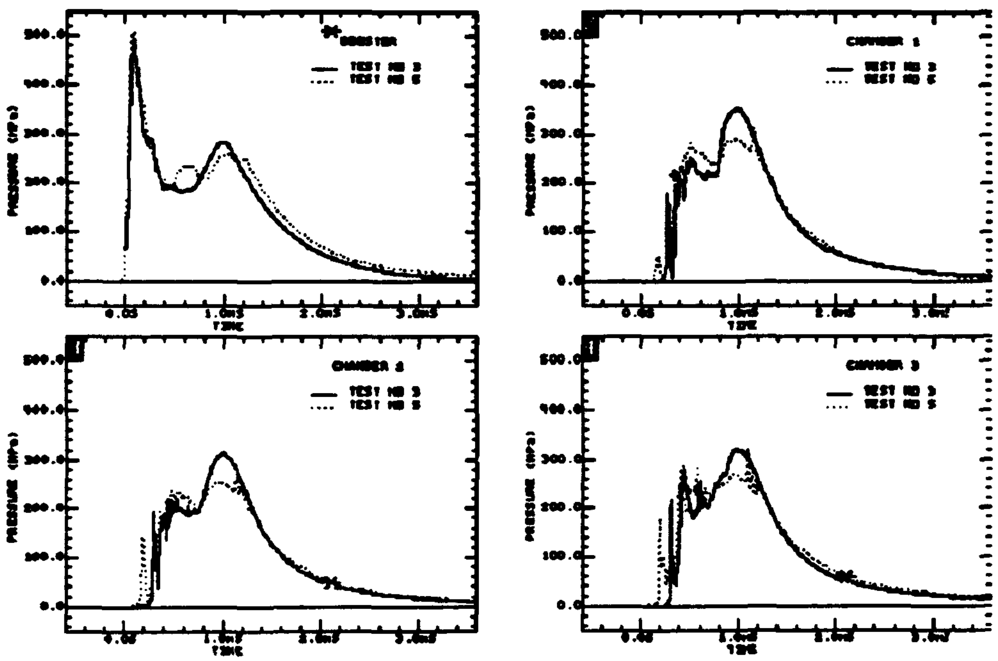

Figure 11. Pressure-time trace reproducibility in 6.35 Multi G chambers.

Test No. 6 was conducted using a 9.52 Multi G-type chamber insert, shown in Figure 7, to explore the effect of an increase in length of the 19.30-mm-diameter opening of the chamber insert at the projectile end. This length was 6.35 mm in Test No. 3 and 5, and the increased length for Test No. 6 was 9.52 mm. The rationale for examining this length change was to learn if the conjecture of turbulence-enhanced and/or in-barrel combustion was associated with the formation of the second pressure peak observed during Test No. 3 and 5, or whether these effects (which should be affected by the length change) were non-operative, and some other effect might be involved. The results of the G-type multi-chamber firings of Test No. 5 and 6 are compared in Figure 12. This comparison indicates that the longer front region of Test No. 6 increases the maximum value of the second pressure peak. Hence, it appears that our initial assessment of this peak being influenced by the chamber geometry at the front of the in-line multi-cylinders is essentially correct—although it does not indicate whether turbulence or other in-barrel effects are responsible. No attempt was made in this Phase I program to further assess the nature of this second pressure peak or to smooth, reduce, or control it. Its source appears to be identified, and techniques may be applied to further influence its behavior later in a Phase II effort.

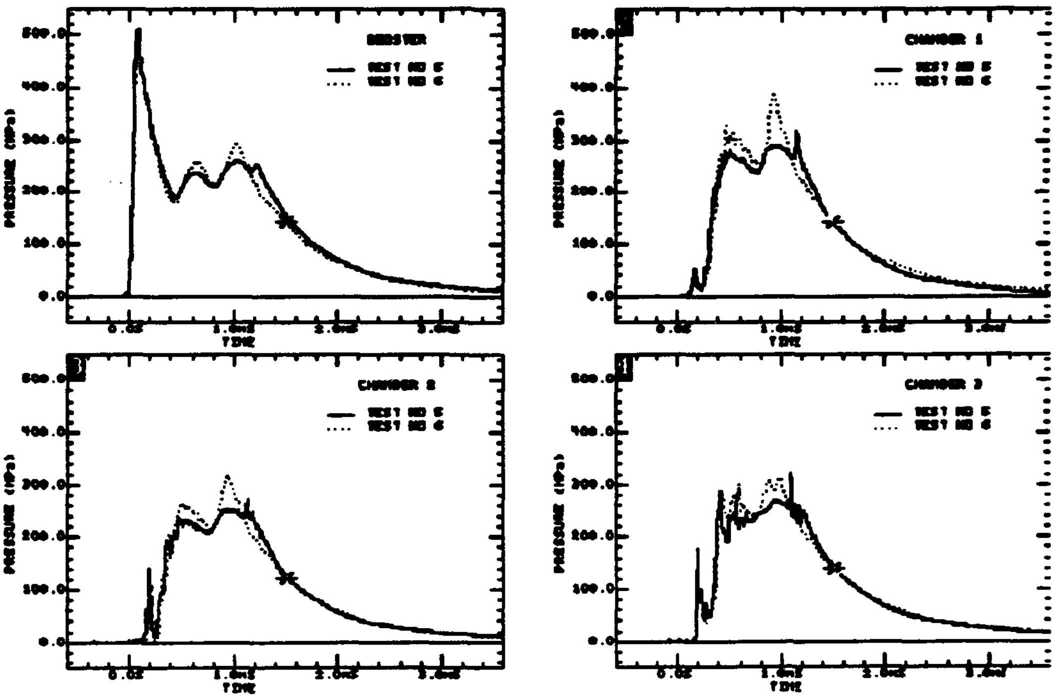

Figure 12. Comparison of pressure-time behavior in two different multi chambers.

Test No. 7 explored the effect of increasing the diameter of the single chamber section closest to the booster orifice.

The previous multi-chamber Test No. 2, 3, and 5 used an 11.5-mm-diameter first chamber, while Test No. 7 used a 14-mm-diameter chamber. This test again illustrates the apparent validity of the general finding that the peak pressure is directly related to the diameter of the first cylindrical chamber section, as can be seen in Figure 13, which compares P-t traces of Test No. 3, 5, and 7.

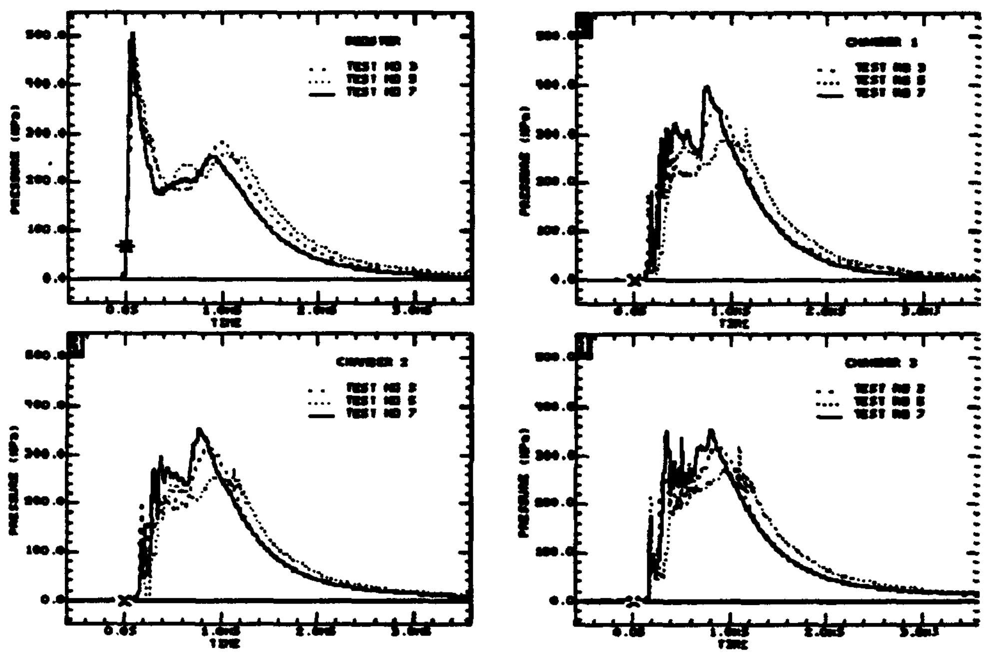

Figure 13. Pressure-time effects from increasing first chamber section diameter.

Test No. 17 was the last multi-chamber test fired during this Phase I program. It used a 6.35 Multi P-type chamber insert, and 43.0 g of Otto II. The purpose of this test was to explore the effects of using a 14.0-mm-diameter first chamber section with 14.0-mm-diameter in-line multi-cylinder chamber. The connecting cylinder splay in the transition region used the original 11.5-mm-diameter cylinders, rather than those with the larger 14.0-mm value. This was deliberate to see if significant pressure changes or time delays developed by using these connecting cylinders. The pressure-time trace for Test No. 17 are given in the appendix.

No apparent time delay effects resulted from these geometry changes, but the peak pressure values corresponding to the first peak increased, and the magnitude of the second pressure peak increased significantly. This suggests that more of the combustion in the ballistic cycle took place in the region ahead of the multi-cylinder complex than was the case, for example, in Test No. 7. The high pressure spike near the center of the second pressure peak in Test No. 17 is of undetermined origin, but it is real and has probably arisen from a particular combustion pulse that occurred in the barrel ahead of the chamber. The pulse arrived first at the forward-most pressure transducer in the chamber and successively later at the more rearward transducers. The fact that such a pulse occurred is not viewed with any alarm at this step of investigation and is exactly the type of combustion anomaly the authors are seeking to overcome by stabilizing the combustion process. Obviously, the configuration used in this test does not meet this goal.

5.2 Single Cylinder-Type Chamber Concepts. The test series that examined single and step-chamber type concepts was conducted using the LP XM46.

Test No. 4, which was the first run in this series, used the 11.5-mm (0.453-in) B-type straight chamber shown in Figure 14. The propellant load was 15.0 g of XM46, and the primer-booster combination was a CCI-400 primer and 335 mg of Hercules Canister Powder Unique as the booster.

A set of pressure-time traces for Test No. 4 and for a test fired in a previous program using Otto II as the liquid propellant in the same geometry is shown in Figure 15. The interesting feature about these comparison plots, beside the near duplication of the pressure-time profile, is that the lower impetus Otto II (866 J/g) generated a higher overall pressure than that of the XM46 (898 J/g). This agreement between the Otto II test and the XM46 test, in the straight 11.5-mm chamber, shows promise that the XM46 propellant can be as controllable in the geometric chamber configurations as is the Otto II.

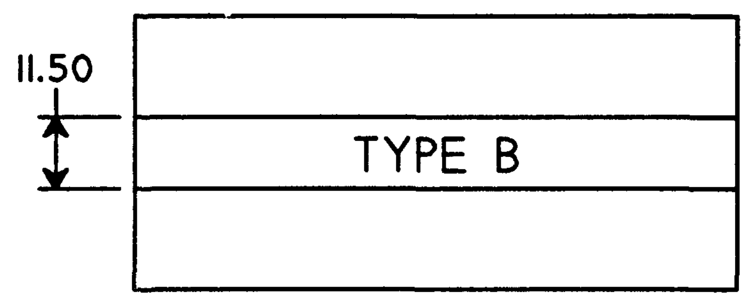

Figure 14. Single cylinder chamber insert.

Figure 15. Comparison of pressure-time traces in current and past tests using different LPs.

Test No. 8 was the next test run in this series. This test was run in the Type B, 11.5-mm-diameter single cylinder chamber—the same chamber geometry as used in Test No. 4. The type of booster powder was changed from Hercules Canister Powder Unique to Hercules Canister Powder 2400, in an attempt to lower the initial pressure spike observed in Test No. 4 by lowering the gas temperature of the booster powder.

To keep the mass of the booster powder approximately the same, a new booster housing was fabricated to obtain the new required volume. Comparing the pressure-time traces of Test No. 4 and 8 (these P-t traces are shown in the appendix), it is evident that this approach did succeed in diminishing the initial pressure spike.

Test No. 9 was conducted to investigate the effect of increasing the diameter of the chamber on the chamber pressure. The diameter was increased to 14 mm, using an O-type chamber insert, as compared to Test No. 4 and 8, which used the 11.5-mm-diameter Type B chamber insert. The propellant was 21.7 g of XM46, initiated by 338 mg of Hercules Canister Powder 2400 and a CCI-400 small rifle primer. An increase in peak chamber pressure was expected, since the diameter of the combustion chamber was enlarged. However, as shown in the appendix, Test No. 9 (booster) displayed a very long ignition delay. This long delay of approximately 3.8 ms was too long to allow recording of the chamber pressure time curves, because the event took place outside the time window set on the recording device.

An erroneous analysis was made initially of both the chamber and booster pressure records acquired during Test No. 9. Since the chamber P-t traces showed no pressure readings, it was first assumed that a misalignment of the pressure ports caused the loss of chamber pressure data. The P-t trace for the booster was misread. Hence, Test No. 10 was run to duplicate Test No. 9. Later analysis of the booster pressure-time curve, after Test No. 11 was run using a wider time window, identified a delay in ignition as the true cause for the lack of observed chamber pressure-time curves. This analysis of the booster pressure trace for Test No. 9 enabled the peak chamber pressure to be estimated from the pressure back flow into the booster housing through the 1.32-mm orifice. This estimated chamber pressure was above 340 MPa.

Test No. 10 was a duplicate of Test No. 9, using the O-type chamber insert. However, it produced a fairly respectable pressure-time curve (see Test No. 10 traces in the appendix). Since it was not known at that time that Test No. 9 had a long ignition delay, the authors assumed that Test No. 10 was good and continued to test a larger diameter chamber.

Relying on the data obtained in Test No. 10, Test No. 11 was run, using the A-type chamber insert with a 16-mm (0.6299-in) inside diameter. The results of Test No. 11 were similar to those for Test No. 9 and indicated a long ignition delay. This was found by examining the booster pressure trace obtained in Test No. 11, shown in the appendix. At that time, a close examination of the booster pressure traces of Test No. 9 and 11 indicated an ignition delay in both cases. Test No. 10 would not have been run had this been observed earlier in Test No. 9.

The ignition delays found in Test No. 9 and 11 were indicative of poor ignition and could have been the result of the lower flame temperature of the booster powder used, an improperly sized booster output orifice, too small a quantity of booster powder relative to the quantity of LP, or a combination of these.

Resolution of this early ignition problem was pursued by returning to the use of Hercules Canister Powder Unique as the booster powder. Test No. 12 used an O-type straight chamber insert with a 14.0-mm (0.5512-in.) inside diameter. The igniter configuration consisted of 335 mg of Hercules Canister Powder Unique, initiated by a CCI-400 small rifle primer. The decreased liquid propellant volume and the hotter flame temperature booster propellant produced a reasonable pressure-time curve. The Hercules Canister Powder Unique used in Test No. 12 had a flame temperature 3,379 K compared to Hercules Canister Powder 2400 at 3,214 K used in Test No. 8 through 11.

Test No. 13 continued the series with an increased chamber diameter of 16 mm (0.6299 in.), using the A-type straight chamber insert. The booster combination, 335 mg of Hercules Canister Powder Unique and a CCI-400 primer were used as before. The expected increase in peak chamber pressure did occur. As shown in the pressure time trace for Test No. 13 in the appendix, a high pressure spike occurred in the P-t trace for the Chamber 1 position. This spike is not seen in the Chamber 2 or 3 positions and has been attributed to a "water-hammer" type of effect arising from the way the pressure transducer was installed. This hammer effect has been substantiated by a notation in the test data sheet; the silicone, grease which was placed in the transducer port of the plastic chamber insert, was pushed in farther than normal during assembly, therefore leaving an air gap between the transducer and the grease plug.

In Test No. 14, the combustion behavior was explored in the geometry of an I-type, single-step chamber insert. Again, the same ignition configuration was used as in Test No. 13, 335 mg of Hercules Canister Powder Unique and a CCI-400 primer. As shown in the pressure time traces for Test No. 14 (chambers 1, 2, and 3) in the appendix, an ignition delay occurred. This effect is not desirable as seen in the earlier Tests No. 9 and 11. This ignition delay observed in Test No. 14 was believed to result from an increased amount of liquid compression (for a given pressure) associated with the larger volume of LP contained in chamber insert Type I, compared with the LP volume used in previous tests.

To correct for this delay, two options were available. The first option was to decrease the booster orifice diameter, and the second option was to increase the amount of booster propellant. In either case, the objective of the change was to overcome the effect of an increased amount of liquid compression resulting from the larger volume of liquid propellant—assuming the booster propellant and orifice size combination were within the necessary range of parameters to effectively ignite the liquid propellant.

In Test No. 15, a decreased orifice size of 1.17 mm (0.046 in) was chosen instead of the larger 1.32-mm (0.052-in) diameter used in earlier tests.

An I-type chamber insert was used in Test No. 15, the same as that used in Test No. 14. The booster powder was 325 mg of Hercules Canister Powder Unique, ignited again by a CCI-400 small rifle primer. The pressure-time curve obtained for Test No. 15, and shown in the appendix, indicated that a long ignition delay occurred. This ignition delay further indicated that the 335 mg of the Hercules Canister Powder Unique booster propellant was marginal for this test.

Test No. 16 again used the I-type chamber insert, a larger booster orifice diameter of 1.32 mm (0.052 in), and 390 mg of Hercules Canister Powder Unique booster powder. Increasing the amount of booster powder shortened the ignition delay, but a further increase appears to be needed.

The problems encountered here in igniting XM46 in the single and one-step chambers is unfortunately not completely atypical in the process of determining the correct type of igniter for a BLPG system. In general, it seems that the LP XM46 is somewhat more difficult to ignite than the LP Otto II. Once ignited, however, the combustion behavior of these two LPs appears to be similar phenomenologically, in the sense of being responsive to control by chamber geometry. This result may have significant implications for achieving similar results using different LPs.

6. CONCLUSIONS AND RECOMMENDATIONS

This investigation has shown experimentally that each of the two concepts that were formulated and explored under this program are favorable in controlling the BLPG interior ballistic process by using chamber geometry to control the combustion.

The first concept is an in-line multi-chamber, in which a breech-initiated, first stage, cylindrical chamber is coupled to a cluster of two or more in-line cylindrical chambers, that form the second stage. This concept is a new alternative to the step-chambers scheme, which has been investigated at Veritay recently using the LP Otto II.

The second concept investigated consists of single and one-step cylinder-type BLPG chambers, properly sized and breech ignited to achieve combustion control using the liquid propellant XM46. The innovative aspect of this investigation involved using a different type of LP and briefly comparing its combustion performance with the promising stable combustion results obtained recently in identical BLPG chambers using Otto II.

Mechanical control of the combustion process within a BLPG system by means of chamber geometry has potential to enable a greater range of liquid propellant types to be used in such a system.

The in-line multi-chamber concept provides a means for achieving mechanical control of the combustion process in a BLPG system and has potential to maintain this control if the BLPG system is scaled over a range of sizes.

Although ignition is known to be important in properly starting the interior ballistic combustion process, how the liquid propellant combustion evolves after ignition is the most important factor in achieving a desirable interior ballistics performance in a bulk-loaded liquid propellant gun.

This study has confirmed that ignition and early combustion stability in an initial LP chamber can be achieved by proper choice of the relative diameters of the igniter orifice and the propellant containing chamber.

The study has confirmed that combustion stability in the main liquid propellant gun chamber(s) can be controlled by proper choice of the chamber geometry.

The study indicates that in-barrel combustion can occur and that its control or minimization is essential to achieve overall control of the interior ballistic combustion process in a BLPG system.

On the basis of the investigations conducted during this program, it is recommended that both concepts addressed here be explored and developed further to confirm technical feasibility, to demonstrate effective overall control and repeatability of the interior ballistic process, and to provide the basis for developing BLPG concepts for weaponization.

7. REFERENCES

Knapton, J. D., C. Watson, I. C. Stobie, and G. Klingenberg. "Experiments with Liquid Gun Propellants." BRL-TR-2932, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1988.

Liquid Propellant Gun Technology, A Bibliography. CPIA Publication LS91-12, July 1991.

Talley, R. L. "Diagnostics of Combustion Evolution in a Bulk-Loaded LP Gun." Proceedings of the Twenty-Seventh JANNAF Combustion Meeting, CPIA Publication 557, vol. I, pp. 461–471, November 1990.

Talley, R. L., and A. Bracuti, "Liquid Propellant Gun Diagnostics." Draft Contractor Report, Veritay Technology No. A10-03-90, ARDEC, Picatinny Arsenal, NJ, August 1990.

Travis, K. E., J. D. Knapton, I. C. Stobie, and W. F. Morrison. "Closed Chamber Tests on Liquid Propellants." BRL-TR-2755, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1986.

INTENTIONALLY LEFT BLANK.

APPENDIX:

PRESSURE TIME TRACES

INTENTIONALLY LEFT BLANK.

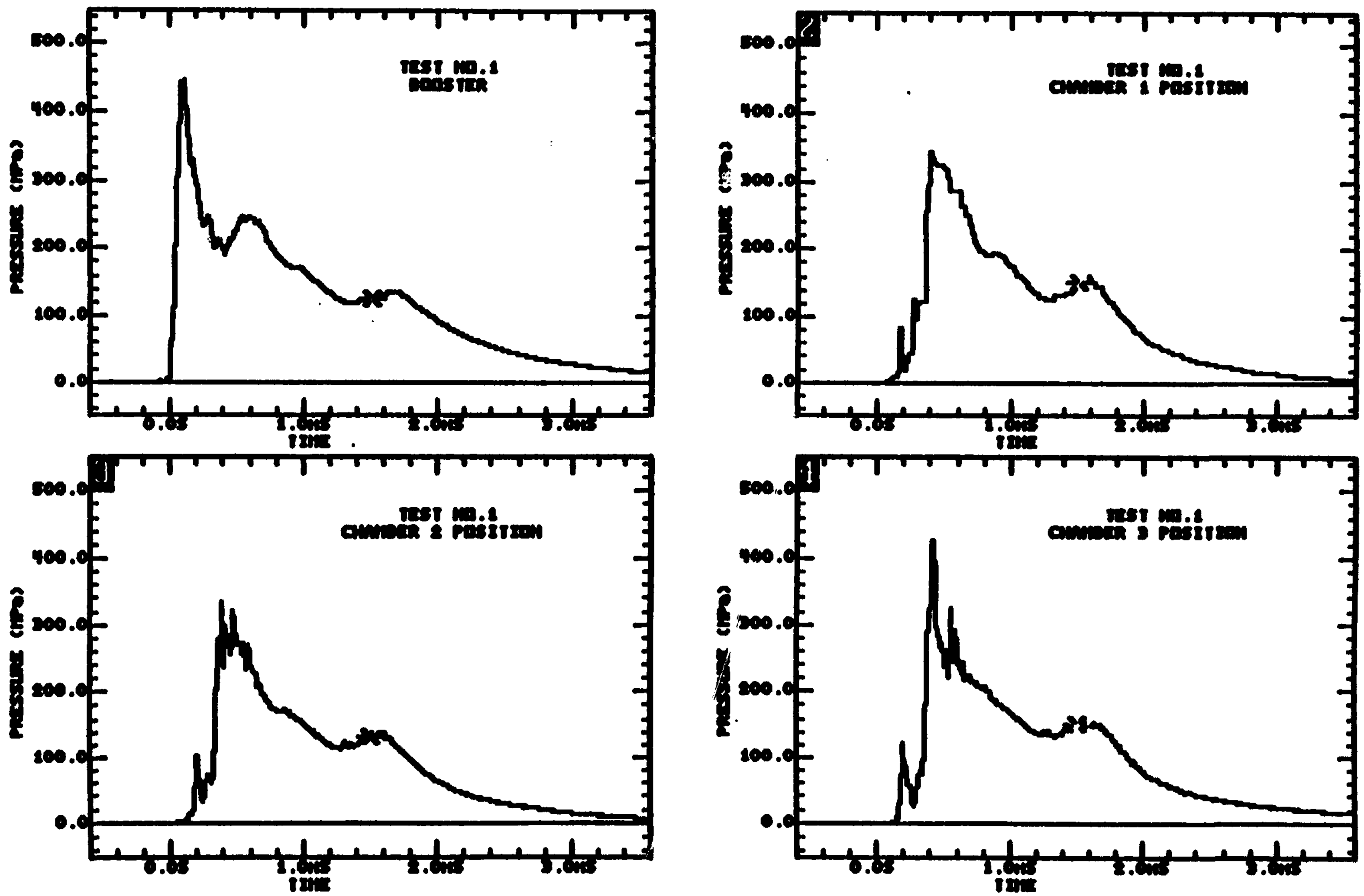

Figure A-1. Booster and chamber pressure-time traces for Test No. 1 with chamber insert Type G.

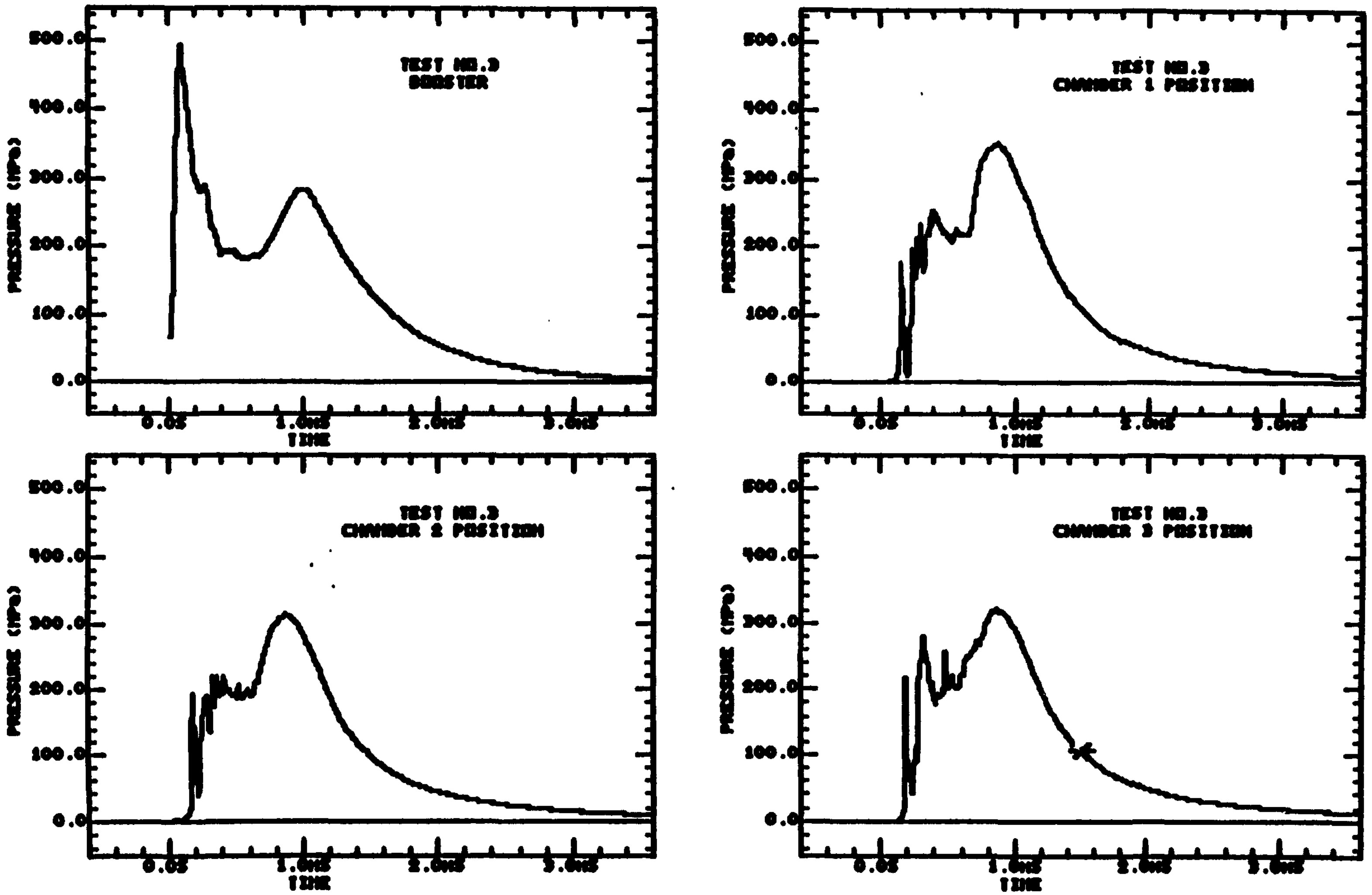

Figure A-2. Booster and chamber pressure-time traces for Test No. 3 with chamber insert type 6.35 Multi G.

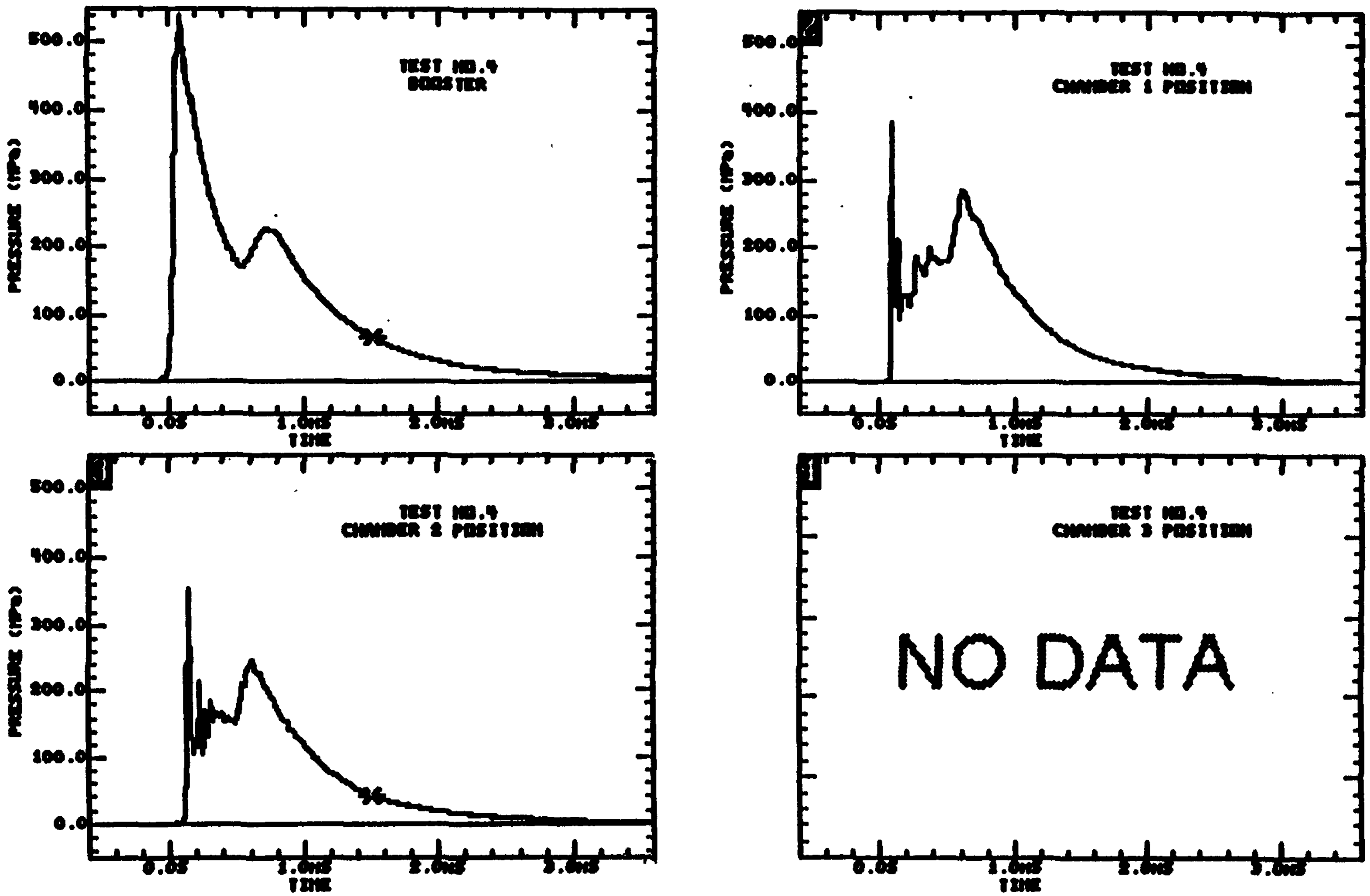

Figure A-3. Booster and chamber pressure-time traces for Test No. 4 with chamber insert Type B.

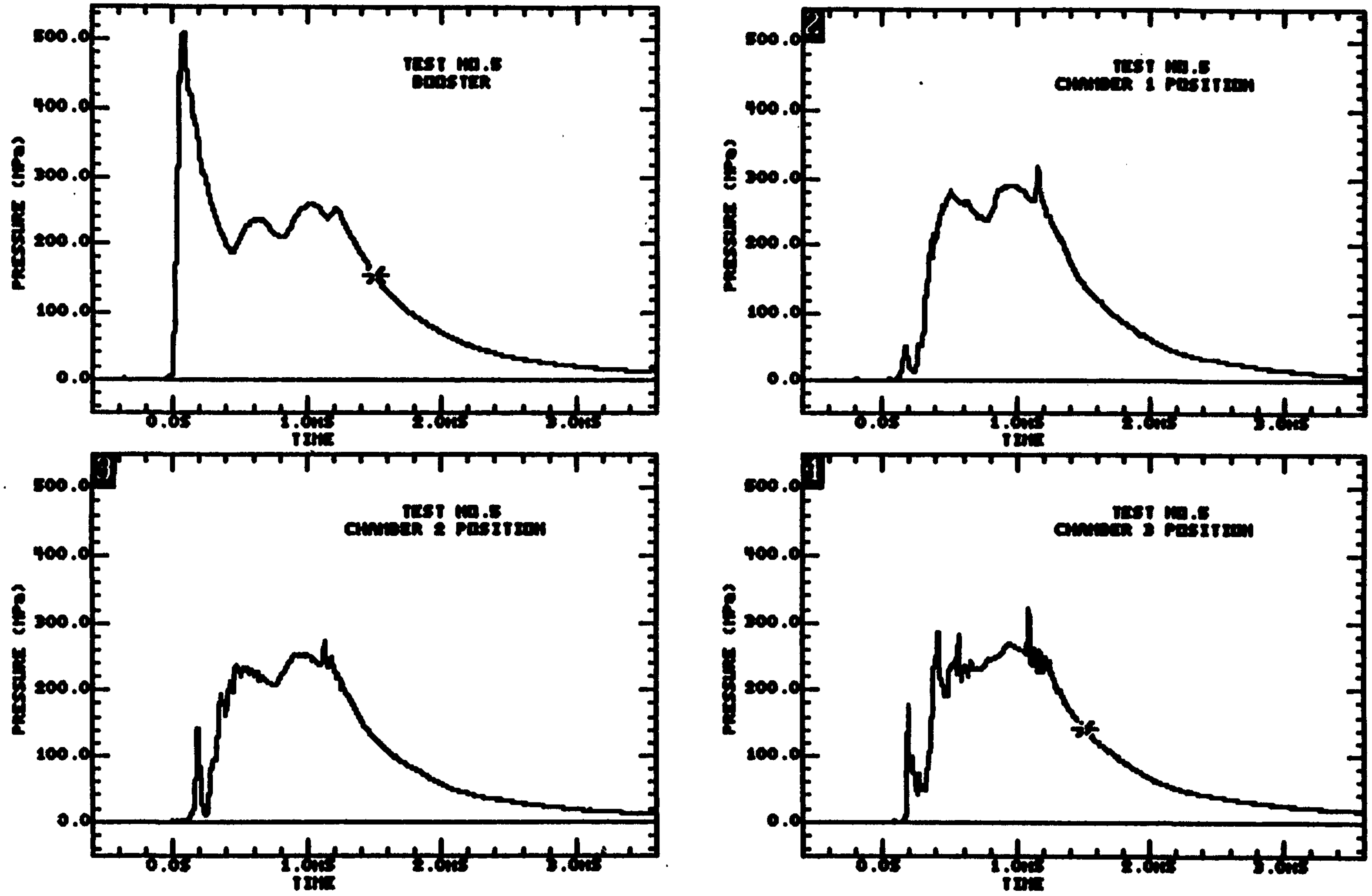

Figure A-4. Booster and chamber pressure-time traces for Test No. 5 with chamber insert type 6.35 Multi G.

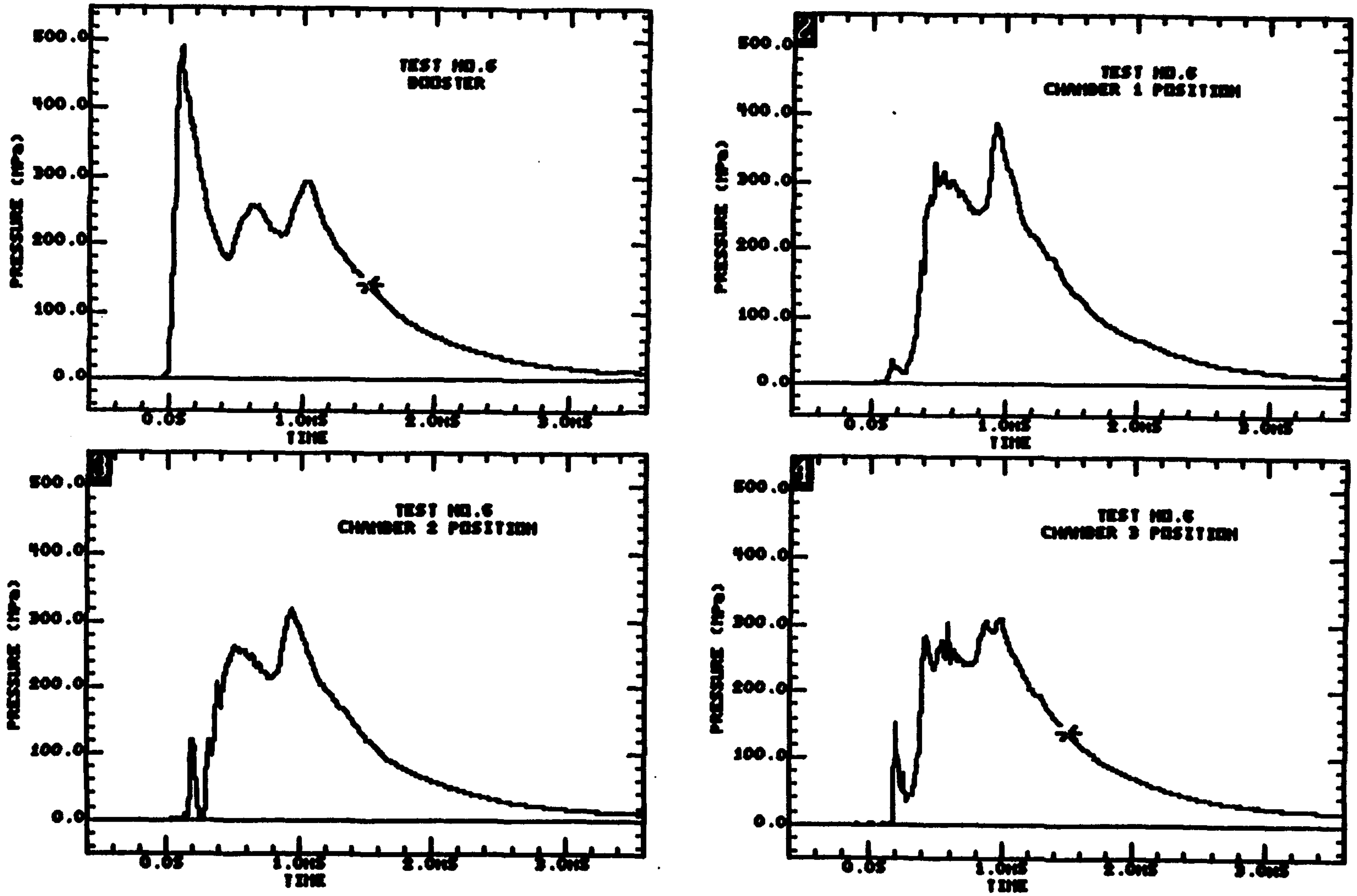

Figure A-5. Booster and chamber pressure-time traces for Test No. 6 with chamber insert type 9.52 Multi N.

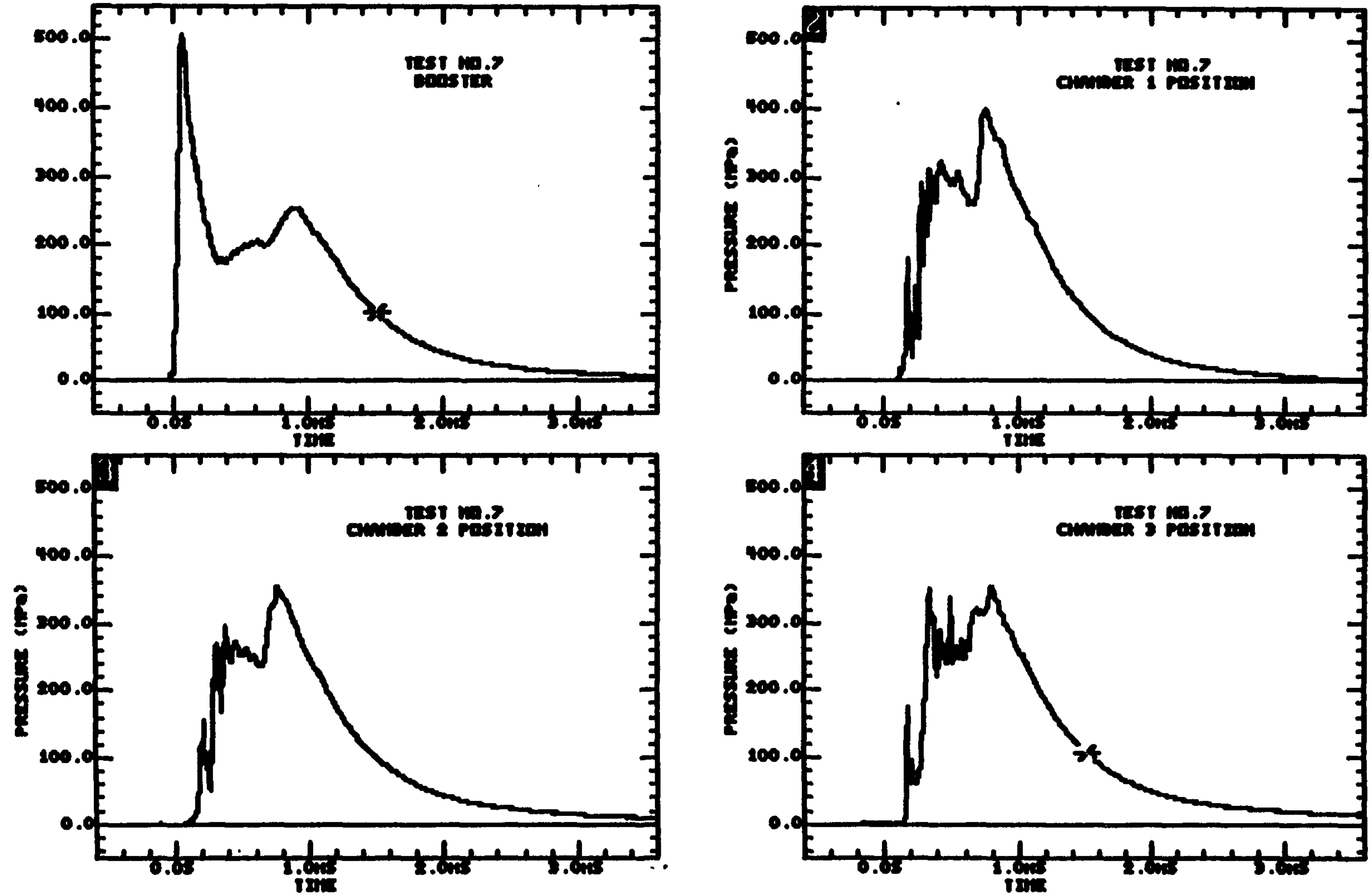

Figure A-6. Booster and chamber pressure-time traces for Test No. 7 with chamber insert type 6.35 Multi G.

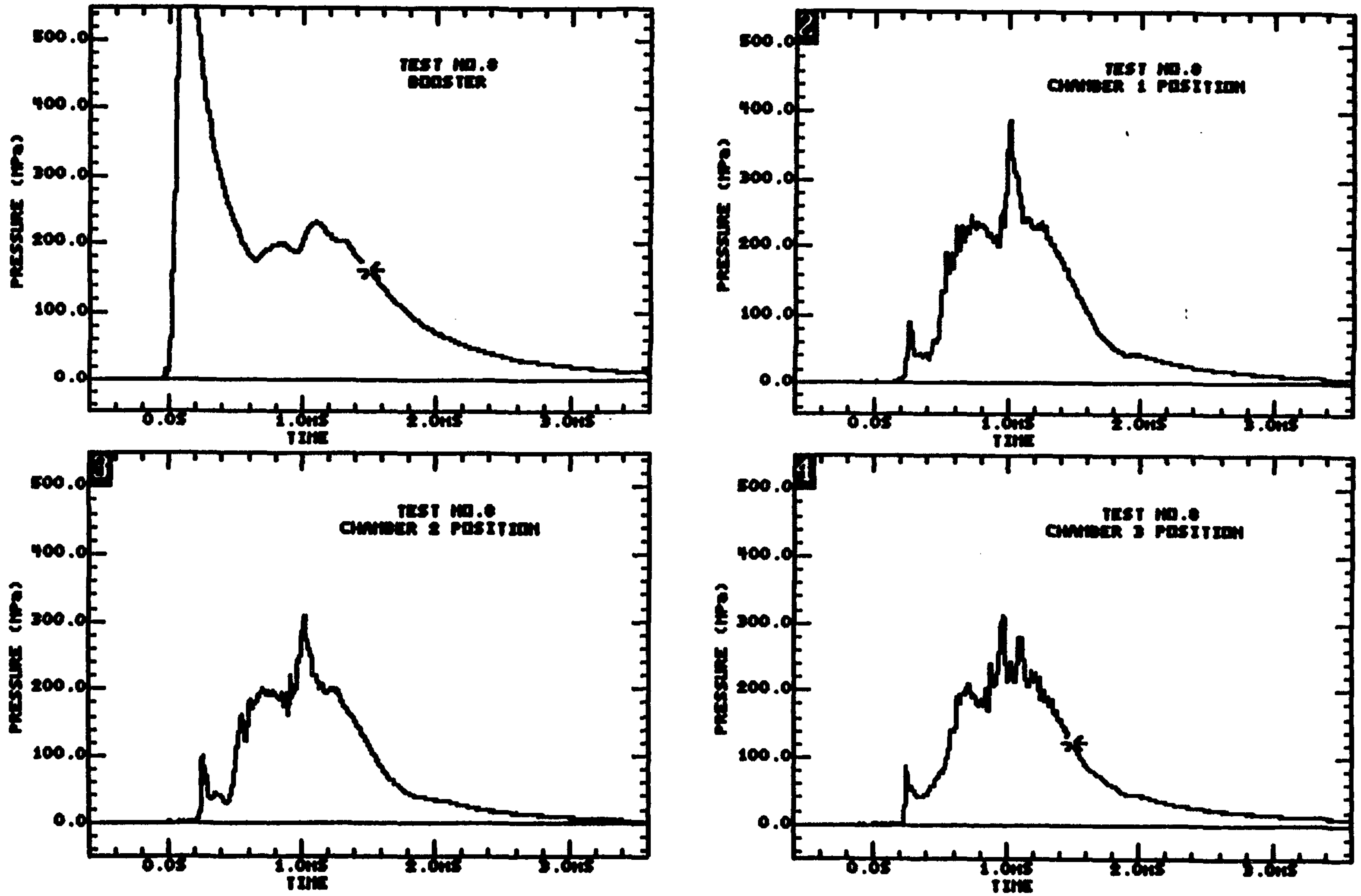

Figure A-7. Booster and chamber pressure-time traces for Test No. 8 with chamber insert Type B.

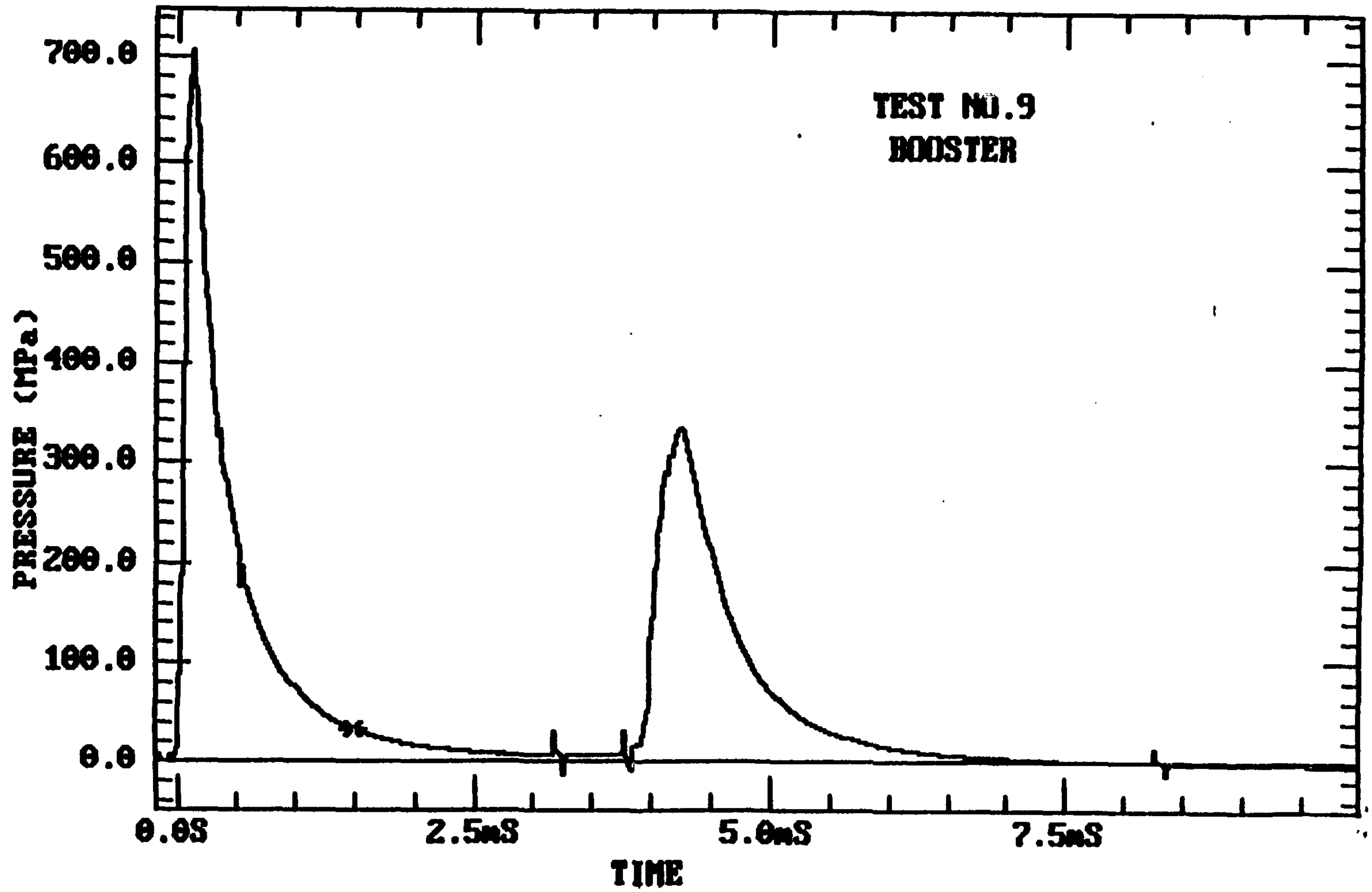

Figure A-8. Booster pressure-time trace for Test No. 9 with chamber insert Type O.

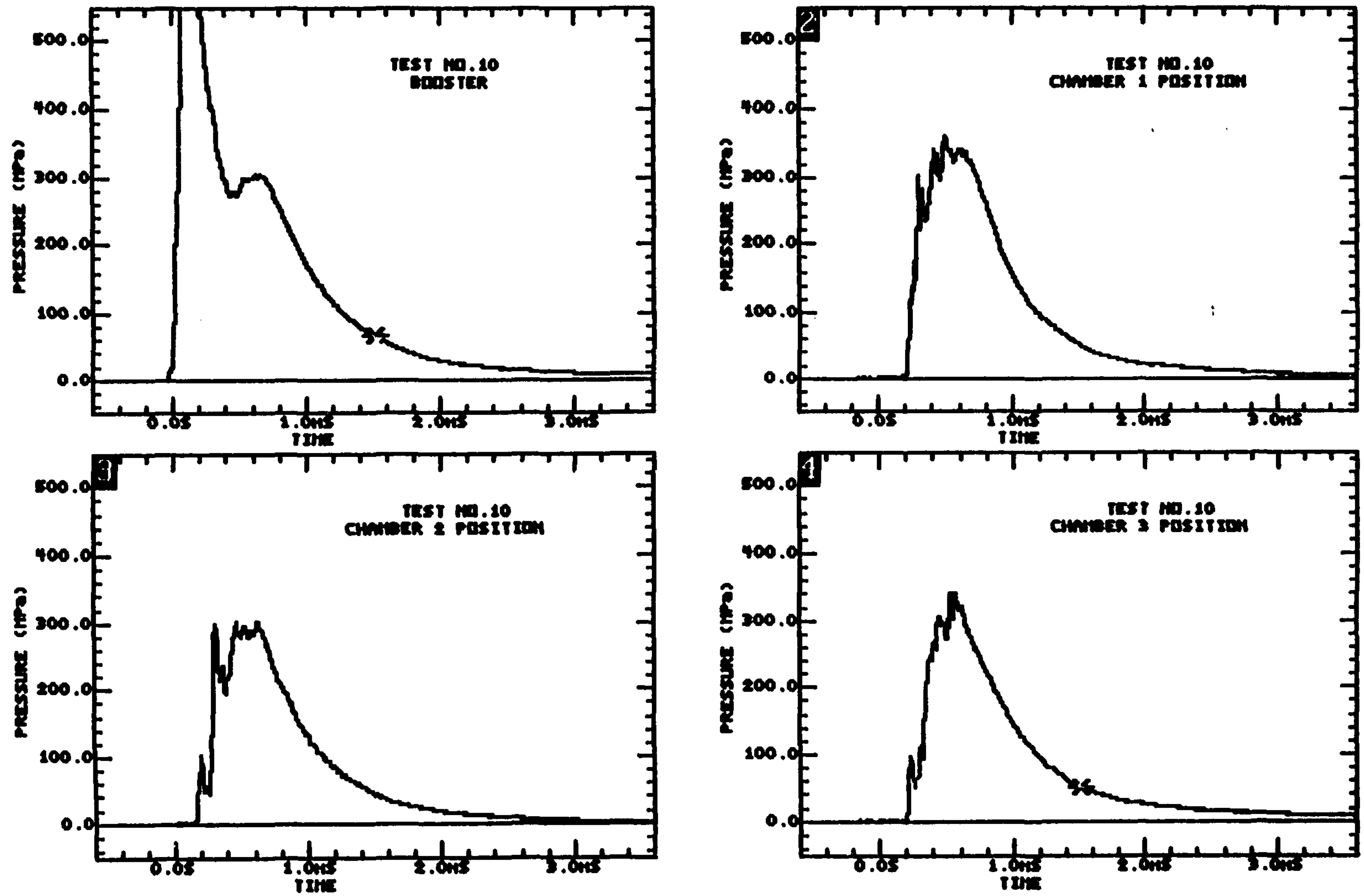

Figure A-9. Booster and chamber pressure-time traces for Test No. 10 with chamber insert Type O.

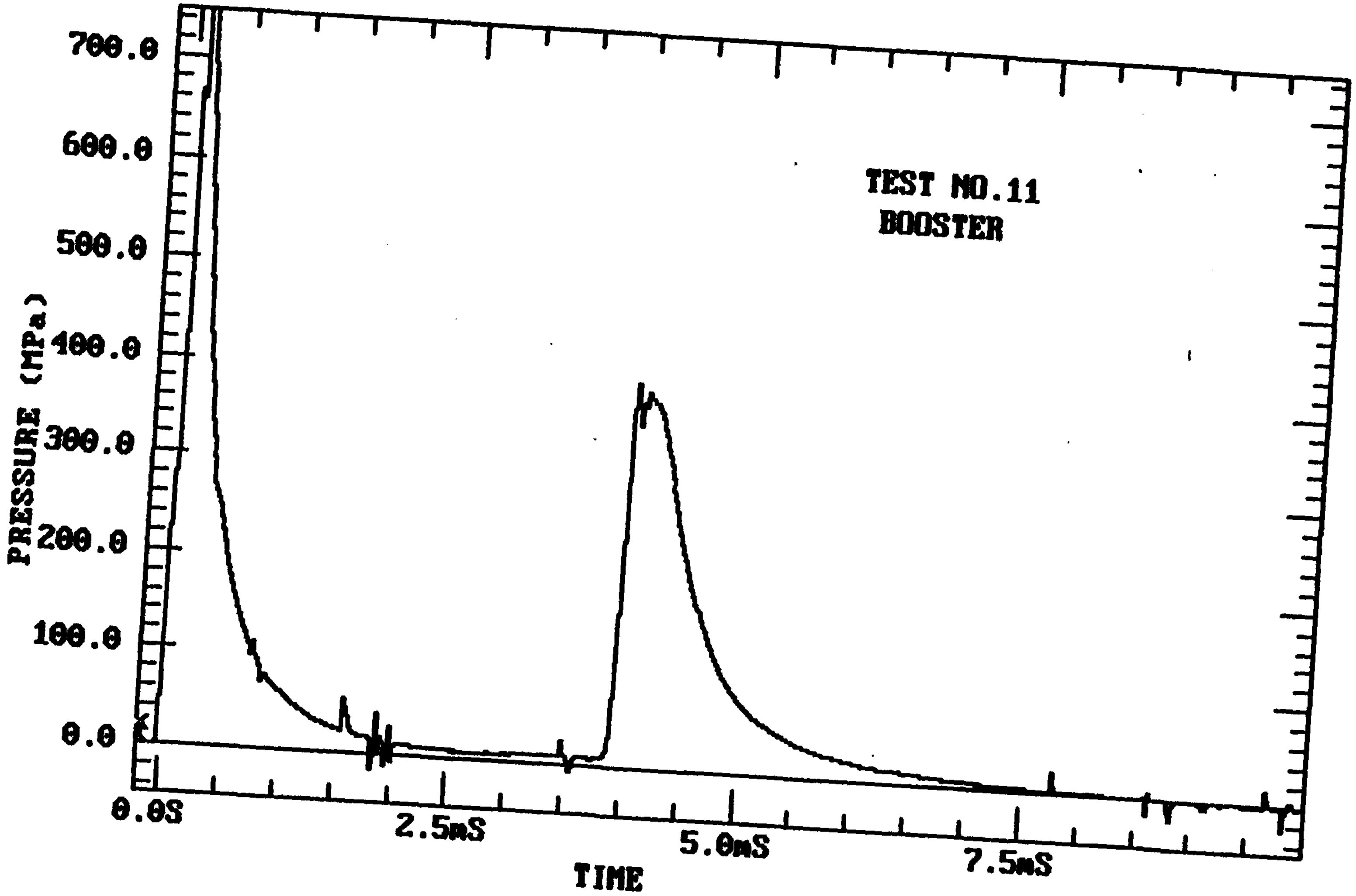

Figure A-10. Booster pressure-time trace for Test No. 11 with chamber insert Type A.

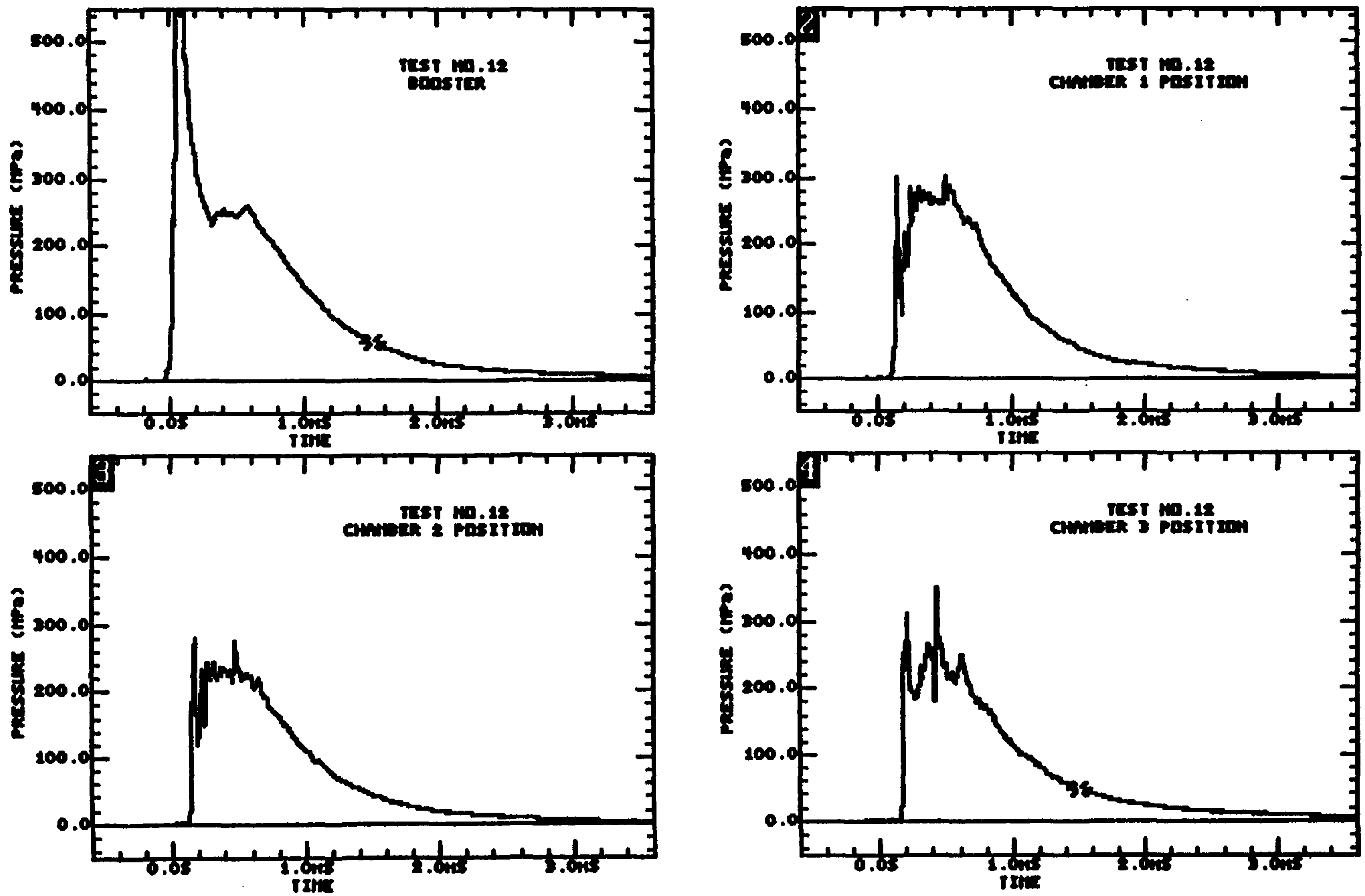

Figure A-11. Booster and chamber pressure-time traces for Test No. 12 with chamber insert Type Q.

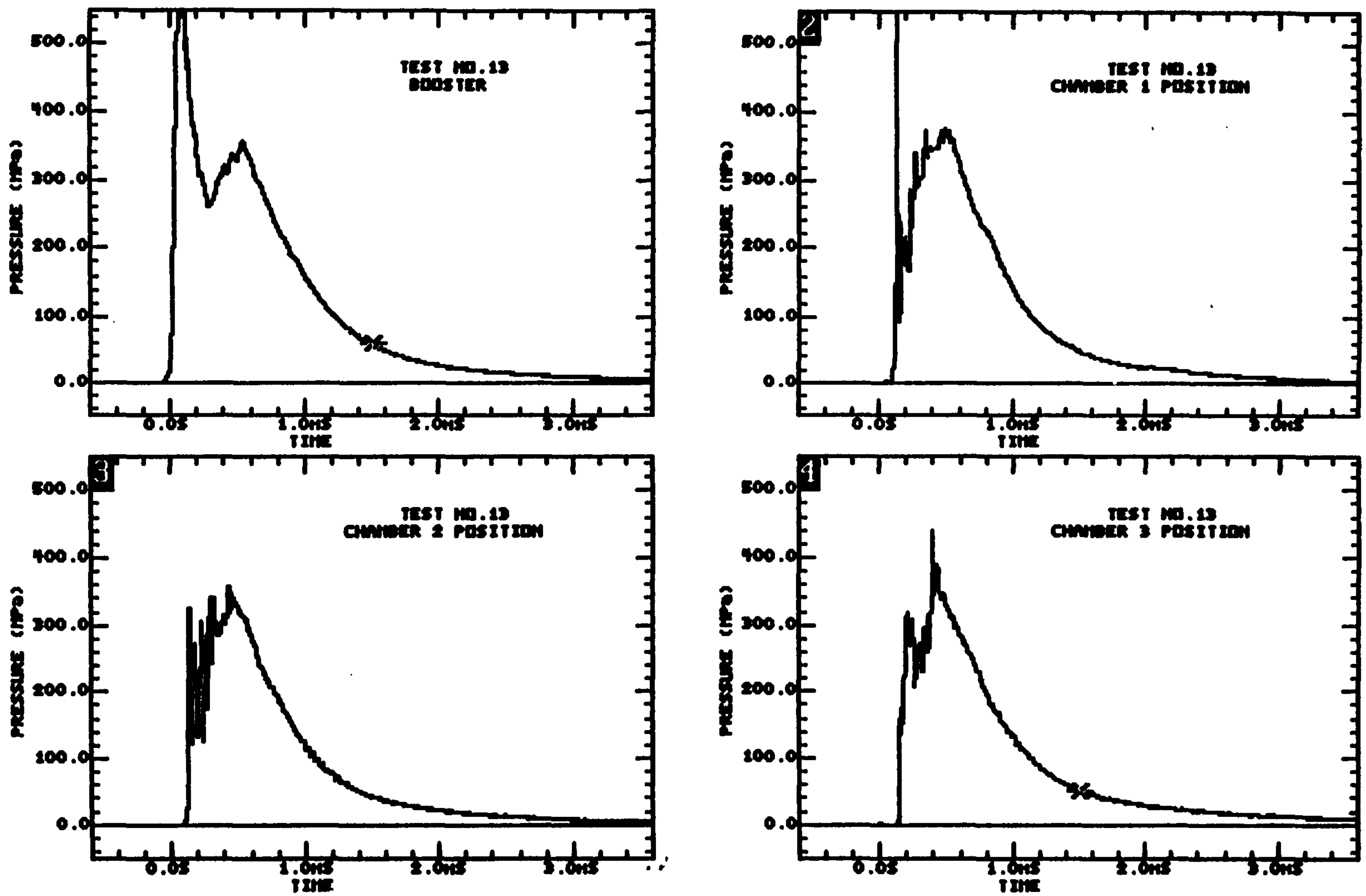

Figure A-12. Booster and chamber pressure-time traces for Test No. 13 with chamber insert Type A.

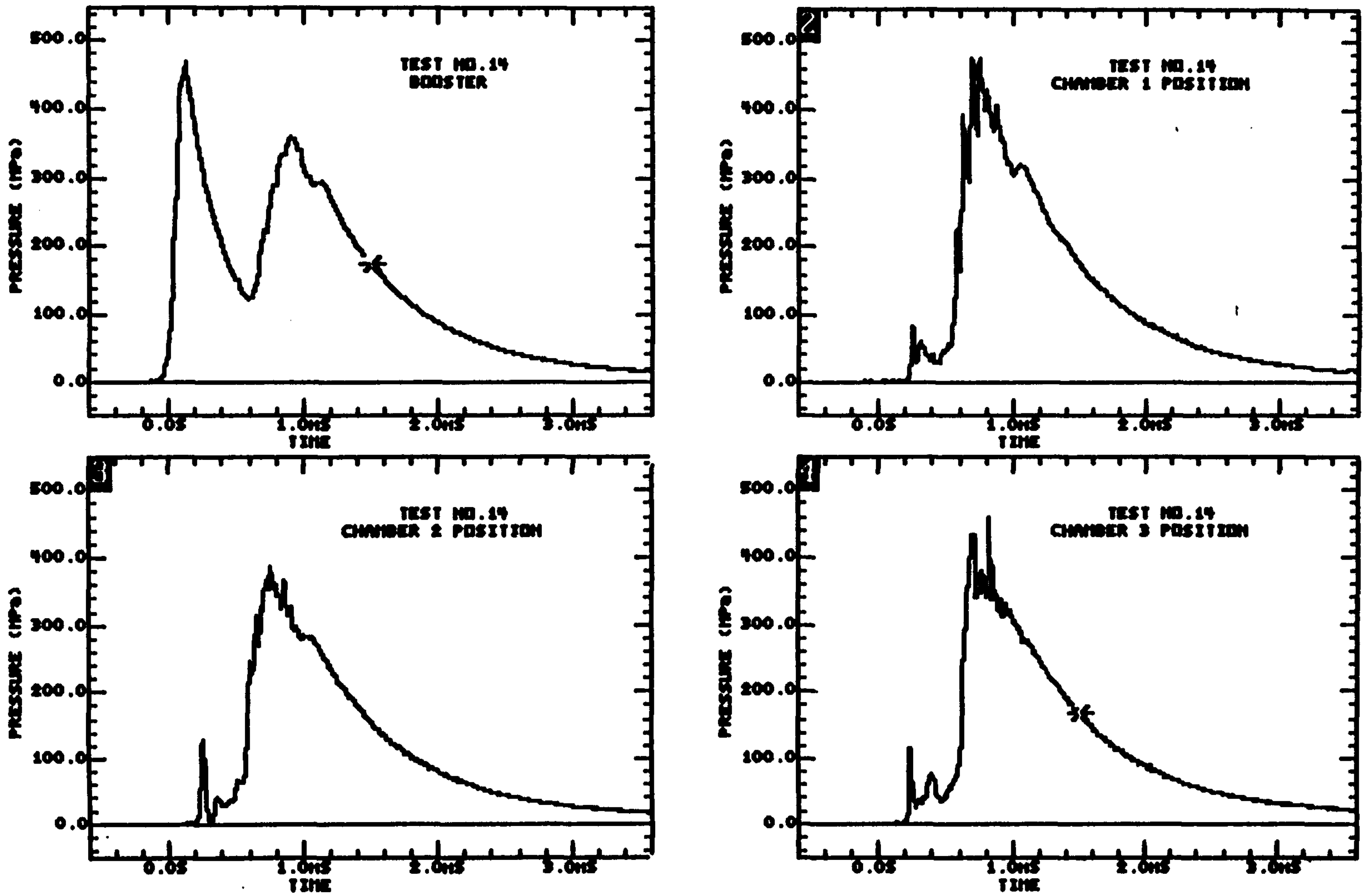

Figure A-13. Booster and chamber pressure-time traces for Test No. 14 with chamber insert Type I.

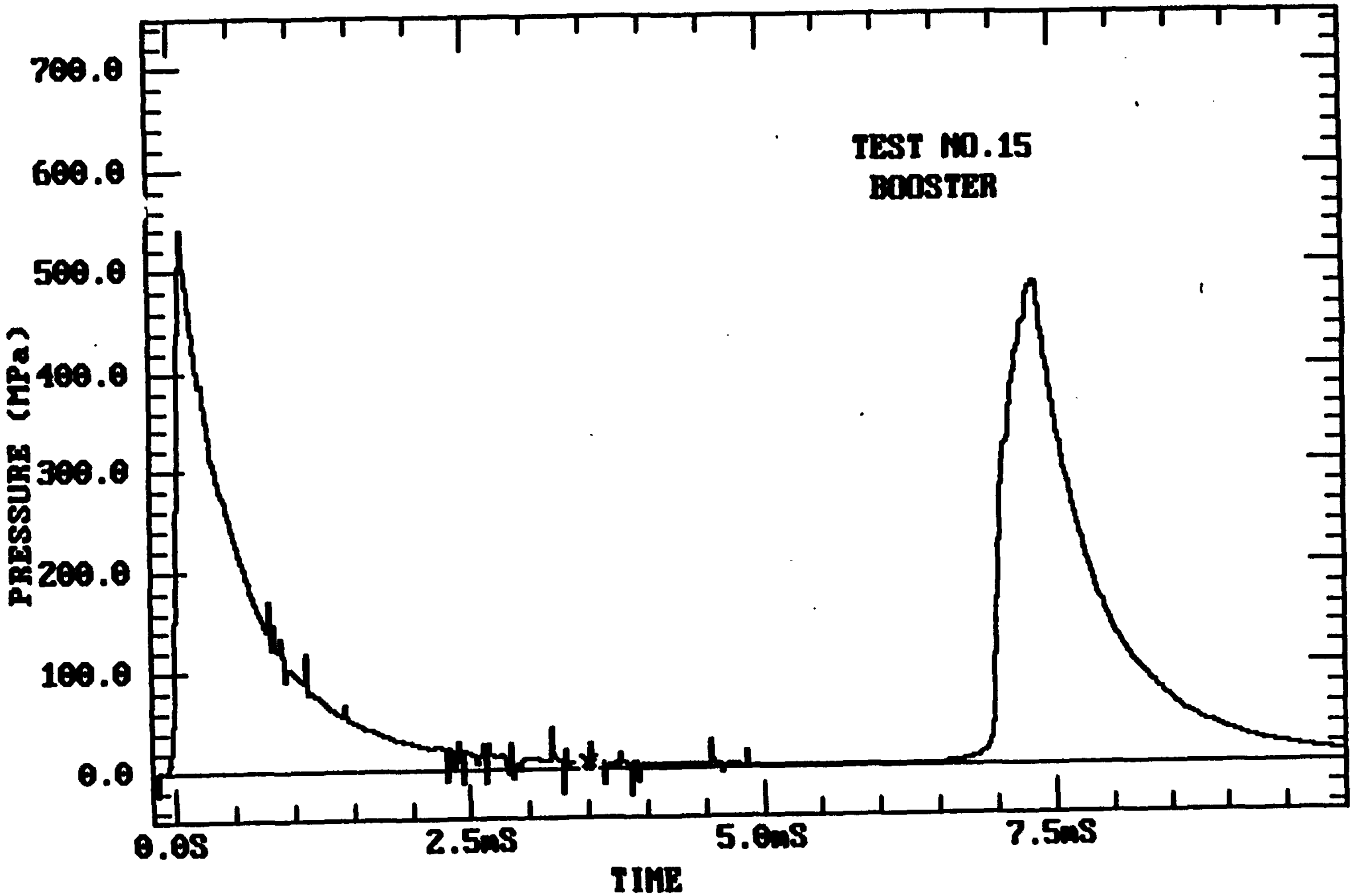

Figure A-14. Booster pressure-time trace for Test No. 15 with chamber insert Type I.

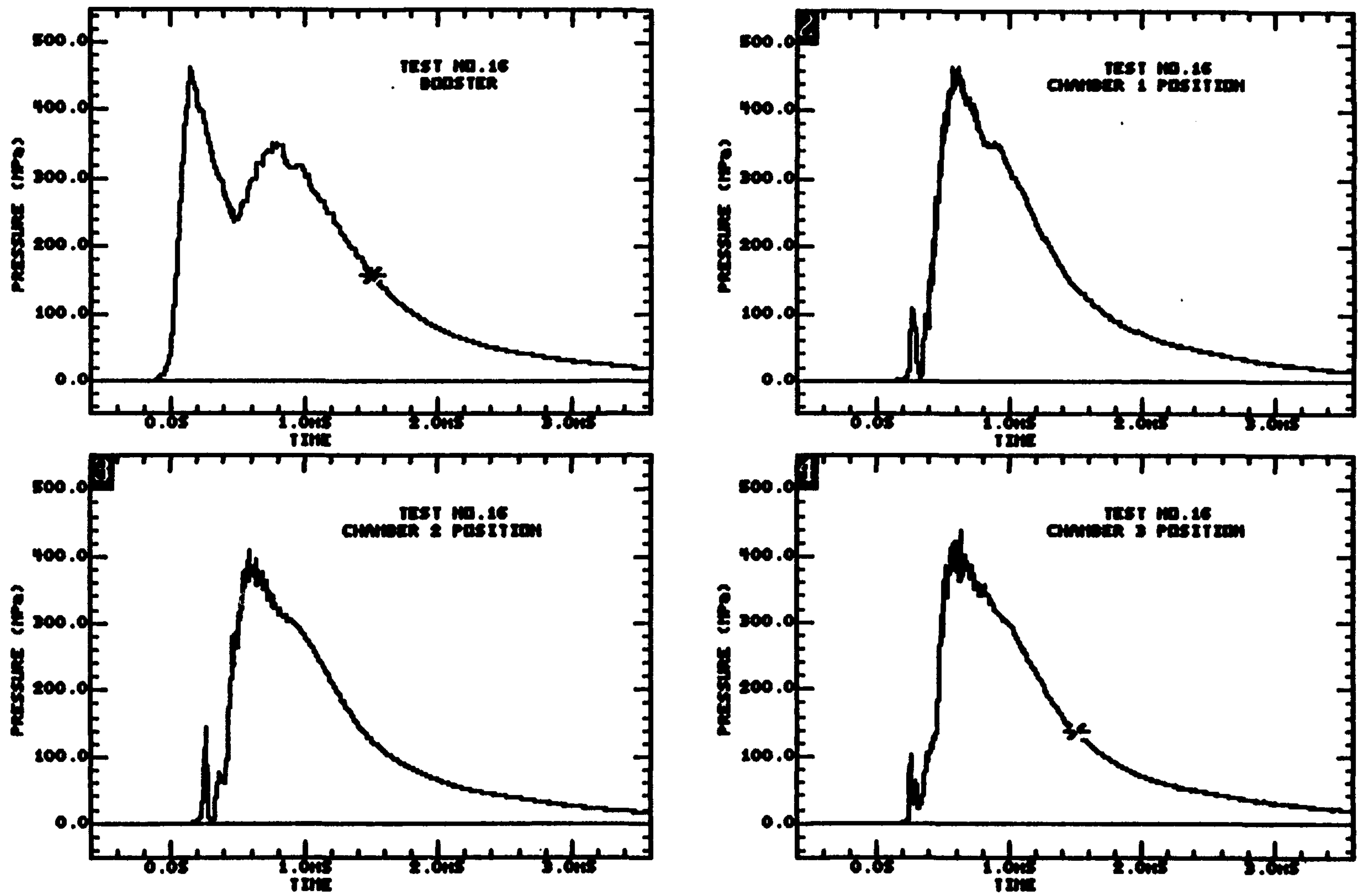

Figure A-15. Booster and chamber pressure-time traces for Test No. 16 with chamber insert Type I.

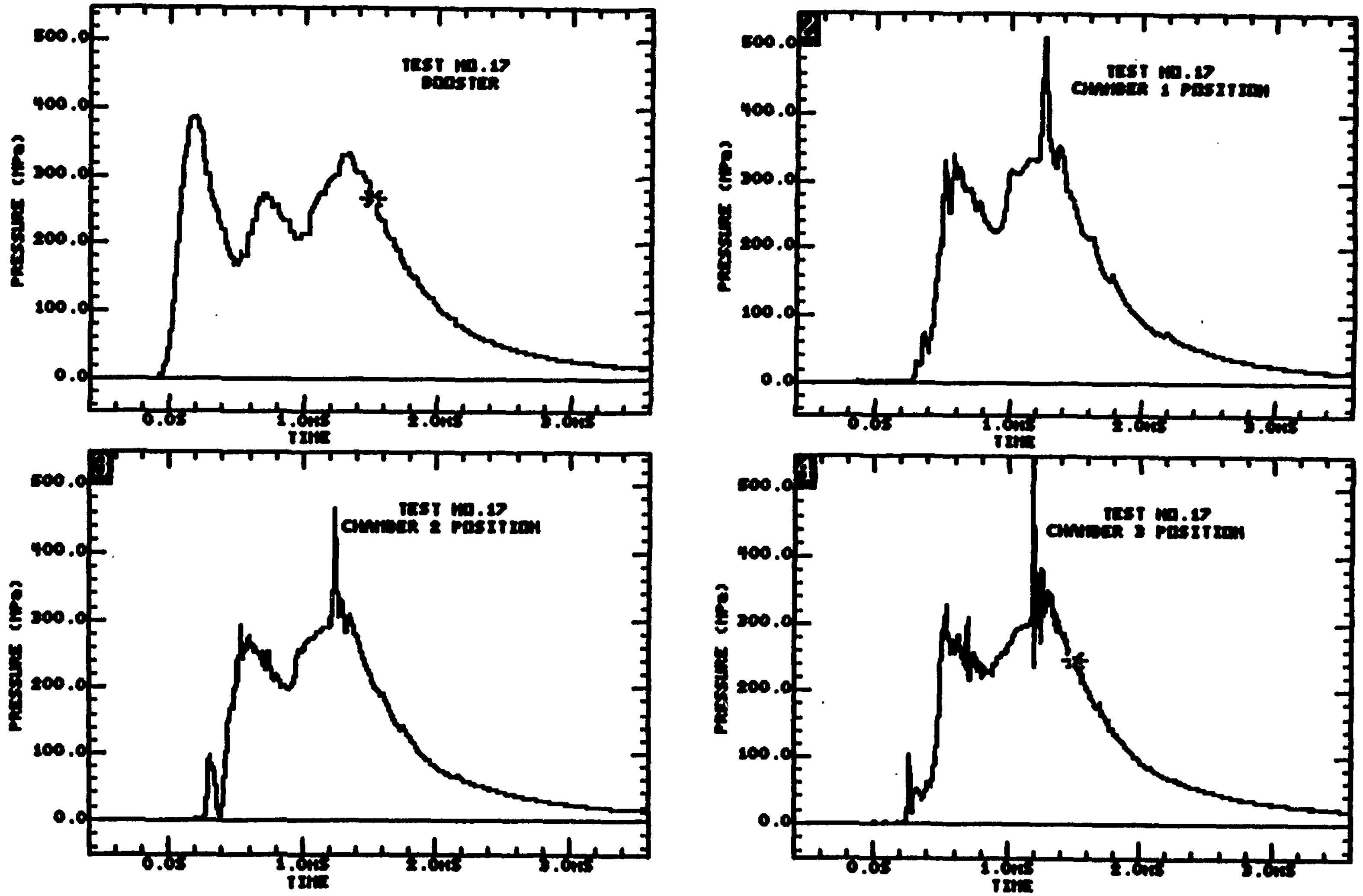

Figure A-16. Booster and chamber pressure-time traces for Test No. 17 with chamber insert type 6.35 Multi P.

No. of Copies	Organization
2	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	Commander U.S. Army Materiel Command ATTN: AMCAM 5001 Eisenhower Ave. Alexandria, VA 22333-0001
1	Director U.S. Army Research Laboratory ATTN: AMSRL-OP-CI-AD, Tech Publishing 2800 Powder Mill Rd. Adelphi, MD 20783-1145
1	Director U.S. Army Research Laboratory ATTN: AMSRL-OP-CI-AD, Records Management 2800 Powder Mill Rd. Adelphi, MD 20783-1145
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000
1	Director Benet Weapons Laboratory U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050
1	Director U.S. Army Advanced Systems Research and Analysis Office (ATCOM) ATTN: AMSAT-R-NR, M/S 219-1 Ames Research Center Moffett Field, CA 94035-1000
1	Commander U.S. Army Missile Command ATTN: AMSMI-RD-CS-R (DOC) Redstone Arsenal, AL 35898-5010
1	Commander U.S. Army Tank-Automotive Command ATTN: AMSTA-JSK (Armor Eng. Br.) Warren, MI 48397-5000
1	Director U.S. Army TRADOC Analysis Command ATTN: ATRC-WSR White Sands Missile Range, NM 88002-5502
(Class. only) 1	Commandant U.S. Army Infantry School ATTN: ATSH-CD (Security Mgr.) Fort Benning, GA 31905-5660
(Unclass. only) 1	Commandant U.S. Army Infantry School ATTN: ATSH-WCB-O Fort Benning, GA 31905-5000
1	WL/MNOI Eglin AFB, FL 32542-5000

<u>Aberdeen Proving Ground</u>

No. of Copies	Organization
2	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
·	Cdr, USATECOM ATTN: AMSTE-TC
1	Dir, USAERDEC ATTN: SCBRD-RT
1	Cdr, USACBDCOM ATTN: AMSCB-CII
1	Dir, USARL ATTN: AMSRL-SL-I
5	Dir, USARL ATTN: AMSRL-OP-AP-L

No. of Copies	Organization
1	Chairman DOD Explosive Safety Board Room 856-C Hoffman Bldg. 1 2461 Eisenhower Ave. Alexandria, VA 22331-0600
1	Director HQ, TRAC RPD ATTN: ATCD-MA, MAJ Williams Fort Monroe, VA 23651-5143
10	Central Intelligence Agency Office of Central Reference Dissemination Branch Room GE-47 HQS Washington, DC 20502
1	Central Intelligence Agency ATTN: Joseph E. Backofen HQ Room 5F22 Washington, DC 20505
1	OSD/SDIO/IST ATTN: Dr. Len Caveny Pentagon Washington, DC 20301-7100
1	Director U.S. Army BMD Advanced Technology Center P.O. Box 1500 Huntsville, AL 35807
1	Department of the Army Office of the Product Manager 155-mm Howitzer, M109A6, Paladin ATTN: SFAE-AR-HIP-IP, Mr. R. De Kleine Picatinny Arsenal, NJ 07806-5000
2	Deputy Commander USASDC ATTN: SFAE-SD-HVL, Mr. Stanley Smith Mr. Stuart Fowler P.O. Box 1500, Wynn Dr. Huntsville, AL 35887-3801
1	Commander U.S. Army TRAC - Fort Lee Defense Logistics Studies Fort Lee, VA 23801-6140
1	Commander Production Base Modernization Agency U.S. Army Armament Research, Development, and Engineering Center ATTN: AMSMC-PMB-E, L. Laibson Picatinny Arsenal, NJ 07806-5000
1	PEO-Armaments Project Manager Tank Main Armament Systems ATTN: AMCPM-TMA Picatinny Arsenal, NJ 07806-5000
1	PEO-Armaments Project Manager Tank Main Armament Systems ATTN: AMCPM-TMA-105 Picatinny Arsenal, NJ 07806-5000
1	PEO-Armaments Project Manager Tank Main Armament Systems ATTN: AMCPM-TMA-120 Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-FSS-DA, R. Kopmann Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-FSS-H, B. Machak Picatinny Arsenal, NJ 07806-5000
3	Project Manager Advanced Field Artillery System ATTN: SFAE-ASM-AF, T. Kuriata J. Shields LTC A. Ellis Picatinny Arsenal, NJ 07806-5000

No. of Copies	Organization
3	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-AEE, A. Bracuti D. Chiu J. Salo Picatinny Arsenal, NJ 07806-5000
5	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-AEE-B, A. Beardell D. Downs B. Brodman S. Einstein J. Rutkowski Picatinny Arsenal, NJ 07806-5000
4	Commander U.S. Army Watervliet Arsenal ATTN: SARWV-RD, R. Thierry L. Johnson G. Cerafano P. Votis Watervliet, NY 12189
3	Commander U.S. Army AMCCOM ATTN: AMSMC-IRC, G. Cowan SMCAR-ESM(R), W. Fortune R. Zastrow Rock Island, IL 61299-7300
1	Commander, USACECOM R&D Technical Library ATTN: ASQNC-ELC-IS-L-R, Myer Center Fort Monmouth, NJ 07703-5301
1	Commandant U.S. Army Aviation School ATTN: Aviation Agency Fort Rucker, AL 36360

No. of Copies	Organization
1	Headquarters U.S. Army Materiel Command ATTN: AMCICP-AD, Michael F. Fisette 5001 Eisenhower Ave. Alexandria, VA 22333-0001
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCD, D. Spring Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCS Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCH-T, L. Rosendorf Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCH-V, E. Fennell Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Materials Technology Laboratory Dyna East Corporation ATTN: Christine P. Brandt, Document Control 3132 Market St. Philadelphia, PA 19104-2855
1	Commander U.S. Army Belvoir R&D Center ATTN: STRBE-WC, Technical Library (Vault) Bldg. 315 Fort Belvoir, VA 22060-5606
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-FSA-T, M. Salsbury Picatinny Arsenal, NJ 07806-5000

No. of Copies	Organization
10	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-FSE, G. Ferdinand T. Gora B. Knutelsky K. C. Pan J. Niles W. Davis C. Durham H. Nabor-Libby A. Graff R. Lundberg Picatinny Arsenal, NJ 07806-5000
1	President U.S. Army Artillery Board Fort Sill, OK 73503
1	Commandant U.S. Army Special Warfare School ATTN: Rev and Tng Lit Div Fort Bragg, NC 28307
1	Commandant U.S. Army Command and General Staff College Fort Leavenworth, KS 66027-5200
1	Commandant U.S. Army Foreign Science and Technology Center ATTN: AMXST-MC-3, S. LeBean C. Beiter 220 Seventh St., NE Charlottesville, VA 22901
1	Commandant U.S. Army Field Artillery Center and School ATTN: ATSF-CO-MW, B. Willis Fort Sill, OK 73503
1	Commandant U.S. Army Field Artillery School ATTN: STSF-TSM-CN Fort Sill, OK 73503-5600

No. of Copies	Organization
1	Office of Naval Research ATTN: Code 473, R. S. Miller 800 North Quincy St. Arlington, VA 22217
3	Commander Naval Sea Systems Command ATTN: SEA 62R SEA 64 SEA 06 KR12, C. Dampier Washington, DC 20362-5101
1	Commander Naval Air Systems Command ATTN: AIR-954-Technical Library Washington, DC 20360
1	Commander Radford Army Ammunition Plant ATTN: SMCRA-QA/HI Library Radford, VA 24141
2	Commander Naval Surface Warfare Center ATTN: J. P. Consaga C. Gotzmer Silver Spring, MD 20902-5000
2	Commander Naval Surface Warfare Center ATTN: K. Kim/Code R-13 R. Bernecker/Code R-13 Silver Spring, MD 20902-5000
1	Commander Naval Underwater Systems Center Energy Conversion Department ATTN: Tech Library Newport, RI 02840
6	Commander Naval Surface Warfare Center ATTN: Code G33, T. Doran J. Copley Code G30, Guns and Munitions Division Code G301, D. Wilson Code G32, Gun Systems Division Code E23, Technical Library Dahlgren, VA 22448-5000

No. of Copies	Organization
1	Commander Naval Weapons Center ATTN: Code 388, C. F. Price Info Science Div China Lake, CA 93555-6001
1	OLAC PL/TSTL ATTN: D. Shiplett Edwards AFB, CA 93523-5000
1	WL/MNSH ATTN: Mr. Donald M. Littrell Eglin AFB, FL 32542-5434
1	Commander U.S. Army Research Office ATTN: Technical Library P.O. Box 12211 Research Triangle Park, NC 27709-2211
1	Naval Research Laboratory Technical Library Washington, DC 20375
1	Commander Naval Surface Warfare Center ATTN: Dr. P. Collins Code R44 10901 N. Hampshire Ave. Silver Spring/White Oak, MD 20902-5000
3	Commander Naval Surface Warfare Center Indian Head Division ATTN: 610, C. Smith 6110J, K. Rice 6110C, S. Peters Indian Head, MD 20640-5035
3	Director Sandia National Laboratories ATTN: S. Vosen D. Sweeney R. Armstrong Division 8357 Livermore, CA 94551-0969

No. of Copies	Organization
5	Director Sandia National Laboratories ATTN: T. Hitchcock S. Kempka R. Beasley D. A. Benson R. Woodfin Advanced Projects Div 14 Organization 9123 Albuquerque, NM 87185-5800
3	Director Los Alamos National Laboratory PLMSE526 ATTN: B. Kaswhia R. J. Trainor H. Davis Los Alamos, NM 87545
1	Director Lawrence Livermore National Laboratory ATTN: M. S. L-355, A. Buckingham P.O. Box 808 Livermore, CA 94550
2	Princeton Combustion Research Laboratory ATTN: M. Summerfield N. Messina Princeton Corporate Plaza 11 Deerpark Dr. Bldg. IV, Suite 119 Monmouth Junction, NJ 08852
1	Director Los Alamos National Laboratory ATTN: R. Richard Bartsch Mail Stop E526 (Group P-1) Los Alamos, NM 87545
2	California Institute of Technology Jet Propulsion Laboratory ATTN: L. D. Strand, MS 125-224 4800 Oak Grove Dr. Pasadena, CA 91109
1	University of Texas at Austin Balcones Research Center ATTN: J. H. Gully Austin, TX 78758-4497

No. of Copies	Organization
1	University of Illinois Department of Mechanical/Industrial Engineering ATTN: Professor Herman Krier 144 MEB; 1206 N. Green St. Urbana, IL 61801
1	Johns Hopkins University/CPIA ATTN: T. Christian 10630 Little Patuxent Parkway, Suite 202 Columbia, MD 21044-3200
1	Pennsylvania State University Department of Mechanical Engineering ATTN: Dr. K. Kuo 312 Mechanical Engineering Bldg. University Park, PA 16802
1	North Carolina State University ATTN: John G. Gilligan Box 7909 1110 Burlington Engineering Labs Raleigh, NC 27695-7909
1	University of Tennessee Space Institute Center For Laser Applications, MS-14 ATTN: Dr. Dennis Keefer Tullahoma, TN 37388-8897
1	State University of New York at Buffalo Department of Electrical Engineering ATTN: Dr. W. J. Sarjeant 312 Bonner ECE-SUNY/AB Buffalo, NY 14260
5	Veritay Technology, Inc. 4845 Millersport Hwy. P.O. Box 305 East Amhearst, NY 14051-0305
1	Battelle TWSTIAC 505 King Ave. Columbus, OH 43201-2693
2	Martin Marietta Defense Systems Division ATTN: Dr. J. Mandzy D. Cook 100 Plastics Ave. Pittsfield, MA 01201

No. of Copies	Organization
1	Science Applications International ATTN: K. Jamison 1247B North Eglin Parkway Shalimar, FL 32579
1	SPARTA ATTN: Dr. Michael Holland 9455 Towne Center Dr. San Diego, CA 92121-1964
2	FMC Corporation ATTN: G. Johnson A. Giovanetti 1300 South Second St. P.O. Box 59043 Minneapolis, MN 55459-0043
3	GT Devices ATTN: Dr. S. Goldstein Dr. R. J. Grieg N. Winsor 5705A General Washington Dr. Alexandria, VA 22312
5	General Dynamics Land Systems ATTN: Dr. B. VanDeusen Mr. F. Lundsford M. Widner D. Toepler R. Boggavarapir P.O. Box 2074 Warren, MI 48090-2074
2	Alliant Techsystems, Inc. ATTN: R. E. Tompkins J. Kennedy MN38-3300 10400 Yellow Circle Dr. Minneapolis, MN 55343
1	Paul Gough Associates, Inc. ATTN: P. S. Gough 1048 South St. Portsmouth, NH 03801-5423
1	Physics International Library ATTN: H. Wayne Wampler P.O. Box 5010 San Leandro, CA 94577-0599

No. of Copies	Organization
2	Science Applications, International Corp. ATTN: J. Batteh L. Thornhill 1519 Johnson Ferry Rd. Suite 300 Marietta, GA 30062-6438
2	Olin Ordnance ATTN: V. McDonald, Library H. McElroy P.O. Box 222 St. Marks, FL 32353
1	Eli Freedman Associates ATTN: E. Freedman 2411 Diana Rd. Baltimore, MD 21209
2	Science Applications, Inc. ATTN: R. Richardson M. Haworth 2109 Air Park Rd., SE Albuquerque, NM 87106
2	Science Applications International Corp. ATTN: S. Dash 501 Office Center Dr. Suite 420 Fort Washington, PA 19034-3211
1	Rocket Research Commpany/OLIN ATTN: Dr. David Q. King P.O. Box 97009 Redmond, WA 98073

No. of Copies	Organization
	Aberdeen Proving Ground
31	Dir, USARL ATTN: AMSRL-WT-T, W. F. Morrison AMSRL-WT-WG, L. J. Puckett AMSRL-WT-P, I. May J. Dante AMSRL-WT-PA, T. Minor A. Birk T. Coffee J. DeSpirito (5 cp) A. Juhasz J. Knapton C. Leveritt M. McQuaid K. Nekula W. Oberle P. Reeves I. Stobie K. White G. Wren AMSRL-WT-PB, E. Schmidt AMSRL-WT-PC, R. Fifer R. Beyer B. Forch AMSRL-WT-PD, B. Burns AMSRL-WT-PE, A. Horst J. Colburn R. Lieb T. Rosenberger