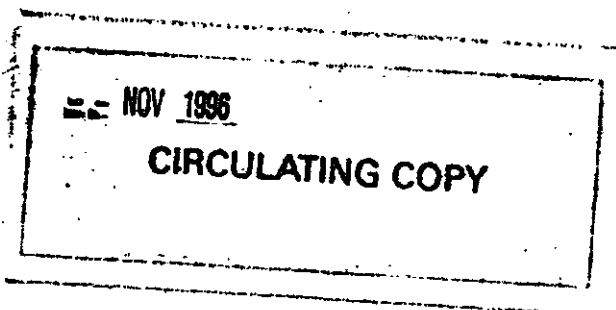


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TECHNICAL REPORT BRL-TR-2709

**AIR COMPRESSION HEATING
IGNITION OF HIGH EXPLOSIVES
IN THE LAUNCH ENVIRONMENT**

**John Starkenberg
Lewis H. Ervin
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February 1986

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Compressive heating ignition has been the subject of extensive analytical and experimental study at the Ballistic Research Laboratory. The experimental investigation was conducted using an apparatus referred to as the activator, originally designed at Picatinny Arsenal as a laboratory-scale artillery setback simulator. Several explosives have now been tested. These are TNT, composition-B (comp-B), composition A3 (comp-A3) type II, R8151 (German formulation for the 120 mm round), LX-14, and EARK-25 (an experimental		

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intermolecular explosive). Pressurization rate and cavity size are the principal parameters governing compressive heating ignition. Although ignition may be inhibited by limiting the peak pressure, this did not appear to occur in the activator. Studies of precompression of both cut and polished and as cast surfaces indicated that the state of the explosive surface grossly affects sensitivity to this ignition mechanism. Sensitivity is greater for surfaces which have been precompressed. Geometries which generate convergent airflow yield ignition with milder stimuli than are required with planar geometries. TNT was found to be more sensitive than comp-B when both were precompressed. Comparison of unprecompressed explosives using bubble test showed that TNT was less sensitive than comp-B and indicated that precompression more effectively seals TNT surfaces. The slow burning of TNT allowed quenching of reaction in the activator and recovered samples showed evidence of burning along fissures. The effect of surface state was further examined using LX-14 pressed to a range of densities. The results clearly showed that sensitivity to compressive heating ignition increases with density in contrast to other mechanisms. Comparison of results for a number of different explosives shows that pre-compression affects sensitivity much more than explosive thermochemistry.

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I. INTRODUCTION

When a small volume of gas is compressed very rapidly such that no energy transport can occur, a high temperature reservoir (hot spot) is created which may subsequently heat an adjacent explosive layer to the point of ignition. This process is referred to as ignition by adiabatic compression of the gas. If, on the other hand, the gas is compressed very slowly, no temperature increase occurs and no explosive ignition can follow. Between these limits lies the compressive heating regime in which the compression occurs sufficiently slowly that considerable energy is transported by conduction and convection during the process. The ignitions observed, for example, by Bowden and co-workers¹ in liquid and solid explosives in the ten to one hundred microsecond time range properly belong to this latter category. For adiabatic compression in the shock wave regime, the heating due to gas compression does not appear to influence sensitivity since other heating mechanisms are dominant.²⁻⁴ Compressive heating has, therefore, received attention primarily as a source of ignition which is active when the observed time to ignition is in the ten microsecond to ten millisecond range. This time scale is typical of the setback of the explosive fill in an artillery projectile during launch and compressive heating has been investigated as a possible cause of in-bore premature explosions.

Compressive heating ignition has been the subject of extensive analytical and experimental study at the Ballistic Research Laboratory (BRL).⁵⁻⁷ The experimental investigation was conducted using an apparatus referred to as the activator, which was originally designed at Picatinny Arsenal, PA, as a laboratory-scale artillery setback simulator.⁸ This was used in its original form in preliminary experiments to produce data which revealed the role of air in causing ignitions during compression.⁶ Subsequently, the activator was modified and further instrumented so that more definitive data could be extracted from the tests and direct comparisons to the predictions obtained from analytical models could be made.⁷ Several explosives have now been tested. These are TNT, composition-B (comp-B), composition A3 (comp-A3) type II, R8151 (German formulation for the 120 mm round), LX-14, and EARK-25 (an experimental intermolecular explosive).

II. THE ROLE OF LABORATORY SCALE EXPERIMENTS

The relationship of laboratory scale experiments and large scale "simulation" (such as with the NSWC simulator⁹⁻¹¹) to gun firings is a difficult issue. The appropriate role of laboratory experiments is not the simulation of the artillery launch environment, but rather the study of ignition mechanisms under pressures representative of setback. The experiments reported herein were conducted in this spirit. Therefore, the activator experimental procedure is not (as it has been called) "an increased severity test". Rather, it is an isolated stimulus experiment which is designed to determine the level of compressive heating or other stimulus required to ignite an explosive as a function of various parameters. If an artillery premature occurred due to compressive heating ignition, we would

conclude that the explosive was locally subjected to the same stimulus level determined in our experiments. In general, this means that the explosive must be subject to the same heating rate. In the case of compressive heating, the heating rate is roughly proportional to the product of the pressurization rate and the cavity depth. In the case of frictional or shear heating, the heating rate is roughly proportional to the product of the pressure and the shear velocity. In both cases many other factors are also important. Pressurization rates and peak pressures measured external to projectile bases appear insufficient to produce the required stimulus. The maximum sliding velocity produced by projectile rotation is somewhat below that required for ignition observed in activator experiments isolating frictional heating.¹² This means that, in order to produce a premature, the stimulus levels applied to the explosive must be amplified over and above those present external to the projectile during launch. This may occur in a number of ways. In the case of compressive heating, it is necessary to amplify the pressurization rate. This can occur if a loose charge impacts the base or if a cavity fails to collapse during the early portion of pressurization and then collapses catastrophically when a critical pressure has been reached. In addition, as a cavity collapses, shear heating may combine with compressive heating to produce ignition. Alternatively, J. Herskowitz¹³ has suggested that prematures are rare because they require two or more low probability conditions to exist simultaneously. For example, a sufficiently large cavity must be coupled with an abnormally severe launch environment. The relationship between the local heating rate experienced by an explosive fill and the pressure stimulus external to the projectile is complicated and has not been established. We have not pursued this avenue. Our approach has been to determine the parameters which govern ignition by the most likely mechanisms in order to provide guidance for the design of more premature-resistant projectile systems.

III. DESCRIPTION OF THE EXPERIMENTS

A. The Activator

The activator, as presently used, is illustrated schematically in Figure 1. The test section consists of a mild steel heavy confinement cylinder enclosing the explosive sample and a hardened steel driving piston. A hardened steel gage block on which a manganin foil pressure gage is mounted is tightly bolted to the back of the confinement cylinder and the explosive sample is inserted into the bore adjacent to the gage. A gap or cavity of some type is left adjacent to the sample. The gage block rests against a rigid stop which incorporates an adjustment screw to accommodate test fixtures of different lengths and to allow easy installation. The driving piston is activated by a larger piston which is initially held in place in the breech using shear pins. The breech is instrumented with a pressure transducer. The free run allowed between the large piston and the driving piston is used to set the stimulus level to be applied.

In order to fire a shot, the breech is pressurized using compressed air until the shear pins fail. The large piston accelerates through the free run and impacts the driving piston. The momentum developed by the pistons is transformed to an impulse delivered to the cavity and explosive sample. The

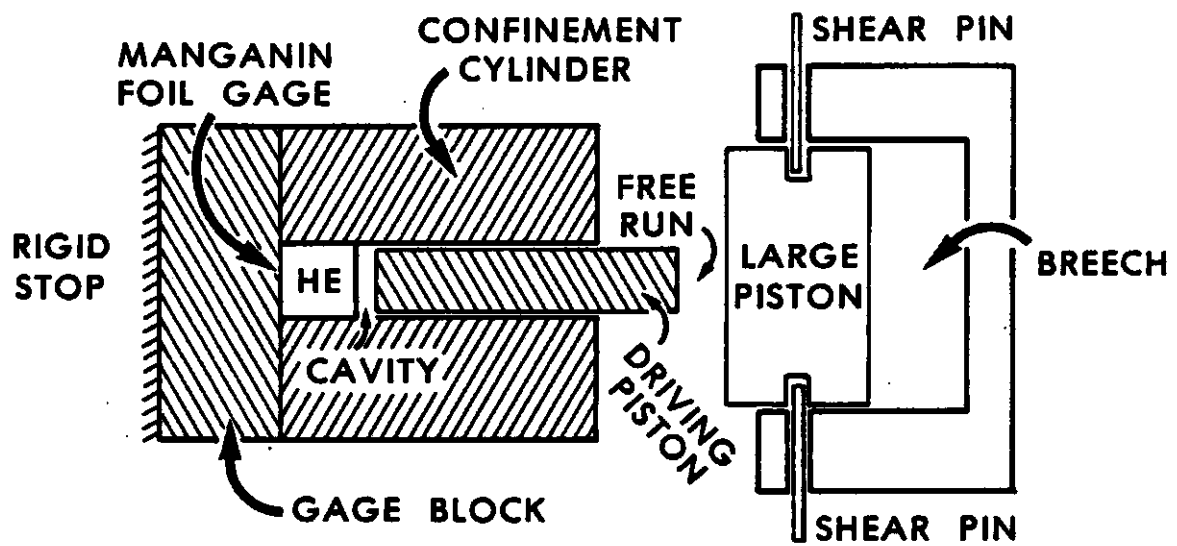


Figure 1. Activator Schematic

pistons may then rebound and strike the explosive again delivering a second impulse.

A disadvantage of this test configuration is that extrusion of explosive between the gage block and the confinement cylinder may occur. Ignitions caused by extrusion may be readily identifiable as late events on the pressure records. We determined that free runs in excess of 25 mm are required to produce extrusion ignitions. This free run, therefore, represents a practical upper limit of activator operation. However, this limit was sometimes violated since it is possible to distinguish extrusion ignitions.

B. Sample Preparation

The comp-B, TNT and EARK-25 samples were prepared by casting short 12.7 mm diameter cylinders with one end against a polished plate. These were then finished to size by cutting and polishing at the opposite end. Examples of the cast comp-B samples are shown in Figure 2. The comp-A3 type II and R8151 samples were prepared outside of BRL and the exact method of their preparation is unknown. The LX-14 samples were prepared by pressing to various densities in an appropriately shaped mold. The densities of all samples were determined and all samples were inspected radiographically. Any sample appearing to have voids was rejected.

C. Test Procedures

The early experiments showed that, in order to enhance repeatability, elimination of air leakage during testing was necessary. Two approaches were devised to provide leakage elimination.

In the first of these, the planar gap test, illustrated in Figure 3a, the explosive must be precompressed in the test fixture in order to prevent leakage past the sample and a shrink-fitted polyethylene buffer is used to prevent leakage past the piston. Precompression is accomplished by placing the driving piston in contact with the explosive and the large piston and pressurizing the breech without shear pins. This effectively seals any clearance between the sample and the confinement. The oversized polyethylene buffer, 6.35 mm thick, is cooled to liquid nitrogen temperature and inserted into the bore in order to establish the desired gap. Upon returning to ambient temperature, it provides a tight seal.

The second approach, the bubble test, illustrated in Figure 3b, does not require precompressed samples and makes use of self-sealing gaps. A hemispherical cavity (bubble) is cast into one end of a soft plastic (Dow-Corning Sylgard 182) cylinder as shown in Figure 2. This is inserted into the bore hole with the end containing the cavity directly against the sample. Since the soft plastic behaves like a liquid, the cavity collapses more or less uniformly towards its center upon application of pressure, thus introducing strong convergence effects.

D. Pressure Measurement

The pressure measured by the manganin gage behind the sample differs from that at the gap because of friction between the explosive and the confinement cylinder. Since the air pressure history is of greater interest, a series of

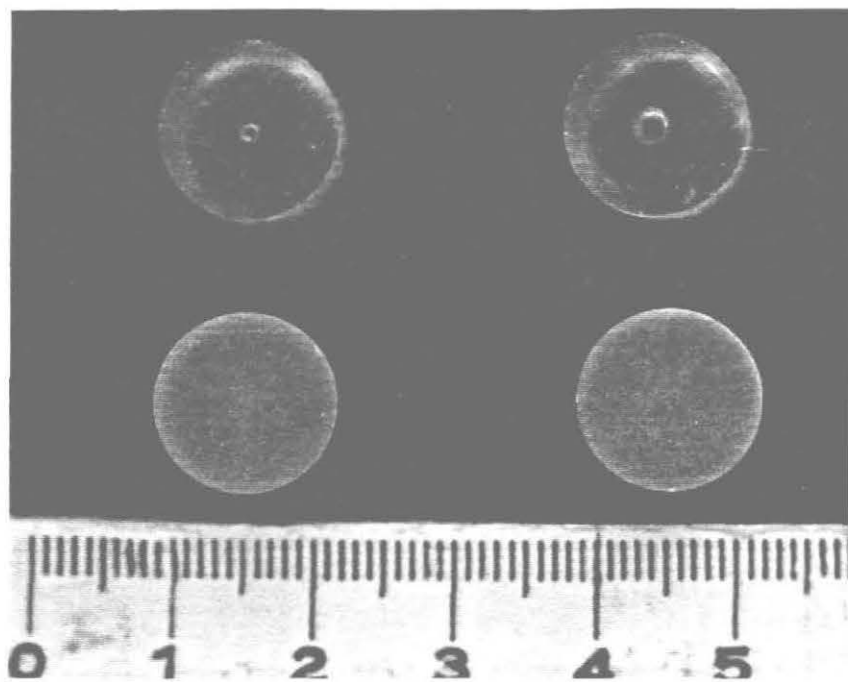


Figure 2. Cast Composition-B Samples and Sylgard Bubbles.

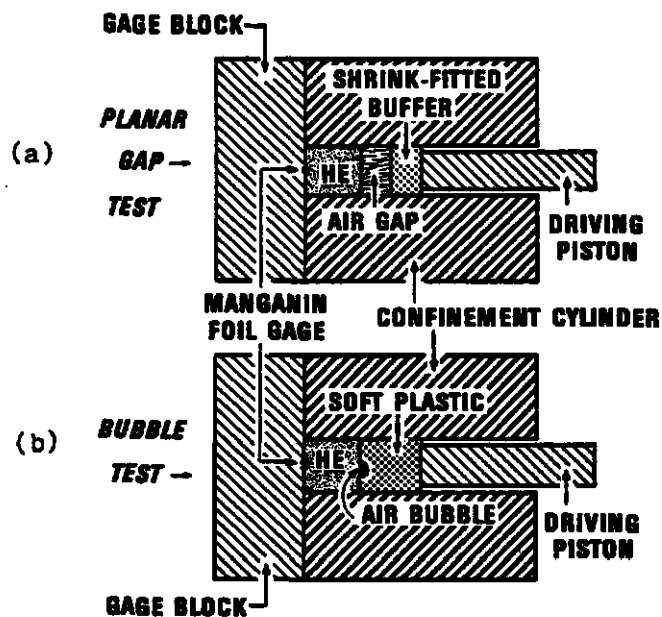


Figure 3. Planar Gap and Bubble Test Configurations.

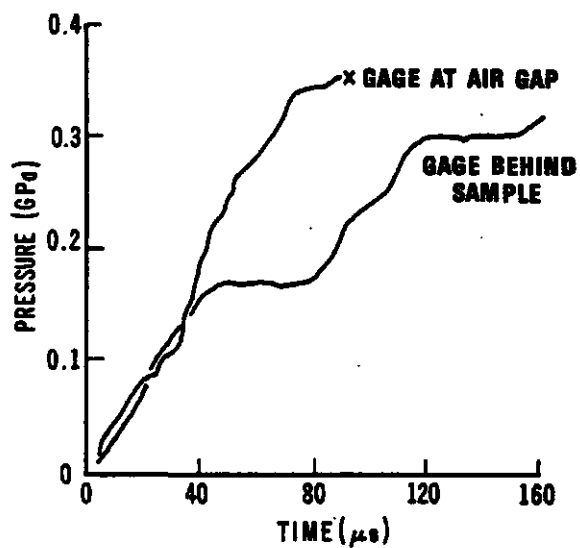


Figure 4. Comparison of Pressure Records from Opposite Ends of Sample.

tests with manganin gages at both ends of the sample was conducted. The results were used to determine how best to interpret records from the back gage. Both TNT and comp-B were tested in this manner. The results were fairly consistent and typical pressure records are shown in Figure 4. The pressure at the air gap end of the explosive rises at an approximately constant rate until the gage breaks. The pressure at the base of the sample initially rises at the same rate and then levels off as the additional load is assumed by a growing frictional force. When the frictional force has reached its maximum, as governed by the shear strength of the explosive, the back pressure begins to rise at the initial rate again. The pressure measured at the back gage may rise in a series of steps. The pressurization rate exhibited between the plateaus has been interpreted to be the same as the pressurization rate of the air in all of the instrumented tests. Typical go and no go pressure records are shown in Figure 5.

The breech pressure is also measured and recorded as illustrated in Figure 6. This shows the pressure to drop more or less linearly with time as the large piston moves forward. An average value is extracted from the measurements as the shear pin failure pressure. This may be used in conjunction with free run to estimate the momentum of the large piston when it impacts the driving piston.

E. Stimulus Characterization

The relation of activator settings (free run and shear pin failure pressure) to the pressure record is a matter of some interest. A knowledge of this dependence would allow judicious selection of test settings. The term setting is used rather loosely here since the free run is controlled quite closely while the shear pins failure pressure is not. Different results are anticipated from the planar gap and bubble tests since the shrink-fitting of the polyethylene buffer used in the planar gap test introduces a variable shear resistance to gap closure. Peak pressure and pressurization rate are plotted versus free run and impact momentum in Figure 7 for the planar gap test on precompressed comp-B. Similar plots for the bubble test on unprecompressed comp-B are shown in Figure 8. In general, peak pressure is only available for nonignitions. As expected, the correlations are much better for the bubble test. The results for the planar gap test are poor but show a slight improvement when impact momentum is used.

IV. RESULTS WITH CAST TNT AND COMP-B

A. Role of Peak Pressure

In these tests, three parameters potentially govern ignition. These are the pressurization rate, the peak pressure (or time of pressurization) and the gap thickness or bubble radius. The analysis⁸ indicates that for a fixed gap size the occurrence of ignition depends on pressurization rate when no peak pressure is specified. Ignitions which otherwise would occur may be inhibited by limiting the peak pressure. Experiments were conducted to determine whether ignition in the activator depends on peak pressure. Different pressurization rates and peak pressures corresponding to the same impulse were

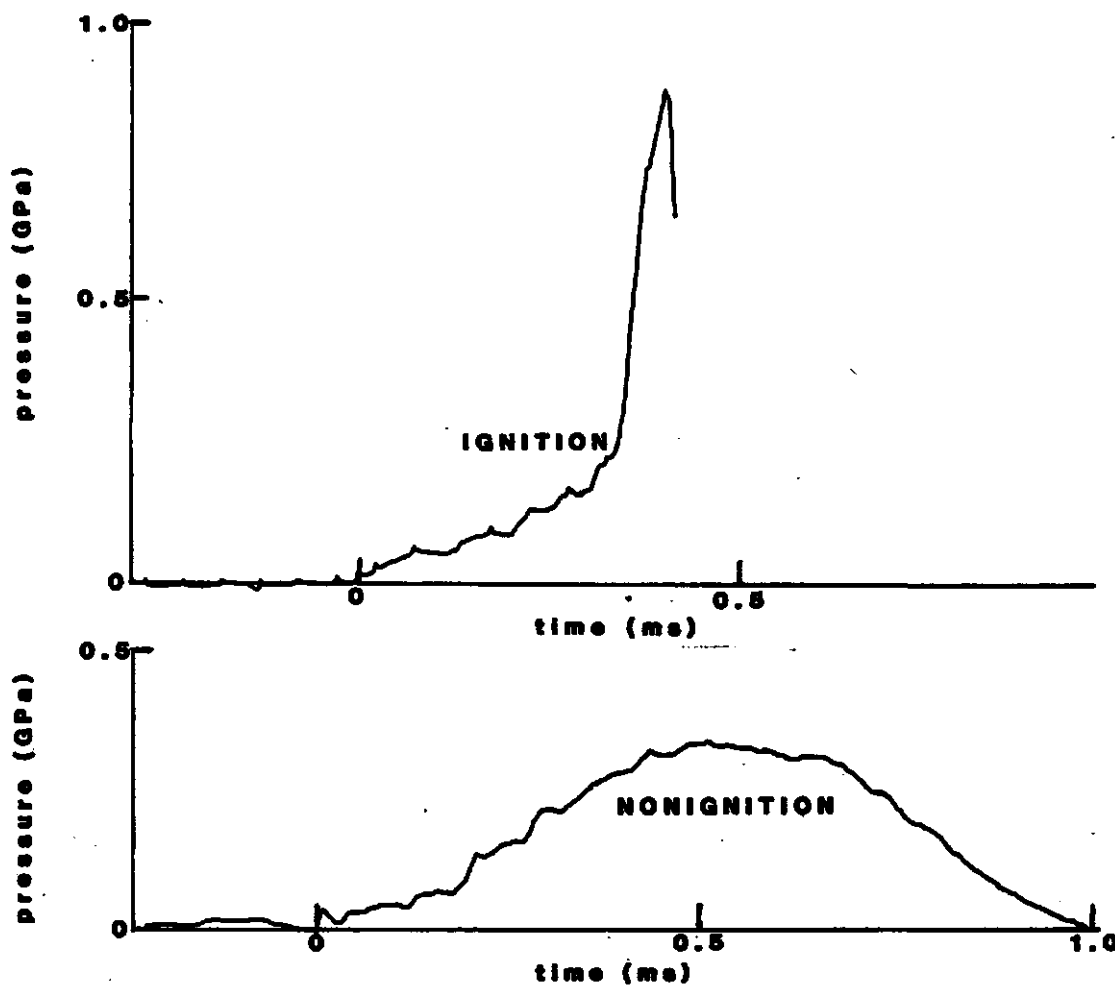


Figure 5. Typical Manganin Gage Pressure Records.

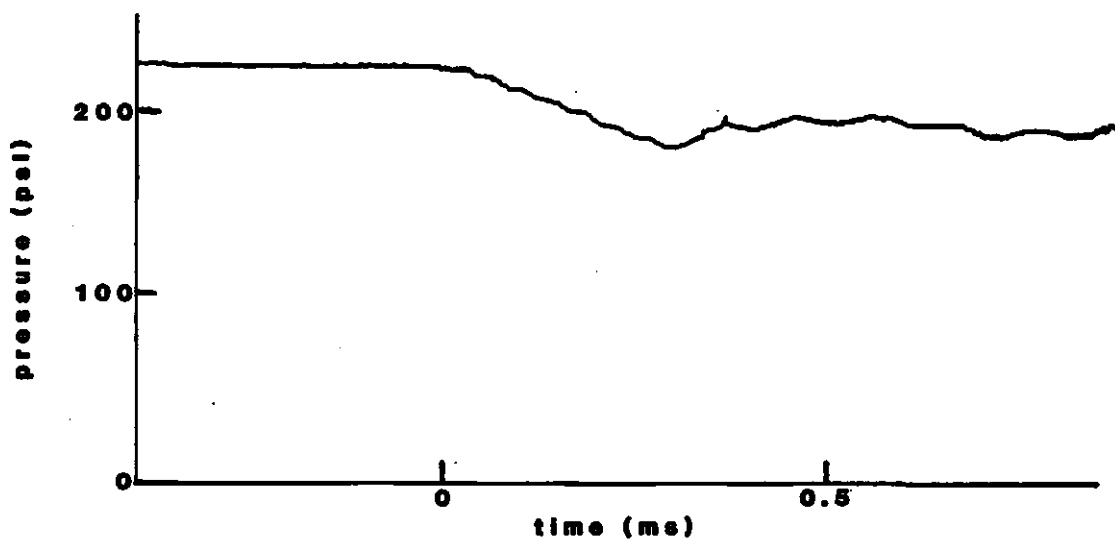


Figure 6. Typical Breech Pressure Records.

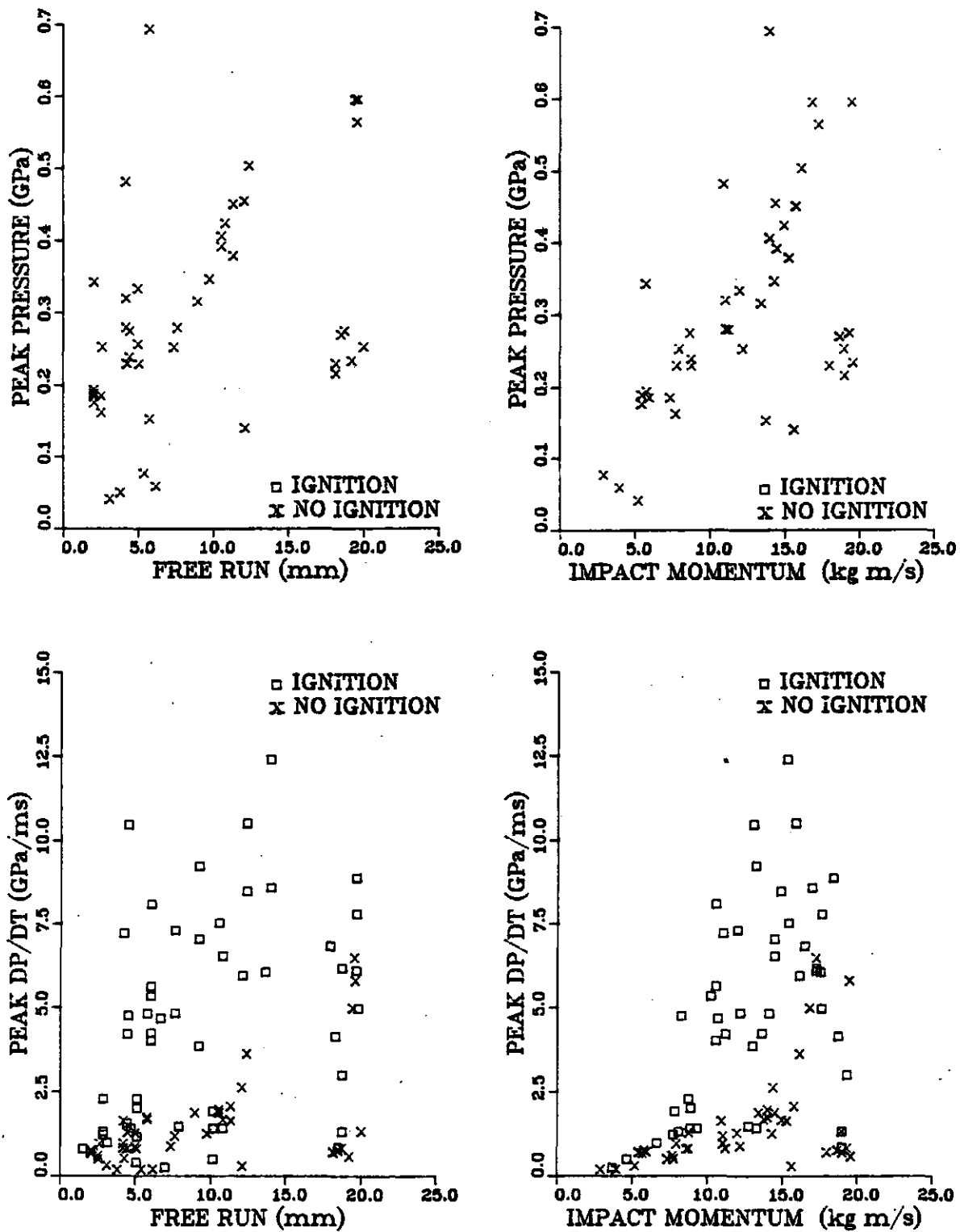


Figure 7. Correlation of Peak Pressure and Peak Pressurization Rate with Free Run and Impact Momentum in the Planar Gap Test.

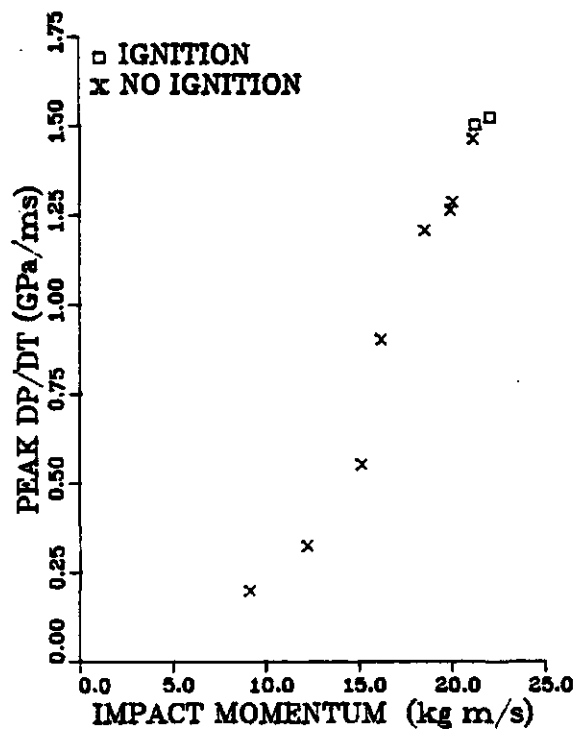
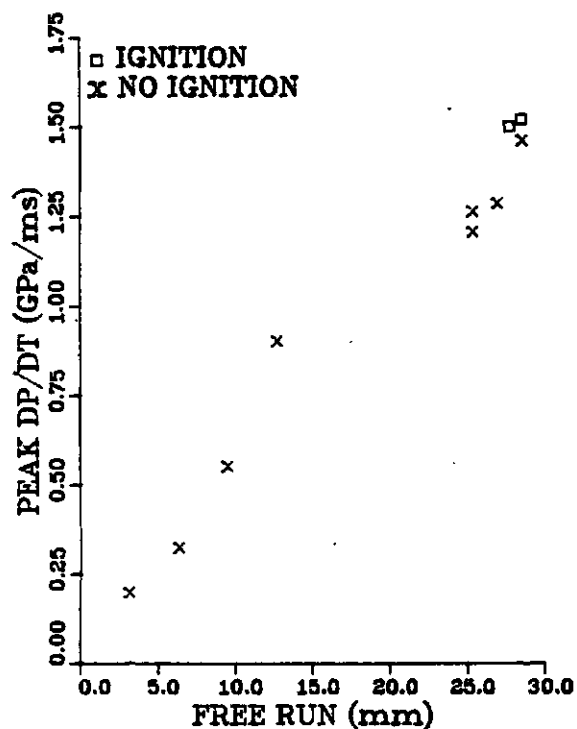
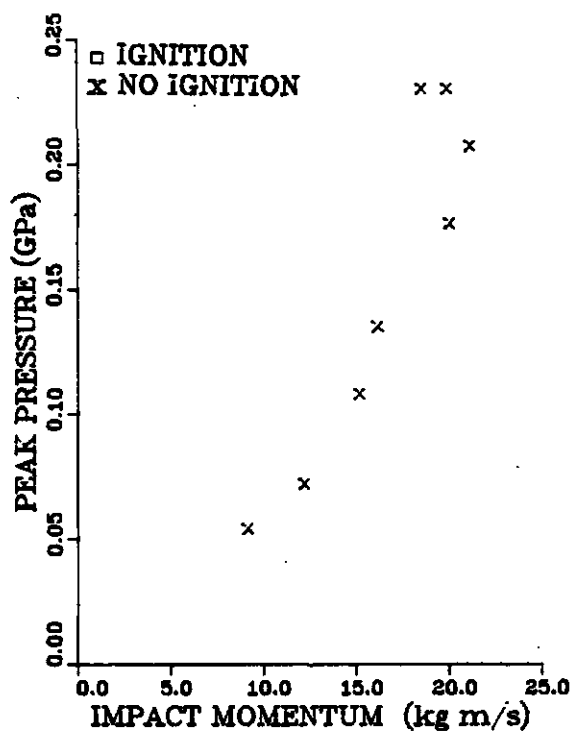
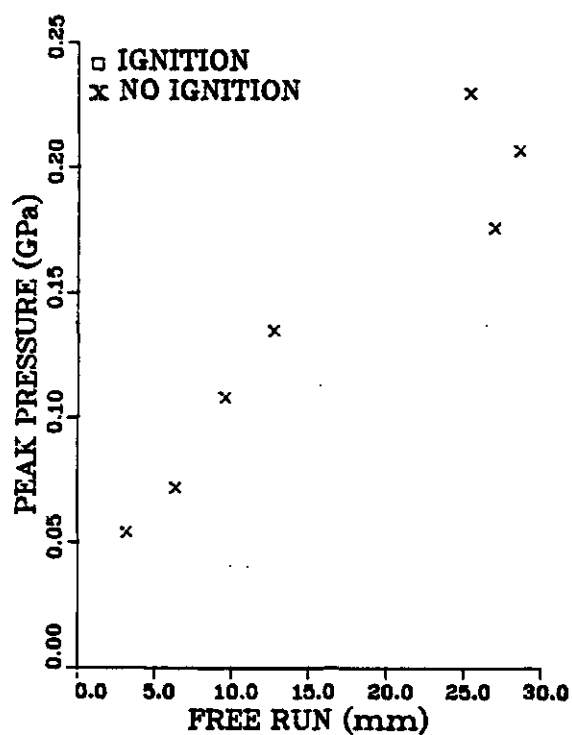


Figure 8. Correlation of Peak Pressure and Peak Pressurization Rate with Free Run and Impact Momentum in the Bubble Test.

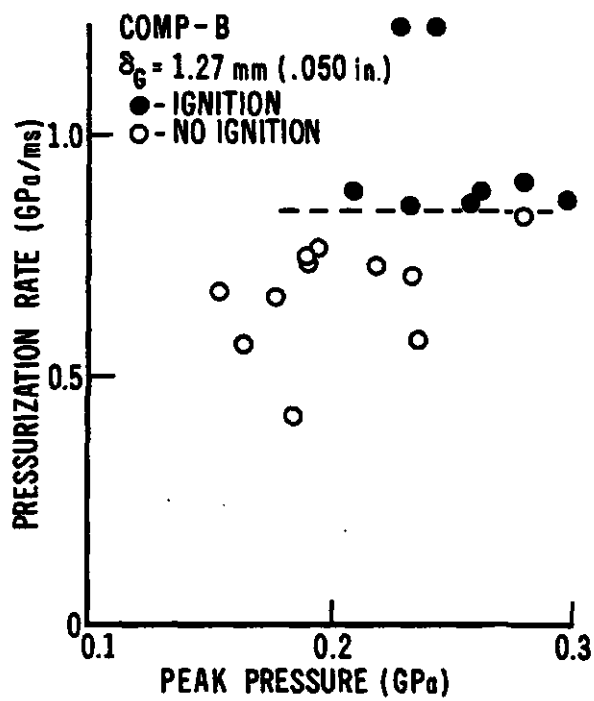


Figure 9. Effect of Limiting Peak Pressure in the Activator.

obtained using driving pistons of different materials with a planar air gap of 1.27 mm and comp-B samples. The results were plotted in the pressurization rate - peak pressure plane with solid symbols used for ignitions as shown in Figure 9. In this case, an ignition threshold which is independent of peak pressure was identified at a pressurization rate of about 0.85 GPa/ms.

B. Explosive Surface and Convergent Airflow Effects

The bubble test provides an opportunity to examine the effect of the state of the explosive surface on sensitivity. Experiments were conducted on both precompressed and unprecompressed comp-B. In each category, both as cast and cut and polished surfaces were tested with 0.7 mm and 1.5 mm radius bubbles. The minimum pressurization rate required for ignition in each case is shown in Table 1. Cut surfaces did not significantly differ in sensitivity from as-cast surfaces in either state. Precompression, on the other hand, significantly sensitized both types of surface. One explanation for this is that an unprecompressed surface is highly porous allowing the compressing gas to escape into numerous small cavities within the explosive thus limiting the quantity of compressed gas available to heat the explosive at the ignition site. Precompression reduces this porosity and renders the sample more sensitive.

Table 1. Minimum Pressurization Rates
for the Ignition of Comp-B in the
Bubble Test (GPa/ms)

Bubble Radius	Surface	Pre- compressed	Unpre- compressed
0.7 mm	as cast	0.6-0.7	>1.4
	cut	0.3-0.5	>1.5
1.5 mm	as cast	~0.02-0.06	1.4-1.5
	cut	~0.05-0.08	1.4-1.5

Results from the planar gap test are compared with those from the bubble test on precompressed comp-B in Table 2. This comparison shows that the convergent geometry permits ignition with a considerably milder stimulus than the planar geometry. Thus, the bubble may be regarded as the equivalent of a much thicker planar gap.

Table 2. Effect of Convergent Airflow
on Sensitivity

	Gap Dimension (mm)	Ignition Threshold (GPa/ms)
Planar Gap Test	1.5	0.7-0.8
Bubble Test	1.5	0.02-0.06

C. Comparison of Composition-B and TNT

By conducting planar gap tests with different size air gaps, experimental plots of ignition thresholds for TNT and comp-B in the pressurization rate - gap thickness plane were produced. Generally, ignition is expected for conditions corresponding to points above and to the right of the curve for each explosive. These thresholds are compared with the theoretical results in Figure 10. The anticipated qualitative agreement was achieved although the explosives are somewhat more sensitive to compressive heating ignition than predicted. A number of explanations for the discrepancies between the theory and the experiments based on aspects of the experiments which are not well modeled have been advanced. It has been suggested that turbulent airflow may develop as the gap closes. This has the effect of enhancing energy transport through the air and results in greater interface heating. If artificially high values of thermal conductivity of air are used in the model in order to simulate turbulence, it is possible to match the predicted ignition thresholds more closely with those observed experimentally. However, in this case, the predicted times to ignition are much shorter than observed. For this reason, turbulence does not appear to be a likely explanation. Another hypothesis is that the explosive is initially heated to its melting point by deformation and is subsequently subjected to compressive heating. Computations for TNT initially at its melting point indicate that the critical gap thickness decreases by only one-tenth of a millimeter for a pressurization rate of 5 GPa/ms. This explanation also appears unlikely. For the analysis it has been assumed that the explosive may be regarded as a semi-infinite layer. If, however, particles or protrusions of fine dimensions are subjected to a hot compressed air bath they will reach higher temperatures and begin to react sooner than the surrounding planar regions. The analytical results indicate that this effect starts to become important for particle dimensions below about fifty microns. In addition, the convergence effect may be active in the planar gap test. The analysis shows that the final thickness of the air gap when ignition occurs is ten microns or less. Microscopic examination of the explosive surface shows that it is essentially smooth with occasional defects where some of the material has adhered to the casting plate. During the final portion of gap closure, large quantities of air may be forced into these defects. Either or both of these latter explanations appears likely.

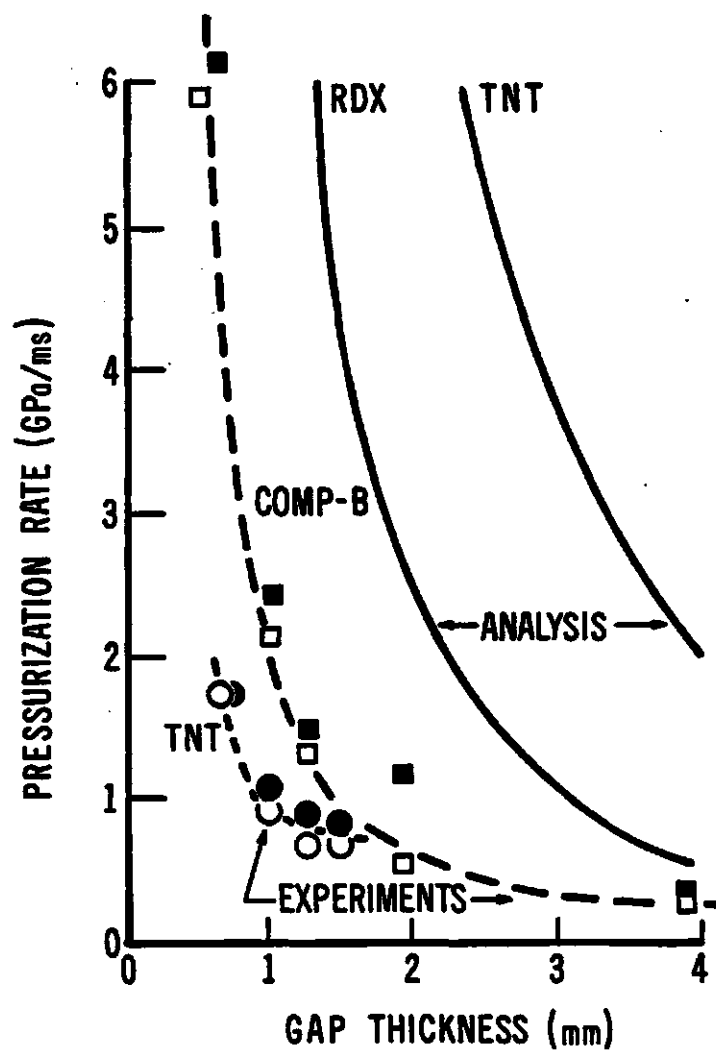


Figure 10. Experimental and Theoretical Ignition Thresholds for TNT and Composition-B.

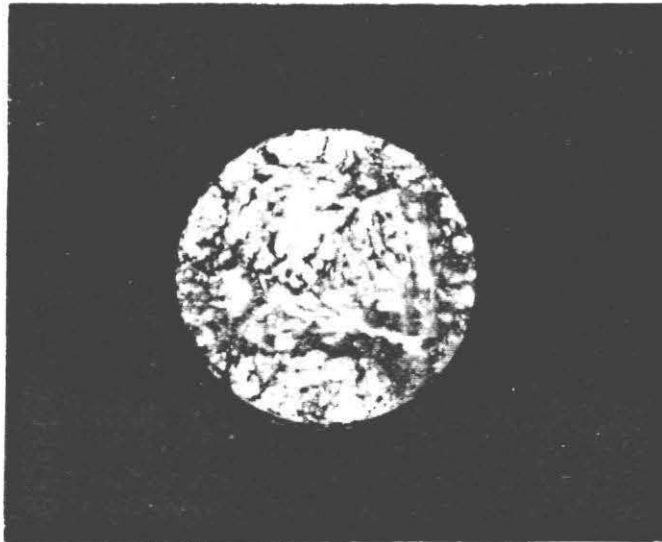
Surprisingly, TNT exhibited greater sensitivity than comp-B when both were precompressed. A similar result was reported in an early study at A.D. Little,

Incorporated.¹⁴ Figure 10 shows that TNT can be ignited at a lower pressurization rate than comp-B (except at the largest gap thickness at which TNT was tested). The theory did not predict this order of sensitivity. Bubble tests were conducted to determine if this occurred because TNT surfaces are more effectively sealed by precompression. The results are summarized in Table 3. Precompressed TNT and comp-B exhibited approximately the same level of sensitivity in these tests. This is consistent with the observation for the larger planar gaps (to which the bubbles are equivalent). In the unprecompressed state the explosives exhibited the expected order of sensitivity. Thus, it appears that the effect of precompression is sufficient to invert the order of sensitivity of TNT and comp-B. Indeed, the state of the explosive surface appears to be a more important determinant of sensitivity than explosive identity.

Table 3. Bubble Test Comparison of TNT and Comp-B

	Ignition Thresholds (GPa/ms)	
	Precompressed $r_b = 0.7$ mm	Unprecompressed $r_b = 1.5$ mm
Comp-B	0.6-0.7	1.4-1.5
TNT	0.6-0.7	1.8

Another difference between TNT and comp-B was also observed. When comp-B ignitions were obtained, the entire sample was always consumed. However, TNT ignitions produced by large air gaps and relatively low pressurization rates resulted in only partial reaction of the samples. This probably occurred because TNT reacts much more slowly than comp-B (as evidenced by the pressure records) and may be extinguished by the expansion of the air and the explosive products which accompanies piston rebound. Photographs of the ignited end and the bottom of a recovered sample are shown in Figure 11. Evidence of burning is visible at both ends. Reaction appears to have propagated through the sample along cracks or fissures.



(a) Ignited End.



(b) Opposite End.

Figure 11. Surfaces of Partially Burned TNT Sample.

V. RESULTS WITH PRESSED EXPLOSIVES

The state of a precompressed explosive sample surface is not representative of that which one would expect to find in production ammunition. We were interested in determining the effect of more usual variations in explosive surface state. Toward this end we pressed samples of LX-14 to densities varying from 1.60 to 1.78 Mg/m³. These were tested with 1.5 mm diameter bubbles. When ignitions were obtained they often appeared as late events on the pressure records as shown in Figure 12. We tested LX-14 in the absence of any air cavity and verified that free runs in excess of 25 mm were still required to produce extrusion ignition. Scrutiny of the pressure records indicated that late ignition occurred on the second strike of the piston after the sample had been precompressed by the first strike. Figure 13a is a plot of pressurization rate versus initial density and Figure 13b is a plot of free run versus initial density in which different symbols have been used for ignition, nonignition and late ignition. The data segregates somewhat better in the former plot except for one anomalous point. The late ignitions may be regarded as nonignitions. The ignition threshold defined in this manner is a clear function of density, showing lower sensitivity at lower density. This result substantiates our surface porosity hypothesis.

Other pressed explosives were tested at a single nominal density. These are composition A3 type II and R8151 (94.5% RDX, 4.5% wax, 1% graphite). The results for these were comparable to those for the cast explosives.

VI. RESULTS WITH AN INTERMOLECULAR EXPLOSIVE

A very limited number of tests were conducted on an experimental intermolecular explosive, EARK-25. The results are plotted in Figure 14 for both precompressed and unprecompressed explosive; four shots with precompressed explosive all produced ignition. In the case of unprecompressed EARK-25 the results appear to be strongly dependent on bubble diameter. The two shots in which ignitions resulted used bubbles exceeding 1.31 mm in diameter. No ignitions were obtained with smaller bubbles over a relatively wide range of pressurization rates. This observation is based on a limited amount of data and is tentative.

VII. COMPARISON OF EXPLOSIVES

Figure 15 is a comparison of data for most of the explosives tested. Free run replaces pressurization rate and logarithmic scales have been used to facilitate presentation in a single plot. Data for explosives in the unprecompressed state is appropriate for assessment of the sensitivity of explosives to setback prematures caused by compressive heating. This data indicates that comp-B and TNT are about equally sensitive, while the type II is somewhat more sensitive and R8151 is slightly less sensitive. A more important observation is that the sensitivity differences produced by precompression and density variation are much greater than those associated with the identity (hence thermochemistry) of the explosive.

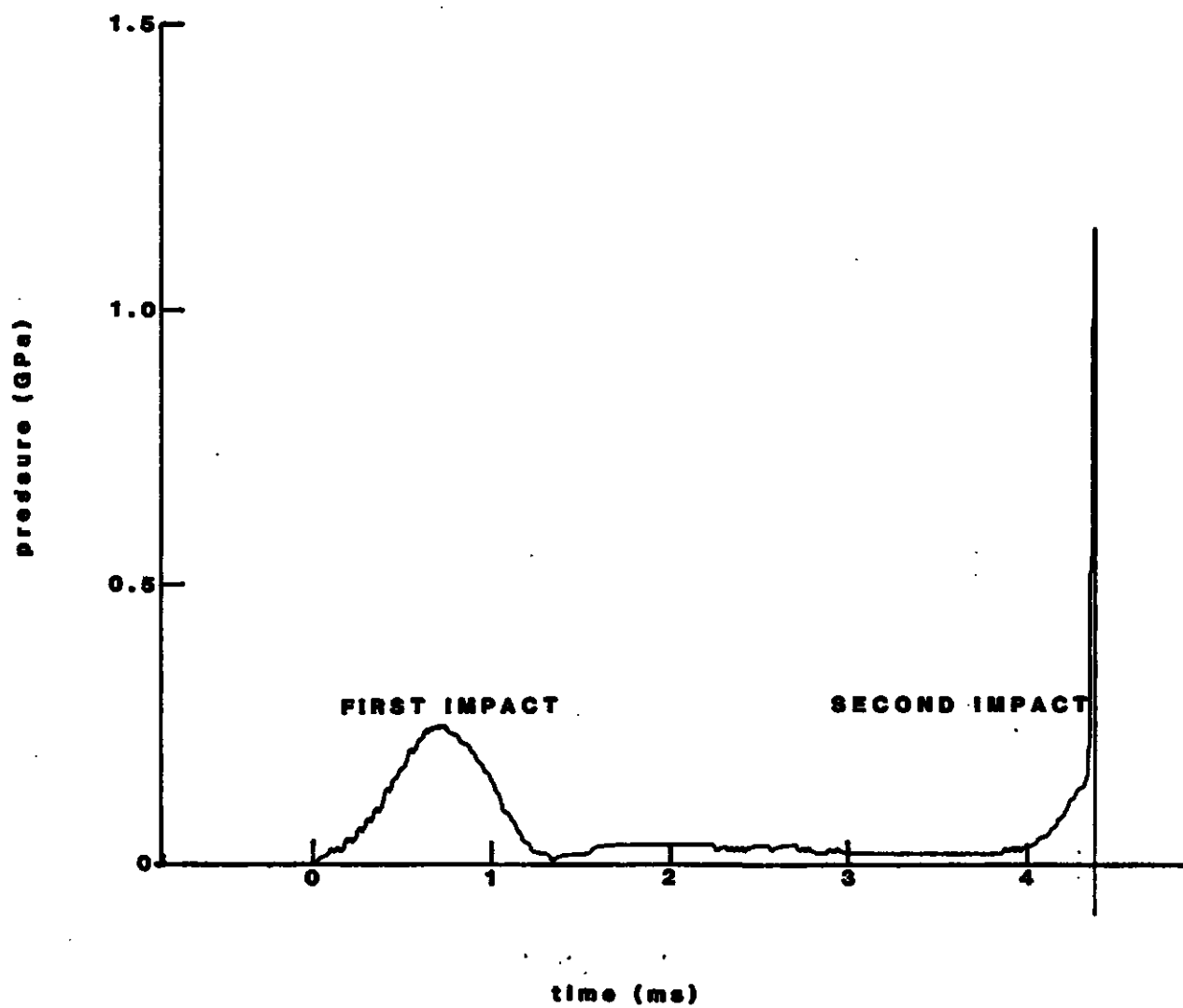


Figure 12. Manganin Gage Pressure Record for Late Ignition with LX-14.

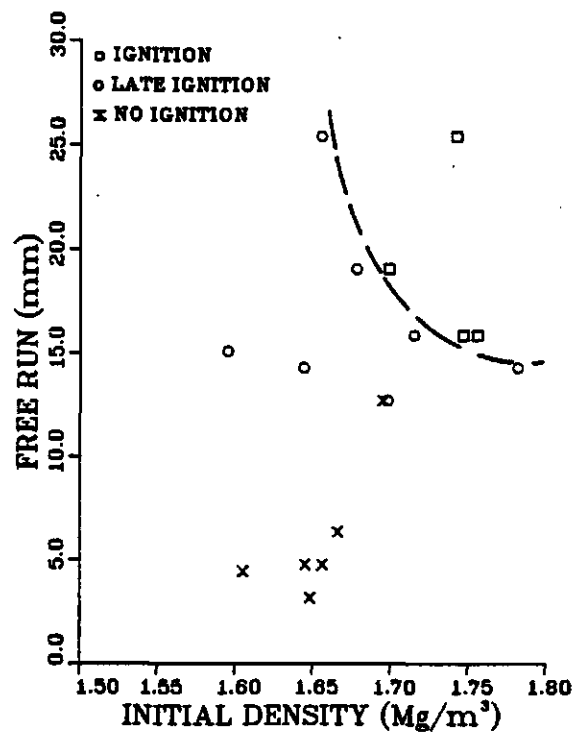
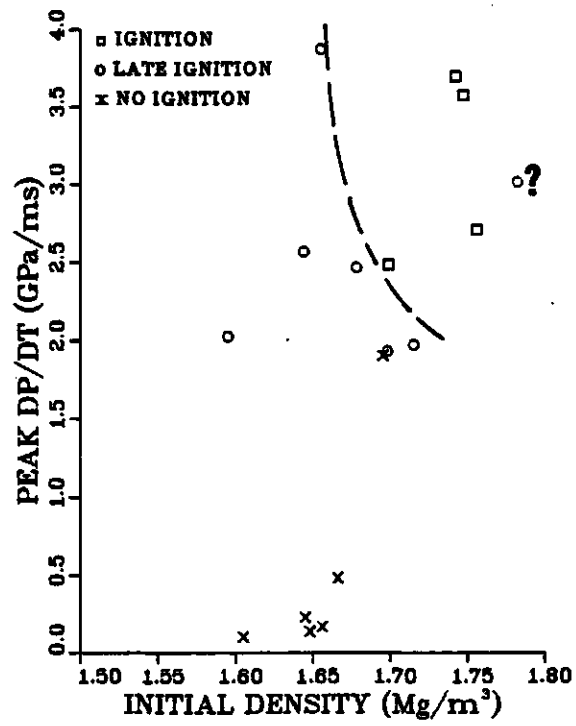
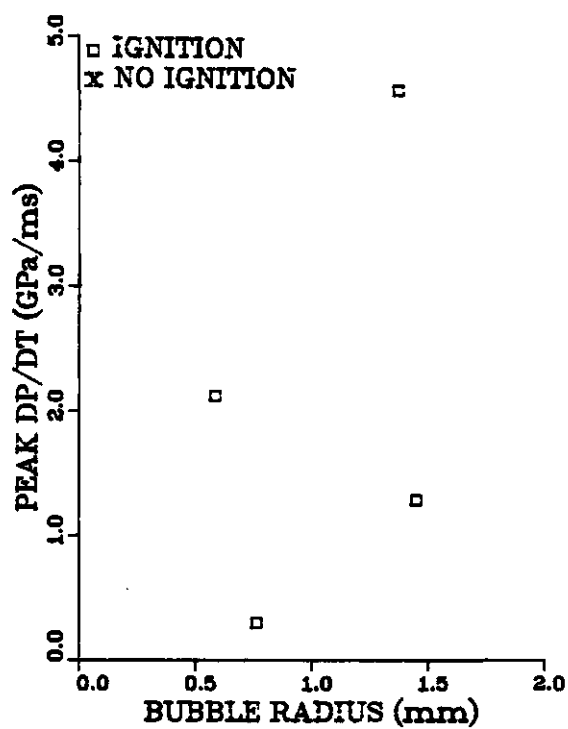
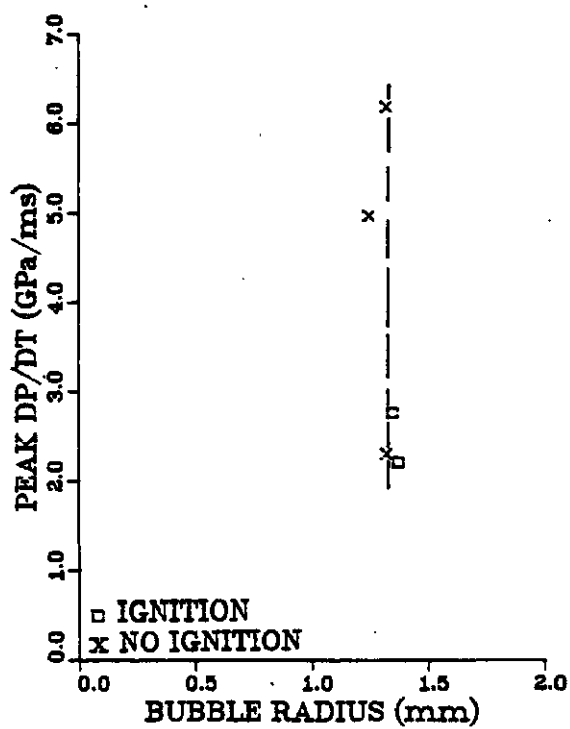


Figure 13. Ignition Threshold for LX-14 as a Function of Density.



(a) Unprecompressed



(b) Precompressed

Figure 14. Ignition Threshold for EARK-25.

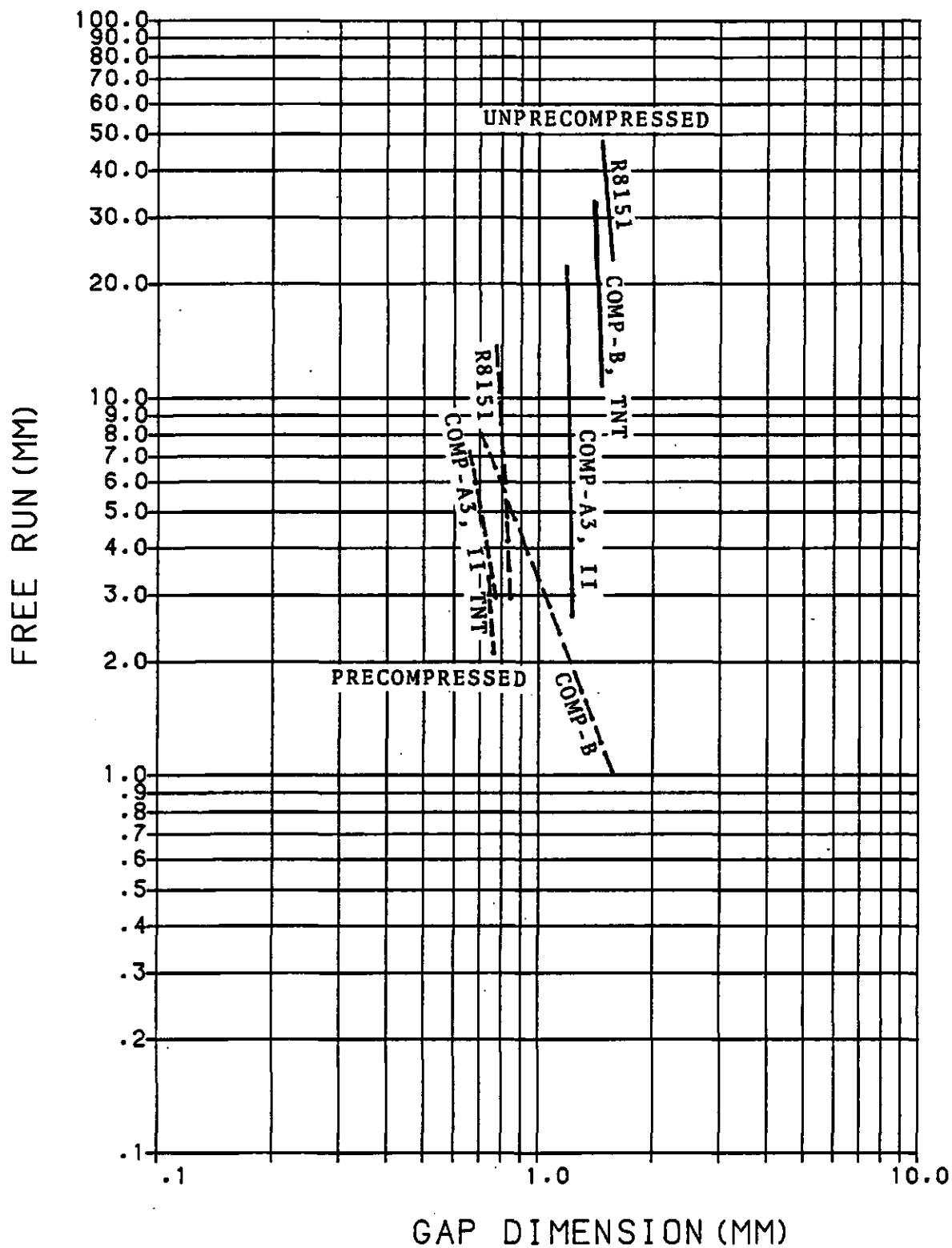


Figure 15. Relative Sensitivity of TNT, Composition-B, Composition A3 Type II and R8151 in the Precompressed and in Unprecompressed States.

VIII. SUMMARY

The early activator tests showed that compressive heating was a viable explosive ignition mechanism. The test procedure was improved so that ignition thresholds could be determined without ambiguity and an analysis was developed to aid in understanding the effects of parameter variations on sensitivity. The analysis and the experiments showed that pressurization rate and cavity size are the principal parameters governing compressive heating ignition. Although ignition may be inhibited by limiting the peak pressure, this did not appear to occur in the activator. Studies of precompression of both cut and polished and as cast surfaces indicated that the state of the explosive surface grossly affects sensitivity to this ignition mechanism. Sensitivity is greater for surfaces which have been precompressed. Geometries which generate convergent airflow yield ignition with milder stimuli than are required with planar geometries. Qualitative agreement between the experiments and the analysis was achieved. TNT was found to be more sensitive than comp-B when both were precompressed. Comparison of unprecompressed explosives using the bubble test showed that TNT was less sensitive than comp-B and indicated that precompression more effectively seals TNT surfaces. The slow burning of TNT allowed quenching of reaction in the activator and recovered samples showed evidence of burning along fissures. The effect of surface state was further examined using LX-14 pressed to a range of densities. The results clearly showed that sensitivity to compressive heating ignition increases with density in contrast to other mechanisms. Comparison of results for a number of different explosives shows that precompression affects sensitivity much more than explosive thermochemistry.

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