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DEVELOPMENT OF EXPLOSIVELY DRIVEN LAUNCHER FOR METEOROID STUDIES

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16. Abstract

The report describes the results of a continuing program to develop an explosively driven 2-stage hypervelocity launcher capable of achieving velocities between 15 and 20 km/sec. Previous efforts had identified incomplete barrel collapse as a limiting factor in launcher performance. Correlation of experimental and computational results obtained in the present study indicate that boundry-layer gases within the barrel act to prevent complete closure. Simplified calculations suggest that in-contact explosives may have insufficient energy densities to collapse the barrel against a developed boundry layer. Higher energy densities, sufficient to produce complete closure, were obtained with the use of steel flyer plates accelerated by a phased explosive lens. However, when flat flyer plates were impacted on the barrel, the sides of the barrel were observed to rupture and leak gas prior to barrel closure. A promising solution to this problem (untested) is to produce a symmetrical collapse with a cylindrical tube around the barrel.

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ABSTRACT

This report describes the results of a continuing program to develop an explosively driven hypervelocity launcher capable of achieving velocities between 15 and 20 km/sec. Major emphasis in this effort was placed on understanding the operation and improving the effectiveness of the second stage. Previous efforts had identified incomplete barrel collapse as the limiting factor in launcher performance.

A series of matched two-stage launcher experiments and computer calculations was performed. From a correlation of experimental and computational results it was concluded that the interaction of boundary-layer gases with the barrel-collapse process is responsible for incomplete collapse.

A simple model for the boundary-layer barrel-collapse interaction indicates that in-contact explosives may have insufficient energy densities to collapse the barrel against a developed boundary layer. Accordingly, a phased explosive lens was used to accelerate a steel flyer plate which acquires significantly higher energy densities than the actual explosive. The flyer plate impacts the barrel producing stresses up to 1 Mbar. This type of lens appears effective in collapsing barrels against the dynamic effects associated with the gas flow. However, when flat flyer plates were impacted on the barrel, the sides of the barrel were observed to rupture and leak gas prior to barrel closure. A promising solution to the barrel rupture problem is to collapse a tube around the barrel. This technique has yet to be attempted on a two-stage launcher.

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SECTION 1
INTRODUCTION

Physics International has been engaged in a continuing effort to develop hypervelocity launchers for achieving the highest possible projectile velocities. The highest velocity achieved has been 12.2 km/sec by a 2-gram projectile (Reference 1). The impetus for this work arises primarily from the desire to simulate meteoroid impact phenomena. As space vehicles become larger and are required to be operative for longer periods of time, the probability of a destructive meteoroid impact increases substantially. Spacecraft designers must account for increased impact probability in vehicle skin designs. An impact facility capable of launching 100 mg projectiles to 20 km/sec would allow design concepts to be tested and evaluated under realistic impact conditions, without resorting to various energy or momentum scaling laws. Possible benefits to be derived from such testing include an accurate determination of the impact resistance of present spacecraft designs and an evaluation of new design concepts which may result in decreased vehicle weight and increased vehicle payload.

This report describes the most recent effort in a continuing series to develop a two-stage explosively driven launcher for use in the 15 to 20 km/sec velocity range. Principal emphasis in this effort was directed toward understanding and improving the operation of the second-stage barrel collapse process. A series of calculations and experiments was conducted which indicated that boundary-layer formation in the gas behind the projectile is responsible for the incomplete barrel collapse observed on all previous two-stage launchers. A new collapse technique in which a flyer plate impacts the barrel was demonstrated to be more effective in collapsing a barrel containing a developed boundary layer.

Section 2 of this report contains brief descriptions of the explosively driven launcher concept, a performance calculation, and a verification experiment. The design of a two-stage explosively driven launcher is discussed in Section 3. Pertinent performance calculations, including the second-stage collapse process, are presented. Accompanying launcher experiments are discussed. Section 4 considers the barrel collapse process and the problems associated with achieving complete collapse. Experimental results of two different collapse techniques are presented. Conclusions drawn from the present work and recommendations for continued launcher development are contained in Section 5.

SECTION 2
EXPLOSIVELY DRIVEN LAUNCHER CONCEPT

The basic element in the hypervelocity launcher concept developed by Physics International is the explosive driver, an efficient device for converting the chemical energy of high explosives into useful gasdynamic energy. The explosive driver consists of a thin-walled steel pressure tube containing helium gas and surrounded by a thin layer of explosive. A detonation wave initiated at one end propagates axially and progressively collapses the steel tube. The collapsing tube acts as a mechanical piston traveling at the detonation velocity of the explosive and drives a strong shock wave into the helium driver gas. Typical achieved conditions in the shocked helium are a flow velocity of 6.3 km/sec (equal to the detonation velocity of nitromethane) and a pressure of 6,000 atmospheres. Approximately 10 percent of the available explosive energy is delivered to the helium driver gas. This energized helium gas provides the initial acceleration of the projectile.

Extensive studies have been made of explosive driver operation during which all ideal and nonideal effects concerning the explosive tube collapse were considered (References 2 and 3). Figure 1 illustrates the ideal driver operation, in which a conical piston is explosively formed and drives a strong shock into the driver gas. A slug of uniformly processed high-energy-density gas is produced. Ideally the length of the gas slug is proportional to the driver length and can be made arbitrarily long by increasing the driver length. However, it has been observed that ideal operation occurs only for short drivers, those having a length-to-diameter ratio of less than 25. At greater lengths nonideal effects influence driver operation and tend to decrease the slug length below its ideal value. At a length-to-diameter ratio of 100 or greater, a steady state situation is attained in which the shock velocity is equal to the detonation velocity and the slug length remains constant. When this occurs, the rate at which gas is lost from the slug is equal to the mass flux being swept up by the incident shock.

Figure 2 illustrates the nonideal effects that are important to launcher operation. Radial expansion of the pressure tube induced by the incident-shock pressure tends to decrease the slug length from its ideal value. For tube expansion greater than 30 percent, dynamic rupture may occur. The rate of expansion is determined by the respective wall thicknesses of the pressure tube and tamper. A second effect controlled by tubing thicknesses is the explosive tube collapse. At large angles of collapse of the pressure tube, jetting of linear material can occur. The high-velocity jet of material contaminates the driver gas and can conceivably damage the projectile. Conversely, at small tube collapse velocities a complete closure may not be attained, gas may be allowed to escape, and the performance of the driver degraded.

A nonideal effect common to all gasdynamic systems is boundary-layer growth. In an explosive driver boundary-layer growth behind the driver shock becomes noticeable at driver length-to-diameter ratios greater than 25. At this point the driver shock velocity begins to fall below its ideal value. Terminal observations of collapsed pressure tubes have shown

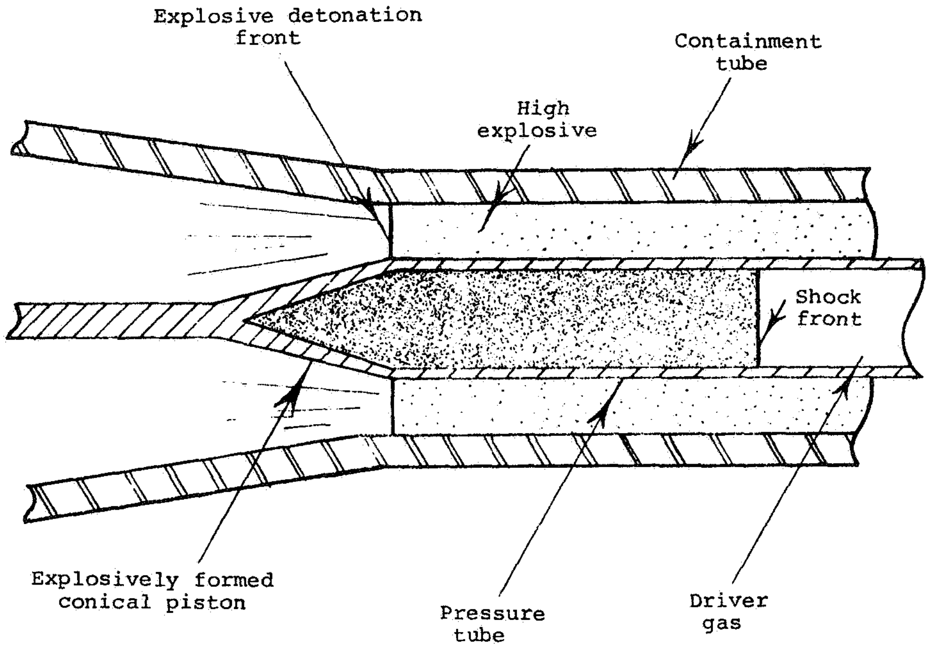


Figure 1 Idealized schematic of linear explosive driver.

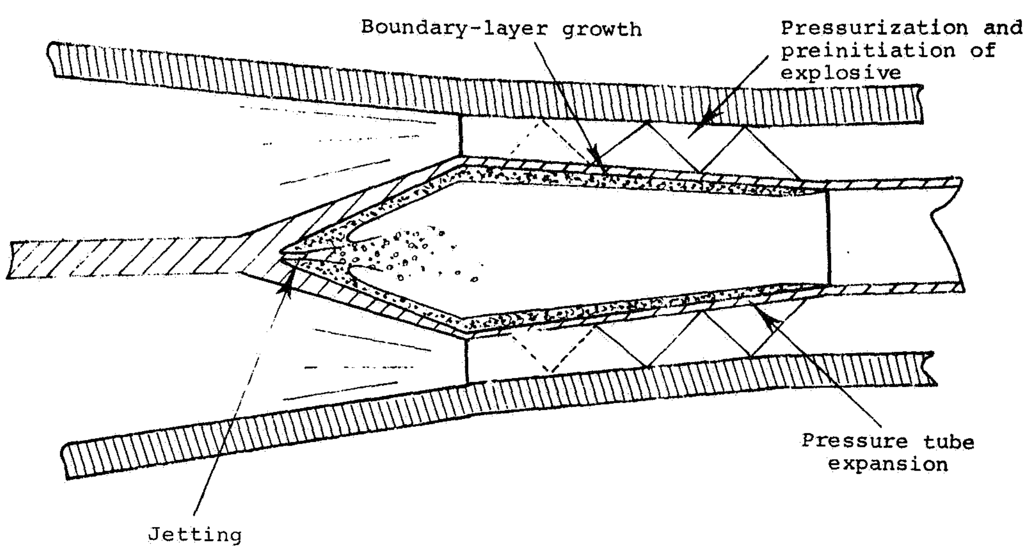


Figure 2 Schematic of nonideal phenomena in explosive drivers.

that complete collapse is achieved only in the initial portion of the driver, after which a progressively larger hole appears. The onset of incomplete pressure-tube collapse and the degradation of shock velocity have been correlated with boundary-layer growth behind the incident shock (Reference 2). The detailed interaction between the boundary layer and the collapse process is extremely complex and the specific mechanism by which the boundary layer inhibits the collapse is not completely understood. This problem is discussed in additional detail in Section 4, as it is of considerable importance in the second-stage launcher operation. For hypervelocity launcher applications, explosive drivers are generally designed with a length-to-diameter ratio of 25 so that boundary layer effects are negligible. In this situation, the explosive driver has proven a reliable and reproducible gasdynamic device.

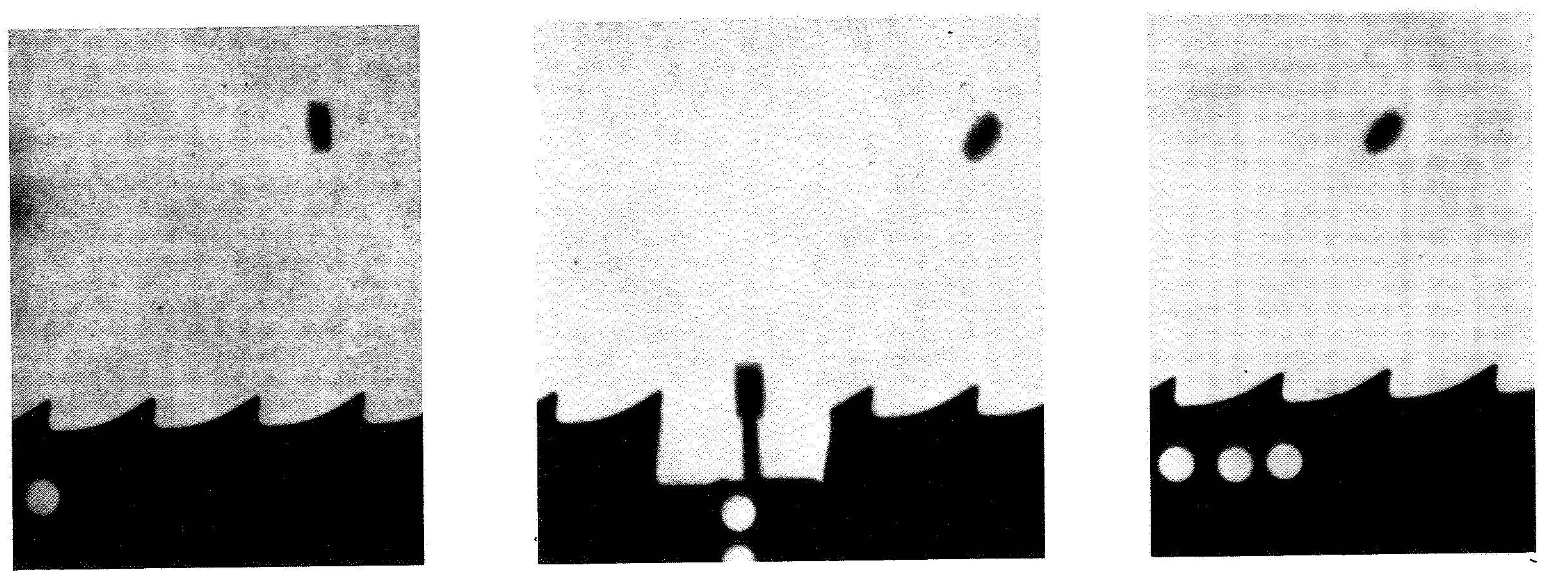
During the past several years a basic launcher design has been developed capable of accelerating an intact projectile to a velocity of 8.8 km/sec. Although the launcher may be employed as a single-stage device, it is primarily intended as the first stage of a two-stage system. This distinction arises because the launcher was designed to provide gasdynamic conditions suitable for second-stage augmentation techniques, rather than to provide maximum obtainable projectile velocity. The launcher utilizes a nominal 3-kbar helium driver having a length-to-diameter ratio of 25. The incident helium shock drives into a conical breech section having a chambrage (area convergence ratio) of 5.6. The projectile is initially located two body diameters downstream from the end of the conical breech. The peak pressure seen by the projectile during the launch cycle exceeds 50,000 atmospheres and occurs when the incident shock reflects off the base of the projectile. Careful design of the breech and projectile allows projectiles to be launched intact despite base pressures far in excess of the projectile yield strength.

2.1 SINGLE STAGE LAUNCHER EXPERIMENT, 245-1

Shot 245-1 was a test of the first-stage launcher operation prior to integration with a second stage. As this launcher was a 0.4 scale version of the standard launcher reported in previous work (Reference 1), the shot provided a verification of launcher performance in the smaller scale and timing data necessary for correct phasing with the second stage. The bore of the launcher was 0.635 cm and the magnesium-lithium projectile had a mass of 140 mg and a length-to-diameter ratio of 1/2. The overall length of the launcher was 90 cm and its weight was 8 pounds. The explosive driver required 160 grams of sensitized nitromethane.

The shot was successful both in terms of data acquisition and launcher performance. The observed muzzle velocity of the projectile was 8.8 km/sec, and the condition of the projectile was judged excellent. Three pulsed radiographs of the projectile in flight are presented in Figure 3. The projectile is tumbling in flight because of the relatively high density atmospheric range. The projectile impacted a 6061-T6 aluminum target just beyond the third radiographic station in Figure 3. The resulting impact crater is shown in Figure 4. Because of areodynamic deceleration, the projectile velocity at impact had decreased to 7.5 km/sec.

Direction of Flight →



Cobra 1
38 Body Diameters Down Range

Cobra 2
60 Body Diameters Down Range

Cobra 3
82 Body Diameters Down Range

Figure 3 Pulsed radiographs of a 0.140-gram projectile in atmospheric range for Shot 245-1. Muzzle velocity was 8.8 km/sec.

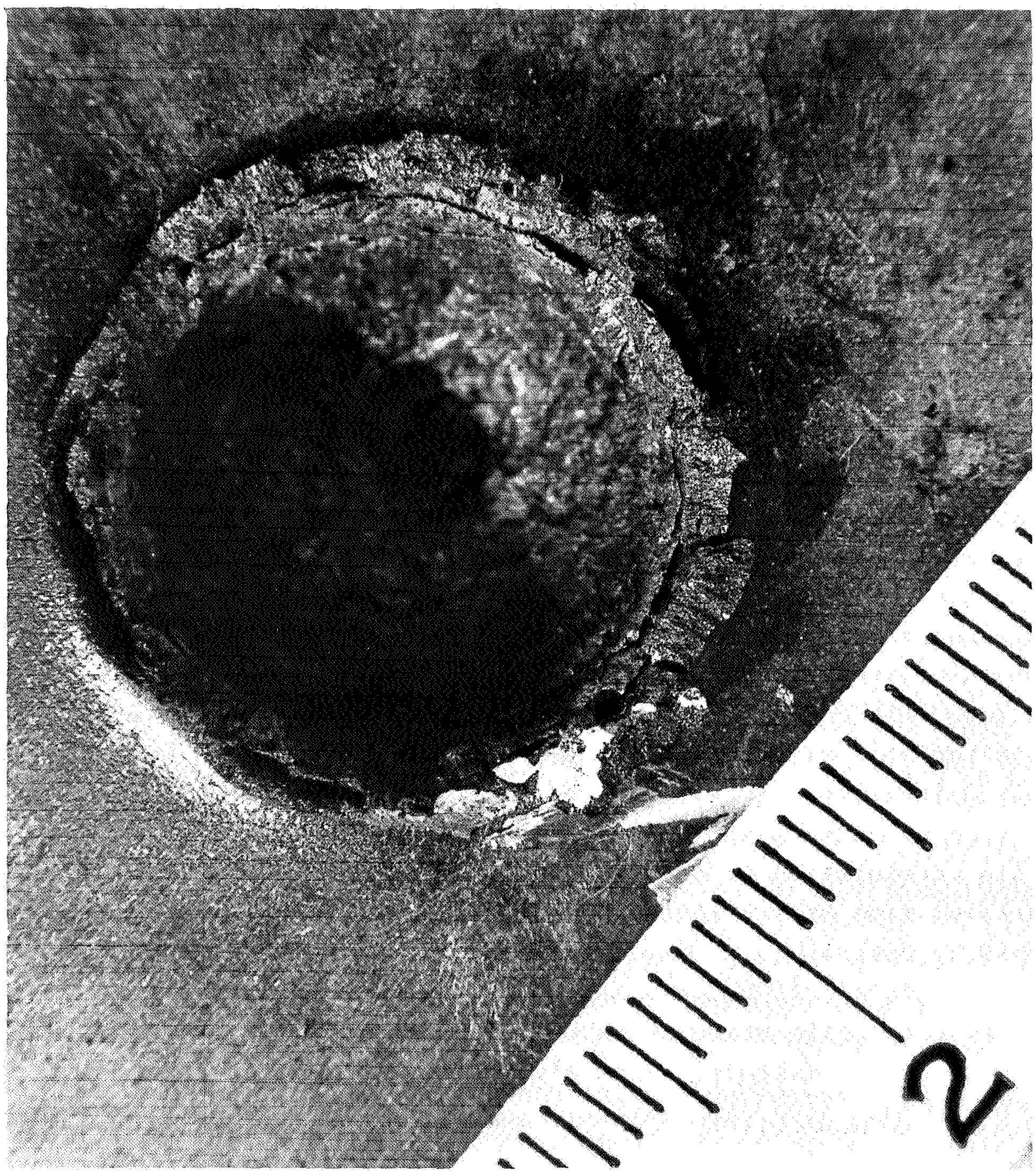


Figure 4   Impact crater in 6061-T6 aluminum target for Shot 245-1. Impact velocity was 7.5 km/sec.

Integration of this basic launcher design with various second-stage augmentation techniques requires a detailed knowledge of the gasdynamics occurring behind the projectile during the initial phase of the launch cycle. However, the extreme conditions of pressure and flow velocity preclude obtaining experimental data on the internal launcher ballistics. A more productive approach is to use Physics International's GANGPOD computer code to calculate the launch dynamics.

2.2 GANGPOD PERFORMANCE CALCULATION

Physics International's GANGPOD computer code is a one-dimensional Lagrangian code designed for calculating nonsteady flow through ducts accompanied by significant radial expansion of the walls. The interaction between the wall expansion and the gas flow is handled correctly to the extent that one-dimensional gasdynamics is valid. Starting from the known state of the driver gas immediately before it enters the conical breech, the code was used to calculate the complete dynamics of the launch cycle. Detailed wave dynamic interactions between the driver gas, projectile, and launcher walls are calculated in a time-stepping manner. The complete time history of the projectile acceleration is calculated including the velocity and arrival time at the launcher muzzle. These two variables are readily observable in experiments and represent convenient comparison points between experiment and calculation. Since the final projectile velocity is determined by the time-integrated base pressure history, it is a meaningful parameter for verifying the complete code calculation.

A GANGPOD calculation was run for comparison with shot 245-1. The reservoir, breech, barrel, and projectile geometry of the basic launcher were included in the calculational geometry. The driver gas state was chosen to have the identical pressure, velocity, and slug length observed in shot 245-1. The calculation was started with the incident helium shock just entering the conical breech. After the calculation had run for 53.5 μsec, the projectile had traveled 33.2 cm down the barrel and had attained a velocity of 8.3 km/sec. By referencing the computed distance and time scales to the observed shock arrival at the nozzle entrance, the GANGPOD projectile trajectory can be compared with the observed results from shot 245-1. Figure 5 presents both the calculated and observed trajectories. The computed trajectory is in excellent agreement with the extrapolated range data, lending credence to the GANGPOD computational technique as well as providing timing data essential for two-stage launcher design. Based upon this successful calculation of launcher performance, the GANGPOD technique was presumed to correctly calculate the internal launcher dynamics and was used as a design tool for integrating second-stage augmentation techniques.

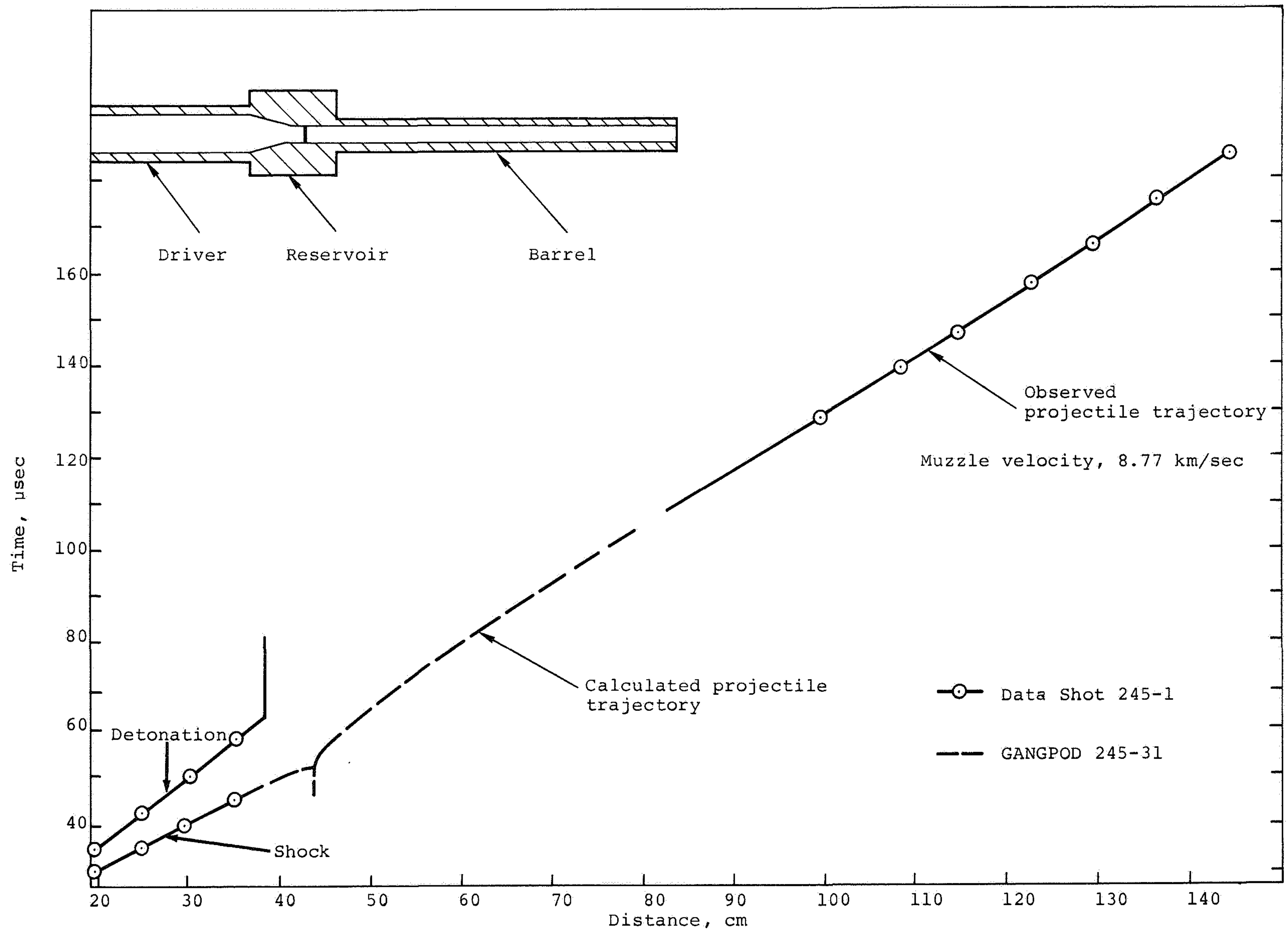


Figure 5   Comparison of calculated and observed launcher performance.

SECTION 3

DESIGN AND OPERATION OF A TWO STAGE LAUNCHER

Conceptually, the operation of a second stage is similar to operation of the first in that an explosively formed piston is used to further increase projectile velocity as it travels down the barrel. The piston is formed by progressively collapsing the barrel walls after the projectile and a predetermined length of gas have passed. After formation, the piston accelerates along a prescribed velocity-distance trajectory, forcing the trapped gas and projectile to high velocities. The piston trajectory is determined by a phased explosive lens system. Typically, the second-stage piston starts moving at 6.3 km/sec and accelerates to 14 km/sec. In the 0.635-cm bore launcher, the acceleration occurs over a distance of 60 cm. Since the time required for barrel collapse at any point is approximately constant and is not dependent upon the axial progression rate of the collapse, the length of the collapse region increases as the piston accelerates. The limiting piston velocity occurs when the collapse region is sufficiently long to contain all of the trapped gas driving the projectile. Further increase in piston velocity will cause the collapse region to overtake the projectile. The maximum projectile velocity attainable with this type of system presently appears to be about 20 km/sec. This velocity limitation can be removed by devising advanced techniques for collapsing the barrel more rapidly. Specific collapse techniques are discussed in Section 4 of this report.

Proper operation of the second stage relies on matching the acceleration of the explosive lens with the acceleration of the projectile as determined by its base pressure and areal density. If the base pressure is too high, the projectile will accelerate faster than the lens, and proper velocity augmentation will not be achieved. If the base pressure is too low, the explosively formed piston may overtake and destroy the projectile. In a properly matched system the piston accelerates just rapidly enough to maintain a constant base pressure on the accelerating projectile.

The base pressure at the startup of the second-stage operation is strongly dependent upon the timing and position of the lens relative to the projectile. As the projectile accelerates down the barrel, the base pressure rapidly decays. Figure 6 shows the results of a GANGPOD calculation of the internal launcher dynamics during the initial phase of the launch cycle. The abscissa scale represents distance from the entrance to the conical breech. On this scale, the initial location of the base of the projectile is 1.8 cm. The two vertical scales include both pressure and velocity. The solid curves represent the projectile-related variables as a function of projectile travel down the barrel. The dashed curves portray velocity and pressure profiles in the gas behind the projectiles when the projectile has reached the 11-cm location.

The minimum allowable startup conditions for the second-stage lens are 5-kbar pressure and 6.3 km/sec velocity. This pressure level is chosen to be low enough not to interfere with the barrel-collapse process, while allowing a rapid acceleration to high velocities. The minimum velocity represents the detonation velocity of undiluted nitromethane, a convenient initial velocity for the second-stage lens. To allow for possible leakage of gas and the elongation of the collapse region at high phased-detonation velocities, it is necessary to initiate the second-stage collapse process some distance behind the projectile. The minimum allowable startup conditions must then be achieved after the projectile has travelled some distance down the barrel. An initial distance of 5 cm was chosen between the projectile and the collapse region.

Assuming the lens starts at the 6-cm point in Figure 6, the projectile should be at the 11-cm point when the second-stage piston starts. The base pressure at 11 cm is 6 kbar, and the projectile has accelerated to 7.25 km/sec. More important, the average pressure in the region of trapped gas between 6 and 11 cm is about 5 kbar and the average flow velocity appears to be 6 km/sec. These are acceptable second-stage startup conditions, as the average pressure is at least 5 kbar and the projectile is traveling faster than the initial piston velocity.

Assuming a constant base pressure of 5 kbar and a projectile areal density of 0.438 gram/cm^2, the resulting acceleration is 0.0114 cm/μsec^2. A piston starting at 6.3 km/sec and undergoing a uniform acceleration of 0.0114 cm/μsec^2 would acquire a velocity of 13.14 km/sec after 60 cm of travel. A second-stage piston following this trajectory should be closely matched to the existing gasdynamics conditions at the start of lens operation.

A series of one-dimensional POD calculations was performed to evaluate the sensitivity of the second-stage performance to second-stage startup conditions. Having chosen a particular piston trajectory (constant acceleration from 6.3 to 13.1 km/sec),

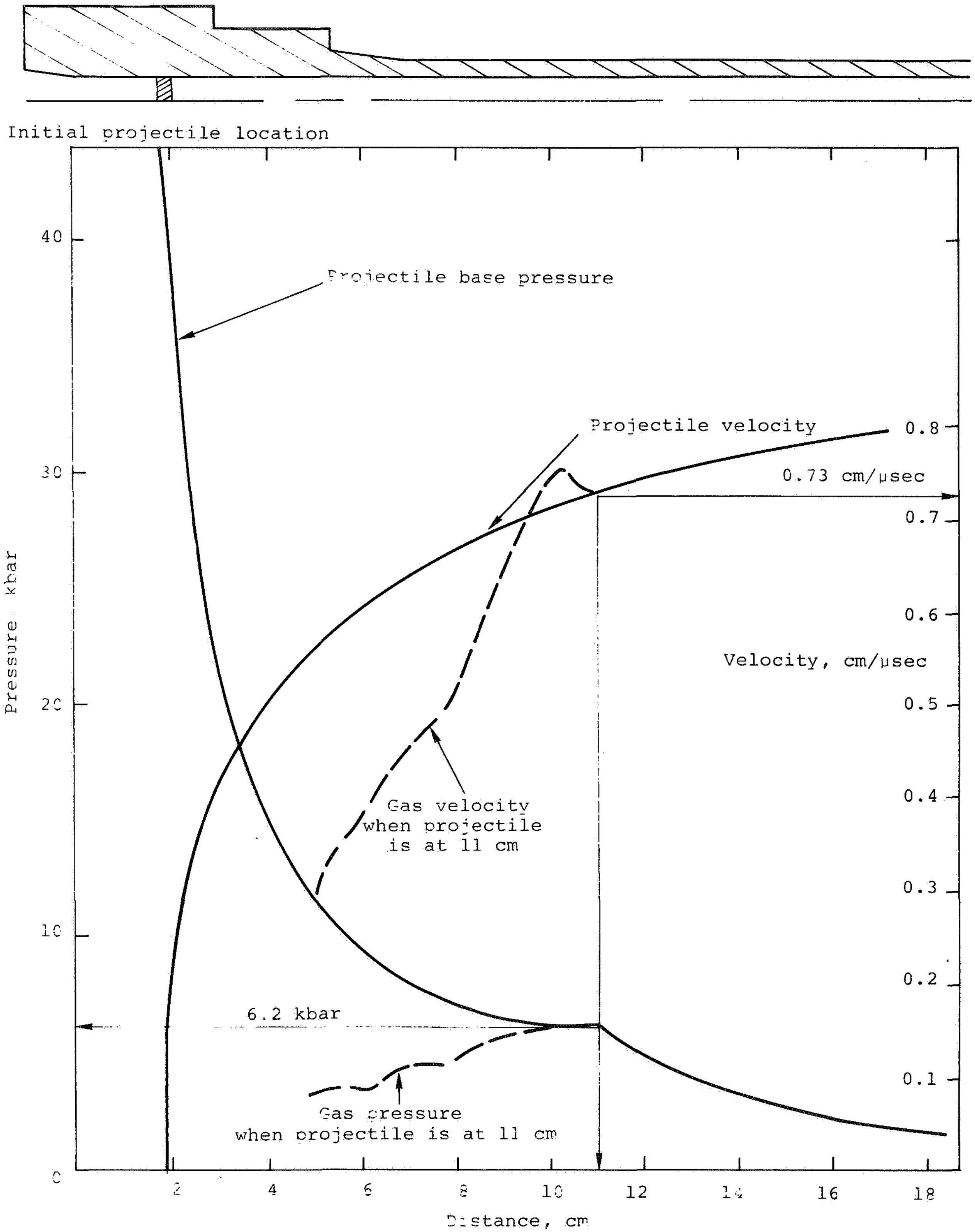
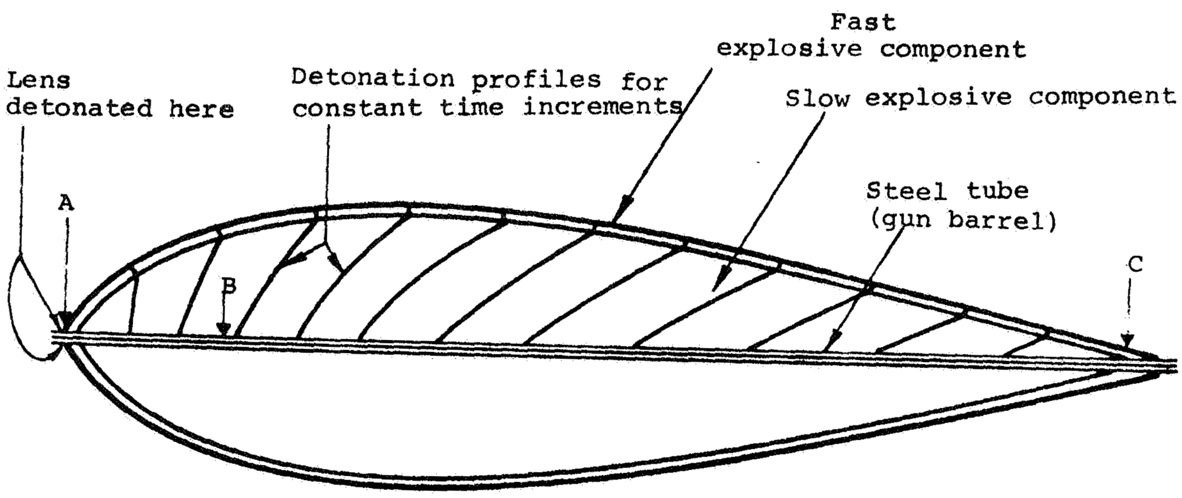


Figure 6 GANGPOD 245-32, base pressure and projectile velocity profiles.

various pressures and velocities were selected for pickup conditions. The calculations indicated that a 20-percent variation in pickup pressure introduced a variation of less than 5 percent in final projectile velocity. The highest final projectile velocity was attained when a low pickup pressure was assumed, although this also carried the greatest attendant risk of the piston overtaking the projectile. Variations of the velocity profile in the gas behind the projectile had no significant effect on the final projectile velocity.

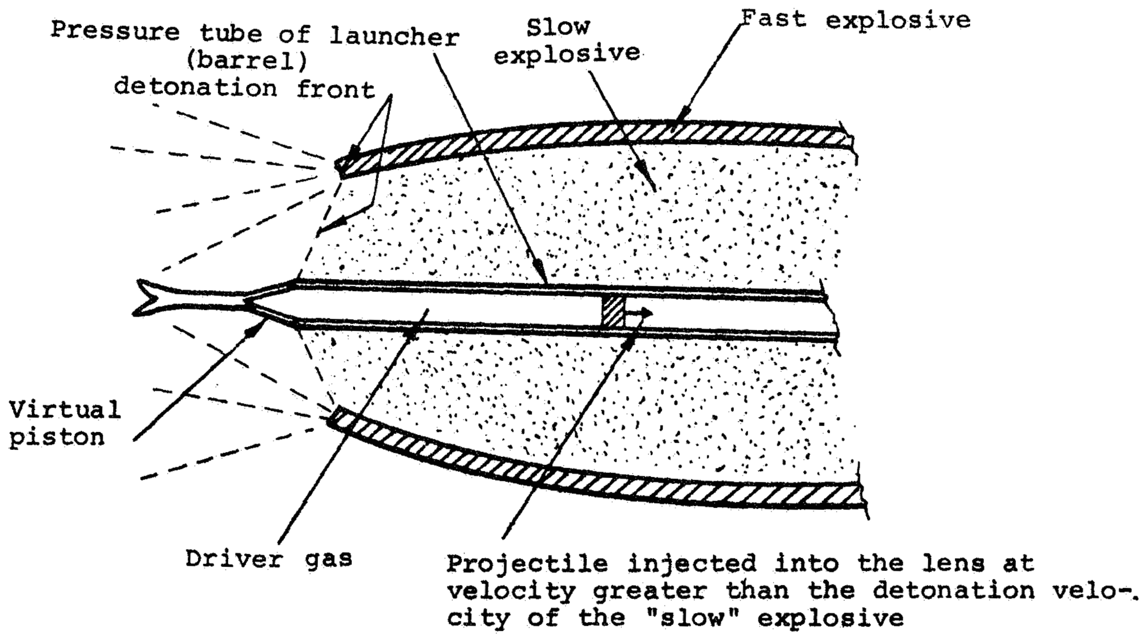
The second-stage piston trajectory is generated by an explosive lens. The operation of such a lens is shown schematically in Figure 7. After the lens is initiated, a detonation wave front proceeds along the barrel at a velocity equal to the detonation velocity in the slow explosive. However, the higher detonation velocity of the fast explosive, combined with the changing contour of the interface between the fast and slow explosives, produces a continuously tilting wave front (phased detonation wave) in the slow explosive. As a result, the piston formed by the collapse of the barrel begins to accelerate. The phase velocity of the lens can be controlled to provide any desired acceleration history in the second stage, including a constant-base-pressure launch cycle. The explosive lens is a predictable technique for producing phased detonation waves for second-stage augmentation schemes. It can be used as an in-contact explosive to directly collapse a launcher barrel, or it can be used to launch a phased flyer plate which in turn impacts the barrel. Initial efforts in this program as in previous programs, used the former approach.

Under Contract NAS 2-4903, the problem of obtaining complete barrel collapse was identified. Several two-stage launchers were fired, having varying lens designs (both symmetric and asymmetric);



Note: Detonation velocity along the outside of the tube is constant from A to B and increases uniformly from B to C.

a. Initial Configuration



b. Lens in Operation

Figure 7 Operation of an explosive lensing system.

however, complete barrel collapse was not observed. Each of these lens designs utilized nitromethane in contact with the barrel, relying on the high-pressure detonation products to collapse the barrel. Having identified incomplete barrel collapse as a limiting factor in obtaining high velocities, the present program concentrated its efforts on studying and finding solutions to the barrel-collapse problem.

Two distinct phenomena were conjectured as being possible causes of incomplete collapse. High pressure in the barrel, resulting from an auxiliary pump cycle or from choking of the gas flow as the barrel begins to collapse, could conceivably prevent closure. This mechanism is only dependent upon one-dimensional gasdynamic interactions and therefore should be calculable with the GANGPOD computed code. The second phenomena considered to prevent barrel closure is the interaction of boundary layer gases with the collapse process. This phenomena is necessarily of a two-dimensional nature and is not calculable using GANGPOD. A matched calculation and experiment were conducted in an attempt to distinguish between these two possible mechanisms.

3.1 PERFORMANCE CALCULATION

A complete GANGPOD calculation of the two-stage launcher was performed, including startup of the second-stage lens. The explosive was initiated at the appropriate time for lens startup. The calculation was run sufficiently long to include the collapse of the barrel and the concurrent interaction with the gas flow behind the projectile. As anticipated, the choking and subsequent stagnation of the gas flow by the collapsing barrel produced a significant pressure increase behind the initial collapse point.

Figures 8 and 9 present calculated pressure and wall profiles at two different times. Figure 8 represents conditions coincident with the initiation of the explosive surrounding the barrel. Eight microseconds later, the initial barrel collapse is complete and the second-stage piston has formed. This situation is shown in Figure 9. A region of high-pressure gas now exists both in front of (mostly due to convergence) and behind the collapse region. However, the calculation indicated that it is possible with the present gasdynamic launch cycle to collapse the barrel and form an effective second-stage piston. Subsequent to this calculation a two-stage launcher was designed and fabricated, incorporating as nearly as possible the same design and timing as the GANGPOD calculation. The shot was intended to confirm or deny the GANGPOD barrel-collapse calculation.

3.2 TWO-STAGE LAUNCHER EXPERIMENTS

3.2.1 Shot 245-2. Shot 245-2 was the first two-stage launcher in the present program. The shot was intended to verify the second-stage design concepts resulting from the GANGPOD calculations. The first stage of the launcher was identical to that of shot 245-1, so that the projectile-acceleration trajectory and timing were known. The outside diameter of the barrel was tapered from the breech to the muzzle, such that the wall thickness decreased linearly from 3/16 inch to 1/16 inch. The decreasing wall thickness should allow easier and more rapid barrel collapse as the effective ratio of explosive and wall mass (C/M) is increased. A decrease in the collapse time will help to offset the lengthening of the collapse region due to the phased detonation velocity.

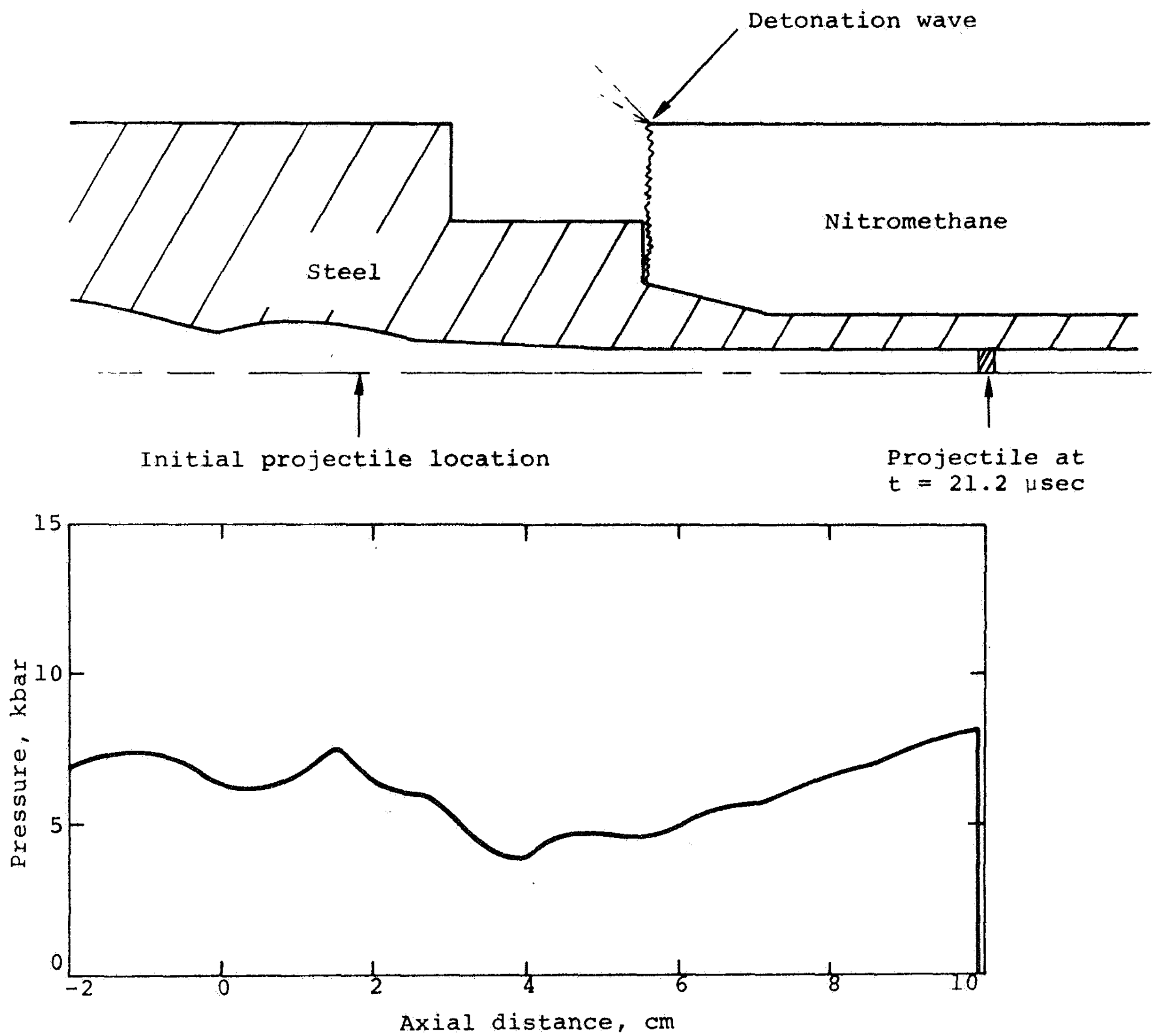


Figure 8 Wall and pressure profiles at t = 21.2 μsec from GANGPOD 245-33.

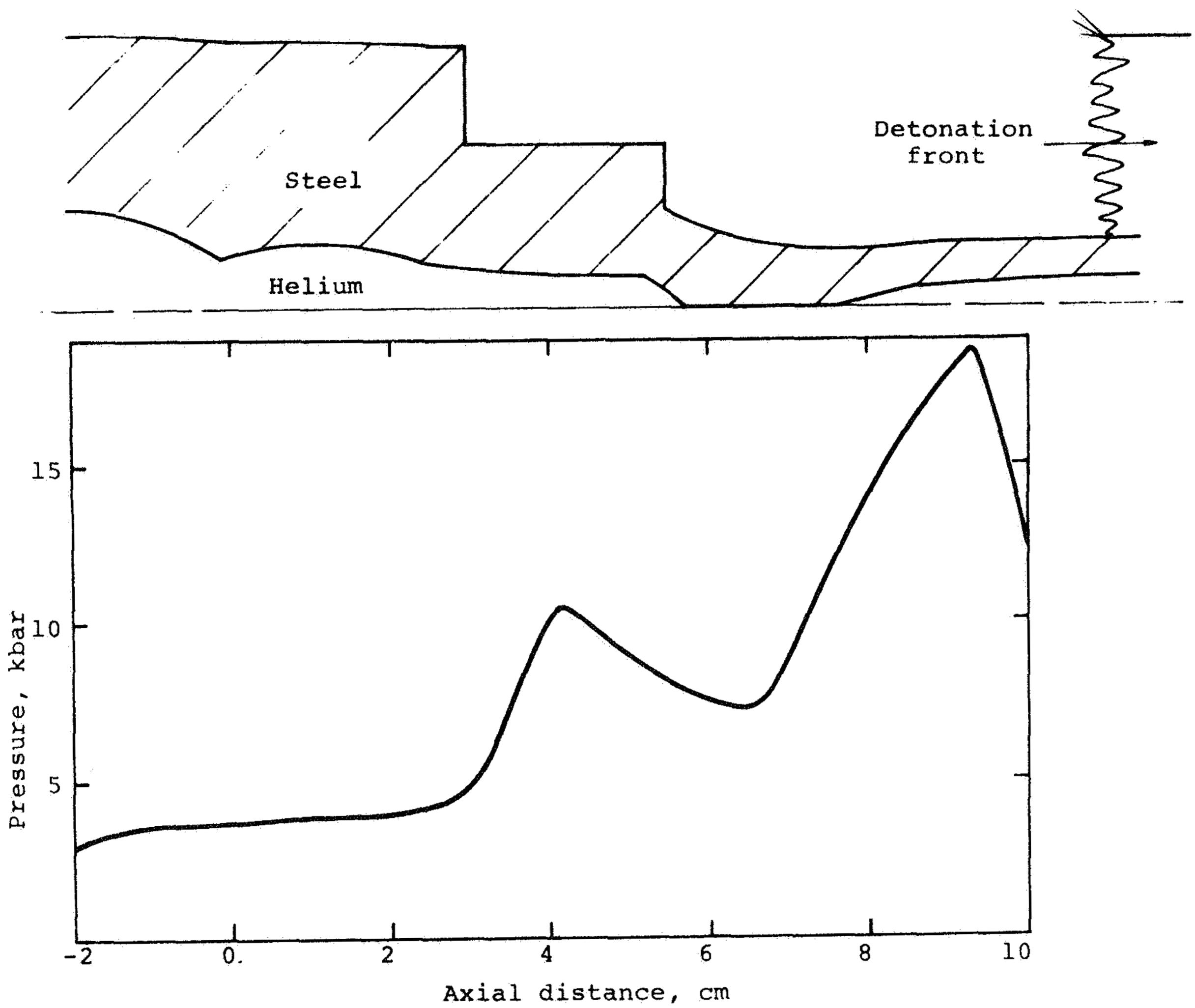


Figure 9 Wall and pressure profiles at t = 29.2 μsec from GANGPOD 245-33.

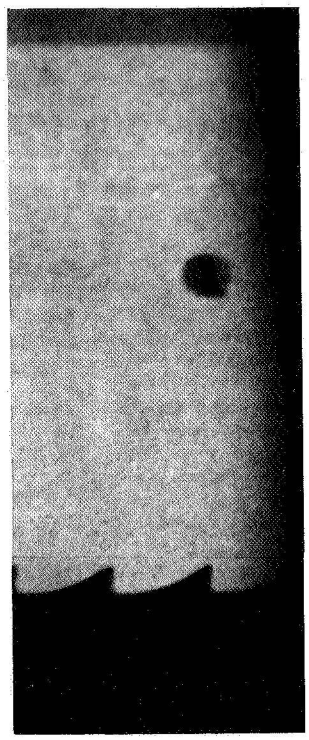
The explosive lens employed a somewhat different configuration and initiation technique. The main nitromethane reservoir was a Lucite tube, phased by two opposing symmetric fins. The initiation end of each fin was fabricated to conform to the desired detonation-front contour at lens startup. A line wave initiator provided simultaneous ignition of the desired contour. This initiation technique did not require a long run-in distance to form the correct wavefront and thereby minimized timing requirements. The programmed lens acceleration was from 6.3 to 13.4 km/sec over 60 cm. This acceleration corresponds to a uniform 5-kbar base pressure acting on a 0.317-cm-thick magnesium-lithium projectile. The lens timing was chosen to allow 5 cm of gas between the detonation wave and projectile at startup.

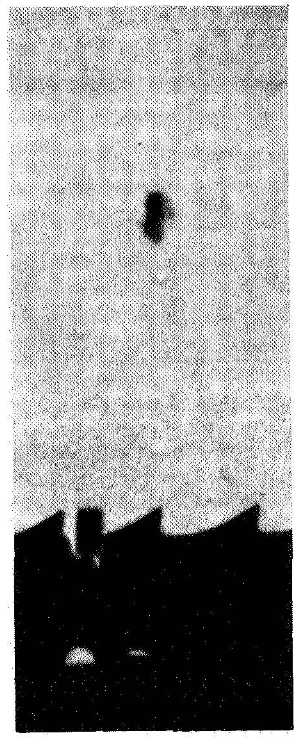
The ideal projectile velocity for this launcher, assuming ideal pickup conditions and complete barrel collapse, is 13 km/sec. A variation in velocity of $\pm$ 1 km/sec can be anticipated from slight deviations in pickup conditions. Larger velocity variations would indicate that the second stage did not function as designed.

The projectile was launched to a velocity of 10.9 km/sec, determined from range switch data, streaking camera record, and pulsed radiographs. The X-rays, shown in Figure 10, indicate that the projectile was rotating in flight and had a small fragment separating from the main body. The lens initiated as programmed, although the detonation front in the lower fins was 3 μsec behind the upper fin. This discrepancy, caused by the somewhat awkward positioning of the line wave initiators, is thought to have not seriously affected the launcher performance. The lens appeared effective in trapping gas, as an estimated 7 cm of gas separated the collapse and projectile at the end of the lens. However, this result is inconsistent with the low projectile velocity.

Cobra 1

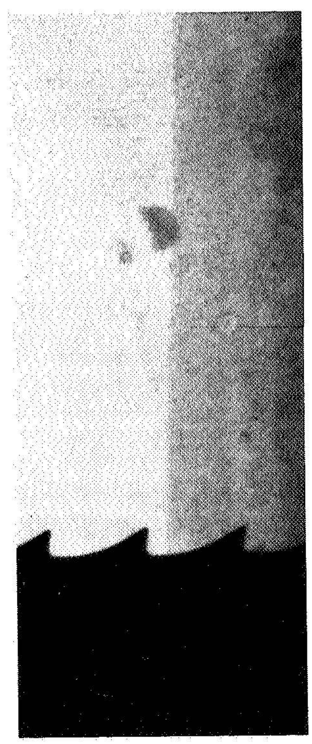
47
body diameters
downstream





Cobra 2

65
body diameter
downstream



Cobra 3

91
body diameters
downstream

Figure 10 Pulsed radiograph of projectile travelling at 10.9 km/sec, Shot 245-2.

The launcher barrel was recovered and sectioned to determine the extent of collapse. The maximum was achieved at the breech end of the barrel and amounted to a 55-percent reduction in the inside diameter of the barrel. The collapse became progressively less towards the muzzle. A 10-percent reduction in inside diameter was observed 30 cm from the breech. The tapered barrel wall was apparently not helpful in achieving more complete barrel collapse.

A possible explanation for the early arrival and low velocity of the projectile observed in this shot is that the projectile underwent a faster than anticipated early acceleration. Projectile mass erosion has the effect of decreasing the thickness (length) of the projectile, which will increase the acceleration caused by a 5-kbar base pressure. Previous computer calculations showed that low velocities resulted from systems where the initial projectile acceleration is faster than the programmed lens acceleration.

It was concluded that the shot was a valid test of the second-stage collapse process, despite the small error in timing of the lower fin. It seemed unlikely that further changes in operating conditions would significantly alter the experimental results. The base pressure against which the barrel is attempting to collapse is already small compared to detonation pressures, and the ratio of explosive to wall thickness for the lens and barrel is essentially infinite. Obviously, an important phenomenon not accounted for in the code calculations exists and prevents complete barrel collapse. Boundary-layer growth behind the projectile is one phenomenon not accounted for which has been presumed to interfere with the collapse process. However, before trying to overcome the collapse problem, it was decided to explore the degree of augmentation achievable with the present system.

3.2.2 Shot 245-3. The objective of this shot was to determine whether significant velocity augmentation could be realized with only partial barrel collapse. The launcher, shown in Figure 11, was nearly identical to that used in shot 245-2; however, some modifications were made in the lens design and operation. The programmed acceleration was from 6.5 to 14.4 km/sec over 60 cm. This increased acceleration was chosen to match that experienced by an eroded projectile with a 5 kbar base pressure. The initiation concept was maintained, although the line wave initiators were replaced by multipoint initiation, five detonators being used on each fin. The latter technique greatly simplified shot setup and improved simultaneity between the fins.

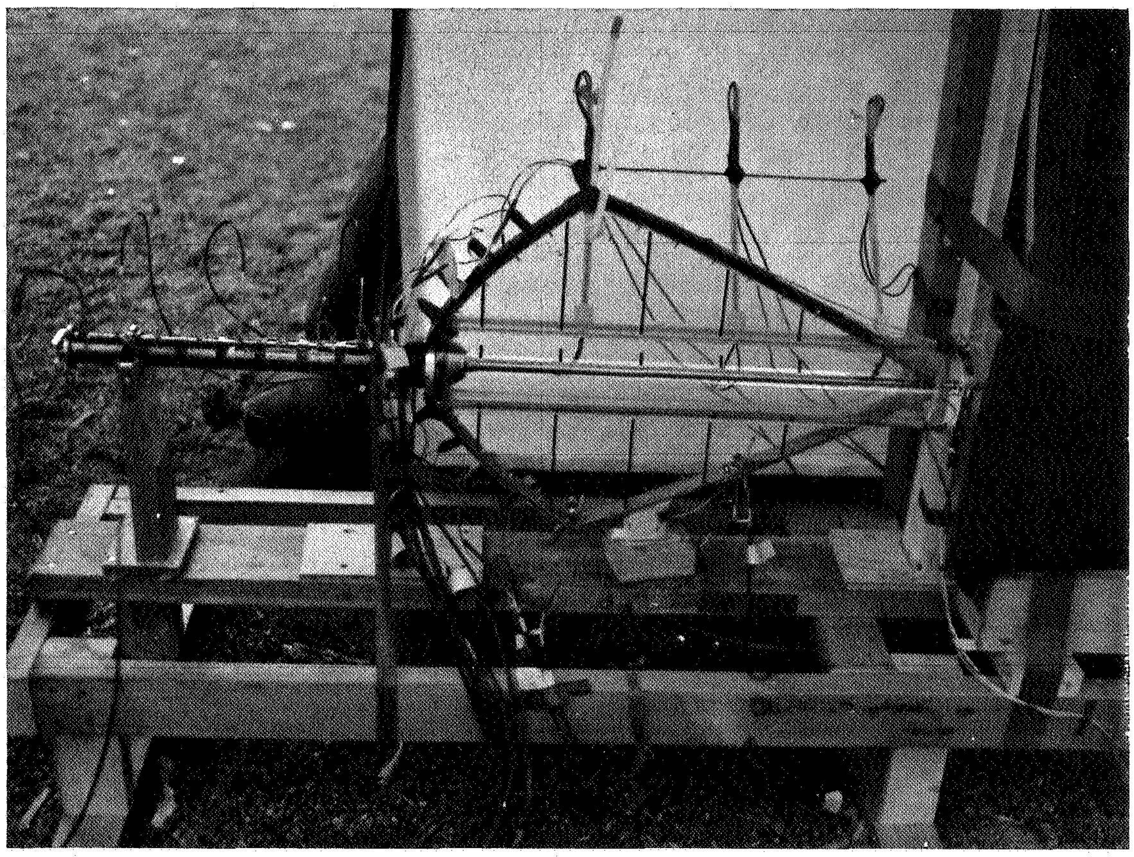


Figure 11 Test setup, shot 245-3.

The shot was fired, and all pin diagnostics and range switches reported. The data indicated that the driver and lens functioned ideally, although the X-rays showed no projectile and the target was only pitted. Range switch data indicated that a very small particle emerged from the muzzle and was rapidly decelerated by aerodynamic drag forces. The particle size was below the resolution of the X-ray system.

It was concluded that the projectile was run over by the detonation, allowing only a small fragment to exit the muzzle. The implication of this result is that a partial collapse of the barrel is not capable of significantly augmenting projectile velocity. It appears likely that the principle effect of the explosive lens is to confine and to provide a limited pumping action on the barrel. This conjecture is also consistent with the results of the shots fired under the previous program, in which the lens typically provided a 2 km/sec velocity boost, regardless of programmed lens acceleration. If the role of the lens is simply confinement and pumping, the details of the phased acceleration are unimportant as long as the detonation does not overtake the projectile.

The primary conclusions from these two shots are that two-dimensional gasdynamic effects prevent barrel collapse and that partial barrel collapse is not capable of significantly augmenting projectile velocity. These results indicated a need to investigate the phenomenon preventing barrel collapse.

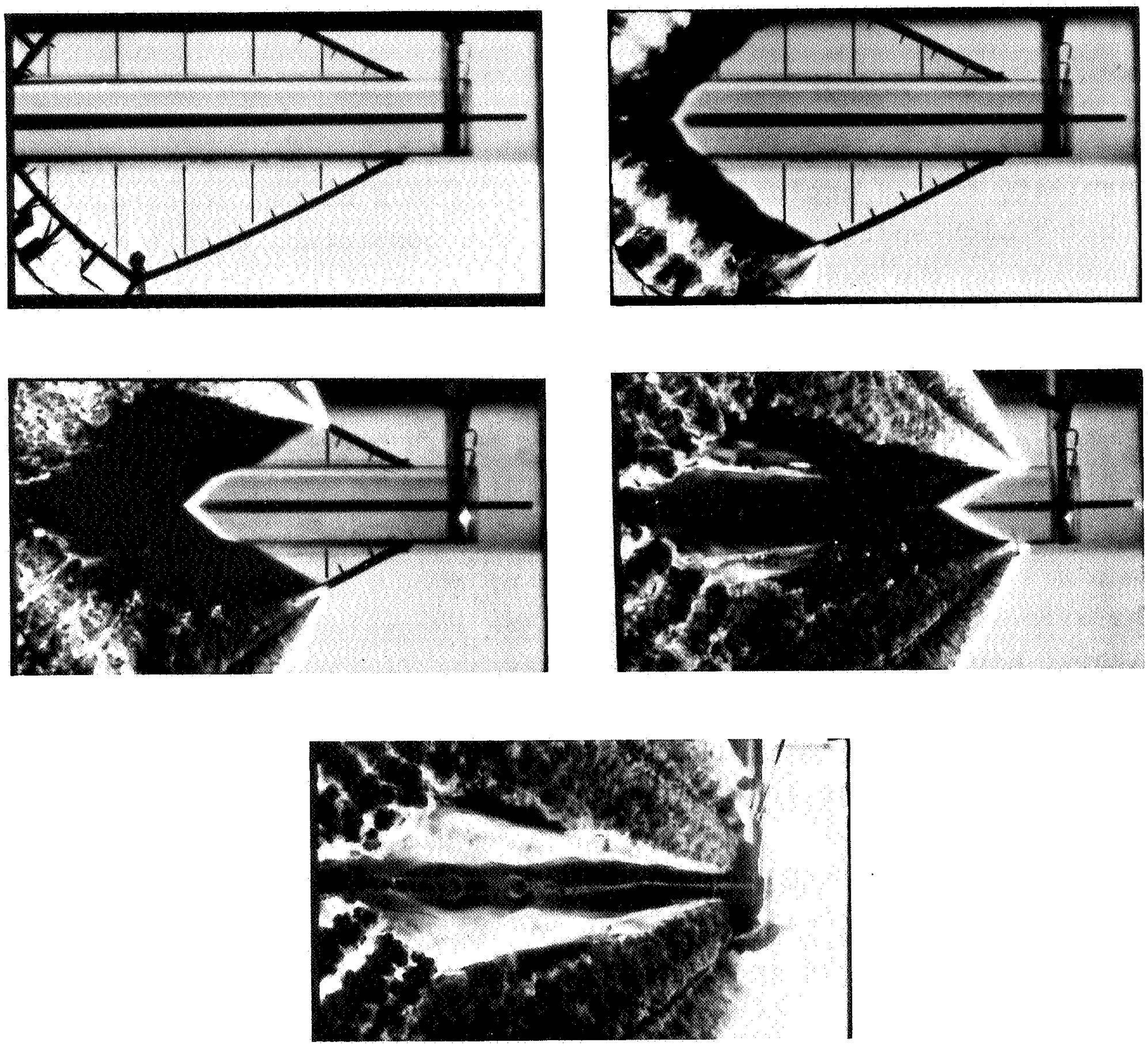
SECTION 4
BARREL COLLAPSE CONSIDERATIONS

The initial two-stage launcher experiments demonstrated the inability of the explosive lens to collapse a barrel containing flowing high-energy gas. To confirm the conjecture that the dynamics of the gas are responsible for preventing collapse, a shot was designed in which the explosive lens operation could be observed without the presence of high-pressure or high-velocity gas flow.

4.1 EXPLOSIVE LENS SHOTS

4.1.1 Shot 245-4. The purpose of shot 245-4 was to observe the effectiveness of the explosive lens in collapsing a barrel without high-pressure or high-velocity gas flow. A lens and barrel identical to that in shot 245-3 were used. The barrel was flushed with helium at 1 atmosphere. A B&W Model 189 framing camera monitored the lens operation.

The camera record from the shot indicated that the lens functioned flawlessly, with the intersection of the phased detonation waves from the upper and lower fin occurring on the centerline of the barrel. Figure 12 shows five selected frames, spaced at 20-μsec intervals. The vertical lines on the upper and lower fins serve as 10-cm grid markers. The detonation propagates from left to right and is visible as the bright front on the photographs. The barrel was recovered and sectioned, and showed



1 2 3 4 5

Figure 12 Selected frames at 20 μsec intervals from framing camera record, Shot 245-4.

complete collapse for the first 31 tube diameters, after which a hole in the center of the barrel grew progressively larger. This behavior has also been observed in driver pressure tubes (Reference 2), where it has not been possible to explosively collapse arbitrarily long lengths of tubing. In pressure tubes, this effect has been correlated fairly well with boundary layer growth.

Conclusions from the experiment are that the flow dynamics (including boundary layer) prevent the initial barrel collapse in a two-stage launcher and that boundary layer growth is responsible for the increasing size of the center hole in long barrels. The results from this and the previous experiments require that a technique be developed to collapse the barrel despite the presence of a boundary layer.

It is instructive to consider a possible interaction between the boundary layer and the collapsing barrel. From a frame of reference traveling with the detonation velocity, the trapped gas ahead of the explosively formed piston appears at rest. The walls of the barrel, however, move into the collapse region at the detonation velocity. Assuming a simple model, in which the boundary-layer gas is moving toward the piston with the wall velocity and has the same density as the free stream gas, we can estimate the stagnation pressure of the boundary-layer gas. This pressure must be overcome by the collapsing walls in order to stagnate the boundary-layer gases flowing into the collapse region. For conditions appropriate to startup of the second stage, let:

$$P = 5 \text{ kbar}, \ u = 6.5 \text{ km/sec and } \rho = 2.1 \times 10^{-2} \text{ grams/cm}^3$$

The stagnation pressure associated with this flow is $P + \rho u^2$, approximately 14 kbar. In addition, convergence and viscous effects will significantly increase the pressure near the collapse point. The resulting pressure levels of several tens of kilobars become comparable to the volume burn pressure of nitromethane (57 kbar) and can have a large influence on the collapse process. It is desirable to generate collapse pressures in the barrel very much larger than the opposing gasdynamic effects. In-contact explosives, however, cannot maintain sufficiently high pressures.

4.1.2 Shot 245-5, Flyer Plate Impact. A technique that can generate barrel pressures of up to 1 Mbar (10^6 atmospheres) is to explosively accelerate a metal flyer plate, which subsequently impacts the barrel. The high energy-density of the flyer plate produces very high pressures upon impact. A phased impact trajectory can be obtained by accelerating the flyer plate with an explosive lens system. This technique has been termed an impact lens.

Shot 245-5 was the first attempt to collapse a barrel using the impact technique. A phased explosive system was used to accelerate a 16-cm-wide by 60-cm-long by 0.635-cm-thick steel flyer plate. The explosive-flyer plate system had a C/M of 2 and was designed to accelerate the plate to 1.7 km/sec. A plane-wave impact stress of 360 kbar is produced in the barrel at this impact velocity. An impact lens was located on both the top and bottom sides of the barrel, with the flyer plates producing a vertically symmetric impact. Each flyer plate had a 3.5-cm standoff from the barrel. The volume between the plates was flushed with helium. Each lens was phased from 6.3 to 14.4 km/sec. Figure 13 shows the lens and barrel ready for firing.

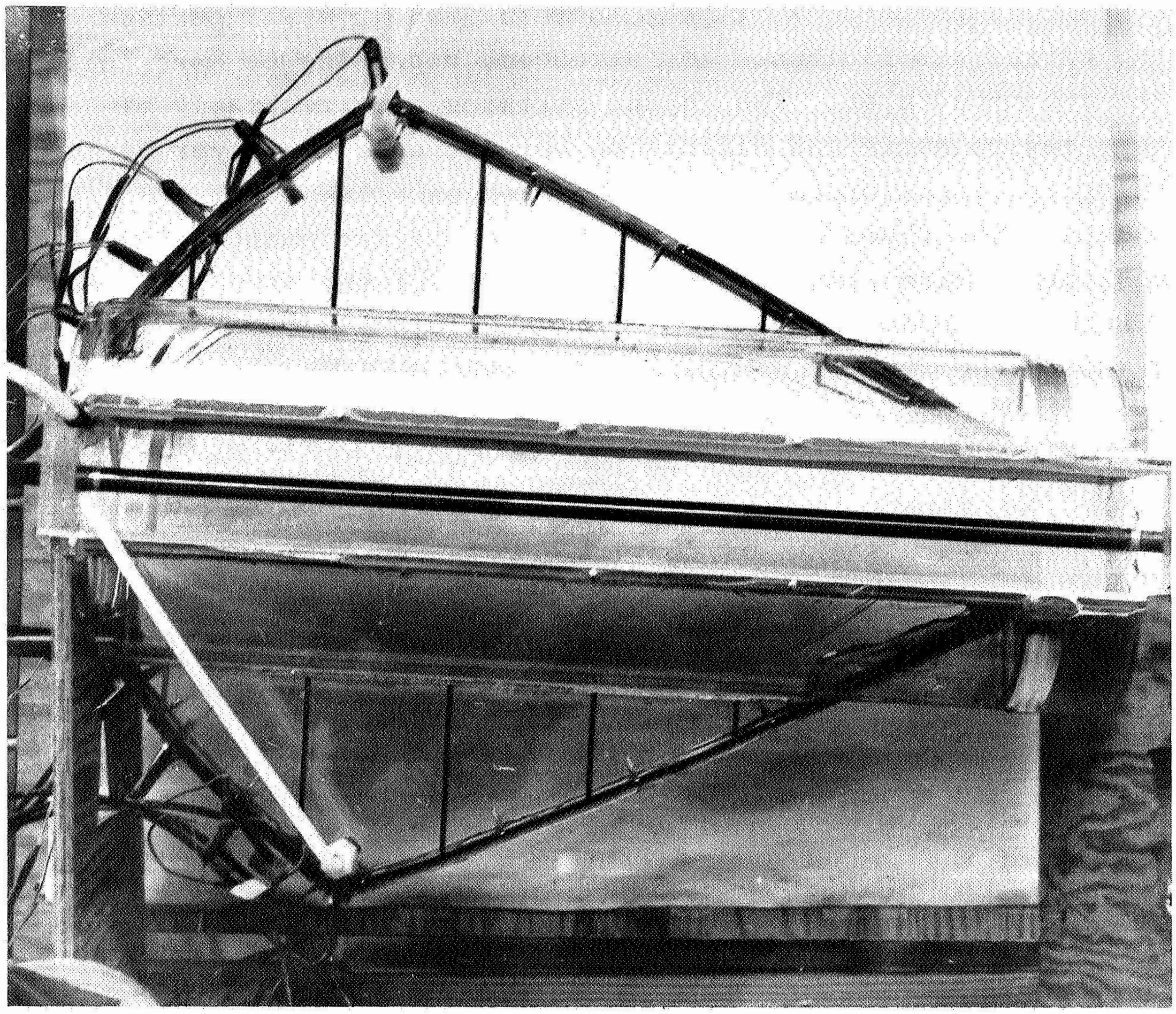


Figure 13 Test setup, Shot 245-5.

The shot was most successful, having collapsed the barrel for the entire 60-cm length of the lens. Sectioning the ends of the recovered barrel revealed that even the muzzle end was completely sealed. This shot was the first barrel or pressure tube to be collapsed for 95 tube diameters. The central portion of the barrel was flattened and shredded, appearing to have collapsed and rebounded open. The impact stresses are presumably higher in this region where end effects do not decrease the flyer plate velocity. Lens operation was observed on a B&W Model 189 framing camera. The flyer plate impact trajectory was monitored by a resistance wire running along the length of the barrel. These diagnostics provided data on plate acceleration time. A photograph of the recovered barrel is presented in Figure 14. The lower two sections of barrel were located between the two flyer plates. The upper section is the muzzle portion which extended beyond the impact region. Portions of the barrel near the breech and muzzle were sectioned to verify complete closure.

The significant result of this shot is that a new technique was demonstrated to be far more effective than in-contact explosives in collapsing tubing. This result stems from the higher energy density attainable in a flyer plate. In addition to being capable of collapsing longer lengths of barrel, the higher energy density of the impact lens technique should allow the attainment of higher phase velocities than an in-contact explosive system, as higher collapse velocities are attainable. The critical test of the technique, however, lies in its effectiveness at collapsing barrels containing high-pressure and high-velocity gas.

4.2 LAUNCHER EXPERIMENTS UTILIZING IMPACT TECHNIQUE

4.2.1 Shot 245-6. The first test of the impact lens as a second-stage augmentation technique on a launcher was shot 245-6.

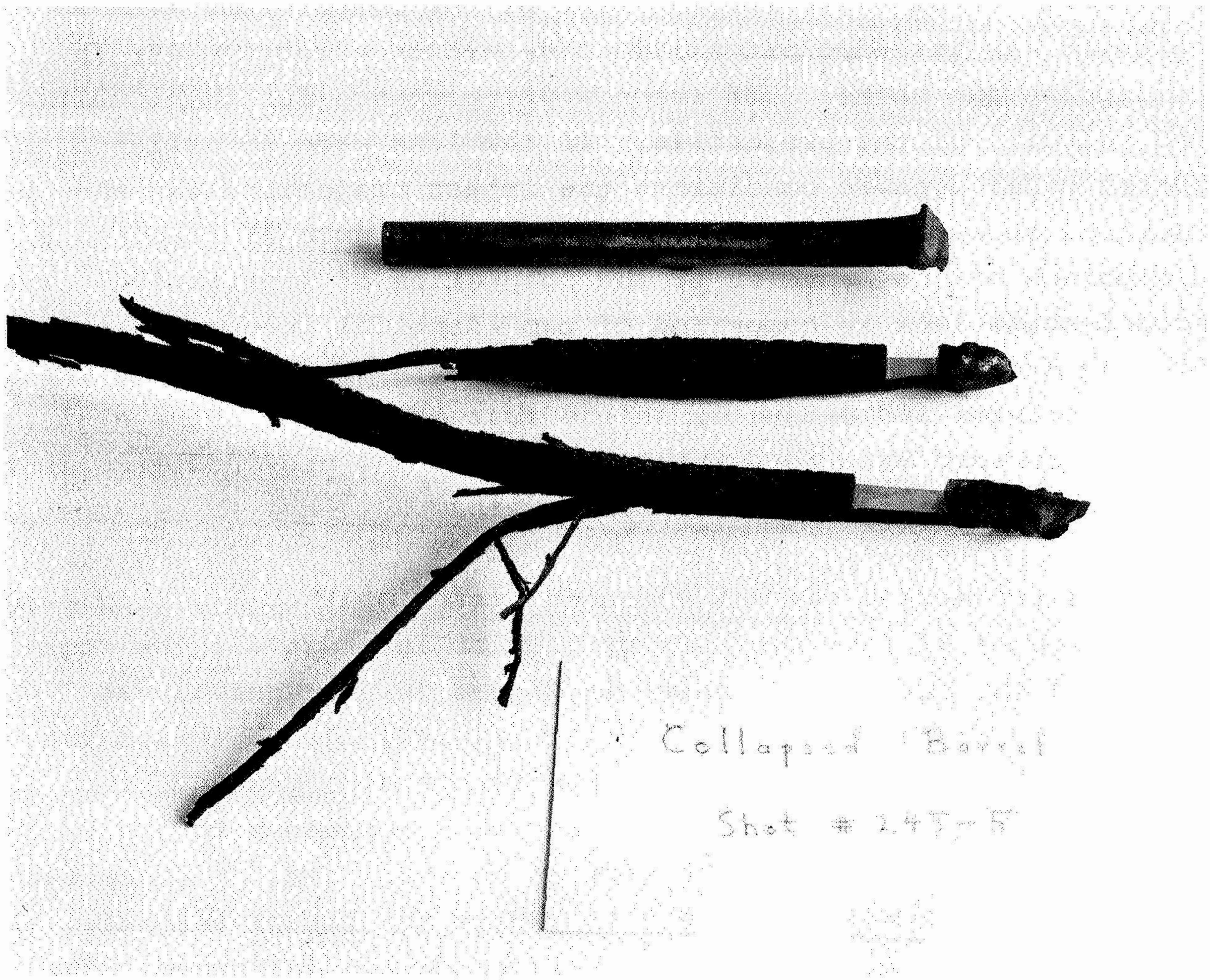


Figure 14   Recovered barrel from impact lens, Shot 245-5.

The lens design successfully fired in shot 245-5 was utilized in conjunction with the basic launcher design from previous shots. Timing data (in particular, plate acceleration time) was obtained from shot 245-5. This initial test of the impact lens with a launcher was intended primarily to determine effectiveness in collapsing the barrel. Of secondary importance was the condition and velocity of the projectile. If the lens were to collapse the barrel under dynamic conditions the impact trajectory can then be modified to optimize projectile velocity. Figure 15 presents a photograph of the launcher at the completion of fabrication. The second-stage lens is comprised of two identical though independent phasing systems and flyer plates. Nitromethane was used as the slow explosive and Detasheet as the fast explosive. Five RP-1 detonators were used to initiate each lens and provided excellent simultaneity between the two phasing fins.

The projectile was not launched intact, although a fragment did emerge at 11.2 km/sec. Of particular interest was the condition of the barrel. As shown in Figure 16, the barrel was sprung open at the breech end, yet completely closed toward the muzzle end. It is presumed from its flattened appearance that the barrel had closed upon impact and then rebounded to its present position. Toward the muzzle, however, the C/M decreased somewhat and end effects tended to reduce the impact velocity. In this region the barrel is more likely to remain collapsed. The severe bend in the barrel is thought to have been caused by the collapsing barrel overtaking the projectile. An enlarged view of the muzzle end, along with a centimeter scale, is shown in Figure 17. The barrel has been sectioned to allow the cross-section to be examined in the vicinity of the projectile over-run. The collapse was found to be complete on the upstream side of the overtake point.

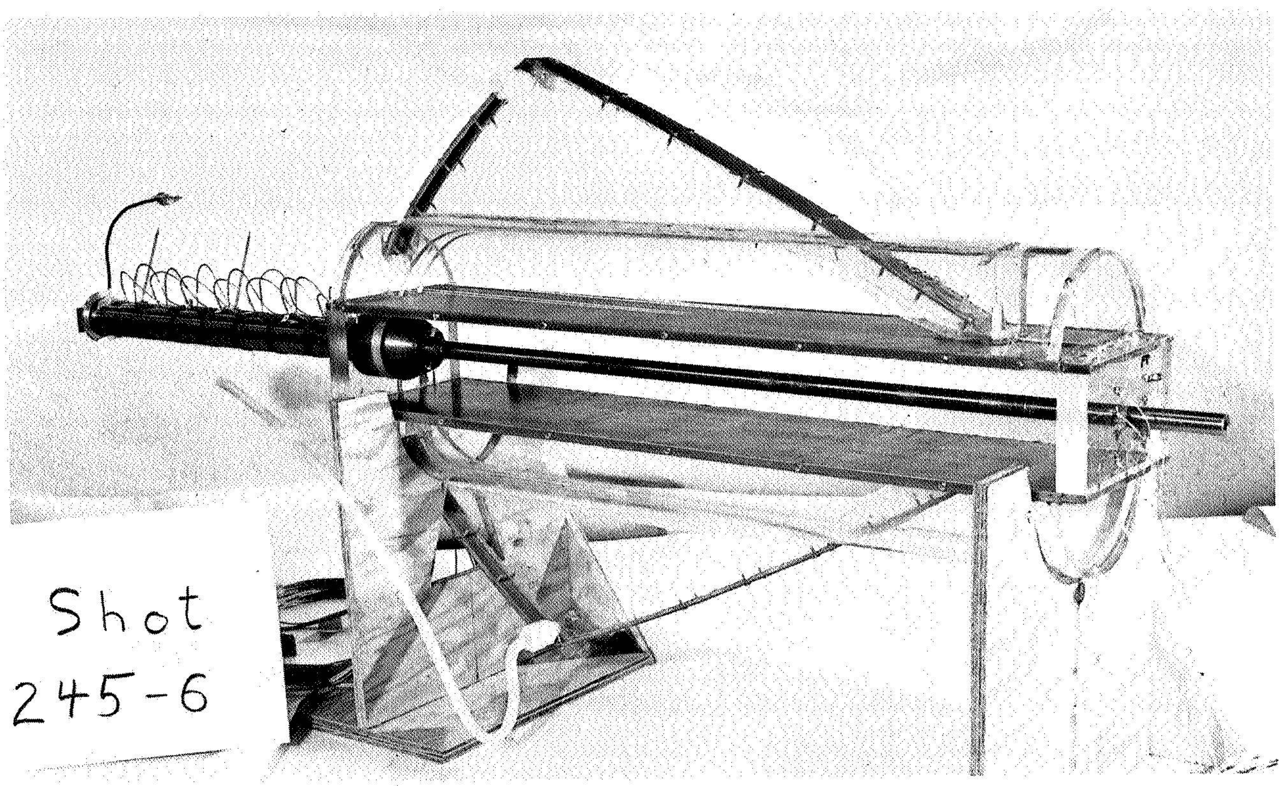


Figure 15 Shot 245-6, the first launcher employing an impact lens.

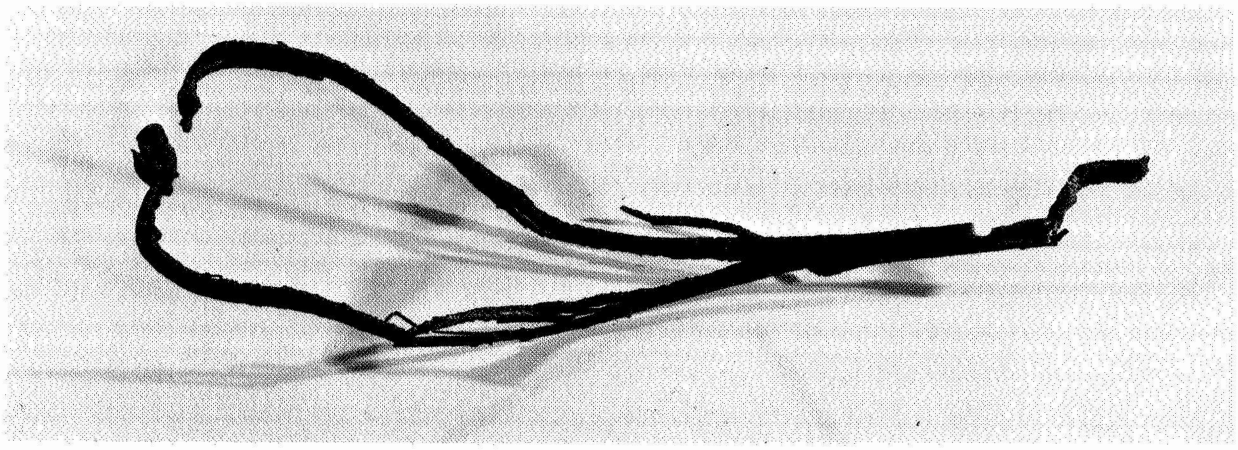


Figure 16   Recovered barrel from Shot 245-6.

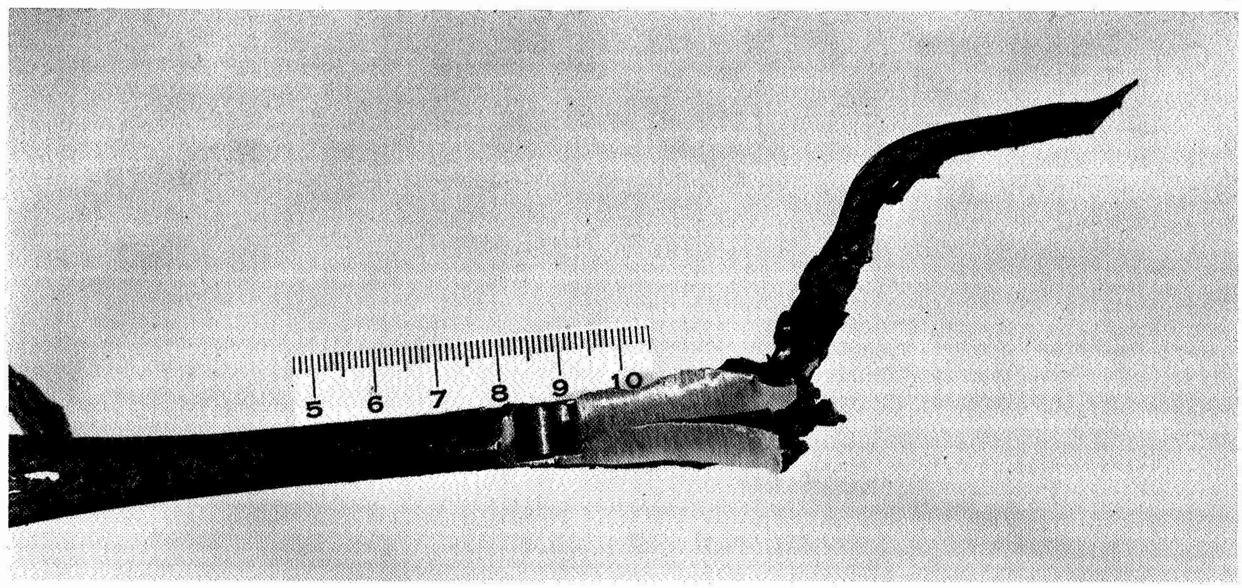


Figure 17   Enlarged view of muzzle end of recovered barrel,
Shot 245-6.

The impact technique apparently was successful in collapsing the barrel despite the dynamics of the gas flow behind the projectile. Although the complete length of barrel was not permanently collapsed, the muzzle end was completely sealed. Based on previous experience the muzzle is the most difficult part of the barrel to collapse. The appearance of the breech end of the barrel was that it had initially closed and subsequently rebounded open.

Analysis of the second-stage trajectory data indicated that the detonation wave arrival at the steel flyer plate was correctly timed and phased from 6.3 to 14.4 km/sec over a distance of 60 cm. However, the flying time of the plate (defined as the time interval between detonation wave arrival and barrel impact at a given point along the lens) varied from 33 μsec at the breech to 27 μsec near the muzzle end of the lens. Consequently, the barrel impact point accelerated more rapidly than the projectile and the projectile was overrun by the barrel collapse. The variable acceleration time resulted from the continuously changing angle between the phased detonation front and the steel flyer plate. As this angle decreases the detonation wave approaches a normal reflection at the flyer plate, which causes a more rapid plate acceleration. This effect is calculable and can be accounted for in the timing and design of phased flyer plate systems.

4.2.2 Shot 245-7. The next shot 245-7 was similar in design to 245-6 except that the lens acceleration was reduced slightly and the timing delayed to better match the acceleration of the projectile. Starting at 6.3 km/sec the phased detonation accelerated to 13.4 km/sec over 60 cm. The detonators initiating the lens were timed such that the impact trajectory including the variation in plate flying time was closely matched to the desired projectile acceleration.

The projectile was launched to 9.5 km/sec although its back side was damaged. The lens timing operated as programmed, as determined by shorting switches on the barrel responding to plate impact. As in the previous shot, the breech end of the recovered barrel appeared to have been collapsed and rebounded open. The muzzle however was completely closed and retained between the two collapsed flyer plates. The recovered flyer plate and barrel assembly was sectioned and is shown in Figure 18. Not only has the barrel been completely collapsed, but the flyer plates are intermittently bonded together.

Despite this impressive barrel collapse, the projectile velocity was relatively low and the second stage provided only a small velocity augmentation. The change in lens timing and decreased acceleration in this shot apparently prevented the projectile from being overtaken by the lens, however, the second stage was no more effective than in shot 245-6. The behavior of the launcher in both instances indicates that the second-stage piston leaks driver gas to the extent that there is virtually no gas trapped behind the projectile. However, the collapse process seems effective as evidenced by the closed muzzle portion of the recovered barrels.

A possible mode of gas leakage is that the flyer plate impact with the barrel causes the sides of the barrel to rupture before collapse can occur. An estimate of the time required to collapse the barrel can be attained from the incident flyer plate velocity of 0.17 cm/μsec. Assuming a plane wave impact (which admittedly is not strictly valid, but is representative of the physics and is easily calculable) of a steel flyer plate on a steel barrel, the inner wall of the barrel will move inward with the characteristic free surface velocity, which is equal to the flyer plate

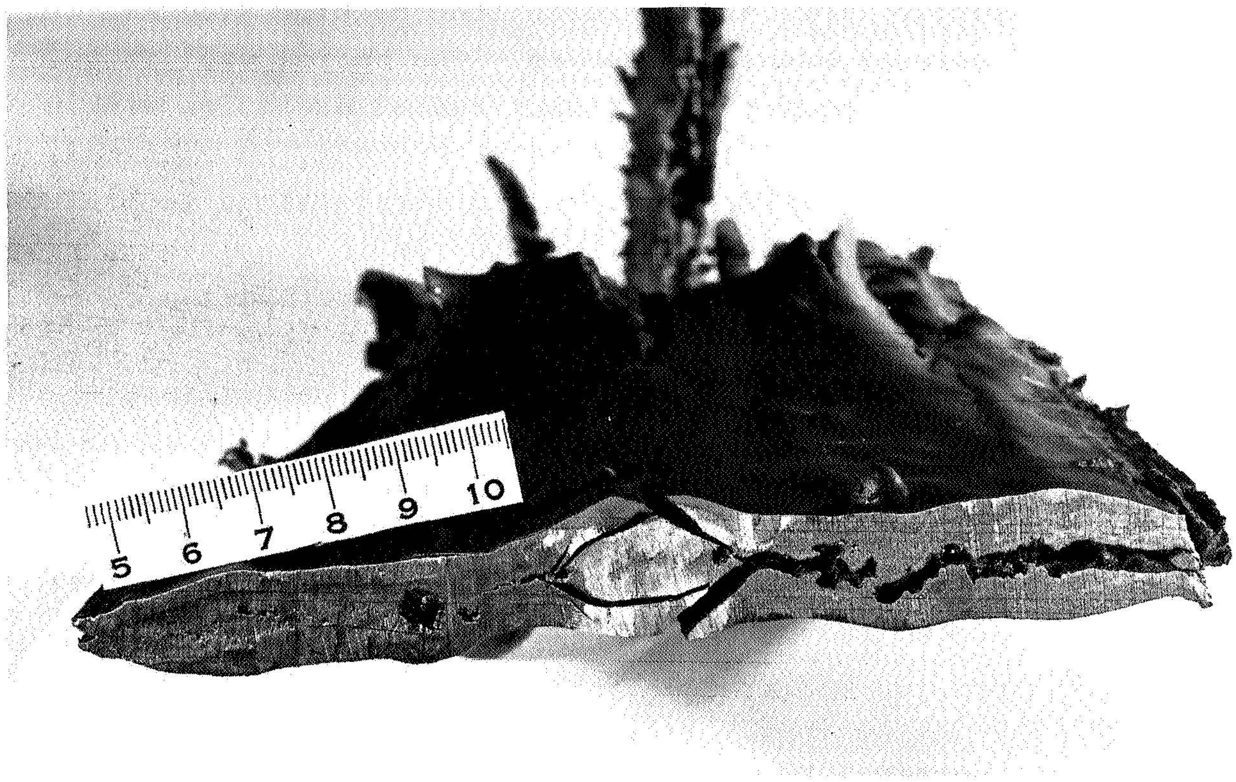


Figure 18 Recovered barrel integral with collapsed flyer plate, Shot 245-7.

impact velocity. For complete collapse to occur the barrel wall has to move inward a distance of one radius, which is 0.317 cm. At a constant velocity of 0.17 cm/μsec, collapse should occur approximately 2 μsec after the incident impact shock arrives at the inner barrel wall. For barrel rupture to occur within this time scale, simple inertial considerations require internal gas pressures of several hundred kilobars. The barrel wall is too thick (0.635 cm) to permit significant radial expansion within the time scale of the collapse process. However, an extremely complex interaction of strong shocks and rarefactions is produced in the barrel walls by the plate impact. It is conceivable that a particular interaction of wave fronts tends to spall off the sides of the barrel, before collapse can be achieved. To determine whether barrel rupture does occur during the collapse process, a shot was designed with particular attention given to observing the flyer plate impact and subsequent collapse.

4.2.3 Shot 245-8. The twofold purpose of this shot was to critically observe the barrel collapse process for gas leakage and to increase the projectile velocity over the previous shot by slight changes in lens timing. The launcher and lens designs were nearly identical to shot 245-7. Modifications of the flyer plate startup and the reservoir to barrel transition were included to preclude any chance of the projectile being damaged prior to acceleration down the barrel. A smooth conical steel transition between the reservoir diameter and barrel eliminated any abrupt discontinuities in wall thickness that could rupture and cause gas leakage under severe radial expansion. The flyer plate was bent to conform to the conical shape and maintain the 3.5-cm standoff distance from the reservoir as well as the barrel.

The lens operation was observed by a framing camera. A square steel bar 0.635 cm on a side was attached along the edge of each flyer plate to retard the expansion of the detonation products into the camera view. Several frames from the resulting camera record are shown in Figure 19. In the first frame, lens initiation has just occurred. The streamlined transition between the reservoir and barrel is visible between the upper and lower impact lenses. In the following two frames, the detonation and subsequent plate acceleration are visible. The last two frames show large quantities of driver gas leaking from the collapse region of the barrel. The sides of the barrel appear to split open as the two flyer plates crush the barrel from the top and bottom. While it is evident that rupture occurs, the exact mechanism cannot be determined from this record. The projectile was overrun by the impact and did not emerge from the muzzle, although a small fragment traveling at 9.4 km/sec tripped the range switches.

This shot verified that barrel rupture associated with the collapse process is responsible for the inability of the impact lens to augment projectile velocity. However, the precise cause of barrel rupture is not known. Perhaps a two-dimensional computer calculation of the flyer plate impacting the barrel would reveal a particular shock-wave rarefaction interaction which can cause immediate barrel rupture.

4.3 LENS CONCEPT, SHOT 245-9

Regardless of the precise cause of barrel rupture, an obvious attempt at a solution is to use a completely symmetric flyer plate, i.e. a collapsing tube. The collapsing tube offers several advantages over the double-flyer-plate technique, in addition to complete symmetry. First, convergence effects during tube collapse serve to increase the impact velocity and stress

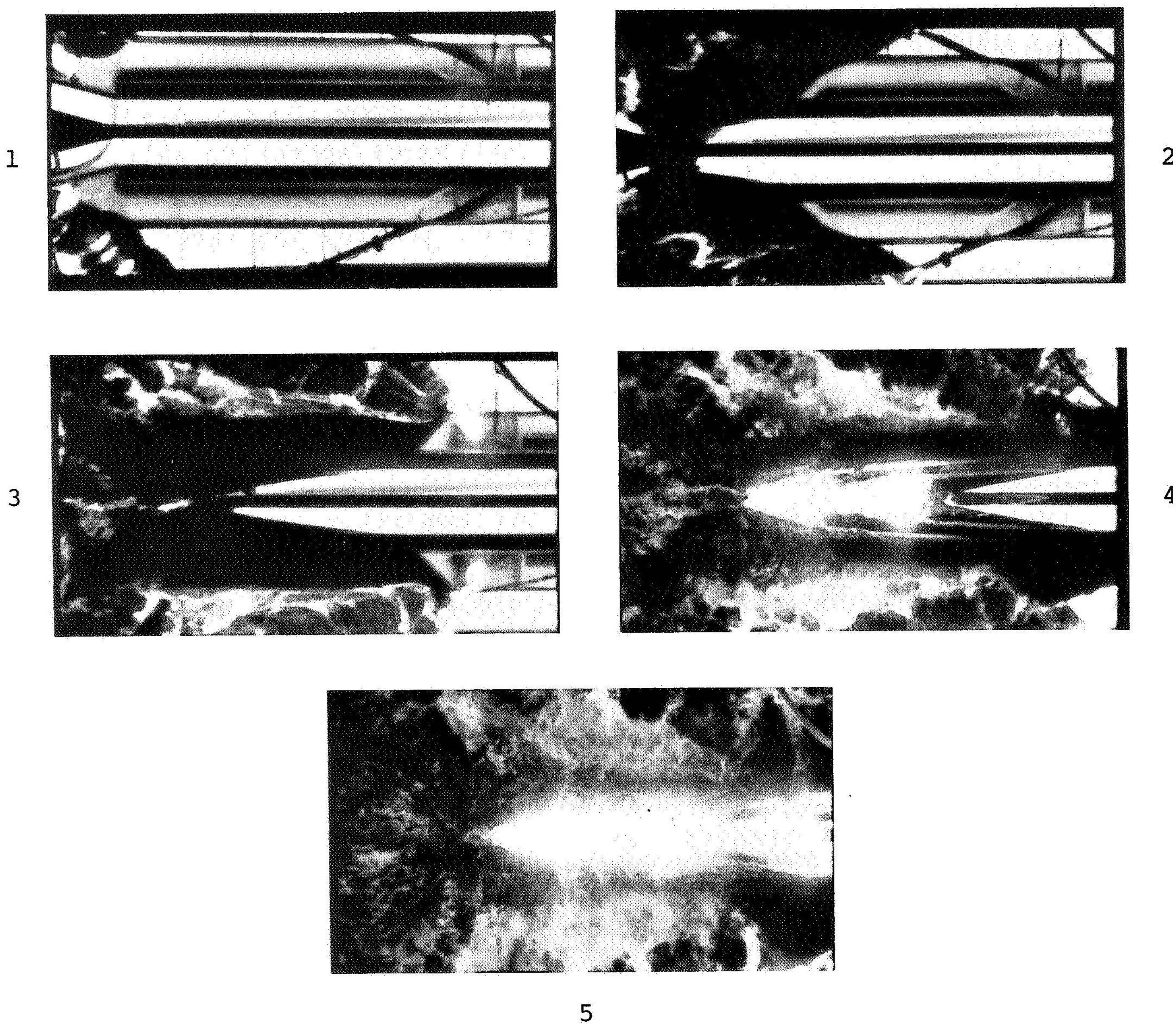


Figure 19 Selected frames at 25 μsec intervals from framing camera record, Shot 245-8.

level over that readily attainable with a flyer plate. Secondly, Physics International has a vast amount of calculational and experimental experience concerning the explosive collapse of tubes.

An experiment (shot 245-9) was designed and conducted to test the effectiveness of using a collapsing tube to impact and close off a barrel. A 6.35-cm inside diameter steel tube having a wall thickness of 0.317 was surrounded by a 3.9-cm-thick layer of composition C-4 explosive. A standard launcher barrel was centered inside the tube. The collapsing tube was designed to have the same thickness and velocity upon barrel impact as the flyer plates, 0.635 cm and 1.7 km/sec respectively. This system represents a linear (constant velocity) second-stage piston traveling at 8.0 km/sec. The shot was intended to verify collapse predictions obtained from one-dimensional POD runs as well as provide timing data on the collapse time of the tube.

The latter objective was attained; however it was not possible to obtain confirmation of complete barrel collapse. It was observed that the barrel collapse drove a strong shock wave ahead of it. Unfortunately, only fragments of the barrel and collapse tube were recovered for post-shot examination.

A cylindrical impact lens, as described above, is easy to fabricate. The cylindrical geometry allows the main explosive reservoir of the lens to be constructed from two concentric lengths of readily available tubing. Phasing fins may be added to the outer tube to obtain any desired acceleration trajectory. The complete lens assembly is independent of the basic launcher and may be positioned around the barrel just prior to firing.

The recommended next step in evaluation of the cylindrical impact lens would be to use a lens identical to that in shot 245-9 in conjunction with a basic launcher. The constant velocity augment at 8 km/sec should produce a significant increase in projectile velocity, while minimizing the complexity of the launcher. The observed performance combined with post-shot observations should allow a reasonable evaluation of the lens technique. Shot 245-9 is sufficient for providing the necessary timing data to integrate the lens operation with the basic launch cycle. Having established the lens effectiveness, phasing techniques may be employed to achieve maximum projectile velocity.

SECTION 5
CONCLUSIONS

This year's efforts have concentrated on obtaining a better understanding of the second-stage launcher operation. Of particular concern was the effectiveness of explosive augmentation techniques in collapsing the launcher barrel and forming an effective piston.

A series of computer calculations of two-stage launcher operation, including the second-stage startup phenomena was performed. The calculations indicated that the explosive lens and barrel configuration was more than adequate to completely collapse the barrel against the high-pressure gas flowing behind the projectile. It is significant though that while the calculation allowed for radial wall motion and its interaction with the gas flow, only one-dimensional gasdynamic phenomena were considered. Therefore, the principal phenomena not accounted for in the calculation is boundary-layer growth. Two carefully controlled two-stage launchers designed to correlate with the calculations were fabricated and fired. In neither case was barrel collapse achieved, although a symmetric nitromethane reservoir and phasing fins were used. The conclusion from the lack of correlation between the calculation and experiments is that two-dimensional gasdynamic effects not included in the calculations, such as boundary-growth, interact in a significant way with the barrel-collapse process. A consideration of the boundary-layer interaction indicated that higher collapse pressures than those attainable with in-contact explosives may be desirable. The importance of the dynamics of the gas flow was confirmed in an experiment consisting of an identical explosive lens and barrel configuration, but without high-velocity gas flow. Complete barrel collapse was achieved for the first 31 tube diameters.

A technique was devised that potentially can overcome the boundary-layer technique and achieve complete barrel collapse. By allowing an explosive lens to accelerate a flyer plate which impacts against the barrel, significantly higher collapse pressures (up to 1 Mbar) can be produced. The flyer-plate impact can be phased to produce an accelerating second-stage piston using existing explosive lens technology.

Several two-stage launcher experiments were conducted utilizing the impact lens technique. The lens appeared effective in collapsing barrels in the presence of gas flow; however, significant velocity augmentation was not achieved. Complete barrel collapse was only achieved near the muzzle end of the barrel. It was demonstrated that barrel rupture occurred during the collapse process, allowing the accelerating gas to escape. The barrel rupture appeared to result from a dynamic failure mechanism, such as intersecting shock and rarefaction waves causing the sides of the barrel to spall.

A collapsing tube maintains complete symmetry of impact and should circumvent the barrel rupture mechanism. A single test shot in this configuration was fired, consisting of a constant velocity lens and a barrel containing ambient air. The lens appeared effective although post-shot confirmation of barrel collapse was not possible. A test of the lens design on a complete launcher is required to properly evaluate its performance.

The impact technique appears promising for overcoming the barrel collapse problem in two-stage launchers. Large flexibility in design is afforded to produce various desired stress levels in the barrel. Also, ease of fabrication results from the physical separation of the explosive lens from the launcher barrel. Finally, it is anticipated that the ultimate projectile velocity attainable with the impact lens is substantially higher than with the in-contact explosive lens. This difference arises from the higher collapse velocities produced by the high energy-density flyer plates. Therefore, an ultimate projectile velocity near 20 km/sec appears feasible for this type of launcher.

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