EXPLOSIVELY DRIVEN HYPERVELOCITY LAUNCHER-- SECOND-STAGE AUGMENTATION TECHNIQUES

PIFR-245-1

(FINAL REPORT)

by
Dennis W. Baum

March 1973

Prepared for
National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035

Under Contract No. NAS 2-5860

PHYSICS INTERNATIONAL COMPANY
2700 MERCED STREET • SAN LEANDRO, CALIFORNIA 94577 • PHONE 357-4610 (415) • TWX (910) 366-7033

EXPLOSIVELY DRIVEN HYPERVELOCITY LAUNCHER--SECOND-STAGE AUGMENTATION TECHNIQUES

PIFR-245-1

(FINAL REPORT)

by

Dennnis W. Baum

March 1973

Prepared for

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035

Under Contract No. NAS 2-5860

Preparing Agency

Physics International Company
2700 Merced Street
San Leandro, California 94577

ABSTRACT

This report describes the most recent effort by Physics International Company to develop a two-stage explosively driven hypervelocity launcher capable of achieving projectile velocities between 15 and 20 km/sec. The effort was directed at the testing and evaluation of a new cylindrical impact technique for collapsing the barrel of a two-stage launcher. Previous two-stage launchers have been limited in ultimate performance by incomplete barrel collapse behind the projectile.

The cylindrical impact technique explosively collapses a steel tube concentric with and surrounding the barrel of the launcher. The impact of the tube on the barrel produces extremely high stresses which cause the barrel to collapse. The collapse rate can be adjusted by appropriate variation of the explosive charge and tubing parameters.

Launcher experiments demonstrated that the technique did achieve complete barrel collapse and form a second-stage piston. However, jetting occurred in the barrel collapse process and was responsible for severe projectile damage. The jetting was suppressed by varying parameters in the cylindrical impact lens. A significant projectile velocity increase was realized using only the startup portion of the second-stage. Additional experiments are needed to determine the ultimate velocity potential of a launcher utilizing a phased cylindrical impact lens.

CONTENTS

ILLUSTRATIONS

SECTION 1
INTRODUCTION

For several years Physics International has been engaged in the development of hypervelocity launchers for achieving the highest possible projectile velocity. Under NASA sponsorship, PI has been continuing the development of a two-stage explosively driven launcher concept designed to achieve muzzle velocities greater than 15 km/sec with a 140-mg projectile mass. The launcher is intended for meteoroid simulation and can be used to test present spacecraft structures and advanced designs for impact resistance at typical meteoroid velocities.

Significant progress has been made in improving the performance and understanding the operation of a two-stage explosively driven launcher. The basic launcher, without any second-stage velocity augmentation technique, is capable of achieving a projectile velocity of 8.8 km/sec. The addition of a second-stage barrel collapse technique has increased the projectile velocity to 12.2 km/sec in two different size scales (References 1 and 2). A more recent program (Reference 3) concluded that the augmentation technique was inadequate to completely collapse the barrel and a different second-stage concept was proposed and designed. The testing and evaluation of the new technique constitute the primary technical tasks of the present program.

This report describes the seven launcher experiments which were fabricated and fired during the present effort. The new second-stage technique was successful in obtaining complete barrel collapse. However, the collapse was apparently violent enough to cause jetting of the barrel which severely damaged the projectile. Several shots were fired attempting to eliminate the jet. A down-range velocity of 11.4 km/sec was obtained on the final shot of the program.

Section 2 of the report presents a brief description of the single- and two-stage explosively driven launcher concept. Section 3 discusses the purpose and results of each of the seven launcher shots. Conclusions drawn from the present work and recommendations for continued launcher development are presented in Section 4.

SECTION 2
EXPLOSIVELY DRIVEN LAUNCHER CONCEPT

2.1 FIRST-STAGE EXPLOSIVE DRIVER

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 in which all ideal and nonideal effects concerning the explosive tube collapse were considered (References 2 and 4). Figure 1 illustrates the ideal driver operation. In this operation a conical piston is explosively formed which drives a strong shock into the driver gas, producing a slug of uniformly processed high-energy-density gas. 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 the effects of boundary-layer growth behind the driver shock become noticeable

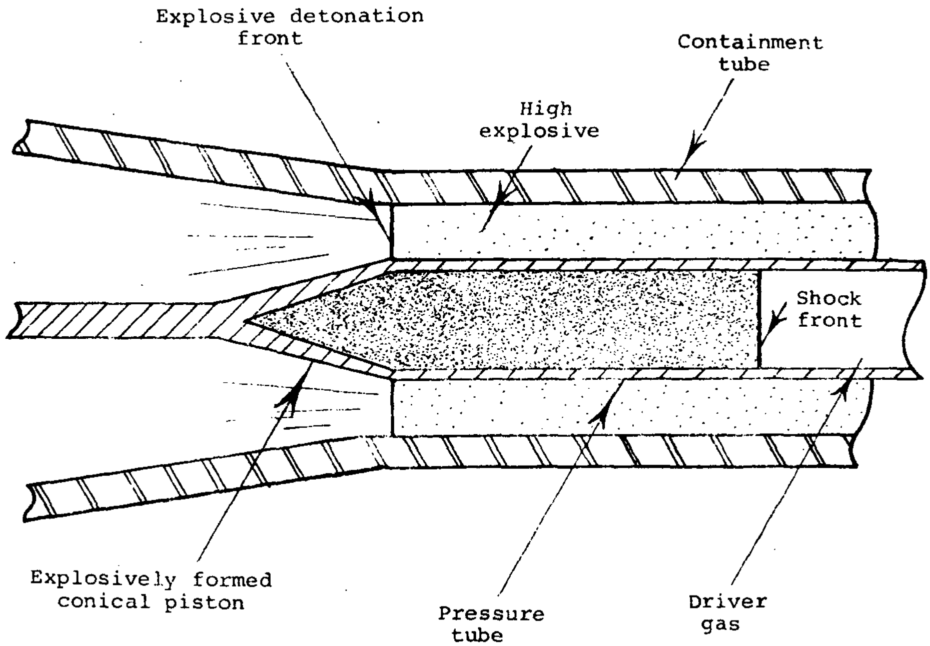


Figure 1 Idealized schematic of linear explosive driver.

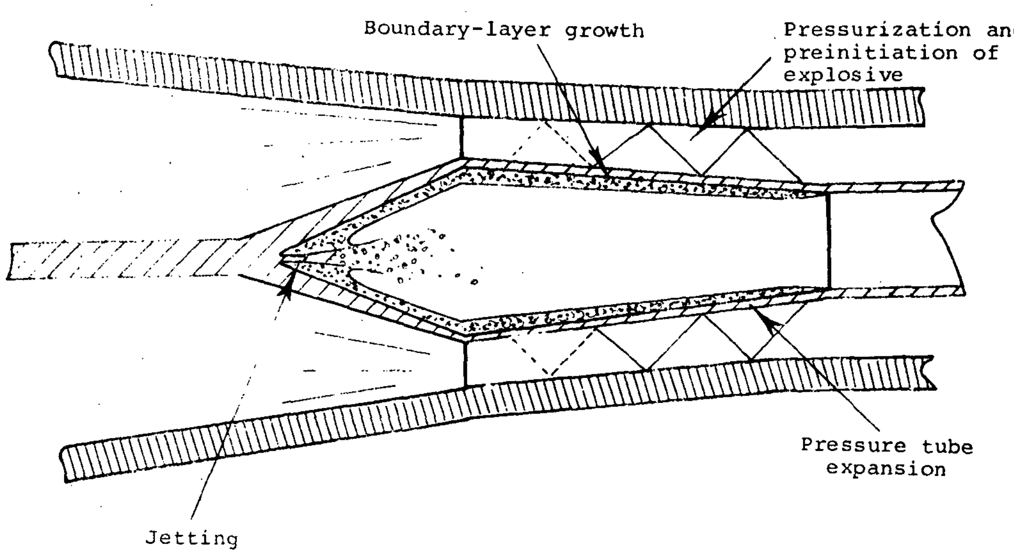


Figure 2 Schematic of nonideal phenomena in explosive drivers.

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 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 1). 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 also 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 in the driver 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 pressures 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.

2.2 SECOND-STAGE OPERATION

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 presently attainable with this type of system appears to be about 20 km/sec.

The barrel collapse technique used with the launchers in References 1, 2, and 3 consisted of surrounding the barrel with a relatively thick layer of explosive. It was observed that it was not possible to collapse and close off the barrel behind a projectile to form an effective second-stage piston with high velocity gas flowing through the barrel. Large variations were made in explosive-charge and barrel-wall thickness, but none of these resulted in complete collapse. It was concluded that the interaction between the boundary layer in the gas behind the projectile and the barrel collapse process produces gas pressure of sufficient magnitude to prevent complete collapse. This conclusion and the relevant experiments are discussed in Reference 3.

An alternate collapse technique, intended to overcome the boundary layer interaction, was then designed and tested (Reference 3). It consisted of using a layer of explosive to accelerate a steel flyer plate which impacts the barrel. The flyer plate has a substantially higher energy density than a chemical explosive and therefore at impact produces stresses in the barrel greater than the detonation pressure of in-contact explosives. Stresses of the order of 1 Mbar (10^6 atmospheres) can be produced by the flyer plate impact technique, compared to stresses of about 0.1 Mbar with in-contact explosive. Launcher experiments were conducted in which two steel plates were driven into the barrel from opposite sides. This technique was capable of collapsing the barrel; however, it did not prove an effective second stage. The sides of the barrel ruptured during the collapse process, allowing the contained driver gas to escape and producing no significant velocity increase.

A solution to the rupture problem is to use a concentric collapsing tube to impact the barrel in symmetric fashion. The operation of this type of second stage is shown schematically in Figure 3. A particular design using Comp C-4 explosive to collapse a 6.98-cm-o.d. by 0.317-cm-wall steel tube around the barrel was selected in Reference 3, based on computer calculations of the collapse process. The wall thickness of the tube was chosen such that at impact with the barrel the tubing thickness would have increased to 0.635 cm due to convergence effects. The 0.635-cm wall thickness, which was chosen to match the barrel wall thickness, is sufficient to prevent rarefactions from the outside of the tubing from reaching the barrel prior to the time of collapse. An initial timing shot consisting of the second stage and barrel, without a first stage or projectile, was fired during the previous program and is described in Reference 3.

The first launcher experiment using the cylindrical impact techique was fired during the present effort and is described in Section 3 of this report along with six additional shots. The basic objective of this series of shots was evaluation and optimization of the cylindrical impact concept as an effective way of energizing a second-stage piston.

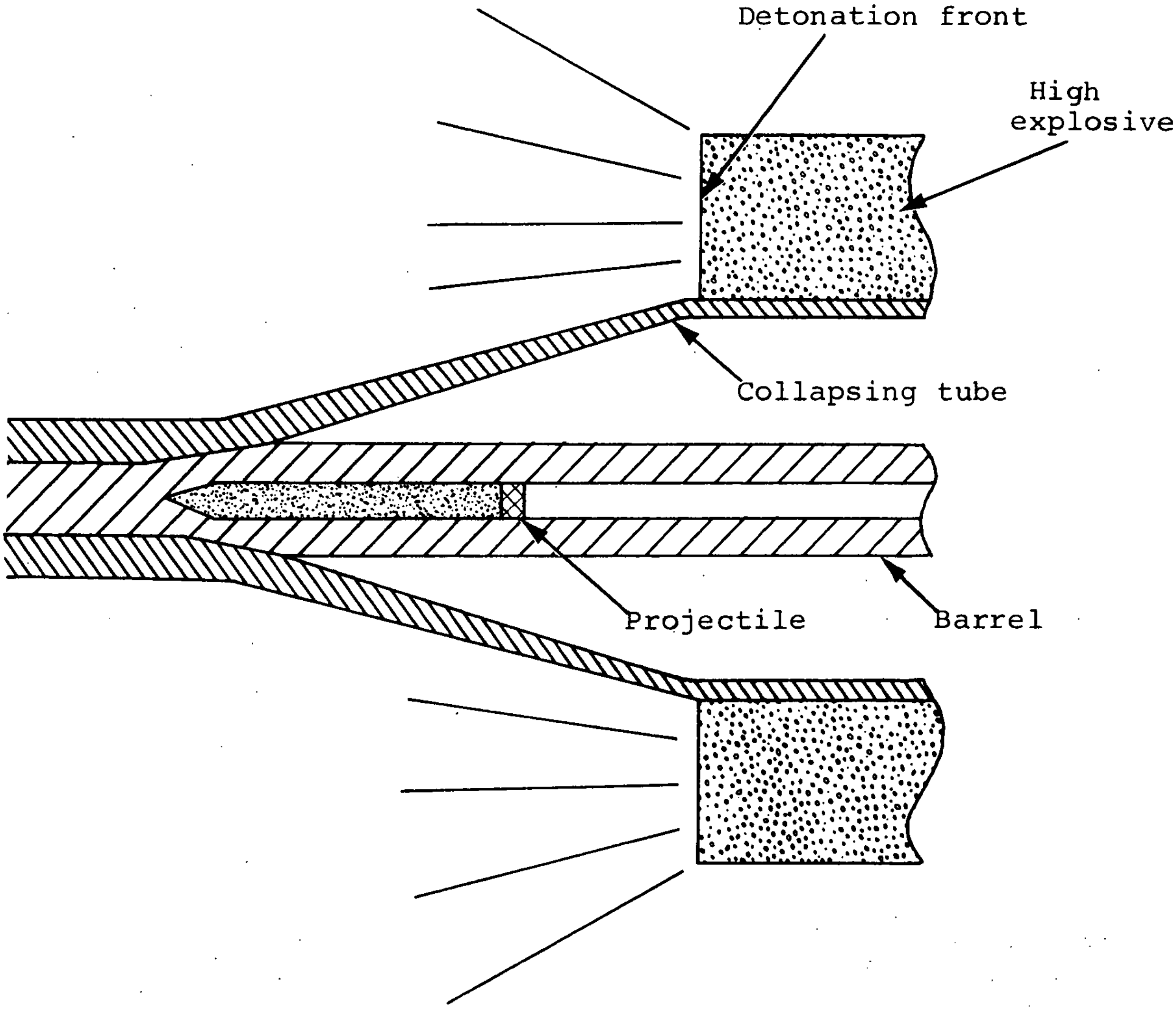


Figure 3 Schematic of cylindrical impact--second stage.

SECTION 3
VELOCITY AUGMENTATION EXPERIMENTS

3.1 LAUNCHER AUGMENTATION TESTS

Shot 245-10. Shot 245-10 was the first test of the cylindrical impact lens as the second stage of a launcher. The experiment was intended to determine the effectiveness of the lens in collapsing the barrel in the presence of high-pressure, high-velocity gas flow with complex boundary-layer interactions. The cylindrical geometry of the collapsing tube prohibits direct observation of the tubing impact and barrel collapse. Therefore, effective operation must be inferred from projectile behavior and terminal recovery of the reservoir, barrel, and collapse tube.

The first stage of this launcher, which consists of the explosive driver, reservoir, barrel, and projectile, was identical to those in the previous effort. Except for variations in barrel length, the first stage design was held constant for all experiments in the present effort.

The second stage for shot 245-10 utilized a cylindrical impact lens having a constant phase velocity of 8 km/sec. The lens consisted of a 3.97-cm-thick layer of hand-packed Comp C-4 surrounding a 6.98-cm-o.d. by 0.317-cm-wall steel tube. A thin-walled aluminum tube formed the outer container for the C-4. The standoff distance between the i.d. of the collapse tube and the o.d. of the barrel was 2.20 cm and was flushed with one atmosphere of helium during the shot. The low-density helium minimized the influence of the shock wave being driven in the gas ahead of the tube collapse. The lens extended for 100 cm, enclosing all of the reservoir and the first 94.5 cm of the barrel. The C-4 was initiated by six simultaneously fired RP-1 detonators equally spaced on the startup end of the explosive layer. While the lens was only intended to collapse the barrel, it was necessary to extend the lens over the reservoir to avoid startup irregularities in the detonation front and tube collapse process. A possible performance benefit may be derived from the dynamic tamping effect of the tube collapsing onto the reservoir.

Diagnostics for the launcher consisted of standard ionization and cap pins for monitoring driver operation, ionization pins on the C-4 to detect the detonation, and range diagnostics to determine projectile velocity and condition. The output of all pins and shorting switches was displayed on oscilloscopes. The range was formed from a 15-cm-diameter Lucite tube. Included as diagnostics were three flash X-ray heads individually triggered by three foil shorting switches, an additional shorting switch on the target face, and a B&W Model 189A framing camera. Backlighting for the camera was provided by two xenon flash lamps. The range was evacuated to about 5-torr air to minimize the aerodynamic drag, deceleration, and ablation of the projectile.

A majority of the data from the shot was recovered and the results were encouraging. A schematic of the launcher and range layout and the data obtained are presented in Figure 4. The explosive driver data indicated its operation was identical to that of shots in the previous effort (Reference 3). The

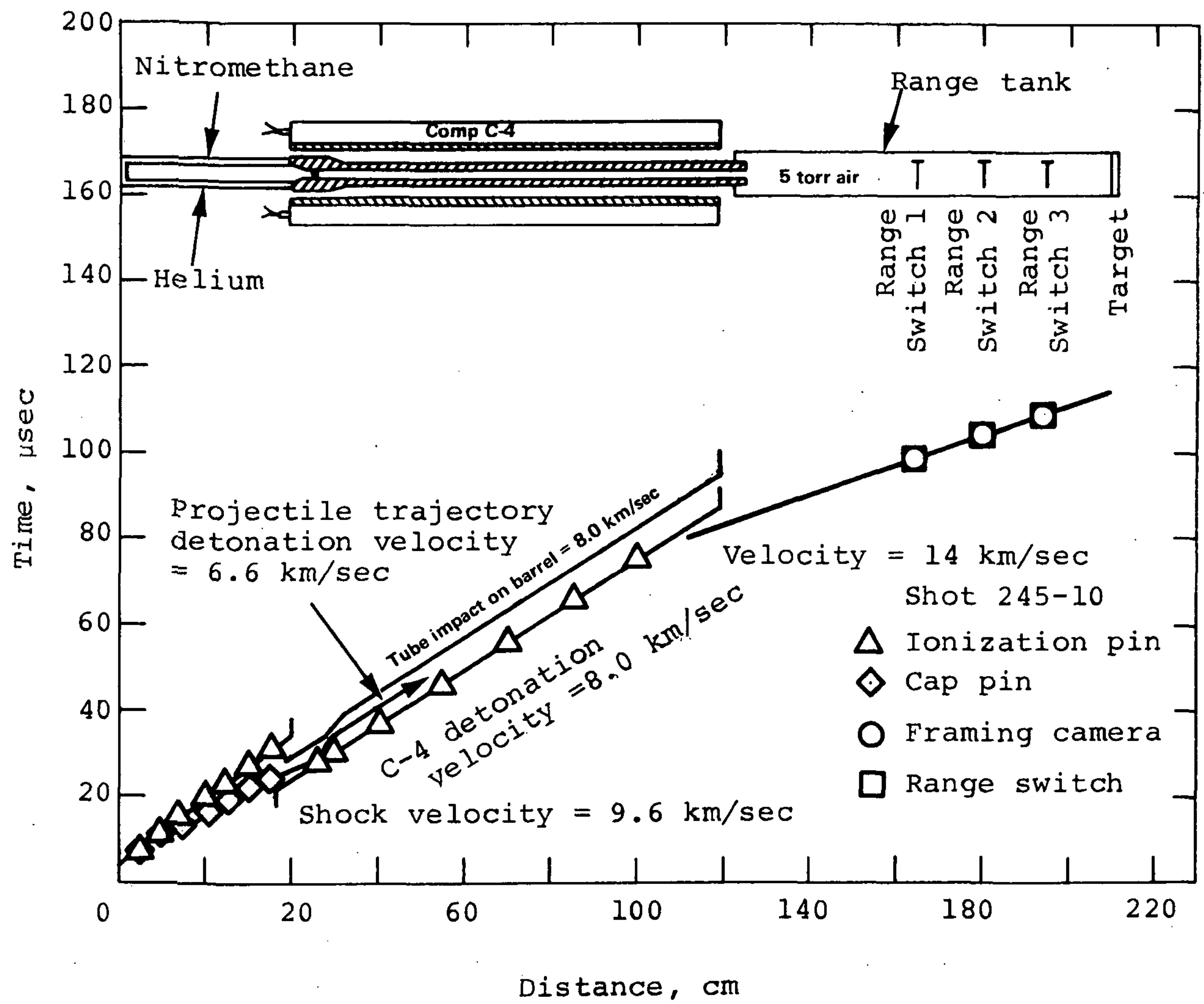


Figure 4 Schematic of launcher and range with resultant data.

C-4 detonation had the anticipated velocity of 8 km/sec and the programmed arrival time. The range shorting switch responses indicated a constant velocity of 14 km/sec down the last 45 cm of the 85-cm-long range. The framing camera record showed a luminous cloud filling the 15-cm diameter of the Lucite tube and propagating down the range at constant velocity. The arrival times of the luminous gas at the shorting switches correlated with the switch responses on the oscilloscope traces. Unfortunately, two of the X-ray units did not fire and the third film was damaged by the blast wave from the C-4. It was difficult to distinguish possible projectile fragments on the damaged film because of numerous pressure marks. The target showed numerous small pits, but none appeared typical of hypervelocity craters. No portions of the barrel were recovered so that barrel closure could not be observed.

Without the radiographs it was difficult to conclude whether the 14-km/sec range velocity was produced by a broken projectile or simply a gas cloud. The lack of deceleration of the luminous cloud would indicate that a substantial mass was moving down the range, as perhaps a broken projectile. However, the lack of a significant target crater or definitive radiograph to confirm the presence of a projectile leaves the result in doubt. Accordingly, it was decided to repeat the shot with appropriate modifications to protect the X-ray cassettes from blast damage.

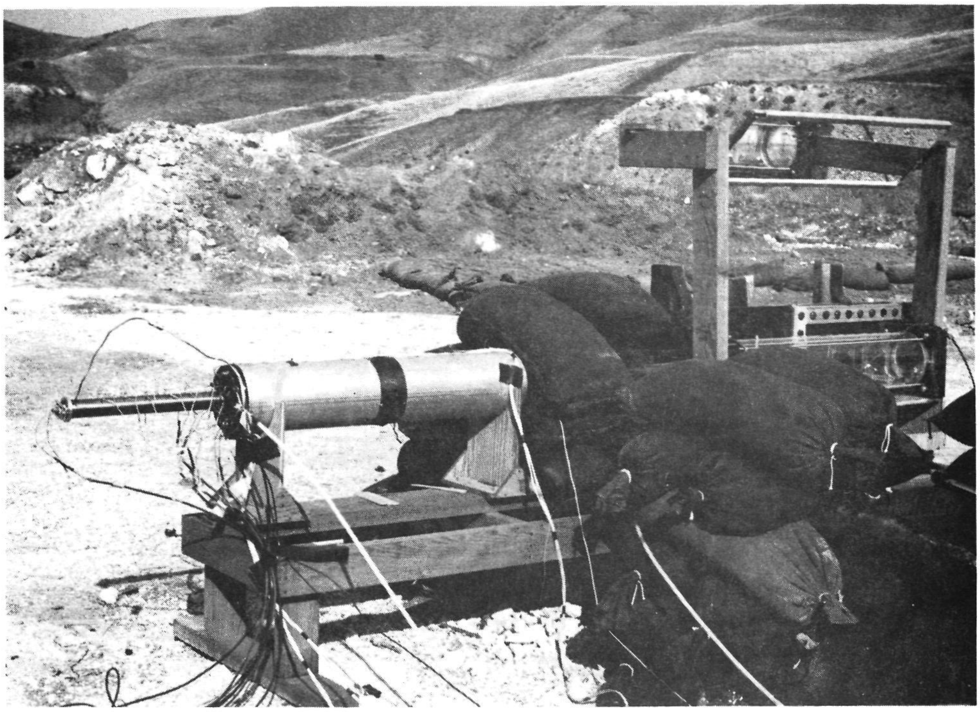
Shot 245-11. This shot was essentially a repeat of shot 245-10 with minor modifications to the second stage. The purpose of the shot was to obtain adequate range data to determine whether the projectile or simply a gas cloud was accelerated to 14 km/sec. The first stage and barrel length were identical to the previous shot; however, the C-4 lens was shortened to 75 cm to reduce the total amount of explosive and allow more distance between the end of the lens and the X-ray cassettes. Two views of the shot are presented in Figure 5: a view from the driver end in Figure 5a and one from the range end in Figure 5b.

The diagnostics for this shot were the same as for shot 245-10, except that the X-ray head closest to the muzzle of the launcher was triggered after a set delay for zero time, rather than by a range switch. Also, the range was extended and the diagnostics moved downstream by 30 cm to provide more separation from the lens explosive. As before, the range was evacuated to about five torr air.

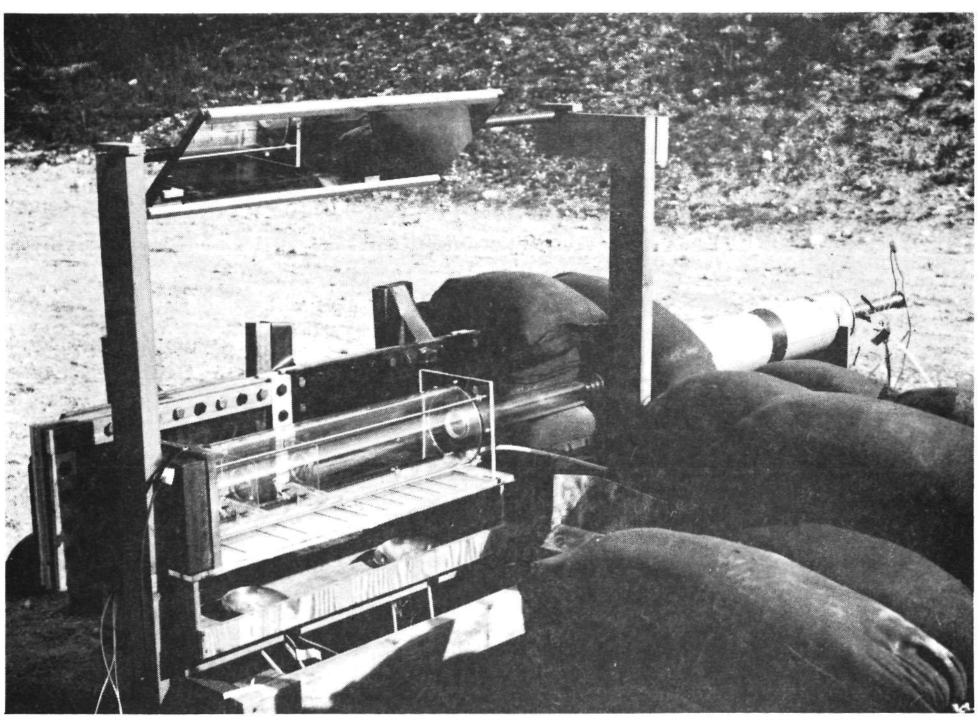
A small change was made in the timing of the second stage initiation. Three microseconds were added to the delay from zero time to ensure that the shock wave transmitted through the reservoir from tube impact or the barrel collapse could not overtake and destroy the projectile.

Data return from the shot was very limited but adequate to determine that the projectile was destroyed prior to emerging from the muzzle. An incorrect selector switch was responsible for the failure to obtain any oscilloscope traces; however, three radiographs, a framing camera record, and an undamaged target confirmed that there was no projectile in the range.

A short section of barrel contained inside a tapered sleeve was recovered after the shot. The sleeve is located where the barrel emerges from the reservoir and forms a smooth transition in wall thickness from the reservoir to the barrel. The sleeve and barrel appeared as one piece, as shown in Figure 6. It can



(a)



(b)

Figure 5 Setup of shot 245-11 prior to firing.

A2519

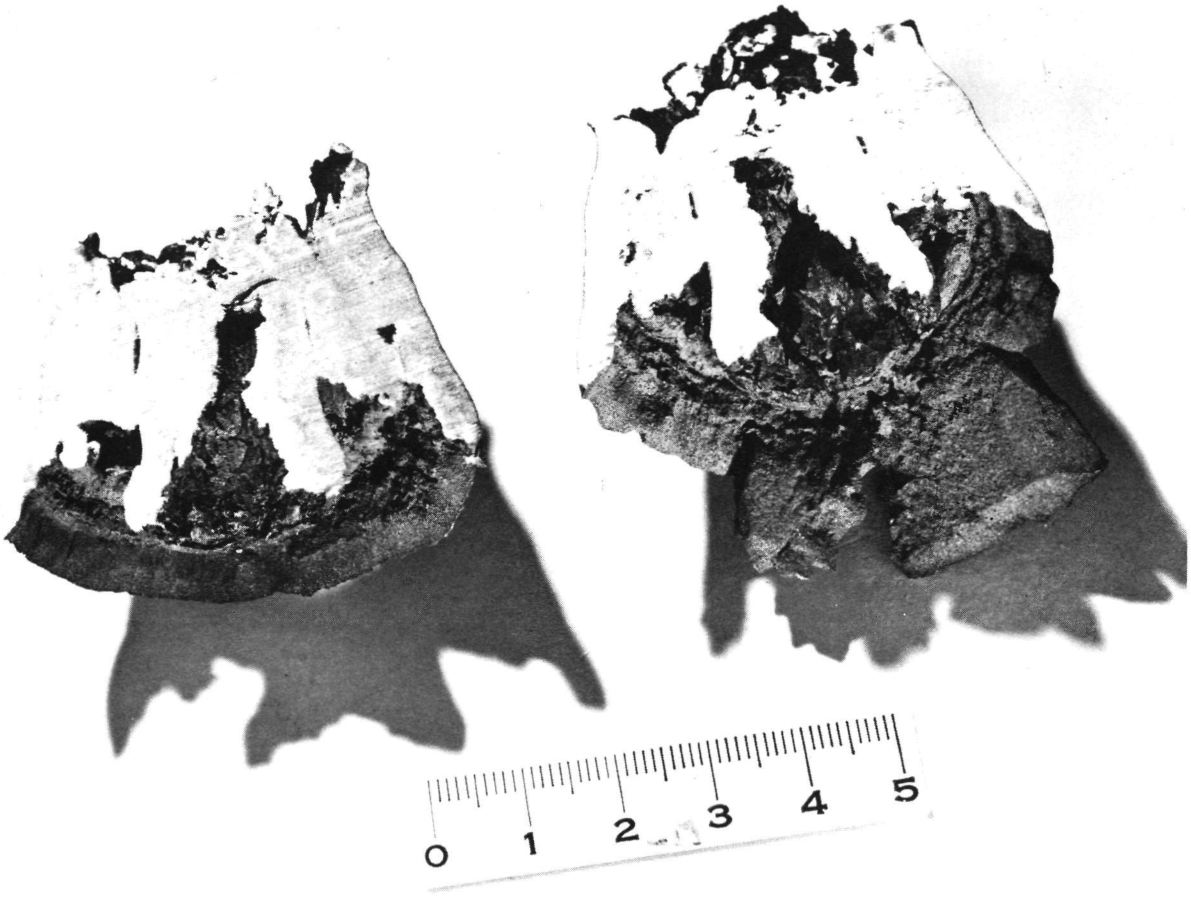


Figure 6 Portion of collapsed barrel from shot 245-11.

be seen in the sectioned halves that the barrel has collapsed. This piece was the first direct evidence that the cylindrical impact technique can collapse the barrel of a launcher and overcome the boundary layer interaction.

Four mechanisms were considered as possible causes of projectile breakup in the barrel. Being overrun by the collapsing barrel would certainly destroy the projectile. However, the timing of the second stage prevents this occurrence. The second-stage piston maintains a constant velocity trajectory of 8 km/sec which can be determined from the C-4 detonation wave arrival times. The timing of the second stage was adjusted such that the piston could not overtake the projectile, even assuming no velocity increase from the second stage. A second possible mechanism for projectile breakup is that the strong shock wave generated by the impact of the collapsing tube against the reservoir overtakes the projectile early in its acceleration cycle. However, this mechanism can also be ruled out on an arrival time basis. A careful calculation of shock wave arrival times in the reservoir wall showed that the projectile had accelerated prior to any possible communication from the tube impact. While these two mechanisms could be evaluated and dismissed on the basis of relative timing of events and communication times, the remaining two mechanisms could not be evaluated or distinguished, except by experiment.

The third possible mechanism was suggested by the pinched-off barrel recovered from shot 245-11. It is postulated that the barrel closure was violent enough that forward jetting of the steel had occurred. The velocity of the leading portion of jet material would be approximately twice barrel collapse progression velocity (2 x 8 km/sec = 16 km/sec) and would overtake and likely destroy the projectile. Unfortunately, there is no direct means for observing whether or not jetting does occur with this particular experimental configuration. Observations of the muzzle are not reliable, since the jet may be destroyed by interaction with the projectile.

A fourth mechanism for breakup that could easily be tested is that a first-stage malfunction was occurring and destroying the projectile independently of second stage operation. Although a first-stage malfunction is unlikely, it is comparatively simple and inexpensive to fabricate and fire a single-stage launcher. Such a shot would verify the operation of the basic launcher with a 100-cm-long barrel and provide a check on the timing of the launch cycle as determined from shot 245-1.

Of the four mechanisms discussed, the jetting barrel collapse appeared the most probable cause of projectile breakup. The recovered barrel and tapered sleeve suggested that the jetting may occur at the startup of the second stage. At startup the boundary layer interaction is comparatively less severe and therefore the collapse is likely to be more violent. Also, the cylindrical shock from tube impact undergoes significant convergence through the tapered sleeve, resulting in a faster collapse and a greater tendency to jet.

It was postulated that jetting did occur at the startup of the second stage and was responsible for breaking the projectile. A series of two shots was planned to confirm the postulated jetting.

3.2 JETTING CONFIRMATION TESTS

Two shots were planned to confirm that jetting of the barrel at the startup of the second stage was responsible for projectile failure in shots 245-10 and -11. The first shot consisted of the basic launcher with a 100-cm barrel and no second stage. The second shot included an identical first stage and the start-up portion of the second stage. If the jetting hypothesis is correct, the first shot should produce a successful launch and the second shot a broken projectile.

Shot 245-12. This shot consisted of the basic launcher with a 100-cm barrel and no second stage. Except for the increased barrel length, the shot was a repeat of shot 245-1. Shot 245-12 was intended to verify the operation of the first stage and provide a check on the timing of the basic launch cycle, which was determined from shot 245-1.

Standard ionization pins and cap pins were used to monitor driver operation. The model 189A framing camera observed the reservoir and tapered sleeve to detect premature rupture and gas leakage. Range diagnostics consisted of four shorting switches, three flash X-ray heads, and a B&W model 100 streak camera. For convenience and because of the comparatively low projectile velocity, an atmospheric range was used.

The shot was successful in that the projectile was launched intact at a velocity of 8.1 km/sec. This velocity was less than the 8.8 km/sec velocity achieved in shot 245-1. The difference was attributable to deceleration in the long barrel. While the 100-cm barrel is required for adequate second-stage acceleration, the peak velocity from the first stage is achieved using a 40-cm barrel. Figure 7 shows a radiograph of the projectile taken 34 body diameters downstream from the muzzle. Significant mass loss has occurred during the launch cycle, as determined by comparison with the reference projectile mounted in a cut-out portion of the sawblade.

This shot did verify the operation and timing of the first stage and eliminated first-stage malfunction as the damage mechanism in shots 245-10 and -11.

Shot 245-13. Shot 245-13 was intended to confirm that second-stage startup was responsible for projectile breakup. The launcher consisted of the same first stage as previous shots and the initial 19 cm used the same design for the cylindrical impact lens. The lens enclosed the reservoir and the first 10 cm of barrel protruding from the reservoir.

Standard driver and second-stage diagnostics were used to monitor detonation and shock wave in the driver, as well as detonation and tube impact for the second stage. The range diagnostics consisted of four shorting switches, three flash X-ray units, and a streak camera.

The principal result of the shot was that the projectile was broken in the barrel, as had been postulated. The last 67-cm portion of the barrel was recovered and showed some interesting results. Figure 8 shows a portion of the barrel. The barrel appears to have experienced a violent rupture at the point where it broke off. This location is 20 cm downstream from where the barrel leaves the reservoir. The first 20 cm

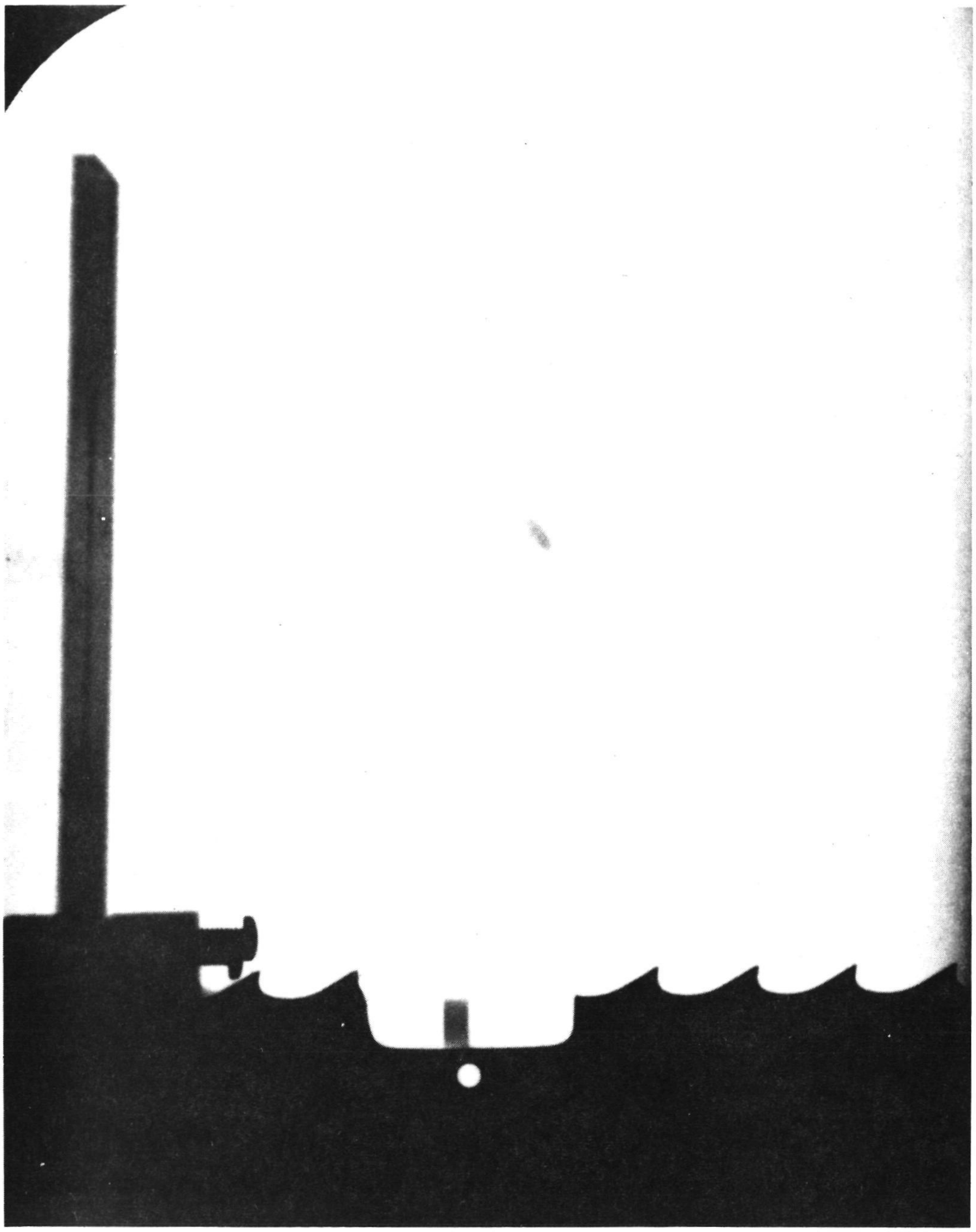


Figure 7 Radiograph of projectile at 8.1 km/sec from shot 245-12.

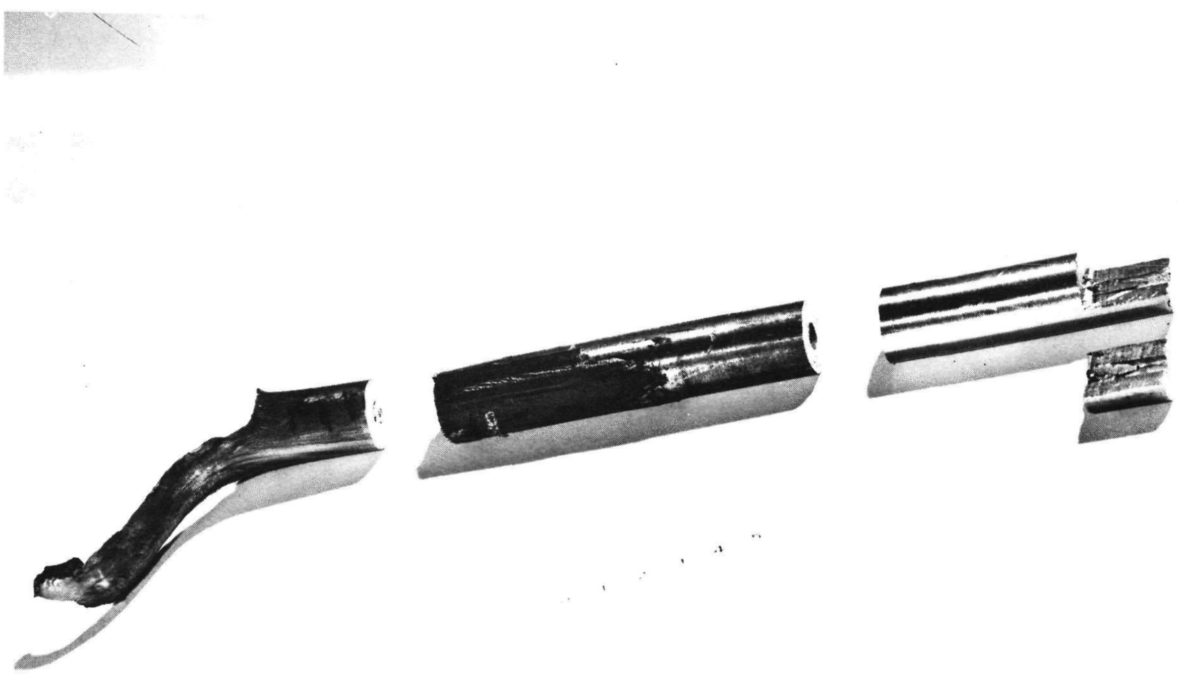


Figure 8 Portion of ruptured barrel from shot 245-13 showing chunks of steel wedged in the bore.

of barrel downstream from the rupture had several chunks of steel wedged in the bore. The steel fragments appeared to be jetted material, although probably not the actual material which hit the projectile. A possible explanation of the rupture is that stresses generated by the impact of the high velocity jet on the slower moving projectile were large enough to cause immediate failure of the barrel. If the rupture had resulted solely from gas pressure on the base of the projectile, the barrel deformation would have a more gradual opening, having the appearance of being peeled back.

The conclusion from the shots 245-12 and -13 was that jetting of the barrel did occur and was the probable cause of projectile breakup in shots 245-10 and -11. While jetting is not a desirable phenomenon, it was most encouraging and significant in that it demonstrated that the cylindrical impact technique can collapse a barrel and form a second-stage piston behind an accelerating projectile. The formation of a second-stage piston, which is the key to the two-stage explosively driven launcher concept, had not been previously achieved.

Before investigating the velocity potential of this launcher design, it is necessary to suppress the jetting of the barrel, while still achieving closure. Jetting can be suppressed by decreasing the radial collapse rate of the barrel walls. Experience with non-jetting explosive drivers shows that there is a critical collapse angle below which jetting does not occur. Because of the unknown quantitative nature of the boundary layer interaction with the collapse process, the proper radial collapse rate for non-jetting collapse cannot be calculated. It remains to experimentally decrease the collapse rate until jetting no longer occurs.

3.3 JET SUPPRESSION TESTS

The barrel collapse rate is dependent both on the impact-tube collapse velocity and the internal barrel pressure opposing collapse. The impact tube collapse velocity can be decreased by lowering the ratio of explosive charge mass to tube mass, which would have the desired effect of decreasing the barrel collapse rate. However, a reduction in explosive charge or an increase in tube mass would change the timing of the second-stage impact. At least one extra shot would then be required to determine the revised collapse time of the tube. An alternate approach is to increase the internal gas pressure, which can be accomplished by adding an auxiliary reservoir pump cycle, as described and employed in Reference 2. This approach has the advantage of forcing more gas into the barrel, which can only increase performance, while hopefully suppressing the barrel jet through increased barrel pressure. Further, this approach does not affect the timing of the second stage and requires no extra timing tests. For these reasons, the pump cycle approach was selected for the first jet suppression test.

Shot 245-14. The objective of shot 245-14 was to suppress barrel jetting by the addition of an auxiliary reservoir pump cycle. The basic shot design was similar to 245-13, with the addition of the pump cycle. The design and timing of the pump cycle was based on the experimental results in Reference 2. A schematic of the launcher showing the combined pump cycle and cylindrical impact second stage is presented in Figure 9. The pump cycle consists of a thin layer of Comp C-4 packed between two concentric steel tubes. The inner tube fits snugly around the reservoir and positions the entire unit. The outer tube extends forward and becomes the collapse tube for the impact

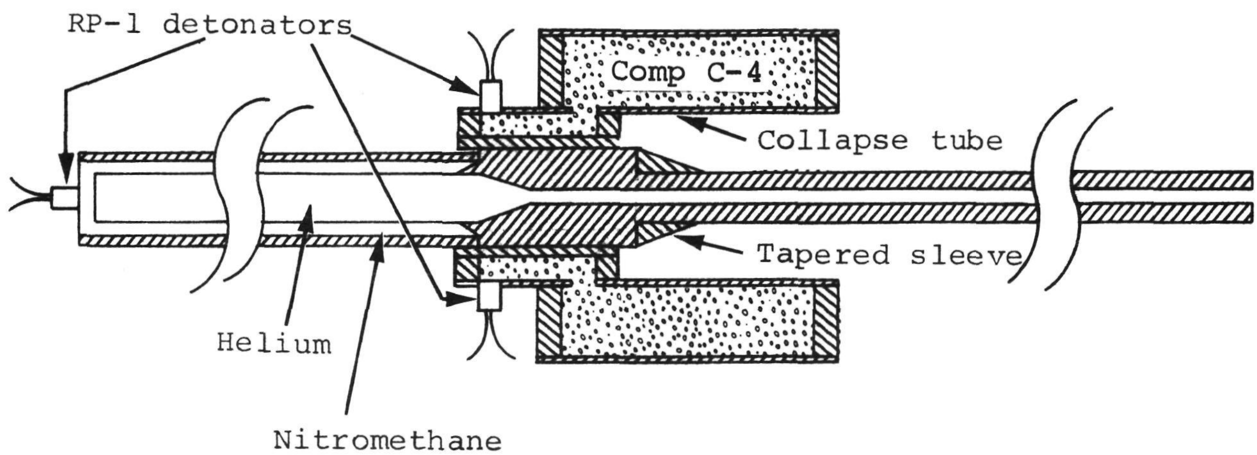


Figure 9   Schematic of launcher for shot 245-14.

lens. The usual layer of Comp C-4 is packed around the collapse tube. The explosive is initiated at the driver end of the pump cycle. The detonation propagates through the pump cycle explosive and through a series of holes in the overlapping portion of the outer tube to initiate the impact lens C-4. The pump cycle is designed to partially collapse the reservoir, thereby forcing more gas into the barrel behind the projectile.

Launcher instrumentation was the same as for previous shots, except that two ionization pins were removed from the lens and added to the pump cycle explosive. The range was evacuated and backfilled with 20 torr of argon to increase the brightness of the particle streaks. The usual shorting switches, flash X-ray units, and streaking camera served as range diagnostics.

The streaking camera record from the shot is presented in Figure 10 and is similar in appearance to the records obtained in shots 245-15 and -16. Time increases from right to left at the rate of 0.5 μsec/mm of film. The entire range is visible with the muzzle of the barrel at the bottom of the record, target at the top, and three shorting switches spaced in between. The major distinguishable events are marked on the record, starting with muzzle gas exiting the barrel at 15 km/sec and quickly decelerating. Eleven microseconds later a faint streak is visible leaving the muzzle and disappearing in the cloud of muzzle gas. The streak has a velocity of about 27 km/sec and appears to be a small fragment of unknown origin. Fifty-four microseconds after muzzle gas appearance, a second streak passes through range switches 2 and 3 at a constant velocity of 12.5 km/sec. No fragments were visible on the radiographs and a small hypervelocity crater 1 mm in diameter was found in the target.

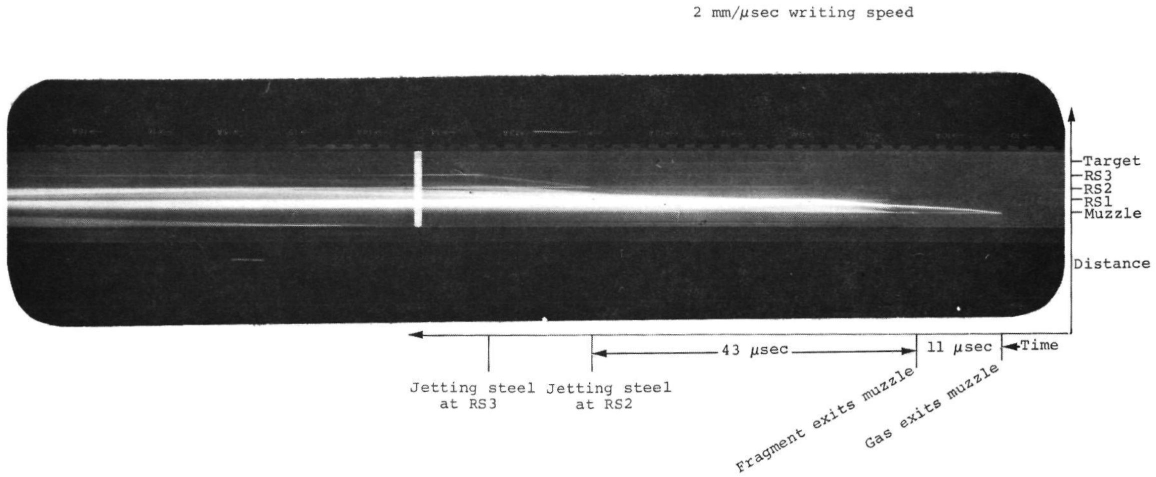


Figure 10 Streaking camera record from shot 245-14.

Oscilloscope records indicated normal driver operation and correct timing of the second stage. Range switch responses correlated with the streak through switches 2 and 3.

The muzzle portion of the barrel was recovered and had ruptured 56 cm from the muzzle. At the point of rupture the bore was expanded to twice its original diameter, indicating that the pump cycle was effective in forcing gas down the barrel. The actual point of rupture is shown in Figure 11 and has a rather abrupt appearance, similar to the previous shot.

The conclusion from the shot was that although the pump cycle was effective in driving more gas down the barrel, it did not significantly suppress jetting.

Shot 245-15. The remaining alternative to suppress jetting was to reduce the radial collapse velocity of the impact tube. For convenience, it was decided to reduce this velocity by increasing the thickness of the tube and maintaining the same explosive charge thickness. A 0.317-cm-thick steel sleeve was fitted over the outside diameter of the impact tube to double the mass of the tube. Because of the reasonably high ratio of explosive charge to tube mass, the resulting decrease in collapse velocity and stress at impact was estimated to be about 30 percent. The sleeve extended over the reservoir and tapered transition between the reservoir and barrel.

Except for the additional sleeve, the design and diagnostics of shot 245-15 were the same as shot 245-14. The initiation timing of the second stage was unchanged; however, the heavier impact tube accelerates slower and results in a slightly delayed impact. The effect of the delay on the startup conditions was

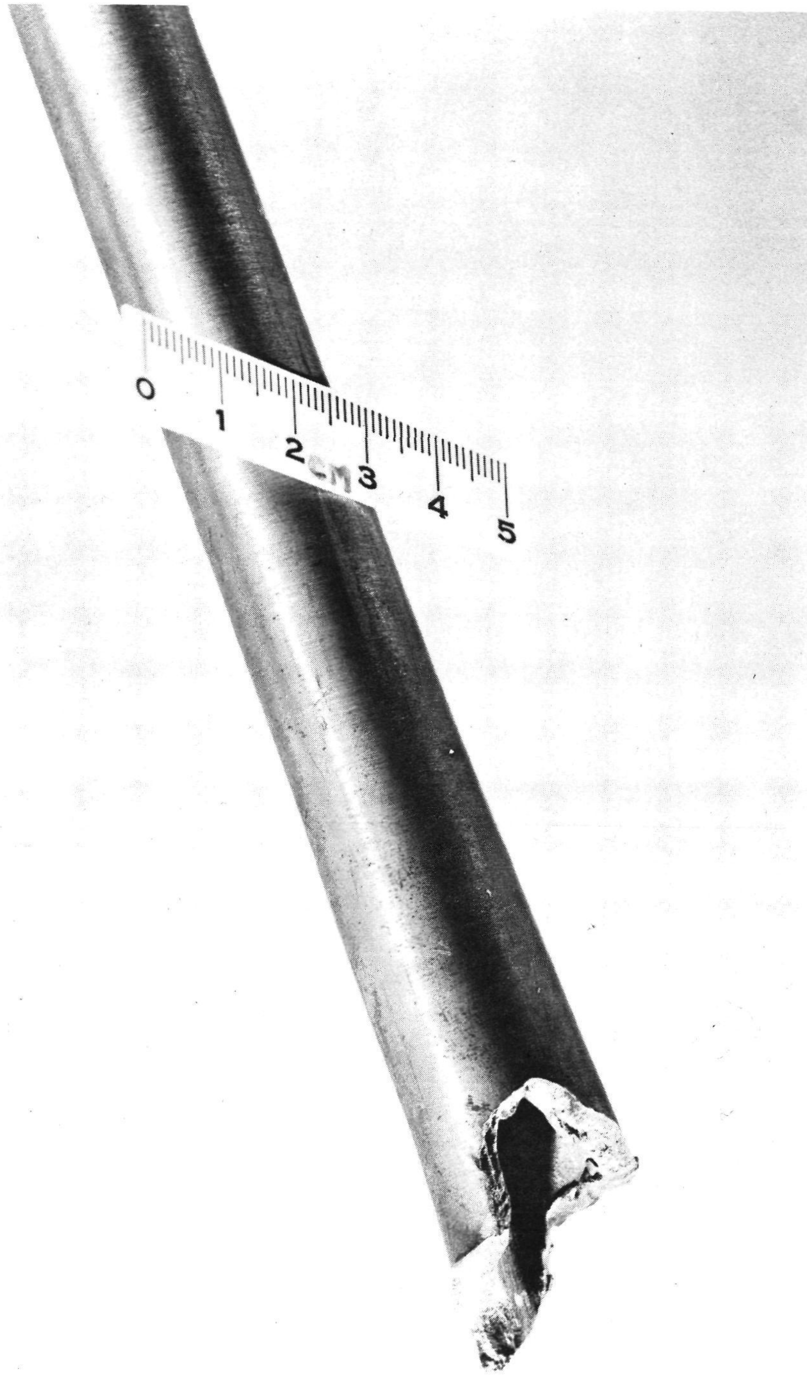


Figure 11 Rupture of gun barrel from shot 245-14.

not as important a consideration at this time as suppression of the jet.

The results of the shot were similar to those of shot 245-14 in that the projectile was destroyed in the barrel and a jet traveling at 15.7 km/sec was visible on the streaking camera record. Small steel particles were also visible on one radiograph, confirming the interpretation of the camera record.

A significant and different result was obtained from the recovery of the reservoir and barrel in the collapse region. It was observed that the portion of the barrel inside the tapered sleeve adjacent to the reservoir was pinched to a diameter of approximately 0.15 cm, but not closed. This portion of the reservoir and barrel was sectioned and is shown in Figure 12 with a centimeter scale. The wide-mouthed end of the barrel is inside the reservoir and the collapsed end is inside the tapered sleeve.

The conclusions drawn from the shot were that the additional sleeve was effective in decreasing the barrel collapse velocity and in eliminating jetting in the transition region. However, jetting was also occurring in the remaining portion of the barrel.

Shot 245-16. The apparent solution to the barrel jetting problem was to extend the sleeve over the entire length of the lens. This modification of the second stage was made in shot 245-16. Also, the barrel length was shortened by 25 cm to minimize damage to the projectile caused by excessive contact with the barrel walls. All other aspects of the shot were the same as the previous shot.

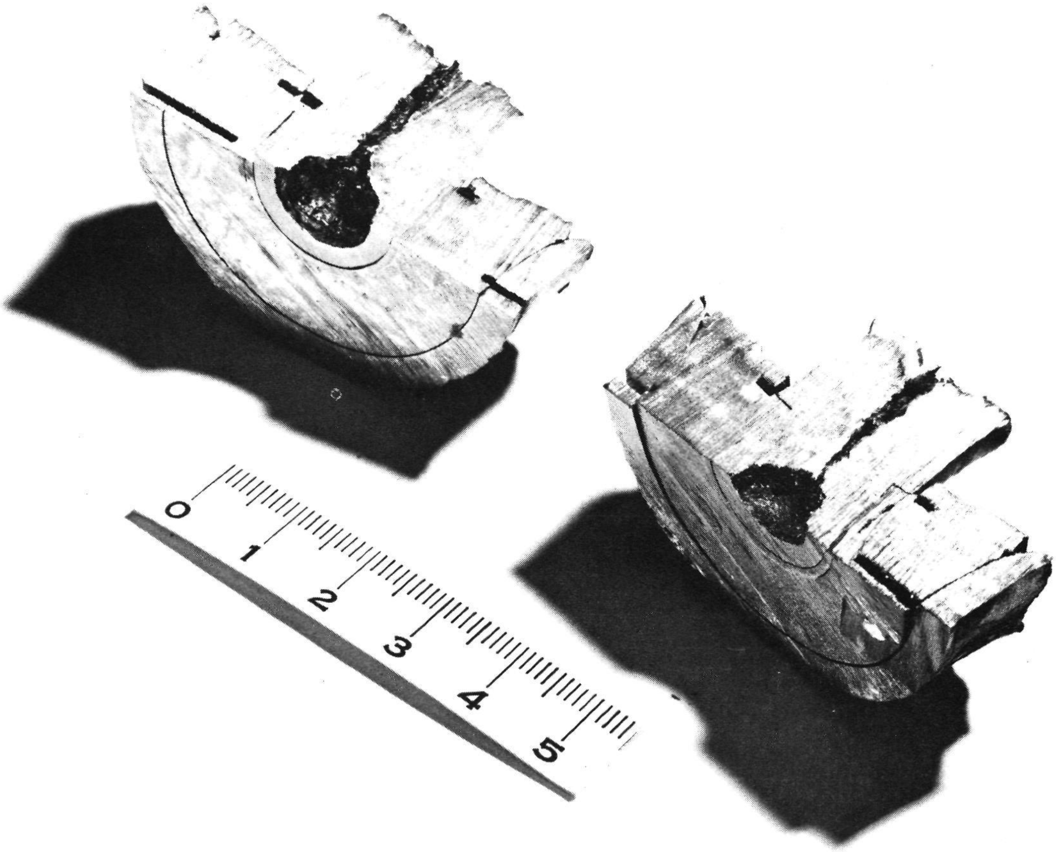


Figure 12 Section of collapsed reservoir and barrel.

Figure 13 shows the launcher prior to assembly, the pump cycle, and the second stage. The complete shot assembly, including pump cycle, second stage, and range is shown immediately prior to firing in Figure 14.

The basic result of the shot was that the projectile was launched to a downrange velocity of 11.4 km/sec; this was confirmed by the streaking camera, range switches, and radiographs. The muzzle velocity was undoubtedly higher, but there was no direct velocity measurement possible at that point. A symmetric hypervelocity crater was formed in the aluminum target. Figure 15 shows the radiograph of the projectile 34 body diameters downstream from the muzzle. Note that steel vapor can be seen expanding from the muzzle. The projectile is slightly distorted and has a small fragment missing from the top edge.

The streaking camera record showed gas exiting the muzzle, followed by a small fragment traveling at 18.2 km/sec. The main portion of the projectile left the muzzle somewhat later and was not visible until it emerged from the cloud of luminous muzzle gas 63 body diameters downstream from the barrel. At this point its velocity was 11.4 km/sec.

The basic conclusion drawn from this shot was that the jetting had been suppressed but not completely eliminated. A likely explanation for the observed results is that a small amount of jet had interacted with the projectile and broken off a small fragment which emerged at 18.2 km/sec. Some driver gas and perhaps jet material was then able to bypass the projectile and emerge on the range prior to the projectile. The design of the cylindrical impact lens appears to be nearly ideal with regard to a non-jetting configuration. An additional shot with a longer lens and perhaps a slight reduction in explosive charge would be desirable to confirm that a non-jetting and effective second-stage design had been achieved.

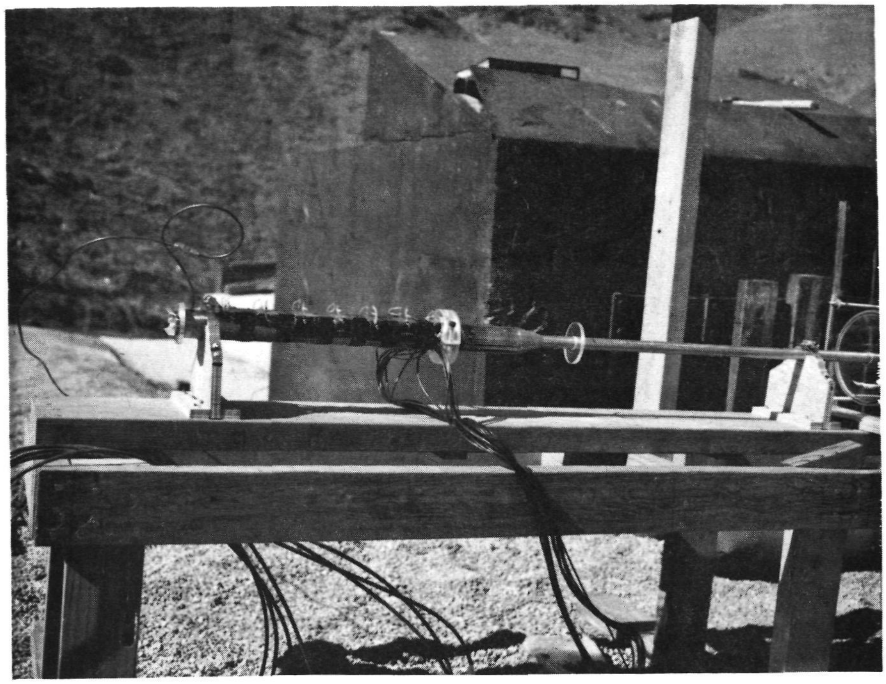


Figure 13 Setup of launcher prior to assembly of shot 245-16.

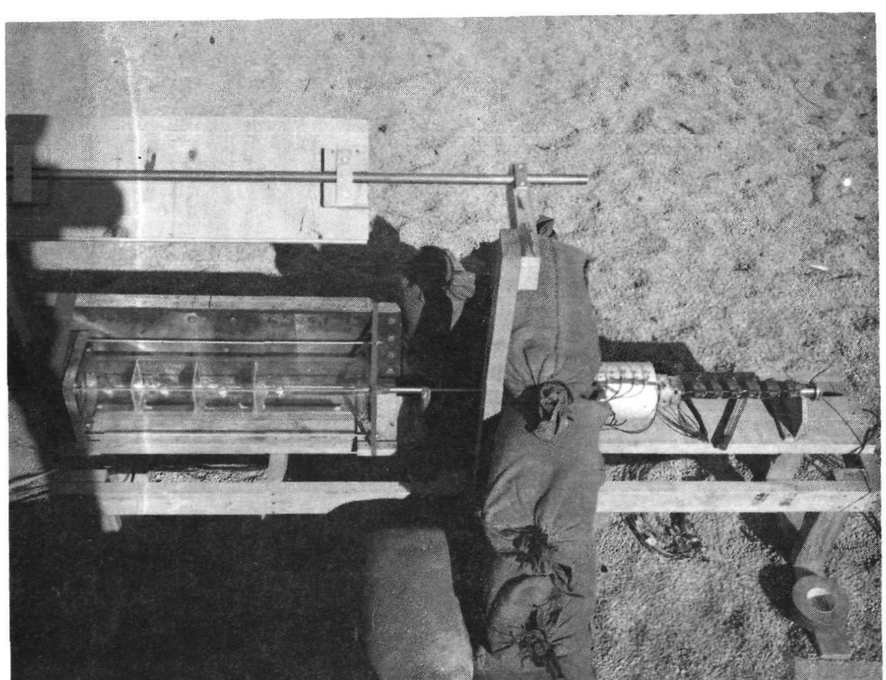


Figure 14 Setup of launcher for shot 245-16.

A2514

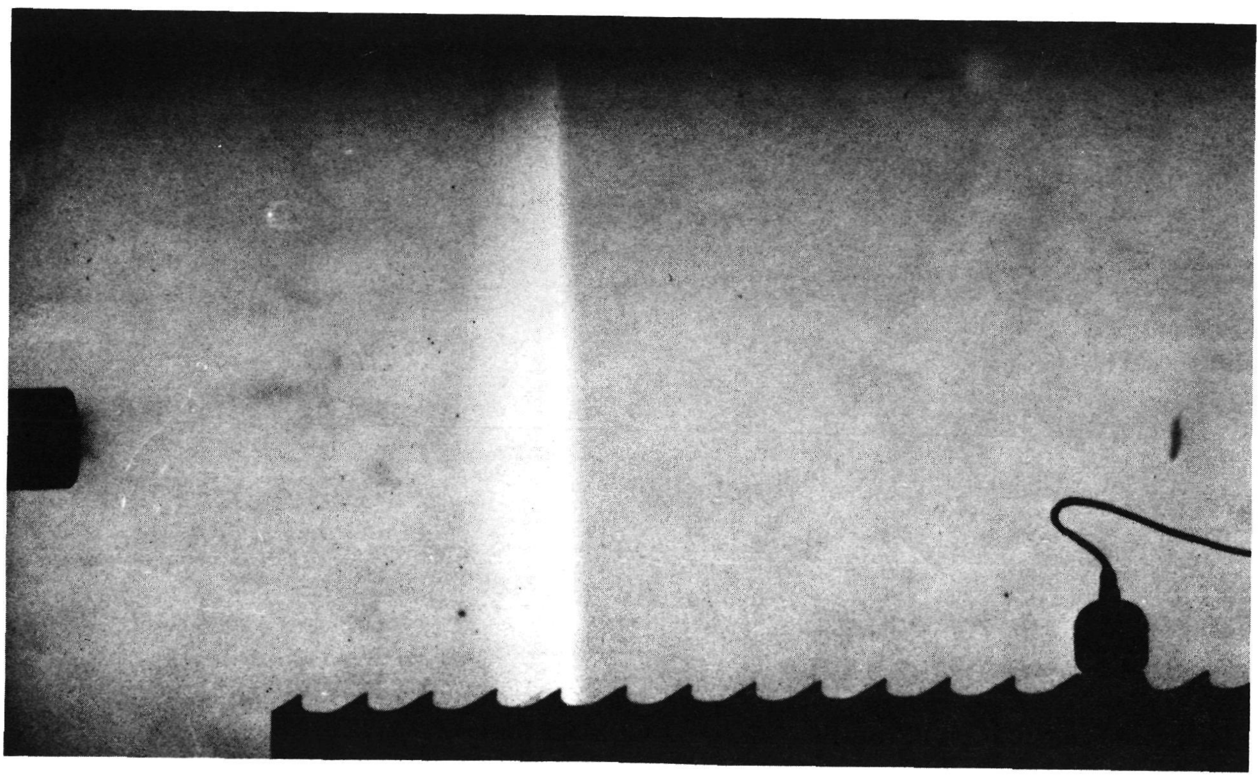


Figure 15 Radiograph of projectile of 11.4 km/sec from shot 245-16.

SECTION 4
CONCLUSIONS

The present effort in hypervelocity launcher development was devoted to the design, testing, and evaluation of a cylindrical impact technique for achieving barrel collapse. In operation, a concentric steel cylinder is explosively collapsed around the barrel of a launcher. The impact of the collapsing tube produces very high stresses in the barrel, causing it to collapse. The barrel collapse rate can be varied as the tube collapse velocity is varied. This element of control allows adjustment of the collapse process so that nearly ideal barrel closure can be achieved.

Seven launchers were fabricated and fired in testing the cylindrical impact technique. The initial two shots did not launch intact projectiles, but did demonstrate that the second stage was capable of producing barrel collapse and closure. It was postulated and confirmed by the next two shots that the barrel collapse was rapid enough to produce jetting of the barrel walls. The high-velocity jet was responsible for destroying the projectile before it emerged from the barrel. The last three shots investigated techniques for suppressing the jet. The internal gas pressure in the barrel was increased by adding an auxiliary pump cycle to partially collapse the reservoir and force more gas down the barrel. In addition, the impact stress was reduced by decreasing the tube collapse velocity. The combination of these two adjustments successfully reduced jetting so that on the final shot of the program, the projectile was launched with only a small fragment separated from the main body.

The important result from this effort is that the cylindrical impact technique has achieved complete barrel collapse and formed a second-stage piston. The technique can be adjusted to provide a more or less rapid barrel collapse process, as required to obtain an effective second-stage piston. Jetting did occur in the bore of the barrel, resulting in the destruction of the projectile. However, it was demonstrated that the jetting can be suppressed by reducing the barrel collapse rate.

It remains to assess the ultimate velocity potential with this second-stage technique. The maximum observed velocity in this effort was 11.4 km/sec, although the muzzle velocity was somewhat higher. Significantly higher velocities should be attainable, as just the startup portion of the second stage was utilized to achieve 11.4 km/sec. The startup was operative only over the first 10 cm of the barrel extending beyond the reservoir and provided a constant-velocity second-stage piston.

Further development work with the two-stage explosively driven launcher concept could be directed at obtaining the highest possible projectile velocities. Previously, high velocities have been limited by the inability to form a second-stage piston. Explosive phasing techniques to produce accelerating pistons could not be adequately tested because of only partial barrel collapse. The cylindrical impact technique should allow the first experimental evaluation of the velocity capability of phased and linear second-stage pistons.

REFERENCES

1. E. T. Moore and C. Godfrey, Explosive Hypervelocity Launchers, PIFR-051, Physics International Company, San Leandro, California, September 1967.

2. J. D. Watson, High-Velocity Explosively Driven Guns, PIFR-113, Physics International Company, San Leandro, California, July 1969.

3. D. W. Baum, Development of Explosively Driven Launcher for Meteoroid Studies, PIFR-245, Physics International Company, San Leandro, California, November 1971.

4. S. P. Gill, et al, Application of Explosive Drivers as an Energy Source for Shock Tunnels, PIFR-110, Physics International Company, San Leandro, California, April 1969.