

INSTITUTE
FOR
AEROSPACE STUDIES

UNIVERSITY OF TORONTO

29 DEC. 1966
TECHNISCHE HOOGESCHOOL DELFT
VLIEGTUIG EN RUWTEKUNDE
BIBLIOTHEEK

MULTIPOINT INITIATED IMPLOSIONS FROM
HEMISPHERICAL SHELLS OF SHEET EXPLOSIVE

by

J. E. Kennedy and I. I. Glass



DECEMBER 1966

UTIAS TECHNICAL NOTE NO. 99

MULTIPOINT INITIATED IMPLOSIONS FROM
HEMISPHERICAL SHELLS OF SHEET EXPLOSIVE

by

J. E. Kennedy* and I. I. Glass

* Research Engineer,
Ballistics and Explosives,
IIT Research Institute,
Chicago, Illinois.

Manuscript received March 1966 (in final form)

DECEMBER 1966

UTIAS TECHNICAL NOTE NO. 99

ACKNOWLEDGEMENTS

We wish to thank Dr. G. N. Patterson (UTIAS) and Mr. V. F. Volpe (IITRI) for their interest and encouragement.

The substantial contributions to the project by D.E. Baker, J.E. Daley, J. Jeslis and J.G. Nelson are sincerely acknowledged.

The discussions with Mrs. H.S. Napadensky and Mr. J.L. Austing (IITRI) and Mr. R.F. Flagg (UTIAS) were very helpful.

The research was supported jointly by the Institute for Aerospace Studies, as a subcontract to Contract No. USAF AF 33(657)-7874, Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio, and the IIT Research Institute (IITRI), and this support is acknowledged with thanks.

SUMMARY

Some preliminary results are given on the generation of implosion waves by simultaneously detonating a hemispherical shell of sheet explosive at 91 individual initiation sites. The 7 in. dia. x 0.168 in. thick shell was formed from eight "orange-peel" segments cemented on a steel backing shell 0.1 in. thick, which was perforated to take the 91 detonators. A scalloped type shock wave surface was generated from the 91 individual detonation sites that imploded into the gas space. The distortions of the shock wave surface increased as the implosion wave gained in strength while converging on the origin. It would seem from the limited experiments that this may not be a useful way of producing implosions. However, it appears to be a useful method of investigating instabilities of implosion waves arising from controlled disturbances.

TABLE OF CONTENTS

	<u>Page</u>
1. INTRODUCTION	1
2. EXPERIMENTAL CONSIDERATIONS	2
2.1 Multiple Point Initiation System	2
a) Mild Detonating Fuze (MDF) Leads	2
b) Booster Button	3
c) Evaluation of Simultaneity of Initiation	3
d) System Concept for UTIAS Launcher	4
2.2 Measurement of the Shape of the Implosion Wave	5
a) Multiple Trace Smear Camera Technique	5
b) Instrumentation for Implosion Experiments	6
2.3 Firing of Prototype Implosion Systems	7
3. DISCUSSION OF RESULTS	8
4. CONCLUSIONS	10
REFERENCES	11
TABLE 1	12
FIGURES 1 to 11	13

1. INTRODUCTION

It is noted in Ref. 1 that novel hypervelocity launchers will have to be employed in order to achieve the desirable current hyperbolic velocities of integral aerodynamic shapes at 50,000 ft/sec or greater. The application of implosion wave dynamics appears to offer such a possibility. Consequently, a pilot Implosion-Driven Hypervelocity Launcher facility has been built at UTIAS, in order to investigate this concept (Ref. 2).

A schematic diagram of the launcher appears in Fig. 1. It consists essentially of an 8 in. dia. hemispherical cavity in a steel block that is covered with a heavy steel instrumentation plate and both members are fastened by a steel locking cylinder. The operation of the launcher is as follows. The hemisphere is pressurized with a stoichiometric mixture of oxygen and hydrogen diluted with hydrogen or helium to produce high gas escape velocities. The mixture is ignited by a short exploding wire thereby inducing a detonation wave about the geometric centre. The detonation wave that races towards the periphery of the hemisphere, which is lined with a thin shell (0.1 to 0.15 in. thick) of solid explosive, collides and initiates the explosive shell. A powerful implosion is sent back into the burned gas mixture which then reflects from the geometric centre thereby producing a pocket of very hot high pressure driver gas. This gas drives the projectile that is located at the geometric centre from the barrel at hypervelocities. It is noted in Ref. 2 that it is theoretically possible to produce muzzle velocities of about 50,000 ft/sec or greater from a 6 ft. long barrel for single calibre projectiles (0.22 in. dia.) made of plastic ($\rho = 1 \text{ gm/cm}^3$) weighing about 130 mgm. To date, by using less than one-third of the amount of explosive energy in the hemispherical shell for which the calculations were done 15,000 ft/sec has been reached and it appears that the goal of 50,000 ft/sec may well be achieved (Ref. 3).

It now appears that the key problems of detonating the hemispherical shells of explosive simultaneously by using gaseous detonation waves, that the implosion waves be stable, and that they focus on the geometric centre, have been solved. An effort is now being made to attain the above parabolic entry velocities from this unique launcher facility by using the full amount of explosive.

An alternate approach to this problem was suggested by J. E. Kennedy, on a visit to IITRI, that is, the use of multipoint detonators to initiate the hemispherical shell of solid explosive. Although it was known that some difficulty might be encountered, it was felt that this approach was nevertheless worthy of investigation in order to complement our knowledge in this field. This technique would have had an added advantage that pure hydrogen or helium could have been used as a driver gas without resorting to combustion.

It was anticipated that the multipoint initiation would give rise to a "scalloped" implosion wave, with a leading point directly beneath each initiation site and a set of lagging contact lines resulting from the local shock-wave collisions that represent the initially trailing portions of the uneven, imploding shock front. The question was whether or not these disturbances would diminish with time and a smooth-surface stable implosion wave would finally reach the geometric centre. The limited experiments tend to show that the implosion waves produced by this method were unstable and are not suitable for the production of a pocket of driver gas for a hypervelocity

launcher. However, this technique does appear to offer a possibility of producing an implosion wave with defined instabilities and it may therefore be a very useful method for systematically investigating the stability of implosion waves when subjected to reasonably defined perturbations.

2. EXPERIMENTAL CONSIDERATIONS

The experimental investigation was undertaken at IITRI with the general goal of assessing the feasibility of the multiple-point initiation method for generating implosion waves in hypervelocity launcher driver gases. It was necessary to devise a method of simultaneously detonating a large number of initiation sites on the hemispherical explosive shell. The required instrumentation capable of determining the implosion wave shape as a function of time also had to be developed. Finally, it was necessary to design, construct and test-fire the prototype implosion wave systems incorporating the multiple-point initiation scheme.

2.1 Multiple Point Initiation System

A number of general requirements were placed upon the proposed initiation systems and associated hardware for the UTIAS Implosion-Driven Hypervelocity Launcher, whether such systems involved multiple point initiation or surface initiation. Because these conditions exerted some influence on the directions which this multiple point initiation system development took, they are listed below:

- (1) The system must be especially safe because students may be operating the launcher.
- (2) The system must be low in cost because of a low operating budget.
- (3) System performance must be reliable and reproducible.
- (4) In firing of the launcher the breechblock with the hemispherical cavity must remain undamaged.
- (5) The system must be unclassified.

a) Mild Detonating Fuze (MDF) Leads

Simultaneous initiation of detonation at two or more positions on the surface of an explosive specimen may be readily accomplished by at least two methods. First, separate detonators may be emplaced at the various locations and all detonators may be fired "simultaneously" through a single electrical firing pulse. The degree of simultaneity which can be achieved in this manner depends upon the quality of the detonators and of the electrical firing circuit. The firing of a large number of detonators all within one microsecond (a maximum reasonable variation in functioning time) requires either the use of sensitive detonators (which cannot be considered safe for student handling) with a firing pulse of perhaps 200v, or the use of much safer "exploding bridgewire" detonators with a pulse of 2kv or higher, very low inductance, and currents in excess of 1000 amperes per detonator. In either case the detonators could be expected to cost \$3 each, or more.

The second method is to route leads of mild detonating fuze (MDF) of equal length, all initiated by the same detonator, to the various initiation sites. This approach is safer, more economical, and eliminates the need for an elegant firing circuit, but it does require tedious connection and routing of many leads of MDF of equal length in such a way that none interferes with the proper functioning of another. This approach was chosen over the use of separate detonators.

b) Booster Button

The output from MDF alone, even in the largest size, is insufficient to initiate Dupont Detasheet EL506A sheet explosive (essentially PETN in a rubberized base) reliably. It was, therefore, necessary to utilize a small booster charge between the MDF and sheet explosive to assure propagation of detonation. On the basis of a substantial number of propagation tests, a booster charge and booster housing button of a design shown in Fig. 2 were chosen. Some of the reasons for its design bear upon the total system design which will be discussed subsequently. The booster charge weight was held to a practical minimum and the button material was chosen to be plastic rather than metal so as to reduce the separation necessary between the booster and the hemispherical breechblock in order to prevent damage to the breechblock. The high-output explosive chosen to fill the booster button was RDX. Fine-grain RDX (sub-sieve) was used because finer explosives propagate more ideally in small diameter columns; when more coarse explosive was used in some trials, propagation failures resulted. The given design was developed for initiation by 5 grain/ft MDF entering through a side port and intersecting the column at a right angle. Propagation "around a corner" thus is more difficult than a straight run. The existing button design was later modified to permit MDF entry along the axis from the top, making RDX initiation easier; that modification was found to cause no difficulty in reliable propagation of detonation.

During the development of these booster buttons, it was necessary to conduct propagation tests. The criterion used to judge whether detonation had propagated from the MDF through the button was the impression of a dent in a steel witness plate upon which the button rested (Ref. 4).

c) Evaluation of Simultaneity of Initiation

The performance of coupled MDF-booster button systems in simultaneously initiating two or more positions on the surface of sheet explosive was monitored mechanically and photographically. In Fig. 3, a sequence of photographs taken one microsecond apart illustrates the degree of simultaneity of initiation at several equally-spaced positions on a flat sheet explosive surface. Detonation first appears at all eleven initiation sites in the same frame. Detonation waves are then seen to propagate radially outward about each initiation site until they collide after about two microseconds.

The collision loci are lines approximately bisecting the regions between adjacent initiation sites. The collision lines appear as bright boundaries surrounding each initiation site in the framing photographs because increased ionization and luminescence of air is developed along these doubly shocked contact lines. If perfectly simultaneous initiation occurred, the contact lines should have formed a honeycomb pattern of regular hexagons. Some deviation

from this pattern is seen in Fig. 3, and the deviation has been quantitatively analyzed to indicate deviation from simultaneity of initiation.

The high temperature and pressure due to stagnation and shock penetration resulting from the collision of detonation waves in solid explosives are of sufficient severity to impress well-defined grooves into the surface of solid aluminum or steel plate upon which the explosive may rest at the time of detonation. These grooves are known as Dautriche lines (Ref. 5). Thus a metal witness plate may be used to measure the time interval (in microseconds) between the initiation of detonation at two known positions on the surface of a solid explosive charge (Ref. 6). An extension of this method to the simultaneous comparison of several initiation points, which would evolve a pattern of intersecting Dautriche lines was used by Stresau (Ref. 7) to evaluate the simultaneity of functioning of several electric detonators. This suggested the photographic evaluation method which resulted in Fig. 3, discussed previously.

By the methods described above, the maximum deviation from simultaneity was found to be approximately 1/2 microsecond, which was judged to be acceptable for this application.

d) System Concept for UTIAS Launcher

Adaptation of the multiple-point MDF initiation system for use in the UTIAS Implosion-Driven Hypervelocity Launcher require provision for the routing of MDF leads and the placement of booster buttons at initiation sites outside the outer surface (i.e., at the larger radius surface) of the hemispherical sheet explosive liner. It is also important to separate the explosive liner from the massive steel breechblock, so as not to damage the breechblock.

A method of fulfilling both of these requirements is sketched in Fig. 4. The interior liner of sheet explosive rests upon a hemispherical steel shell about 0.1 in. thick. A plastic shell about 0.4 in. thick outside the steel shell provides attenuation of damaging effects of the detonation, and provides a medium in which the individual booster buttons and MDF leads can be rather readily emplaced; the plastic may be machined or cast to provide appropriate grooves for MDF leads and holes for inserting booster buttons. Mockup tests with flat assemblies indicated that the detonation of sheet explosive on top of a laminate consisting of 0.4 in. of lucite and 0.1 in. of steel did not damage a block of mild steel upon which the laminate rested. The use of a protective laminate 1/2-in. thick would reduce the interior diameter of the existing implosion chamber from 8 in. (breechblock cavity diameter) to 7 in.

Selection of the number of initiation sites to be located on the surface is arbitrary. The surface area of a 7-in. hemisphere is about 77 sq. in. If initiation sites could be equally spaced over the surface at a density of one per sq. in., which would require a total of 77 sites, the detonation wave from any site would have to travel 0.5 to 0.7 in. before colliding with the detonation wave from the adjacent site. The initial deviation from hemisphericity in the shock wave driven into the central gas space would thus be two to three microseconds. Practical fabrication considerations indicated that no more than 100 initiation sites could be introduced on the surface of the hemisphere.

Ideally one would wish to locate initiation sites in a regular fashion, equally spaced from one another. However the maximum number of equally spaced points which can be located on the surface of a sphere is twelve, these points corresponding to the apexes of a regular icosahedron (Ref. 8). Of these twelve points, either six, seven, or eight can be located upon the surface of one hemisphere, depending upon how a diametrical plane is passed through the icosahedron. No regular polyhedrons having 50 to 100 apexes exist.

It was therefore necessary to approximate equal spacing of points with a convenient total number of sites. A pattern generating 91 initiation sites was chosen, which provides one site for every 0.845 sq. in. of surface. Detonation of the entire surface should be completed within about 2.5 microseconds following simultaneous initiation by the 91 booster buttons. The pattern consisted of a hole at the crown of the hemisphere, five equally spaced holes located about a circle 15° off the crown, ten equally spaced holes 30° off the crown, fifteen holes 45° below the crown, and twenty equally spaced holes each about circles located 60° , 77° , and 86° below the crown. Booster buttons located in these 91 positions may be seen in the figures discussed later in regard to tests on the prototype systems.

2.2 Measurement of the Shape of the Implosion Wave

A photographic instrumentation technique was adapted to measure the three-dimensional contour of the implosion wave. Some experimental development work was conducted on the technique preparatory to its application to the monitoring of the hemispherical implosions.

a) Multiple Trace Smear Camera Technique

In ultra-high speed camera work, argon gas has been employed for some time as a means of producing sufficiently brilliant light to permit photography of objects that are not self-luminous, in exposure times considerably less than one microsecond. By one means or another the argon is strongly shocked so that it ionizes and emits intense light. This light may be photographed directly if it can be so used for instrumentation purposes, or it can be focused on a non-luminous subject for use effectively as a flashbulb.

Consider the general problem of sensing the arrival of a shock wave (whether passing through a gaseous or solid medium) at a given position. A layer of argon in contact with the subject interface will produce a brilliant light pulse which may be photographed easily by a Beckman & Whitley Model 189 streak camera, if the shock wave intensity is sufficient to appreciably ionize the argon.

In the case at hand, it was necessary to sense the arrival of a gaseous shock wave. Given the time of arrival of the shock wave as a function of position, and knowledge of the shock velocity, the shape of the wave can be deduced. If normal streak photography were employed, the shape of the shock front along one straight line portion of a surface could be measured. This provides a two-dimensional rather than three-dimensional picture of the wave. In order to learn something about the shape of the wave as a function of the third dimension, multiple streaks must be employed.

Figure 5 presents an experiment conducted to demonstrate the feasibility of multiple streak photography in monitoring gaseous shock waves. A strip of sheet explosive was initiated by an explosive line wave generator and drove a reasonably planar shock wave into the adjacent air at an angle of about 35° to the original sheet explosive surface. A lucite plate with two milled grooves, each filled with argon, was set at a 35° angle to the sheet explosive, so the air shock impacted the plate normally. The argon along the entire length of each groove was shocked essentially simultaneously, and released a pulse of light simultaneously.

The Beckman & Whitley camera observed the grooves from opposite the shocked face. No slit plate was used in the camera as in normal streak photography; the camera was thus operated as a smear camera, recording in a continuous sweep along the film any light which appeared in the circular field of view. The entire flat surface of the lucite plate was taped over to omit detonation light. A layer of tape covered over each groove, forming a channel-shaped pocket later filled with argon. Thus the only light which the camera should have seen was that emitted by the argon pockets upon arrival of the shock wave.

While some overwritten light reached the film to hide the traces somewhat (probably from insufficient baffling to omit detonation flash), the two rather straight traces produced by argon lighting are clear, and distinct from one another. An important feature of multiple trace streak or smear photography is the ability to "turn off" each light pulse to prevent lingering afterglow and overwrite onto the adjacent trace. This afterglow was eliminated in the present arrangement by the fact that the lucite became opaque upon spallation, due to a tension wave reflected at the surface nearest the camera, after passage of a compression wave.

The results of this experiment demonstrated the capability of the multiple smear camera technique to monitor the "simultaneous" arrival of a gaseous shock wave at a surface, in three dimensions, and to indicate quantitatively small deviations from simultaneity.

b) Instrumentation for Implosion Experiments

This technique was then applied to the problem of monitoring a hemispherically imploding gaseous shock wave. Photographs of a grooved-base plate and a grooved hemispherical dome plug, both made of lucite, are shown in Fig. 6. The dome plug was inserted into the base plate and the steel hemispherical shell was fitted over a recessed portion of the base plate such that the dome plug and the steel shell were concentric. The middle groove in the plate and all three grooves in the dome plug were to be flushed with argon just before carrying out an implosion experiment. The Beckman & Whitley streak camera in a smear mode was to be used to view the argon in the grooves. As the implosion wave approached the dome plug, its velocity should be measurable from the slope of the light trace generated by the argon in the diametral groove in the base plate. The deviation from simultaneity (or deviation from hemisphericity) of the implosion wave should be indicated by the shape and relative spacing of the three traces from the argon grooves in the dome plug.

2.3 Firing of Prototype Implosion Systems

Two prototype systems were fired to permit a preliminary assessment of the feasibility of using multiple-point initiation for the generation of hemispherical implosion waves.

It was not feasible to fire the prototype hemispheres in a massive steel breechblock comparable to that of the UTIAS Implosion-Driven Hypervelocity Launcher. Because of this, it was found to be experimentally expeditious to deviate in some respects from the prospective system discussed in Sec. 2.1 d) for the UTIAS launcher, but it is believed that the essential features of the implosion generation system were not significantly affected by the differences.

The sheet explosive liner, steel shell, and ninety-one booster button positions were unchanged. Thirteen leads of 10 grain/ft MDF, all of equal length, were brought from a single detonator-booster to junctions consisting of paired Dupont X349 and C63 boosters. At each junction, a single strand of 10 grain/ft MDF was positioned to initiate an X349, and was crimped in place. The X349 in turn detonated a C63 detonator into which were crimped seven leads of 5 grain/ft MDF of equal length, which were used to initiate seven individual booster buttons. In this way all ninety-one booster sites were initiated nearly simultaneously. The MDF leads, rather than being routed closely around the steel shell surface as would be necessary in use with the launcher, were brought directly away from the surface. Prototype hemispheres in various stages of fabrication are shown in Fig. 7.

The steel breechblock and base plate used in the UTIAS launcher provide very good confinement of the implosion, which was not possible to match in testing the prototype hemispheres. The necessity of maintaining a line of sight to portions of the plastic base plate so that photographic data could be recorded precluded very strong base plate confinement.

In the first prototype test, the steel hemisphere was backed by loose sand for confinement, and the plastic base plate was unconfined. In the second prototype test, the steel hemisphere was backed by a minimum of 3 in. of Hydrostone* cement. The face plate rested against two 1-in. thick plates of mild steel with torch-cut slots and center hole to permit observation of the argon grooves by the Beckman and Whitley camera. Preparations for testing prototype hemispheres are shown in Fig. 8. Each prototype system was built into the side of a wooden box to facilitate loading of the confining media about it.

The annular gas space between the explosive liner and the dome was filled with helium for both tests. The procedure for filling consisted of emptying a complete lecture bottle (capacity 2 cu. ft) of helium through a nozzle through a hole in the plastic base plate, while allowing gas to flow out of the annular space through a second hole. Both holes were taped over after filling, and about ten minutes elapsed before the shot was fired. No gas analysis was made to determine helium purity.

* Hydrostone is a trade name used for a U.S. Gypsum high-strength die-molding cement. It has a tensile strength of 1,200 psi, compressive strength of 7,000 psi, and flexure strength of 2,360 psi, all superior to respective values for concrete, and undergoes little expansion during curing (Ref. 9).

Argon was purged through the slots in a similar manner just prior to inserting the detonator into the charge in the field. On both days of testing, the outside ambient temperature was about 45°F.

The sheet explosive used in all cases was Dupont Detasheet EL506A-4 (4g/sq. in.), which is 0.168 in. thick. A total weight of about 300 g of sheet explosive was used in each hemisphere.

3. DISCUSSION OF RESULTS

The findings from the two implosion experiments are tabulated in Table 1 and presented in graphic form in Figs. 9 and 10. The performance of the multiple-point initiation system for the explosive charge was found to be excellent on each shot on the basis of the number and location of Dautriche lines found in fragments of the steel shell. In no case was evidence found that any booster had failed to initiate the sheet explosive.

As may be seen in Fig. 9, the steel shell separated into much smaller fragments in Shot No. 1 than in No. 2. Furthermore, the breaks were usually along Dautriche lines in Shot No. 1, whereas breaks were between adjacent holes and not along Dautriche lines in Shot No. 2. Both of these effects were probably caused by the difference in external confinement between shots. The breakup of the shell in Shot No. 1 apparently occurred very early, due to stress waves induced by the detonation, as evidenced by fracture along the Dautriche lines where reflected stress wave amplitude is greatest. Thus the loose sand was a very ineffective confinement for the hemisphere.

The fact that stress waves were insufficient to fracture the shell along Dautriche lines in Shot No. 2 implies a good mechanical coupling between the steel and Hydrostone, and a less severe acoustic impedance mismatch. Ultimate fracture of the shell in large segments followed lines between booster button holes, where stress concentration would be maximized under static loading conditions. It appears that internal pressure caused this fracture at some relatively late time. The Hydrostone therefore provided rather effective confinement for the hemisphere.

No such experimental evidence existed regarding the difference caused by confinement of the base plate. However, consideration of the particle velocity induced in steel as compared with lucite by the detonation of sheet explosive (roughly equivalent in output to TNT) in contact with each indicates that the plastic would be driven off at twice the velocity of steel. The steel is thus preferred because the gap through which rarefaction waves could "enter" the chamber is smaller with steel than with plastic.

In the field preparation of Shot No. 1, argon was inadvertently omitted from the side slots in the dome, and only the center slot was filled. Thus one should have expected a single rather than triple smear trace to appear on the record. It developed that this oversight was a fortunate one because the wave shape was not as near to hemispherical as had been expected; also, the apparent "jetting" (see Ref. 11, the "jetting" observed here requires further study and may be quite different from that described by Bowden and McOine) accompanying the wave caused penetration of the plastic dome and resulted in a continuous light output rather than permitting extinction by plastic spallation or crazing. Thus the multiple smear technique was not

workable with the ragged implosion wave. Only the center groove was used in Shot No. 2 also, for this reason.

A number of important features of the implosion waves are revealed by the traces obtained by the Beckman & Whitley camera in Shots No. 1 and 2. In Shot No. 1 at $r/R = 0.5$, the apparent velocity of the helium shock approaching the central dome is 4,100 m/sec, which from Hugoniot data on helium (Fig. 11) indicates a shock pressure of 22 atm. In Shot No. 2 at $r/R = 0.25$, the apparent helium shock velocity is 6,400 m/sec, indicating a shock pressure of 53 atm. These figures compare reasonably with calculated values of the shock velocity and pressure induced in the helium in contact with the detonating sheet explosive (assumed to be equivalent to TNT, since they have the same detonation pressure) at the outer surface of the hemisphere. The shock velocity in the helium at the surface is calculated to be 3,780 msec, at a shock pressure of 18 atm. It thus appears that the shock strength grows continuously as the wave implodes.

The general curvature of the central portion of the record indicates that the portion of the wave beneath the crown of the hemisphere (the centerline of the trace) generally reaches the dome plug earliest, and is thus leading the remainder of the wave. The wave travelling nearly along the base plate surface lags badly, probably because of lateral rarefactions and rarefactions from the rear taking their greatest toll near the base plate, plus boundary layer retardation.

Because the wave front along the base plate lags so much there is a chance for "communication", so that oblique waves from a more advanced portion of the front may expand sideways to the argon groove thereby producing an artificially elevated apparent shock velocity. Therefore the helium shock velocities measured from the film records must be considered with some caution.

Considering any given region of the central portion of the trace (the implosion wave), it is seen that the profile is jagged, with high frequency oscillations. It may be noted by comparison with the calculated wave forms at the outer boundary (knowing the points of initiation) and assuming smooth inward propagation at a constant rate with no interactions that the wave front starts out in a rather severely scalloped shape, but, if the flow were stable, smoothing of the wave should have greatly reduced the amplitude of the scallops by the time the wave reaches $r/R = 0.5$, and even further at $r/R = 0.25$. The continuing presence and substantial growth in amplitude of these variations indicates apparent jetting at the intersections of adjacent shock front surfaces. When variations from symmetry in a flow regime tend to become magnified rather than reduced as flow progresses, the flow is unstable. The evidence obtained in these first two experiments appears to indicate that the imploding shock wave driven by multiple-point initiated detonation is unstable. If this be true, then the multiple-point method of initiation is not satisfactory for use in the UTIAS Implosion-Driven Hypervelocity Launcher.

Additional details of the entire wave system over an extended time (30 μ sec) for Shot No.1 and Shot No. 2, appear in Figs. 10h and 10i, respectively. The motion of the imploding wave surface along the base plate groove and of the jet-like scalloped surfaces along the dome groove are well illustrated. The subsequent implosive compression and explosive expansion of the gas in the interior of the hemisphere can also be readily seen.

4. CONCLUSIONS

Any conclusions that can be drawn on the basis of the reported work are necessarily tentative because only two implosion experiments were conducted. In addition, the two experiments explored different conditions. Nevertheless, on consideration of the data some important points can be made.

The photographic streak traces obtained in the two shots show an apparent degradation of wave integrity as the implosion progresses towards the geometric centre. Significant protruberences (jetting) appear at $r/R = 0.5$, and they become much more pronounced at $r/R = 0.25$. It thus appears that this multiple-point initiated implosion wave is not stable, and does not tend towards a hemispherical shape as the implosion propagates.

Other related experimental factors tend to justify this conclusion. Dautriche lines in the steel shells indicate very good performance of the explosive system in each shot (a point especially strongly proven for the second shot, at $r/R = 0.25$). In addition, the confinement offered the system in the second shot was superior to that in the first shot, which should have helped in improving implosion performance. The facts that large segments of the steel shell remained intact and that pressure-failure occurred at some late time testify to the improved confinement in the second shot. Assuming that the performance of the system is reproducible, the poorer wave integrity in the second shot can only be reasonably ascribed to the fact that the implosion had progressed farther, and not to lack of confinement or a suspicion of improper functioning of the explosive charge.

In view of the above, it must be concluded that this method of generating implosion waves is not suitable for the production of driver gases for hypervelocity launchers. However, this system might be used to advantage to study the stability of implosion waves when subjected to instabilities produced through multiple-point initiation.

One avenue which has not been explored in connection with the multiple-point initiated system is the use of a detonable gas mixture in the interior gas space. The detonation reaction may tend to stabilize the wave as implosion progresses. This factor would probably tend to have more effect in regions where the shock driven by the explosive liner is at a velocity comparable to the detonation velocity in the gas. Otherwise the unreactive shock would outrun the detonation front and become decoupled from it.

It is worth noting that the problem of initiating hemispherical shells of explosive by using gaseous detonation waves has been solved at UTIAS, and this method has apparently produced stable implosions. The driver gases which were generated in this manner in initially stoichiometric hydrogen-oxygen mixtures have launched single-calibre 0.22 dia. cylinders, weighing about 100 mgm to velocities of 15,000 ft/sec. In these cases, less than one third of the design explosive energy was used and it is anticipated that the achievement of 50,000 ft/sec may be possible in the near future.

REFERENCES

1. Glass, I.I. Hypervelocity Launchers, Part 2: Compound Launchers - Driving Techniques, UTIAS Review No. 26, 1965.
2. Glass, I.I. Shock and Combustion-Wave Dynamics in an Implosion-Driven Hypervelocity Launcher. UTIAS Review No. 25, Jan. 1965.
3. Flagg, R.F. Ph.D. Thesis, Institute for Aerospace Studies, University of Toronto (preliminary results attained in 1965).
4. Slie, W.M.
Stresau, R.H. Conditions Behind the Reaction Zone of Confined Columns of Explosives - Notions Derived from Plate Dent Experiments. Second ONR Symposium on Detonation, Office of Naval Research, Washington, D.C., February 9-12, 1955.
5. Johansson, C.H.
Langefors, U. Conditions for Precision Measurements of the Speed of Detonation by the Dautriche Method. Sartryck ur IVA 22, No. 1, 1, 1951.
6. Kennedy, J.E.
Gardiner, L.A.
Hrdina, D.J.
Scharres, E.H. Weapon Impact Testing Using Rocket Sleds. DASA 1276, Vol. v, Part 1, March 1964.
7. Stresau, R.H. Private communication in August 1963
8. Wells, W.
Hart, W.W. Plane and Solid Geometry. D.C. Heath and Company Publishers, New York, 1915.
9. Hofer, K. Private communication, April 1965.
10. Austing, J.L. Private communication, April 1965.
11. Bowden, F.P.
McOine, M.P. Cavities and Micro Munro Jets in Liquids: Their Role in Explosions. Nature, vol. 208, pp. 380-383, 24 April, 1965.

TABLE 1 RESULTS OF PROTOTYPE IMPLOSION

SYSTEM EXPERIMENTS

Shot No.	1	2
Wave Shape Evaluation Position	r/R = 0.5	r/R = 0.25
Confinement of Base Plate	None	2-in. Steel
Confinement of Hemisphere	Loose sand	Hydrostone
Performance of Explosive Charge Initiation System	Excellent	Excellent
Velocity of Helium Shock Approaching Dome, m/sec	4,100	6,400
Calculated Shock Pressure in Helium near Dome, atm.*	22	53
Maximum Deviation from Simultaneity, μ sec	~2	~4
General Shape of Wave	Crown leading	Crown leading
Integrity of Wave	Some jetting apparent	Severe jetting apparent

*Note: Calculated pressure induced in ambient helium by adjacent detonation of sheet explosive at the hemispherical surface is 18 atm, and shock velocity is 3,780 m/sec.

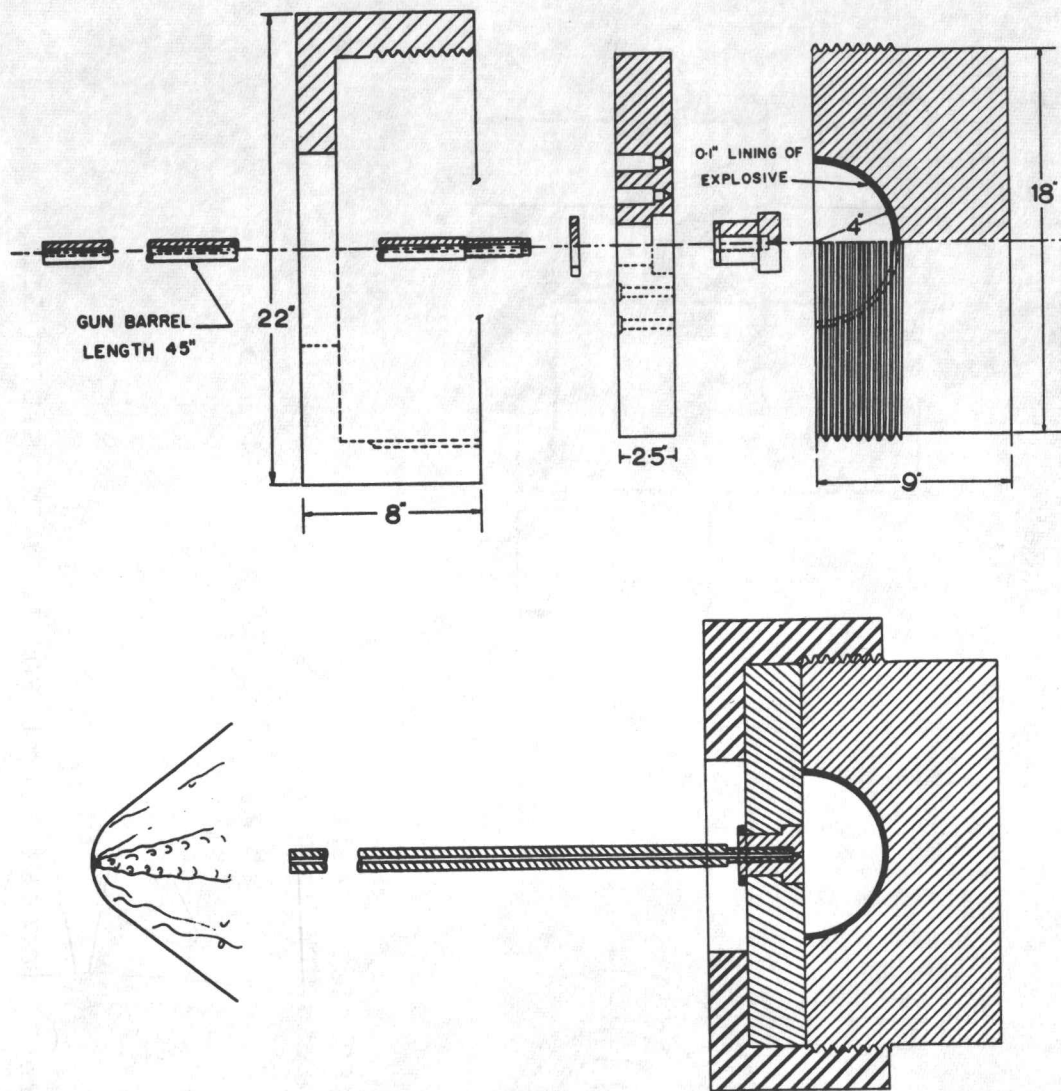
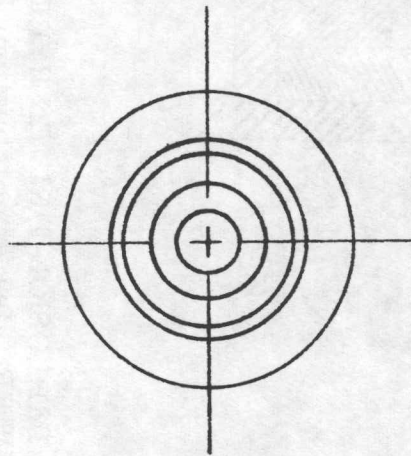
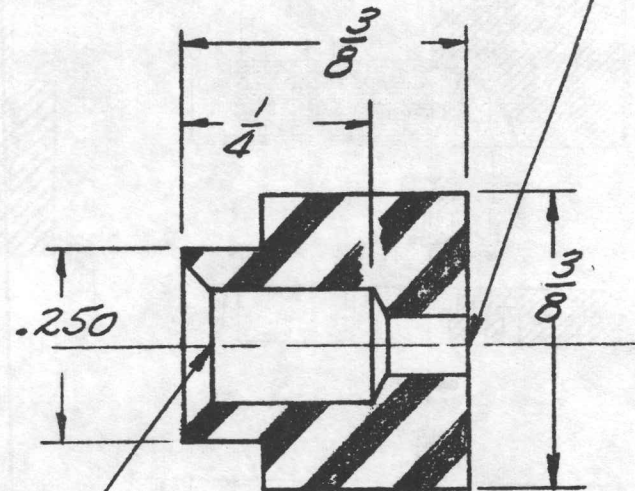


FIG. 1 UTIAS IMPLOSION-DRIVEN HYPERVELOCITY LAUNCHER (view of combustion chamber, gun barrel, and gun-barrel attachment)

MAT'L: PVC

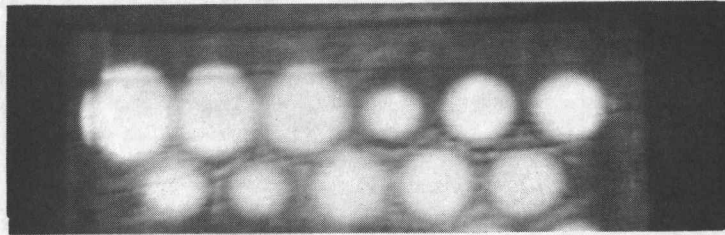
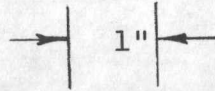


#48 (.076 Dia.) Drill; MDF Inserted Here
(Hole may alternatively enter central
column from side)

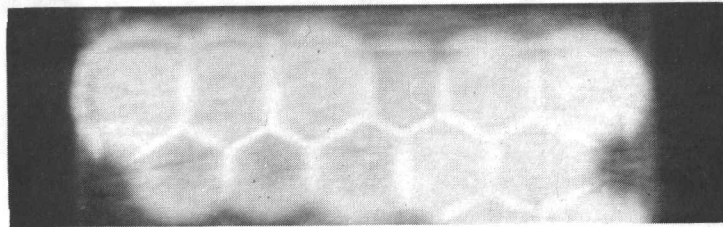


#24 (.152 Dia.) Drill
(Fine-grain RDX loaded
under 650 psi)

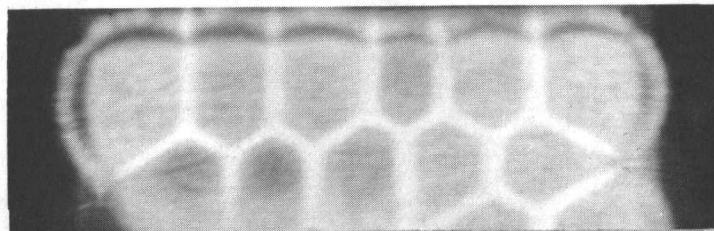
Figure 2 BOOSTER BUTTON FOR EACH INITIATION SITE



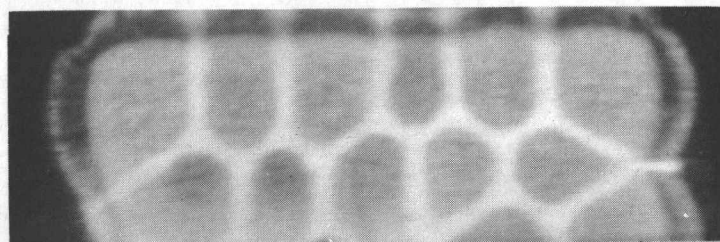
(a) First breakthrough of detonation on face of sheet explosive initiated at eleven points by MDF - booster buttons



(b) One microsecond later, detonation wave collisions occur



(c) Two microseconds after breakthrough



(d) Three microseconds after breakthrough

FIGURE 3 SHOCK WAVE COLLISION PATTERN FOLLOWING MULTIPLE - POINT INITIATION OF DETONATION IN SHEET EXPLOSIVE

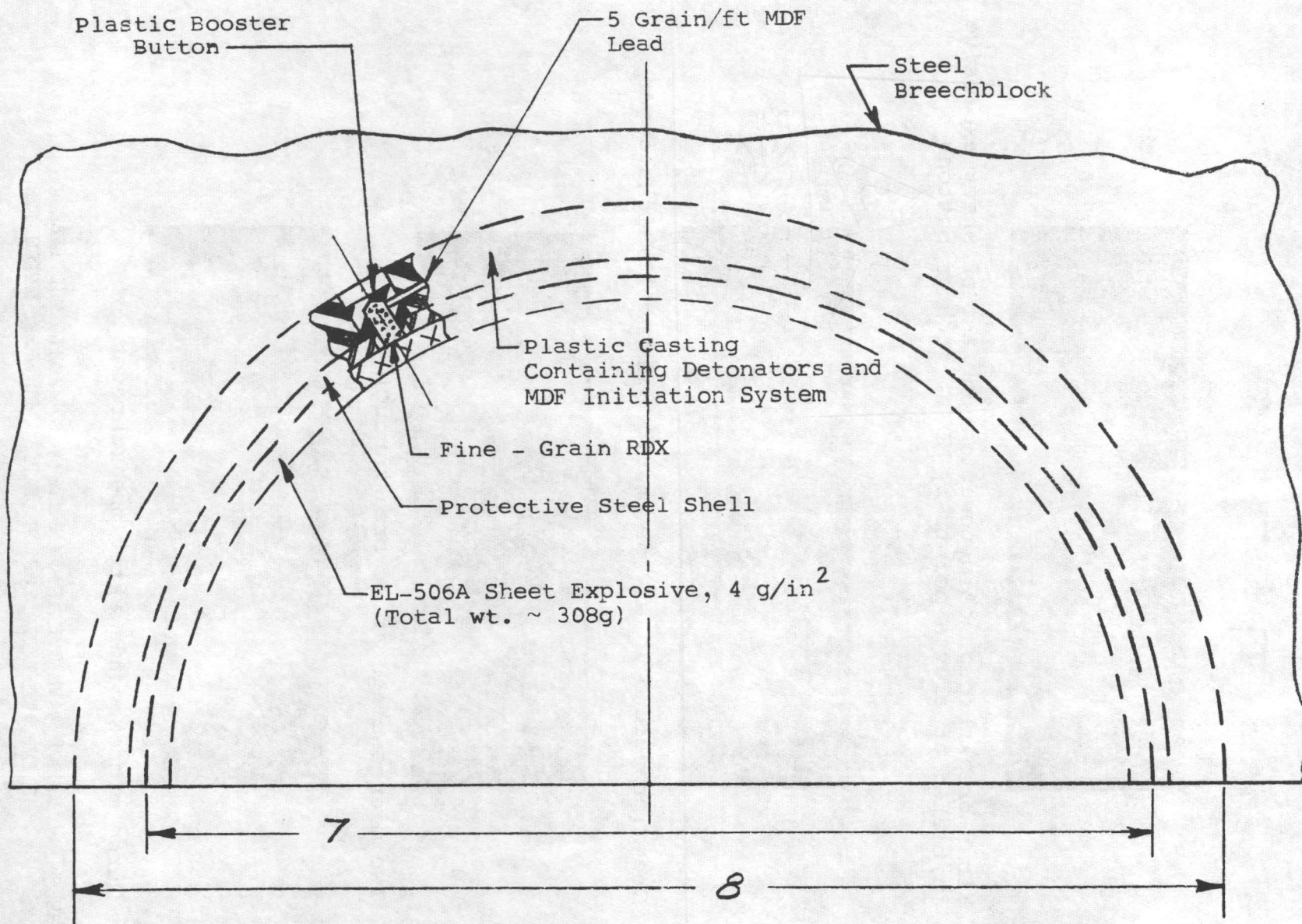


Figure 4 PROTECTIVE LINER FOR HEMISPHERICAL CAVITY

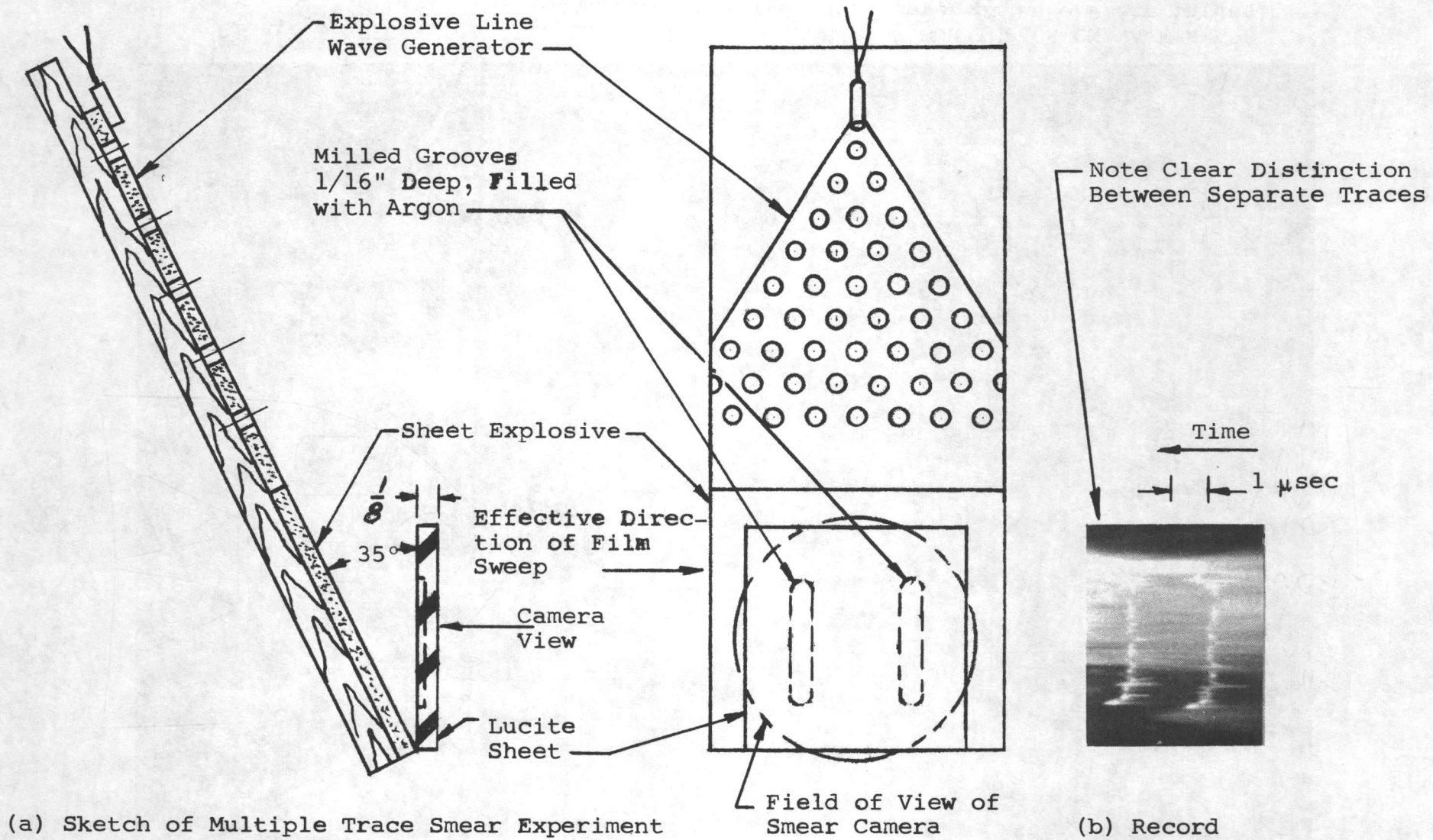


Figure 5 MULTIPLE SMEAR RECORD OF ARRIVAL OF A PLANAR AIR SHOCK

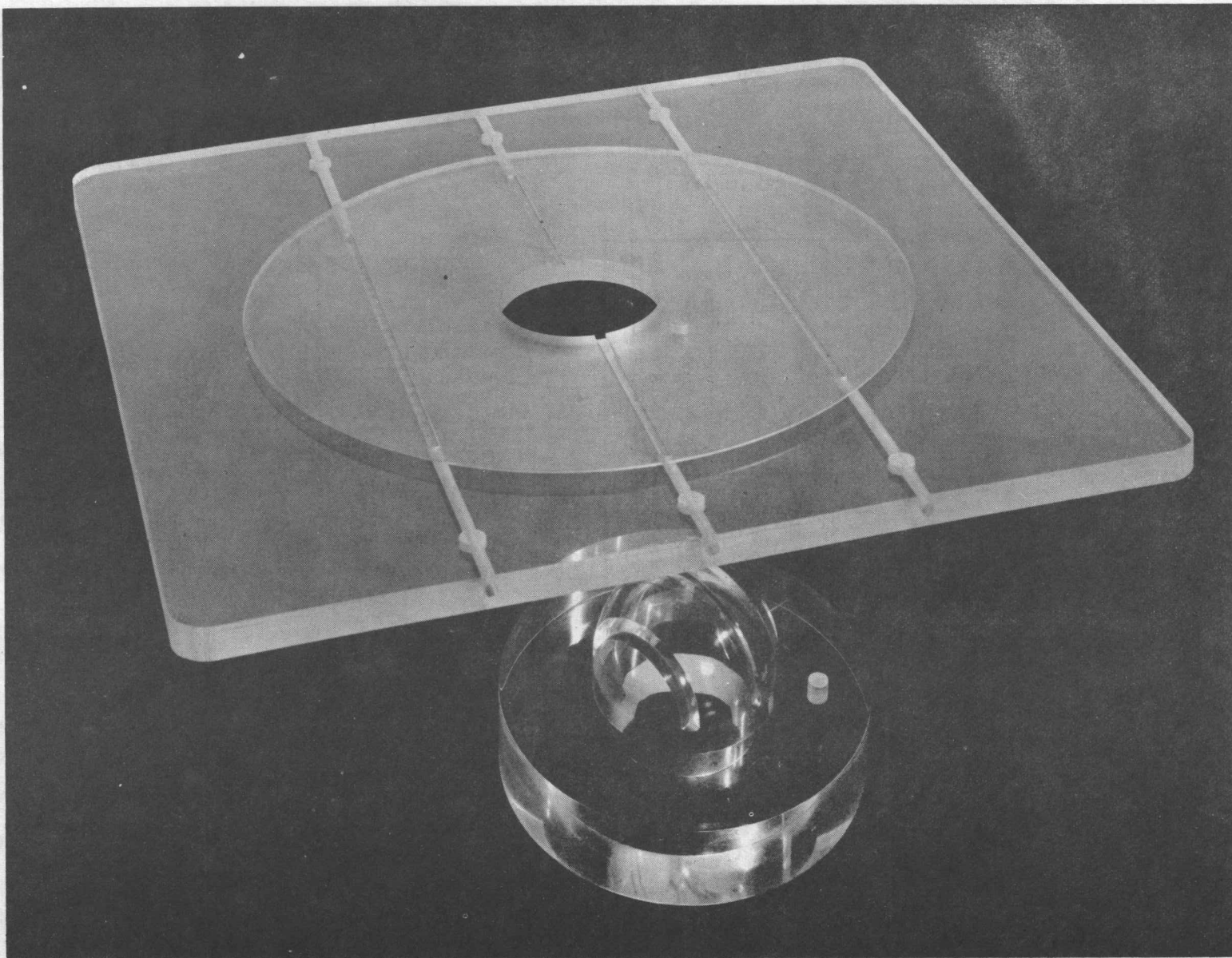
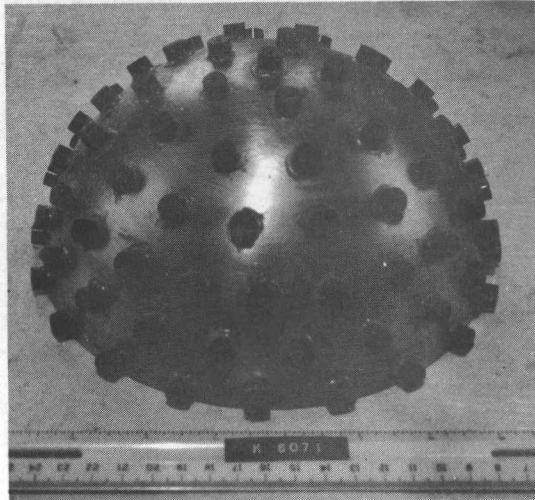
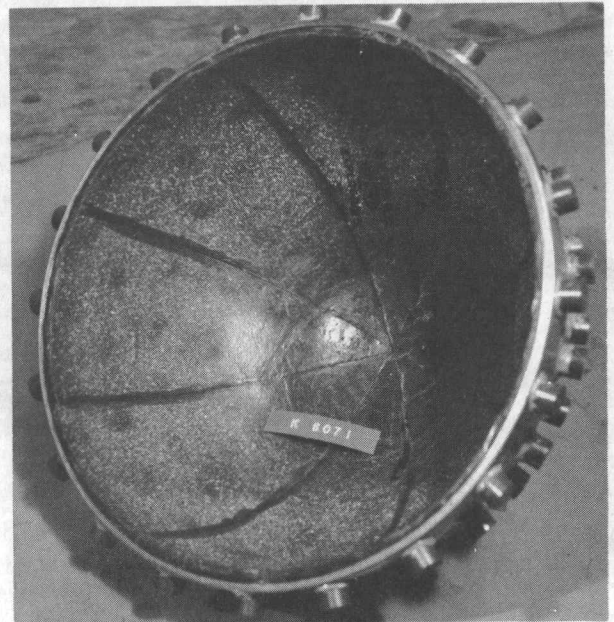


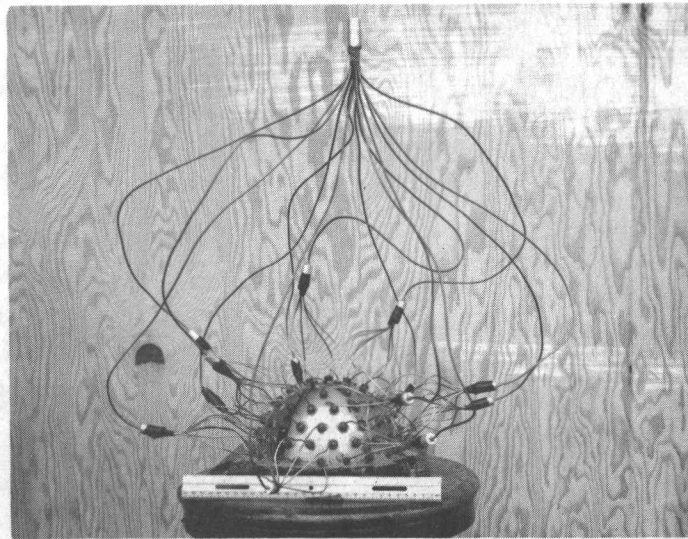
Figure 6 GROOVED LUCITE BASE PLATE AND DOME PLUG FOR IMPLOSION WAVE SHAPE EVALUATION (Dome Plug Inserted into Center of Base Plate in Use)



(a) Ninety-one booster button emplaced on steel shell

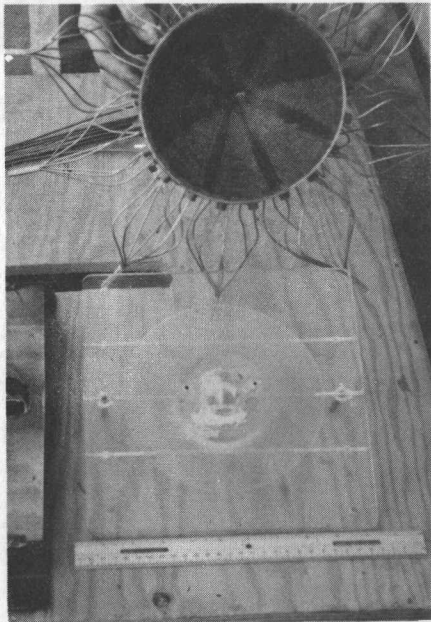


(b) Orange-peel segments of sheet explosive joined to form hemispherical explosive liner

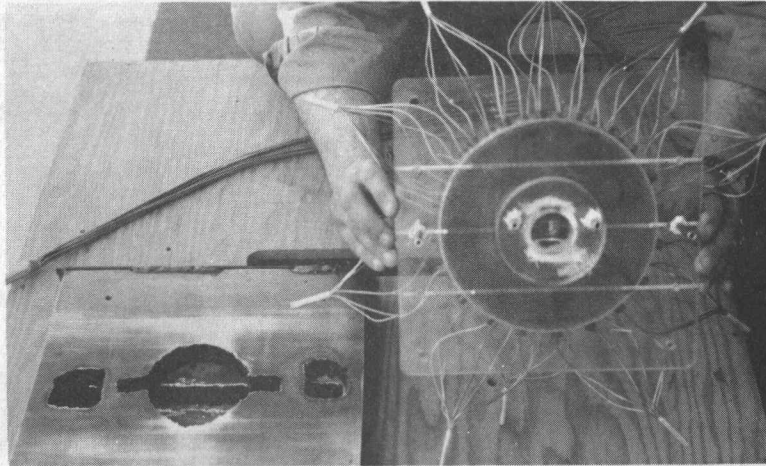


(c) MDF leads attached for initiation by single detonator (Charge assembly for Implosion Shot No. 1)

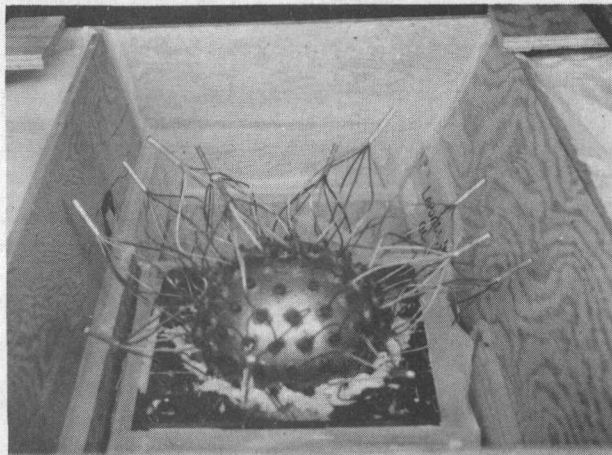
FIGURE 7 VARIOUS STAGES OF ASSEMBLY OF HEMISPHERICAL SHELL OF EL-506 EXPLOSIVE SHEET USED TO GENERATE IMPLOSION



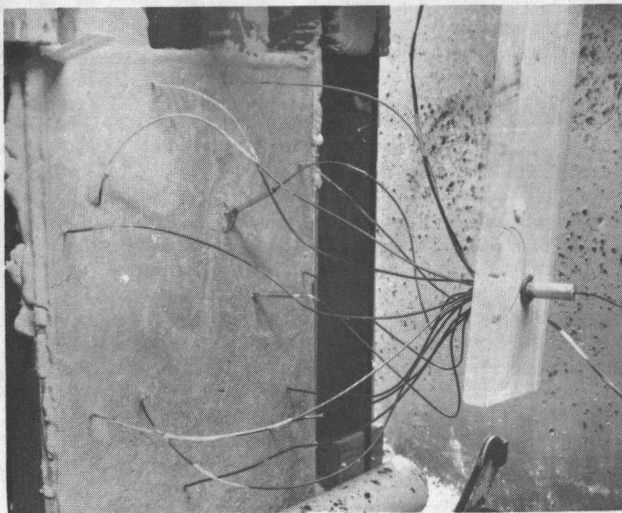
(a) Sheet explosive liner for hemisphere made of orange-peel segments; grooved lucite base plate and dome plug for wave evaluation



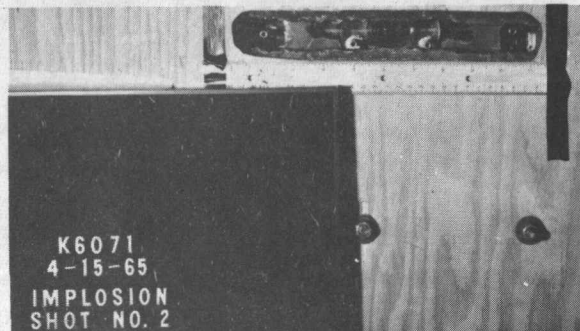
(b) Grooved lucite assembly mated to hemisphere; note slotted steel plate for base plate confinement



(c) Assembled hemisphere in box ready for attachment of primary MDF leads and pouring of Hydrostone for confinement

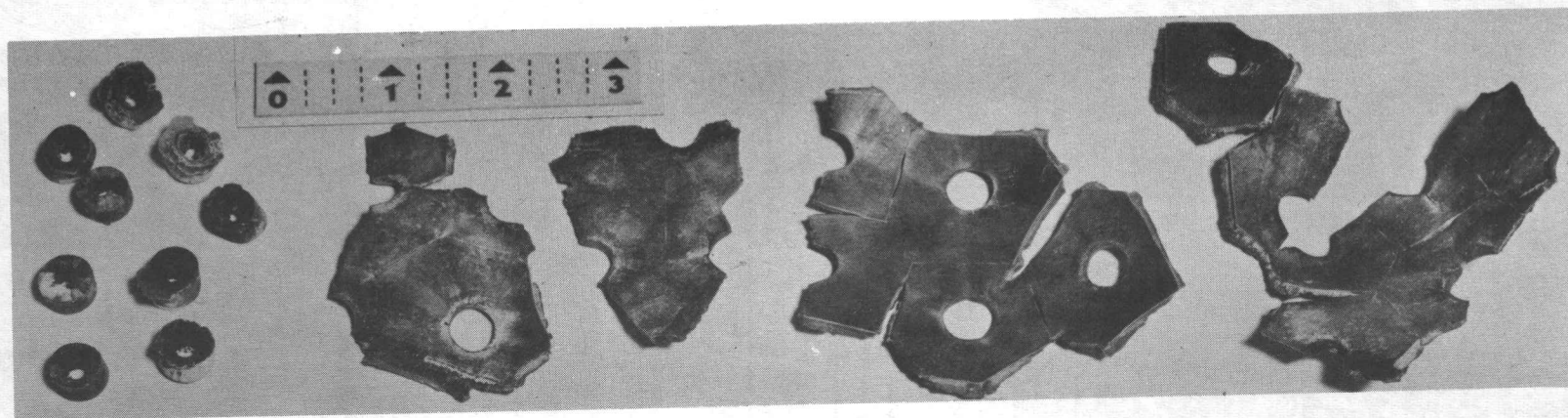


(d) Rear view of potted charge assembly, stood on end for firing

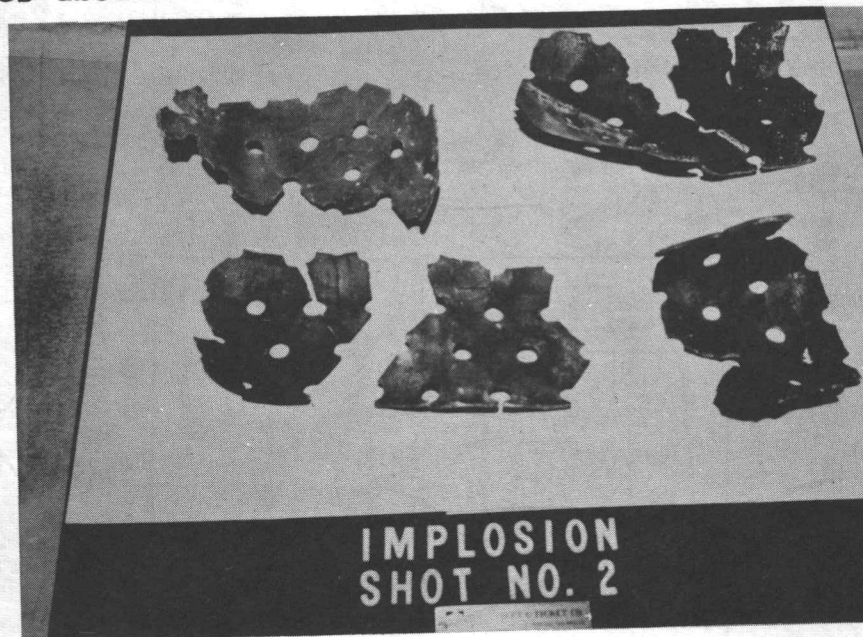


(e) Camera view of grooves in base plate and tube for admitting argon and helium

Figure 8 PREPARATIONS FOR TESTING PROTOTYPE HEMISPHERE

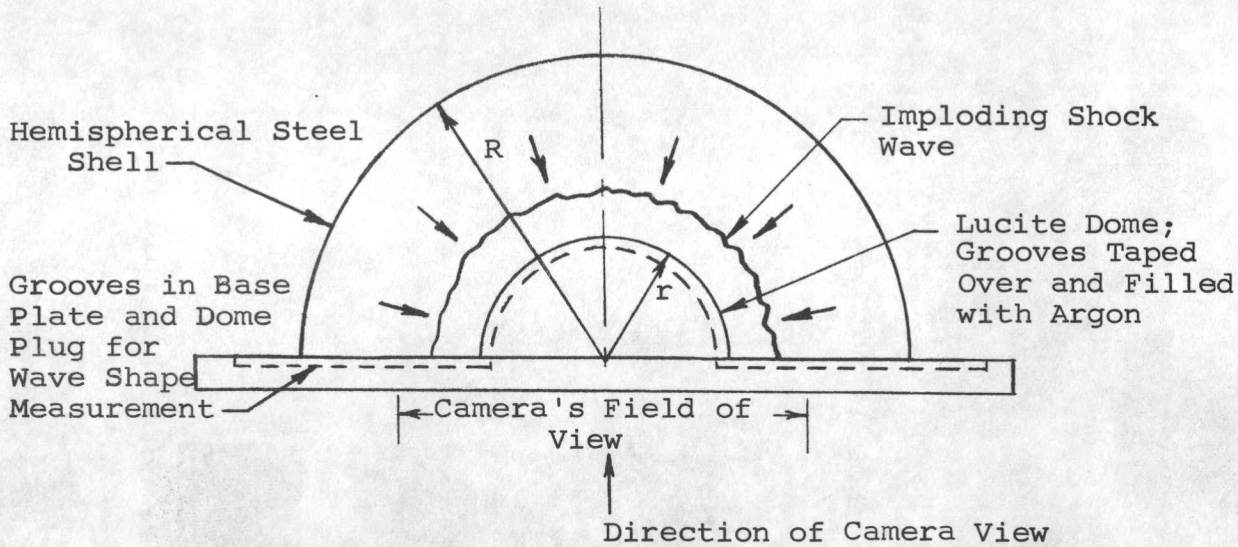


(a) Fragments and spent booster buttons from Implosion Shot No. 1; note sharp Dautriche lines about booster holes.

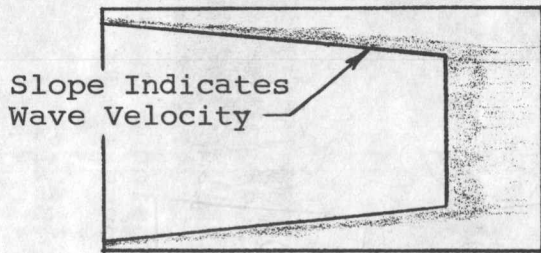


(b) Larger fragments recovered after Implosion Shot No. 2; note that failures occurred through holes rather than around them

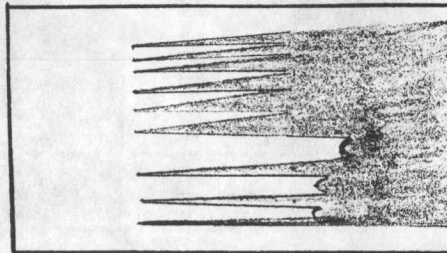
Figure 9 FRAGMENTS OF HEMISPHERICAL STEEL SHELL



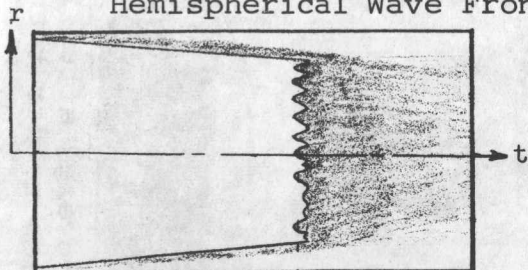
(a) Schematic Diagram of Instrumentation Scheme



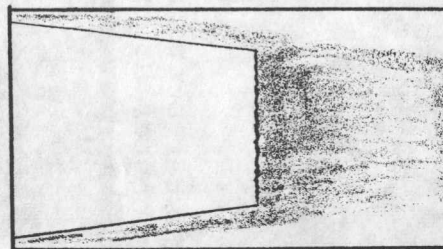
(b) Ideal Trace Indicating Hemispherical Wave Front



(c) Calculated Wave Shape at Explosive Liner Surface, $r/R=1$



(d) Calculated Wave Shape at $r/R=0.5$ Assuming No Interactions



(e) Calculated Wave Shape at $r/R=0.25$, Assuming No Interactions

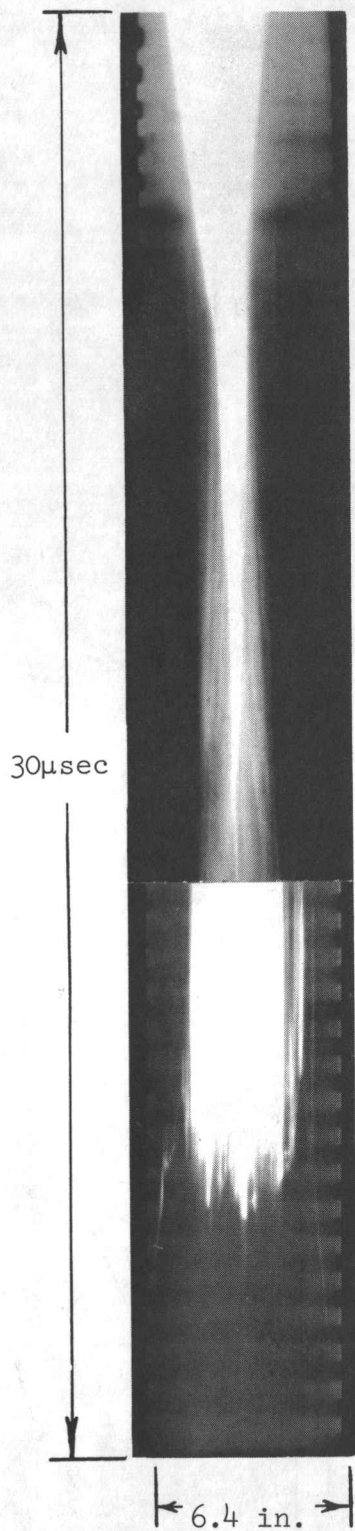


(f) Observed Wave Shape at $r/R=0.5$ (Shot No. 1); Streaks Indicate Jets

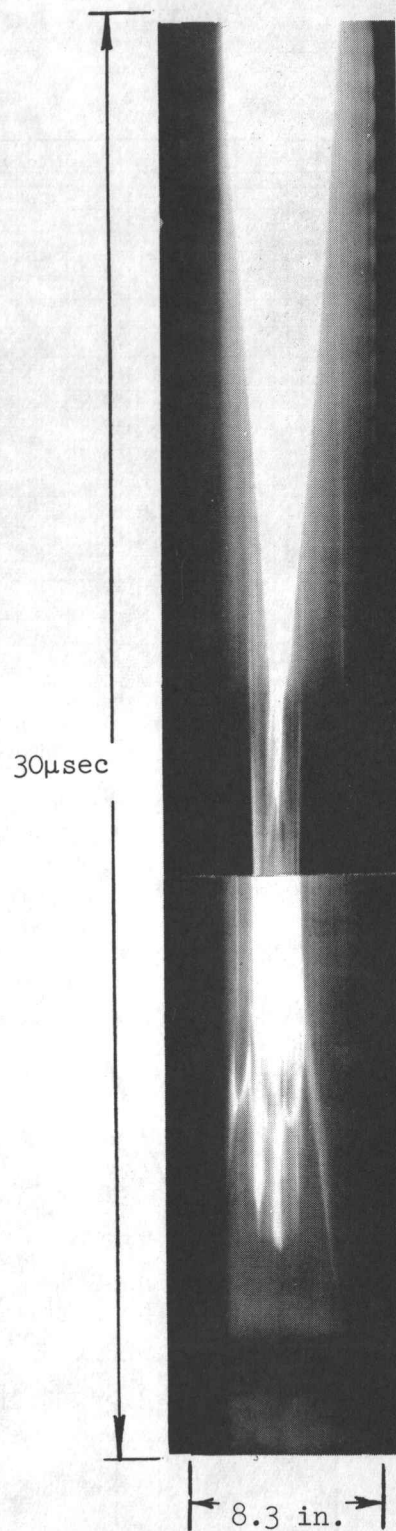


(g) Observed Wave Shape at $r/R=0.25$ (Shot No. 2); Jets More Pronounced

Time Scale for all Traces: $1 \mu\text{sec}$ → ←



(h) Details of Flow for Shot No. 1 for a Period of About 30 μ sec Following Initiation



(i) Details of Flow for Shot No. 2 for a Period of About 30 μ sec Following Initiation

FIGURE 10 (concluded)

Note: Two separate contact prints were required to bring out the initial and later features of the flow.

NOTE: Sound Velocity (Ideal) = 985 M/sec for Helium at $P_0 = 1$ Atma, $T_0 = 280^\circ\text{K}$

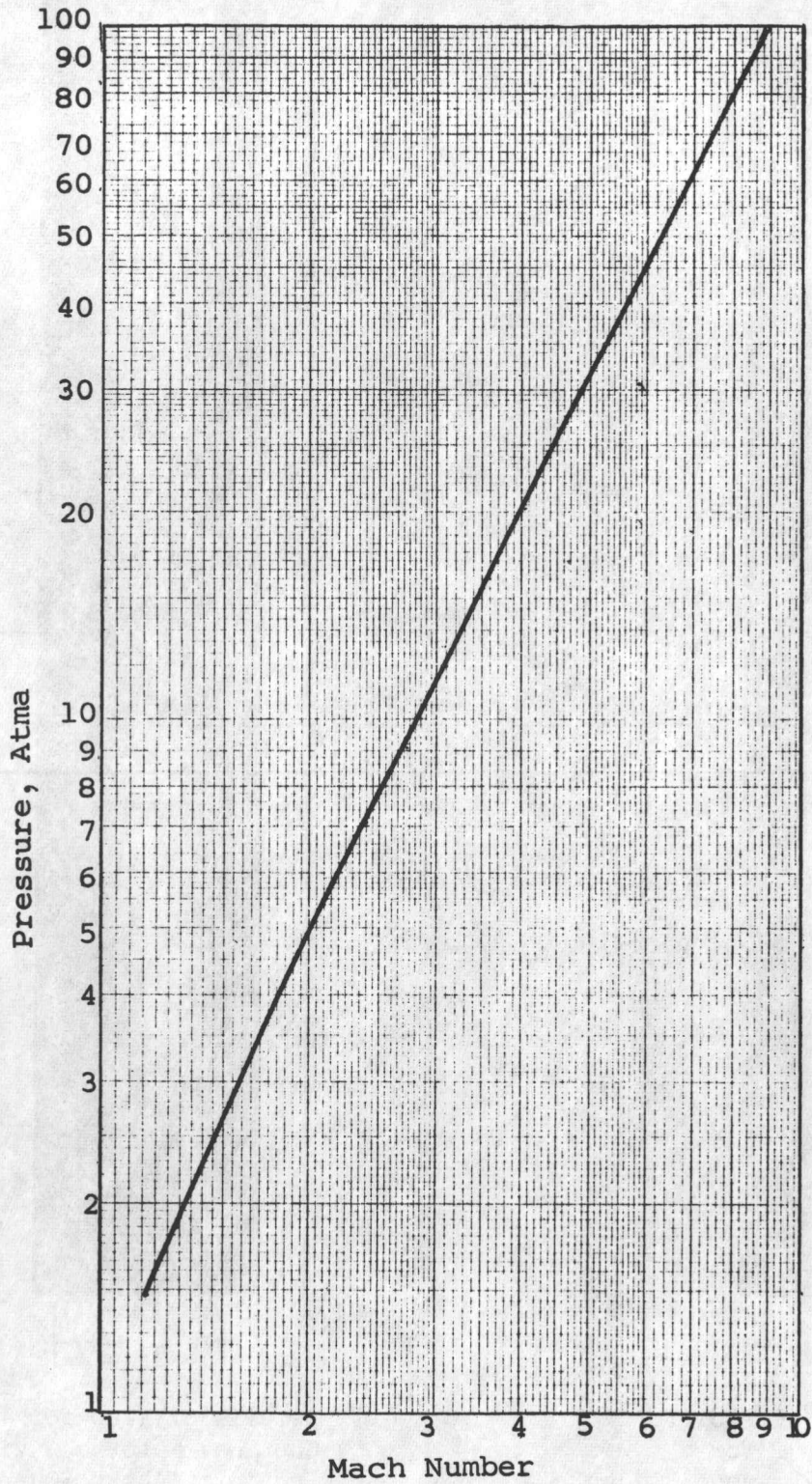


FIGURE 11 IDEAL SHOCK HUGONIOT FOR HELIUM (Ref. 10); Initial Conditions $P_0 = 1$ atma, $T_0 = 300^\circ\text{K}$