ARMY RESEARCH LABORATORY

Final Report on Anomalous Energy Transfer From a Detonation

by Louis Zernow

ARL-CR-421 April 1998

prepared by

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425 West Bonita Avenue, Suite 208
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under contract

DAAK-83-C-0033

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Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

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Abstract

Early work (1974) by the Navy, which involved studies of the front portion of the detonation products from overdriven explosive cylinders of PETN, suggested two anomalous mechanisms of energy transfer in the forward direction. These included a "prompt" (optical) mechanism and a "detached plasma" mechanism. An independent study in 1983 by the present author indicated that the prompt mechanism could not be confirmed from the existing Navy data; neither could the single Navy experiment, which displayed the detached plasma phenomenon, be repeated. However, persistent "hot" (bright) plasma regions, located at the front end of the detonation products, were shown to be present in virtually all cases. This present follow-on study, which was carried out in 1985 with the experimental assistance of Mr. George Hauver of the U.S. Army Ballistic Research Laboratory (BRL), clearly showed that the prompt (optical) energy-transport mechanism was not present. However, time-resolved optical measurements of material removal from a thin, aluminum foil target on a transparent plastic substrate, located at a long distance forward of the charge, yielded extremely high, mass-removal rates and very high, deduced-energy-deposition rates, very early in the interaction between the hot front end of the detonation products and the aluminum target foil. More work remains to be done to explain these residual phenomena.

Acknowledgments

It is a pleasure to acknowledge the experimental skills and analytical inputs by Mr. George Hauver, U.S. Army Research Laboratory (ARL), during the entire interval in which this cooperative effort was underway. This was the second part of a two-part study. The first part was reported by the present author in January 1986.

Appreciation is again expressed to Mr. Joseph E. Backofen for calling the attention of the author to the very early work by the Naval Weapons Center (NWC) (China Lake), indicating the potentially anomalous observations, which served as the starting point of this two-part study.

The continuous assistance provided by Dr. George Thomson, ARL, in all administrative aspects of this program, as well as in the technical aspects, is also gratefully acknowledged.

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1. Introduction

In the mid-1970s, the Naval Weapons Center (NWC), China Lake, CA, (Sewell, Mallory, and Pearson 1974) reported a series of experiments that purported to show unexpected, apparently high-velocity phenomena taking place in detonations of certain explosives. About 11 yr later, a further study (Zernow 1986), comprised of a critical examination of the NWC evidence and additional tests, was carried out by the author of this report. It confirmed that there was clear evidence for some unexpected energy-transfer processes associated with the self-luminous, plasma-like configurations found moving at the front of the detonation products from small (64–106 g), peripherally initiated, PETN explosive charges. Surface-melting damage, which was apparently induced by these entities, appeared on aluminum target plates at distances of up to 4 ft away from the charge.

Perhaps the most explicit manifestation of this phenomenon was one optical observation made earlier by the Navy investigators (Sewell, Mallory, and Pearson 1974) (Figures 1–3). It displayed a relatively transparent and coherent plasma-like entity (apparently running out ahead of the mainstream of detonation products), which clearly deposited energy when it touched a 1/4-in (6.35 mm)-thick aluminum target. This plasma-like phenomenon has been named the "Blue Ghost" because of its pale-blue color and transparency, as recorded in the original color photographs.

The evidence for the energy deposition by the Blue Ghost took the form of an extremely bright flash, which first became visible when the "plasma" first touched the target face. The flash size grew very rapidly with time as the remainder of the plasma continued to collide with the target. In addition, when the target was examined after the experiment, clear evidence of surface melting and displacement of the molten aluminum target surface could be found. These observations prompted the Navy investigators to propose an explanation based upon the existence of unconventional processes occurring in the detonating material.

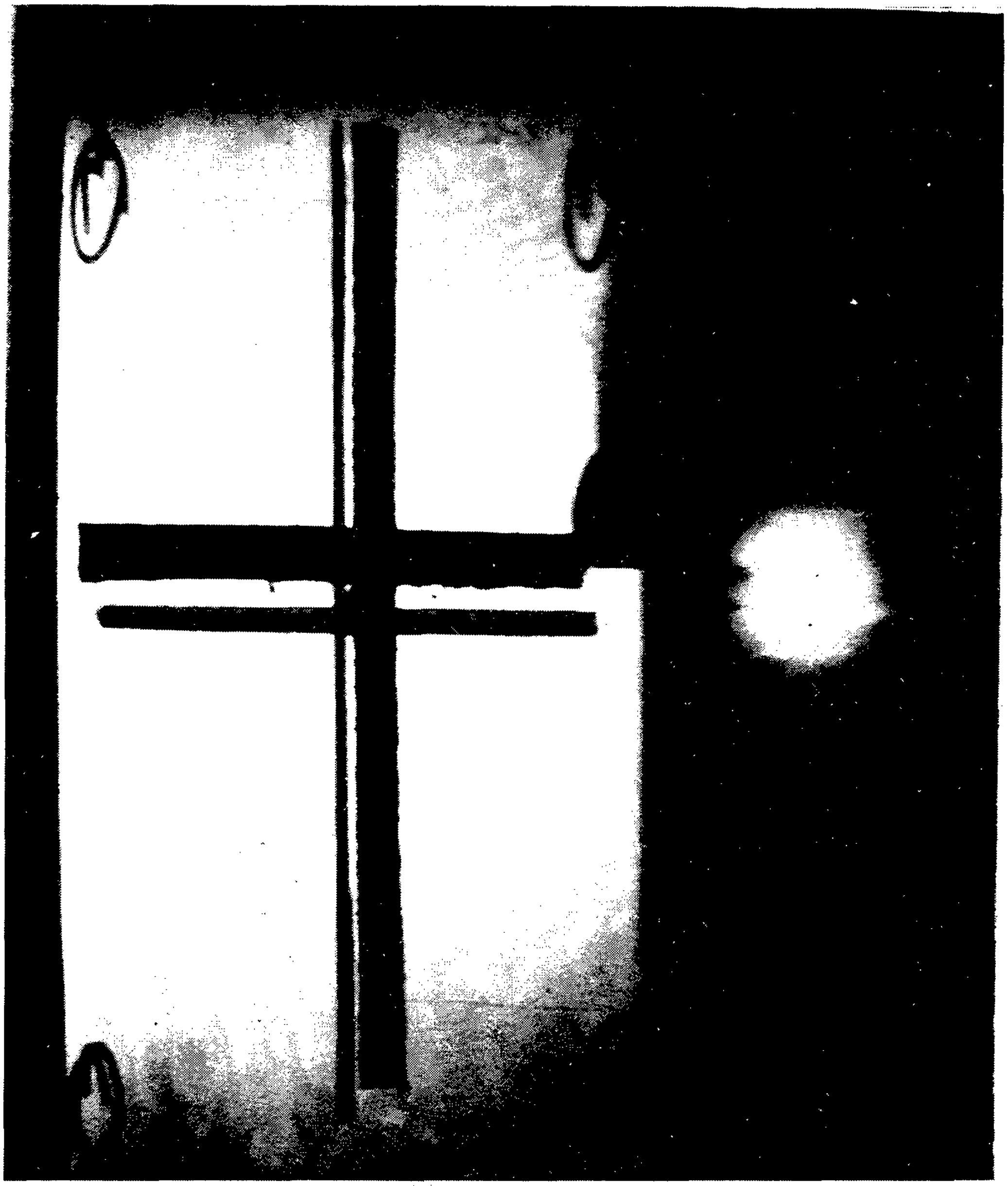

Figure 1. Frame No. 1 in the Sequence—Taken at 500,000 frames/second.

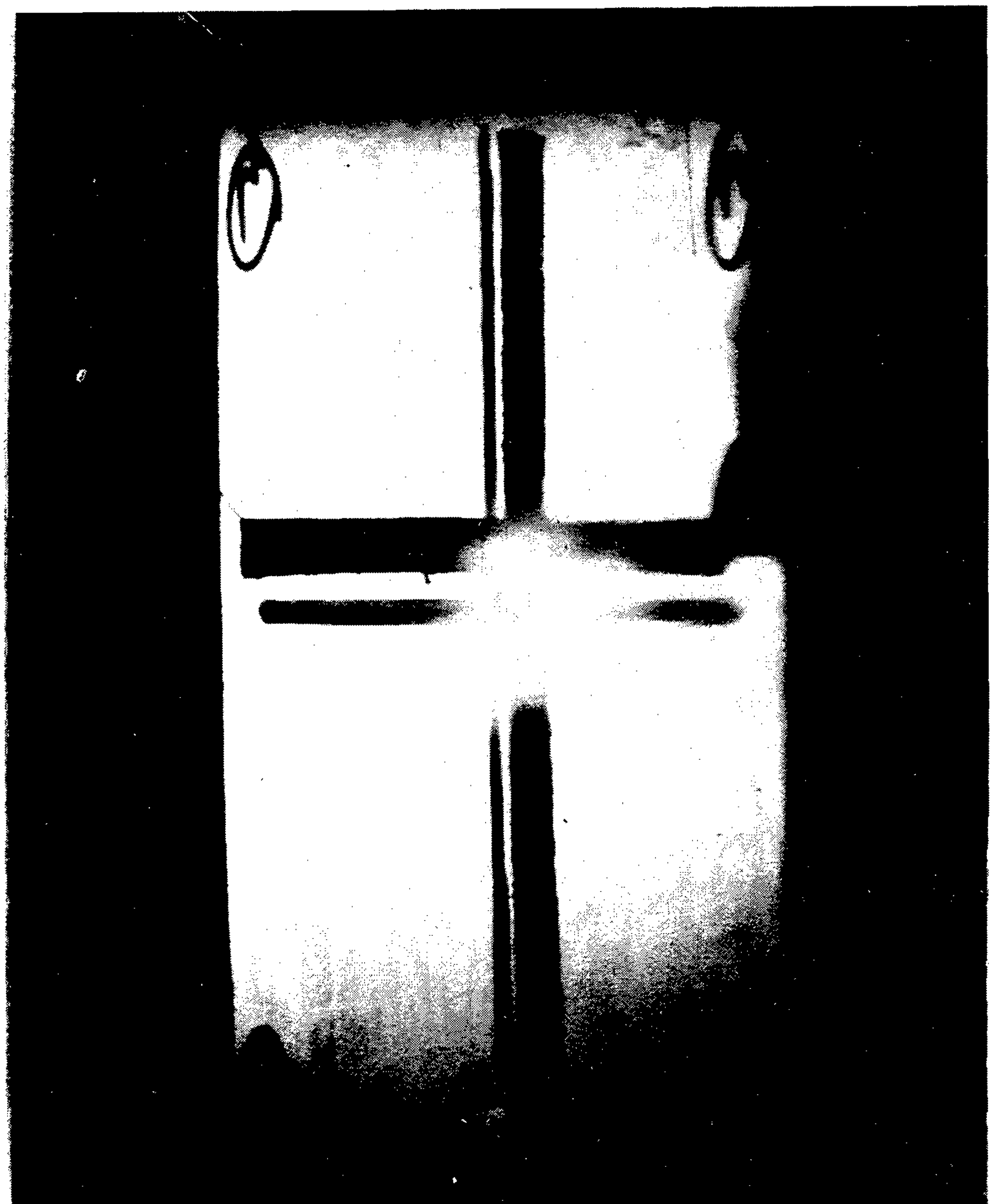

Figure 2. Frame No. 3 in the Sequence—Taken 4 μs Later Than Frame No. 1.

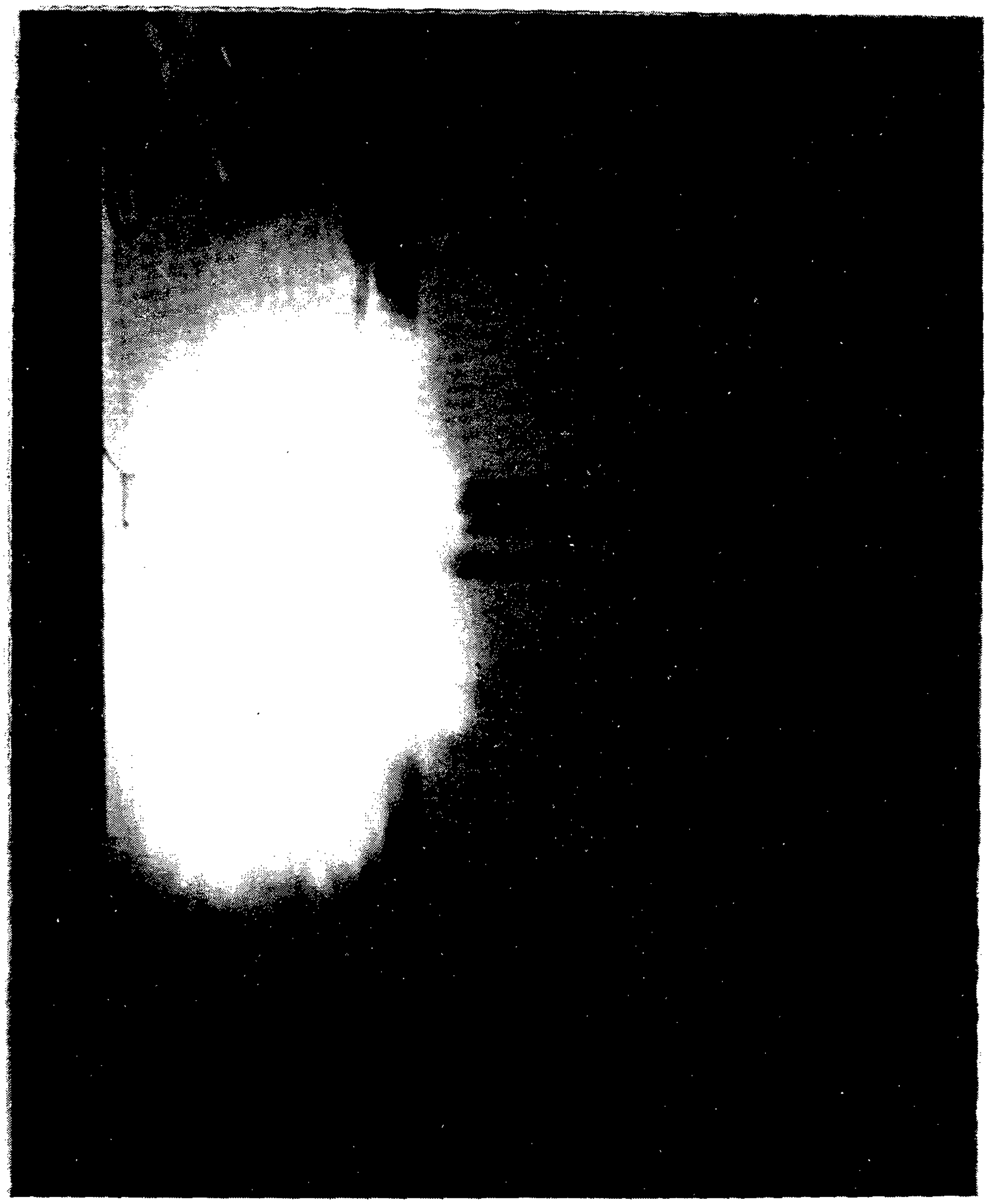

Figure 3. Frame No. 4 in the Sequence—Taken 2 µs After Frame No. 3.

In the more recent studies (Zernow 1986), it was always found that a very bright and surprisingly persistent "hot" region was generated at the front of the detonation products. Further, this hot region showed the same bright-flash phenomenon when it touched the aluminum target plate, as was seen in the original Navy observations (Sewell, Mallory, and Pearson 1974), as well as the same target-melting signature of the aluminum. A typical target-melting signature is shown in Figure 4. The more recent studies also found that the charge configuration, and especially the geometry of detonation initiation, played a key role in creating the hot regions.

2. Plan for the Present Program

2.1 General. Following the completion of the initial, limited study by Zernow (1986), it became clear that additional studies must be undertaken if these earlier observations were going to be resolved, explained, and examined for potential applications.

2.2 Separation of Unconventional Questions. The question of unconventional processes as proposed by the China Lake investigators has been excluded from the present work and this report. This was done because the high-speed photographs of Zernow (1986) show no evidence of any process requiring the invocation of such models in the present situations. Further investigation of these most interesting effects is left to another effort.

2.3 Major Planning Objectives of Present Program. The improved understanding of the energy-deposition phenomenon on the target plates called for measurements that might define the amount of energy deposited and provide some estimate of the time interval in which this energy deposition occurred.

Simultaneously, it was planned that attempts would be made to obtain a separated Blue Ghost running ahead of the detonation products by using "overdriven" detonations, which more strongly accelerate the emerging detonation products.

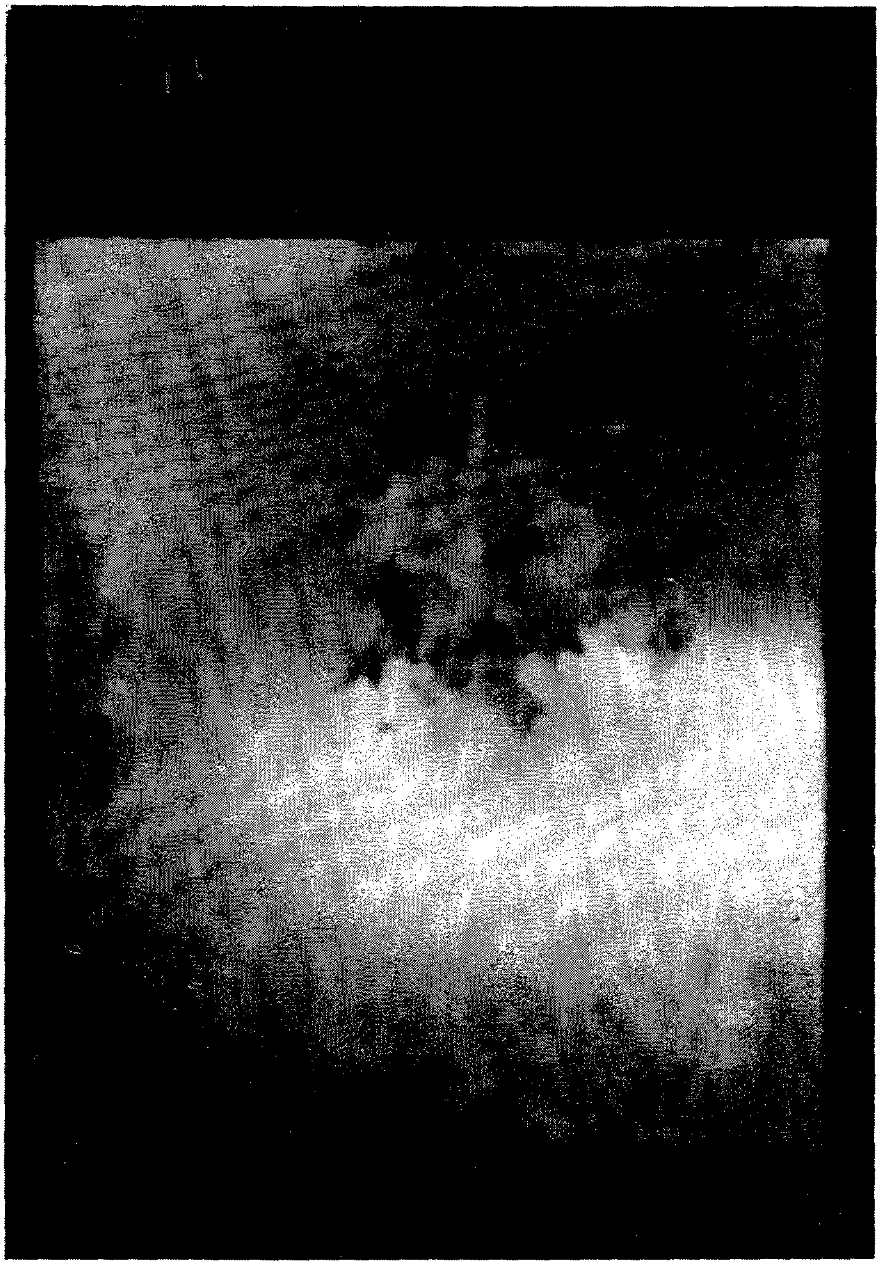

Figure 4. Melt Zone on Surface of 1/4-in (6.35 mm) Aluminum Alloy Target.

Finally, additional optical observations were planned in air and in vacuum. These were to include the use of spectroscopic observations, as well as electrical-conductivity probes to help characterize the plasma, which seemed to play the key role in the energy-deposition process.

2.4 Cooperative Experimental Plan. It was the U.S. Army Ballistic Research Laboratory's (BRL)* desire to execute the experimental phase of the study of the energy deposition from the plasma at the BRL facilities. This took the form of a cooperative program with Mr. George Hauver of the Terminal Ballistics Division,† who had appropriate facilities under his jurisdiction. Dr. George Thomson continued to be involved in assisting administratively and in an advisory capacity.

2.5 General Summary of Results. The funding originally allocated to Mr. George Hauver (BRL) for the experimental work was drastically reduced during the time that this program was in effect, due to financial crises in other BRL programs. Thus, it was not possible to execute all portions of the original experimental-program plan. However, several portions of the plan were successfully carried out. One part of the experiment estimated the amount of aluminum removed from the target as a function of time during the early stages of plasma impact. An initial, overdriven-charge experiment was also executed. The velocity and deceleration measurements on the hot front end of the detonation products were improved. Finally, the lack of significant energy deposition at the target prior to arrival of the plasma was verified. The spectroscopic observations, vacuum firings, and the overdriven-charge experiment continuations were not possible under the reduced budget finally assigned to Mr. George Hauver by BRL.

The remainder of the report provides details and conclusions derived from these experiments.

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* On 30 September 1992, BRL was deactivated and subsequently became part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

† Under ARL, this is now the Terminal Effects Division.

3. Experimental Results

3.1 Preliminary Experiments. The initial experiments were designed to obtain basic information, such as detonation velocity and detonation product velocity necessary to properly synchronize and time the later experiments. These experiments were carried out with the PETN pellets transferred to BRL from the prior contract and came from the same lot of pellets used in some of the experiments described in Zernow (1986).

The two charge configurations initially examined were the point-initiated configuration (Figure 5) and the peripherally initiated configuration (Figure 6). Two PETN pellets were used in each charge with a total explosive mass of approximately 127 ±1 g. The PETN pellets used were pressed without any additive or binder. They were 44.5 mm in diameter and 25.4 mm in length. The pressed densities of the PETN pellets were approximately 1.60 g/cm^3.

Figure 7 shows the experimental setups used for the first two experiments. In the first experiment with point initiation, simple ionization switches were used to obtain the detonation transit time from the booster to the face of the first pellet, thereby providing an estimate of the detonation velocity in the PETN pellet. The time of arrival of the shock front and detonation products, at a point 609.6 mm away from the face of the front pellet, was determined by means of a time-of-arrival sensor, shown schematically in Figure 8.

In the second experiment, with the peripherally initiated charge, there was also an ionization switch between the two pellets, as well as a time-of-arrival sensor, again located 609.6 mm away from the front face of the explosive charge.

3.2 Results Obtained From Preliminary Experiments.

3.2.1 Point-Initiated Charge. From the ionization probes inserted at the front and rear of the first PETN pellet in the charges, the detonation velocity in the PETN was estimated to be

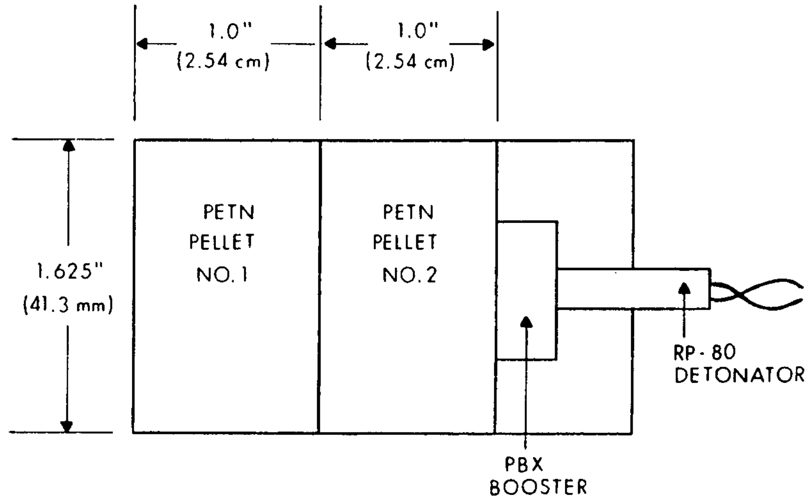

Figure 5. Point-Initiated Charge Used in First Experiment.

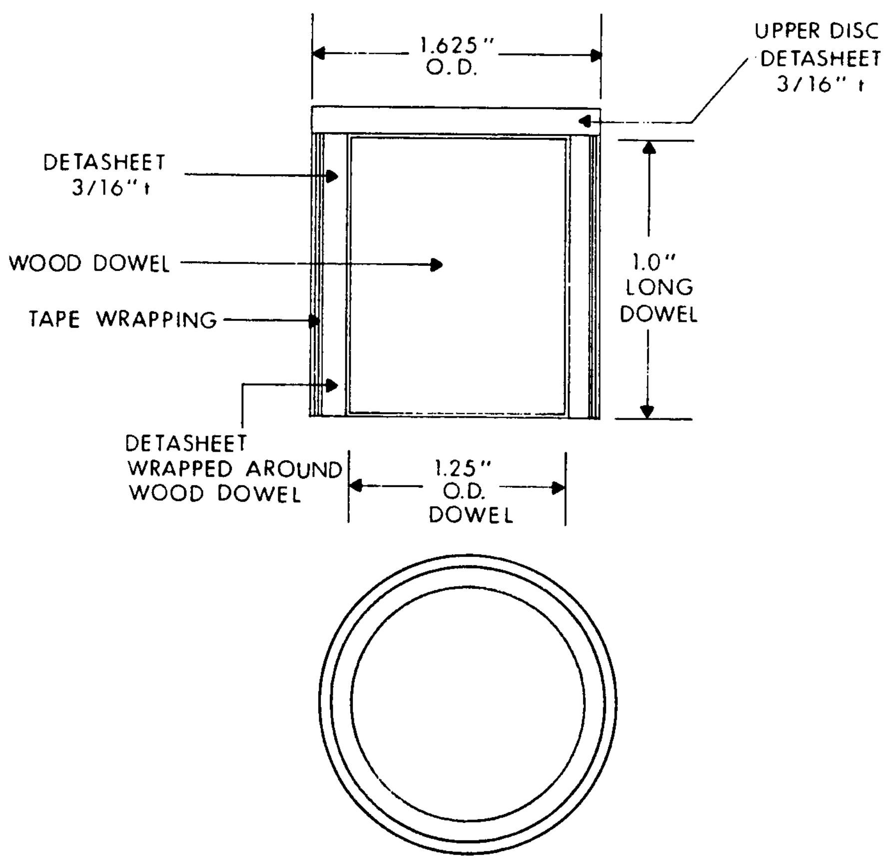

Figure 6. Peripheral-Initiation Booster Used on All Successive Shots.

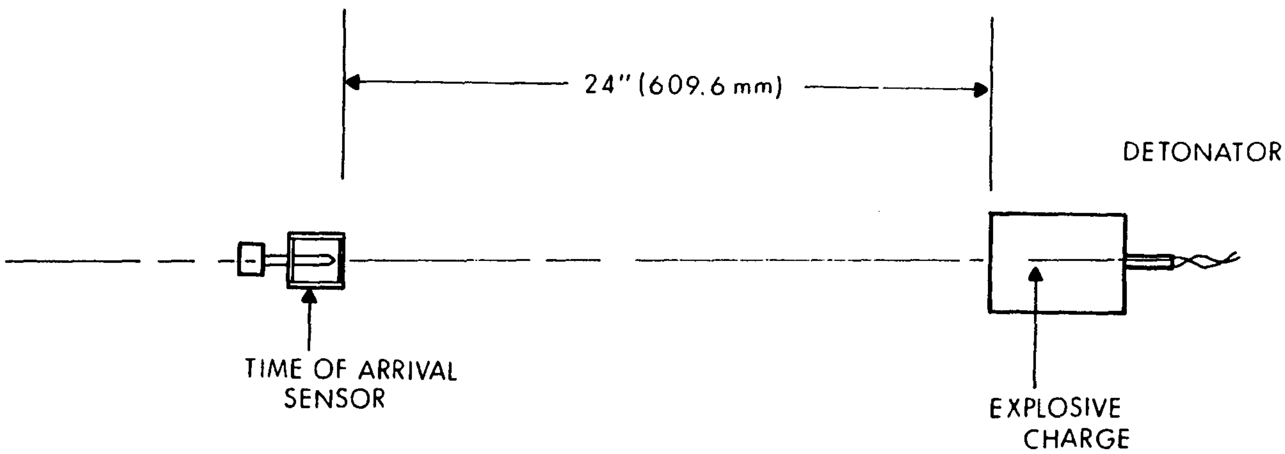

Figure 7. Schematic of Experimental Setup for First Thermal-Sensor Observation.

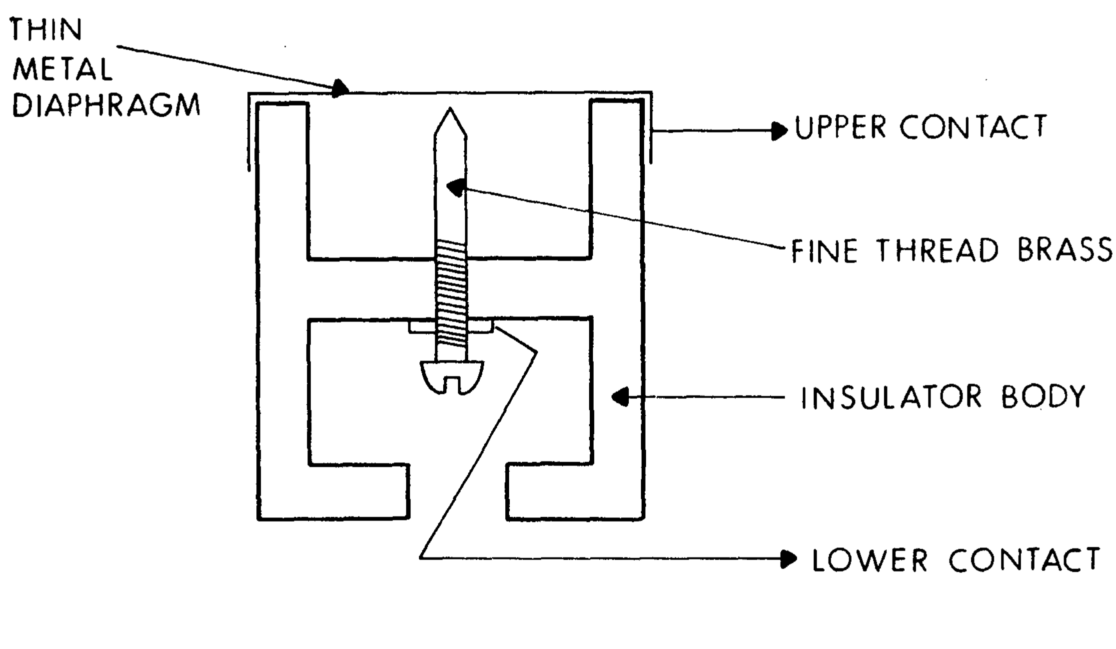

Figure 8. Schematic Description of Time-of-Arrival Sensor (Designed by Hauver).

7.70 ±27 mm/μs. The average velocity of the air shock, driven by the detonation products, was estimated to be 4.44 mm/μs, over the 609.6-mm path.

3.2.2 Peripherally Initiated Charge. The average velocity of the shock driven by the detonation products for the peripherally initiated charge was about 42% higher and was estimated to be 6.31 mm/μs over the 609.6-mm path.

3.3 Verification of Melting Signature. In the third experiment, the time-of-arrival sensor was replaced with a 1/4-in (6.35 mm)-thick aluminum alloy target plate, also located 609.6 mm away from the front pellet of the charge. The peripherally initiated charge configuration was used for this experiment. The molten aluminum surface signature obtained was typical and similar to those previously obtained (Sewell, Mallory, and Pearson 1974; Zernow 1986) and shown earlier in Figure 4.

4. Experiment With Temperature Sensor and Electrical-Conductivity Probes

4.1 Description of the Experiment. The fourth experiment involved the deployment of a temperature sensor at the target. This sensor was a copper-resistance thermometer, which used a thin-vacuum, evaporated layer of copper as the resistance element. There were also two electrical-conductivity probes of the volumetric type placed along the expected path of the detonation products. The temperature sensor and the conductivity probes were designed and assembled by Mr. George Hauver; they are shown schematically in Figures 9 and 10, respectively. The experimental setup is shown schematically in Figure 11. The peripherally initiated charge configuration was used in this experiment.

4.2 Data Obtained From the Shot. The primary data were obtained from the measured arrival times at the two electrical-conductivity probes and at the thermal sensor. These arrival times are given in Table 1.

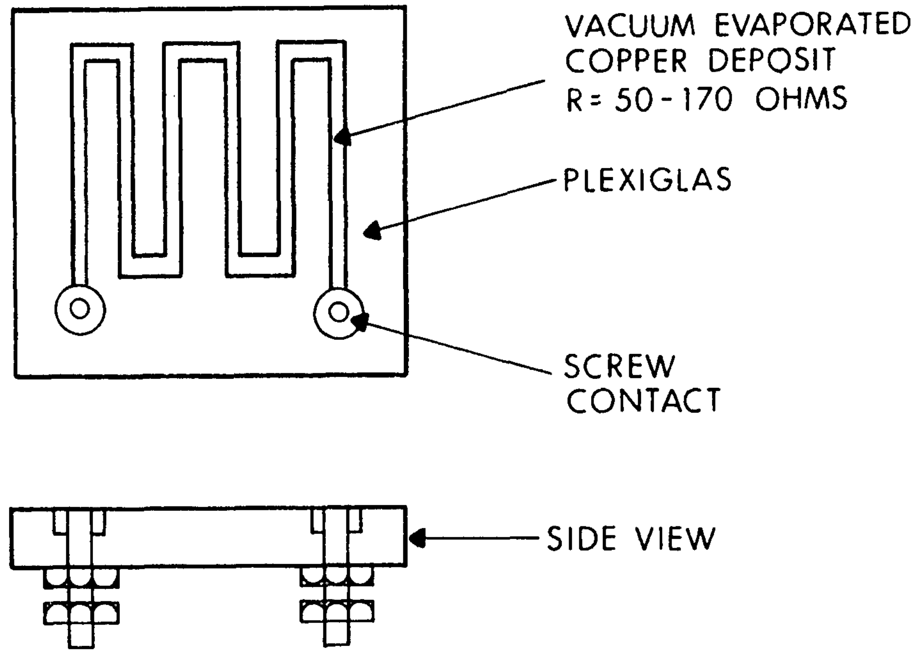

Figure 9. Schematic of Copper-Resistance Thermometer (Designed by Hauver).

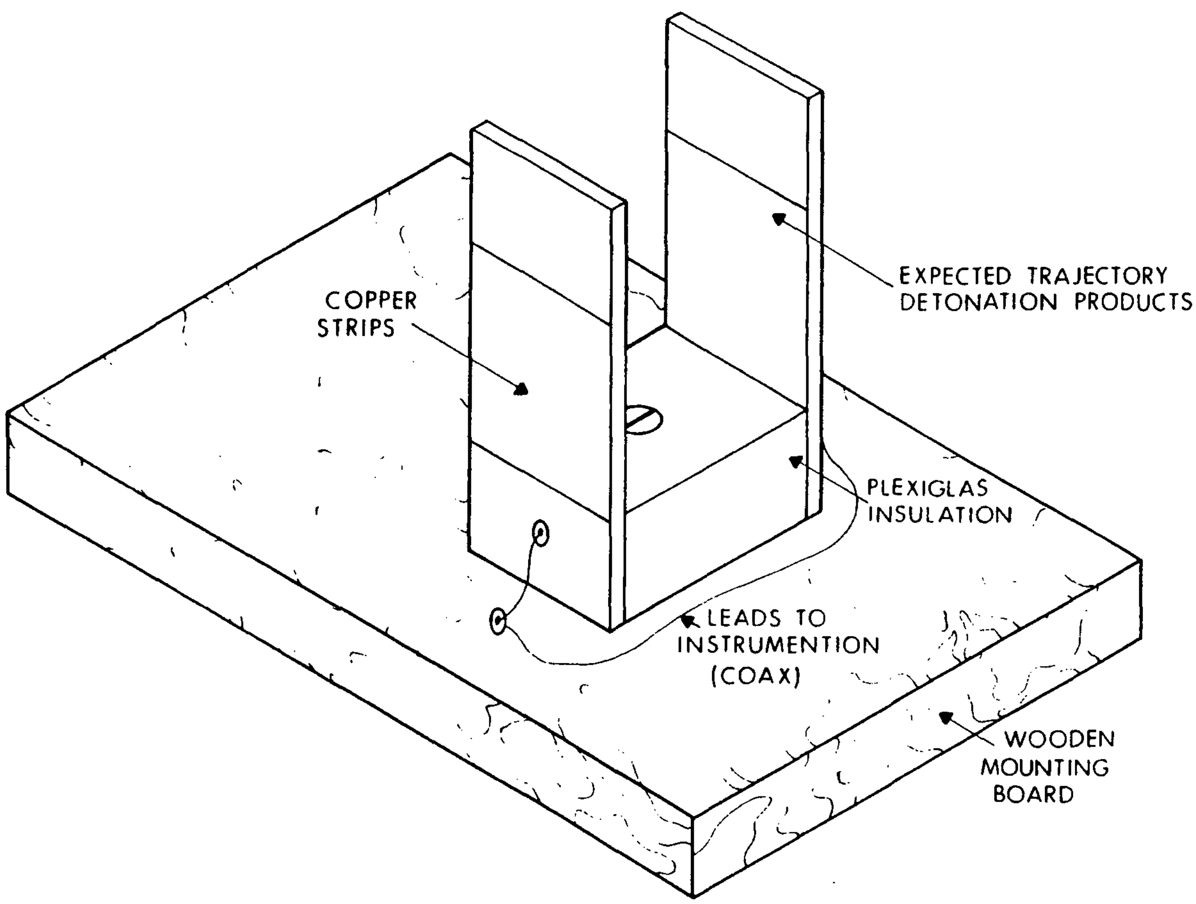

Figure 10. Schematic of Vertically Mounted, Volumetric, Electrical-Conductivity Probe.

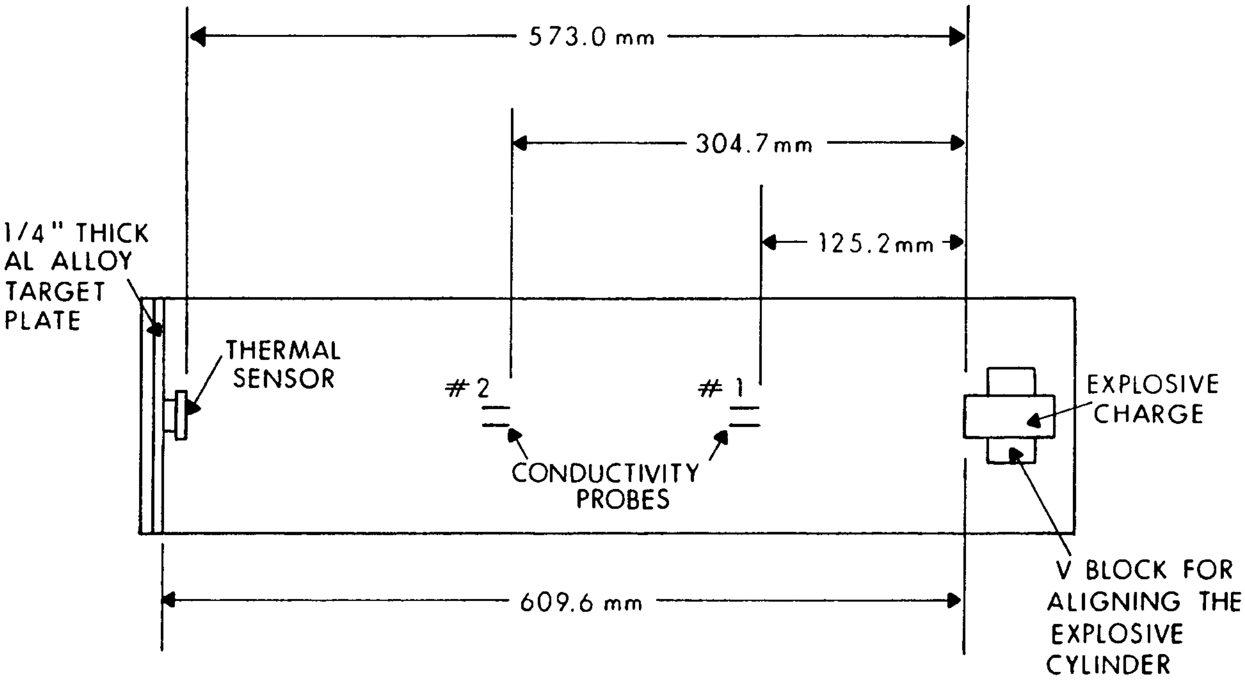

Figure 11. Plan View of Experimental Setup for Simultaneous Observation of Electrical Conductivity, Thermal Deposition, and Times of Arrival.

Table 1. Arrival Times

Sensor	Location Relative to High Explosive (HE) Face (mm)	Measured Time of Arrival (µs)	Corrected Time[a] of Arrival (µs)
First Conductivity Probe	125.2	25.0	13.0
Second Conductivity Probe	304.7	49.3	37.3
Thermal Sensor	573.0	94.8	82.8

[a] Corrected for 12 µs, zero-time reference relative to face of explosive charge.

The shock-displacement time curve and the shock-velocity time curve over the path from the front of the HE pellet to the thermal sensor are shown in Figure 12. These curves were derived by a quadratic fit to the displacement-time data and differentiation of the derived displacement-time curve, to obtain the instantaneous-shock velocities.

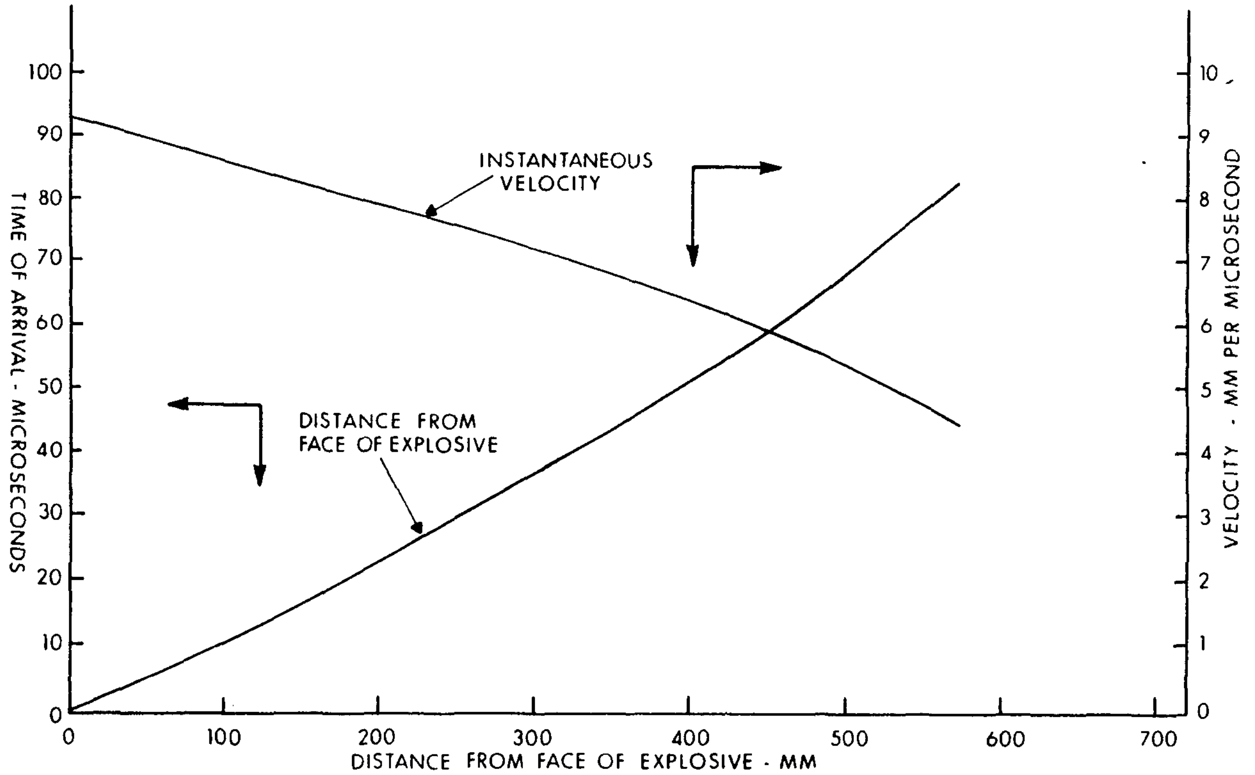

Figure 12. Displacement and Velocity Curves for the Detonation Product Front Obtained From Quadratic Fit to Data for Peripherally Initiated Charge.

It is noted that the thermal sensor did show a small (<0.5°) temperature rise when the shock front was 113 mm away (i.e., the shock front was at X = 460 mm).

4.3 Optical Observations of the Event. The fifth shot was observed optically with the high-speed framing camera, at a relatively slow framing rate of 250,000 frames/second. Thus, there were 4 μs between frames. The exposure time on each frame in Figure 13, which is a contact print, was estimated to be approximately 2 μs.

The target was oriented at 45° toward the camera line of sight in order to observe the impact on the target face. There was a 1-in (25.4 mm) × 1-in (25.4 mm) grid marked on the target face. No external illumination was used so that the self-light from the front of the event was the sole illumination up until the impact flash occurred. Figure 13 shows that after the front end of the

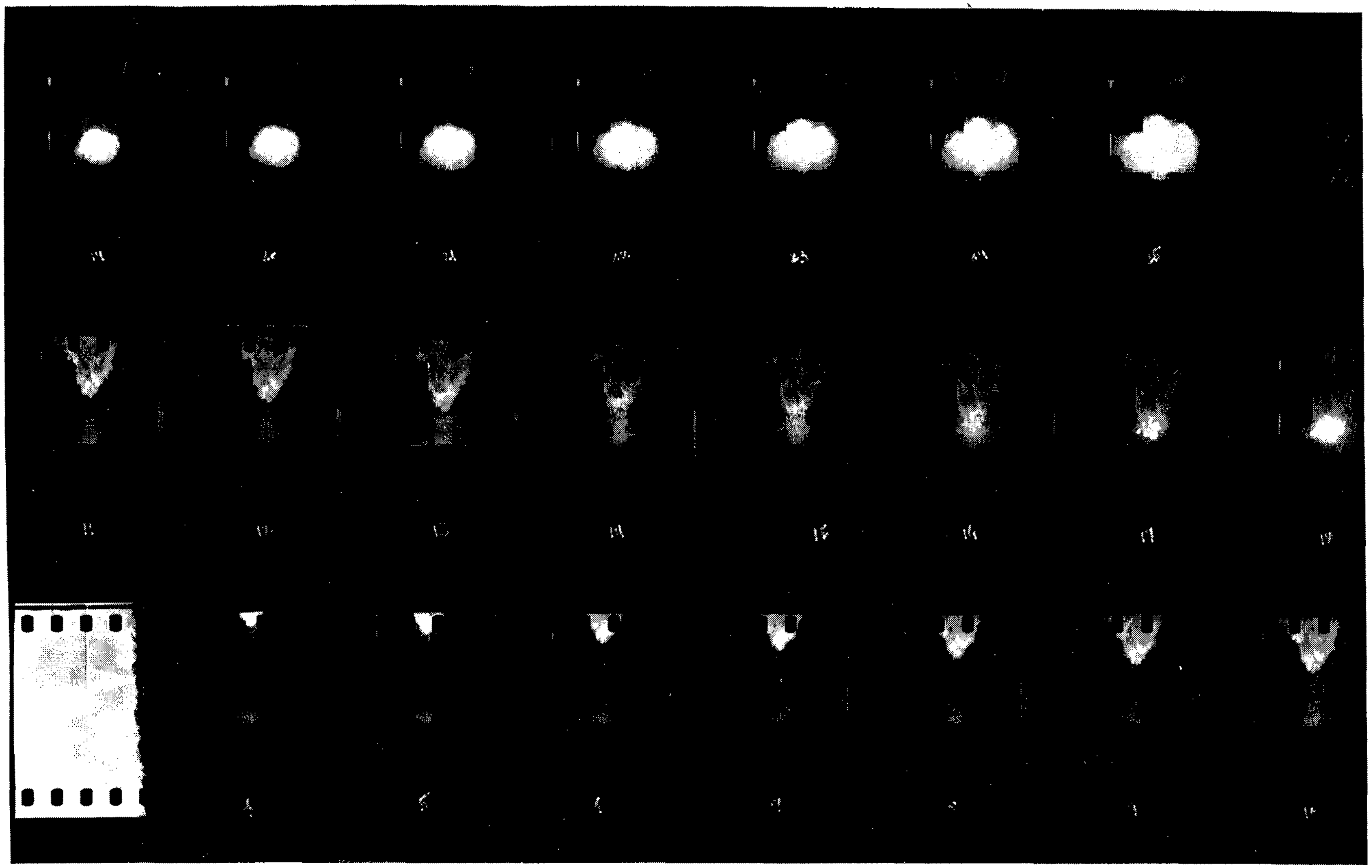

Figure 13. Oblique View of Peripherally Initiated Charge With Detonation Product Striking Aluminum Target—Framing Rate, 250,000 frames/second; Exposure Time, 2 μs.

detonation products touches the target, the flash grows rapidly to a maximum brightness in about three frames (approximately 12 μs).

The first impact flash seems to be barely starting in frame no. 16, in which some of the grid marks can be seen clearly through the front, bright region. This can either be interpreted as a reflection of the hot front off the metallic target plate, just prior to impact, or evidence of transparency in the front region of the detonation products. Frame no. 17 shows about six separated, simultaneously growing, impact flashes, which merge in frame nos. 18 and 19 and which are bright enough in frame no. 17 to be clearly seen through the front detonation products.

5. Single Experiment With an Unlined Cavity Charge

Mr. George Hauver evaluated a single, point-initiated, unlined, Composition B cavity charge with a comparable diameter and a 42° included angle. The jet of detonation products slowed so rapidly, compared to the peripherally initiated, cylindrical test charges previously used, that the camera observation was incomplete due to the improper synchronization.

There was an early small signal on the thermal sensor, but the aluminum plate, located 609.6 mm away from the charge, showed no surface damage or melting signature.

6. Overdriven Charge

6.1 Description of Experiment. The overdriven charge consisted of a series of four PETN pellets, surrounded by an annular cylinder of LX-14 with a peripheral initiator (Figure 14).

The purpose of this charge design was to determine whether the higher detonation velocity of the overdriven explosive, which would in turn generate a converging, overdriven detonation in the PETN pellets, would result in a Blue Ghost that would separate from the mainstream of detonation products, as was found to be the case in Figures 1–3.

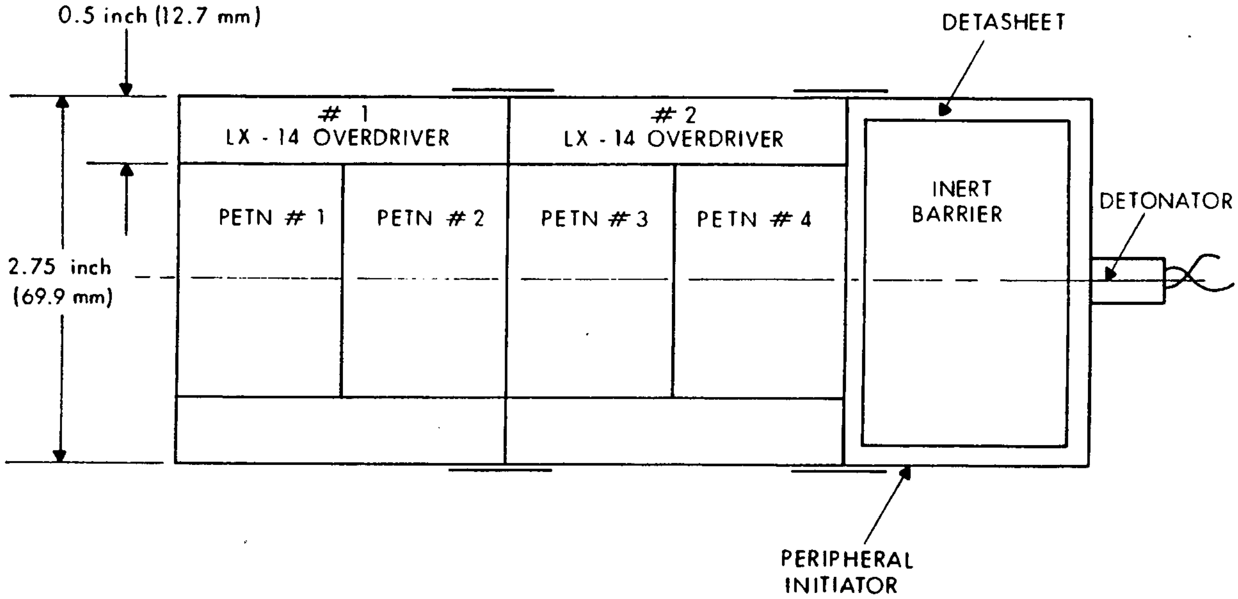

Figure 14. Schematic of Assembled Overdriven Charge.

The detonation velocity of LX-14 is 8.83 mm/μs, while the nominal detonation velocity estimated for these specific PETN pellets in the first experiment described in this report is 7.70 mm/μs. The literature value (Dobratz 1981) of the detonation velocity for PETN at a density of 1.60 g/cm^3 is 7.90 mm/μs. Thus, the estimated detonation-velocity ratio for the overdriver and the PETN pellets would range from 1.15 to 1.12.

The experiment was set up with two simplified conductivity probes, which were placed 280 mm and 430 mm from the explosive charge. These were fabricated by Mr. George Hauver from small-diameter (~ 1/8 in [3.18 mm]) ceramic tubing with two axial holes. This tubing was originally designed for use with thermocouple wires.

A 1/4-in (6.35 mm)-thick aluminum alloy target plate was also placed 609.6 mm away from the front of the explosive charge and perpendicular to the charge axis. A temperature sensor of the type described in Figure 9 was also placed at the center of the target plate.

The experimental setup is shown in Figure 15. The two conductivity probes and the thermal sensor at the target can be readily identified in the photograph.

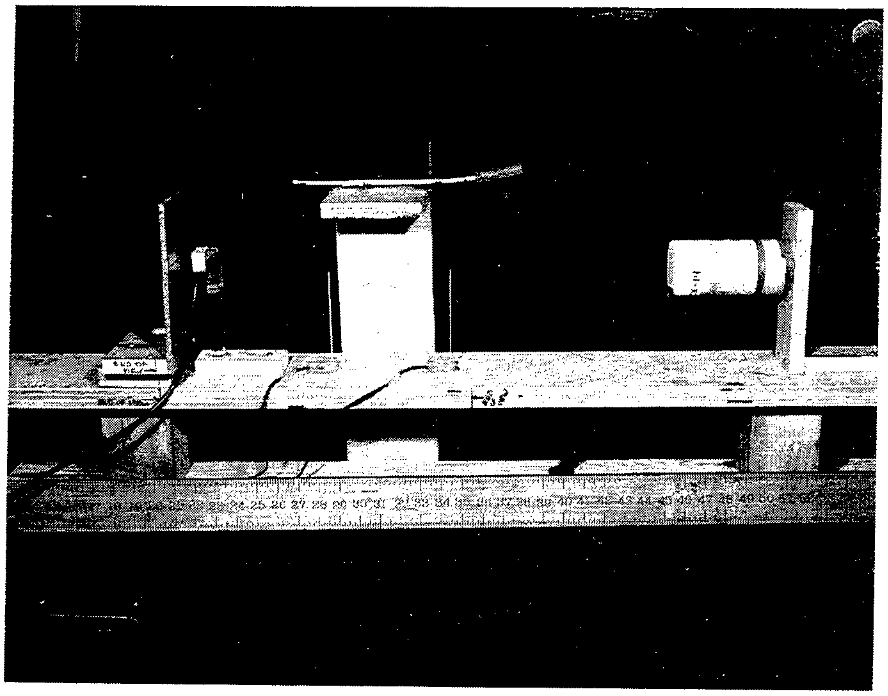

Figure 15. The Experimental Setup for the Overdriven Charge.

6.2 Results of the Experiment. The time-of-arrival data obtained from the two probes and the thermal sensor permitted the fitting of a quadratic curve defining the instantaneous velocity of the front of the detonation products as a function of the distance from the explosive charge. These data are compared in Figure 16 with the equivalent measurements obtained with peripheral initiation only, in the experiment described in section 4.2. It is clear that the overdriven charge showed a significantly higher propagation velocity for the front of the detonation products, in comparison with the simple peripherally initiated charge. The overdriven charge resulted in an increase of 1.35–1.50 mm/μs in the velocity of the front of the detonation products.

The photographic record of this experiment is shown in Figure 17, which is a contact print. The framing rate for this film was 500,000 frames/second, but the effective exposure time was further

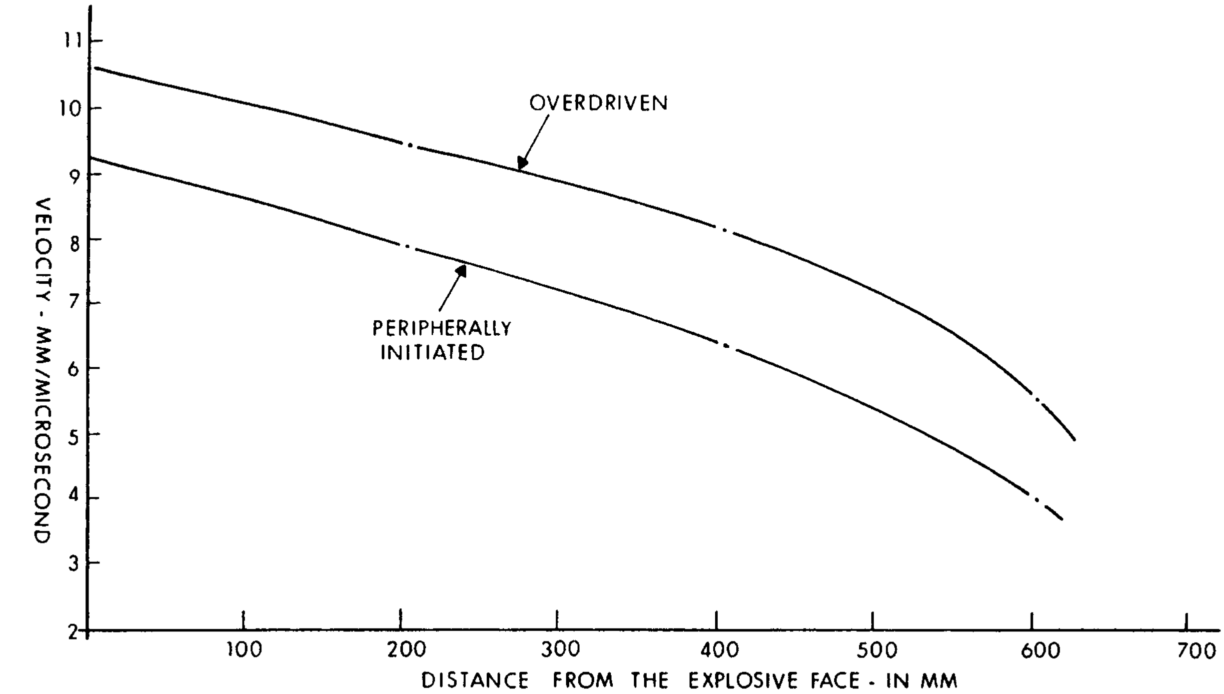

Figure 16. Comparison of Instantaneous-Detonation Product-Front Velocities for Peripheral and Overdriven Charges.

reduced by decreasing the width of the objective- and relay-lens slits. The exposure time is estimated to be 0.4 µs. Note the transparency of the bright front.

In comparing Figure 17 with Figure 13, one should keep in mind the fact that, for Figure 13 (peripherally initiated shot), the exposure time was 2 µs/frame, while, for Figure 17 (overdriven shot), the exposure time was only 0.4 µs/frame. Despite the reduced (1/5) relative exposure time for the overdriven shot, the hot front of the detonation products, arising from the interior, overdriven PETN charge, appears brighter and larger in volume than the comparable region on the peripherally initiated charge because it has been compressed to a higher pressure and heated to a higher temperature by the overdriving process. This is evident from the fact that the overdriven PETN-detonation, product-front velocity has been substantially increased (Figure 16) over the velocity obtained with the peripherally initiated charge.

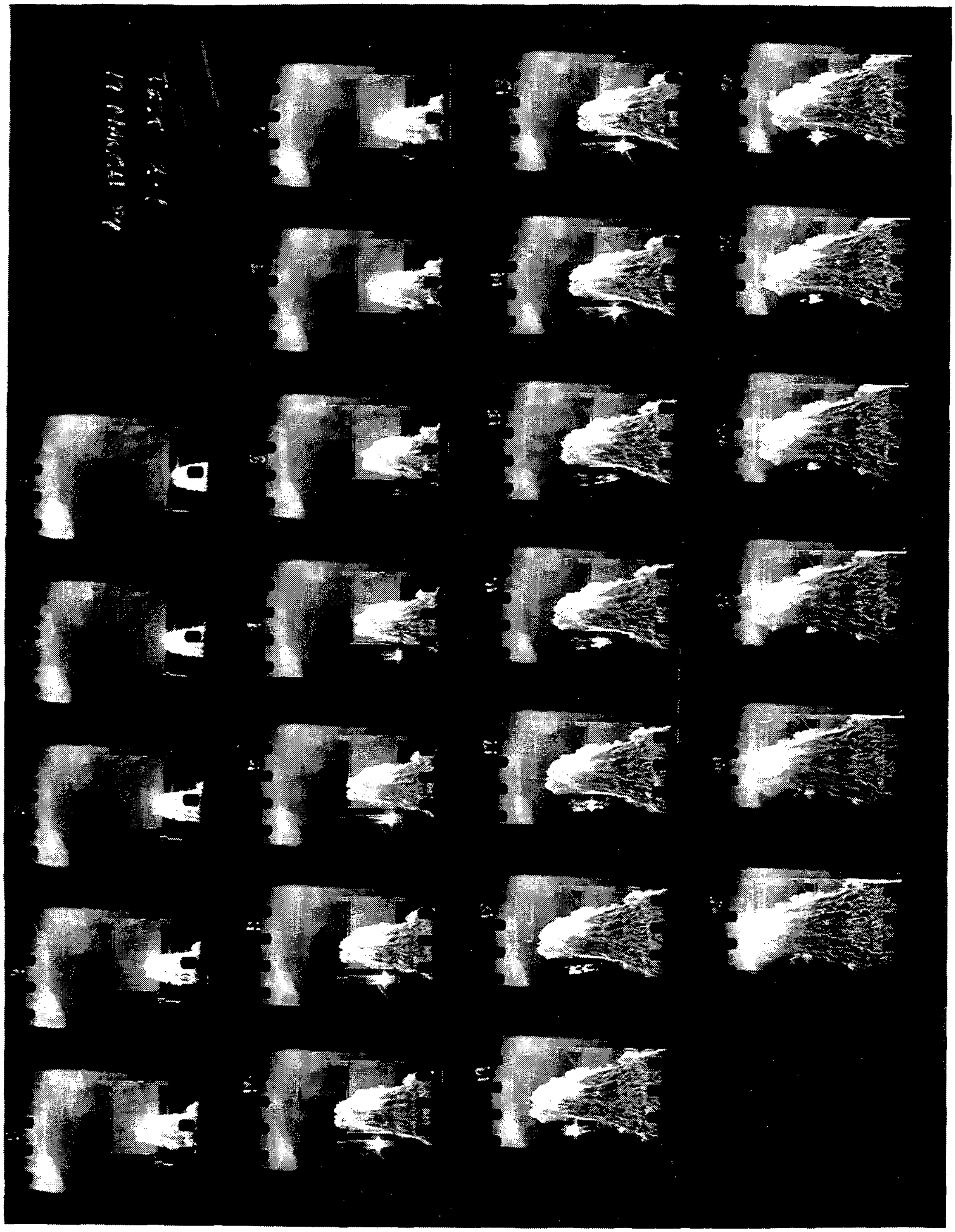

Figure 17. Optical Observation Side View of Detonation Products From Overdriven Charge—Framing Rate, 500,000 frames/second; Exposure Time, 0.4 μs.

The aluminum target plate used in the overdriven shot was fractured into many small pieces, which, when recovered, again showed the characteristic melted-surface signature.

It had been planned that additional overdriven and peripherally initiated experiments would be carried out, over path lengths longer than 609.6 mm, to ascertain whether the bright front would ultimately separate itself from the trailing-detonation product stream and run ahead of it (as shown in Figures 1–3). These were among the experiments eliminated by the reduction of the funding to Mr. George Hauver.

7. Experimental Estimation of Energy Deposition by the Bright, Detonation Product Front

7.1 General. One of the important aspects of quantifying the interaction of the bright front of the detonation products with the target plate involved experiments to infer the energy-deposition rate, by estimating the amount of aluminum removed during the interaction.

Three methods were considered for experimentally estimating the amount of aluminum removed. These are described schematically in Figure 18.

Methods A and C would determine the total mass removed after the entire interaction of the target with the full stream of detonation products. These methods could not provide time-resolved data, especially at very early times before the mainstream of detonation products had impacted the target. However, method B was potentially capable of providing time resolution and, therefore, mass-removal-rate data, since it could, in principle, continuously monitor the area removed from a layer of known, preselected thickness of aluminum. Mallory (1980) had made optical observations of this kind, but had not quantified the energy-deposition rates.

7.2 Experiment With 0.002-in (0.051 mm) Aluminum Foil. Accordingly, method B was selected for the final series of experiments. The experimental setup for these shots is shown

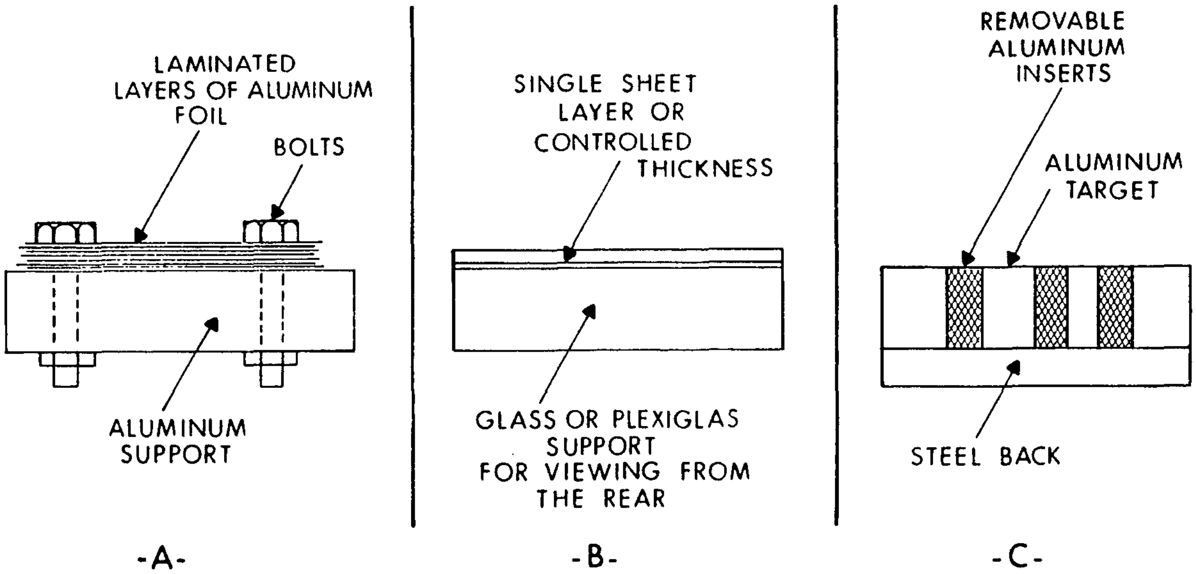

Figure 18. Schematic of Three Methods for Obtaining Target-Erosion Data, Including Erosion-Rate Data and Amount of Erosion or Melting.

schematically in Figure 19. The camera simultaneously observes the front and rear of the aluminum foil on the transparent substrate, by means of the 45° mirror located behind the target. Therefore, in principle, after initial contact of the bright front of the detonation products, directly visible to the camera, the removal of the aluminum foil on the front of the target should result in a bright region, visible from the rear, whose size should be proportional to the area of aluminum foil removed. This can be followed from frame to frame to obtain time resolution.

The initial choice of aluminum foil thickness was 0.002 in (0.051 mm), and the transparent substrate was selected to be Plexiglas. Figure 20 is a contact print of the observations in the first of these experiments. The framing rate was again 500,000 frames/second, and the estimated exposure time per frame was 0.4 μs.

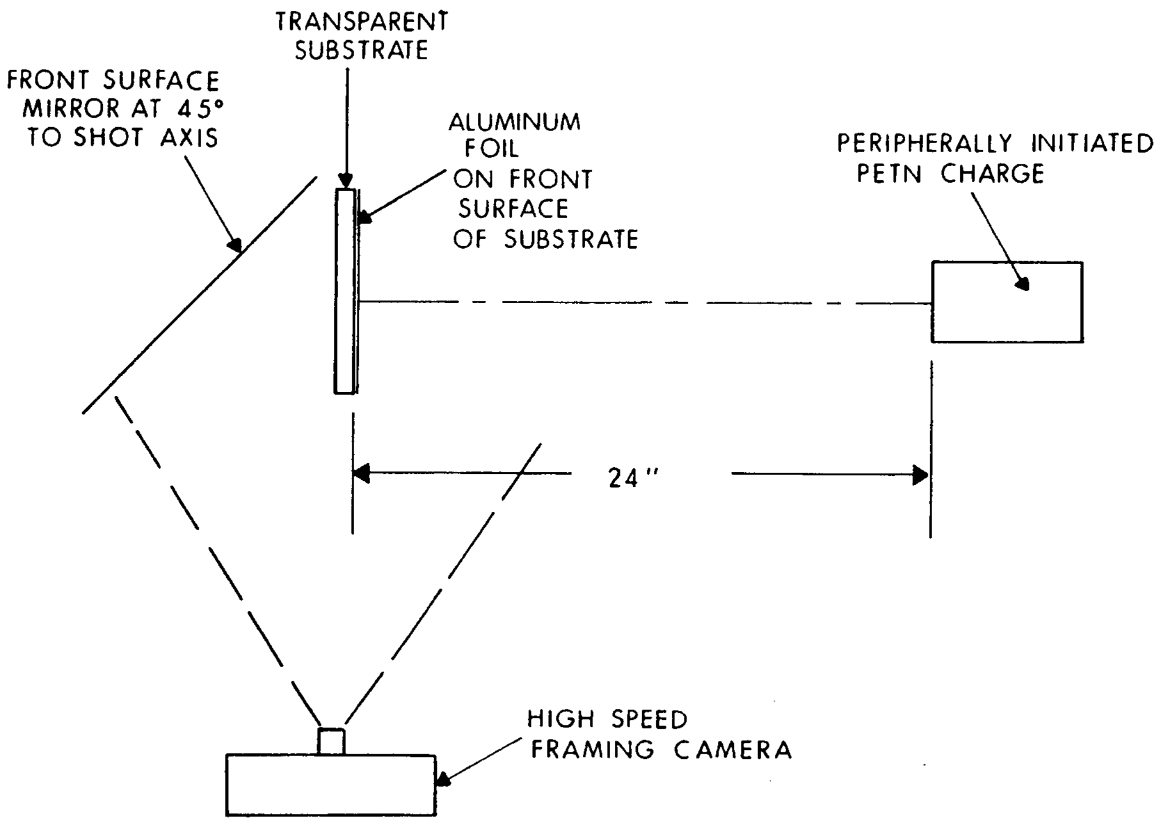

Figure 19. Schematic of Setup for Aluminum-Removal Experiments.

There is evidence of rewrite on this record, in the form of a large, cloud-like object in the field of view, even in frame no. 1 before the detonation products became visible at the left. This means that there was a double exposure due to sufficient intrinsic or reflected brightness in the field of view to re-expose the film when the rotating mirror on the camera made its second scan of the field. As a result, this film is more difficult to read, but still permits the data to be extracted. The first touching of the bright front on the aluminum foil can still be identified by the first bright flash on the front of the target plate in frame no. 15.

The rear view of the 0.002-in (0.051 mm)-thick foil, which can be seen in the 45° mirror, indicates that the foil has been removed in a few initial spots after first contact. These spots increase in both number and area as time progresses.

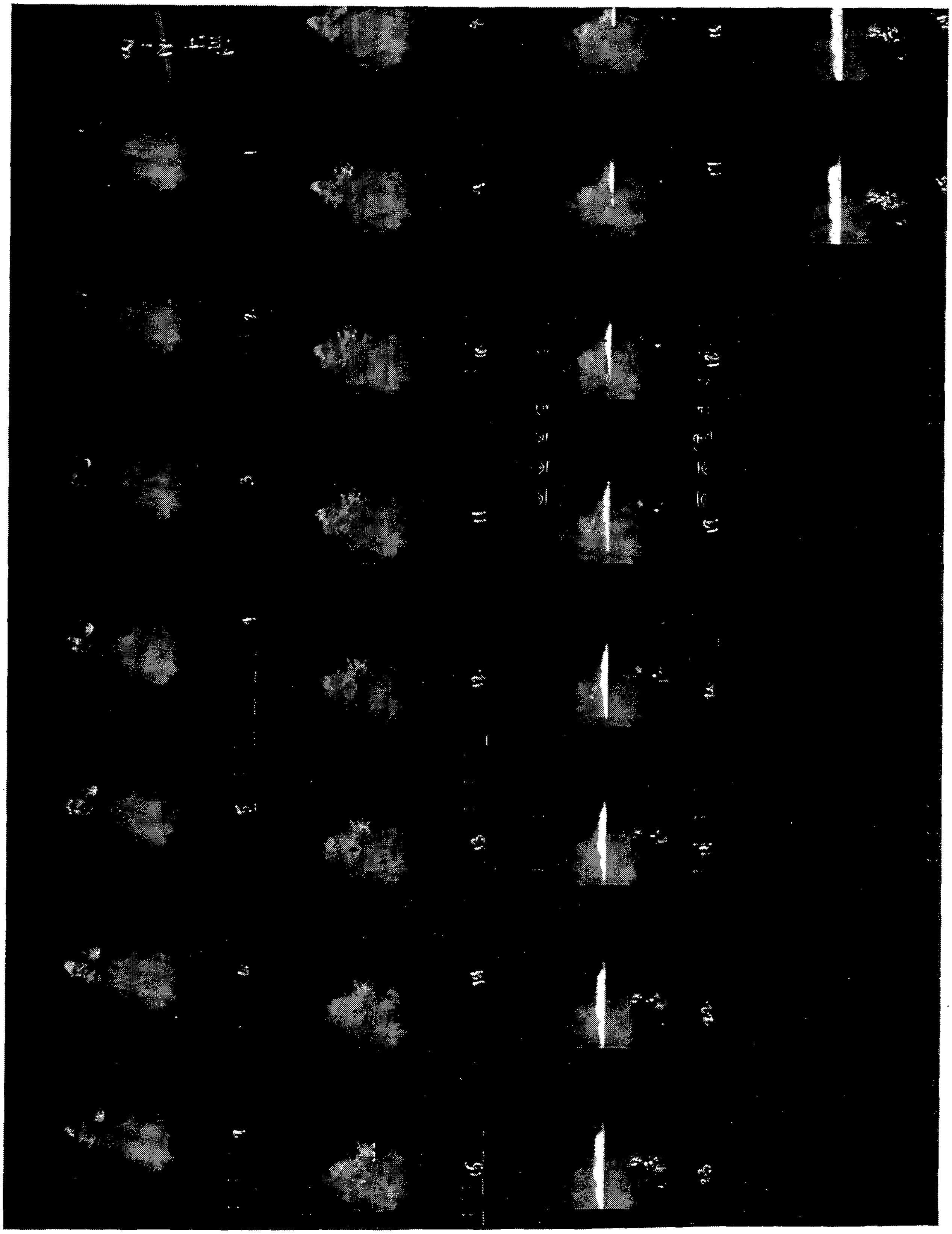

Figure 20. Simultaneous View of Front and Rear Surface of 0.002-in (0.051 mm) Aluminum Foil, Peripherally Initiated Charge—Framing Rate, 500,000 frames/second; Exposure Time, 0.4 µs.

The hot front on this particular shot does not appear to be as bright as was observed on previous peripherally initiated shots. However, the characteristic growing flash on the front of the target foil is clearly seen, growing in size from frame no. 15 to frame no. 25. It is estimated from the observed bright regions seen from the rear that roughly one square inch of 0.002-in (0.051 mm)-thick aluminum foil was removed in this sequence between frame no. 15 and frame no. 25, which encompassed 20 μs.

It was evident from these pictures that to increase the sensitivity of this experiment, it would be necessary to decrease the thickness of the aluminum foil on the front of the target.

7.3 Experiment With 0.0005-in (0.013 mm) Aluminum Foil. The final shot was, therefore, fired against a target having a 0.0005-in (0.013 mm)-thick aluminum foil on the front of the Plexiglas substrate. A contact print of the photographic data from this shot is shown in Figure 21.

The bright hot front can be seen in frame nos. 1 and 2 just prior to impact on the foil, which is first seen in frame no. 3, after it has already happened and with light already showing in the rear view through the regions where the aluminum foil has been removed. The increases in the area of foil removed continue throughout the observation, although the highest removal rates appear to occur during the earliest stages of the interaction.

There is an additional interesting observation on this film that indicates substantial axial displacement of a portion of the Plexiglas target substrate itself, in the region impacted by the bright front, as if a disk-like section of the plastic was accelerated forward by the impact. The initial diameter of the displaced disk-like section of Plexiglas, seen clearly in frame nos. 8–12, appears to be comparable to the diameter of the bright hot region at the front of the detonation products, which can be seen in frame nos. 1 and 2 just prior to target impact. The Plexiglas displacement is also visible in the reflected view of the rear of the target as a darker circle in frame nos. 13, 14, and 25 of Figure 21.

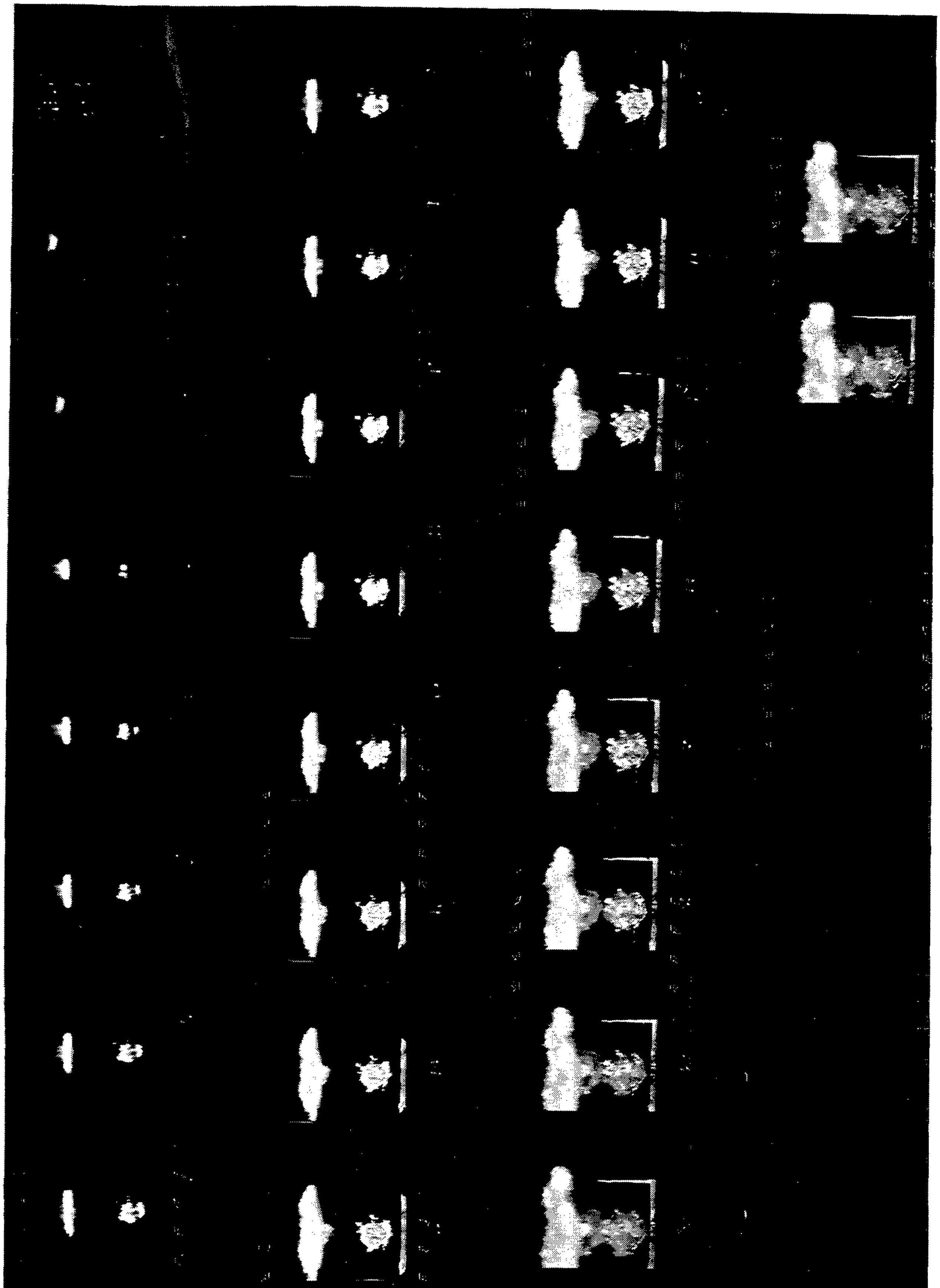

Figure 21. Simultaneous View of Front and Rear Surface of 0.0005-in (0.013 mm) Aluminum Foil, Peripherally Initiated Charge—Framing Rate, 500,000 frames/second; Exposure Time, 0.4 μs.

7.4 Approximate Energy-Deposition-Rate Estimates. One can make rough estimates of the energy-deposition rate by assuming that the amount of aluminum removed is either melted or melted and vaporized.

The amount of aluminum removed is considered to be proportional to the illuminated area, as seen from the rear through the transparent substrate.

Since energy may still continue to be deposited on the illuminated area after the removal of the aluminum, these estimates may tend to be lower than the actual energy-deposition rates.

The illuminated area seen from the rear (Figure 21) is found to grow in successive frames, from about 0.11 in^2 in frame no. 3 to about 7.1 in^2 in frame no. 19. Between frame nos. 6 and 19, the rate of change of illuminated area with time is found to be approximately linear and equal to about 5.1 in^2 in 26 µs, which corresponds to a rate of about 0.20 $in^2/\mu s$. When converted to mass-removal rate for a 0.0005-in (0.013 mm)-thick foil, this corresponds to

$$\dot{M} = (0.20)\ in^2/\mu s\ (0.0005)\ in\ (16.39)\ cm^3/in^3\ (2.7)\ g/cm^3 ,$$

and

$$\dot{M} = 4.43 \times 10^3\ g/s \text{ or } 4.43\ kg/s\ .$$

This is clearly a very high, mass-removal rate.

The heat of fusion for aluminum is found to be 90 cal/g, while the heat of vaporization is found to be 2,720 cal/g.

If one assumes that only melting occurs, so that only the energy of fusion* is deposited, the lower bound, on-energy-deposition rate is found to be

* This is conservative in that it ignores the energy required to bring the aluminum foil up from room temperature to the melting point at 660° C.

$$\dot{E}_m = 4.43 \times 10^3 \text{ g/s} \times 90 \text{ cal/g}$$

and

$$\therefore \dot{E}_m = 3.99 \times 10^5 \text{ cal/s} .$$

If, in addition, it is assumed that vaporization of the melted aluminum also occurs, then the addition of the vaporization energy increases the energy-deposition rate to

$$\dot{E}_m = 4.43 \times 10^3 \text{ g/s} \times 2{,}810 \text{ cal/g},$$

and

$$\therefore \dot{E}_m = 12.45 \times 10^6 \text{ cal/s} .$$

The question of whether all or any of the melted aluminum also undergoes vaporization is not easy to answer, although with such high energy-deposition rates, superheating the molten aluminum and subsequent vaporization should be possible. Therefore, the very large contribution to the energy-deposition rate, arising from the large, latent heat of vaporization of aluminum, essentially serves to define an upper bound to the estimated energy deposition.

7.5 Conclusion From the Thin-Foil Experiment. It is, therefore, estimated that the energy-deposition rate, as deduced from the final experiment with the 0.0005-in (0.013 mm) aluminum foil on the Plexiglas target, lies somewhere between

3.99×10^5 cal/s, corresponding to melting only, and

12.45×10^6 cal/s, corresponding to both melting and vaporization of the aluminum foil.

The question of high-speed gas erosion as an alternate, primary mass-removal mechanism cannot, at present, be unequivocally eliminated; although the results from the previous thick-foil experiment (Figure 20), as well as this thin-foil experiment, do not appear to strongly support such a primary erosion mechanism, since much of the high, mass-removal rate occurs at a relatively early time, before the main mass of the detonation products has had an opportunity to flow over the target. However, there is no question that gas flow can be a secondary, material-removal mechanism because, after aluminum melting occurs, the gas flow can remove the molten material away from where it was formed. An examination of the molten target signatures, on solid 1/4-in (6.35 mm)-thick targets, shows that thin sheets of molten aluminum can be peeled off the surface of the target at locations 3 or 4 in (76–102 mm) away from where the molten material was originally formed.

8. Summary and Conclusions

Earlier observations of what appeared to be anomalous energy transfer from a detonating cylinder of PETN (Sewell 1974) were examined in Zernow (1986), to determine whether the specific anomalous "prompt" energy-transfer mechanism postulated in Sewell (1974) could be independently confirmed. The results of the Zernow (1986) study indicated that the specifically postulated anomalous prompt energy-transfer mechanisms could not be unambiguously confirmed. Neither was it possible to confirm the repeatable generation of a detached, hot, ionized region at the front of the detonation product stream (named the Blue Ghost by the present author), which would separate and run ahead of the remainder of the detonation products, as reported in Sewell (1974).

Prior early work on separating detonation-generated plasma, reported in Cook and McEwan (1958), is of interest in this connection, as is also a disagreement about the interpretation of the observations in Cook and McEwan (1958) and Davis and Campbell (1960). The latter do not believe that there is coherent plasma involved in the process and that the observations in Cook and McEwan (1958) are due to a shock wave and overexposed image smear, attributable to long exposure times.

Nevertheless, clear evidence was obtained for the presence of a coherent, hot (bright), ionized region at the front of the detonation product stream. Clear evidence was also obtained confirming the concentrated local energy deposition and deformation damage on an aluminum target placed at a relatively large distance (>29 charge diameters) in front of the charge, indicating an unexpected coherence of the energy density at the front of the detonation products. Deposition of this energy caused melting, material removal, and target deformation in a localized area on the aluminum target, where the front hot plasma impacted the target. Even in the absence of the prompt energy-transfer mechanism, these observations are still of considerable interest because they are somewhat surprising, when viewed as conventional energy-transfer mechanisms.

The present study was originally designed to help further quantify the observed phenomena. Unfortunately, financial support problems at BRL prevented the local implementation (at BRL) of some of the basic spectroscopic observations that were intended to shed light on the ionization processes involved in the coherent, bright hot region at the front of the stream of detonation products. Nevertheless a number of useful experiments were completed, within the more restricted budget.

The absence of a prompt energy-transfer process, to account for the target-melting effects, was clearly confirmed by means of thermal sensors (very thin, 0.024-μm-thick, vacuum-evaporated, copper-resistance thermometers) placed on the target. These sensors could easily and quickly detect temperature increases at the target of as little as 0.2° C. These observations also confirm those prior observations (shown in Figures 1–3) that clearly indicate no target response until the Blue Ghost touches the target face.

The association of the contact of the hot, ionized front end of the detonation product stream, with the material-removal processes at the target, was confirmed by means of high-speed photographic observations, which recorded the material-removal process from thin, aluminum (0.0005 in, 0.0127 mm) target layers on transparent substrates. These observations were made simultaneously at the front and rear surfaces of the targets in order to provide time correlations between the material-removal process and the contact of the hot region with the target surface.

The surprising result obtained from a time-dependent analysis of the material-removal process indicated enormously high, energy-deposition rates, based on the assumptions that the target layers were either melted or both melted and vaporized.

These energy-deposition rates were calculated to range from about 4×10^5 cal/s to 12.5×10^6 cal/s, depending on whether or not vaporization was assumed to take place. Since these target-removal phenomena could be seen to occur relatively early during the plasma-impact process, it is not believed that simple erosion by the long-term, detonation product flow could play a significant role in the early material-removal process, without the assistance of the melting plus vaporization phenomena.

Clearly, many new questions have been raised by these preliminary energy-deposition rate studies, especially with regard to the state of the apparently coherent, bright, hot front end of the detonation product stream that permits it to generate localized target damage at standoff distances >29 charge diameters. This does not appear to be consistent with the damage expected from a normally expanding shock wave without plasma.

It is worth noting again that detached, detonation-generated plasmas have been the subject of extensive discussion in the detonation literature starting in the late 1950s (e.g., Cook and McEwan [1958]). The front cover of this issue of the *Journal of Applied Physics* contains photographs of such a detached plasma. The subject has also generated some major controversies (Davis and Campbell 1960) that have detracted from a dispassionate examination of the associated processes. Hopefully, these experiments have contributed to some clarification of the questions that still need to be asked and answered.

Further questions need to be answered with respect to the apparent coherence of the plasma at the front of the detonation product stream, evident from the long-range target damage, the source of the plasma's high energy density, the nature of the energy-deposition process at the target, and the spectroscopic analysis of the emitted light, which would help understand the processes going on within the plasma while it is in flight and during energy deposition.

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13. ABSTRACT *(Maximum 200 words)*

Early work (1974) by the Navy, which involved studies of the front portion of the detonation products from overdriven explosive cylinders of PETN, suggested two anomalous mechanisms of energy transfer in the forward direction. These included a "prompt" (optical) mechanism and a "detached plasma" mechanism. An independent study in 1983 by the present author indicated that the prompt mechanism could not be confirmed from the existing Navy data; neither could the single Navy experiment, which displayed the detached plasma phenomenon, be repeated. However, persistent "hot" (bright) plasma regions, located at the front end of the detonation products, were shown to be present in virtually all cases. This present follow-on study, which was carried out in 1985 with the experimental assistance of Mr. George Hauver of the U.S. Army Ballistic Research Laboratory (BRL), clearly showed that the prompt (optical) energy-transport mechanism was not present. However, time-resolved optical measurements of material removal from a thin, aluminum foil target on a transparent plastic substrate, located at a long distance forward of the charge, yielded extremely high, mass-removal rates and very high, deduced-energy-deposition rates, very early in the interaction between the hot front end of the detonation products and the aluminum target foil. More work remains to be done to explain these residual phenomena.

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