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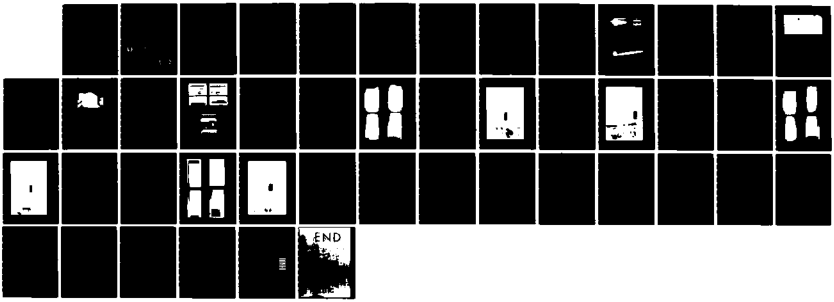

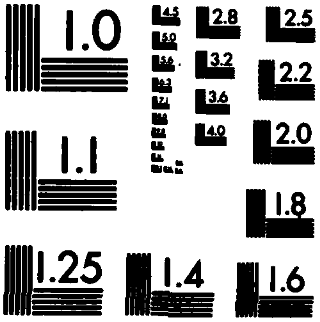

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TECHNICAL REPORT ARBRL-TR-02568

IGNITION PHENOMENA IN DEVELOPMENTAL, STICK PROPELLANT, COMBUSTIBLE-CASED, 155-MM, M203E2 PROPELLING CHARGES

Thomas C. Minor
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July 1984

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The US Army is currently developing a new top-zone propelling charge to replace the M203 Charge for the 155-mm, M198 Towed Howitzer. While the M203 Propelling Charge is a bagged charge consisting of granular M30A1 propellant and a centercore igniter, the new charge will feature stick propellant and a rigid, combustible cartridge case. The stick propellant is expected to eliminate pressure-wave problems; simplify igniter requirements, and, because of

higher loading densities, allow use of a cooler, lower energy M31-type propellant, while the rigid case will facilitate automated handling and loading in future artillery weapons.

During the course of development of the new charge, designated M203E2, a problem was experienced with high maximum chamber pressures when firing cold-conditioned charges. This report documents an experimental study commissioned by the Office of the Project Manager, Cannon Artillery Weapons Systems, to investigate the interplay among igniter, propellant, and case during the early portion of the interior ballistic cycle in order to identify potential contributors to and solutions for the problem. Of particular concern was the possibility of propellant fracture either caused directly by the brisance of the basepad igniter or resulting from charge motion and impact against the projectile base.

M203E2 Propelling Charges were provided by the charge developer, the Large Caliber Weapon Systems Laboratory of the US Army Armament, Munitions and Chemical Command, for testing in the Ballistic Research Laboratory's 155-mm howitzer simulator. The charges were modified to permit direct viewing of the interior of the charge, conditioned to the desired temperature, and fired in the simulator using transparent plastic chambers. High-speed cinematography was used to record the path of flamespread and early response of the case, while flash X-rays, triggered at a pre-determined pressure, were taken to monitor the behavior of the solid phase. In addition, spindle pressures and pressures and forces on the base of the projectile were recorded. Testing of cold, unmodified charges indicated a preferential flow of igniter gases around the outside of the charge, leading to compaction of the charge and an associated reduction in propellant bed permeability to igniter and perhaps subsequent combustion gases. A further test with the igniter charge packaged in a cloth bag rather than the original plastic cup displayed the intended mode of ignition, with igniter gases penetrating and igniting the main charge and fracturing the cartridge case from within.

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I. INTRODUCTION

The advantages of stick propellants over granular propellants, especially in high-performance propelling charges, have long been known. The natural channels presented by bundled stick propellants offer substantially less resistance to the flow of igniter and early combustion gases, leading to a significant reduction in the potential for the formation of axial pressure waves[1-4] and facilitating the use of simple basepad ignition systems even with high-performance charges. Moreover, the higher loading density made possible by the regular packing of the stick geometry allows the use of a larger charge weight of a cooler, lower energy propellant to achieve the same performance, with possible benefits in terms of barrel wear and muzzle flash and blast. Alternatively, the higher loading density may be exploited for performance growth potential with existing propellant formulations. Several foreign propelling charges currently employ stick propellant, notably the Tri-Partite (UK, Germany, Italy) charges for the 155-mm, FH70 Howitzer. Until recently, however, stick propellants have seen no application in US charges, primarily due to the lack of a large-scale manufacturing capability. Efforts are now underway to upgrade US propellant manufacturing facilities, and charges employing stick propellant for current and future howitzers and tank guns are undergoing development.

We have previously discussed the detailed phenomenology of base- and centercore-ignited, granular propelling charges.[5] In particular, we addressed the details of primer impingement on the base of the charge, system-dependent igniter output, convective heating of propellant grains leading to flame propagation through the charge, and interphase drag associated with the tortuous path of flow through the packed bed, contributing to both the formation of axial pressure waves and the movement of the solid phase. In this report, we wish to focus our attention on the phenomenology of the stick propelling charge,[4] shown generically in Figure 1. Functioning of such a charge involves initiation of the basepad by the primer and subsequent

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[1] S. Weiner, "Investigation of Stick Propellant for 155-mm Howitzer, XM198," Interim Memorandun Report, Picatinny Arsenal, Dover, NJ, July 1975.

[2] T.C. Smith, "Experimental Gun Testing of High Density Multiperforated Stick Propellant Charge Assemblies," Proceedings of 17th JANNAF Combustion Meeting, CPIA Publication 329, Vol. II, pp. 119-124, November 1980.

[3] F.W. Robbins, J.A. Kudzal, J.A. McWilliams, and P.S. Gough, "Experimental Determination of Stick Charge Flow Resistance," Proceedings of 17th JANNAF Combustion Meeting, CPIA Publication 329, Vol. II, pp. 97-118, November 1980.

[4] T.C. Minor, "Mitigation of Ignition-Induced, Two-Phase Flow Dynamics Through the Use of Stick Propellants," ARBRL-TR-02508, Ballistic Research Laboratory, USA ARRADCOM, July 1983 (AD A133685).

[5] A.W. Horst and T.C. Minor, "Ignition-Induced Flow Dynamics in Bagged-Charge Artillery," ARBRL-TR-02257, Ballistic Research Laboratory, USA ARRADCOM, August 1980 (AD A090681).

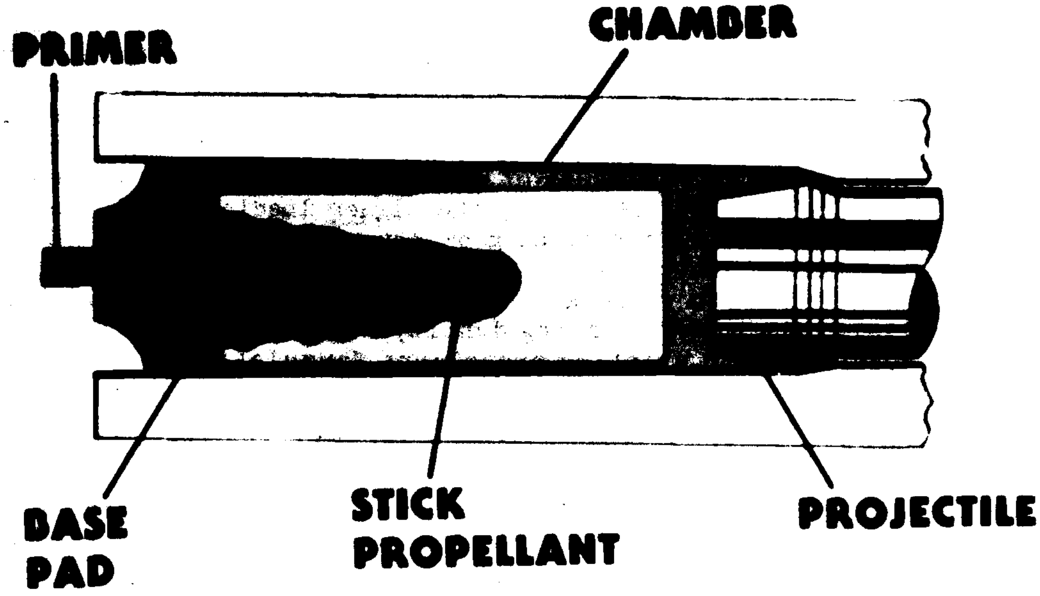

Figure 1. Stick Propelling Charge

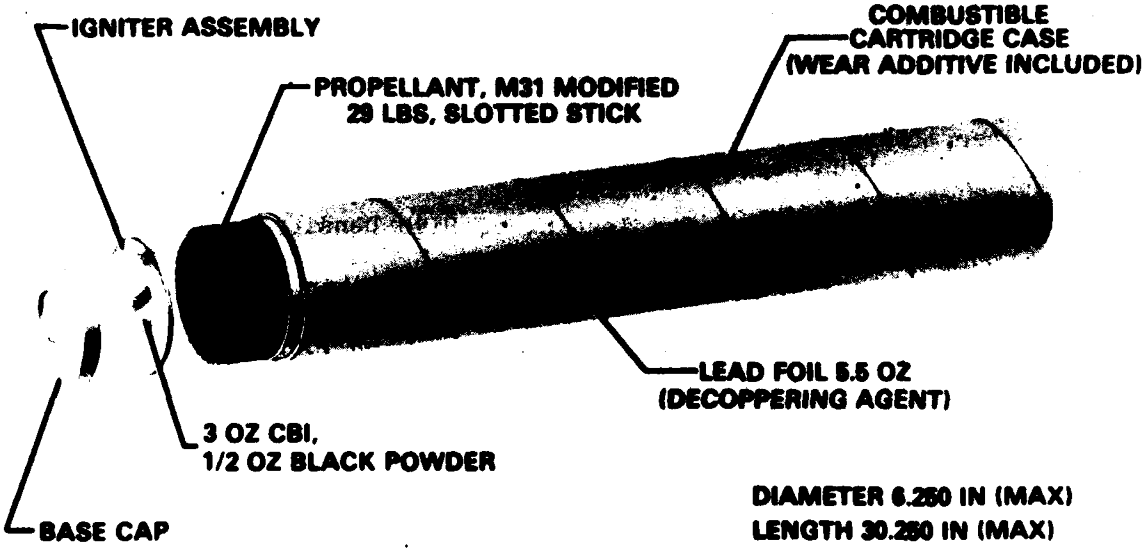

Figure 2. 155-mm, M203E2, Propelling Charge

transfer of ignition to the stick propellant itself. The igniter gases are expected to penetrate easily into the natural channels in the bundle of sticks, with flamespread proceeding rapidly down the charge in a one-dimensional fashion. Moreover, the minimal resistance to axial flow and the accompanying near uniformity of pressurization over the length of the charge greatly diminish the likelihood of substantial charge motion or the formation of severe pressure waves.

A closer examination, however, reveals that this simplified analysis does not account for several details that may greatly impact the overall interior ballistic process. The output of a brisant basepad igniter could fracture the ends of the propellant sticks, particularly if cold-conditioned, creating unprogrammed burning surface which may lead to locally high pressures. Should the channels between the sticks collapse or become obstructed in the process, the possibility of pressure waves arises. Rapid internal pressurization of the long perforation in the stick, perhaps even in the presence of a slot if not substantially opened, may lead to splitting or fracture of the sticks,[6,7] again creating unintended burning surface with attendant problems. The sequence of flamespread into a stick charge is not well characterized; it is not known when flame penetrates the long perforation, nor is it even known exactly how the flame propagates along the external surfaces of the sticks. There exists some photographic evidence[8] that the charge ignites essentially uniformly over its entire length after being sufficiently bathed in hot igniter gases which have flowed unimpeded through and around the bundle of sticks. Unfortunately, this picture is further complicated when the charge is packaged in a combustible case. While a rigid, combustible case offers obvious advantages for automated handling and loading, its initial impermeability, mechanical strength, and ignition and combustion characteristics may play major roles in characterizing the above sequence of events.

One such charge is the 155-mm, M203E2 Propelling Charge, currently undergoing development by the Large Caliber Weapon Systems Laboratory (LCWSL), Armament Research and Development Center (ARDC), US Army Armament, Munitions and Chemical Command (USA AMCCOM) for the 155-mm, M198 Howitzer. The M203E2 Charge, one version of which is shown in Figure 2, employs M31A1E1 stick propellant packaged in a rigid, combustible cartridge case, while the current M203 Propelling Charge, a centercore-ignited, granular-propellant charge, uses the somewhat hotter M30A1 propellant formulation, and is loaded in a cloth bag. Two designs are currently under consideration for the M203E2

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[6] F.W. Robbins and A.W. Horst, "A Simple Theoretical Analysis and Experimental Investigation of Burning Processes for Stick Propellants," ARBRL-MR-03295, Ballistic Research Laboratory, USA ARRADCOM, June 1983 (AD A132968).

[7] F.W. Robbins and A.W. Horst, "Continued Study of Stick Propellant Combustion Processes," ARBRL-MR-03296, Ballistic Research Laboratory, USA ARRADCOM, June 1983 (AD A133004).

[8] T.C. Minor, "Experimental Studies of Multidimensional Two-Phase Flow Processes in Interior Ballistics," ARBRL-MR-03248, Ballistic Research Laboratory, USA ARRADCOM, April 1983 (AD A128034).

cartridge case: the spiral wrapped version shown in the figure and a molded version used in all tests discussed in this report. The igniter assembly, at the beginning of this study, consisted of 15 g of Class 3 black powder in a small bag and 85 g of loose Clean Burning Igniter (CBI), with both powders sealed in a plastic (cellulose nitrate) cup and placed between a singly perforated base cap (shown), to allow primer gas impingement on igniter material, and a multiply perforated cup (not shown), to facilitate early venting into the main stick-propellant charge.

Once in production, propellant for the M203E2 Charge will be manufactured at the Radford Army Ammunition Plant (RAAP), but much of the early developmental propellant was produced by ARDC in order to expedite pilot production of the various design iterations. During June of 1982, test firings of the M203E2 Charge, using propellant manufactured at ARDC, yielded higher maximum chamber pressures at cold temperatures than at ambient or hot temperatures.[9] For example, a charge with an assessed ambient pressure of 351 MPa resulted in pressures of 397 MPa at -54°C and 337 MPa at 63°C. In an attempt to determine the source of this inverse temperature sensitivity, additional charges were fired at LCWSL with split cases and with a cloth-bound basepad replacing the plastic cup igniter; little effect was seen with the split case alone, but the combination of changes yielded about a 50-MPa drop in the still unacceptably high peak pressure for the cold-conditioned round. This report documents an experimental study conducted at the Ballistic Research Laboratory (BRL), commissioned by the Office of the Project Manager, Cannon Artillery Weapons Systems (PM/CAWS), in full cooperation with LCWSL, to investigate the interplay among igniter, propellant, and case during the early portion of the interior ballistic cycle in order to identify potential contributors to and solutions for this undesirable behavior.

II. EXPERIMENTAL

A. Apparatus

The apparatus used at BRL to conduct a variety of studies of the detailed phenomenology of propelling charges is shown in Figure 3. The massive mount, constructed of armor plate, accepts either plastic chambers or axially reinforced, filament-wound fiberglass chambers (not shown). The plastic chambers were commercially available cast acrylic tubing with inner and outer diameters of 165 mm and 191 mm, respectively. Although the clear plastic fractures at significantly lower pressures than the fiberglass chambers, they offer a much better view of the events transpiring within, and thus were used for this study. The pressure limit for these tubes has been found to be variable from sample to sample, and is pressure-rise-rate dependent. The muzzle end of the chamber was closed by a projectile seated in a section of gun tube machined to the dimensions of the M199 cannon. The breech end of the chamber was closed by a spindle similar to the mushroom configuration of the M185 Cannon with the centrally venting primer spithole. The spindle accepted three piezoelectric pressure transducers; and an instrumented projectile baseplate (Figure 4),

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[9] O. Colitti and R.S. Westley, Large Caliber Weapon Systems Laboratory, USA AMCCOM, Dover, NJ, unpublished data, private communication, July 1982.

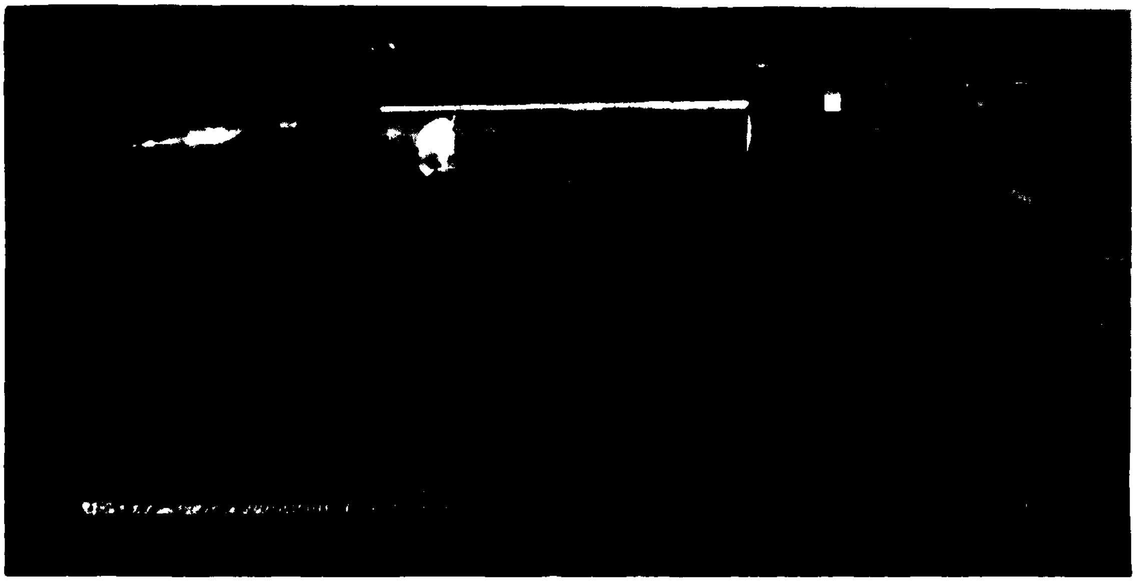

Figure 3. 155-mm Howitzer Simulator, Plastic Chamber

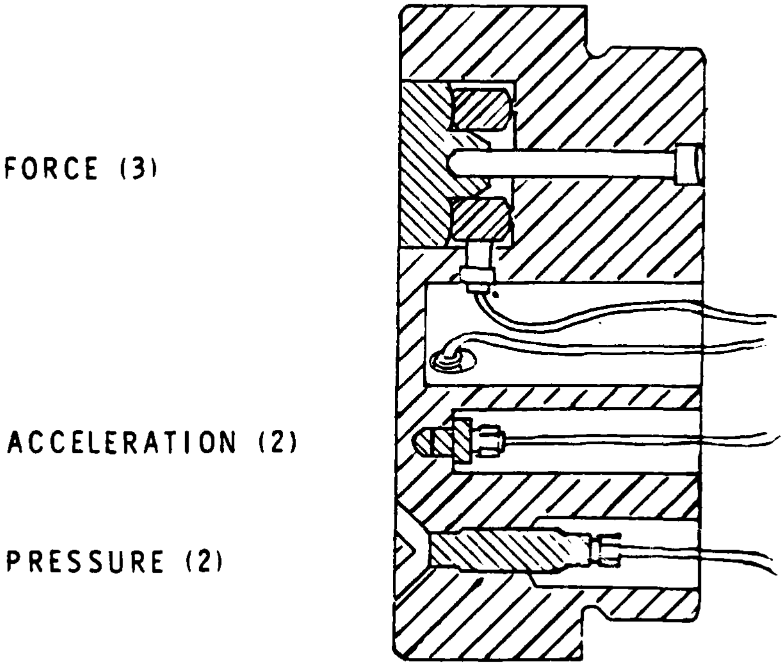

Figure 4. Instrumented Projectile Baseplate

similar to that employed earlier by the Naval Surface Weapons Center, Dahlgren,[10] permitted two gas pressure, three total force, and two acceleration measurements at the projectile base. To further monitor the impact of the charge on the projectile base for some of the shots, the baseplate was covered with a lead witness plate, shown in Figure 5.

Photographic data were recorded with two or three high-speed 16-mm cameras. For each shot, one camera was mounted with a wide angle lens to record the overall aspects of the event; and another used a telephoto lens to allow detailed examination of the critical base region of the charge. For some of the shots, an additional camera was employed to view the overall event from a direction orthogonal to that of the first camera. With all of the cameras, data were recorded at a framing rate of approximately 5000 pictures per second. One-kHz timing signals were placed on the films by electronic circuits internal to the cameras, and the firing fiducial (time at which the firing voltage is applied to the gun) was also placed on the films to aid in correlation of the film data with other data.

Flash radiography was used to monitor the behavior of the solid phase during the interior ballistic cycle. Two 300-kV X-ray heads were employed, aligned perpendicular to the chamber axis and sufficiently separated from each other to allow coverage of the entire chamber length. One image (a "static" shot) was taken of the charge in the chamber before firing; and a second, on a separate film, was recorded during the event by X-rays triggered at a predetermined spindle pressure (a "dynamic" shot). The X-ray film was protected from the blast of the disposable chamber by a wooden cassette, with the forward face composed of layers of air spaces and sacrificial wooden plates.

Figure 6 depicts the system for experiment control, data acquisition, and data reduction. The Ballistic Data Acquisition System (BALDAS) performed these tasks, driven by a PDP 11/45 minicomputer. By starting a programmed sequence timer, BALDAS controlled the firing of the high-speed camera and enabled an X-ray trigger circuit. At the appropriate time, BALDAS exercised an in-line, five-step calibration for each channel, then fired the cannon and acquired and digitized the data through a 16-channel, 10-bit, 24-K word, analog-to-digital converter. At the same time, a backup analog record was made on a 14-channel FM magnetic tape recorder. BALDAS-resident digital counters recorded the time of the firing fiducial and other events, such as the X-ray trigger pulse. After the data were acquired, BALDAS calibrated the data via a second-order, least-squares fit to the calibration staircase and then reduced the data, through suitably introduced gage constants.

B. Charge Design

Charges from two lots of 155-mm, M203E2 Propelling Charges, both employing ARDC-manufactured M31A1E1 propellant, were provided by the LCWSL for testing. One charge lot contained two stacked bundles of 370-mm-long slotted sticks from propellant Lot RDD E153, and the other charge lot contained a

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[10] R. Burrell and M. Wheeler, Naval Surface Weapons Center, Dahlgren, VA, private communication, June 1980.

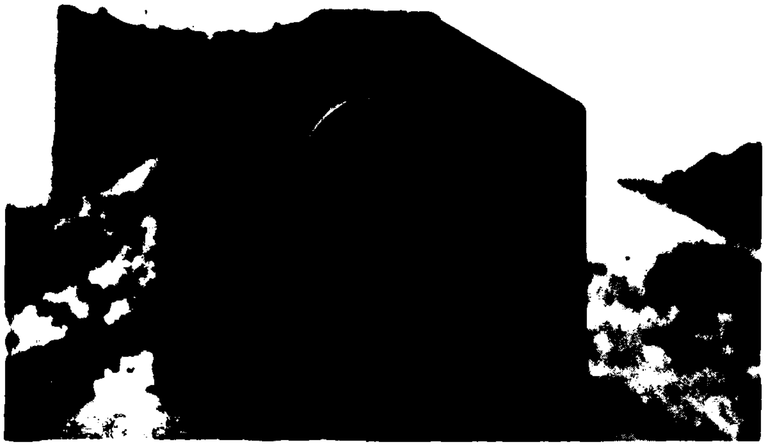

Figure 5. Instrumented Projectile Baseplate With Witness Plate

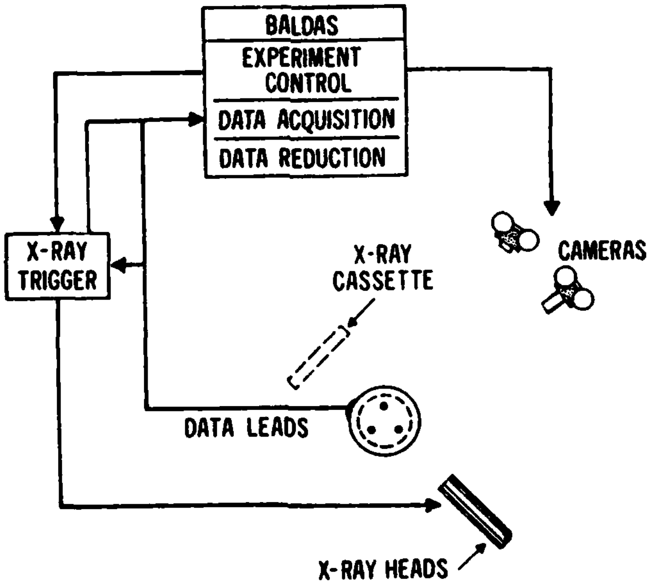

Figure 6. System for Experiment Control, Data Acquisition, and Data Reduction

single bundle of 737-mm-long slotted sticks from propellant Lot RDD E146. The charges were encased in molded nitrocellulose cases, as opposed to the spiral wrapped cases illustrated in Figure 2. The propellant weight for each lot was 12.9 kg. To facilitate viewing the interior of the charge during the firing event, the combustible case was perforated with windows measuring either 51 mm by 76 mm or 51 mm by 51 mm along the length of the case. The windows were covered on the inside of the case with a sheet of plastic 0.38 mm thick, 102 mm wide, and 635 mm long. These were the dimensions deemed necessary to support case pressurization while covering a minimum amount of the interior of the case surface. The sheet was glued to the interior of the case with contact cement. Upon re-assembly, the charges were restored as nearly as possible to their as-received condition.

Figure 7 illustrates the two charges fired with propellant Lot RDD E153. The top view shows the broken-down charge, including the two bundles of propellant (one tied), the lead foil on the forward bundle, the CN-cup igniter assembly, the base cap (with the perforated nitrocellulose cup under it), and the windowed case. The propellant sticks were coded by several means to permit later identification of their location in the charge. The bottom view shows the assembled charge. Note that the forward large window was positioned to show the interface of the two stick bundles.

Figure 8 illustrates the first charge fired with propellant Lot RDD E146 (Round 3). The top view again shows the broken-down charge, with the single bundle of full-length sticks, the as-received CN-cup igniter, the singly perforated base cap, and the multiply perforated nitrocellulose cup. Note that as received, the propellant bundle had neither tie strings nor a lead sheath, this probably due to variations in R&D charge candidates. The windows were placed in the same positions as for the charge made with Lot RDD E153. Again, the ends of the stick grains were coded to allow a correlation of the effects of the interior ballistic cycle with their location in the charge. Here too, the bottom view displays the assembled charge.

Figure 9 shows the second charge fired with propellant Lot RDD E146 (Round 4). For this shot, the CN-cup igniter was replaced with a cloth basepad containing 71 g of the CBI used in the other charges, along with 14 g of Class 3 black powder. All other aspects of the charge remained as shown in Figure 8.

C. Firing Results

The charges were conditioned at the required temperatures for at least 24 hours prior to firing. With one exception (noted below), approximately 15-17 minutes elapsed between the time each of the charges was taken from the conditioning box and fired, and during essentially all of this period the charge was in the plastic chamber. The charges were positioned with a nominal standoff of 25 mm and initiated with M82 primers. Using pieces of the combustible case material, the charges were wedged against the side of the chamber nearest the camera to minimize obscuration of the windows by smoke. The size and positioning of these pieces of combustible case were deemed not to influence appreciably the flow in the ullage. After loading, there was an axial distance of approximately 50 mm between the forward end of the charge and the base of the projectile. For each shot, a flash X-ray was recorded when the spindle pressure reached 7 MPa.

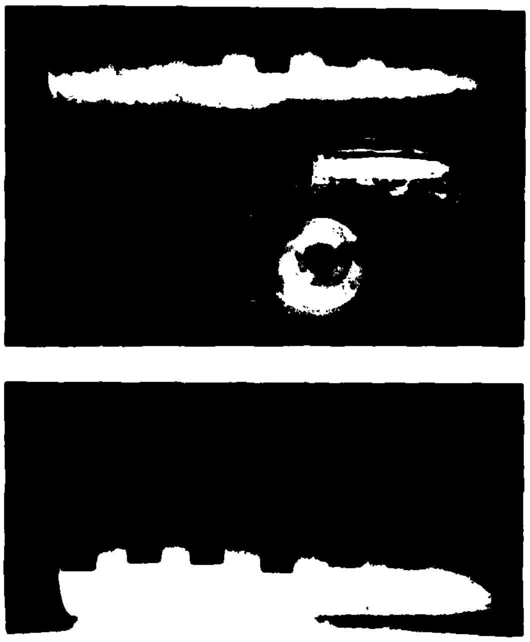

Figure 7. Modified 155-mm, M203E2 Propelling Charge, Propellant Lot RDD E153, CN-Cup Igniter, Rounds 1 and 2

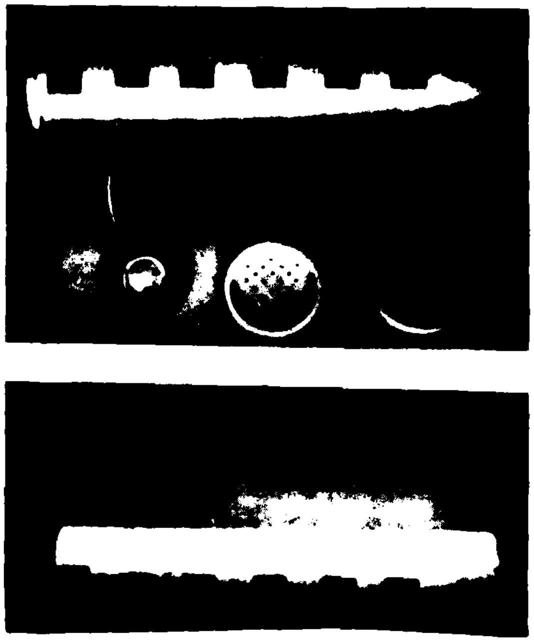

Figure 8. Modified 155-mm, M203E2 Propelling Charge, Propellant Lot RDD E146, CN-Cup Igniter, Round 3

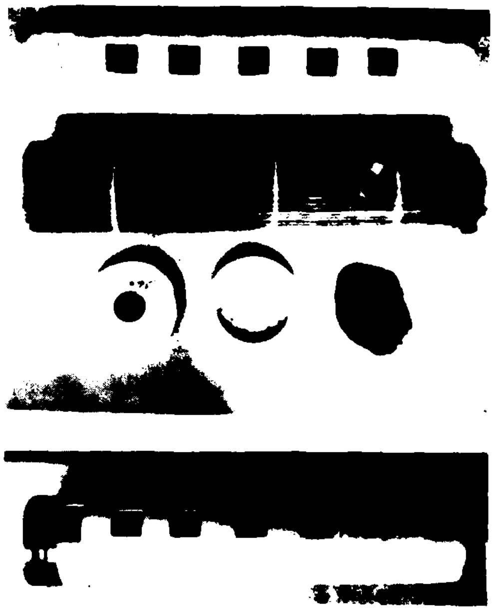

Figure 9. Modified 155-mm, M203E2 Propelling Charge, Propellant Lot RDD E146, Cloth-Bag Igniter, Round 4

<u>Lot RDD E153, Round 1</u>. Figure 10 depicts the spindle pressure and pressure and force on the base of the projectile for Round 1 of propellant Lot RDD E153. The times are referenced to the instant at which the firing voltage was applied to the gun. The ignition delay, on the order of 100 ms, was longer than the average obtained with this charge in development testing; but it is within the bounds of those observed previously. During the long ignition delay, the charge was pushed forward to touch the base of the projectile (described below), although the gages showed no responses above those indicated at the 91 ms time on the plot of Figure 10 (for example, no spindle pressure in excess of 0.1 MPa). Since a pressure of 1 MPa is equivalent to a force of 745 N for these force gages, we note that the pressure measured by the projectile base pressure gage is in excess of that measured by the projectile base force gage at times; and indeed, the response of the projectile base pressure gage may be an artifact given that the gage was covered by the front of the charge by this time. However, this response may be a result of compression of gases between the charge and gage face. (Perhaps a more clear indication of this occurrence is given later in the discussion of the results obtained with Lot RDD E146, Round 3.) We note that although the force gage provided very little response prior to 91 ms, during the time that the charge contacted the projectile, it nevertheless provided a later record of force on the base of the projectile, presumably as a result of pressurization of the rear portion of the chamber and a force applied to the base of the charge. The chamber failed at approximately 13 MPa.

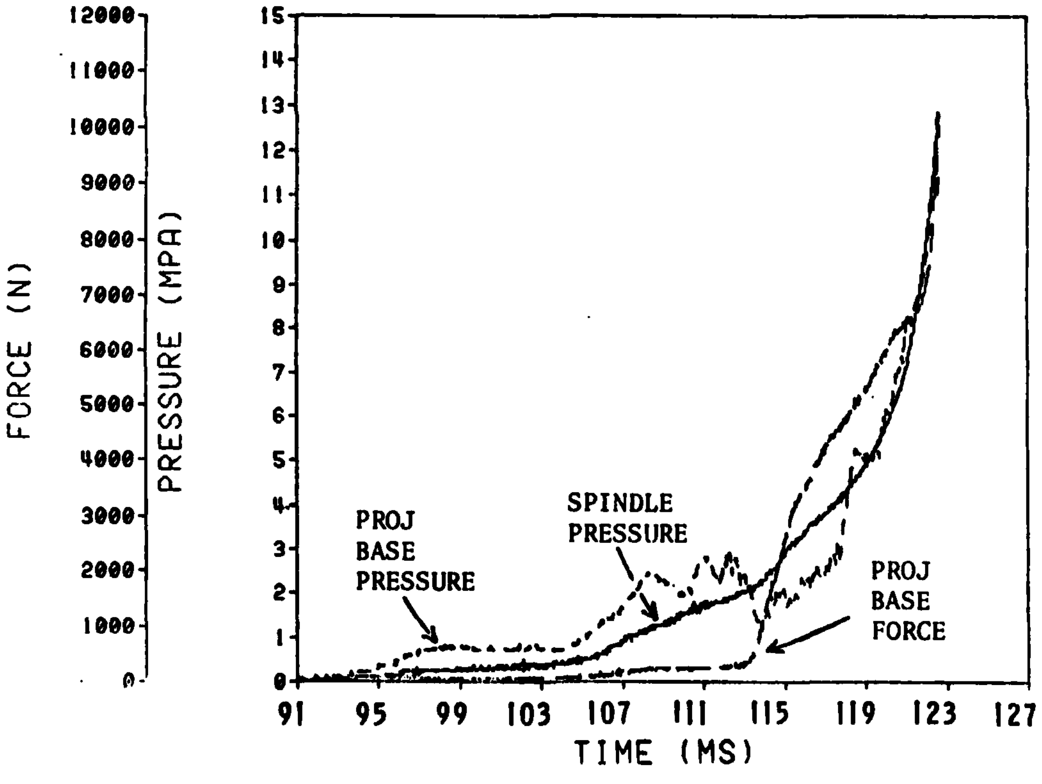

Figure 10. Pressures and Force for Round 1, Propellant Lot RDD E153, CN-Cup Igniter, -54 °C

The forward face of the combustible case survived intact. It showed very clear imprints of the details of the witness plate attached to the projectile base on one side and slight imprints of stick propellant ends on the other. The witness plate itself was unmarked.

The high-speed films recorded many details of the charge functioning. At 1.6 ms after application of the firing voltage, a plume of flame with a full angle of about 75 degrees was seen, of duration of less than 0.2 ms. From 2.2 ms to 3.0 ms, flame was visible again in the base region, attached to the base of the charge. This luminosity disappeared and then reappeared, again attached to the charge base, from 3.7 ms to 6.6 ms. There was yet another flame, attached to the charge base, beginning dimly at 9.4 ms, increasing in luminosity until 10.5 ms, and then decreasing steadily until it disappeared at about 15.2 ms. During these periods, flame was observed nowhere in the chamber with the exception of the region between the spindle and charge base. At 11.5 ms, the charge began to move and was propelled forward to impact the projectile base at approximately 49.8 ms. The velocities as determined from closely spaced times varied but were within a range of 1-2 m/s. No luminosity was seen in the chamber again until 98.9 ms, though several small patches of smoke drifted down the chamber from 63 ms to 94 ms. At 98.9 ms, flame was again visible in the ullage near the base region of the charge; and this increased in intensity and extended into the radial ullage at the bottom of the chamber beginning at 107 ms. Until this time, no flame was seen inside the charge through the windows, though the windows remained unobstructed from smoke on the outside of the charge. At 111.2 ms, flame appeared in the third window from the rear of the charge; at 112.8 ms, at the fourth window; and at 114.9 ms, at the fifth window. Flame began to fill the radial ullage beginning at about 113.0 ms. The chamber fractured at approximately 123 ms.

Figure 11 is a photograph of the static X-ray recorded before the shot. Several details are of interest. Easily seen are the spindle at the left and the axial ullage between the spindle and charge base. The combustible case body, the coupling ring between the body and base cap, the cup, and the plastic igniter assembly with the CBI and spot of black powder are all easily identifiable. Note the ullage within the case between the propellant sticks and the case sidewall and the annulus inside the base cap. The second portion of Figure 11 shows the static X-ray taken of the forward part of the charge. Easily discernible here are the projectile base at the right, the ullage between the charge and projectile, the combustible case, the propellant within the case, and the axial ullage between the forward end of the propellant bed and the front of the case.

Figure 12 is a dynamic X-ray taken at a spindle pressure of 7.2 MPa. The base cap and plastic cup with igniter powder were consumed; but the combustible, perforated cup remained. The case and propellant bed were noticeably compacted radially, especially in the area of the coupling ring between the case body and base cap and the area of annular ullage inside the base cap. The outside of the case at the coupling ring was compacted from a diameter of 159 mm to 150 mm. The propellant bed itself suffered some compaction, from a diameter of 144 to 140 mm. It appeared that the case wall buckled out into the top radial ullage, beginning at 56 mm from the base of the charge, and approaching the chamber sidewall at 120 mm from the base. Turning to the X-ray recorded of the front of the charge, we note that the charge impacted the projectile base, that the front of the case was buckled to

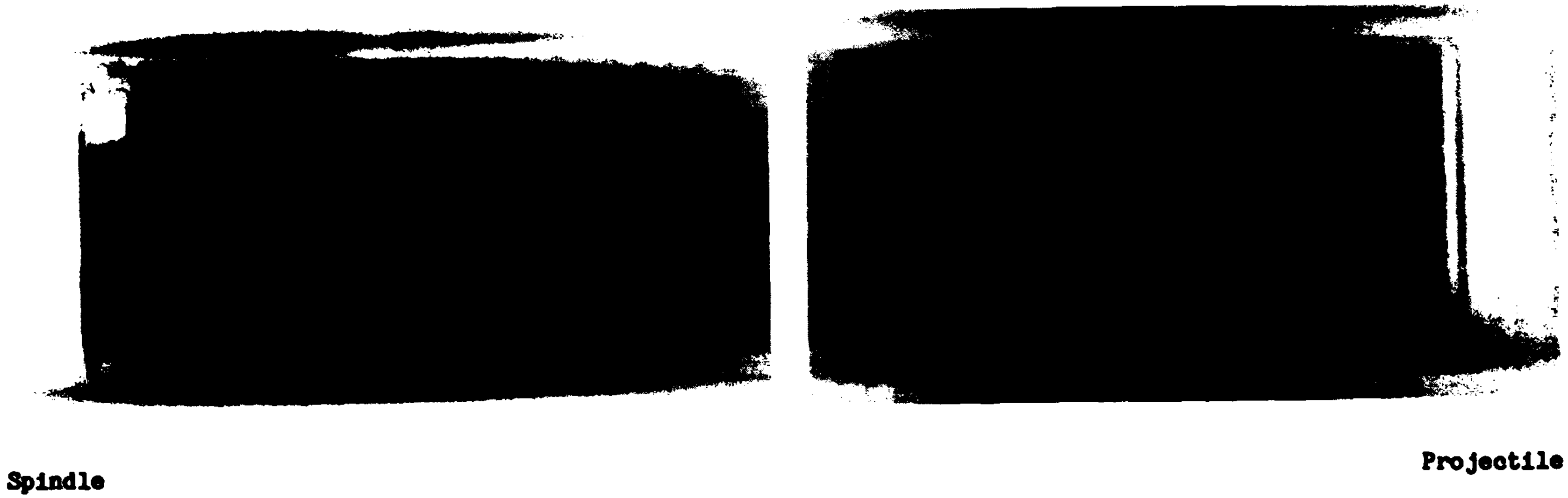

Figure 11. Flash X-ray for Round 1, Propellant Lot RDD E153, CN-Cup Igniter, -54 °C, Before Shot

Figure 12. Flash X-ray for Round 1, Propellant Lot RDD E153, CN-Cup Igniter, -54 °C, Spindle Pressure 7.3 MPa

give a slight lip, and that the ullage between the forward end of the propellant bed and the case disappeared. The forward end of the case suffered some radial compaction as well, with the diameter reduced from the original 150 mm to 146 mm. The propellant bed itself expanded radially at the forward end, from an original diameter of 141 mm to a diameter of 143 mm.

It is noteworthy that there was no evidence in the data gathered that gross fracture of the propellant took place in the early portion of the interior ballistic cycle. The high-speed films recorded no such fracture, viewed through the windows, even in the base region of the charge; and the lack of fracture on a noticeable scale is obvious from the dynamic X-rays. Representative grains gathered from the site after the test are shown in Figure 13. The overwhelming majority of the propellant grains were split axially opposite the location of the slot. A closer examination of many of the pieces at a magnification of fifty revealed no microscopic cracks in the grains. Since the breaks were not charred, one might assume that the grains broke as a result of the sudden depressurization at chamber failure coupled with the internal pressurization of the propellant perforations. However, the other surfaces of the grains that must have burned to pressurize the chamber to the extent measured also showed no real evidence of charring. Thus we cannot conclude whether the grains fractured within the chamber after the X-ray was taken but before the chamber failed. Grain fragments of a variety of lengths, including some whole ones, were found; and the ends of the grains from the base of the charge were not noticeably different from the ends that were located either in the middle or at the front of the charge.

The remaining webs of several propellant grains recovered after the firing were measured in an attempt to determine the burning characteristics of the propellant. The differences in remaining webs were at most 0.1 mm out of remaining thicknesses of 2.2 mm to 2.3 mm, without any obvious pattern of differential burning along the length of the grain. No real comparison can be made with the nominal initial web of 2.3 mm since it could not be measured accurately due to the pliability and ovality of the original propellant.

<u>Lot RDD E153, Round 2</u>. The circumstances surrounding this firing were identical to those of Round 1 except that the charge was conditioned to 63 °C. The spindle pressure is shown in Figure 14. The records for the pressure and force on the base of the projectile were not suitable for reduction; however, the force measurement perhaps indicated an impact of the charge on the projectile base at about 22 ms. The chamber fractured at approximately 6.1 MPa. Since the flash X-ray was set to trigger at a spindle pressure of approximately 7 MPa, dynamic radiographic data were not recorded for this event. The static X-ray revealed details similar to those recorded in Figure 11.

The high-speed film recorded substantially different behavior for this shot than the previous one, particularly on the part of the rear of the case. The primer vented on the base of the charge at 1.5 ms; and the basepad began to burn, with the luminosity increasing in the region of the base without penetrating either the propellant bed or the radial ullage surrounding the charge. At 2.5 ms, the rear, single-perforated endcap began to balloon out into the rear axial ullage, with the flame visible within the endcap. The balloon continued to grow, without rupturing, until 8.6 ms, when it had

Figure 13. Charge Remnants from Round 1, Propellant Lot RDD E153, CN-Cup Igniter, -54 °C

expanded into the rear ullage by about 50 mm on the charge axis. During the period from 1.5 ms to 8.6 ms, the luminosity of the flame increased, then diminished to almost nothing, with no flame visible within the charge or radial ullage. At 10.6 ms, luminosity again became visible in the rear ullage; and the endcap had ruptured along its rim at the top of the charge, forming a flap of combustible case. As the charge burned in the rear, with an expulsion of turbulent flame into the rear ullage, this flap further separated from the case, pivoting on the point of attachment at the bottom of the charge. At 15.4 ms, the luminosity in the base region had again decreased so that it was almost invisible. Flame again appeared at the rear at 21.2 ms; and by 23.1 ms, it had grown more intense and began to spread into the radial ullage along the side of the charge. Some faint luminosity was seen in the rear window at 24.2 ms and in the second window at 25 ms, both becoming brighter by 27.7 ms, with no flame in any of the forward windows. By 28.3 ms, there was flame all along the top ullage; and there was faint luminosity visible in all the windows. The luminosity in all the windows had become bright by 29.6 ms. At 30.4 ms, there was bright flame at the front and rear of the chamber and throughout the unruptured charge.

Representative propellant sticks gathered from the firing site after the test are shown in Figure 15. Of the sticks recovered, practically none showed any damage whatsoever. It should be noted, however, that very few sticks were recovered from the base region of the charge. When the chamber fractured at this low pressure, sticks from the base region were thrown en masse only a short distance from the apparatus and could not be extinguished. The recovered sticks were very pliable and almost could be tied into knots.

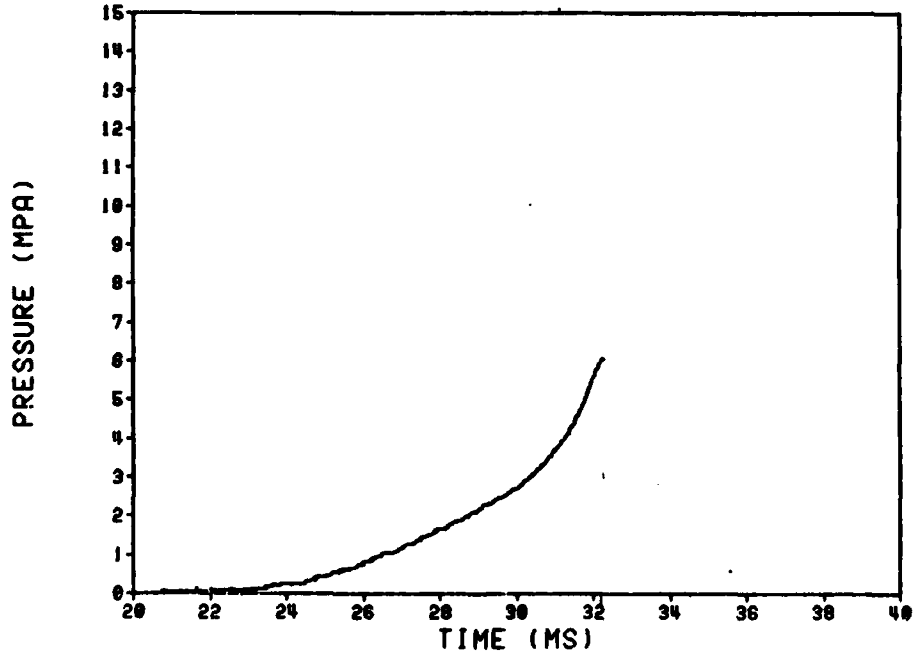

Figure 14. Spindle Pressure for Round 2, Propellant Lot RDD E153, CN-Cup Igniter, 63 °C

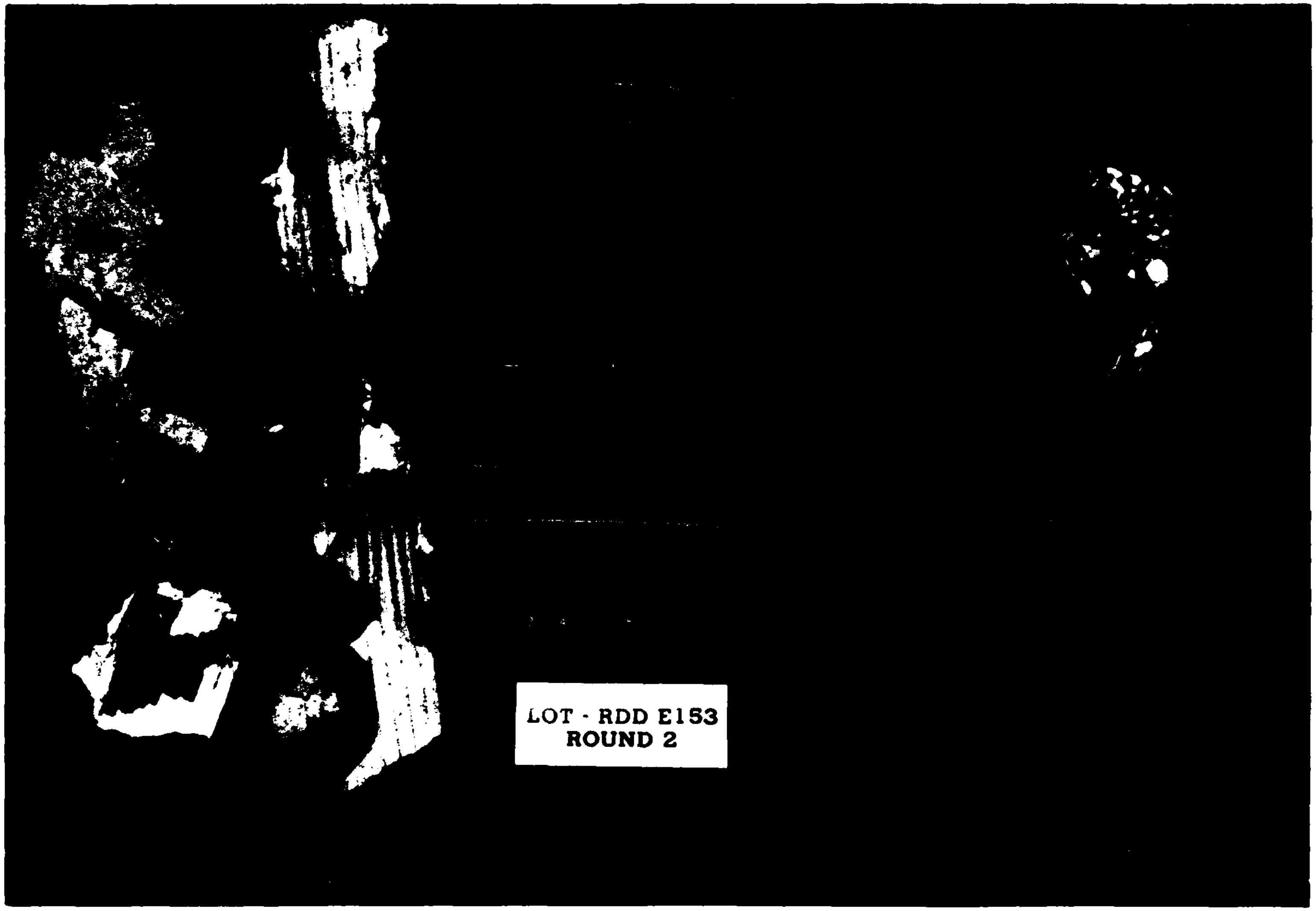

Figure 15. Charge Remnants from Round 2, Propellant Lot RDD E153, CN-Cup Igniter, 63 °C

<u>Lot RDD E146, Round 3</u>. The spindle pressure and pressure and force at the base of the projectile for Round 3, the first shot using propellant Lot RDD E146, are given in Figure 16. This charge used the ignition system as received, with the CN-cup igniter, and was conditioned to -54 °C prior to firing. The times on the plot again are referenced to the instant at which the firing voltage was applied to the gun. The chamber fractured at approximately 15 MPa. The different slopes of the spindle pressure curve from 14-25 ms and 25-28 ms may be indicative of the burning of primarily the basepad followed by combustion of the propellant. Such a scenario is supported by the film record of the event, described below. The peaks in pressure and force measured at the projectile base at approximately 18 ms coincide with the impact of the charge on the projectile. That the recessed pressure gage record displays a spike in response to the charge impact is difficult to explain. It may be a consequence of gas trapped and then compressed in the ports between the baseplate surface and the gage. The second pressure and force gages mounted at this location showed the same behavior (not shown). As indicated by the oscillations, one could speculate that the charge was twice pressed against the projectile and relaxed away from it, perhaps due to an ignition-driven pressure wave, before being driven against the projectile by the eventual pressurization of the chamber.

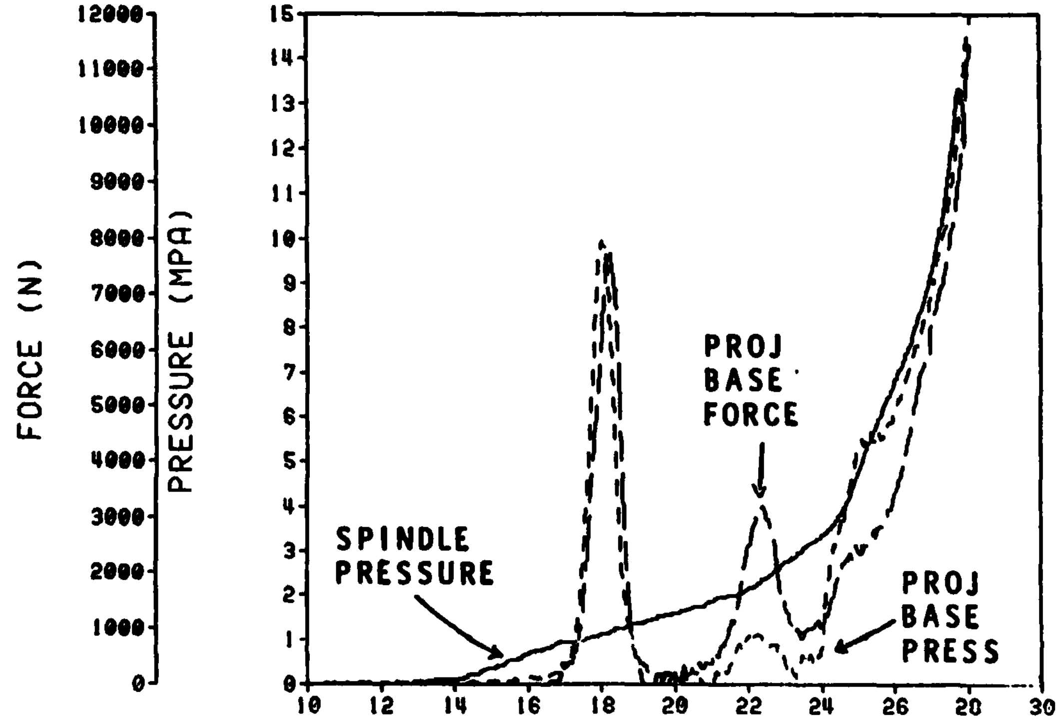

Figure 16. Pressures and Force for Round 3, Propellant Lot RDD E146, CN-Cup Igniter, -54 °C

The film from the high-speed camera focussed on the rear of the charge did not yield data suitable for reduction, but the camera recording the overall view provided the required data. A cone-shaped plume from the spithole, of less than 0.2 ms duration, was seen at 1.0 ms. Flame of varying intensity filled the ullage between the spindle and the charge starting at 1.2 ms. Between 1.9 ms and 2.3 ms, there was apparent discharge from the base of the charge in addition to the more general luminosity in this ullage. The first perceptible motion of the charge began at 3.6 ms; and the charge accelerated, though not uniformly, until it impacted the projectile base at 18 ms with a velocity on the order of 8 m/s. Beginning at 4.4 ms, there was noticeable flame from the basepad, and the combustion increased until the entire rear ullage was full of intense flame by 14.8 ms. Considerable smoke covered the rear half of the charge by 20.1 ms, so much so that the rear three windows were obscured by it. At 22.2 ms, several spots of flame had moved into the radial ullage on the side of the chamber; and by 26.5 ms, there was flame in the bottom and side radial ullage from the spindle to the projectile base. With some dark spots present, this flame along the length of the chamber continued to intensify until the chamber failed at 27.9 ms. At no time was any flame seen through any of the windows in the side of the charge, nor was there any flame in what began as the top annular ullage.

Figure 17 shows the static flash X-ray of Round 3 taken before the firing. The details in the chamber and charge assembly are essentially as described in the static shot for Round 1, the difference being that this charge had one tier of propellant rather than the two tiers in the charge made with Lot RDD E153. Figure 18 displays the dynamic flash X-ray, recorded at 26.4 ms when the spindle pressure was 7.3 MPa. As with the dynamic radiograph from Round 1, we note that the charge was noticeably compacted radially; and indeed, in this firing, it was lifted off the bottom of the chamber and compressed against the top of the chamber for most of its length. There was some ullage remaining between the front of the charge and the top chamber wall, but the charge was pushed against the projectile base; the 3.5-mm ullage between the forward end of the propellant bed and the front of the case was collapsed; and propellant sticks were splayed outward, away from the axis of the charge. The outside diameter of the case at the rear was reduced from 159 mm to 144 mm, and the diameter of the propellant bed in the same region was reduced from 141 mm to 133 mm.

The projectile-base witness plate melted, providing no useful data.

From the limited view afforded by the high-speed movies in this shot, and from the dynamic flash X-rays, there again was no evidence of gross grain fracture during the portion of the interior ballistic cycle examined in this apparatus. Propellant grains gathered after this firing, shown in Figure 19, displayed the same characteristics as those retrieved after the previous cold-conditioned firing, Round 1. For the most part, they were fractured axially, opposite the location of the slot. The breaks were not charred, again offering the possibility but not the proof that the fracture may have been an artifact of the sudden depressurization at chamber failure. Microscopic examination again showed no fine cracks. Longer pieces were of course found after this firing than after the previous shot. The remaining web along the length of some fractured grains varied, with no discernible pattern, by at most 0.1 mm out of remaining thicknesses of 2.1 mm to 2.4 mm. Previous comments about the original web apply here.

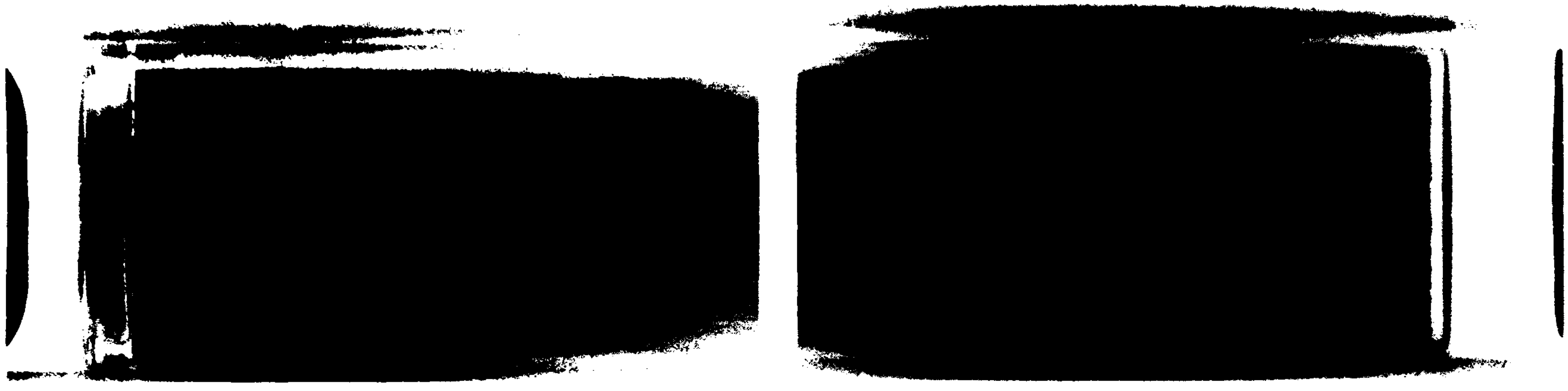

Figure 17. Flash X-ray for Round 3, Propellant Lot RDD E146, CN-Cup Igniter, -54 °C, Before Shot

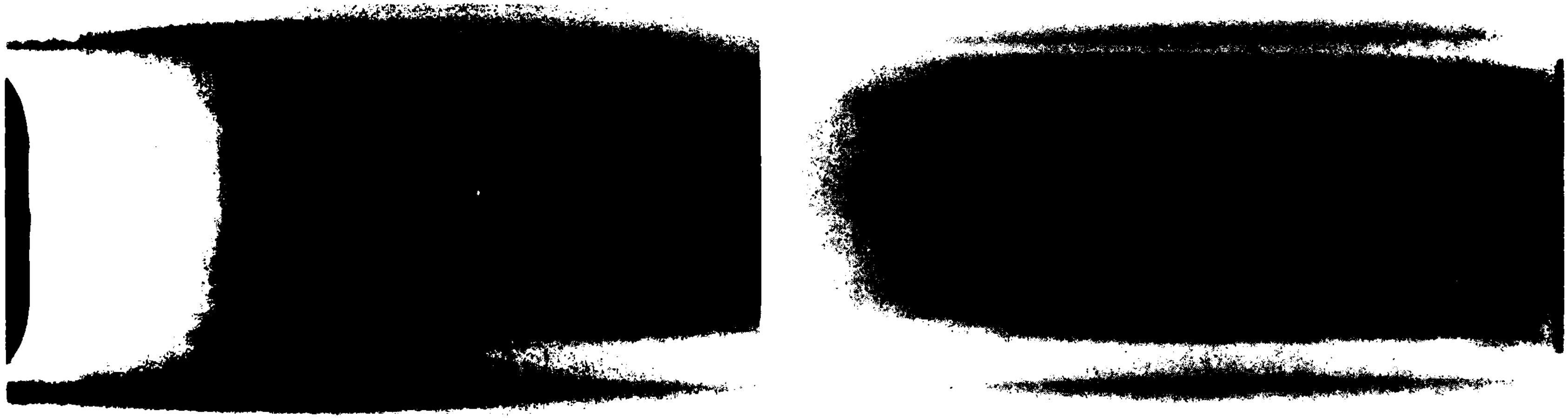

Figure 18. Flash X-ray for Round 3, Propellant Lot RDD E146, CN-Cup Igniter, -54 °C, Spindle Pressure 7.2 MPa

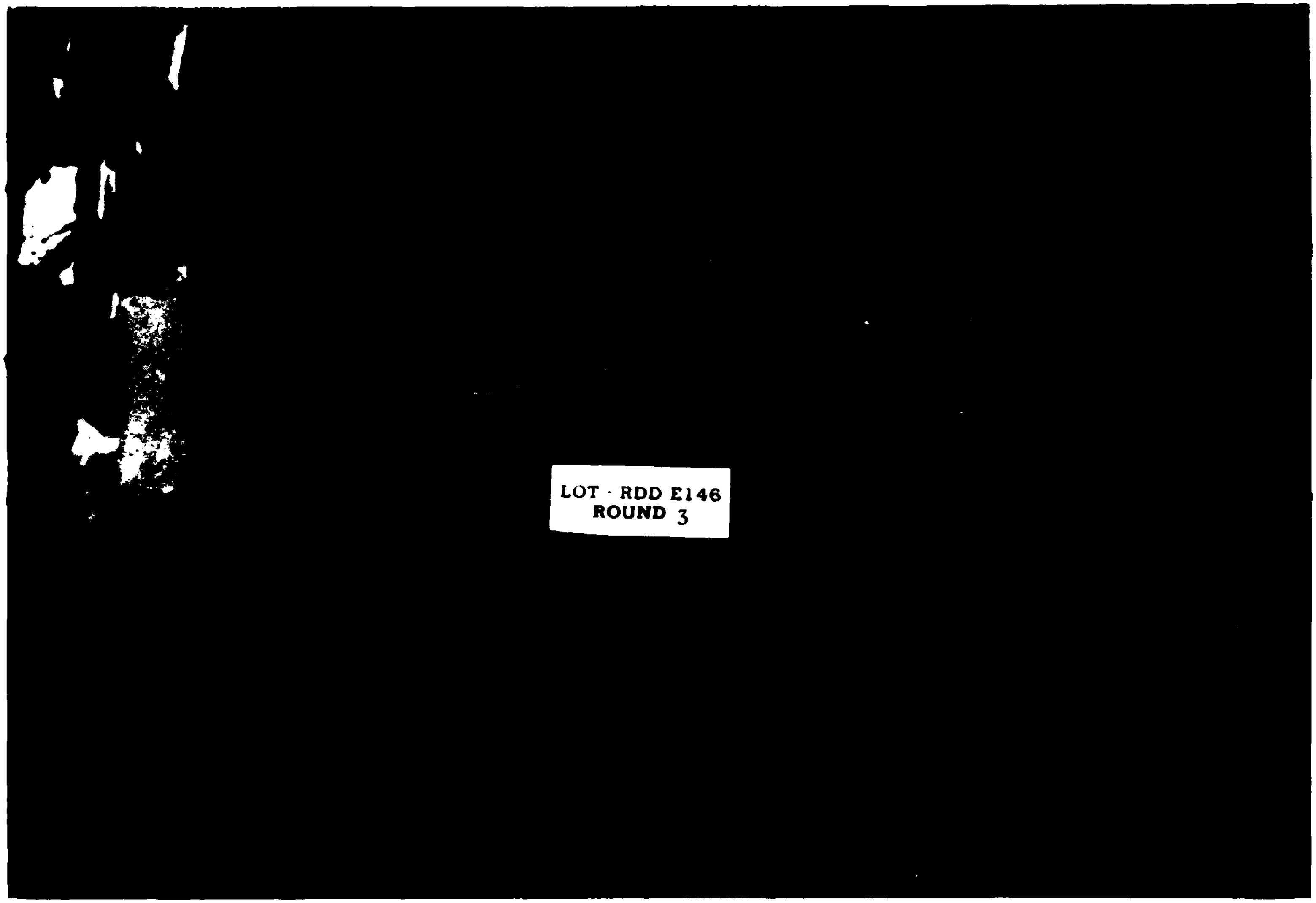

Figure 19. Charge Remnants from Round 3, Propellant Lot RDD E146, CN-Cup Igniter, -54 °C

<u>Lot RDD E146, Round 4</u>. This shot employed a different igniter from that used in the foregoing tests. For this round, 71 g of CBI and a 14-g spot of black powder were packaged in a cloth basepad rather than the CN cup. This charge was conditioned to -54 °C prior to firing, rendering possible a direct comparison of this firing with Round 3. The spindle pressure and force on the base of the projectile are shown in Figure 20; the record of the pressure on the base of the projectile was unsuitable for reduction.

As expected, the high-speed films showed that the igniter and early combustion gases penetrated the propellant bed more easily than was seen with Round 3. The primer vented onto the base of the charge at 1.2 ms; and the basepad began to burn at 1.3 ms, with the luminosity increasing until 1.7 ms and diminishing to almost nothing at 7.7 ms. Luminosity again appeared at 11.5 ms, with patches of white by 16.3 ms. The charge was pushed forward to impact the base of the projectile at about 18 ms, with intense luminosity in the rear ullage and nowhere else within the chamber. At about this time, oscillations of luminous patches between the spindle and the base of the projectile began and persisted until about 26.9 ms. By 27.9 ms, there was a strong, orange luminosity at the base of the projectile, swirling toward the spindle. At 28.8 ms, some luminosity appeared in the third window from the rear of the charge; and it became considerably stronger in the third and fourth windows by 33.7 ms, when a slight luminosity in the second window

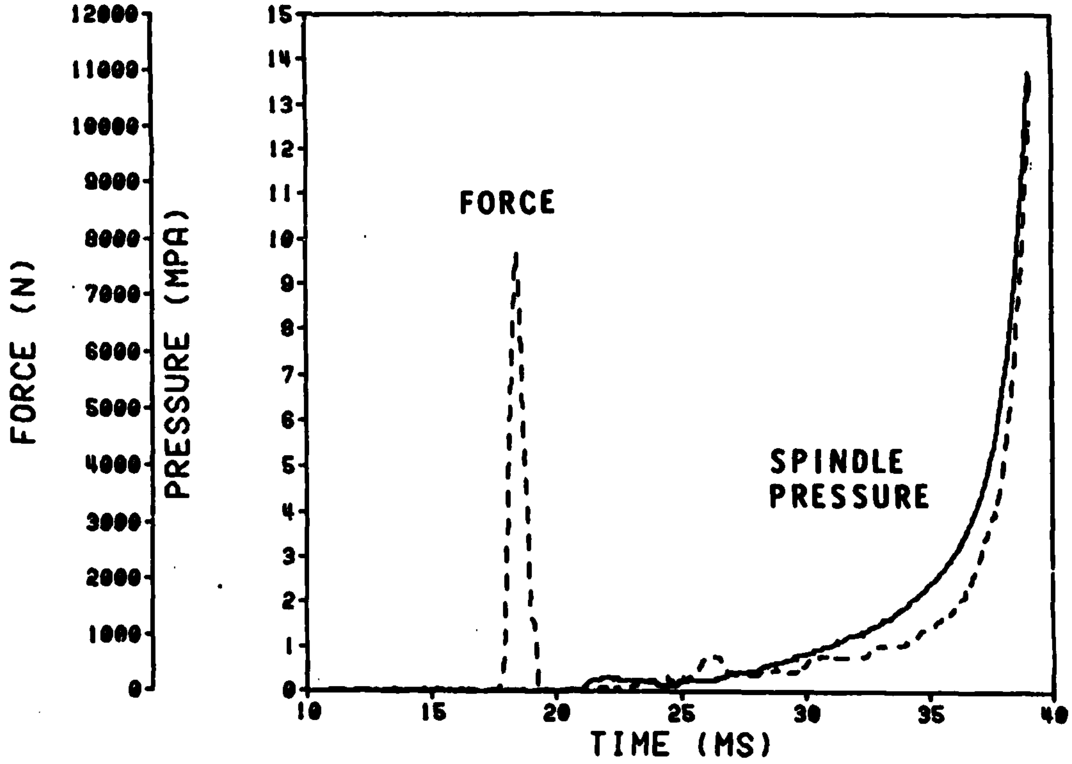

Figure 20. Spindle Pressure and Force for Round 4, Propellant Lot RDD E146, Cloth-Bag Igniter, -54 °C

became apparent. Between 34 ms and 35 ms, the combustible case ruptured along the top and between the third and fourth windows, at a spindle pressure of about 2-3 MPa. The flame in the chamber continued to grow in intensity until the chamber failed at about 39 ms.

The static X-ray for Round 4 is shown in Figure 21. Readily apparent, in comparison to the static X-ray for Round 3, are the absence of the CN-cup igniter and the reduction in the amount of CBI. The dynamic X-ray, recorded at a spindle pressure of about 7.2 MPa, is given in Figure 22. In this case, the charge was not compacted radially as in the previous shot; and indeed, it is obvious that the case ruptured and buckled at the top and was pushed out into the annular ullage. While it appears that some vestiges of the multiply perforated combustible cup may have remained in the rear ullage at this time, there was no barrier remaining between the gases in the ullage and the propellant bed, as was indicated in Figure 18.

Representative propellant sticks and samples of combustible case retrieved after the shot are shown in Figure 23. Generally, the sticks that split did so axially, as seen with the earlier shots. However, there were more whole sticks and longer pieces with this firing than remained after Round 3. The comments made previously regarding burning patterns and fracture of the sticks apply here as well.

CONCLUSIONS

This study has elucidated several phenomena which should serve as a helpful start in compiling a data base for stick propelling charges which use combustible cases. While the larger details of flow dynamics and flamespread are reasonably well understood for bundles of stick propellant, we have noted from this study that the packaging of the bundle in a case can significantly affect the details of the charge ignition. Given recent anomalies with the M203E2 Propelling Charge, we can surmise that these same phenomena may lead to considerable impact on the overall interior ballistic cycle. Specifically, the findings from this study are:

a. The permeability and mechanical strength of the packaging materials encasing the charge have a significant effect on the flow of combustion gases in the early portion of the interior ballistic cycle, below pressures of a few Mpa. In particular, the materials in the vicinity of the base of the charge warrant special attention, since it was demonstrated that a thin but relatively impermeable barrier between the igniter and the propellant had a profound effect on the penetration of the igniter and early combustion gases into the propellant bed.

b. Given the proper boundary conditions, such as pressurization of the ullage rather than the interior of the charge due to the phenomenon described in paragraph a, the stick-propellant bed can be compacted severely in its radial dimension, reducing the apparent, advantageous permeabilty of the propellant bundle.

c. Perhaps contrary to intuitive expectations, the stick charge was seen to move and impact the base of the projectile, albeit at a low

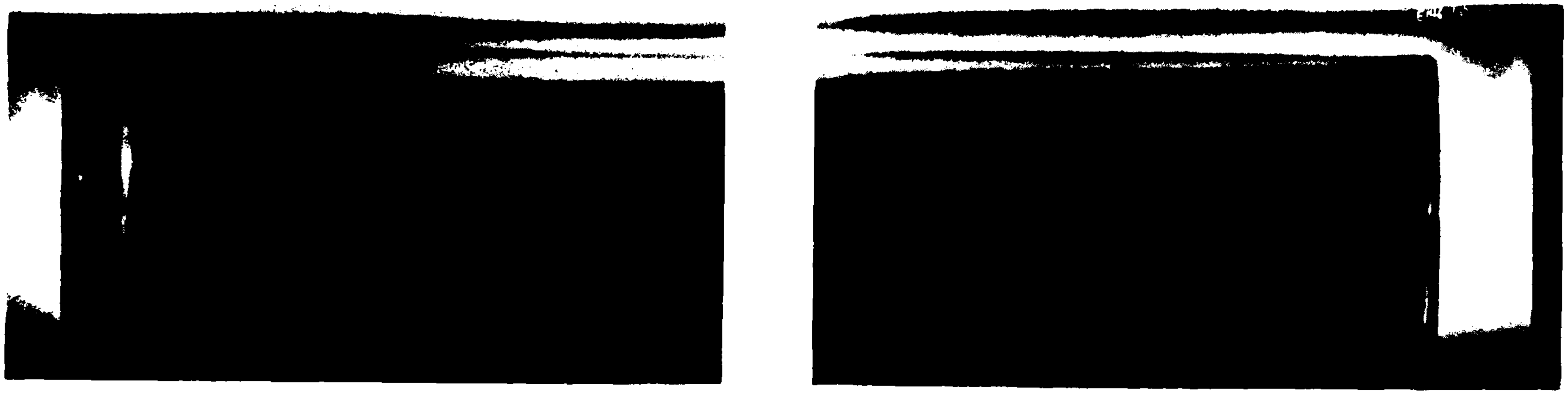

Figure 21. Flash X-ray for Round 4, Propellant Lot RDD E146, Cloth-Bag Igniter, -54 °C, Before Shot

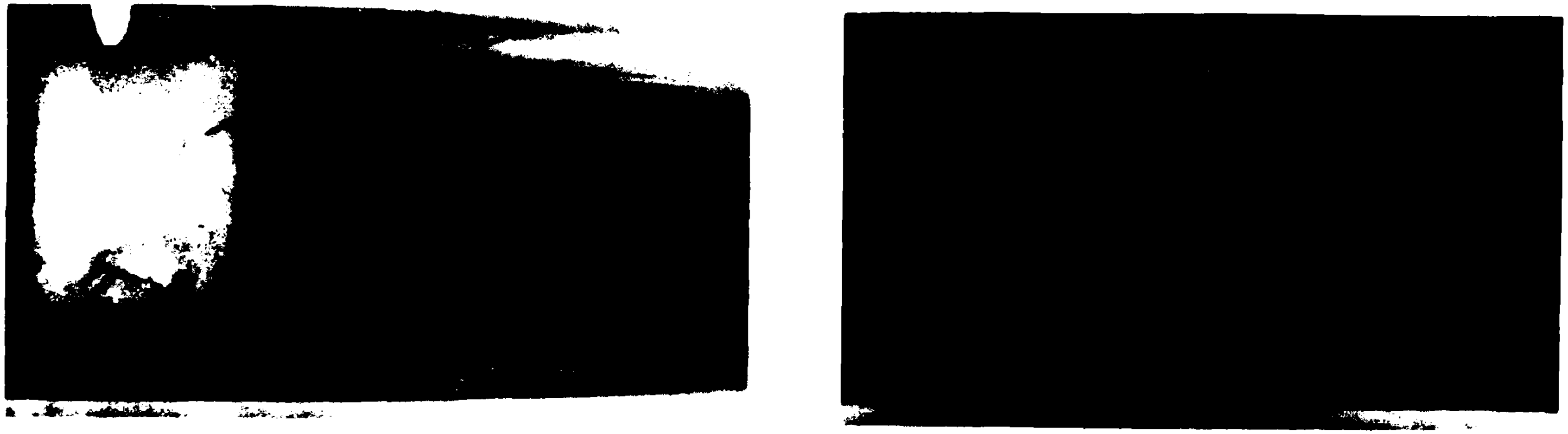

Figure 22. Flash X-ray for Round 4, Propellant Lot RDD E146, Cloth-Bag Igniter, -54 °C, Spindle Pressure 7.2 MPa

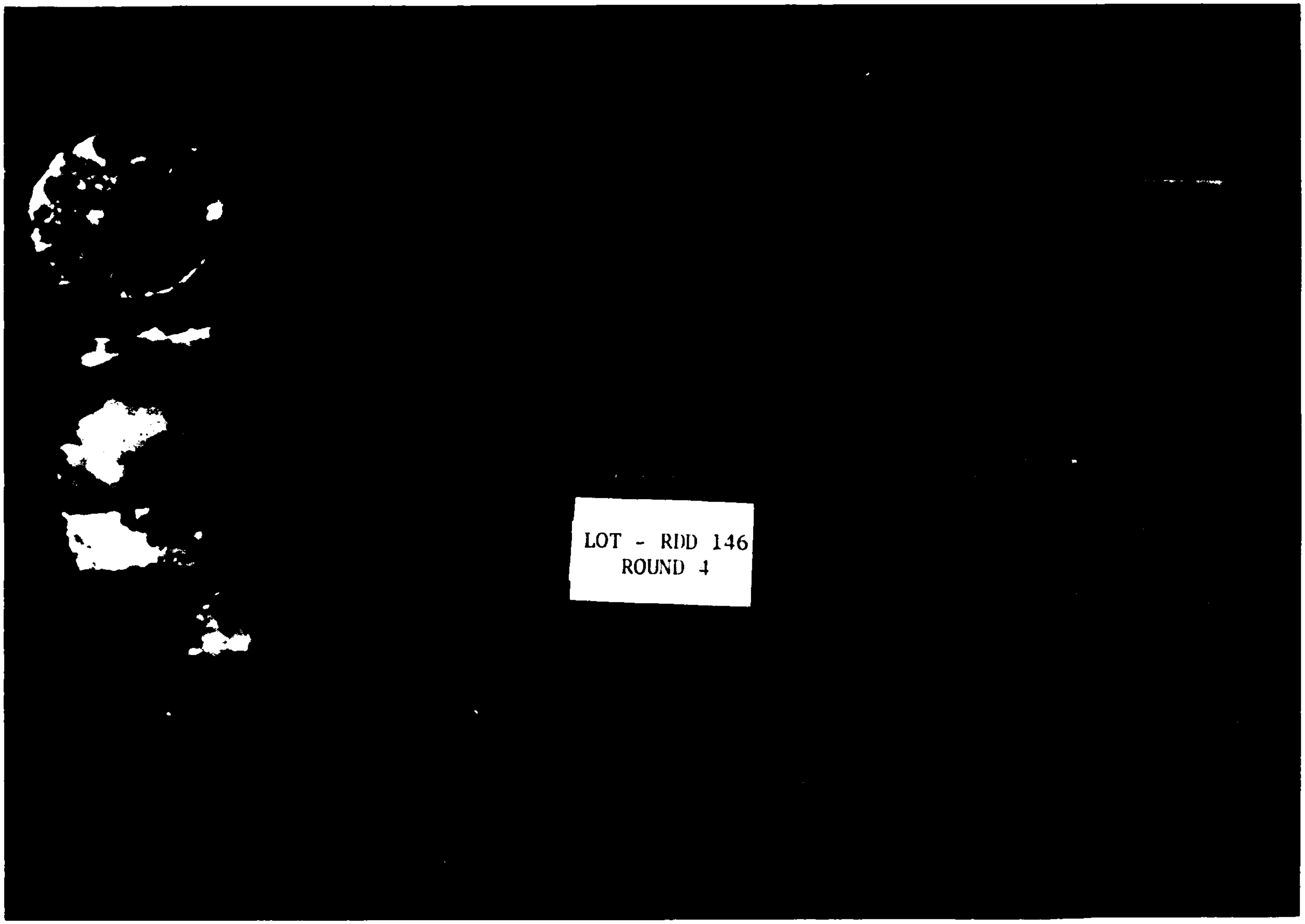

Figure 23. Charge Remnants from Round 4, Propellant Lot RDD E146, Cloth-Bag Igniter, -54 °C

velocity. Our expectations for no significant motion, however, stem from the two-order-of-magnitude reduction in interphase drag offered by stick propellant when compared to granular, a comparison which is based on pressure drop data taken within the respective stick and granular beds. On consideration of entrance conditions, however, we would not be surprised to find considerable resistance offered to igniter gases as they first try to enter the tightly packed bundle of sticks, a condition which would exacerbate ignition problems already addressed in this report. Experimental study of jump conditions at the boundaries of stick bundles now appears warranted.

d. No conclusive evidence was found regarding the fracture of the propellant sticks. While the long propellant sticks did indeed split, generally axially opposite the slot, the fracture may be an artifact of the sudden depressurization at the exterior surfaces of the sticks imposed by the nature of the tests. However, one postulated sequence of events explaining the elevated pressures with cold-conditioned charges invokes stick splitting upon ignition and rapid overpressurization within the perforations at a time when the sticks are tightly compacted from early flow exterior to the charge. The unprogrammed burning surface then leads to the observed increase in maximum chamber pressure. With the preferred mode of flamespreading, early igniter products flow into the bundle of sticks, pressurizing and rupturing the case and dispersing the sticks radially. Ignition and pressurization within the perforations can then readily lead to a slight opening of the slots and rapid equilibration of pressures inside and outside the sticks, preventing any significant splitting. Complete verification of this hypothesis is beyond the scope of this investigation.

The interplay of the various design parameters for this charge, including the propellant geometry, charge casing, and igniter packaging were, at the least, qualitatively demonstrated in this study. It remains clear, however, that a great deal of further investigation is required to quantify the contributions of these many parameters, the ultimate goal being to determine the extent to which they can be manipulated to arrive at optimal performance, safe and reliable charges.

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