Subcritical Plutonium Experiments at the Nevada Test Site

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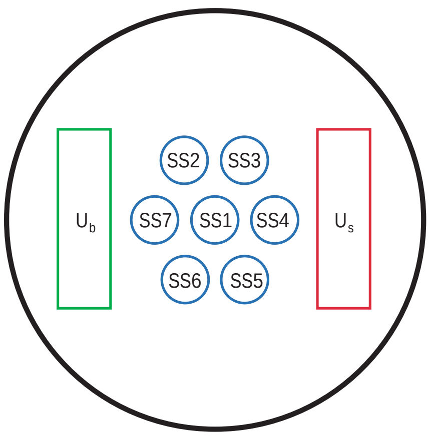

***Figure 1.** Schematic of the layout for the Rebound 170-GPa experiment. The U_b region contains the diagnostic for measuring flyer plate velocity (see Fig. 2). The U_s region contains the diagnostic for measuring the shock velocities in the plutonium samples (see Fig. 3). The circular regions labeled SS1 through SS7 are the locations of the sound speed samples.*

Introduction

In 1997 and 1998, a series of three subcritical plutonium experiments was conducted at the Nevada Test Site (NTS). These experiments, which are the first of their kind to be completed at NTS since the moratorium on underground nuclear testing in 1992, have several purposes. Foremost among these purposes is the study of plutonium physics and the maintenance of our readiness to resume underground nuclear testing should the need arise. These experiments were designed and fielded by the Dynamic Experiments (DX) Division in collaboration with the Physics Division and other Los Alamos divisions, as well as Sandia National Laboratory and Lawrence Livermore National Laboratory. The equation-of-state (EOS) measurement techniques were developed in DX Division, and they have been used by DX Division and its predecessors (GMX and M Divisions) for the past 40 years. Many of the diagnostic and recording techniques, especially for remote data collection, were developed by Physics Division for underground nuclear tests and pulsed power facilities.

The first two experiments, called Rebound and Stagecoach, were executed in July 1997 and March 1998, respectively. Their focus was the plutonium EOS. The third experiment, Cimarron, was conducted in December 1998. Its focus was the ejecta produced when a shock in the plutonium releases into the surrounding vacuum. The data from all three experiments are classified; therefore, this discussion will focus on the experiments themselves and the roles of the Detonation Science and Technology (DX-1), Hydrodynamic and X-Ray Physics (P-22), and Neutron Science and Technology (P-23) groups.

Rebound

The experimental techniques used on Rebound (and Stagecoach), such as the use of explosive-driven flyer plates to shock the samples and flash gaps to identify shock arrivals, were developed at Los Alamos National Laboratory in GMX Division and its successors over the last several decades. Adapting these techniques to the specific plutonium experiments described in this research highlight was done principally by the DX-Division authors listed above, but with significant contributions from the Physics Division. Physics Division personnel came to be involved because of the need to bring the signals out of the enclosed containment room (called the Zero Room because historically it was the room surrounding "ground zero" in underground nuclear testing) to record them at a remote location in the NTS environment. To accomplish this, the direct-view rotating-mirror cameras typically used at the GMX-, M-, and DX-Division firing sites to detect the flashgap signals (described in McQueen, *et al.*[1]) were largely replaced by fiber optics that took the light from the experiment to optical receivers or electronic streak cameras. For Rebound, DX-1, P-22, and P-23 collaborated on a series of seven local experiments to ensure that these diagnostic changes would retain high data quality and to refine the specific geometric parameters of the experiments. These local experiments were very successful.

The goal of Rebound was to study how small plutonium samples, typically a few tens of grams each, respond to shock compression at three specific high-pressure conditions—80 GPa (800 kbar), 170 GPa (1.7 Mbar), and 230 GPa (2.3 Mbar). Three separate experimental assemblies were fielded. Each of the assemblies used a 300-mm-diameter stainless-steel flyer plate that was driven down a barrel by high-explosives (HE) product gases until the plate struck a Lexan target plate holding several samples of gallium-stabilized, delta-phase plutonium. The thickness of the explosives charge, combined with the driver-plate thickness and run distance, determined the driver-plate velocity and consequently the pressures induced in the samples. The aim was to determine the shock Hugoniot (the locus of end points that can be reached in shock wave compression) and sound speed behind the shock front at all three pressures.

The success of the experiment was made possible by close collaboration among DX-1, P-22, P-23, and the other participants. DX-1 used its expertise in shock-wave physics to design experiments most likely to provide results in the EOS regime where the most serious uncertainties lay. Physics Division drew on its experience in underground testing to ensure high-quality data with precision adequate to meet the stringent requirements for such experiments. This is noteworthy because traditionally shock experiments are done under controlled laboratory conditions. In these fundamental subcritical experiments, the research is done underground in a "mining" environment, making it challenging to measure the fiducials, achieve accurate timing, and maintain experimental precision while doing the measurements remotely. Diagnostics included 112 fiber optic pins to measure the velocities and flatness of the flyer plates, shock velocities in the plutonium samples, and sound speeds in shocked plutonium; two electronic streak cameras, each with 35 data channels, which determined any tilt or bowing in the 170-GPa flyer plate and obtained high-time-resolution shock and flyer-speed data; and an energy release measurement to verify that the plutonium was never in a critical-mass configuration and that no self-sustaining fission reaction occurred. Following is a brief outline of the Rebound experiment, explaining what was done and why.

Figure 1 shows the schematic layout of the target plate for the 170-GPa assembly, which had the simplest configuration. The layout for the 800-kbar experiment was similar except two more samples, similar in size and shape to the sound-speed samples and placed near them, were used by DX-Division and Sandia researchers for VISAR (an acronym for "velocity interferometer system for any reflector") measurements of the free surface velocity. The layout for the 2.3-Mbar experiment was also similar except a sample, similar in size and shape to the sound-speed samples and placed near them, was used by Livermore for a release-adiabat measurement. Figure 2 shows a detailed schematic for the diagnostic that measured flyer plate velocity (u_d). The diagnostic consists of fiber-optic pins behind steel of two thicknesses and a flash gap containing argon or xenon that emits light when shocked. Signals travel on fiber optics and are detected by photomultiplier tubes

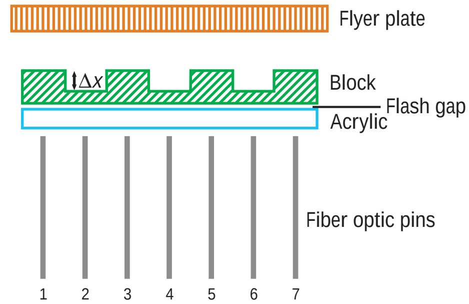

Figure 2. Schematic of the U_b block for measuring flyer plate velocity at the time of impact with the target plate.

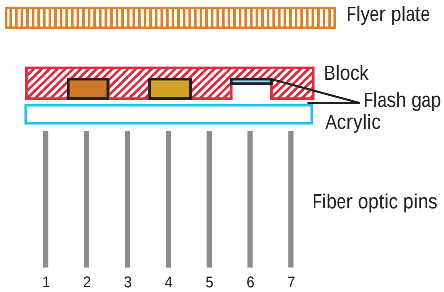

Figure 3. Schematic of the U_s block for measuring the sample shock velocities from the impact of the target plate.

(PMT), avalanche photodiodes (APD), and, when fast recording speed is particularly important, high-speed electronic streak cameras. Flyer plate velocity is determined from the arrival times of signals at two levels. When the flyer plate first strikes the block, a shock forms in the thick regions of the block; when the shock emerges, the flash gap light is detected by the odd-numbered pins. A short time later, the plate strikes the bottom of the notches, where it induces a shock of the same pressure, and that shock is detected by the even-numbered pins. The time difference between the even and odd pins (Δt) is related to notch thickness (Δx), flyer velocity (u_d), and the shock velocity in the block (u_s) by the following equation:

$$\Delta t = \Delta x(1/u_s - 1/u_d)$$

Flyer velocity can be determined by using the known EOS for stainless steel to eliminate u_s. The same principle is used with fiber optics coupled to the streak cameras, except that a closely-packed array of fibers replaces each pin. In this way we can measure detailed local variations in shock arrival times at the flash gap to determine spatial variations in the shock arrival profile, such as might arise from tilt or curvature of the flyer plate.

A detailed schematic for the diagnostic that measured the shock velocity in the plutonium samples is shown in Fig. 3. Two plutonium samples and a piece of transparent Lucite are placed in notches in a stainless steel block. The plutonium shock velocity is determined from the time delay between the start signal when the shock enters the samples, and the stop signals when it leaves the samples. The plutonium start signal is measured through the Lucite and also calculated from stop signals and the shock velocity in the block.

Optical signals proportional to the light intensity were taken from the experiments to the recording stations on fiber optic cables. Long fibers went to either PMT or APD receivers, some in an above-ground station ~1 km away, and some in an underground station about 150 m away. Longer fiber-optic lengths cause increasing distortion of the signals from dispersion, so the data requiring higher time resolution were recorded in the closer station. In the 1-km station, we used 40-nm-wide, 850-nm wavelength filters as a compromise to get adequate light into the receivers while limiting dispersion effects to a few nanoseconds. The fibers were carefully cross-timed in two different ways, one using an optical time domain reflectometer and the other using light from a diode laser injected into many fibers simultaneously. Fibers of similar lengths were timed relative to each other to within 1 ns. This fine control on the cross timing was necessary for the success of the experiment.

Redundant signals from the 170-GPa experiment were also taken a short distance, just a few meters, to a pair of streak cameras located just outside the Zero Room. One camera recorded the flyer speed and one the shock speeds. Before timing, these fibers were cut to lengths such that, as closely as we could determine before the experiment, the signals would all arrive simultaneously at the camera, allowing us to increase the camera sweep speed. We used five times as many fibers as pins (35 fibers each for U_b and U_s) to image the flashgap region so that we could better determine the shock profile across this region. The imaged spots were spaced along the line of pins so that the shock breakout was determined along the entire length of the flashgap. Although the technique was somewhat developmental, it gave a good measurement of the shock spatial profiles, as well as the shock and flyer speeds. This method also provided us a path for making these measurements on Stagecoach, where they were crucial to our obtaining good data on two of the experiments.

In addition to measuring fundamental quantities, such as shock and particle velocities, in plutonium samples, we also made measurements of a derivative quantity, the sound speed. Sound speed data provide valuable constraints to the EOS when combined with shock Hugoniot data. To measure sound speed, the rarefaction-overtake method described in McQueen, *et al.*[2], and shown in Fig. 4 was used. At the center of the target plate are seven samples of different thicknesses, each backed by a piece of high-density glass that serves as an analyzer material, emitting light when the shock arrives. The flyer plate strikes the samples, driving shocks into them and eventually into the glass. Meanwhile, another shock moves back through the flyer. When it reaches the interface with the driving HE gases, a rarefaction fan is reflected into the flyer, eventually moving into the samples and the glass. The pressure changes gradually in this rarefaction rather than suddenly as in a shock wave, but the rarefaction moves faster than the shock front and eventually overtakes it. The samples are thin enough so that, in most cases, the rarefaction overtake occurs in the glass, where it reduces the pressure and causes the light emitted by the glass to be reduced rapidly. The sound speed (the speed of the leading edge of the rarefaction wave), is determined from Δt, the time from first light in the glass until the light just begins to fade, for each sample thickness. Extrapolation to $\Delta t = 0$ gives the sample thickness for which the overtake would have occurred exactly at the sample-glass interface. The sound speed may be calculated from this thickness and other known quantities.

It is important to have an estimate of the signal levels before the shot so that the recording can be set up appropriately. For the flashgaps, the signals were only a few nanoseconds in duration, and their timing could be determined adequately even if they were slightly saturated. Compressed-gain amplifiers on some of the APDs also helped by increasing the dynamic range of the recording. For the sound speed data, however, any saturation would have caused us to lose the information on when the light began to dim. Compressing the signals would have also obscured the timing of the break. Furthermore, the sound-speed light levels from the lowest-pressure assembly were very low. We were able to obtain good sound-speed data by using redundant receivers and recorders with different gains, and for the low-pressure experiment we replaced the 850-nm APDs with ones based on GaAs photodiodes that operated around 1.3 µm. At these longer wavelengths the signals were large enough to make the experiment a success. Just as crucial were the light levels in the streak

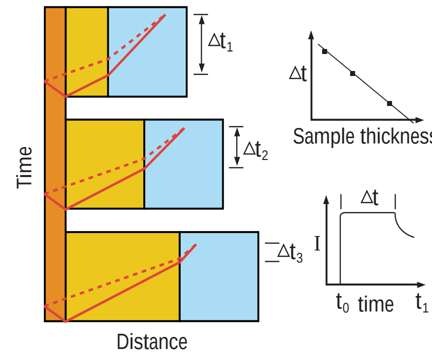

Figure 4. Rarefaction-overtake method for measuring sound speed in samples (yellow) backed by high-density glass (blue) and struck by a flyer plate (orange). The red lines in the sketch show time vs. position for the shock front (solid line) and the fastest rarefaction wave (dashed line). The lower graph illustrates a typical optical signal. The light comes on suddenly when the glass is shocked, remains constant for a time, Δt, until the pressure in the glass is reduced, and then drops gradually as the rarefaction fan overtakes the shock. The upper graph shows Δt for different sample thicknesses.

cameras. All of the levels were estimated from the signals in the seven local experiments.

After corrections for bow and tilt of the flyer plate and other experimental effects, the Rebound experiments produced three points on the shock Hugoniot for the plutonium alloy of interest. Preliminary uncertainties in the u_s-u_p plane were $< \pm 1.5\%$. Sound speeds for the same three pressures were determined with a similar uncertainty. Uncertainties in the release adiabat have not yet been published by Livermore, but they are expected to be slightly larger.

Stagecoach

Stagecoach, the second in this series of experiments, was conducted to improve our understanding of the plutonium EOS, to study the effects of plutonium aging on the EOS, and to develop new diagnostics for future subcritical experiments. The plutonium aging question is complex because plutonium's radioactivity can cause changes in material properties, and we must do experiments to see whether or not it does.

Stagecoach consisted of five experimental assemblies similar to those used in Rebound. Pressures in the plutonium samples ranged from 30 to 320 GPa. All five assemblies had a flyer velocity diagnostic like the one shown in Fig. 2 and a shock speed diagnostic like the one shown in Fig. 3. Each shock assembly included two samples, as shown in Fig. 3, and two of the assemblies included two such shock speed diagnostics. Each assembly had one sample of the plutonium alloy tested on Rebound and one or three aged plutonium samples, providing a test of the response of the aged plutonium at all five pressures. Overtake measurements were made for two assemblies. Four streak cameras were fielded to measure the shock and flyer speeds on the lowest-pressure assembly, where distortion of the flyer plate was of concern, and on the highest-pressure assembly, where the faster speeds made better timing essential. All of these measurements were conducted as described for Rebound, and they returned data of comparable quality at all five pressures.

In addition to the EOS work, we used this opportunity to test new diagnostics intended for measuring the surface temperature of samples on Cimarron. While the pressure, density, and internal energy can be determined from traditional shock-wave measurements of mechanical variables, temperature cannot, and therefore it requires a separate measurement. Shock temperature is an important parameter for benchmarking the EOS, and also for studying phenomena such as insulator-metal transitions, melting, and dissociation. Furthermore, the addition of temperature as a measured quantity, when combined with measured mechanical properties, allows determination of a complete EOS. Including this type of thermodynamic information is often a much more sensitive test of theoretical models such as the EOS than pressure-volume information alone. Temperature data are also useful for modeling phase changes, such as melting and the formation of ejecta at a free surface.

Pyrometry measurements of the shocked material provide the temperature only at the sample surface or interface, while it is the temperature behind the shock front that is of interest. However, the surface temperature is very useful in validating models that estimate the internal temperature. To obtain the free-surface temperature accurately it is necessary to eliminate ejecta from the field of view. One way to reduce the ejecta to manageable levels is by polishing the sample surface to a metallographic finish. However, plutonium is very difficult to polish and it oxidizes quickly, further compromising the surface finish. Another technique involves using a transparent window, or anvil, fastened to the plutonium surface to tamp the ejecta and maintain the release pressure at a higher value, closer to the shock pressure than for free-surface release. The interface temperature is thus closer to the internal temperature and the model validation should be more accurate. Lithium fluoride (LiF) is currently the best material for use as an anvil and as a window to transmit the radiation from the interface. Its heating under shock is low and its emissivity is small. It is important that there be no air or other shock-light-emitting material in the plutonium-LiF interface, although this is difficult to achieve because of the difficulty of polishing plutonium.

We fielded six-channel infrared pyrometers on both polished samples and samples with windows attached to determine which provides better results and to obtain data for release both into vacuum and LiF. We also fielded a comparison measurement of a polished surface and one with a coarser finish to determine whether the ejecta problem was severe enough to require polishing Cimarron samples. With the information from the Stagecoach pyrometers we were able to design the Cimarron temperature samples for optimum chances of success. Pyrometric measurements were also fielded by personnel from Sandia. Data quality and results were similar to ours.

Cimarron

As the nuclear weapons stockpile ages, it will be necessary to make occasional small changes in the materials used and the processes by which the manufacturing is done. Materials in nuclear weapons, including plutonium, HE, and plastics, are subject to change from effects such as oxidation and radioactivity. As it becomes necessary to remanufacture weapons or change out parts, we must be sure that the effects of any changes are minimized and that the changes are understood as much as possible. Furthermore, we need to make baseline measurements of current unaged weapons so that we will know when they have changed.

Cimarron was designed to study the ejecta emitted from a shocked plutonium surface. Ejecta production is sensitive to the surface roughness and oxidation, the material grain structure, and the shock profile. Cimarron diagnostics fielded by the Physics Division included holography to measure the distribution in ejecta size, x-ray shadowgraphy to measure ejected mass density, visible-light shadowgraphy to observe the ejecta cloud, fiber-optic pins to measure the shock timing and profile, pyrometry to measure the temperature of the shocked surface, and, as on the other subcritical experiments, a measurement of the energy release from the experiment to verify lack of criticality.

The in-line Fraunhofer holography technique, developed on the Pegasus pulsed-power system, has been adapted to make three-dimensional measurements of ejecta particles. Because the ejecta particles are moving at velocities of many millimeters per microsecond, a short-pulsed light source is required to stop their motion on film. Also, the explosive energy from the experiment is such that any hardware located nearby is destroyed. As a source, we used a 100-ps-pulsed, 200-mJ Nd:YAG laser with a 532-nm wavelength. This laser was developed by the Laboratory's Materials Science and Technology (MST) Division in collaboration with Bechtel Nevada. A 4.5-m-long optical relay system, consisting of 16 lenses, was designed to protect the laser and the holographic film, which were placed outside the Zero Room. The holography measurement is designed to resolve particles as small as 15 mm in diameter in a cylindrical image volume 1.5 cm in diameter and 6 mm in depth.

The x-ray imaging system also originated at Pegasus, the result of multi-year development of a unique wide-dynamic-range, four-frame framing camera; a newly-designed, blue-transmitting fiber-optic bundle; and modification of the stacked, pulsed x-ray sources used at Pegasus. The system has evolved so that ejecta can be measured over a 25-mm spatial extent at four arbitrary times. Time-dependent measurements were made possible by stacking four x-ray heads and independently triggering the anodes. Each source had a dose of 100 mRad at 30 cm. The heads were 50 to 70 cm from the imaged region and were nearly coaxial, so that they gave nearly the same view at four different times. The imaging system viewed a 4-mm-wide slot above the shocked surface using a powdered yttrium ortho-silicate (YSO) phosphor about 25 mm from the source and isolated from the plutonium region by a beryllium window. The phosphor was deposited directly onto a 120-mm-long fiber-optic plug, which was then directly coupled to a coherent fiber-optic bundle 2.7 m in length. The image passing through the bundle was reduced in size by a fiber-optic taper and connected to a blue-sensitive photocathode framing camera recently built by Bechtel Nevada. Finally, a cooled charge-coupled-device (CCD) camera coupled to the framing camera was used to record the images. The framing camera was fielded in the Zero Room in an environmentally-shielded enclosure. The increased sensitivity and uniformity of field resulting from substituting the coherent bundle for lenses permitted greatly-improved image quality. We also gained valuable experience to allow future, more complex Zero Room experiments with fewer penetrations of the containment wall.

The optical shadowgraphy system was designed around a pair of newly-developed Bechtel Nevada cameras capable of taking four images each. The four images can be gated individually with separate trigger times and intervals down to 50 ns. Light is taken from the Zero Room to the cameras using an optical line of sight, and the readout is done by a Pixel Vision 1,600 × 1,600-element CCD camera. System resolution for static images is about 25 μm over a 2-cm field of view. Although the system was initially intended to work with a ruby-laser backlighter, technical complications during setup dictated the removal of the laser. Consequently the shadowgraphy experiment's emphasis was modified to observe background light and background-light-illuminated ejecta, respectively, with somewhat slower gating of the cameras.

The pins and pyrometers were similar to those described for Rebound, except that the pins served to measure the shock arrival, not the plutonium EOS. Detailed results are not available because the experiment was executed only a few days before this article was written; however, it appears that all of the Physics Division diagnostics returned their data.

Conclusions

We have now completed three subcritical experiments at the NTS. The first two studied the basic EOS of plutonium and the third studied the ejecta produced under specific conditions. All three experiments returned high-quality data. In all three experiments, energy-release measurements showed that there were no neutrons or gamma-rays produced above the level of the background radiation from spontaneous fissions in the plutonium. Given the small plutonium samples involved in the experiments, this is not at all surprising. Other experiments not involving Physics Division personnel were not described in this research highlight, but it is worth noting that DX Division and Sandia researchers fielded optical interferometers to measure spall strength, surface velocity, and total ejecta mass, while researchers from Livermore measured shock releases on Rebound and Stagecoach. Excellent data were obtained on these experiments.

Presently there are no firm plans for further EOS measurements on NTS subcritical experiments. Although more data are needed, the funding situation will not now support another major EOS experiment. Should the need for data persist, we hope to revive the EOS work on JASPER, the plutonium gas gun to be built at NTS. We will continue the ejecta studies begun on Cimarron and also begin to study plutonium spall strength on subsequent subcritical experiments.

References

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