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Small Intercontinental Ballistic Missile (SICBM) Rocket Motor Sympathetic Detonation Study

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ABSTRACT

The Air Force Research Laboratory (AFRL) Propulsion Directorate at Edwards Air Force Base California utilized two surplus Small Intercontinental Ballistic Missile (SICBM) rocket motors in a sympathetic detonation test with a spacing of 15 feet (4.6 meters) between them (typical max spacing in storage bunkers and transport trailers) to gain technical value from assets deemed undesirable for test firing. The Stage 1 SICBM motor containing 19,200 lbs (8709 kg) of detonable Hazard Division (HD) 1.1 propellant was used as the donor motor and the Stage 3 SICBM motor containing 3040 lbs (1379 kg) of the same propellant formulation was used as the acceptor motor in the test. It was assumed that the propellant and rocket motor community would be interested in observing how large the differential can be between detonation by shock-to-detonation transition (SDT) initiation values and by lesser shocks that might occur with operational scenarios of nearby detonation shocks or flight fallbacks. In addition, observation of fragment throw/impact data from modern, carbon composite, case rocket motors could help determine fragment hazards from such events. Such data might provide the modeling and simulation community information that could be coupled to rocket motor hazard codes for predicting rocket motor responses to shock and fragment stimuli. This paper outlines the sympathetic detonation test conducted at AFRL, to observe interactions between a detonating Stage 1 Small ICBM rocket motor and a nearby Stage 3 Small ICBM rocket motor.

INTRODUCTION

Threshold SDT experiments have been conducted with HD 1.1 propellants that are very similar to the formulation used in the SICBM rocket motors. Typical propellant sizes for these experiments have ranged from the 1.44-inch (3.6-cm) diameters of the Large-Scale Gap Test (LSGT) and Naval Ordnance Lab (NOL) card gap test specimens on up to specimens 4.5 inches (11.4-cm) in diameter.

Measurements by Lawrence Livermore National Laboratory (LLNL) have indicated SDT threshold transitions for HD 1.1 propellants in the range of 30 kbar (435,000 psi). However, Delayed Detonation Transition (XDT), a.k.a. Unknown Detonation Transition, can be observed in such propellants with input shocks less than that needed for promoting a SDT. The difference is the time delay before a detonation process begins, following a shock impact event. With SDT, time delays can range from microseconds to at most a few milliseconds. However, with an XDT event, the time delay may range from five to 100 milliseconds or more, with a delay time duration dependent upon the size of the propellant piece being shocked.

XDT outcomes occur at decreasingly lower shock pressures and increasingly greater time delays, as the thickness of the propellant specimen gets larger. Very few XDT events have been observed for highly explosive propellants at ≤ LSGT/NOL diameters. For example, one HD 1.1 propellant formulation exhibited the following response:

- SDT events at NOL card gap test values less than 145 cards
- Zero detonations at 145 cards and
- 25% detonation occurrence by XDT at 175 cards.

However, when tested in 4.5-inch diameter samples, the same propellant detonates by the XDT process at shock input magnitudes much less than those required for SDT. At larger diameters, XDTs and SDTs are distinguished by time delays following the input shocks. When HD 1.1 rocket motors get to substantial operational diameters, XDT events can be triggered by much lower shock magnitudes than for an SDT event.

Reference to the 1997 Graphite Epoxy Motor (GEM) II solid rocket motor fallback events that occurred during a failed space launch of a Delta II launch system may serve as an example. Full 40-inch (1 meter) diameter pieces of GEM II rocket motors and propellant fell back to earth with impact shocks of approximately 3 kbar (about 45,000 psi).

Although the hydroxy-terminated polybutadiene (HTPB) binder rocket propellant was a HD 1.3 material-and at the GEM II motor diameter of 40 inches, detonation of the propellant will not occur at a shock stimulus of 3 kbar-partial energetic yields and violent, ground-cratering explosions did occur.

Assuming somewhat parallel behavior in stimulating violent explosive activity, a HD 1.1 rocket motor of similar diameter could be expected to have a shock threshold even less than for the HD 1.3 rocket motors. Comparing explosive events due to shock impact for HD 1.1 and HD 1.3 propellant filled rocket motors, obviously, does not seem a very good analogy.

The dearth of data involving large size rocket motors has forced estimated and conservative judgments of hazards behavior based on few observations.

Sympathetic detonation events between two detonable HD 1.1 rocket motors can occur by either SDT or XDT. If SDT is triggered by air shock alone, the donor explosive event has to be very close to the sympathetically detonating recipient article, because air shocks of adequate magnitude wane below SDT shock requirements with only a small distance of separation. Since XDT events can be initiated by much lower air shock levels than for SDT events, distances between the donor explosive and recipient explosive article can be substantially further. However, SDT events can be stimulated by fairly distant donor explosive events if the case material or components surrounding the donor explosive forms fragments having an adequate combination of mass and velocity to penetrate deeply into the acceptor explosive material (even if it is surrounded by some container structure). Supersonic metal fragments in small fractions of an inch mean diameter (a few mm) can readily provide shock to detonation requirements in explosive materials that may have explosive critical diameters smaller than 0.1 inches (2.5-mm).

In failed launch fallbacks near the launch site, impact velocities will almost never be adequate to provide the approximate 30 kbar shock needed to provoke a SDT event. Case penetration by sharp objects on the ground at relatively slow, fallback, impact velocities are also unlikely to create concentrated shock adequate to make a SDT happen. XDT events would be the most likely violent responses to ground impacts in launch fallback scenarios and under conditions of strong, flat planar shocks provided by donor explosive air shock combined with non-case-penetrating fragment events.

If there are published descriptions of fragmentation from detonations of large diameter, HD 1.1 rocket motors having lightweight carbon fiber composite cases, they have not been seen by the authors. Since fragment hazards are a major risk from detonating articles, a description of the fragmentation produced by detonation of modern, carbon fiber cased, HD 1.1 large rocket motors should show how fragment risk compares with detonating rocket motors having thick walled composite or metallic cases. A reduced fragment hazard risk in detonations of HD 1.1 articles in thin wall, high strength fiber, composite casing would be expected.

From metallic casings, the higher density fragments would extend lethality out to greater ranges than for fiber composite casings. Extensive damage of the weak resin binder material between fibers could result in very small fragments having throw distances limited by heavy aerodynamic drag losses and minimal mass penetrating power when impacting structural surfaces. Thin composite case walls due to minimal energetic attenuation in detonation shock passage from the inside to the outside of the walls might be expected to promote the probability of a relatively complete shattering of the wall structure.

With fifteen feet between the donor and acceptor rocket motors, air shock was estimated by LLNL as being roughly 1 kbar (about 15,000 psi). This air shock is surely too low to cause a SDT event. In conducting a probable sympathetic detonation event between two explosive HD 1.1 rocket motors having lightweight, carbon fiber composite motor cases spaced fifteen feet (4.5 meters) apart, one of three probable outcomes seems likely:

1. Immediate SDT due to deep fragment penetration from the donor rocket motor.
2. XDT due to the combination of air and non-penetrating fragment surface shocks in a roughly planar fashion.

3. No sympathetic detonation because shock impingements on the acceptor motor were inadequate to stimulate a violent response. A mild fire response might happen if a detonation response did not take place, but motor structure and propellant breakup did occur.

Data intended to be gathered from the sympathetic detonation test were: blast overpressures versus distance, shock pressure pulse at the acceptor motor distance, motor structure fragment pickup recorded with distance from ground zero, high speed fragment size estimation by examining hole sizes produced by impact with 0.03-inch (0.08-cm) thick aluminum fragment screens, and use of video observation to see if any firebrands were made by the event.

BACKGROUND

The Explosives Safety Assessment Team (ESAT) at AFRL had identified anomalies in two SICBM rocket motors stored at AFRL. Upon discussion with AFRL rocket propulsion program managers, engineers and safety personnel, the two motors were selected for removal and destruction by open detonation (OD). The first SICBM motor was a first stage motor containing 19,200 pounds of HD 1.1 propellant. The second SICBM motor was a third stage motor containing 3,040 pounds of HD 1.1 propellant.

The anomalies in both motors consisted of regions of low density within the propellant in the dome regions of both motors. The motor anomalies made these motors less desirable for test firing, but did not present an increase in hazards in terms of storage and transportation. However, because these motors were stored for over fourteen years with no aging studies to assess motor service life and a propensity for other issues, such as plasticizer migration, it was recommended by propellant experts at the motors manufacturer and AFRL, that both motors be transported as short a distance as possible, to a suitable site for open detonation.

The selected detonation site was Test Area 1-36D because it was less than three miles from the storage area, which reduced the overall exposure risk to personnel conducting the disposal operation and personnel in the vicinity. In addition, the OD site location had been previously used for large rocket motor hazards testing and was originally constructed and approved for explosive limits up to 1,000,000 pounds (~453,500 kg) of TNT or equivalent and permitted for testing up to 30,000 pounds (~13,500 kg) of solid propellant without modeling studies.

This area had also been used for especially high-risk tests of rockets, rocket motor components, and propellants hazard testing. In addition, the OD location was accessible from the storage area along a road that services only one active test area. The test pad has earthen barricades protecting instrumentation, electrical and camera equipment and has desert tortoise exclusion fencing in place.

PURPOSE AND OBJECTIVES

The purpose of this test was to produce a sympathetic reaction between two rocket motors spaced at a distance representative of that in a storage bunker. The objectives of this test were to provide experimental data on fragment throw/impact and shock-to-detonation initiation pressures to be compared with theoretical values estimated by LLNL.

DISCUSSION/EXPERIMENTAL

SICBM First Stage:

The first stage SICBM rocket motor was 46 inches (1.2 meters) in diameter, nominally 220 inches (5.6 meters) long, and contained 19,200 pounds of HD 1.1 propellant. The overall weight of the motor was 22,000 pounds (9980 kg). The motor to be used as the donor in the test had no nozzle and was fitted with two steel handling rings weighing approximately 1500 pounds (680 kg) each. The ends of the case had metal closures fitted with desiccant packs. The motor was wrapped in plastic sheet and was supported horizontally in a robust steel cradle by the end rings. The overall weight of the assembly was estimated to be at about 25,900 pounds (~11,750 kg). A photo of the motor and support cradle is shown in Figure 1.

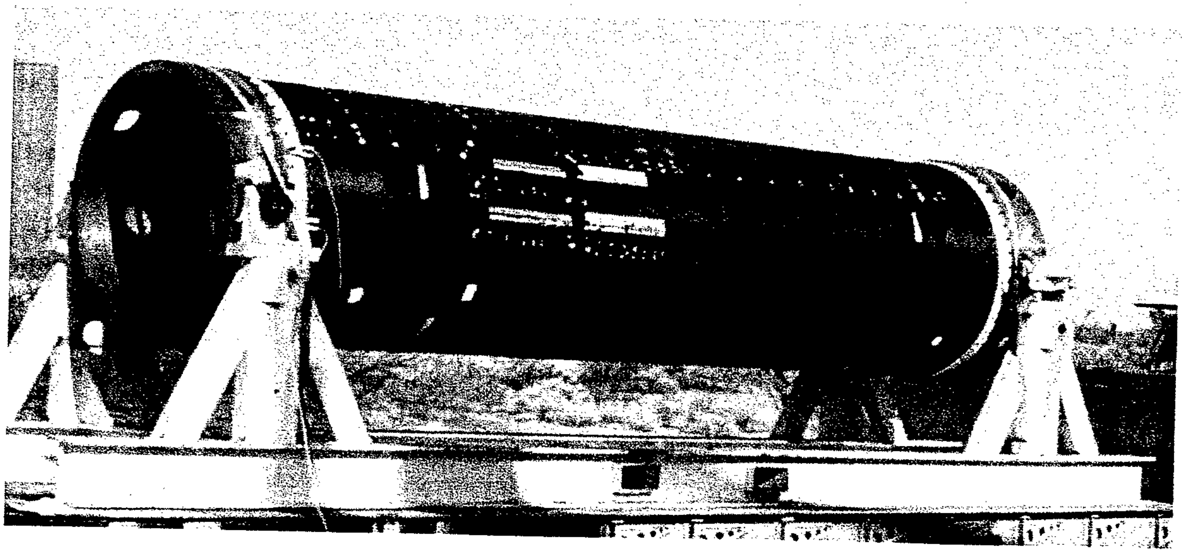

Figure 1. First Stage SICBM Motor Photo

SICBM Third Stage:

The third stage SICBM motor was 46 inches in diameter, 55 inches (1.4 meters) long, weighed 3300 pounds (~1500 kg) and contained 3040 pounds of Class 1.1 propellant. The motor to be used as the acceptor in the test also had no nozzle and was fitted with the same type of handling rings as Stage One. The ends were also fitted with closures and desiccant packs. The third stage motor was placed vertically on a support structure, which served as the base of a storage container. A photo of the motor on its shipping palate is shown in Figure 2.

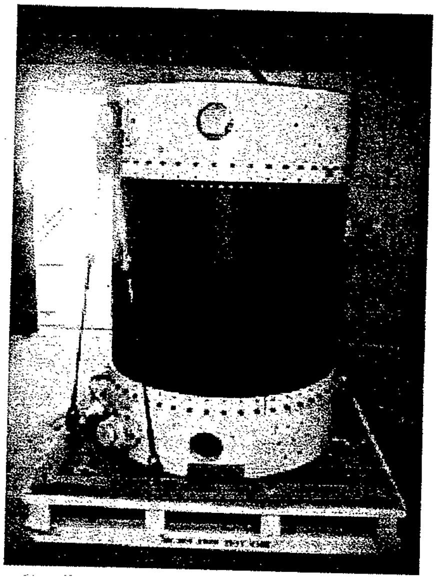

Figure 2. Third Stage SICBM Motor Photo

Polyvinylidene Fluoride (PVF_2) Pressure Gauges

Four polyvinylidene fluoride (PVF_2) gauges were placed on a heavy metal bar approximately 2 inches by 40 inches (5-cm by 101-cm), placed laterally 15 feet from the side surface of the Stage 1 motor and 4 feet above ground level. The PVF_2 gauges spaced the same distance from the donor rocket motor to the acceptor motor would help discern the character of impact insults upon the acceptor motor. Measurement of shocks significantly above 1 kbar would indicate substantial shock contribution by donor motor fragment impacts. These gauges were capable of measuring pressure pulses from about 0.5 to 30 kbar (7500 to 435,113 psi). Location of the PVF_2 gauges is shown in Figure 3.

Overpressure Gauges

A total of six acoustical gauges were placed at distances of 350, 500 and 1000 feet (107, 152 and 305 meters) from Ground Zero. The gauges were capable of measuring up to 50-psi overpressures. The layout of the overpressure gauges is shown in Figure 3.

Fragment Screens

To assess size and size distribution of probable fragments from the Stage 1 motor case, four soft aluminum plates approximately 4 feet by 4 feet (1.2 meters by 1.2 meters) were placed on the opposite side of the donor from the Stage 3 motor. Two were placed 15 feet from Stage 1 approximately 4 feet apart and 2 feet (0.61 meters) above ground level. The other two were placed 50 feet (15 meters) away from the Stage 1 motor approximately 20 feet (6 meters) apart, also 2 feet above ground level. The location of the fragment screens is shown in Figure 3.

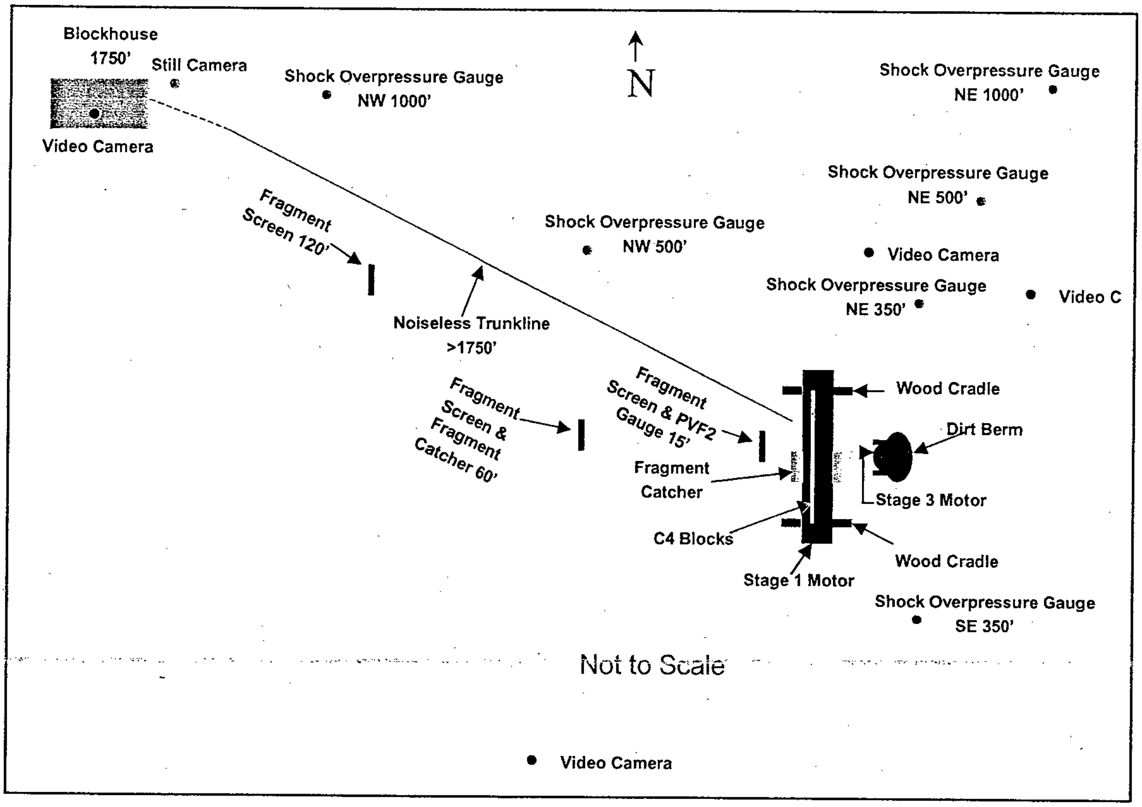

Figure 3. Ground Zero Layout

Fragment Catchers

Two boxes were designed and fabricated to allow the capture of motor fragments. The first box was constructed of wood with the following dimensions: 48 inches wide by 48 inches high by 48 inches deep (1.2 meters by 1.2 meters by 1.2 meters) filled with pumice. This box was located at ground level directly under the Stage one donor motor. The second box was a heavy 1/2-inch (1.3-cm) thick steel box with the following dimensions: 30 inches wide by 48 inches high by 48 inches deep (0.8 meters by 1.2 meters by 1.2 meters) that was originally used as a rocket motor shipping container. This box was filled with 2-in (5-cm) thick Styrofoam panels and was placed 60 feet (18 meters) away (midline) from the Stage one donor motor. The location of the fragment catchers is shown in Figure 3.

Cameras

Standard video cameras were placed in armored boxes at three locations approximately 400 feet (122 meters) from Ground Zero. A single 20 frame-per-second (fps) Photo-Sonics 14S, 70mm high-speed medium format still/sequential camera was placed in an armored box near the blockhouse, approximately 1700 feet (518 meters) from Ground Zero. The location of the cameras is shown in Figure 3.

In addition, a Milliken DBM-5, 16mm high-speed (400 fps) motion picture camera and a Sony Beta Cam video camera were mounted on a tracker unit located approximately 8400 feet (2560 meters) from Ground Zero.

Test Area Preparation

Ground Zero was prepared by filling an existing crater with decomposed granite, and grading and compacting the surface to adequately support the truck and mobile crane used in moving the Stage 1 donor and the Stage 3 acceptor motors into their test positions. A bonded grounding rod was installed near Ground Zero to assure adequate electrical grounding during rocket motor placement and test preparation.

Underground wiring from the overpressure gages was checked for continuity to the Terminal Room. The high-speed amplifiers used to process the signals from the PVF gages were calibrated to validate the measured data. The various cradles, support structures and passive data collection devices were fabricated and certified as necessary.

Predictions

Dr. Ed Lee from LLNL offered the following as a preliminary assessment of the test conditions. "The acceptor motor is within the expansion range of the detonation products where chemical reactions may not be complete. Lacking precise input data air shock calculations would not be credible. The expansion ratio of the product gases as they impact the target motor will have reached a value of between 40 (cylindrical) and 250 (spherical). Since air shock at 15 feet distance will be about 1 kbar, impact of explosive products on the Stage 3 motor would result in average shock pressures much less than 10 kbar (145,000 psi). However, case fragments from the Stage 1 motor will likely impact and penetrate the Stage 3 motor case, producing shock pressures, perhaps, up to 100 kbar (1,450,000 psi) in the propellant across impacting fragment cross sections. Fragment velocities could range up to 4 mm/µs or more. Typically shocks of roughly a minimum of 30 kbar (435,000 psi) are required to cause prompt initiation of explosive Class 1.1 propellant of the SICBM type. However, without precise data on gas expansion at the Stage 3 motor and knowledge of the size of Stage 1 case fragments, it is not possible to provide reliable estimates for shock pressure history and initiation behavior. Shock-to-detonation behavior of the Stage 3 motor is predicted due to fragment impact attack from the Stage 1 motor."

LLNL predicted that the Stage 3 motor would detonate when subjected to the combination of fragments and overpressure from the Stage 1 detonation at a distance of 15 ft. The shock input predicted at the Stage 1 motor propellant surface was >280 kbar (>4Mpsi) and the overpressure predicted at the Stage 3 motor was 1 kbar. What could not be predicted were the size and weights of the fragments coming off the Stage 1 motor, therefore, determining the force of the fragment impacts was not possible.

In discussion with NAWC, China Lake, personnel, it was stated that the minimal shock input needed to cause SDT in a typical HD 1.1 motor was roughly 40 kbar (580,000 psi). Thus, both LLNL and NAWC predictions were that simple air shock in the sympathetic detonation test would not be capable of causing a SDT reaction of the Stage 3 motor. They agreed that the SDT threshold of the acceptor motor could only be exceeded with the combination of fragments and blast overpressure, not with overpressure alone. This is shown graphically in Figure 4.

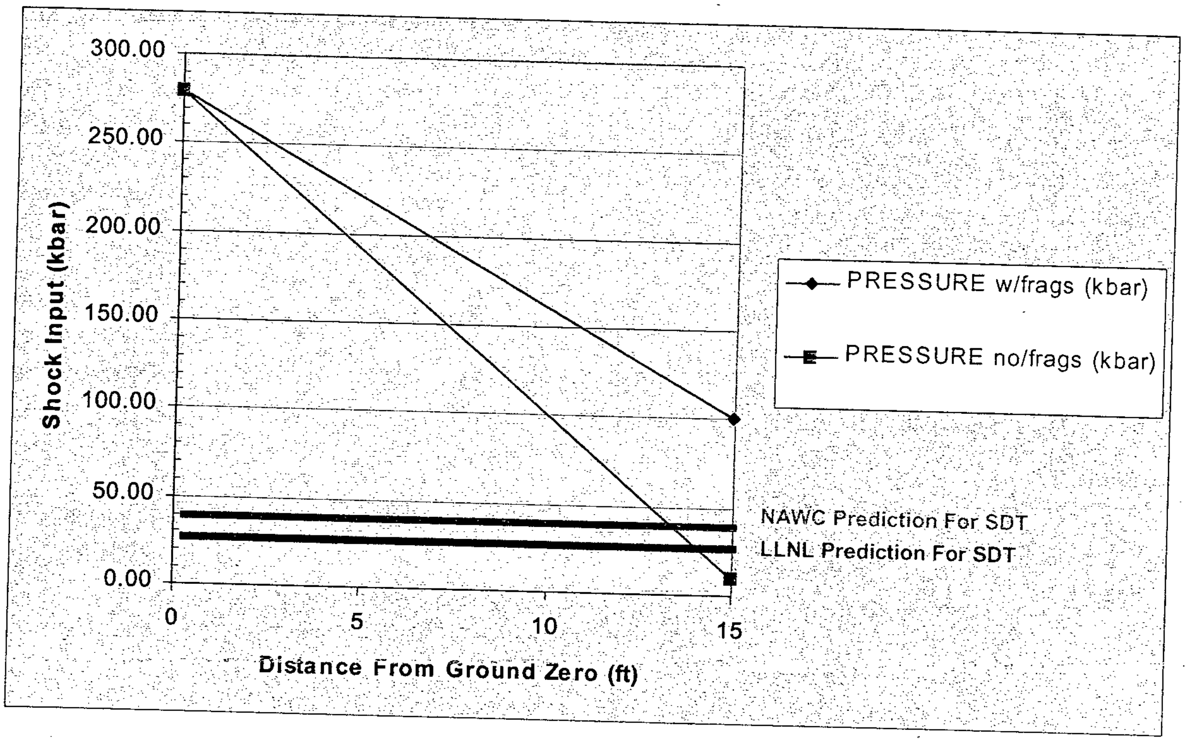

Figure 4. Shock Input vs. Distance From Ground Zero

The TNT air blast equivalency for the sympathetic detonation test was estimated by multiplying the weight of HD 1.1 propellant involved by 1.26. The 1.26 TNT factor was based on past TNT calibration tests conducted at the Air Force Rocket Propulsion Laboratory (now Air Force Research Laboratory). The combined propellant weight of both motors was 22,240 lbs (10,100 kg), when multiplied by 1.26 yielded 28,022 lbs (12,737 kg) of TNT equivalent explosive and assumes a sympathetic detonation.

Prior to the test, overpressures and reflected pressures were calculated for distances from 65 to 10,000 feet (~20 to 3050 meters) using the Low Airshock Computational Formula for Scaled Distances greater than 60 feet (18 meters) shown below. Air shocks at Scaled Distances greater than 5000 feet (1525 meters) were calculated to judge the minimum distance for unprotected observers. This resulted in the minimum allowable distance between the test event and unprotected observers being about 10,000 feet (3050 m).

Scaled Distance = Distance / (Cube Root of TNT Equivalency). The TNT Equivalent Weight = 1.26 (22,240 lbs) = 28,022 lbs.

Formula: $P = 2226.618\,(\text{Scaled Distance})^{-1.4066}$

or

$P = 2226.618\,[\text{Distance} / (\text{TNT Equiv})^{0.333333}]^{-1.4066}$

Reflected Pressure = 2(P)

In addition, Sound Pressure Levels (SPL) were calculated using the measured effective pressure amplitude of the sound wave (P_e) and the reference effective pressure amplitude (P_{ref}).

Formula: $\text{SPL} = 20\log (P_e / P_{ref})$

The values for the pressures and sound levels are shown in are shown in Table 1.

Table 1. Overpressure, Reflected Pressure and Decibel Levels vs. Distance

Distance (ft)	Scaled Distance (ft)	Overpressure (psi)	Reflected Pressure (psi)	Sound Pressure Level (dB)	Sound Pressure Level Reflected (dB)
65	2.14	77.71	155.41	208.56	214.58
350	11.52	7.28	14.56	187.99	194.01
500	16.46	4.41	8.81	183.63	189.65
1,000	32.93	1.66	3.32	175.16	181.18
2,000	65.85	0.63	1.25	166.70	172.72
3,000	98.78	0.35	0.71	161.74	167.76
4,000	131.71	0.24	0.47	158.23	164.25
5,000	164.64	0.17	0.35	155.50	161.52
6,000	197.56	0.13	0.27	153.27	159.29
7,000	230.49	0.11	0.22	151.39	157.41
8,000	263.42	0.09	0.18	149.76	155.78
9,000	296.35	0.08	0.15	148.32	154.34
10,000	329.27	0.07	0.13	147.03	153.05

Pretest Operations

Prior to transporting the SICBM rocket motors, the end closures were removed from both motors and replaced with wood covers to minimize metal fragments. In addition, the massive steel handling rings attached to the ends of both motors would also be removed to minimize metal fragments once the motors were positioned at the test pad.

On 11 Dec 2002, meteorological data showed conditions to be within the Standard Area 1-36D wind restrictions of 5-20 knots and 240-350 degrees direction and favorable forecasts for the following three days. AFRL System Safety and Ground Safety gave the authorization to transport the Stage 3 SICBM rocket motor from the environmentally controlled storage bunker at Area 1-38 to Area 1-36D.

The Stage 3 SICBM rocket motor was transported to Area 1-36D and placed on the pad first. Using the existing top handling ring and appropriate lift fixtures, the motor assembly was lifted by crane high enough above the base to allow removal of the bottom handling ring. The motor was then lifted and placed vertically in its final position, in a wooden structure that would closely cover the back, sides, top and bottom of the motor when assembled.

The exposed side of the Stage 3 motor was placed 15 feet from where the outside of the Stage 1 mid-cylinder section of the motor would be placed. Again, this distance roughly represented the maximum separation normally available in a storage bunker.

With the motor in place, the top handling ring was removed. The wooden box was backfilled, and a berm of dirt was placed around the back of the Stage 3 motor to secure it and inhibit it from moving should it not sympathetically detonate.

With the Stage 3 motor in place, the Stage 1 SICBM motor and the motor/cradle assembly were transported to Ground Zero at Area 1-36D. Using a mobile crane, the existing handling rings, spreader bar and lifting straps, the motor was removed from the cradle and set horizontally on two wooden cradles emplaced at Ground Zero. These cradles placed the bottom of the motor approximately 2 feet above the ground and spaced just inside the handling rings. The steel handling rings (the same as for the Stage 3 motor) were then removed with lifting fixtures.

The Stage 1 SICBM rocket motor was placed with its length oriented in an approximate NNE direction. This orientation placed the existing shock overpressure gage arrays symmetrically about the center of the motor in a South and a Northeast direction (approximately 125 degrees). The layout for Ground Zero is shown in Figure 3.

"Tap" tests of each overpressure gage were conducted to assure that the appropriate signal was being received at the recorder in the blockhouse. Tests were also run on the video recorders and the framing camera to assure they were operating correctly.

Test Operations

The nonelectrical system used to detonate the Stage 1 motor consisted of Dyno Nobel Nonel® Noiseless Trunkline, Ensign-Bickford Primadet® nonelectric delay detonators and M112 Composition C4 block demolition charges triggered by a shot shell primer mechanical initiator.

The noiseless trunkline consists of a small diameter plastic shock tube containing a thin layer of HMX and powdered aluminum. The reaction in the tubing is initiated by the simultaneous combination of heat and shock impact. The reaction is best described as a small dust explosion traveling through the tubing at approximately 5,500 feet per second (1675 meters per second) [1]. The Primadet® nonelectric delay detonator consists of a lead azide and pentaerythritol tetranitrate (PETN) blasting cap with an integral delay assembled onto a shock tube end [1].

The non-electric initiation system was chosen because it is an industry standard and offered the best combinations of safety (non-electric systems cannot be initiated by static electricity, stray current or RF energy), precision, reliability, ease of use and economy. Another advantage was the capability of using the Primadet® detonators to trigger other circuits and the ability to time delay the triggering of circuits.

Also tied into the initiation system were two separate instrumentation trigger blocks, each consisting of a bunch block, Primadet® detonator, 1 or 2 crystal pins and a coil of wire wrapped around the bunch block, which upon detonation of the Primadet®, would break the circuit and start the instrumentation. The first instrumentation trigger block started the framing camera. The second instrumentation trigger block was initiated by a 1.8 sec delay Primadet® detonator, which triggered the LeCroy recorders to collect blast overpressure data from the four PVF_2 gauges located 15 feet from Ground Zero. The 1.8 sec delay allowed the framing camera to be operating at about 20 frames per second when the detonation event occurred.

On 13 December 2002, meteorological data showed conditions to be within the Standard Test Area 1-36D wind restrictions for speed and direction. The countdown was initiated at 1330 Pacific Standard Time. Per the detailed procedures, the Red Crew rolled out approximately 1800 feet (550 meters) of Noiseless Trunkline from the blockhouse to Ground Zero. Next, the C4 block demolition charges were placed end to end on top of the Stage 1 rocket motor along the length of the cylindrical portion of the motor case between the forward and aft skirts. Additional C4 charges were placed on top of the previously placed C4 blocks over most of the length of the motor. The total amount of C4 placed on the donor motor was 26 blocks weighing 32.5 lbs (14.7 kg).

A Primadet® detonator with a 16-ft (5 meter) piece of Noiseless Trunkline was inserted into the instrumentation bunch block. Coming out of the instrumentation bunch block were two Primadet® detonators, each with 1-ft (30-cm) leads. The two Primadet® detonators were then inserted into two of the C4 blocks.

Detonation

The Stage 1 motor was detonated at 1415 PST on 13 December 2002. The detonation was detected by seismograph readings at the California Institute of Technology (CalTech) 60 miles away (96 kilometers). The event registered a magnitude of 1.61 on the Richter scale. A photo of the detonation is shown in Figure 5.

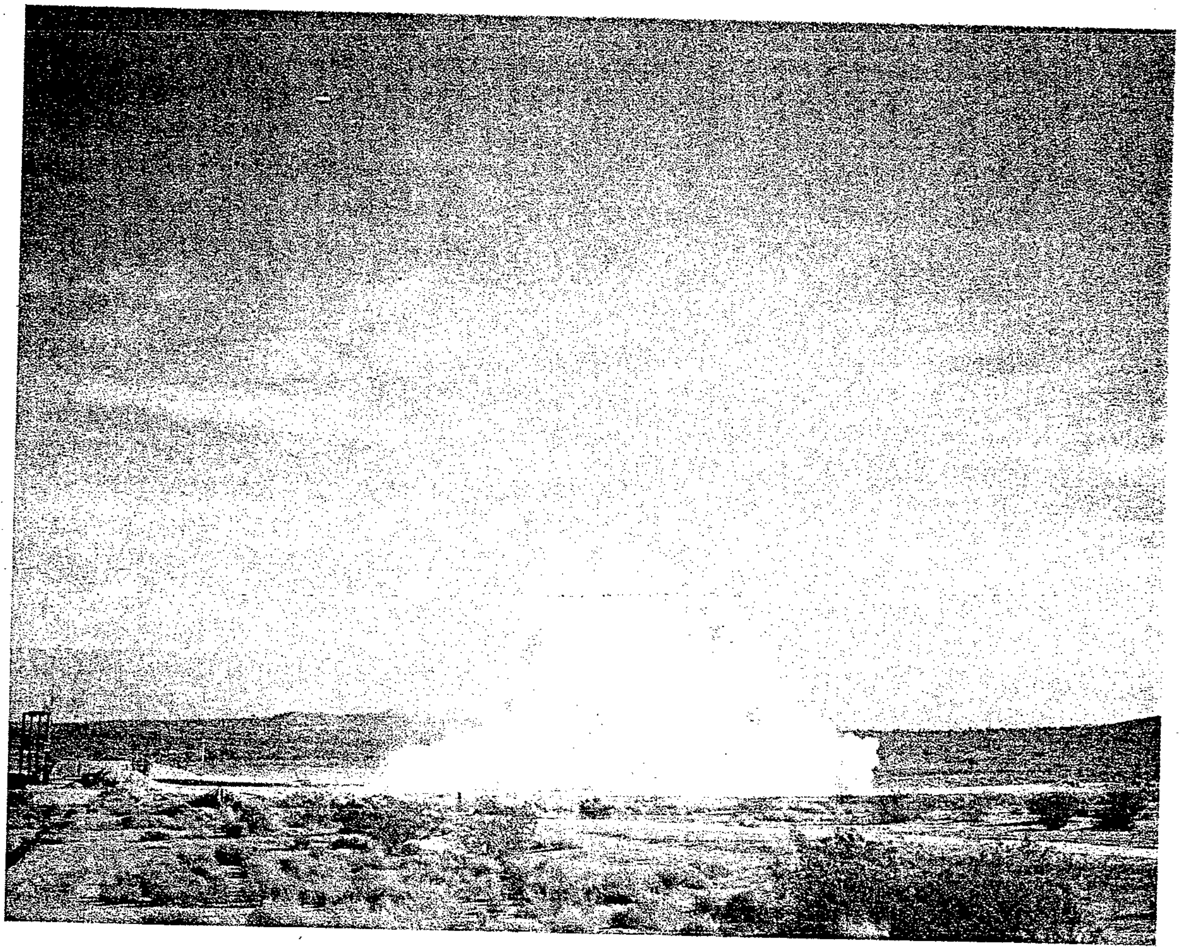

Figure 5. Detonation

The Test Conductor inside the blockhouse reported that the monitors showing the images from the two video cameras nearest to Ground Zero lost their signal immediately after the detonation. Images from the two remaining video cameras (monitored from inside the blockhouse) showed no sign of the Stage 3 motor. No brush fires were observed despite luminous ejecta being expelled out the ends of the Stage 1 motor where the aluminum polar bosses and stage skirts were located. Observers near the camera crew, located approximately 8400 feet away (2560 meters) radioed the blockhouse, stating they also could find no sign of the Stage 3 motor. After waiting the required 1-hour hold period, the Red Crew was dispatched to Ground Zero to check the pad.

RESULTS

Ground Zero Observations

When the Red Crew arrived at ground zero, they found a crater 65 feet (20 meters) across and approximately 15 feet (4.5 meters) deep. The Red Crew verified that the Stage 3 motor was detonated by the Stage 1 acceptor motor detonation.

The only recognizable component of the Stage 3 motor recovered was the solid aluminum forward polar boss found (mostly intact but distorted) in the crater. Pre-detonation, the forward polar boss was facing downward, ½-in (1.3-cm) from the plywood support on which the motor was resting. The post detonation crater at Ground Zero is shown in Figure 6.

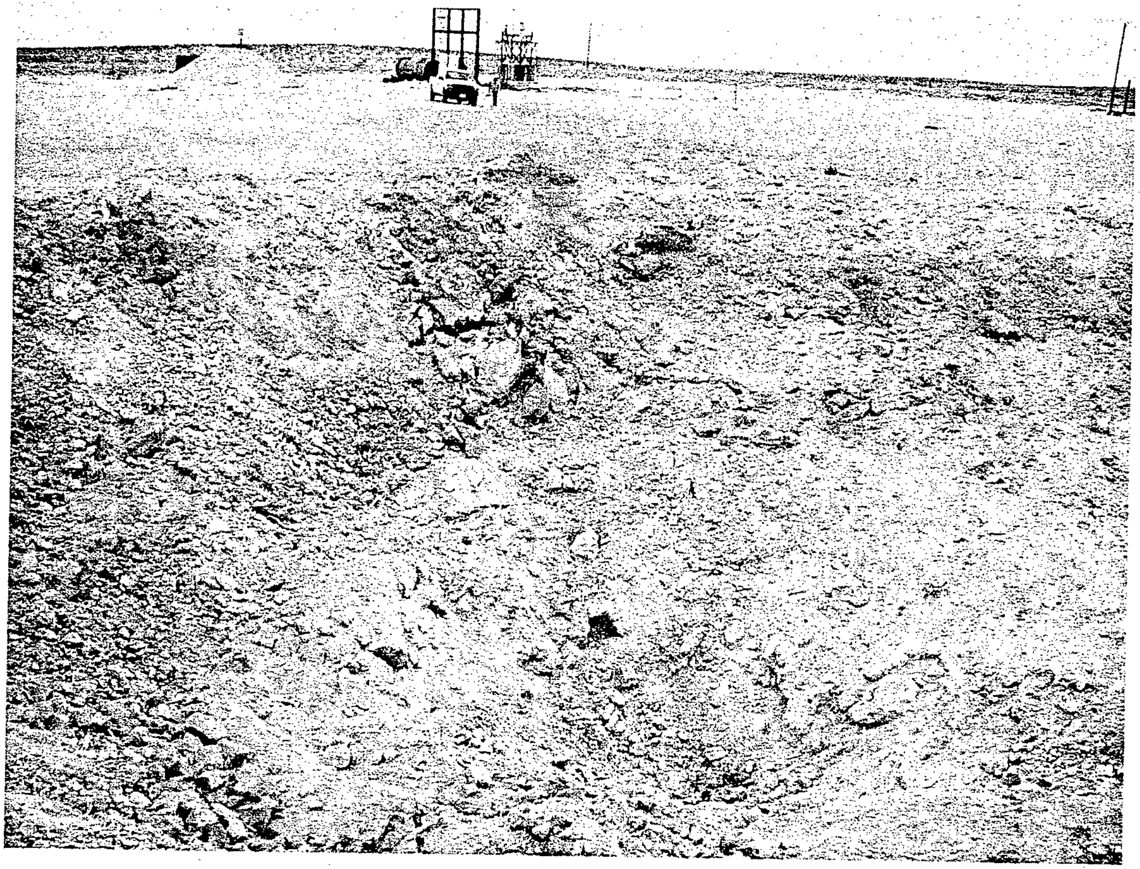

Figure 6. Ground Zero Post-Detonation

The damage at Ground Zero and Pad D was extensive. Surprisingly, the fragment catchers and fragment screens were destroyed by the detonation shock wave, including the ½-inch thick steel plate fragment catcher box located 60 feet (18 meters) from the Stage 1 motor. The five steel plates making up the fragment catcher box were blown apart and one of the plates (the back side) traveled approximately 3700 feet (1125 meters) from Ground Zero.

As mentioned earlier, the two video cameras closest to Ground Zero ((approximately 400 feet (122 meters) from Ground Zero)) were also damaged. The blast-resistant camera housings were exposed to enough overpressure to breach the housings, disabling the two video cameras.

Video, Camera and Motion Picture Observations

The video cameras recorded the events of a typical detonation, including the overall detonation, shockwave, afterburning/air entrainment, dirt entrainment and the rising dirt cloud. However, it was the motion picture and sequential cameras that captured the finer details of the sympathetic detonation, including initiation of the C4 charges, individual detonations of the donor and acceptor motors and the resultant propagating hemispherical air shock bubble.

The 400 frame-per-second motion picture camera captured the Stage 1 motor's forward and aft aluminum polar bosses coming off the motor and burning in the atmosphere. In the video, one can even see the differences in the intensity of the fragmentation and burning of the forward polar boss (more intense) which had propellant next to it and the aft polar boss which did not (less flame/fragments).

The 20 frame-per-second sequential camera captured the detonation image shown in Figure 6. Using the tower as a reference point ((bottom to top of antenna = 50 feet (15 meters)) Figure 6 shows the fireball to be approximately 250 feet wide by 125 feet high (75 meters by 38 meters).

From the sequential camera pictures taken at 50 millisecond intervals, the late appearance of the blast from the Stage 3 SICBM motor (seen in the lower left of the fireball) indicated that an XDT process initiated it. This means that the Stage 3 motor experienced a delayed detonation of, approximately, 20-50 milliseconds after the Stage 1 motor detonation shock arrived at the surface of the Stage 3 motor.

Immediate SDT at the time of arrival of fragments (almost simultaneous with blast shock) coming from the Stage 1 motor was expected. Blast shock coming from the Stage1 SICBM motor was roughly estimated by Drs. Ed Lee and Jack Reaugh of LLNL to be 1 kbar. As stated previously, a 1 kbar shock by itself is considerably lower than the 30 to 40 kbar shocks needed to cause immediate shock-to-detonation of the high energy HD 1.1 propellants. However, case fragment impacts from a large motor detonation typically do cause small area shocks in excess of that needed for immediate shock-to-detonation processes of explosive HD 1.1 solid propellant even at considerable distances from a large motor detonation. Fragments from a detonating rocket motor case can be propelled at speeds up to 10,000 ft/sec (3048 m/sec).

Also stated previously, delayed detonation processes of HD 1.1 propellants have been observed with shocks considerably below SDT, and shock thresholds for XDT occur at lower magnitudes as the diameter of the shocked propellant becomes larger. The SICBM Stage 3 motor diameter of 46 inches makes it the largest size of propellant where an XDT has been observed. Previous XDT experimental measurements conducted by LLNL have been limited to about 4.5 inches diameter.

Precisely how an XDT occurs is not known, but propellant/explosive material fragmentation and friction in a reverberating reflected shock environment have been considered.

Motor cases for the SICBM motors used in the Sympathetic Detonation test were made from state-of-the-art (SOTA) carbon fiber composites. AFRL personnel had not before witnessed what character of fragments would come from a large, detonating, carbon fiber-cased rocket motor. If multiple layers of composite material were produced by the detonation process, they would surely have had adequate mass and consequent impact energy at a distance of 15 feet to penetrate the Stage 3 carbon fiber motor case to produce immediate SDT. However, since an XDT occurred, this indicated that case fragments from the Stage 1 motor hitting the Stage 3 motor were small and lacked enough kinetic energy to easily penetrate the Stage 3 motor case.

Fragment screens were positioned at close distances to the Stage 1 SICBM motor to provide evidence of motor case fragment sizes by the area of the holes produced by fragment penetration. The fragment screens were specified to be 4 ft by 4 ft, 0.03-inch thick (0.08-cm), 1100 alloy aluminum (highly pure aluminum) sheets that would be expected to stretch up to 50% elongation before fracturing. Unexpectedly, the fragment screen shattered into pieces ranging from about 0.5 to 10 inches (1.3 to 24-cm) widths and lengths from the experimental shock. Substitution of a brittle alloy for the aluminum screen sheets is suspected. However, many pieces of fragment screen material were retrieved from the test site.

While many small dents were observed, infrequent small, crisp holes through the aluminum sheet material were observed of sizes less than one-eighth inch width. A few holes measuring greater than ¼-inch wide were discovered with substantial aluminum sheet distortion. These holes can be explained as caused by secondary, slower moving rock fragments picked up by the detonation event. The few carbon case fragments picked up near Ground Zero were very small and typically consisted of only one to two layers of carbon fiber.

Fragment data indicates that the Stage 1 motor cylinder region of the case came apart into low mass fragments that had very limited penetration power upon impingement on the thin aluminum sheet. Since the Stage 3 carbon fiber motor case material should be extremely more resistant to fragment penetration than the aluminum sheet material, fragment penetration into the Stage 3 motor propellant may not have occurred. The accumulative effect of vast numbers of lightweight, spaced out, carbon fiber composite fragments impinging upon the Stage 3 motor surface could produce accumulated shock intermediate between a 1 kbar air shock and the 30 to 40 kbar fragment impact shock needed to produce a SDT. Lack of case penetration in the sympathetically destroyed motor and intermediate shock level might explain why an XDT process was observed for the Stage 3 motor in the test.

Ground Zero Fragment Survey

Due to the destruction of the fragment catchers and screens, an alternate plan was devised to collect the fragment data. The plan called for personnel to search the pad area up to a 400-ft radius from Ground Zero. Markers were placed to outline radii of 100, 200 and 400-ft (30, 60 and 120 meters).

With the markers in place, the crew collected pieces from the aluminum fragment screens, but searched fruitlessly for composite case fragments from the cylindrical area of the Stage 1 motor. Screening of dirt samples at various locations out to 400-ft from the lateral sides of the Stage 1 motor's original position did not find any carbon case fibers.

Composite case fragments from the forward and aft skirt regions (not adjacent to propellant) of the Stage 1 motor were collected. The largest fragment was approximately 8 inches long by 3 inches wide (20-cm by 7.5-cm).

Data From PVF_2 Pressure Gauges

Of the four PVF_2 gauges placed 15 feet from the Stage 1 donor motor and 4 feet above ground level, three of the gauges collected data (Gauge B failed to take readings) and indicated short pressure pulses ranging from 0.57 to 1.43 kbar (8,267 to 20,740 psi). Two of the gauges (C and D) started reading pressure pulses at approximately 1.25 milliseconds; Gauge A started reading at 1.27 milliseconds. The highest reading on Gauge D may have been due to fragment impacts or perhaps a secondary earth fragment. Since pressure values around 1 kbar are at the lower limit for PVF_2 gauge detection, differences in pressure values may have been closer together than indicated. The pressure vs. time plot of the PVF_2 gauge data is shown in Figure 7.

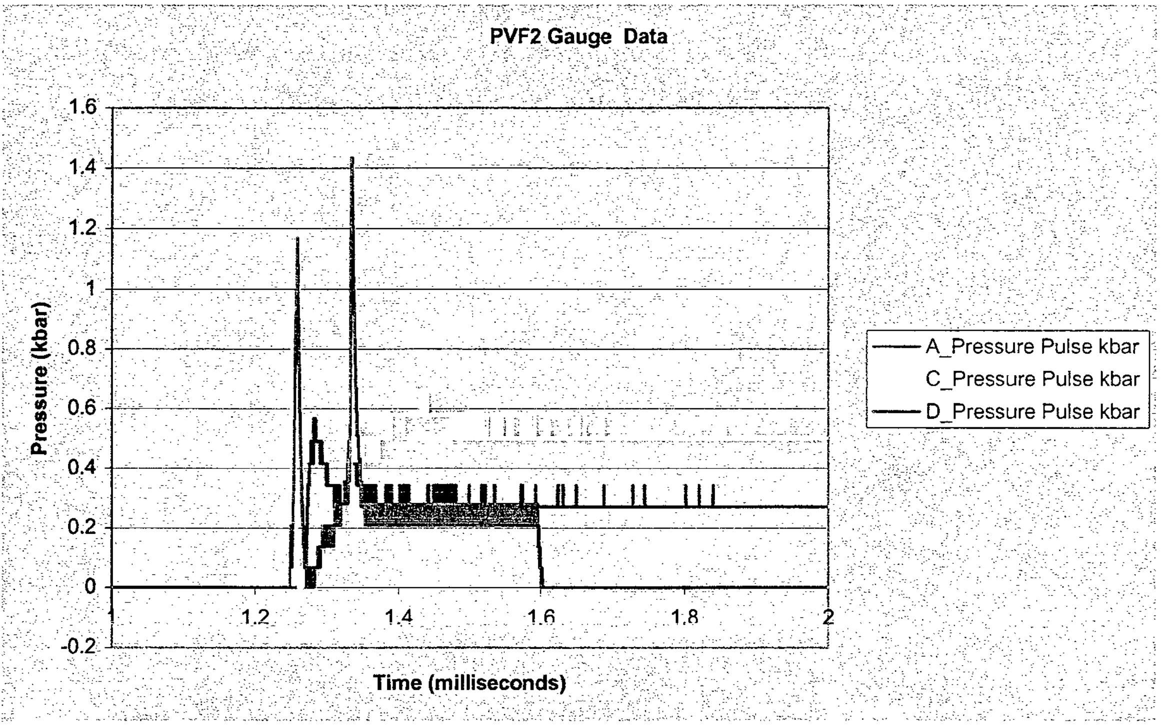

Figure 7. Pressure vs. Time Plot of PVF_2 Gauge Data

Data From Overpressure Gauges

Of the six acoustical gauges placed at distances of 350, 500 and 1000 feet from Ground Zero, five collected data. The maximum overpressure measured at 350 feet from Ground Zero was approximately 7 psi. This value correlated very well with the 7.2 psi overpressure value predicted by the airshock formula. At 500 feet from ground zero, the overpressure dropped to a little over 5 psi, which is close to the airshock formula prediction of 4.4 psi. At 1000 feet the overpressure reading from the one functioning gauge was approximately 0.05 psi. This value was significantly lower than the 1.6 psi airshock formula prediction. The pressure vs. time vs. distance (from Ground Zero) plot of overpressure data is shown in Figure 8.

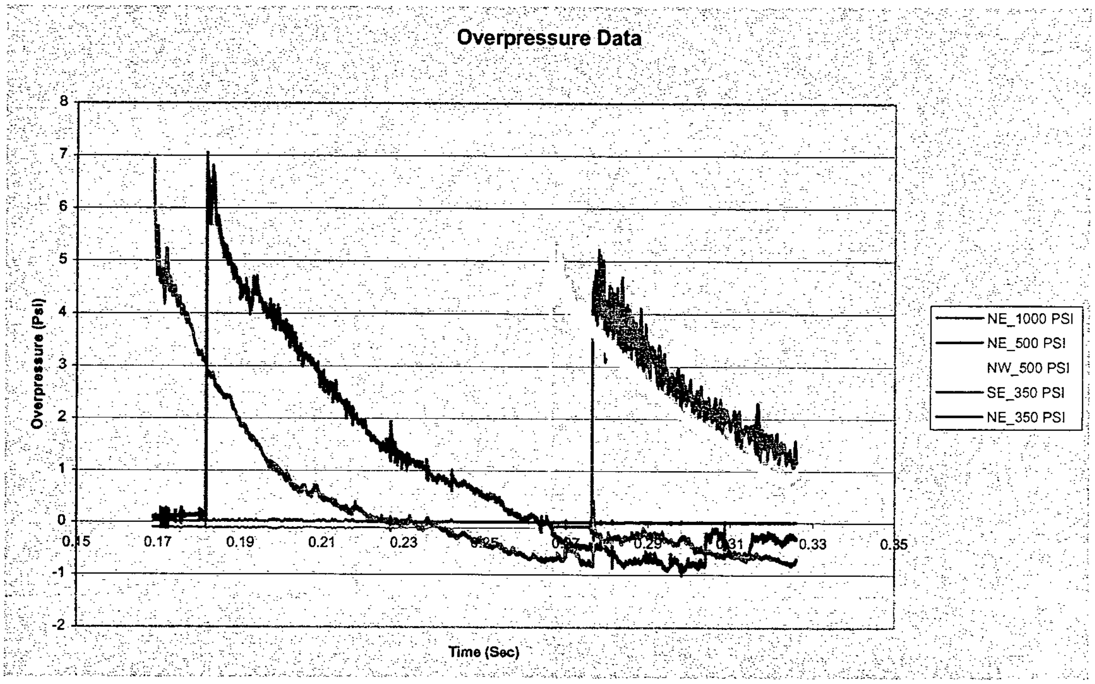

Figure 8. Pressure vs. Time vs. Distance Plot of Overpressure Data

CONCLUSIONS

Sympathetic detonation of the Stage 3 SICBM motor provided surprising results. By photo indication, the violent response of the Stage 3 motor was a delayed detonation, XDT, of about 20 to 50 milliseconds. Pretest expectations were that the Stage 3 motor would detonate by an immediate SDT process triggered by Stage 1, fragment impacts penetrating through the Stage 3 motor case into the solid propellant with adequate energy to produce a SDT event. Also surprising were the shock indications yielded by the PVF_2 gauges. They showed shock magnitudes near 1 kbar, which would only account for the airshock, not the expected shock contribution by donor motor fragment impacts.

Differences between PVF_2 gauge indicated values (e.g., 0.6 and 1.4 kbar) should not be regarded as quantitatively accurate, since such low shock magnitudes are near the lower end of detectability for such gauges. The low indicated shock from the Stage 1 motor at 15 feet distance indicated that fragment impacts from the cylinder part of the Stage 1 motor provided very little added shock above that predicted for air shock alone. Indications from examination of aluminum screen pieces showed that many small dents were produced and exceedingly few crisp penetrations occurred. Aluminum screen data indicated that penetration of the Stage 3 carbon composite motor case by case fragments from the side of the Stage 1 motor was very unlikely, since only marginal penetration of the weaker, thinner 0.030 inch (0.75 mm) thick aluminum took place.

Paul Salzman of TRW years ago postulated that detonable HD 1.1 motors in diameters of about 4 feet (1.2 meters) or more might have a delayed shock-to-detonation threshold as low as 1 kbar or less. Results obtained from the sympathetic detonation test largely corroborate such a view.

People trying to develop insensitive munition rocket motors have known for some time that fiber composite motor cases confer minimal fragment hazards for the motors. The sympathetic detonation test confirms that conclusion. Fragments from the sides of the cylindrical section of the carbon fiber composite-cased SICBM Stage 1 motor provided a much lower physical shock hazard than the air shock produced by the motor detonation. Cracking of the resin matrix between carbon fibers and even brittle subdivision of carbon fibers into short lengths would produce fragments having very low individual kinetic energy, resulting in minimal penetration power such as seen in the sympathetic detonation test. Such an extensive breakup for the thin-walled carbon composite case material adjacent to detonating solid propellant could explain why no readily visible fibers from the sides of the Stage 1 motor could be found.

Even though the Stage 1 composite case fragments impacting the Stage 3 motor were sufficient to cause XDT of the Stage 3 acceptor motor, they are much more benign than steel case fragments. Because composite fragments have minimal penetration power, sympathetic detonations to adjacent rocket motors could be substantially reduced or eliminated by incorporating mitigation measures such as shipping/ storage containers, deflectors and barriers (water, foam or pumice) [2].

REFERENCES

1. Alpha Explosives Safety Training Study Guide. Alpha Explosives 2000.
2. NIMIC Newsletter, 4th Quarter 2002.

ACKNOWLEDGEMENTS

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Small Intercontinental Ballistic Missile (SICBM) Rocket Motor Sympathetic Detonation Study

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31st U.S. Department of Defense Explosives Safety Seminar 24-26 August 2004

Approved for public release; distribution unlimited

Objectives

- Produce a Sympathetic Reaction Between Two Rocket Motors Spaced at a Distance Representative of That in a Storage Bunker
- Generate Composite Case Fragment Throw/impact Data From a Large-scale Rocket Motor Detonation
- Determine If Composite Case Fragments Produce a High Enough Shock Impact to Sympathetically Detonate an Acceptor Motor
    - Spacing is far enough apart such that overpressure alone will not cause a prompt shock-to-detonation (SDT) event

Approach

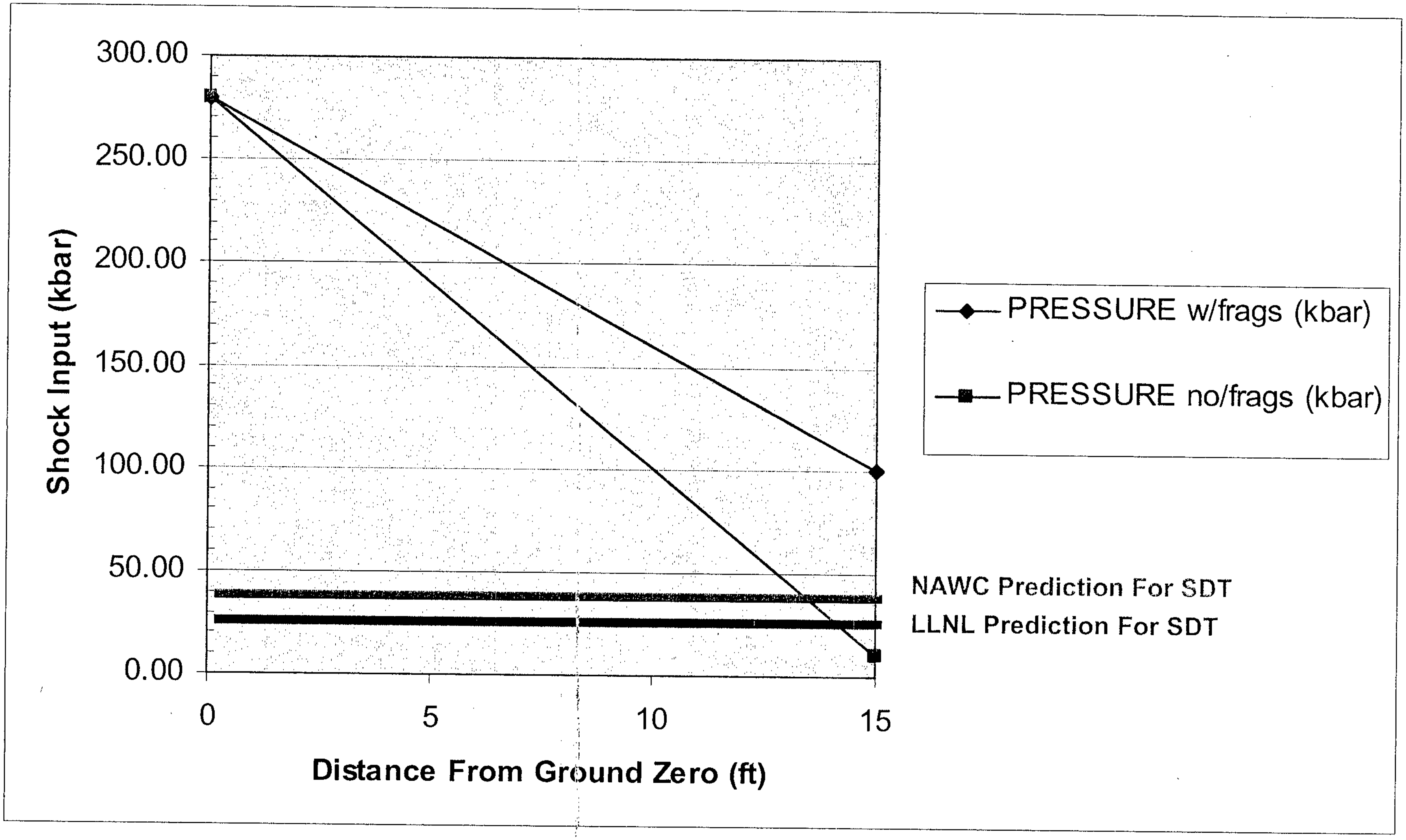
- LLNL Suggested Motor Spacing and Estimated Test Results
  - Detonate a Stage 1 SICBM motor placed 15 ft from a Stage 3 SICBM motor
    - Full-sized large rocket motors containing HD 1.1 propellant represent a worst-case storage and transportation threat scenario
  - Configure test to collect data on blast overpressure and composite case fragment impact overpressure effects

Predictions

- The shock input predicted at the Stage 1 motor propellant surface >280 kbar
- Target motor within the expansion range of the detonation products--air shock calculations not applicable
- 40 kbar shock overpressure needed for SDT, per NAWC telecon
- 30 kbar shock overpressure needed for SDT, per LLNL estimate*
- LLNL estimates 100 kbar on target motor due to case fragments impacting target motor at 15 ft range*

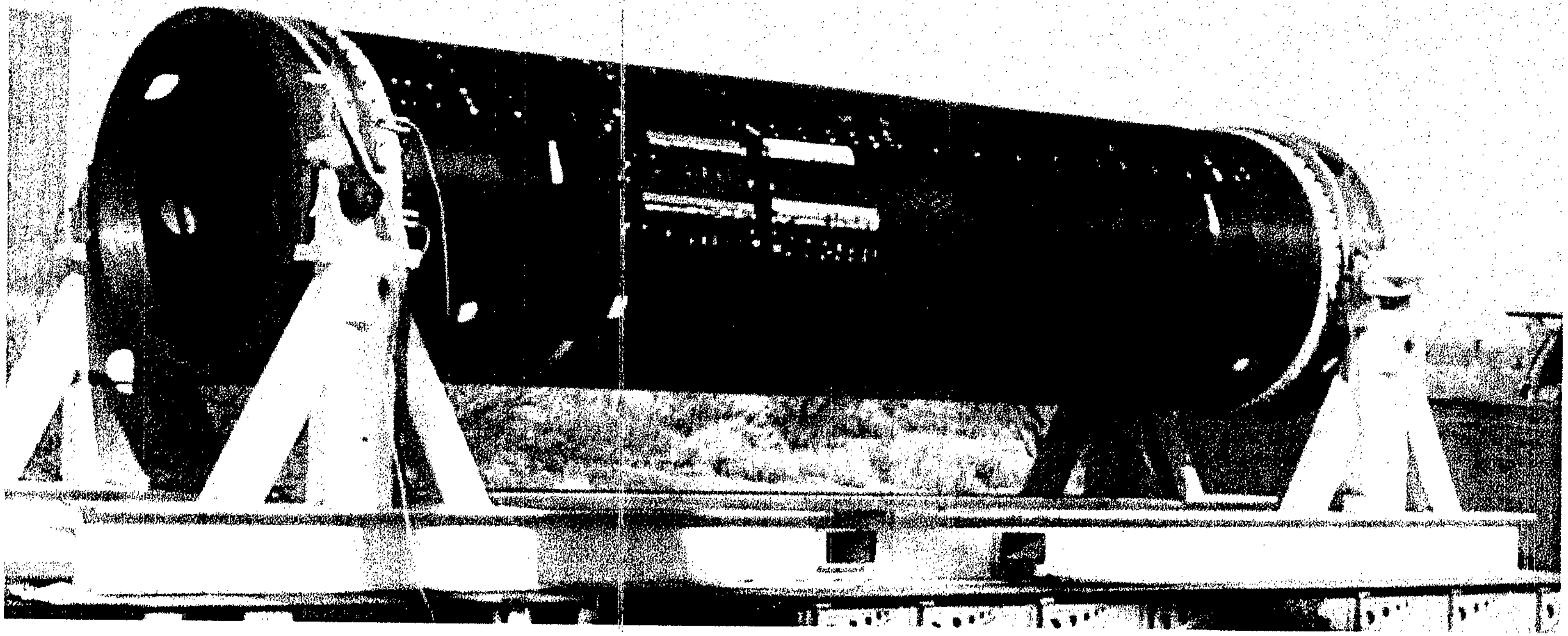
* *However, without hydrodynamic calculations of various possibilities, it is not possible to provide reliable estimates of the pressure history and initiation behavior—Ed Lee, LLNL*

Shock Input Estimates



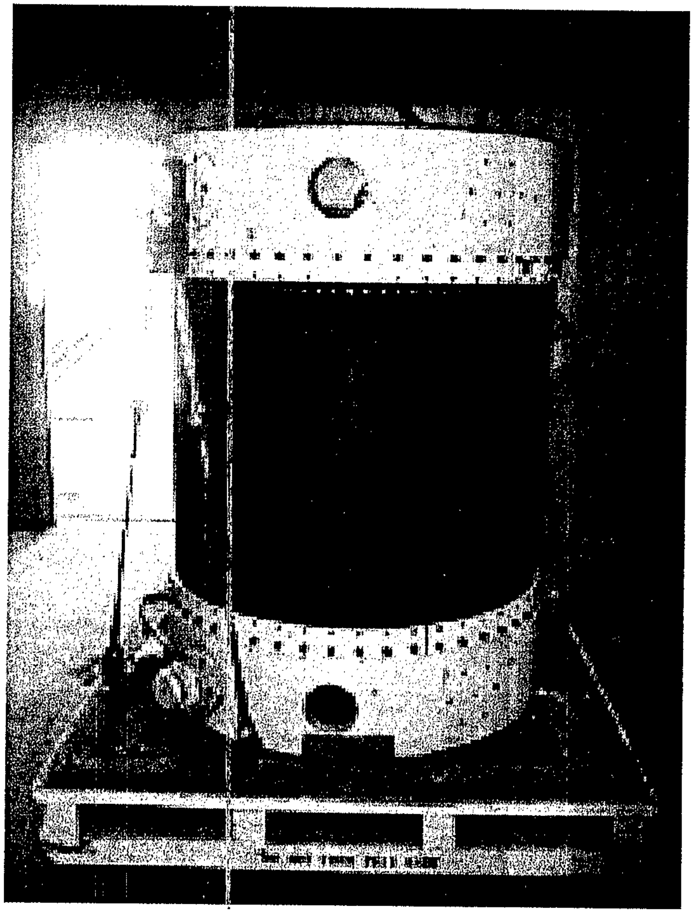
Stage I Small ICBM Motor

- 46 inch diameter, 220 inch long, 22,000 lbs total weight
- 19,200 pounds of Hazard Division (HD) 1.1 propellant



Stage III Small ICBM Motor

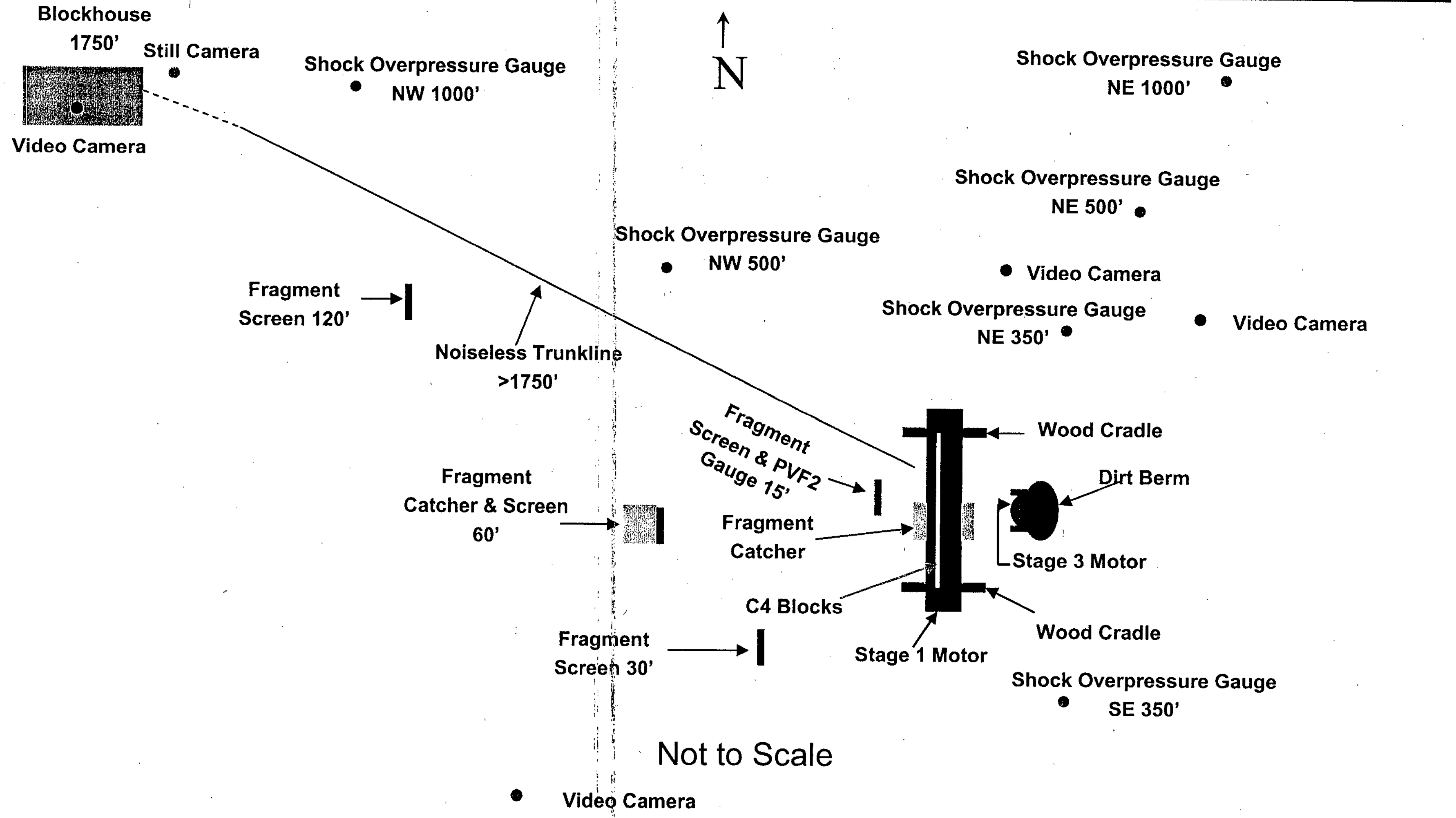
- 46” diameter, 55” long, 3,300 pounds total weight
- 3040 pounds of HD 1.1 propellant



Instrumentation & Control

- **Cameras**
  - Three Video
  - One Still Camera (5-20 fps)
  - Combination (24-400 fps)
  - Site Surveillance and Test Observation/Recording
    - 3 Video cameras
    - 3 VCRs
- **2 LeCroy Recorders**
  - Max Overpressure Sensors
  - 1 LeCroy Trigger Circuit (4 channel)
  - 4 PVF_2 gauges 15-ft from ground zero
    - 2 PVF_2 gauges/LeCroy
- **Datamax Recorder**
  - Blast Overpressure Sensors:
  - 6 Sensors:
    - NE 350^{ft} NE 500^{ft} NE1000^{ft}
    - NW 500^{ft} NW1000^{ft}
    - SE 350^{ft}
- **Manual Control**
  - Video recorders (VCRs)
  - Shot shell primer initiator
    - Triggers Primadets
      - Still Camera
      - LeCroys
      - C4 ignition/detonation
- **Passive Data Collection**
  - Fragment catchers & screens

Test Area 1-36D Ground Zero Layout



Blockhouse
1750'

Still Camera

Video Camera

Shock Overpressure Gauge
NW 1000'

N

Shock Overpressure Gauge
NE 1000'

Shock Overpressure Gauge
NE 500'

Shock Overpressure Gauge
NW 500'

Video Camera

Fragment
Screen 120'

Shock Overpressure Gauge
NE 350'

Video Camera

Noiseless Trunkline
>1750'

Fragment
Screen & PVF2
Gauge 15'

Wood Cradle

Dirt Berm

Fragment
Catcher & Screen
60'

Fragment
Catcher

Stage 3 Motor

C4 Blocks

Wood Cradle

Fragment
Screen 30'

Stage 1 Motor

Shock Overpressure Gauge
SE 350'

Not to Scale

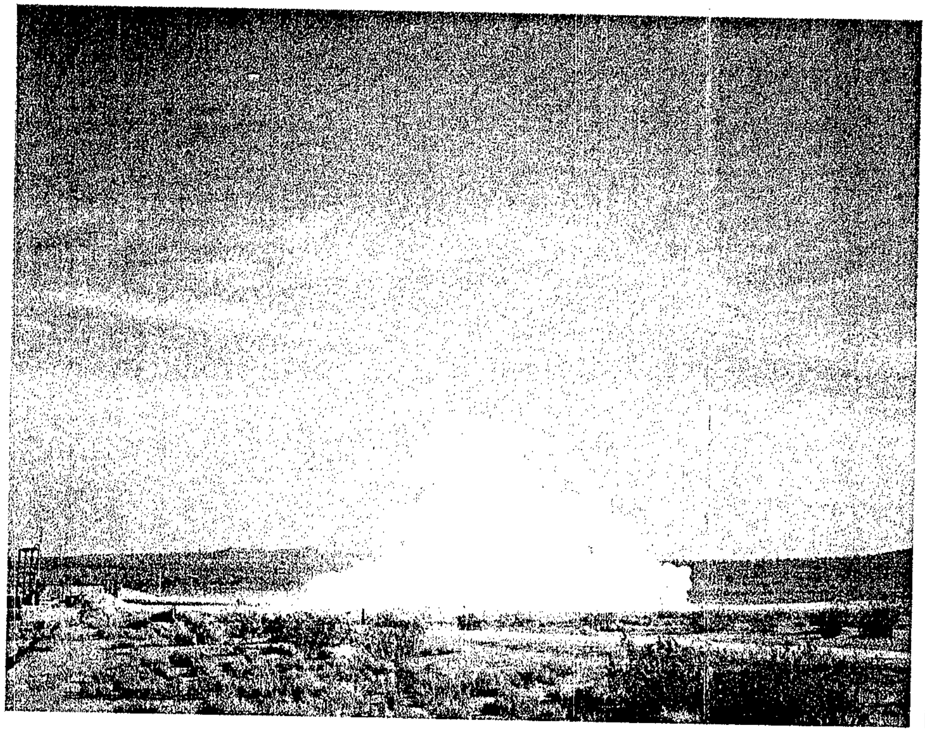
Video Camera

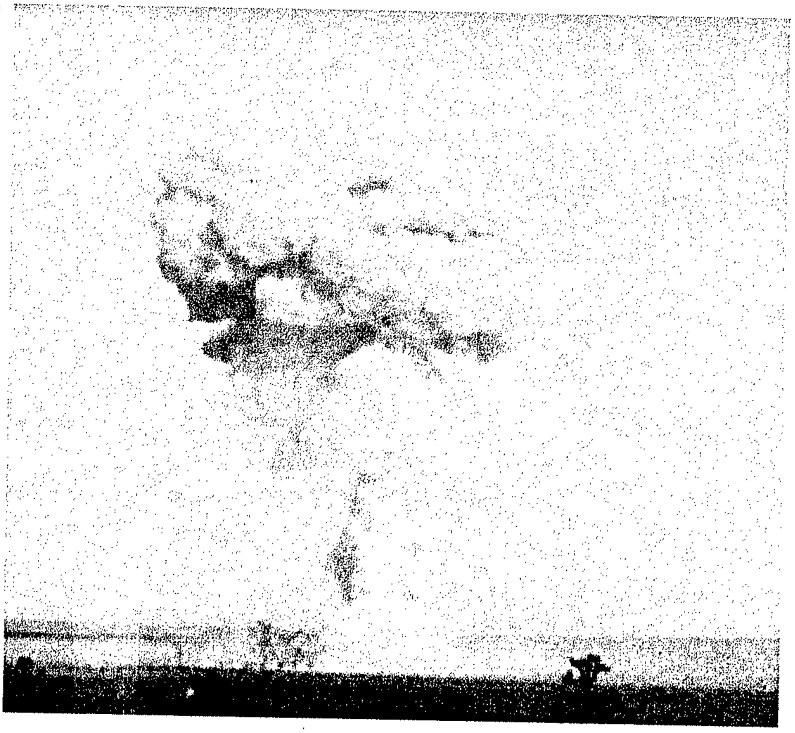
Nonelectrical Initiation System

- Dyno Nobel Nonel® Noiseless Trunkline
  - Small diameter plastic shock tube containing HMX and powdered aluminum
  - Reaction in the tubing is initiated by the simultaneous combination of heat and shock impact
- Ensign-Bickford Primadet® nonelectric delay detonators
  - Lead azide and pentaerythritol tetranitrate (PETN) blasting cap with an integral delay assembled onto shock tube
- M112 Composition C4 block demolition charges
- Triggered by a shot shell primer mechanical initiator
- Non-electric initiation system was chosen because it offered the best combinations of:
  - Safety (non-electric systems cannot be initiated by static electricity, stray current or RF energy)
  - Precision, reliability, ease of use and economy

Detonation

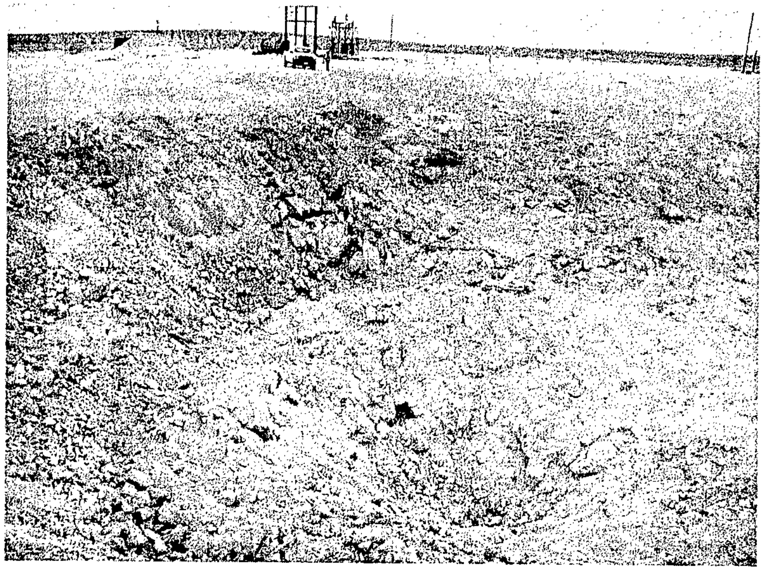
- The TNT Equivalent Weight = 28,022 Lbs
- The Detonation Was Detected in Seismographic Readings From Caltech 60 Miles Away
  - Registered a reading of 1.61 on the Richter scale

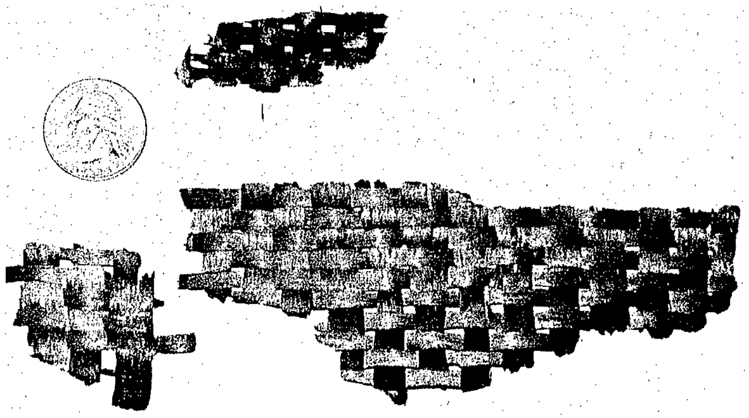




Ground Zero Observations

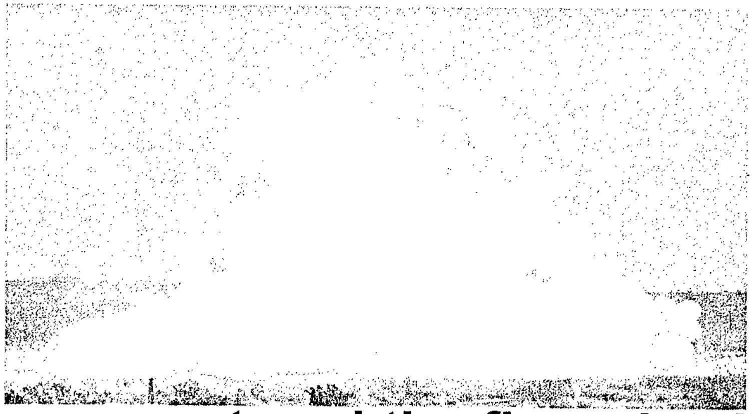
- Detonation Created a Crater 65 Feet Across and Approximately 15 Feet Deep
- The Stage 3 Motor Sympathetically Detonated
- All the Fragment Catchers & Screens Were Destroyed by the Detonation and Shock Wave
- No readily visible case fibers from the sides of the Stage 1 motor could be found
- A layer of carbon fiber weave material from the motor skirt showed a clean separation of the carbon fibers from the composite matrix material





Video, Camera and Motion Picture Observations

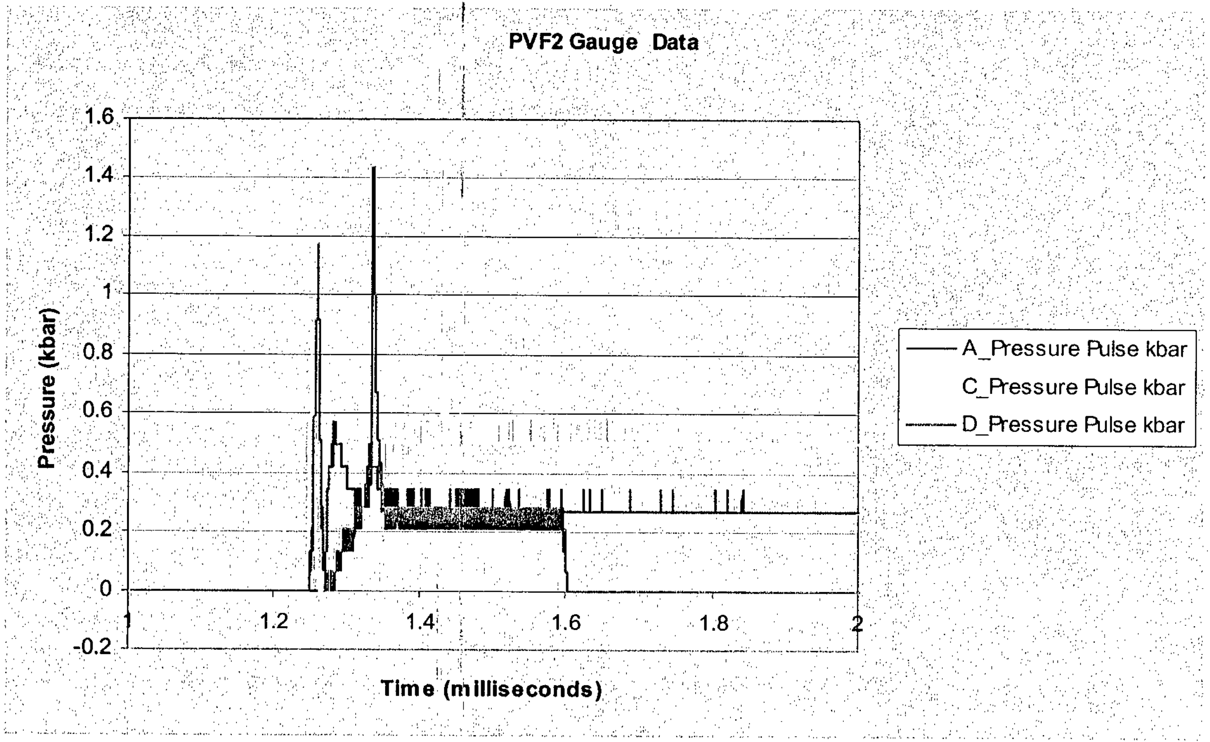
- Video cameras recorded the events of a typical detonation:
  - Overall detonation
  - Shockwave
  - Afterburning/air entrainment
  - Dirt entrainment
  - Rising dirt cloud



- Motion picture and sequential cameras captured the finer details of the sympathetic detonation:
  - Initiation of the C4 charges
  - Individual detonations of the donor and acceptor motors
  - Hemispherical air shock bubble
- Stage 3 motor detonated while the Stage 1 detonation was in the afterburning/air entrainment phase
  - Stage 3 motor experienced XDT (25 - 50 milliseconds)

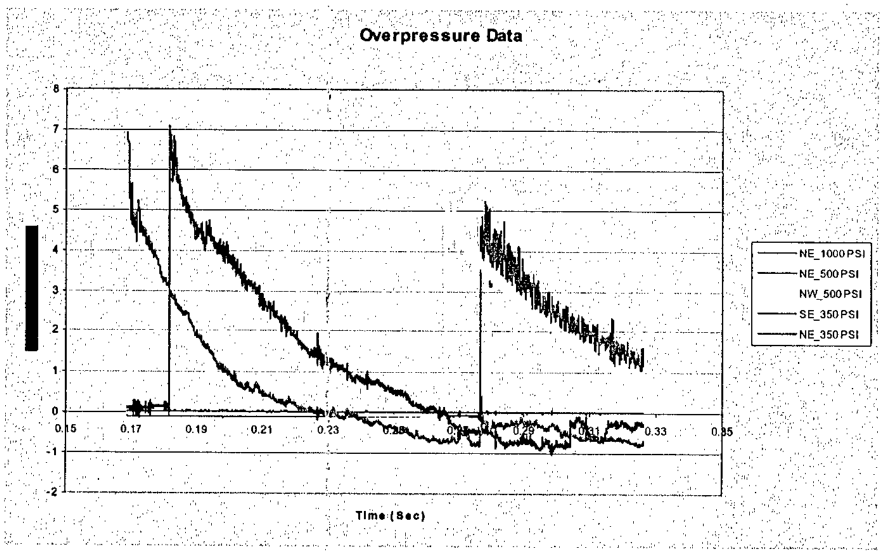
PVF_2 Pressure Pulse Data

- PVF_2 gauge readings at 15 feet from Ground Zero indicated short pressure pulses ranging from 0.57 to 1.43 kbar (8,267 to 20,740 psi)
- Highest reading may have been due to fragment impacts or perhaps a secondary earth fragment



Data From Overpressure Gauges

- **Max overpressure of 7 psi at 350 feet from Ground Zero correlated with the 7.2 psi overpressure value predicted by the airshock formula**
- **At 500 feet, the overpressure dropped to a little over 5 psi, which is close to the airshock formula prediction of 4.4 psi**
- **At 1000 feet the overpressure reading from the one functioning gauge was approximately 0.05 psi, significantly lower than the 1.6 psi airshock formula prediction**



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Conclusions

- Sympathetic detonation of the Stage 3 SICBM motor provided surprising results
  - Stage 3 motor response was an XDT, of about 20 to 50 milliseconds
  - Low shock from the Stage 1 motor at 15 feet indicated that fragment impacts provided very little added shock above predicted air shock
  - Aluminum screen data indicated that penetration of the Stage 3 motor case by Stage 1 motor case fragments was very unlikely
    - Only marginal penetration of the weaker, thinner 0.030 inch (0.75 mm) thick aluminum took place
  - Fragments from the sides of the SICBM Stage 1 motor provided a much lower physical shock hazard than the air shock produced by the motor detonation

Conclusions (cont)

- Destruction of the composite resin matrix between carbon fibers and breakup of carbon fibers would produce fragments having very low individual kinetic energy
  - This would result in minimal penetration power such as seen in the sympathetic detonation test
  - Such an extensive breakup of the case material adjacent to detonating solid propellant could explain why no readily visible fibers from the sides of the Stage 1 motor could be found
- Lightweight, composite case fragments provide a very benign hazard condition compared to that exhibited by metal case fragments
  - Fragment hazards could be substantially reduced by :
    - shipping/storage containers
    - Deflectors and barriers (water, foam or pumice)