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AND OTHER
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1. (BMO 81-296) "Protective Vertical Shelters" by Ian Narain, A.M. ASCE, Jerry Stepheno, A.M. ASCE, and Gary Landon, A.M. ASCE.

2. (BMO 82-020) "Dynamic Cylinder Test Program" by Jerry Stephens, A.M. ASCE.

3. (AFCMD/82-018) "Blast and Shock Field Test Management" by Michael Noble.

4. (AFCMD/82-014) "A Comparison of Nuclear Simulation Techniques on Generic MX Structures" by John Betz.

5. (AFCMD/82-013) "Finite Element Dynamic Analysis of the DCT-2 Models" by Barry Bingham.

6. (AFCMD/82-017) "MX Basing Development Derived From H. E. Testing" by Donald Cole.

7. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Experimental Program" by J. I. Daniel and D. M. Schultz.

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9. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Instrumentation and Load Control" by N. W. Hanson and J. T. Julien.

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11. (BMO 82-003) "Small-Scale Tests of MX Vertical Shelter Structures" by J. K. Gran, J. R. Bruce, and J. D. Colton.

12. (BMO 82-001) "Determination of Soil Properties Through Ground Motion Analysis" by John Frye and Norman Lipner.

13. (BMO 82-062) "Instrumentation for Protective Structures Testing" by Joe Quintana.

14. (BMO 82-105) "1/5 Size VHS Series Blast and Shock Simulations" by Michael Noble.

15. (BMO 82-126) "The Use of Physical Models in Development of the MX Protective Shelter" by Eugene Sevin.

*16. REJECTED: (BMO 82-029) "Survey of Experimental Work on the Dynamic Behavior of Concrete Structures in the USSR" by Leonid Millstein and Gajanen Sabnis.

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1/5 SIZE VHS SERIES BLAST AND SHOCK SIMULATIONS

By Michael L. Noble[1]

INTRODUCTION

A high explosive test series was conducted in 1981 to evaluate the respective performance of simulation techniques for Blast and Shock environments. Two tests were conducted on a 1/5 size Verifiable Horizontal Shelter (VHS) in the Multiple Protective Shelter (MPS) configuration. The purpose of the 1/5 size tests was to compare the effectiveness of a Shaped High Explosive Simulation Technique (HEST) to the Dynamic Airblast (DABS) technique for Blast and Shock effects simulation through the response of the test structure before proceeding to the first full size test on an MX prototype horizontal shelter. The nuclear airblast simulation environment was produced in the D-1 test through the DABS technique in which, the dynamic blast interacted with the target's geometry. The resultant pressure loads were reproduced by a multipressure-zoned HEST in the SH-1 test. A HEST characteristically produces a waveform without the physics that occur due to diffracted and reflected shocks. The simulation objective of the 1/5 VHS test series was to demonstrate the capability of a High Explosive Simulation Technique (HEST) simulator to adequately duplicate the test structure's input loads. This paper will highlight the simulation aspects of the 1/5 VHS test series. The discussion will focus primarily on the comparisons of the two simulator's loading waveforms.

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BACKGROUND

Defense requirements for the simulation of nuclear weapons effects were recognized when the Limited Nuclear Test Ban Treaty was signed in the fall of 1963. Specifically, the Nuclear Hardness and Survivability (NH&S) criteria and assessment tasks were initiated in designing and testing military structures to withstand severe nuclear environments. Development of Blast and Shock simulation techniques for testing defense structures ensued. The Air Force Weapons Laboratory (AFWL) has maintained an ongoing research and development program to meet the NH&S needs of present and future defense systems. In the absence of nuclear blast effects data to determine a system's response, simulation tests using conventional explosives are performed. Two of the most successful for simulating nuclear airblast effects are the Dynamic Airblast Simulator (DABS) and the High Explosive Simulation Technique (HEST).

DABS

The DABS is basically a large expendable shock tube. The explosive driver chamber contains an explosive charge array placed against the rear wall of either steel plate or concrete. The driver's chamber is lined with a steel plate to minimize the amount of debris thrown into the shock-induced flow by the explosion. Upon explosive driver initiation the hot gases flow down the tube forming a shock wave in the air of the tunnel. The tunnel section confines the shock wave. The wave propagates down the tube to the target section where the test structural model is subjected to the specified waveform. A tube runout section is normally required past the target to prevent the post shock rarefactions from limiting the simulation time of the air shock's positive phase. A DABS can be constructed in several cross-sectional configurations, preferably, either a full circle or hemicylinder tube.[1]

HEST

The typical HEST consists of explosives arranged within a planar cavity of air or foam which is confined by soil overburden. The target section (structure) is placed in the ground, either surface flush at the bottom face of the cavity or buried in the test bed. The explosive array can be initiated either simultaneously or sequentially. Initiation in the vertical direction will produce a near-instantaneous spike while horizontal initiation will produce a sweeping wave. Either can be tuned to achieve the appropriate loading signature required on the test structure. Also, the distribution of explosives within the cavity can be varied for the specified pressure profile loading effect. The overburden covering the explosion cavity serves as a tamping agent to contain the high-pressure gases created by the explosives and to tailor the simulation time of the experiment. A HEST can be constructed in any size or pattern necessary to obtain the desired simulation.[1]

Originally conceived, the HEST was not thought to be useful for test articles sensitive to dynamic pressure loads associated with the flow behind a nuclear shock front. However, the 1/5 VHS test series work has shown not only the feasibility but the application of using the blast overpressure from a specially designed HEST to approximate the dynamic and reflected shock loading on above ground structures. If the structural loads are known for a particular dynamic airblast environment, either from calculations or from previous experiments, a HEST can be designed to reproduce those loads. The nuclear airblast simulator used in the SH-1 test was a recently developed variation of the High Explosive Simulation Technique (HEST) which has been used in the past. The variation, called "Shaped-HEST," presumes knowledge of the airblast waveform which is to be applied in several regions on and about the target structure.

HEST simulators possess a distinct cost advantage over other nuclear airblast simulation techniques such as, free-air conventional explosives or the Dynamic Airblast Simulator (DABS). HEST is at least an order of magnitude cheaper than these other methods, but one must be willing to accept the dominant nonsimulation effects. A HEST is designed to generate nuclear shock-front overpressures without the dynamic winds normally associated with shock propagation. Therefore, it is not possible to use the HEST in examining the shock flow phenomenology of shock interactions with structures. Once again, if through previous tests or calculations, the dynamic airblast loading can be specified, then the HEST may be used to simulate this loading just as though it was an incident overpressure. The airblast waveforms, which were applied in designing the multizone SH-1 test, were established using data from the D-1 test's loads and earlier DABS developmental tests.

TEST SERIES CRITERIA

The Blast and Shock environment was formulated to be consistent with the NH&S validation objectives for a one-on-two surface burst attack on a shelter spacing of 1585 m (5200 ft). The airblast loading objective at the structure closure (door) was 3 MPa from a 24 KT surface burst, equivalent to a 3 MT yield at full scale. The test structure was located at a 50 degree aspect angle to the airblast which is consistent with an attack scenario for the MPS basing geometry. D-1 pretest analysis projected that the region of the first Stragegic Arms Limitation Talks (SALT) verification port had the highest susceptibility for deformation. As a result, both simulators and testbed designs focused on providing the longest simulation at that point. Simulation time for the events corresponded to the projected time span required to achieve peak ovaling response at the first SALT port location. This criteria set the simulation time at 16 ms. The first ground shock relief effects originate at each simulator's boundaries. The first SALT port, located near the center of the testbeds, is the last to receive these relief effects. The SH-1 simulator size was chosen on the basis of shear wave propagation velocities, a dominant factor in non-simulation relief wave interactions.[2]

TEST SERIES OBJECTIVES

The test series was planned to yield data required to meet the following composite objectives: (1) Determine location, distribution, magnitude and duration of loads on a generic MX horizontal shelter design; (2) Evaluate localized effects on loading and response due to the incorporated baseline structural details. The details incorporated in the test article are: two SALT verification ports, a closure transition area with a hinge mass region, and the cylinder with a single rebar cage and steel liner; (3) Evaluate analytical techniques for hardness design procedures; (4) Evaluate a Shaped-HEST as a technically viable alternate simulator to the DABS technique. The fourth objective is the thrust of this paper.[2]

TEST CONSTRUCTION

D-1 Simulator Facility

The D-1 DABS facility, shown in Figure 1, is the largest of its type to date. The facility was constructed using commercially available double-corrugated metal arch sections to achieve a span of 17.4 m, a rise of 7.72 m and a length of 60 m. The driver end of the facility was closed off by a cast-in-place reinforced concrete wall 0.6 m thick. To prevent the explosives from cratering and injecting debris into the flow, a steel plate covered a concrete floorpad extending over the entire width of the facility and to a downstream range of 6.1 m. Additionally, a 0.3 m thick layer of concrete was cast over the steel arch to a range of 6.0 m.

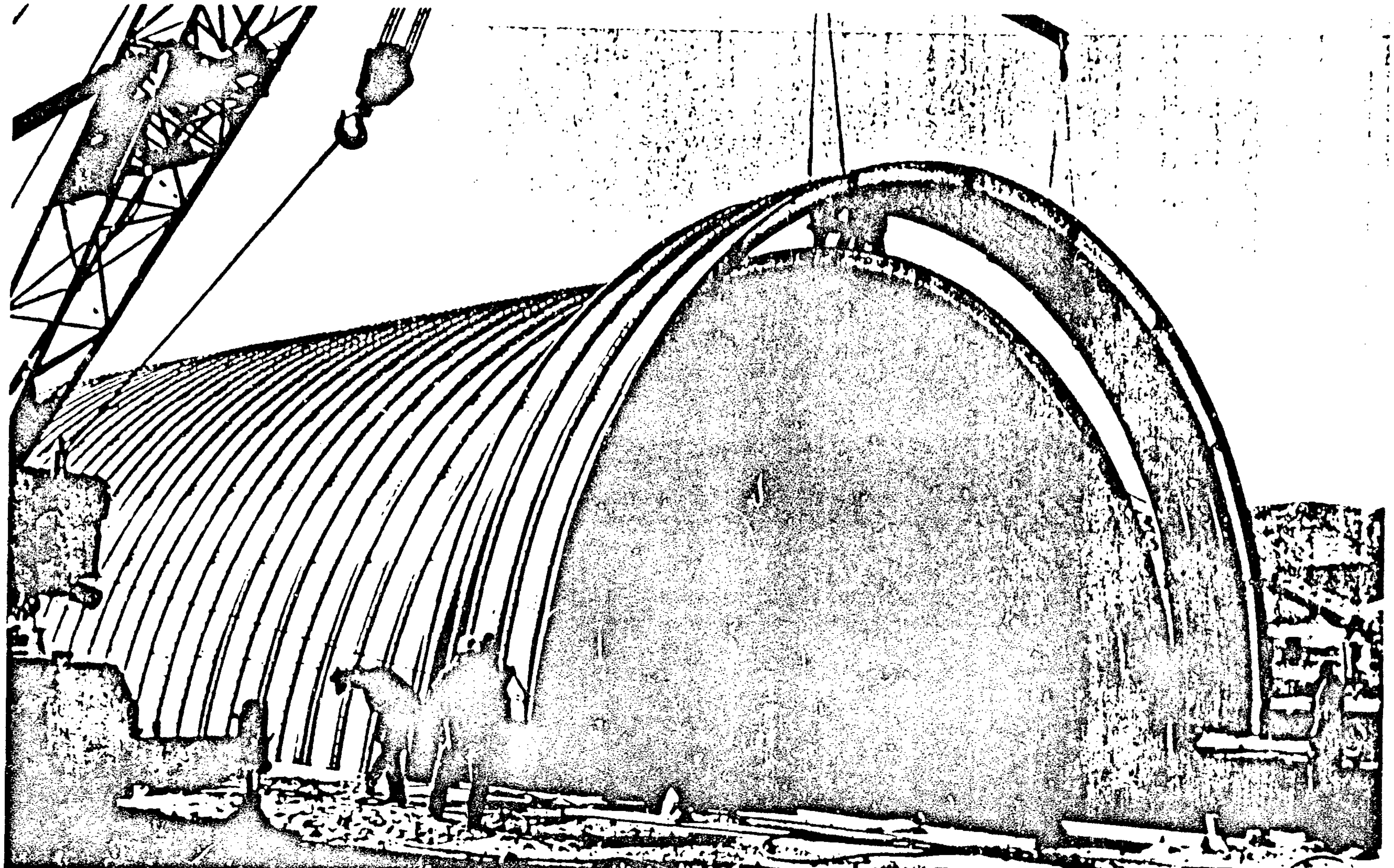


Figure 1. D-1 DASS Facility

The D-1 explosive charge consisted of Iretol 30T27-C blocks, a castable TNT-sensitized AN (ammonium-nitrate) slurry explosive. The blocks were uniformly distributed over the endwall of the DABS facility (Figure 2). Each block weighed approximately 20 kg and was initiated by a Pentolite booster and by a length of detonating cord. The charge array was initiated simultaneously by a three-dimensional array of 54-grain detonating cord which branched out from two initiation points in front of the explosives to achieve a near simultaneous detonation of each charge. Redundancy in the detonating cord array was provided to insure reliability of initiation. Unconsolidated soil overburden was placed over the arch and outside the concrete endwall. This overburden was designed to provide confinement during the 16 ms simulation time, but also to allow the entire facility to blow out and away from the testbed after completion of the simulation (t_s>100 ms). To facilitate this process of facility expansion and overburden dispersal, the base of the arch was attached to a concrete footing to provide lateral restraint and to provide a hinge for rotation. Additionally, a minimum of 1 m overburden depth was placed over the crown with increasing depths progressing down the side to provide maximum velocity near the top and to cause rotation of the arch and overburden around the hinge at the base. Typical behavior of the simulator facility is for most of the overburden and arch materials to be thrown clear of the testbed. The arch and overburden did not disperse as well as desired, but this had no effect on the overall simulator performance.[3]

SH-1 Simulator Facility

The SH-1 simulator was constructed with polystyrene beaded foam, cord type explosives and soil overburden. The testbed's planar dimensions were 26.5 m by 25.6 m. The foam for the SH-1 test had a density of .016 gms/cm^3 (1.0 lbs/ft^3)

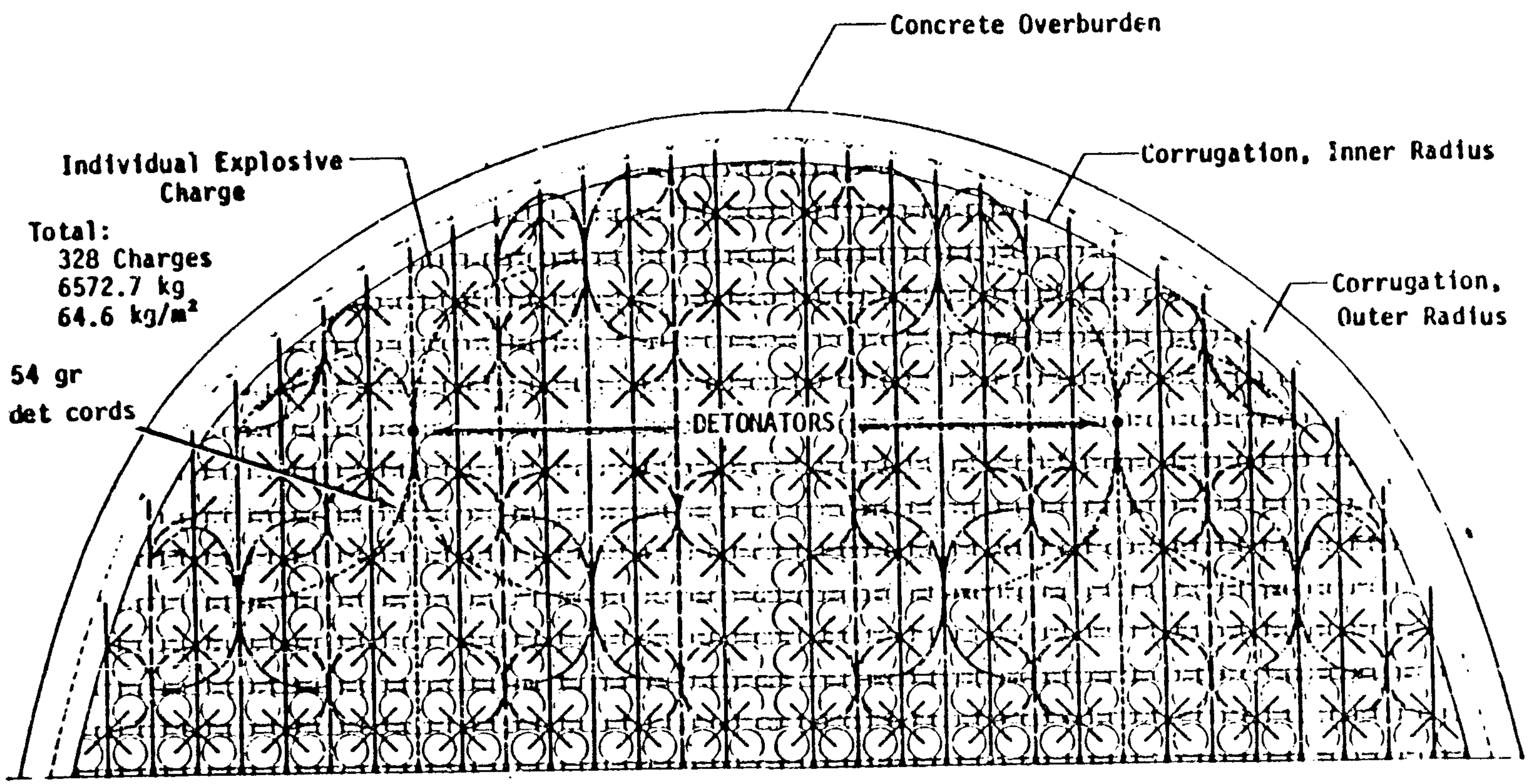


Figure 2. D-1 DABS explosive charge with detonating cord initiation system.

while the 1.3 m native soil overburden had a nominal dry density of 1.76 gms/cm^3 (110 lbs/ft^3). The test used a 100% foam structure to form each HEST cavity zone. This construction structure provides for both the maintenance of the proper explosive charge dimensions and for supporting the overburden. Figure 3 shows a testbed detail of the SH-1 simulator during construction. The explosive charge was constructed using 400-grain PETN detonating cord. Zones 1, 2, 3 and 4 were preassembled and placed on the testbed. Zones 8-1, 8-2, 5 and 6 were fabricated in place as shown in Figure 3. The major zones' primary timing system was through edge timing with the tie-zone concept for interior zones. The tie zones interconnect splices, used to ensure timing continuity across zones 8-1, 8-2, 5 and 6, were preassembled and placed on the testbed prior to assembly of the major zones. The tie-zones' foam panels were grooved to accept both the primary detonating cord and the redundant firing system.[4]

The SH-1 simulator consisted of eight separate representative HEST zones (Figure 4), each with a specific peak overpressure and airblast waveform. Each zone has the same environment in terms of peak pressure and decay over its entire area, with the exception of zone 4. Zones 8-1 and 8-2, both identical in design, were intended to simulate the free field airblast from a 24 KT nuclear explosion at the 3 MPa overpressure range through the use of the Brode nuclear equation. Zone 4, located along the headwall and closure of the test structure, contained the low pressure and high pressure cavity designed to produce the flow-resultant double peak waveform. All the nearfield zones were designed to produce a specified overpressure and waveform defined in D-1 loads data. Each sloped region on the D-1 testbed had a different pressure time history resulting from the dynamic component of the flow.[4]

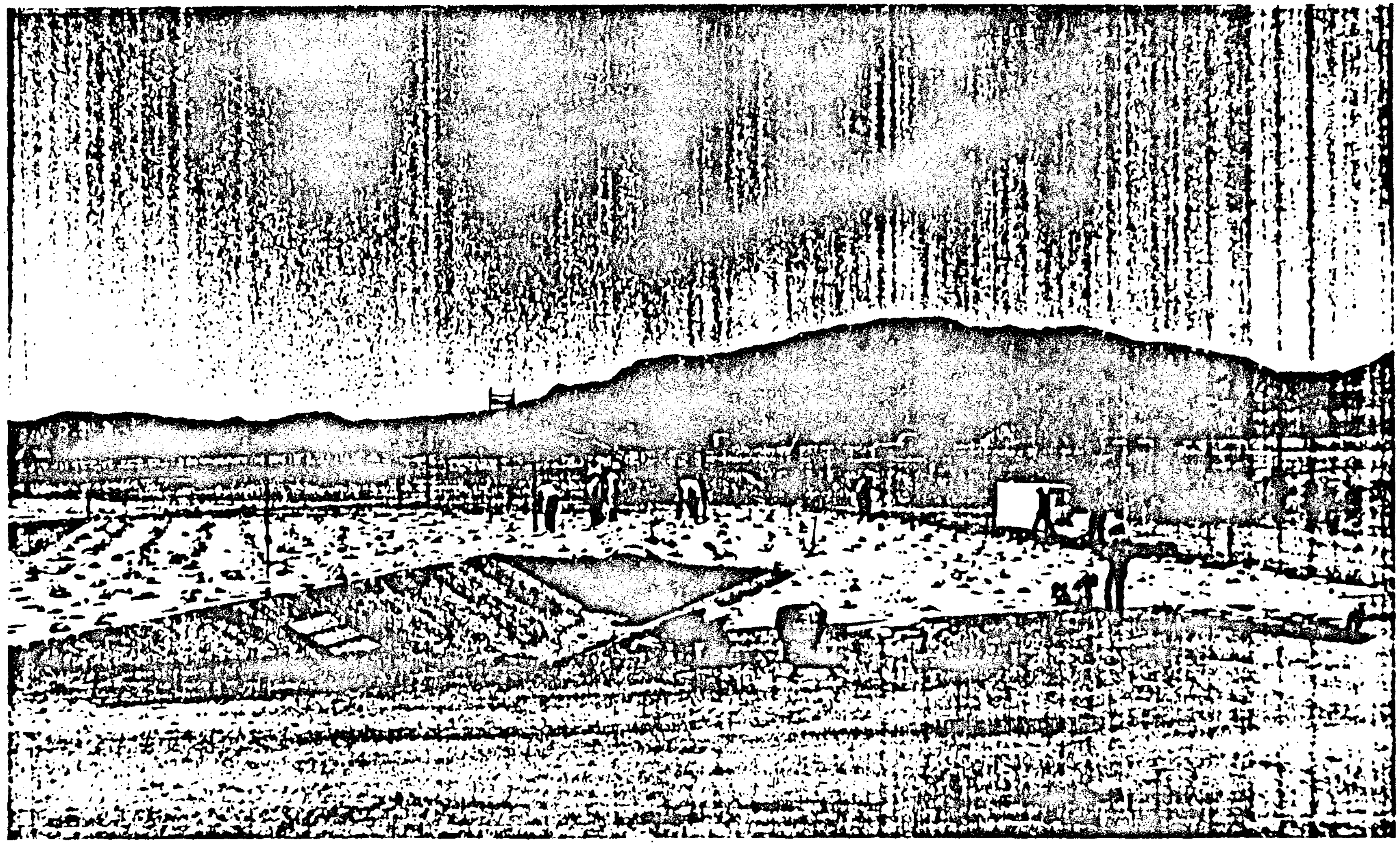
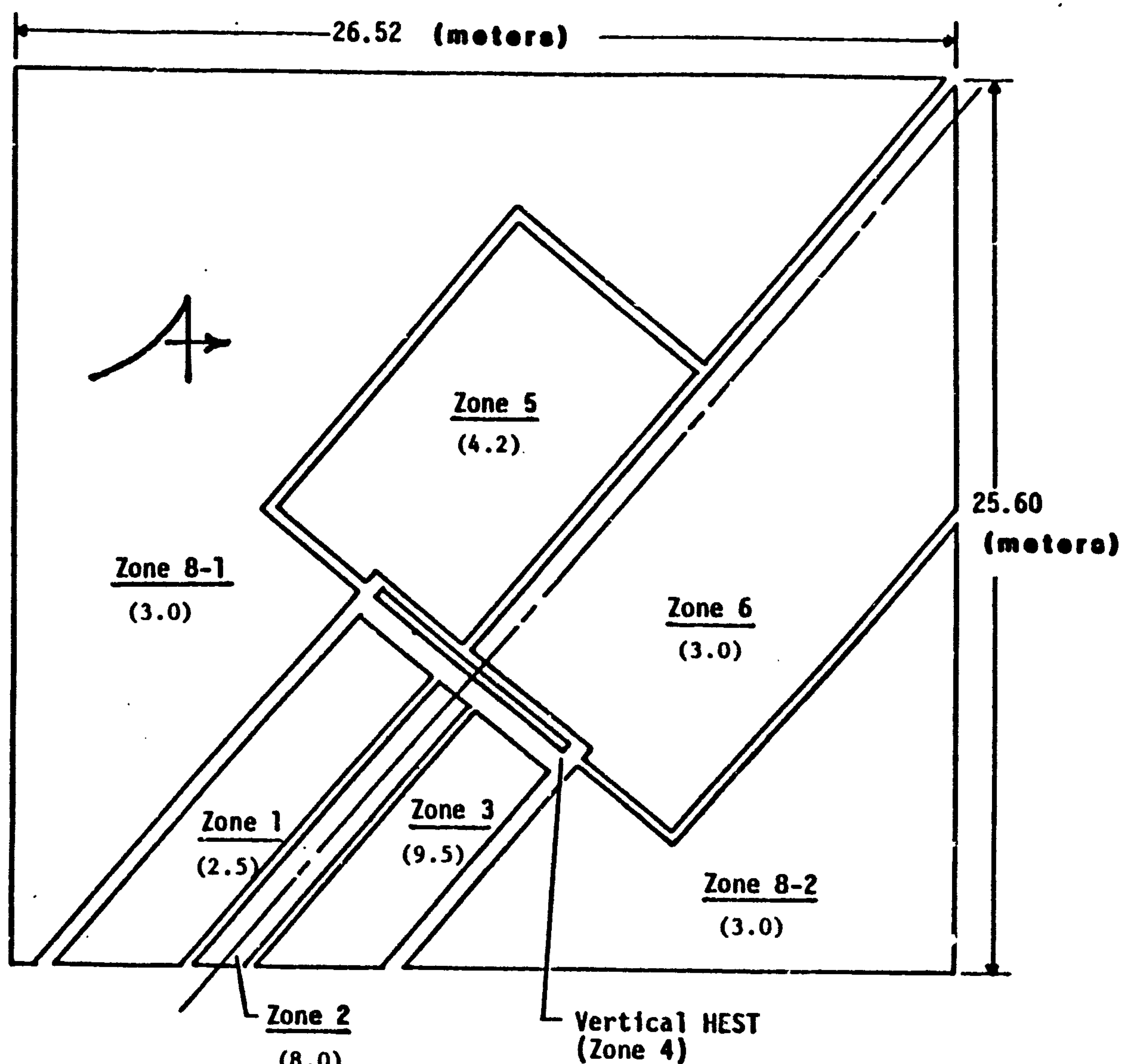


Figure 3. SH-1 Testbed.



( )Overpressure design in MPa

Figure 4. SH-1 testbed plan view.

SIMULATOR INSTRUMENTATION

The instrumentation fielded to assess the airblast simulation consisted of piezoelectric crystals, blast pressure gages, and photopoles. The crystals measured time of arrival (TOA) of the blast wave at various simulator locations for determining the velocity and planarity. Blast pressure gages were installed both direct and side-on to the blast wave to measure the overpressure waveforms at various locations across each testbed. Locations of near field and structural gages were essentially the same for both tests. A comparison of diagnostic (pressure) gage locations between D-1 and SH-1 is shown in Figure 5. The photopoles in SH-1 served to provide impulse histories for each zone. The velocities of these poles when combined with the density and thickness of the overburden are indicative of the impulse in each HEST zone and provide a means of assessing the HEST cavity performance.

AIRBLAST EFFECTS

The D-1 test provided the baseline data for the test series airblast effects associated with the shelter's configuration. The MPS configuration geometry had significant affects upon the nominal 3 MPa targeted overpressure environment. Primary differential loading factors were the 50 degree aspect angle, the shelter's berm exposure, the driveway cut and the headwall profile.

Headwall Shock Dynamics

The shock front reached the entry point into the driveway ramp prior to reaching the structure's closure. The blast began to move down the ramp, across the driveway and up the opposite side. Upon impact with the ramp on the opposite side, a reflected shock was generated and moved along that side ramp towards the structure.

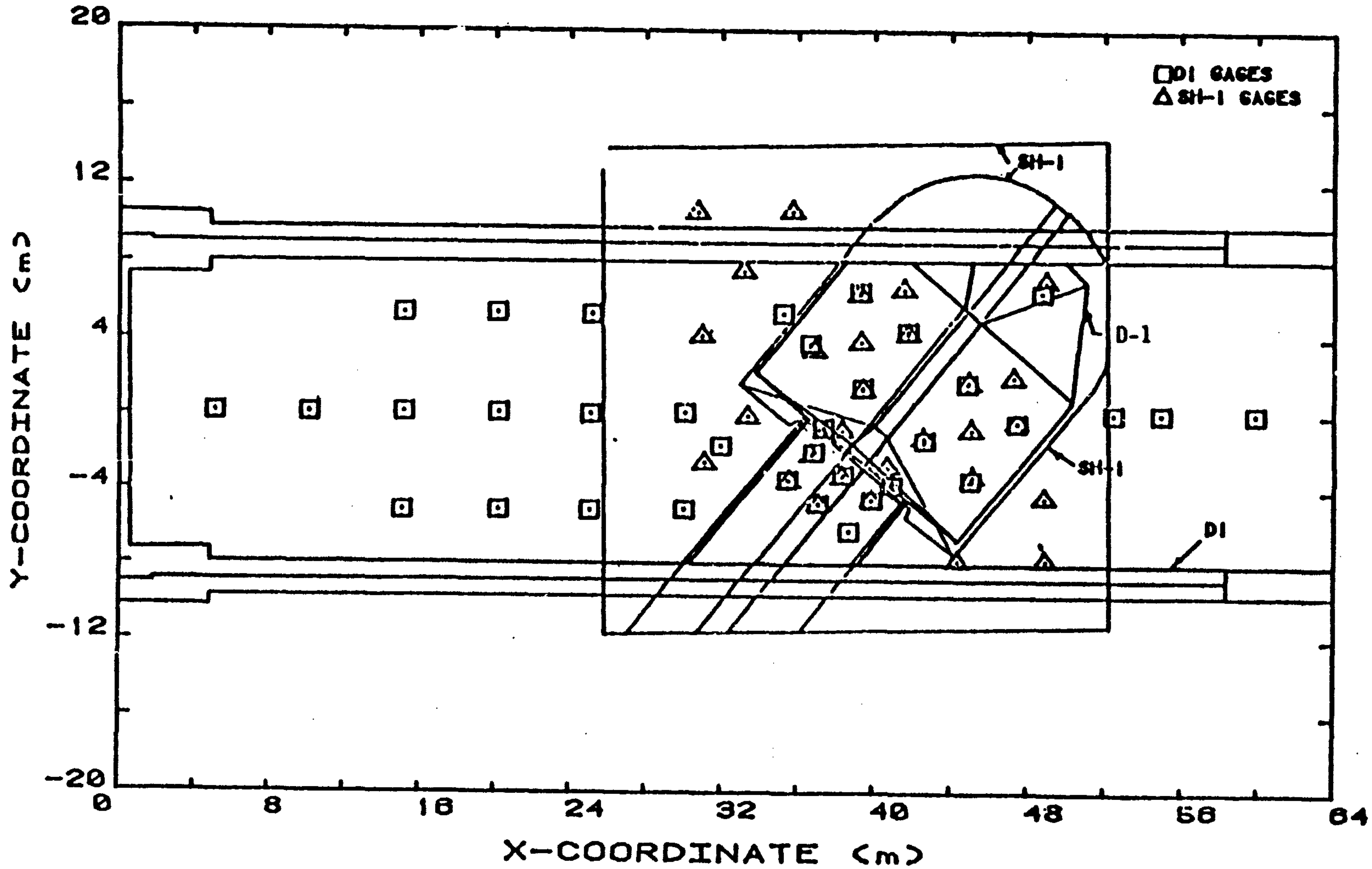


Figure 5. SH-1 and D-1 plan view gage comparison.

Meanwhile, the main shock front encountered the front face of the headwall and began moving across it. These two shock systems collided near the face of the structure near the y = -2 m structure coordinate (Figure 6). This shock collision spawned a large reflected shock which accounts for the 27 MPa peak pressure observed at the y = -2 m range and the other high pressures in that headwall region.[3] This strong reflected shock is similar to what would be expected from a nuclear airblast loading at the 50 degree aspect angle for a 3 MPa overpressure. In general, the airblast pressures on the headwall and closure were higher on the downstream side (right) compared to those upstream.

Berm Area Dynamics

Overpressure waveforms measured as the blast wave passed over the shelter model are shown in Figure 7. Pressures along the upstream side of the berm are approximately 20 percent higher than along the downstream side. The airblast arrived at the first airblast gage on the upstream berm at 16 ms and then swept over the berm traveling at 1900 m/s. The airblast moved from this gage to the last near-field gage in about 5 ms. Figure 7 shows the locations and waveforms of several airblast measurements on the berms and the driveway of the structure. At axial distances of several meters behind the headwall, the vertical overpressure on the upstream berm (left) was higher than the downstream. The peak overpressures on the headwall and door varied (from left to right) from about 6 MPa to 11 MPa. Except for the region within approximately a meter of the headwall, peak overpressures on the upstream berm were about 4 MPa $\pm$ 0.4 MPa while peak overpressures on the downstream (right) berm were about 3.1 to 3.5 MPa.[3]

COMPARATIVE ANALYSIS

Scope

Replication of the preceeding D-1 headwall and berm areas airblast loading effects were the goals in the SH-1 HEST test. A principal feature of the SH-1

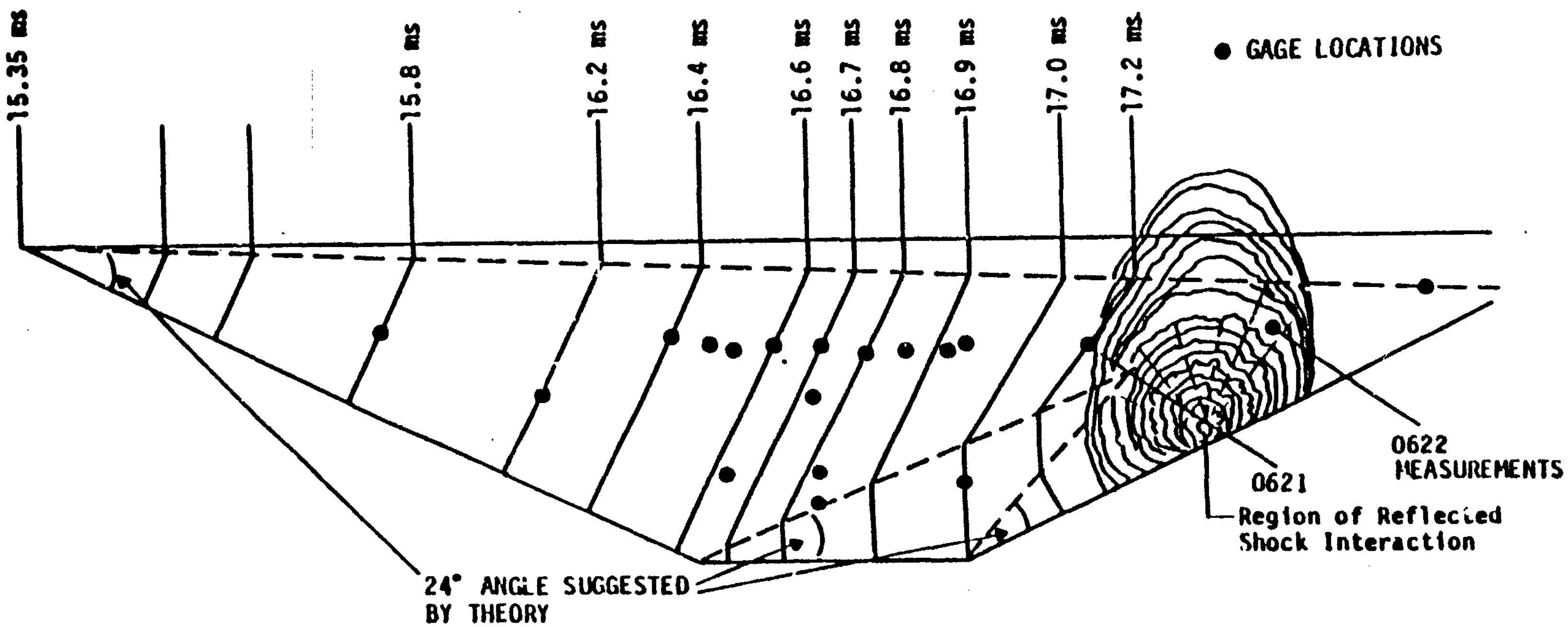


Figure 6. Sweeping shock wave and focus point on D-1 headwall.

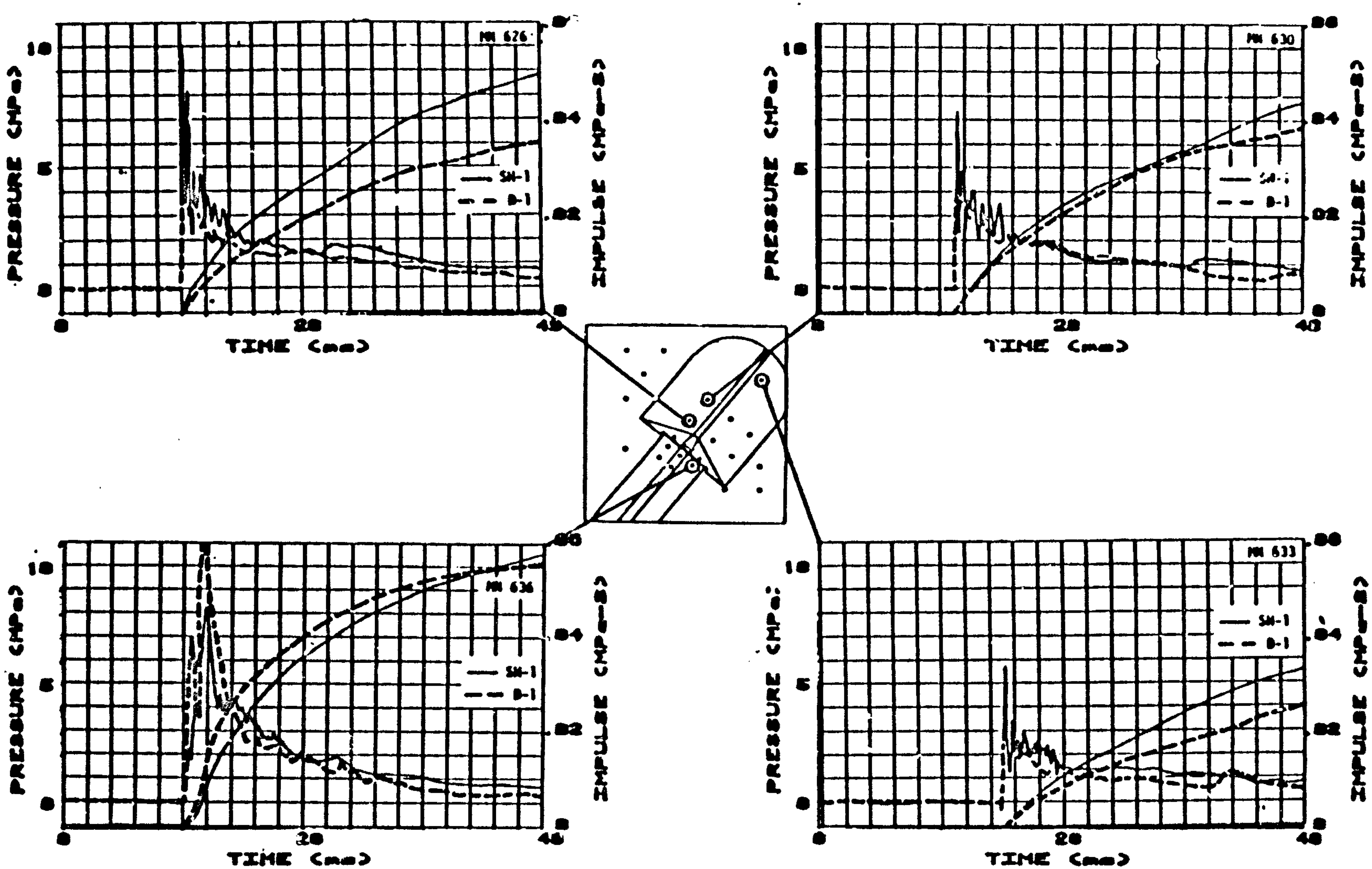


Figure 7. SH-1 to D-1 pressure and impulse comparison.

simulator design was the requirement to produce the double peak waveform across the headwall and closure face. This was accomplished by using a HEST (zone 4) designed to produce a low pressure region and a high pressure region, both within the same cavity. The detonation of the explosives in the low pressure region produced a working gas through which secondary shocks could propagate. Upon detonation of the high pressure region a secondary shock propagated back through the low pressure region creating the second peak and the desired waveform.

A redundant zone-interconnecting and timing system was used to ensure the proper propagation rate of the shock front across each region and from one region to the other. The SH-1 simulator timing was a critical simulation feature. In order to be completely successful, all zones must fire at the proper time and sweep at the required rate. The detonating front in each zone was designed to travel at the free-field nuclear velocity 1684 m/s (5525 ft/s) and at a direction of 50 degrees to the longitudinal axis of the structure. The blast wave's propagation timing the various zones in SH-1 was done externally and does not result from flow, except as stated in the secondary wave of zone 4. The near-field zones were designed to produce the peak effective pressures resulting from the blast flow dynamics with the berm. The pressures were normalized in the areas shown in Figure 4.

Headwall and Closure

The times of arrival of the blast wave propagating across the headwall and face of the structural model are shown in Figure 8 along with the arrival times for the second pulse which travels back across the face and headwall. The primary blast wave traveled across the headwall at approximately 2486 m/s, which was slightly faster than the 2424 m/s predicted value. The second pulse caused by the high pressure region in zone 4 traveled back across the headwall at approximately 630 m/s. The SH-1 value was slower than the 850 m/s rate observed in the D-1

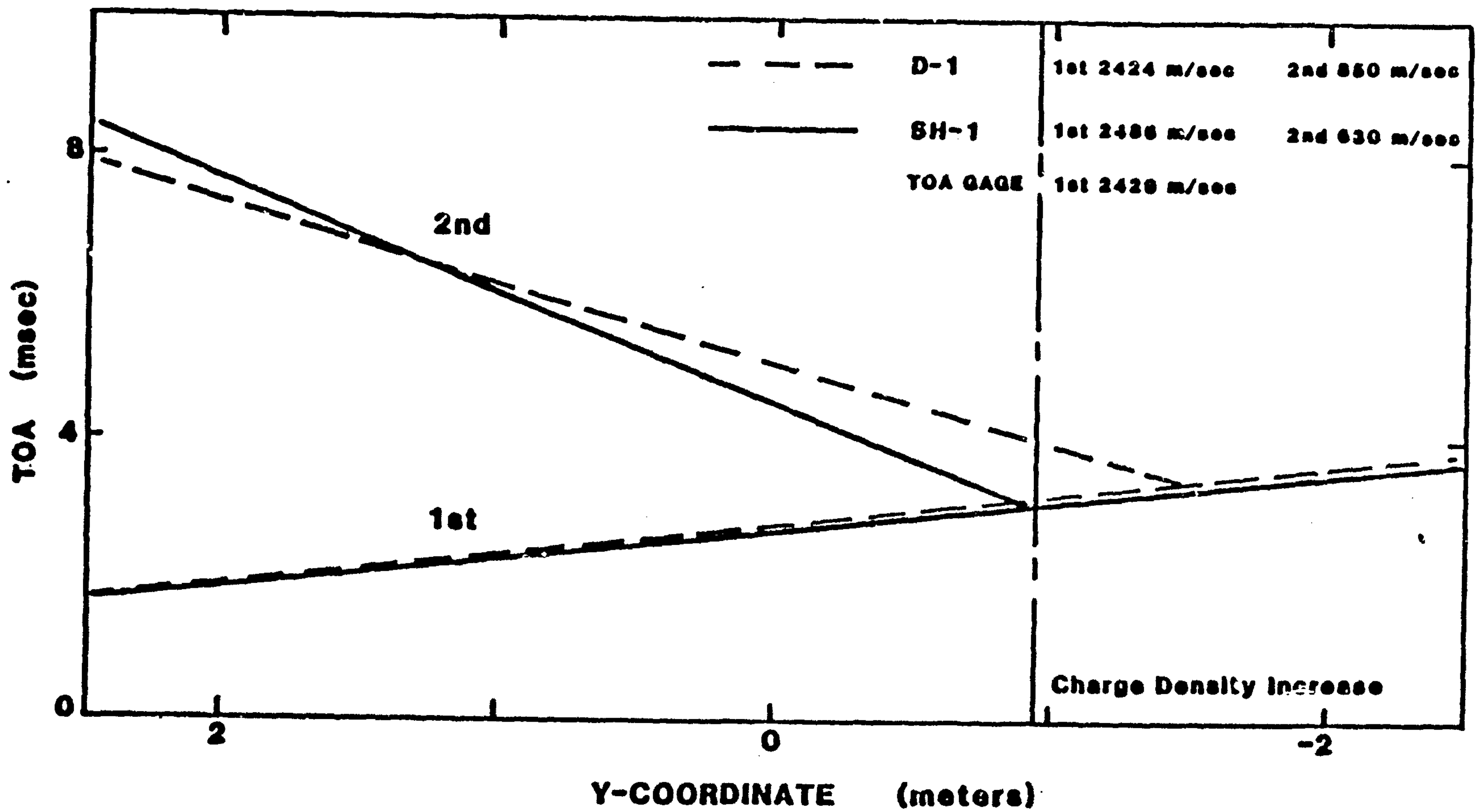


Figure 8. Wave Propagation on headwall.

test. The second shock in SH-1 propagated through a gas composed of detonation products and vaporized foam rather than air, which accounts for its rate being slower than that observed in D-1. The blast overpressure waveforms measured at selected locations across the headwall and closure are shown in Figures 9, 10 and 11. The single peak waveform over the downstream high pressure region and the double peak waveform over the upstream low pressure region are clearly observable. Waveforms measured at comparable locations in the D-1 test are overdrawn on the SH-1 waveforms. Values for peak simulation pressure (PP_S) and for the second peak were plotted as a function of the y-coordinate across the headwall and face of the structure in Figure 12. Smooth curves were visually fitted through the data and corresponding data for D-1 were also included. PP_S in the low pressure region of zone 4 (upstream headwall) was approximately 9.5 MPa for SH-1 as compared to 6.5 MPa for D-1. In the high pressure region of zone 4 (downstream headwall) the PP_S was approximately 34 MPa in SH-1 as compared to 27 MPa for D-1.[5]

Free-Field and Berm (Testbed)

The blast overpressure waveforms at selected locations across the SH-1 testbed are shown in Figure 13 with comparisons of the associated Brode waveforms. Although the front end spikes and oscillations typical of a HEST are present, the waveforms produced agree well. The free-field overpressure is estimated to be 3.5 MPa and yield to be 24 KT, slightly higher than the 3 MPa, 24 KT design goal.[5]

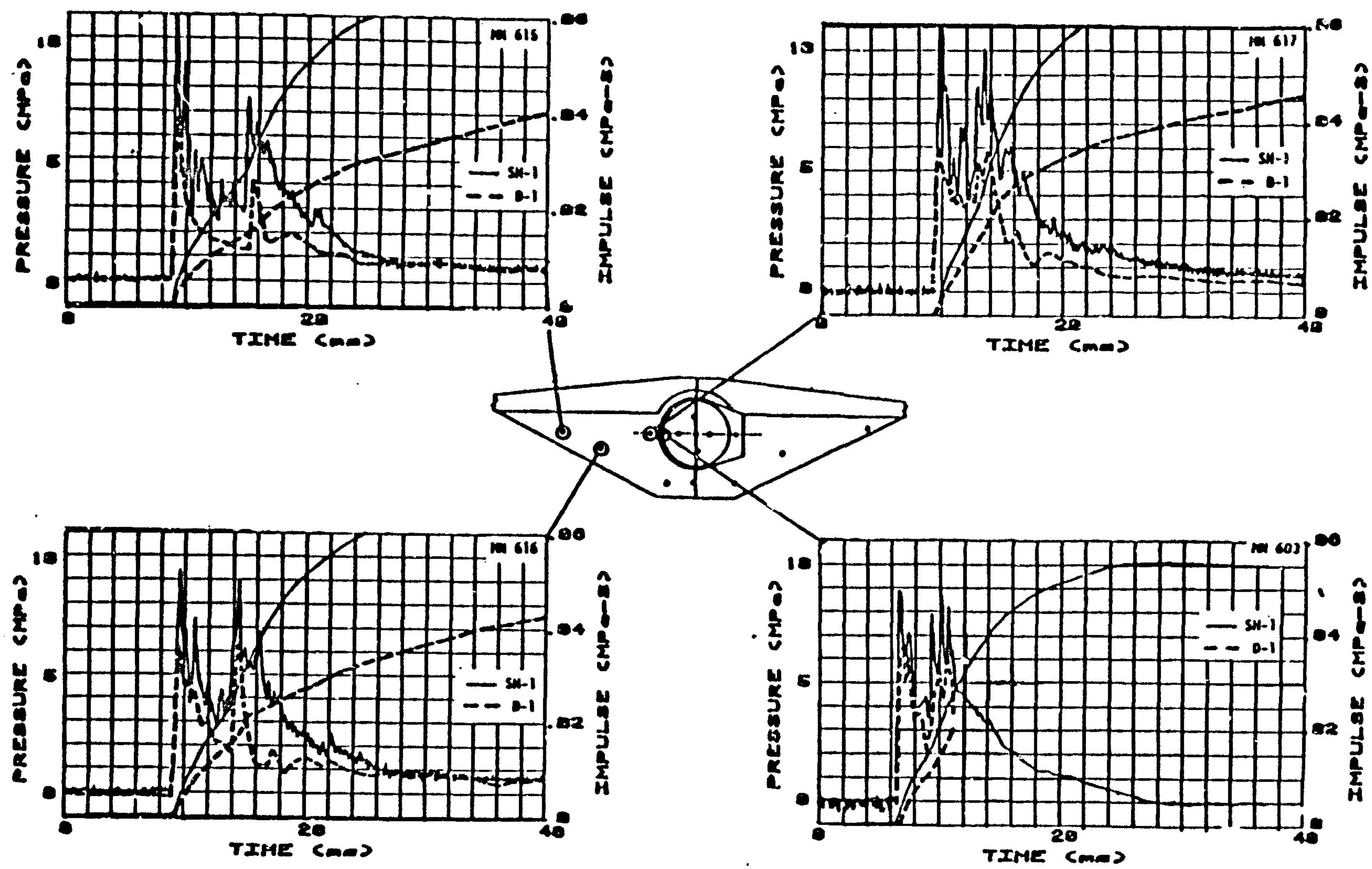


Figure 9. SH-1 to D-1 pressure and impulse comparison.

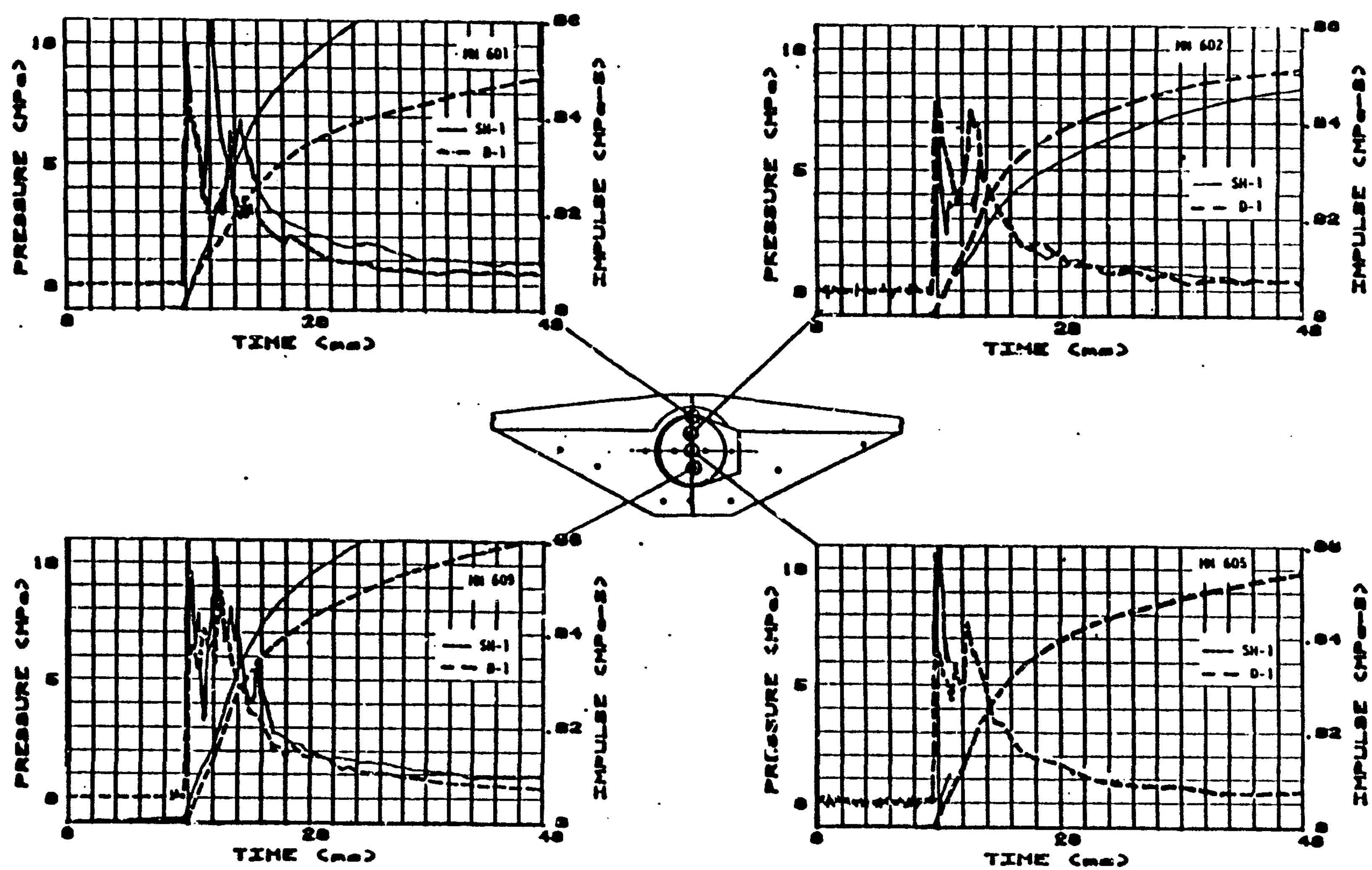


Figure 10. SH-1 to D-1 pressure and impulse comparison.

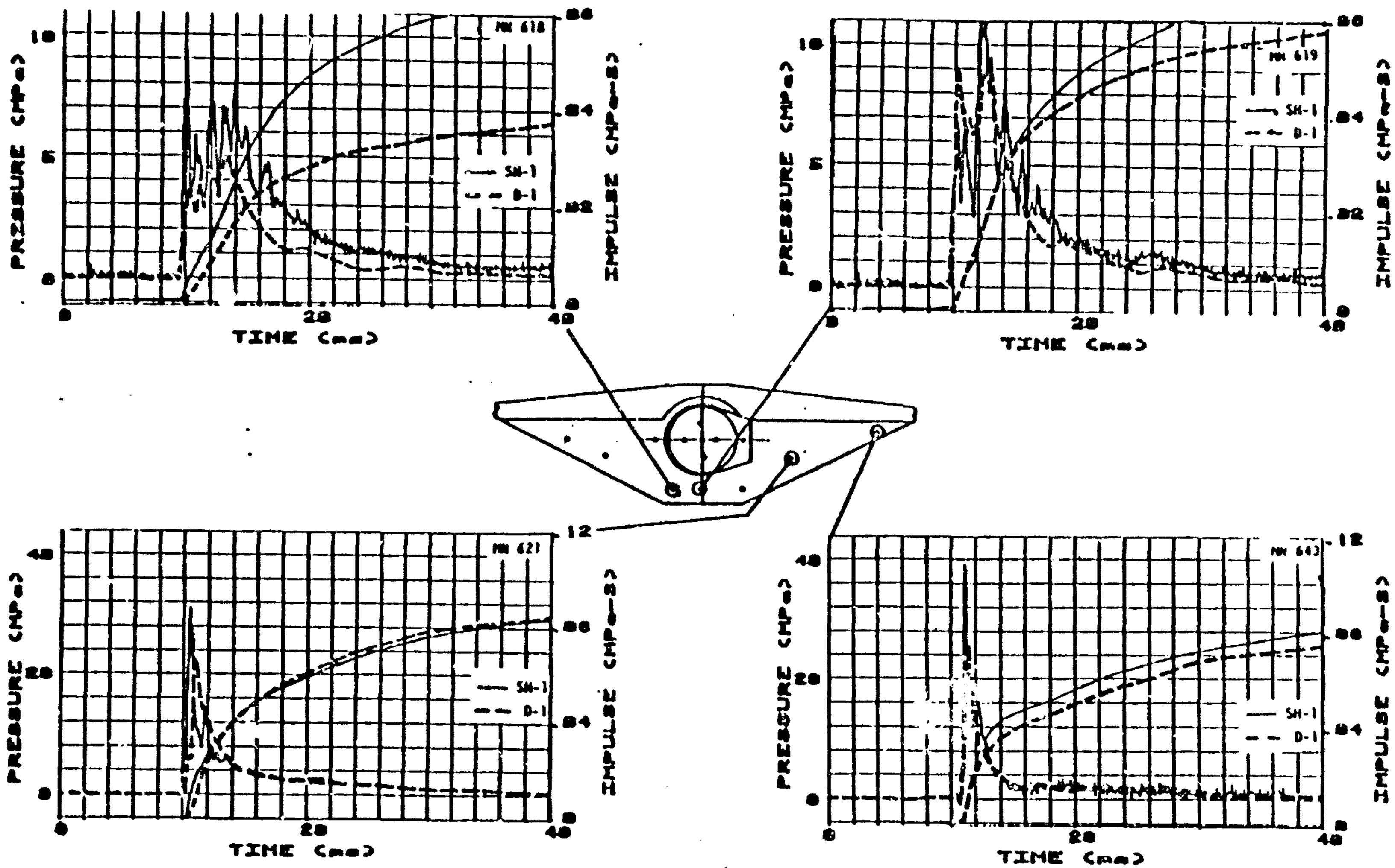


Figure 11. SH-1 to D-1 pressure and impulse comparison.

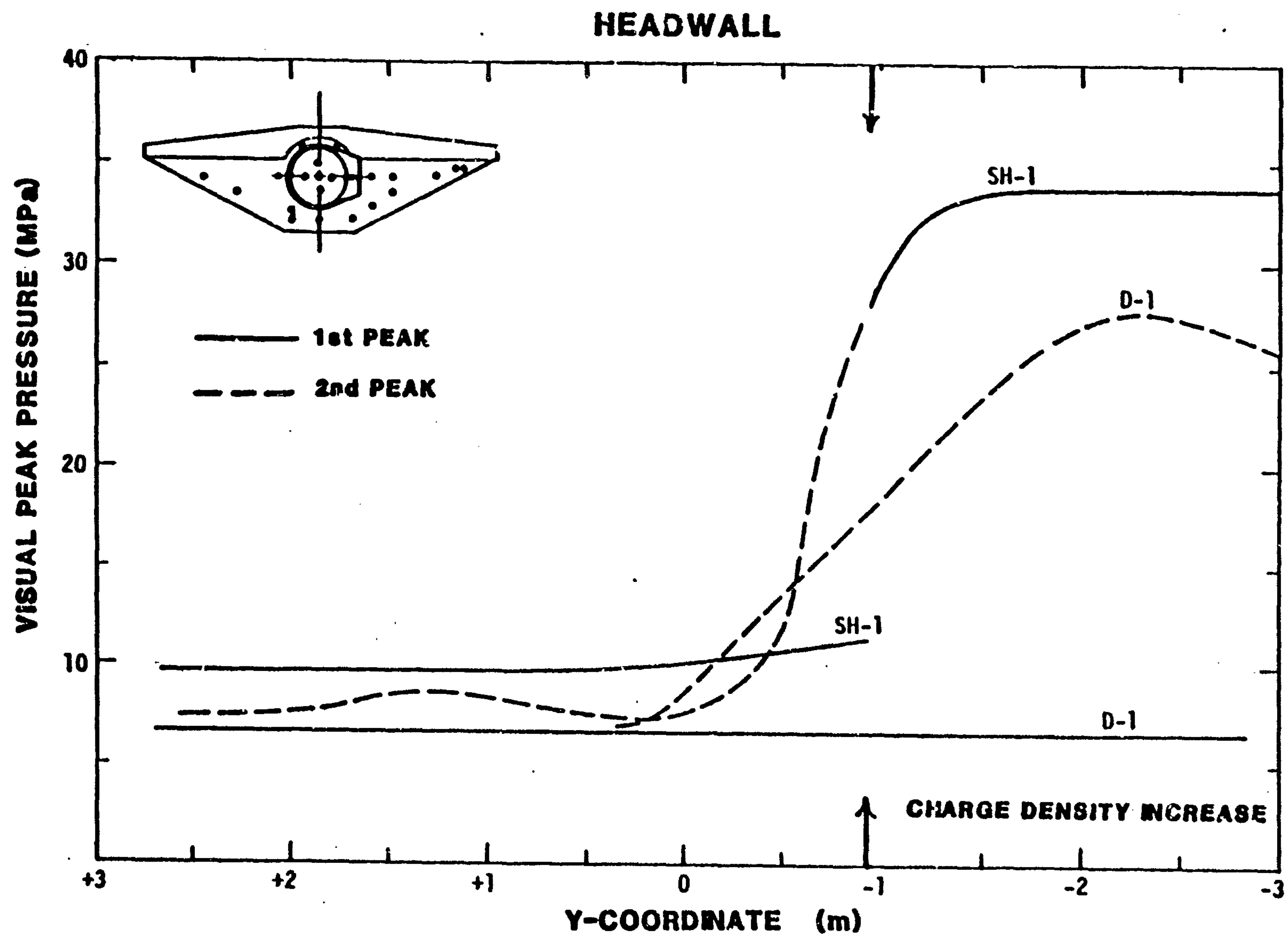


Figure 12. D-1 to SH-1 1st to 2nd Peak Pressure Comparisons

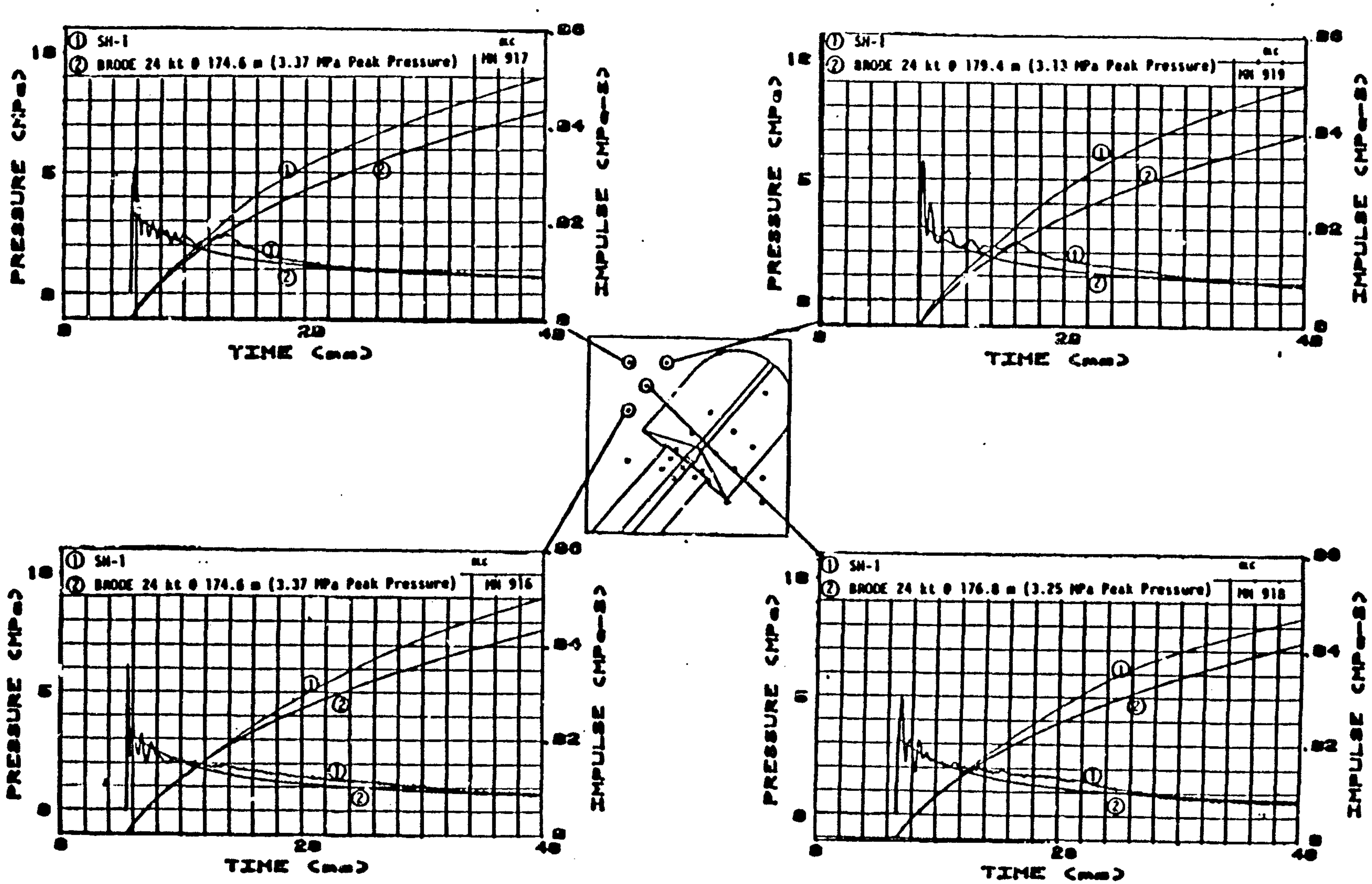


Figure 13. SH-1 to 24 kt Brode pressure and impulse comparison.

SUMMARY

The Shaped-HEST simulator performed very well as a nuclear Blast and Shock loader for exposed surface structures. Evaluation of the SH-1 simulator adequacy was a primary concern as to modeling the complex nuclear airblast loading waveforms. This HEST technique reflects the best state-of-the-art as a low cost simulator alternative to the DABS. Comparable load characteristics were produced. Overpressure waveforms very similar to the 24 KT nuclear waveform at the 3 MPa range were produced in the free-field regions (zones 8-1 and 8-2). The airblast waveforms produced over the top of the structure were quite comparable to those produced in the D-1 test. Along the headwall and closure double peaked waveforms were produced which were very similar to those produced in D-1. The zone 4 high pressure region along the downstream headwall produced secondary peaks very similar to the D-1 test. Propagation of the HEST blast wave over the testbed was uniform and planar, providing proper times of arrival in each of the test zones. Peak overpressures were slightly high in the free field as compared with the 3 MPa nuclear and 25 to 50 percent higher than the D-1 test across the headwall and the face of the structure. Impulse loading appears to be correspondingly high in most regions and approximately 20 percent higher over the closure. The HEST-generated high amplitude spikes and high frequency oscillations are present in the blast pressure waveforms during the first few milliseconds, but effectively produced minimal energy transfer.

Further HEST development to adjust and improve the quality of the nuclear airblast simulation provided in SH-1 is recommended prior to full-size test applications. However, the simulator has proven its utility for producing both multiple shock effects and multi-pressure loadings on reflection and drag sensitive structures.

Appendix I - References

1. Furbee, E., et al, "A Status and Capability Report on Nuclear Airblast and Ground Shock Simulators for Large Scale Structural Testing," AFWL-TR-79-195, Air Force Weapons Laboratory, Kirtland AFB NM, Jul 1980, pp. 7-21, 44-53.

2. Noble, M., et al, "D-1 Pretest Prediction," AFWL-TR-81-106, Air Force Weapons Laboratory, Kirtland AFB NM, Oct 1981, pp. 7-32.

3. Noble, M., et al, "D-1 Quick Look," AFWL-TR-81-107, Air Force Weapons Laboratory, Kirtland AFB NM, Nov 1981, pp. 31-67

4. Noble, M., Edwards, J. and Bell, K., "SH-1 Simulation Environment Pretest Prediction," AFWL-TR-81-220, Air Force Weapons Laboratory, Kirtland AFB NM, Feb 1982, pp. 1-13.

5. Noble, M., et al, "SH-1 Quick Look," AFWL-TR-81-221, Air Force Weapons Laboratory, Kirtland AFB NM, Mar 1982, pp. 14-68.

Appendix II - Notation

The following symbols are used in this paper:

cm = centimeter

ft = feet

gms = grams

gr = grains per foot

KT = Kiloton

kg = Kilogram

lbs = pounds

MPa = Megapascals

MT = Megaton

m = meter

ms = millisecond

s = second

t_s = simulator disassembly time

y = structure coordinate horizontal axis

1/5 Size VHS Series Blast and Shock Simulation by Michael L. Noble. The capability of a High Explosive Simulation Technique (HEST) simulator to adequately duplicate complex airblast waveforms was demonstrated. Dynamic test comparisons showed the HEST simulator's utility for providing both multiple shock effects and multi-pressure loadings on reflection and drag sensitive structures.

1/5 SIZE VHS SERIES BLAST AND SHOCK SIMULATIONS

KEY WORDS: Civil Defense; Explosives; Field Tests; Military Engineering; Technology Assessment; Dynamic Air Blast Simulator (DABS); High Explosive Simulation Technique (HEST); Airblast; Simulator.

ABSTRACT: The simulation objective of the 1/5 Verifiable Horizontal Shelter (VHS) test series was to demonstrate the capability of a High Explosive Simulation Technique (HEST) simulator to adequately duplicate complex airblast waveform loadings. A principal feature of the HEST design was the requirement to produce double-peaked resultant overpressures. The modeling baseline was established by a test (D-1) producing dynamic flow. The HEST test (SH-1) comparably matched the loading waveforms both in relative magnitude and phase characteristics. The HEST simulator has proven its utility for both multiple shock effects and multi-pressure loadings on reflection and drag sensitive structures.