Analytical Certification of ARMCO Revetments for Preventing Sympathetic Detonation

by

Kevin Hager and James Tancreto
Naval Facilities Engineering Service Center
Pt Hueneme, CA

and

Michael Swisdak
Naval Surface Warfare Center, Indian Head Division
Indian Head, MD

ABSTRACT

ARMCO revetment walls are used as barricades to separate and prevent sympathetic detonation (SD) among munitions. These revetment walls are constructed and located to form modules to protect ordnance handling and aircraft servicing areas. The Naval Facilities Engineering Service Center was tasked by the Department of Defense Explosives Safety Board to determine by analogy and analysis the maximum credible event for which ARMCO revetment modules prevent SD of thin case and robust case munitions.

Based on analysis and test results, it is recommended that the maximum net explosive weight (NEW) stored in an ARMCO revetment module with 7 foot thick revetment walls be limited to 18,000 lb when thin case ordnance is located in an adjacent module. The 7 foot thick, sand filled ARMCO revetment wall is required to prevent SD of the worst case missile acceptor. The minimum required size of the storage area is 85' by 50' and a minimum 10' standoff is required between any explosive and a revetment wall.

It is recommended that the maximum NEW stored in an ARMCO revetment module with 5.25 foot thick revetment walls be limited to 5,000 lb NEW. The 5.25 foot ARMCO revetment wall will prevent SD of the worst case missile acceptor. This donor maybe placed anywhere in the minimum sized storage area of 85' by 50'. A minimum 10' standoff is required between any explosive and a revetment wall.

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1.0 INTRODUCTION

1.1 Background

The U.S. Air Force currently uses ARMCO revetments as barricades to separate and prevent sympathetic detonation (SD) among munitions. Revetment walls are constructed and located to form modules to protect aircraft and to separate munitions in handling areas. Tests have shown the ability of revetment modules to prevent SD of robust (thick-cased) ordnance, including both the Mk80 series of bombs and M117 and M118 bombs. Based on these tests, the Air Force has authorized storage of 30,000 pounds of NEW per revetment module. No tests have been conducted to certify that the ARMCO revetment prevents SD of robust (missile) or thin-cased munitions.

1.2 Objective

The Naval Facilities Engineering Service Center (NFESC) has been tasked to determine by analogy and analysis the maximum credible event (MCE) for which ARMCO revetment modules prevent SD of robust (missile) thin-cased munitions.

1.3 Scope

The NFESC has analyzed the ARMCO revetment layouts to determine the wall loading environment, wall response, acceptor loads, and critical acceptor deformation and peak explosive fill pressure. The acceptor loads and response have been compared to reaction threshold criteria to evaluate ARMCO revetments for selected conditions.

The Mk103 torpedo was chosen to represent thin-cased munitions. The WAU-17 represents robust missile warheads with thicker casings which are designed and manufactured to rupture and fragment.

The load environment and response of the revetments are calculated using AUTODYN-2D, a finite-difference hydrocode. Three combinations of donor charge weight, wall size, and acceptor type have been analyzed:

- A 30,000-pound donor charge opposite a 7-foot-thick revetment wall, with Mk103 torpedo and WAU-17 Sparrow warheads as acceptors.
- An 18,000-pound donor charge opposite a 7-foot-thick revetment wall, with Mk103 and WAU-17 warheads as acceptors.
- A 5,000-pound donor charge opposite a 5.25-foot-thick revetment wall, with Mk103 and WAU-17 warheads as acceptors.

Acceptor impulse and energy loads, deformations, and peak explosive fill pressure are calculated using AUTODYN-2D and DYNA-3D. The ARMCO revetment panels (and the earth/sand fill behind the panels) cannot transfer all of their energy and momentum to an acceptor during impact because they are flexible and will deform during impact. However, threshold reaction tests use steel plates which do not deform during impact with an acceptor. For these reasons, the analyses must provide:

- The effective area of the revetment wall for loading the acceptors.
- A relation between rigid flyer plate test threshold loads and flexible, ARMCO revetment loads.
- Acceptor loads and response for comparison with reaction threshold criteria.

2.0 REVETMENT WALL LOAD ENVIRONMENT

This section presents the expected revetment module layout at various sites, and the assumptions for determining the worst case impulse loads on the revetment wall and the resulting wall response.

2.1 Revetment Module Setup

A single ARMCO revetment module consists of a series of revetment walls and an explosives storage and handling area. Reference 1 describes the hardware needed to assemble revetment walls and possible module configurations for barricading storage areas. The two basic types of revetment wall cross-sections are a 12-foot-high by 5.25-foot-wide Type B wall and a 16-foot-high by 7-foot-wide Type A wall. Revetment walls are divided into sections using cross panels (web stiffeners through the wall thickness) to connect the side panels and to close off the wall ends. The connected panels form a complete structure to contain the sand fill material.

The configuration of the revetment module usually depends on the intended use, such as aircraft drive throughs or ready storage of explosives. For example, revetment modules may be use to form aircraft drive-throughs for loading and offloading munitions. The modules are a series of parallel revetment walls separating the explosives handling areas.

Revetment walls may also be arranged to form a basic U-shaped revetment module for ready storage of munitions. The module may consist of a series of parallel revetment walls oriented perpendicular to a single revetment wall. Ordnance may be stored on trailers parked in three lines along the length of the storage area.

Donor orientation and standoff distances to individual revetment walls vary according to requirements at different user sites. For this analysis to be applicable for all user sites, revetment wall locations have been chosen to obtain a worst case impulse load. Generally, loads on the revetment wall will increase as the storage area and standoff distances decrease. Figure 1 shows the critical revetment module geometry used in the analyses. Three modules are shown. Each module consists of revetment walls arranged in a U-shaped pattern along three sides of a 50- by 85-foot explosives storage area. A minimum 10-foot standoff is required between the revetment walls and any explosives located in the storage area.

Charge locations are the most significant unknown in the analysis. Loads were calculated for three potential worst case donor layouts in the storage area. Figure 2 shows the three donor configurations for the center revetment module to determine the worst case revetment loads for a 30,000-pound donor. Mk82 bombs were chosen to represent large charge weight donors, such as Mk80 series bombs, which can be stored in the worst case donor layout. In Figure 2a, pallets of Mk82 bombs are uniformly distributed on the center-line running the length of the storage area. The pallets may also be arranged along the edges of the storage area, see Figure 2b, and along the edges and center-line of the storage area, see Figure 2c.

To calculate the impulse loads for an 18,000-pound donor, pallets of Mk82 bombs are distributed uniformly along one, two, or three axes along the length of the storage area. The axis locations are the same as those previously chosen for the 30,000-pound donor. Average standoff distances from the pallets to the revetment walls are the same for both donors. The only difference in these two analyses is the charge weight.

Figure 3 shows the location of the 5,000-pound donor in the corner of the storage area near two revetment walls. Calculation of impulse loads on the revetment wall from the 5,000-pound donor assumes a single point charge. This assumption is different than the assumption made for the 18,000- and 30,000-pound donors. Based on Figure 3, the impulse from 18,000- and 30,000-pound donors assumes line loads parallel to the revetment walls.

2.2 Donor Model Setup

The impulse loads on the revetment walls from the 18,000- and 30,000-pound donors are calculated using AUTODYN-2D. AUTODYN-2D models a cross section of the storage area using a two-dimensional euler mesh to calculate detonation and expansion of explosive materials.

A model of the vertical cross section for calculating revetment loads is shown in Figure 4. In this model, the 30,000-pound donor is represented by a single cylinder of TNT elevated 2 feet off the ground and on the center-line of the storage area. Taking advantage of symmetry, only half of the module is modeled with the mesh. The left-hand border of the mesh is the line of symmetry passing through the donor charge's center. The mesh is 25 feet wide by 25 feet high.

Reflecting and flow surfaces are placed along the rest of the mesh to model proper boundary conditions. Reflecting surfaces do not transfer any pressure or mass out of the mesh. These surfaces are located along the bottom (concrete floor) and between the 0- and 16-foot elevations of the right-hand border (revetment wall). These boundary conditions represent the floor and revetment wall of the storage module. Flow surfaces transmit the outward movement of shock and gas pressures from the mesh without reflections. These surfaces are located on the top border of the mesh and between the 16- and 25-foot elevations of the right-hand border.

A conservative upper limit load environment is calculated by using a reflecting surface to represent the revetment wall. This assumption avoids problems inherent in determining the load at different elevations of a moving wall.

Figure 5 shows a second two-dimensional model of the worst case revetment module. The 30,000-pound donor is represented by three cylinders of TNT running lengthwise and parallel to the revetment. Boundary and symmetry conditions are the same as those in the single charge model.

The impulse loads on the revetment walls from the 5,000-pound donor are calculated using SHOCK. SHOCK calculates the shock pressure and impulse on a flat surface bounded by one to four rigid reflecting surfaces. The shock impulse includes the effects from incident and reflected shock waves. The shock waves are assumed to originate from a single point charge. Wall loads vary with range and angle from the donor source. The design load was conservatively defined as the average load on the wall within the projected area of the Mk82 donor.

2.3 Predicted Revetment Loads and Response

The impulse load on the revetment wall is dependent on the donor charge weight and the distribution of the explosive throughout the storage area. Calculations show impulse loads increase with charge weight and decrease as the charge becomes more uniformly distributed throughout the storage area. For all charge weights and distributions, impulses are highest at the bottom of the revetment wall.

Table 1 compares results for various donor charge distributions (1, 2, and 3 lines). Figure 6 shows maximum calculated impulse versus increasing wall elevation for the 18,000- and 30,000-pound donors modeled with 1 and 3 line charges. The impulse load at 0-foot wall elevation exceeds the impulse at 6-foot wall elevation by 15 percent. Most acceptors are assumed to be located on stands or pallets below the 6-foot elevation. No significant advantage will be gained by elevating the acceptors or donors. Design impulse loads were conservatively based on loads at the bottom of the revetment wall.

Distribution of the donor explosive will vary according to requirements at different user sites. As shown in Table 1, impulse loads can change by as much as 50 percent by rearranging the layout of the explosive charges in the storage area. Impulse loads calculated for the single line charge at the center of the storage area and the double line charges at each edge of the storage area show only a 10 percent difference. Distributing the charge uniformly in a 3 line layout significantly reduces wall loads. The worst case wall loads, from a single line charge, were used in the acceptor response analyses.

3.0 ACCEPTOR STRUCTURAL RESPONSE

This section reports the finite element model and calculated acceptor structural response to revetment wall impact. Actual acceptor response is dependent on several factors including: debris mass and velocity, debris characteristics, the number of acceptors, distances of the acceptors from donor and acceptor revetment walls, and packaging of acceptors on pallets and trailers.

Debris materials will include revetment side panels, interior bracing panels, corner posts, and the sand fill. The connections for the prefabricated panels are designed to resist lateral soil pressures from the sand fill and will break under dynamic loads. The combined momentum of an individual side panel and its confined sand fill represents the largest debris size and the worse debris hazard.

Packaging of the acceptors mitigates acceptor structural response to debris impact. For example, the Mk103 and WAU-17 warheads will typically be a component of a larger weapon. These larger weapons are stored in groups on pallets and trailers. The structure of the larger weapons system will add structural resistance to wall impact and reduce the total load on the warheads. Also, the available kinetic energy of the wall may be divided among multiple acceptors and transport trailers. These mitigating factors are conservatively ignored in the analyses.

3.1 DYNA-3D Analysis: Acceptor Model Setup

DYNA-3D was used to determine the acceptor response to impact with the revetment wall. The models use solid and shell elements, impact-slide-line surfaces, and nonlinear materials to predict acceptor structural response to short duration impulse loads. DYNA-3D calculates nonlinear structural response at large deformations and large strains.

The worst case impact is assumed to be caused by a normal side-on impact and crushing of individual Mk103 and WAU-17 warheads between two revetment walls (the donor wall and a rigid wall on the opposite side of the acceptor). The initial velocity of the donor revetment wall is calculated from the worst case donor loads. The acceptors are assumed to be parallel to the revetment walls.

Figure 7 shows a typical model of a donor revetment wall crushing an Mk103 warhead against a rigid acceptor revetment wall. The x-z plane is a symmetry plane passing through the acceptor and the wall. No out-of-plane movement is allowed for all acceptor and wall nodes located on this plane. This restrains tumbling and rotating of the acceptor in the y-direction. Out-of-plane motion is not allowed in donor wall surfaces parallel to the x-axis.

The explosive fill of the warhead is modeled with solid, brick-shaped elements. The peak explosive fill pressures are calculated at the center of mass of these elements. Nodes are located at the eight corners of each solid element. Displacement of the explosive fill is calculated at these nodes. Differences in displacement of nodes at various locations in the explosive fill are used to calculate the deformation of the warhead.

The acceptor revetment wall is conservatively modeled as a non-movable rigid plate. This non-responding barrier will increase the acceptor deformation and peak explosive fill pressures. This setup represents the worst case load environment on the acceptor.

3.2 DYNA-3D Analysis: Acceptor Deformation and Pressure Time Histories

Acceptors were analyzed for response to impact by revetment panels of various sizes (with the appropriate sand mass). The revetment side panels form the largest possible tributary areas (36 by 144 inches and 16 by 120 inches) that can load the acceptors. A tributary area of the revetment wall is defined as the largest projected area of the wall that can contribute to an acceptor's response. The momentum of any wall mass found outside of the tributary area does not increase the relative deformation or pressure response of an acceptor.

Figure 8 shows locations of nodes and elements on the x-z symmetry plane cutting through the center of a Mk103 warhead. The nodes used for calculating the warhead deformation are highlighted and numbered in Figure 10a. The elements used for calculating the explosive fill pressures are numbered at the center of the elements as shown in Figure 10b. The pressure and deformation response at these locations represents the overall response of the acceptor and should capture the maximum responses.

Figure 9 shows locations of nodes and elements on the x-z symmetry plane passing through the center of a WAU-17 warhead. The nodes used for calculating the warhead deformation are highlighted and numbered in Figure 9a. The elements used for calculating the explosive fill pressures are numbered at the center of the elements as shown in Figure 9b. The pressure and deformation response at these locations represents the overall response of the acceptor and should capture the maximum responses.

The calculated peak pressure response of the Mk103 and WAU-17 to a 30,000-pound donor are less than 2.1 Kbar. Maximum relative deformations are less than 25 percent for the WAU-17 and less than 45 percent for the Mk103. Maximum pressures typically occur during maximum deformation.

The design impulse load on the revetment wall from an 18,000 pound donor is 16.14 psi-sec and the wall velocity is 108 ft/sec. The calculated peak pressure response of the Mk103 and WAU-17 is less than 1.3 Kbar. Maximum relative deformations are less than 34 percent for the WAU-17 and less than 37 percent for the Mk103.

The design impulse load on the revetment wall from a 5,000 pound donor is 15.0 psi-sec and the velocity for the 5.25-foot wall is 133 ft/sec. Calculated peak explosive fill pressures for the WAU-17 warhead are less than 1.1 Kbar and the maximum relative deformations are less than 33 percent.

4.0 ACCEPTOR REACTIONS

4.1 Threshold Load Criteria and Acceptor Reactions

The empirical data for determining sympathetic reactions are based on flyer plate crush tests completed at the Energetic Materials Research and Testing Center (EMRTC), Socorro, New Mexico. Ordnance, including melt cast and plastic-bonded explosive-loaded Mk103 torpedo warheads and WAU-17 Sparrow warheads were impacted with explosively-driven ‘rigid’ steel plates. These crush tests are designed to simulate a low velocity, massive wall impacting and crushing a warhead against a solid wall. For each test, a flyer plate is propelled by an explosive charge into the crush plate which in turn crushes the acceptor against the back plate. The crush plate is constructed of alternating layers of plywood and steel plates to ensure that any reaction is caused by crushing of the acceptor. Detailed descriptions of test setups and ordnance response to impact loads are found in Reference 2. Because the thin-cased munitions easily deform, rupture, and burn, threshold loading criteria are based on limiting the unit momentum and unit energy loading applied to the acceptors (Ref 3).

Table 2 summarizes the reaction of Mk103 warheads to flyer plate impact tests. The unit impulse and unit strain energy applied to the explosive fill of the warheads are shown in columns five and six. Unit impulse is defined as the initial total momentum of the flyer plate divided by the projected area of the warhead. Unit energy is defined as the change in kinetic energy in a plastic collision divided by the volume of the explosive. Sympathetic detonation of explosives was not detected in any of these tests. Burning of the explosive did occur for the entire range of impulse loads.

Table 3 lists the weights of the flyer and back plates, and measured flyer plate velocities for three flyer plate impact tests on the WAU-17 warhead. The unit impulse and unit strain energy applied to the explosive fill of the warheads are shown in columns five and six. In the first and third flyer plate tests, the warhead reacted and caused the flyer and crush plates to rebound away from the warhead. No fragment hits were observed on the back plate.

As in Reference 3, the peak calculated fill pressure must not exceed 75 percent of the Underwater Sensitivity Test (UST) ignition threshold pressure. The explosive fills are H6 or PBXN-103 for the Mk103 warhead and PBXN-103 for the WAU-17 warhead. Calculated explosive fill pressures caused by initial impact and crushing of the acceptor must not exceed 4.8 Kbar for H6 and 6.7 Kbar for PBXN-103.

4.2 Acceptor Loads and Predicted Response

Threshold reaction loads are based on ‘rigid’ flyer plate data in which the entire momentum and kinetic energy of the flyer plate loads the acceptor. The non-rigid ARMCO panels (and the sand/earth fill behind the panel) that impact the acceptor cannot transfer all of their momentum and energy to the acceptors because they deform. (Also see References 4 and 5, which show results of 1/3 scale tests of non-propagation walls in which granular fill material, such as sand, reduced the coupling of wall momentum into acceptors).

It is assumed that an ARMCO revetment would transfer approximately the same momentum and energy to the acceptor as a rigid plate that produces the same deformation in the acceptor. Figures 10a and 10b show the calculated relative deformation versus effective area of: (1) a rigid plate, and (2) an ARMCO panel impacting a Mk103 and a WAU-17. The velocity, unit momentum, and unit energy were kept constant for the wall panel and the rigid plate and are based on the worst case load from a 30,000-pound donor. Figures 10c and 10d show the same relative deformations based on loads for an 18,000-pound donor. Figure 10e shows the relative deformation of the WAU-17 based on loads from the 5,000-pound donor.

The results in Figures 10a and 10b (based on the 30,000-pound donor) show that increasing the ARMCO revetment corresponding weight above 7,500 pounds does not increase the relative deformation above 45 percent for the Mk103 and 40 percent for the WAU-17. These same relative deformations correspond to the reaction from a rigid panel (as used in the threshold flyer plate tests) with a weight of 1,760 pounds for the WAU-17 and 2,320 pounds for the Mk103.

In Figures 10c and 10d, the relative deformations of the WAU-17 and Mk103 warheads (based on the 18,000-pound donor) reach a maximum of 35 percent for ARMCO revetment wall weights above 7,500 pounds. The effective weights for the rigid panels are 1,950 pounds for the Mk103, and 1,830 pounds for the WAU-17.

In Figure 10e, the relative deformations of the WAU-17 warhead (based on the 5,000-pound donor and the 5.25-foot-thick wall) reach a maximum of 32 percent for wall weights less than or equal to 8,000 pounds. The effective weight for the rigid panel is 1,310 pounds for the WAU-17.

Based on weights of the equivalent rigid panels determined in Figures 10a-e, Table 4 shows the calculated impulse and energy loadings on the Mk103 and WAU-17 warheads from the ARMCO revetment for the 18,000-pound and 30,000-pound donors, and the WAU-17 for the 5,000-pound donor. Unit impulse is defined as the total momentum of the equivalent rigid wall panel divided by the area of the warhead cross section. The unit energy is defined as the kinetic energy of the rigid wall panel divided by the volume of the warhead.

The load environments from the 18,000- and 30,000-pound donors on the Mk103 warhead are compared to flyer plate threshold tests in Figure 11. For the expected ARMCO environment, the Mk103 warhead will rupture and burn. No explosion or detonation is expected.

The load environments from the 5,000-, 18,000-, and 30,000-pound donors on the WAU-17 warhead are compared to flyer plate threshold tests in Figure 12. In Test #2, the warhead ruptured into two large pieces. Also, the explosive material was contained in one piece and the remaining material was inside a 40-foot radius of the warhead. In Tests #1 and #3, the flyer plate and crush pack were deformed and blown back from the warhead, indicating a possible explosion.

No fragment marks were observed on the back plate, indicating that the warhead did not detonate.

5.0 CONCLUSIONS

The worst case impulse loads are 14.5 psi-sec for the 5,000-pound donor, 16.14 psi-sec for the 18,000-pound donor, and 23.8 psi-sec for the 30,000-pound donor. These calculated loads are applicable for all reasonable donor locations inside a revetment module at any user site.

Crushing of the WAU-17 warhead and Mk103 warheads between two revetment walls simulates the worst case impact loads on these warheads. Predicted peak explosive fill pressures are below the reaction threshold criteria.

Based on flyer plate threshold tests, burning is the worst case reaction and is predicted for the Mk103 warhead in all three donor environments.

Flyer plate tests indicate the load environment from a 30,000-pound donor could cause a WAU-17 warhead to burn or explode. More flyer plate tests are required to determine the reaction threshold of the WAU-17 to the 30,000-pound donor environment. The load environment from a 5,000-pound donor or an 18,000-pound donor will crush and rupture a WAU-17. No reaction more severe than a burn is expected.

6.0 RECOMMENDATIONS

It is recommended that the maximum NEW stored in an ARMCO revetment module be limited to 18,000 pounds when thin-cased ordnance (like the Mk103 warhead) and robust (missile) ordnance (such as the WAU-17 warhead) are adjacent to the donor. The 7-foot-thick, sand-filled ARMCO revetment wall (Ref 1) is required to prevent SD of the WAU-17. The minimum size of the storage area is 85 by 50 feet and a minimum 10-foot standoff is required between any explosive and a revetment wall (see Figure 1).

A 5.25-foot ARMCO revetment wall (Ref 1) will prevent SD of thin-cased ordnance and robust (missile) ordnance from a 5,000-pound donor. This donor may be placed anywhere in the storage area shown in Figure 1. A minimum 10-foot standoff is required between any explosive and a revetment wall.

The maximum NEW stored in an ARMCO revetment module remains unchanged at 30,000 pounds when robust (non-missile) ordnance, such as the Mk80 series and M117 bombs, are adjacent to the donor. The 7-foot-thick, sand-filled ARMCO revetment wall (Ref 1) is required to prevent SD of robust (non-missile) ordnance. The minimum size of the storage area is 85 by 50 feet and a minimum 10-foot standoff is required between any explosive and a revetment wall (see Figure 1).

7.0 REFERENCES

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2. Energetic Materials Research and Testing Center. Report No. FR-94-34: Magazine crush tests results for thin skinned ordnance items, by Harry Reeves. New Mexico Tech, Socorro, NM, 15 Dec 1994.

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Table 1. Calculated Revetment Wall Load Environment and Response

ARMCO Type	Wall Thickness (ft)	Wall Weight (psf)	Charge Weight (lb)	Number of Line Charges (a)	Impulse (psi-sec)	Wall Velocity (ft/sec)
A	7	700	30,000	1	23.78	158
A	7	700	30,000	2	21.60	144
A	7	700	30,000	3	13.59	90
A	7	700	18,000	1	16.14	107
A	7	700	18,000	2	14.50	96
A	7	700	18,000	3	8.87	59
B	5.25	525	5,000	(b)	15.00	133

(a) Impulse load based on charge being uniformly distributed on lines parallel to the revetment wall using AUTODYN-2.
(b) Impulse load is calculated from a single point using SHOCK.

Table 2. Mk103 Warhead Flyer Plate Threshold Reaction Test Results

Test	Flyer Plate (b)		Acceptor (c)			
(a)	Weight (lb)	Velocity (ft/sec)	Type of Explosive	Unit Impulse (psi-sec)	Unit Strain Energy (ft-k/cu in.)	Reaction
7	4,000	296	PBXN-106	87	1.80	Partial Burn
8	4,000	304	PBXN-106	89	1.90	Partial Burn
9	2,000	127	PBXN-106	19	0.18	Partial Burn
10	2,000	278	PBXN-106	41	0.88	Partial Burn
11	2,000	526	PBXN-106	77	3.20	Partial Burn
12	2,000	278	H-6	41	0.88	Very Local Burn
13	2,000	526	H-6	77	3.20	Very Local Burn
14	4,000	304	H-6	89	1.90	Very Local Burn

(a) Test setup included 10-inch crush pack (alternating layers of plywood and steel) between flyer plate, and acceptor and a 12- x 49.5- x 49.5-inch backstop (8,500 pounds).
(b) Flyer Plate: 4-foot x 4-foot x t-inch steel plate (t = 3 or 5 inches).
(c) Mk103 torpedo warhead: explosive weight, area = 221 sq. in., volume = 2,256 cu in.

Table 3. Unit Impulse and Energy Loads for WAU-17 Flyer Plate Threshold Reaction Tests

Test (a)	Flyer Plate Weight (lb)	Flyer Plate Velocity (ft/sec)	Back Plate Weight (lb)	Unit Impulse (psi-sec)	Unit Energy (k-ft/cu in.)	Reaction
1	2,000	265	6,000	59.8	2.00	Burn/Explo
2	4,000	120	6,000	46.3	0.70	No Reaction
3	2,000	275	8,000	70.3	2.22	Burn/Explo

Note: Test setup includes a 3600-pound crush plate of alternating layers of plywood and steel (1-in. plywood+2-in. steel+1-in. plywood+1-in. steel +1-in. plywood +2-in. steel+2-in. plywood).

Table 4. Predicted Mk103 and WAU-17 Unit Impulse and Energy Design Loads from ARMCO Revetment

Weapon Type	Donor Weight (lb)	Wall Thickness (ft)	Wall Velocity (ft/sec)	Effective Weight (lbs)	Unit Impulse (psi-sec)	Unit Energy (k-ft/cu in.)
Mk103	30,000	7	158	2,420	51.6	0.40
WAU-17	30,000	7	158	1,760	60.0	0.75
Mk103	18,000	7	108	1,950	29.6	0.16
WAU-17	18,000	7	108	1,830	42.6	0.37
WAU-17	5,000	5.25	133	1,310	37.5	0.40

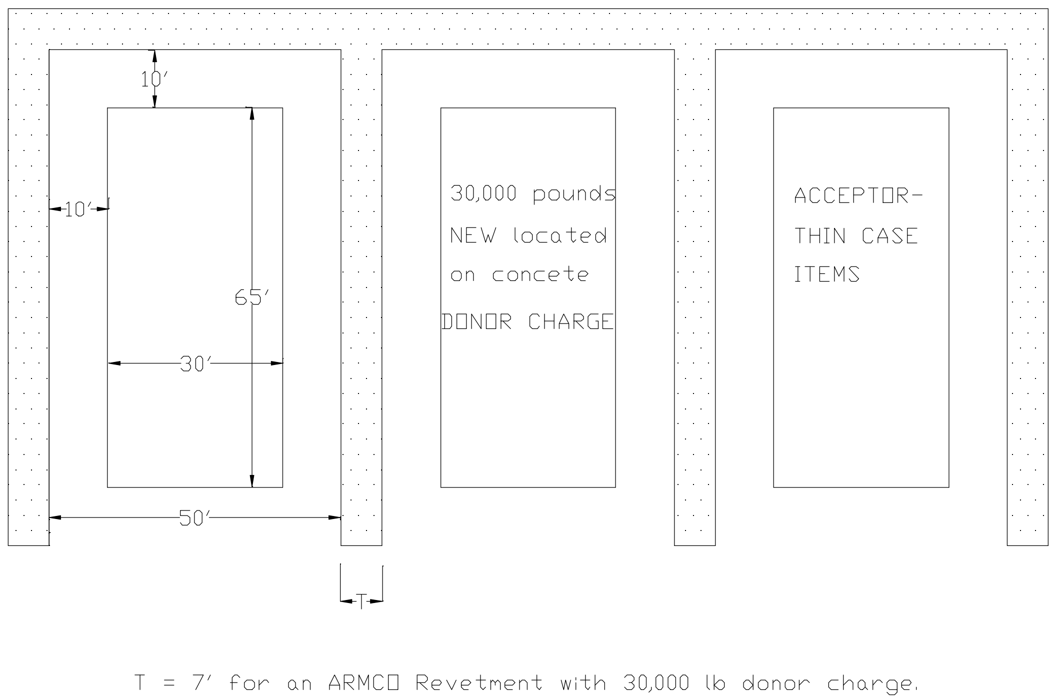

Figure 1. Worst Case Revetment Module Layout for Impulse Loads.

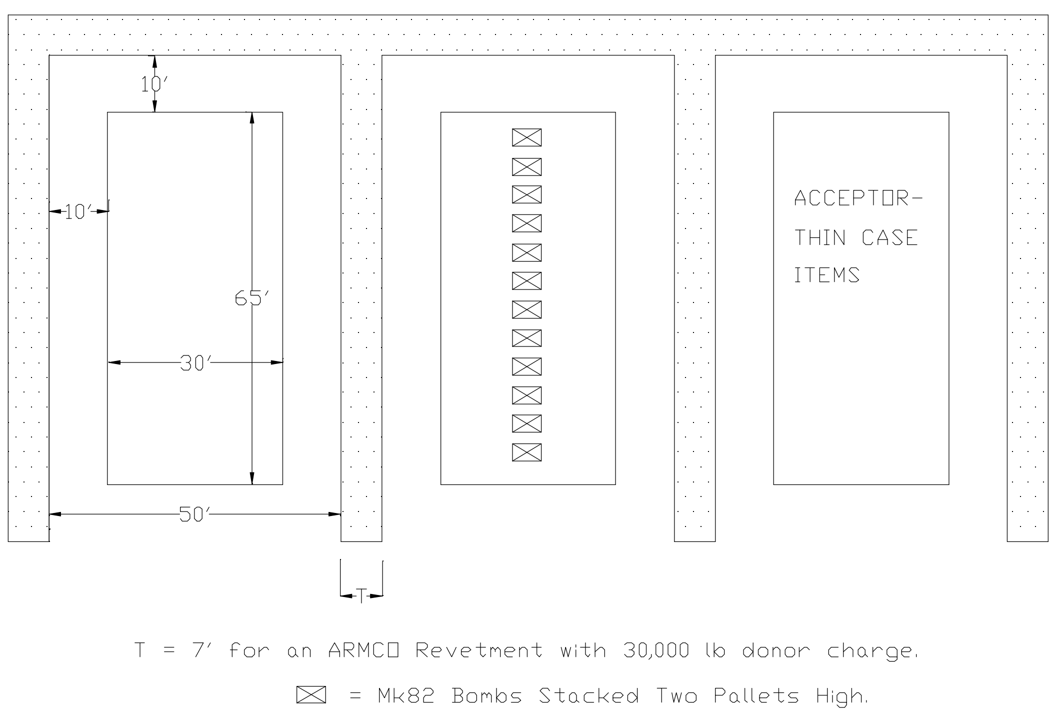

Figure 2a. Donor Layout for Worst-Case Module Impulse Loads, Single Row of Bombs.

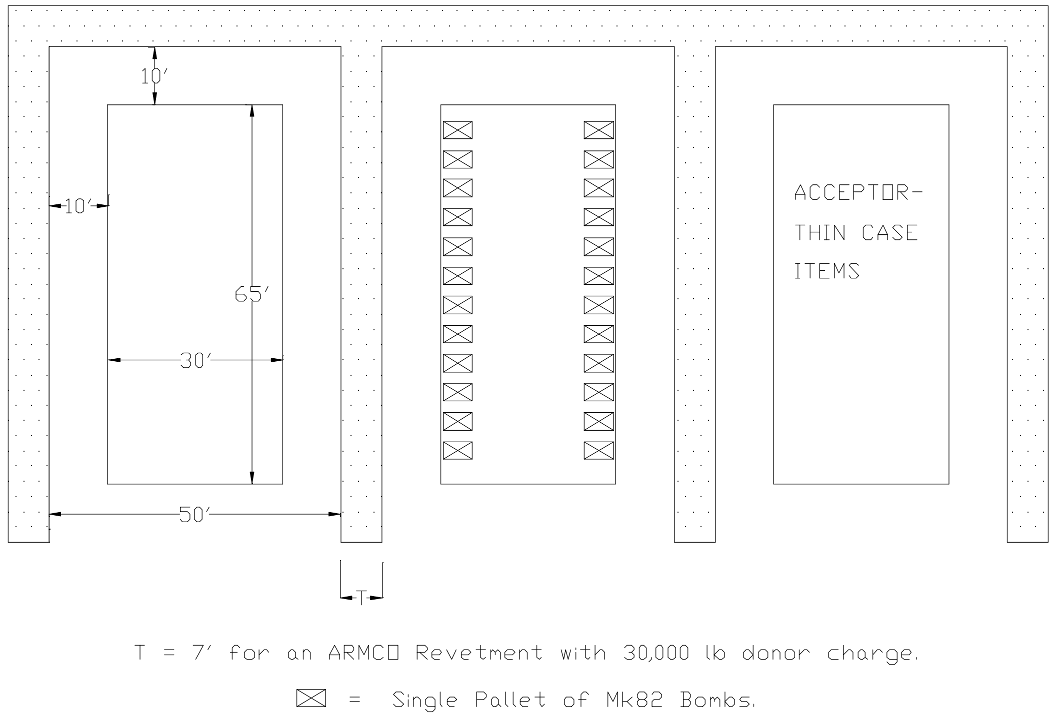

Figure 2b. Donor Layout for Worst-Case Module Impulse Loads, Double Row of Bombs.

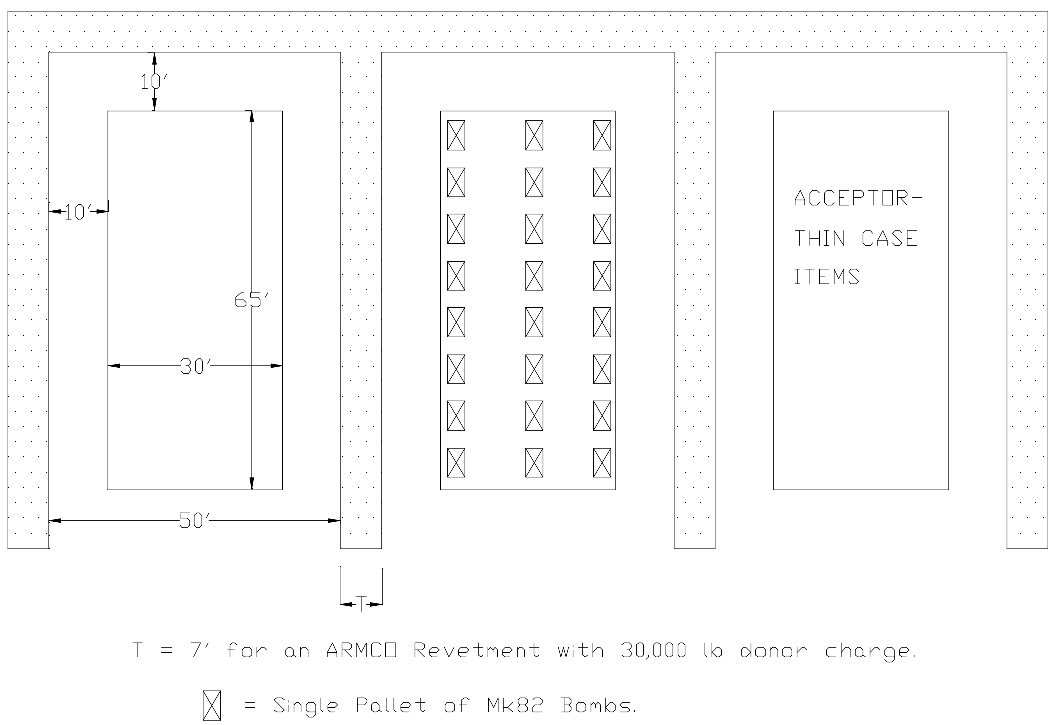

Figure 2c. Donor Layout for Worst-Case Module Impulse Loads, Triple Row of Bombs.

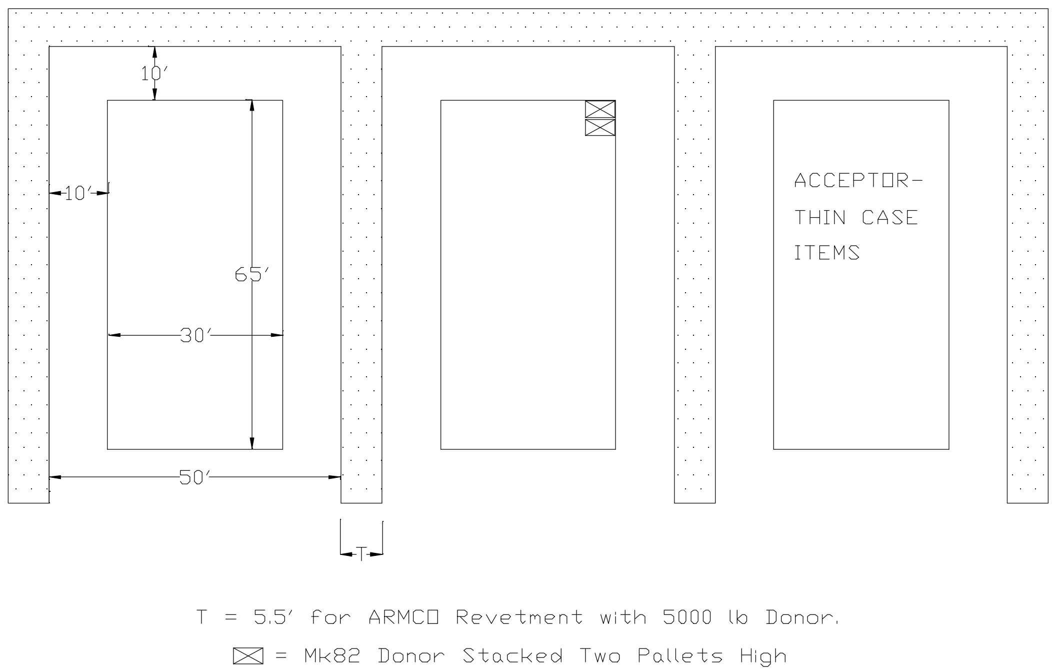

Figure 3. Donor Layout for Worst-Case Module Impulse Loads, 5,000 lb Charge.

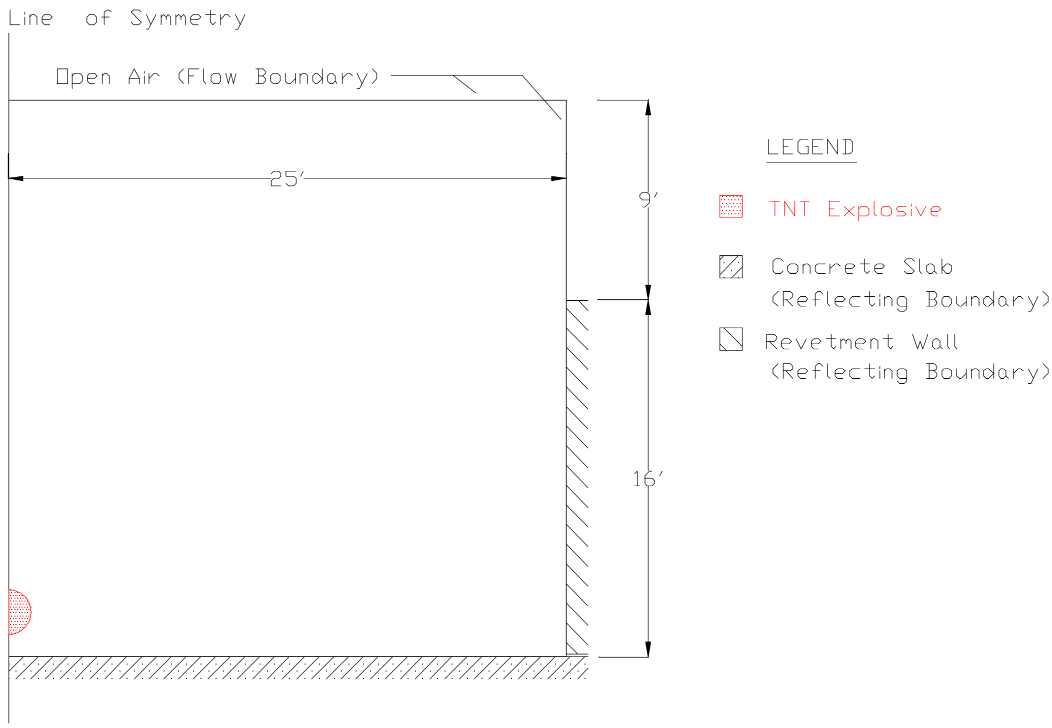

Figure 4. Cross-Section of AUTODYN-2D Model, 30,000lb Donor Single Charge.

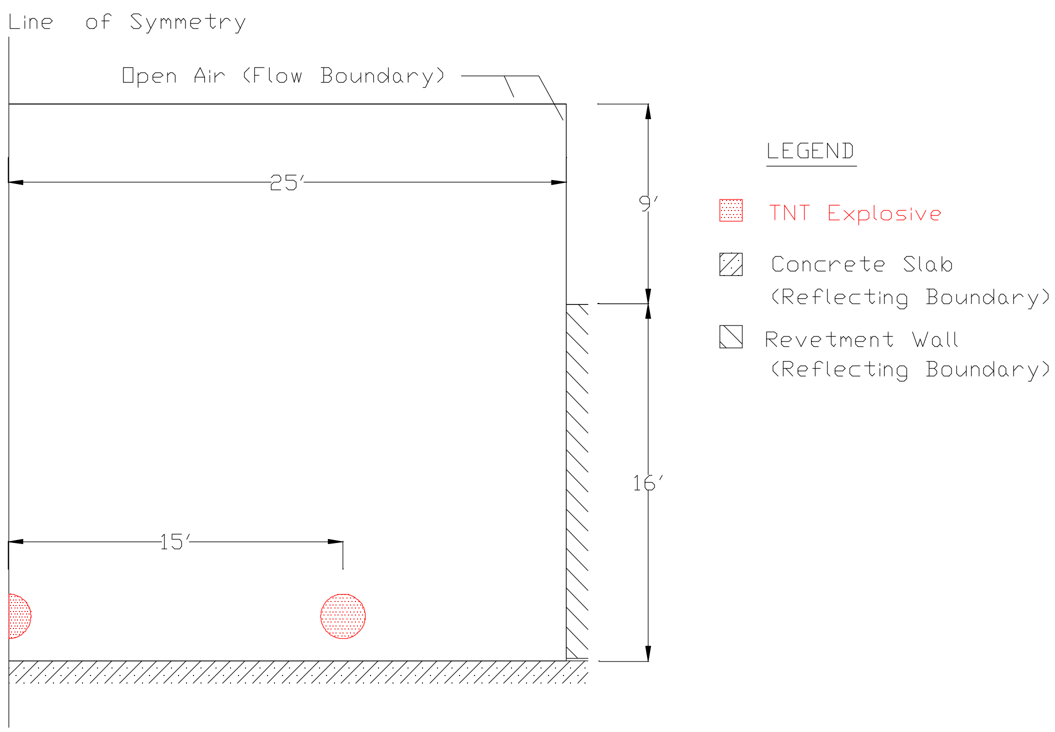

Figure 5. Cross-Section of AUTODYN-2D Model, 30000lb Donor Three Charges.

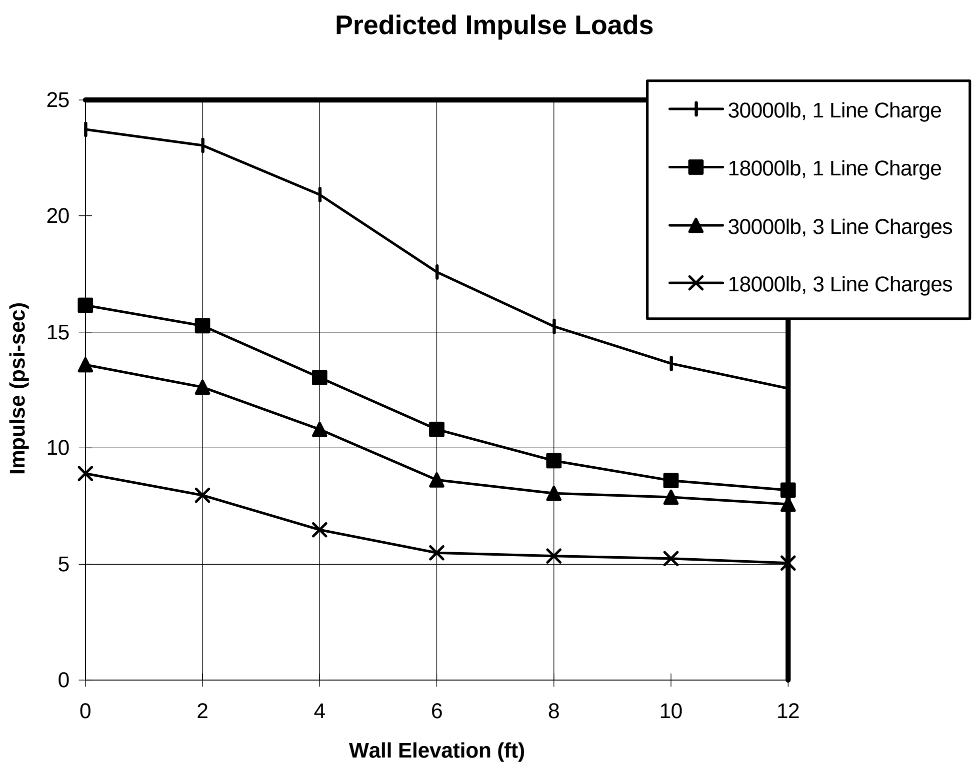

Figure 6. Impulse Loads at Different Wall Elevations for Different Donor Layouts, AUTODYN-2D.

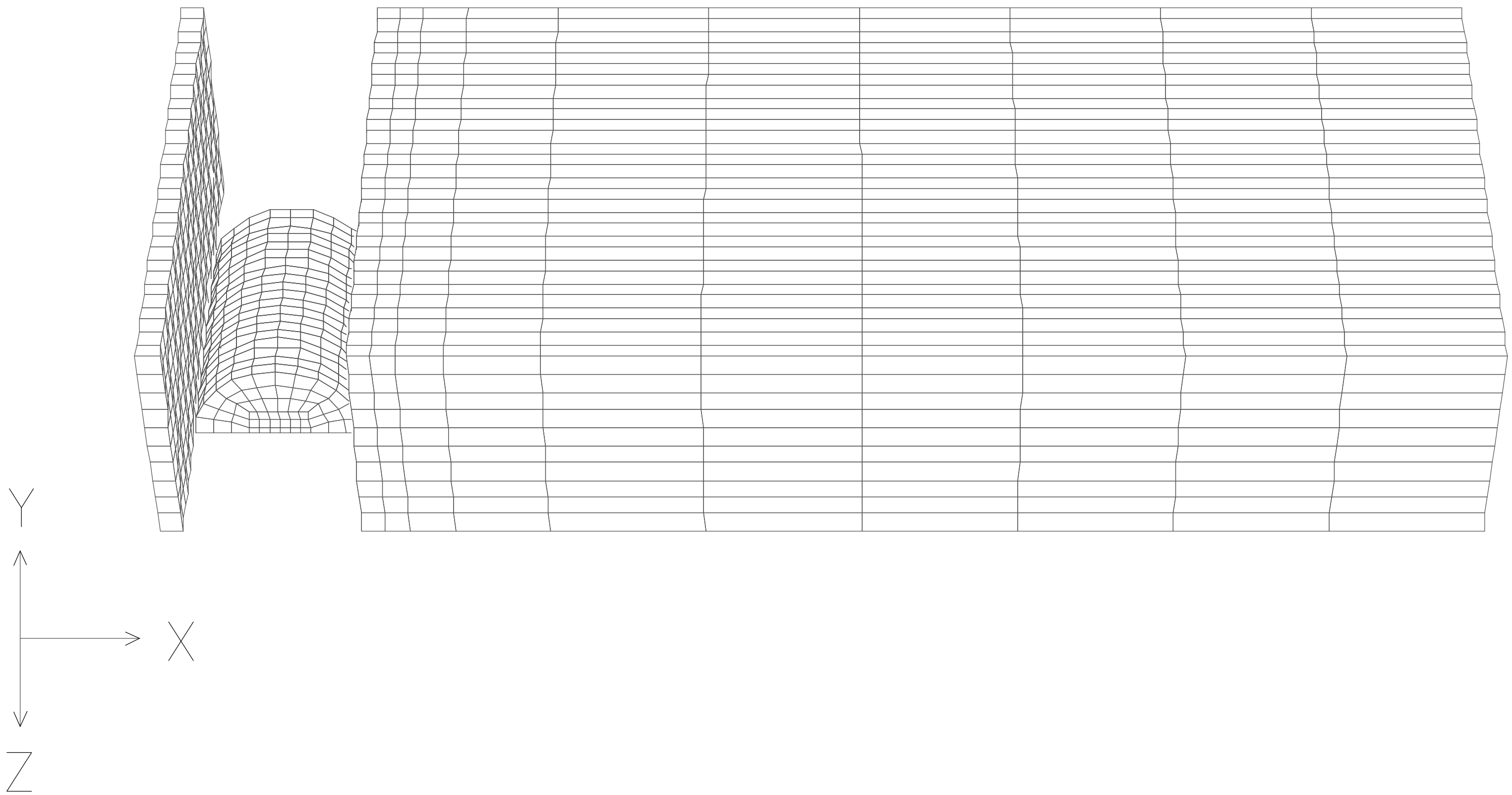

Figure 7. DYNA-3D Mk103 Crush Model, 3’ x 3’ Tributary Wall Loading Area.

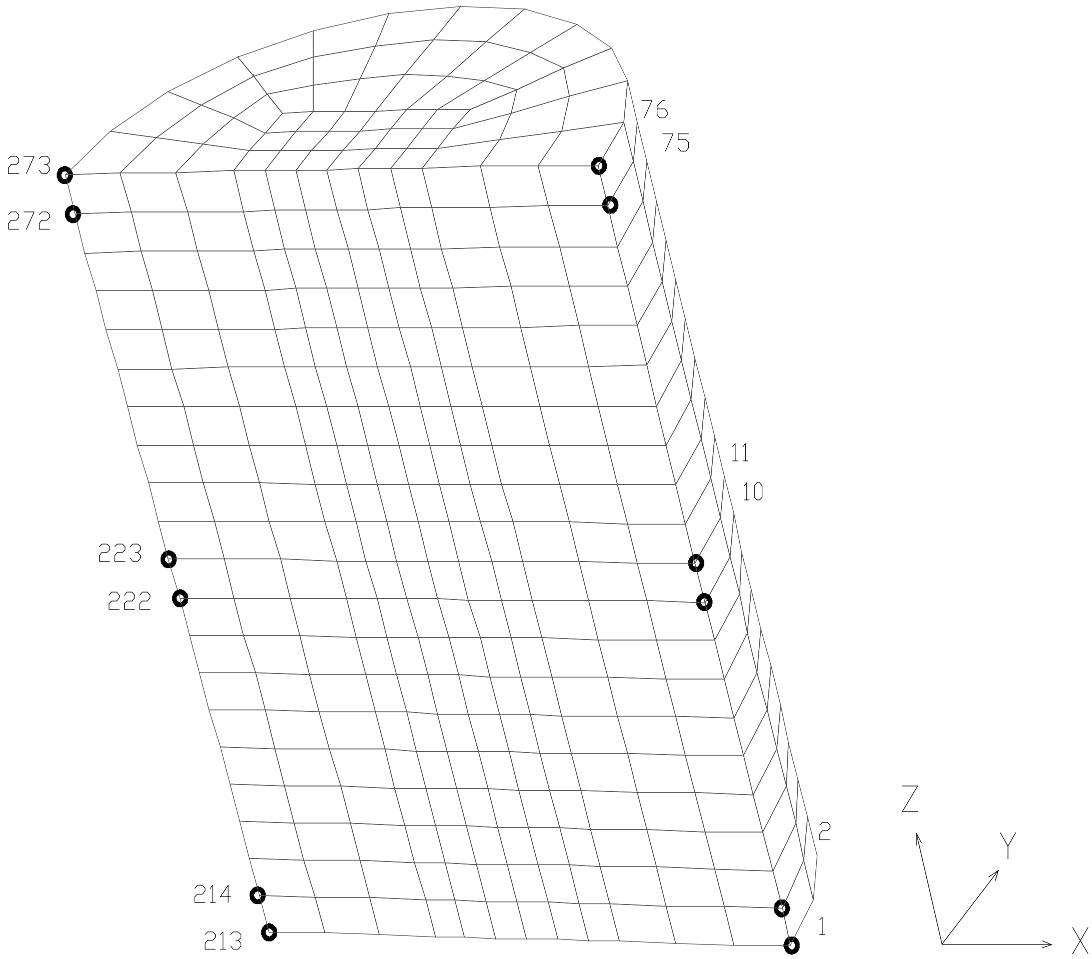

Figure 8a. Nodal Locations in Mk103 Explosive Fill, x-z plane.

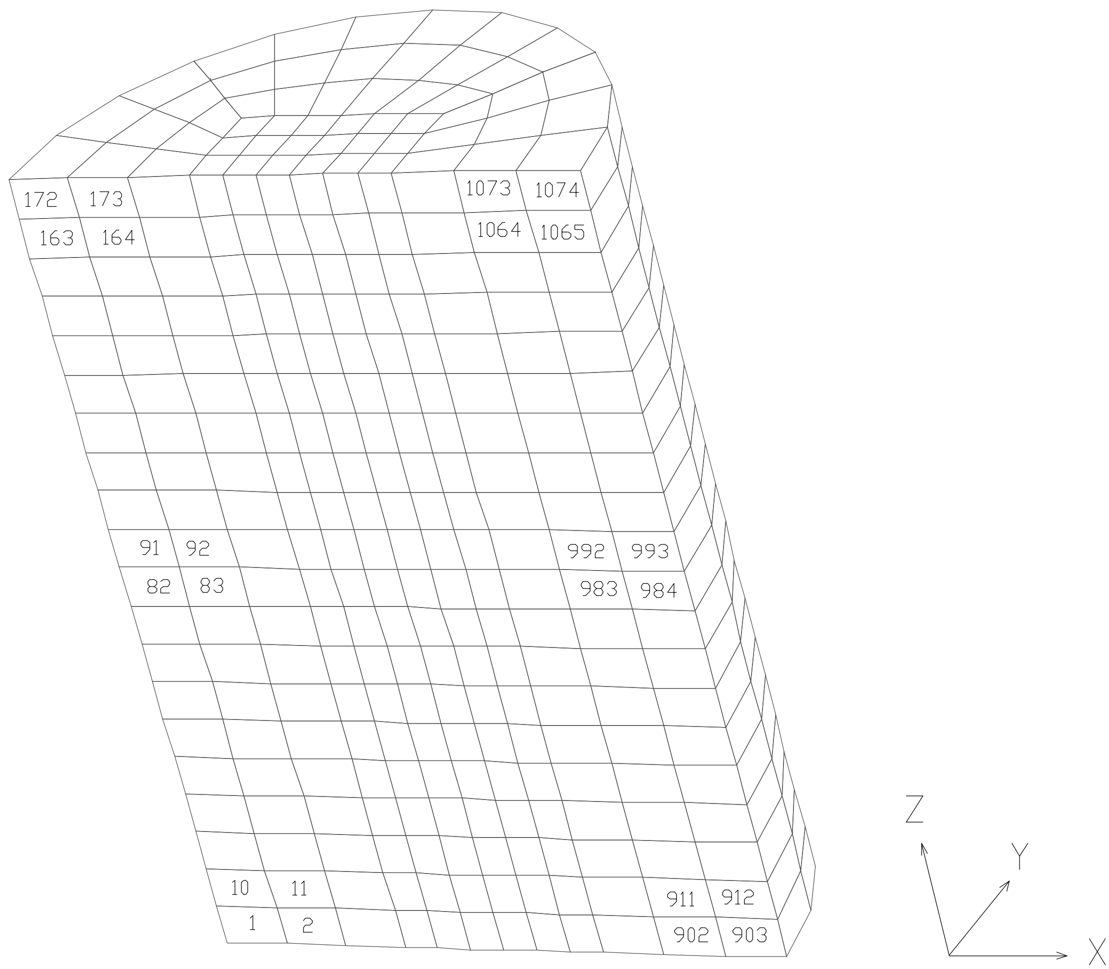

Figure 8b. Elements Locations in Mk103 Explosive Fill, x-z plane.

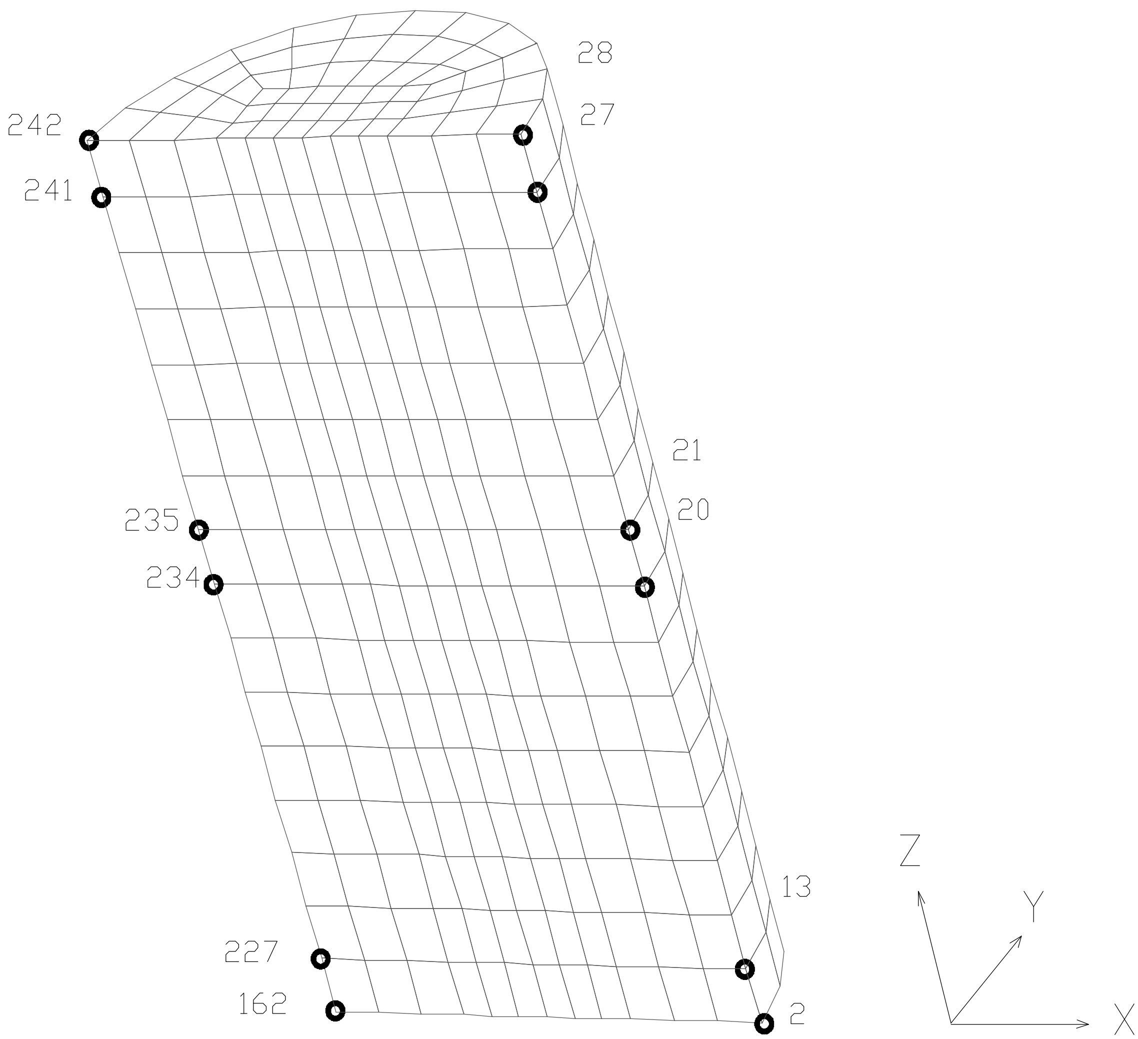

Figure 9a. Nodal Locations in WAU-17 Explosive Fill, x-z plane.

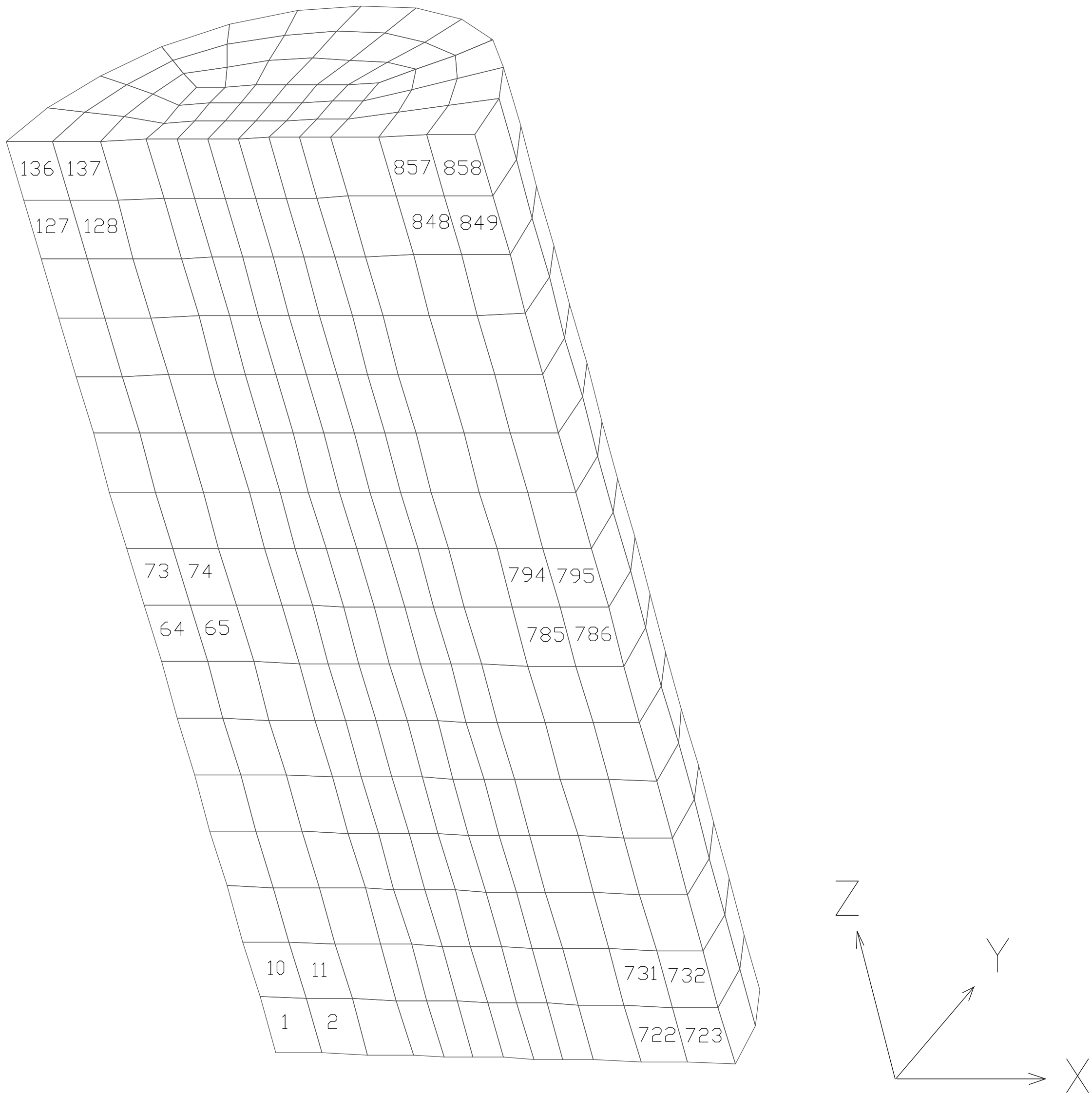

Figure 9b. Elements Locations in WAU-17 Explosive Fill, x-z plane.

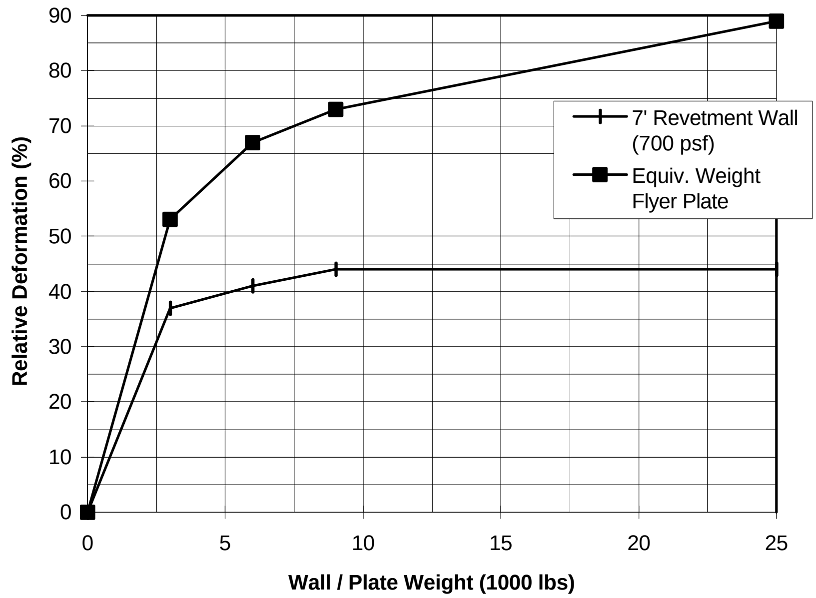

Figure 10a. Mk103 Relative Deformation Curves, 30000 lb Donor.

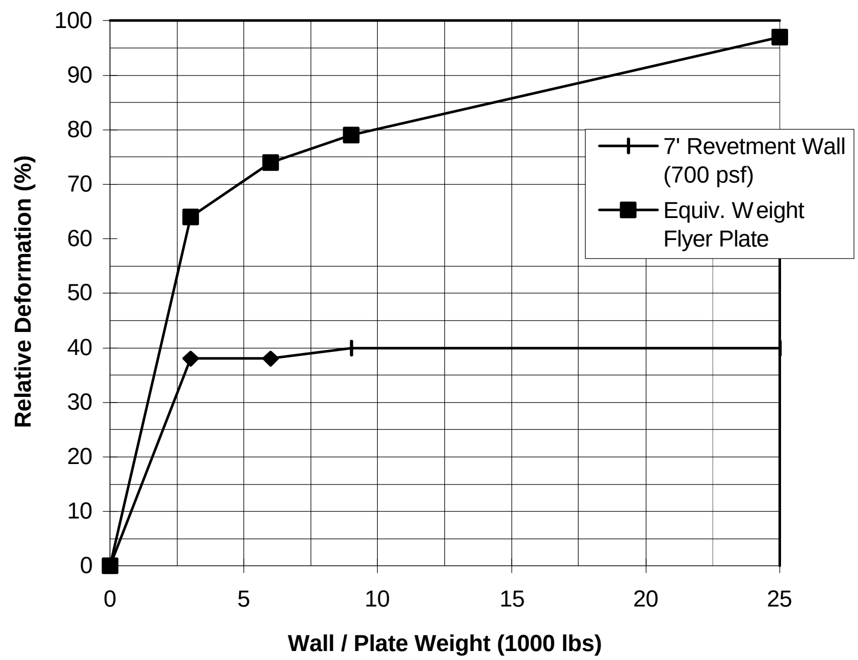

Figure 10b. WAU-17 Relative Deformation Curves, 30000 lb Donor.

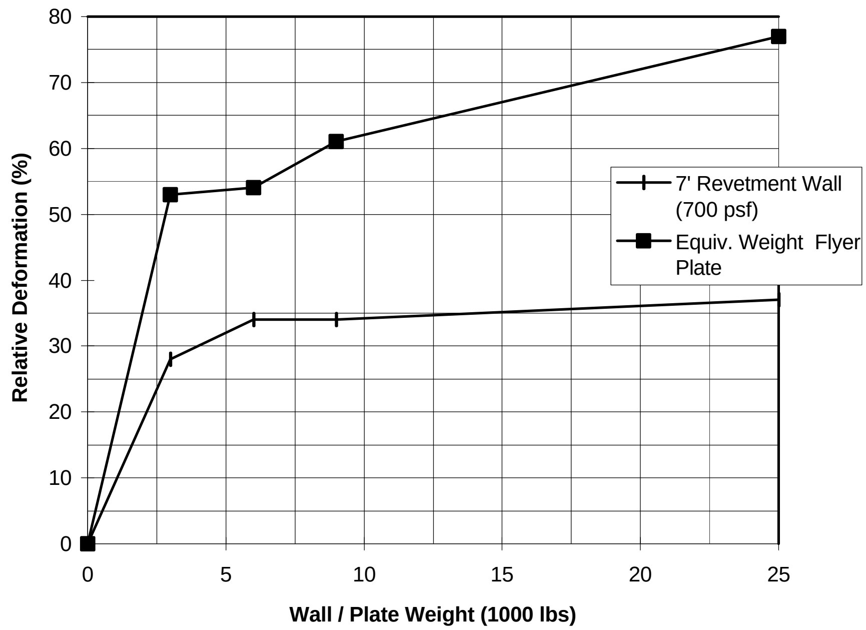

Figure 10c. Mk103 Relative Deformation Curves, 18000 lb Donor

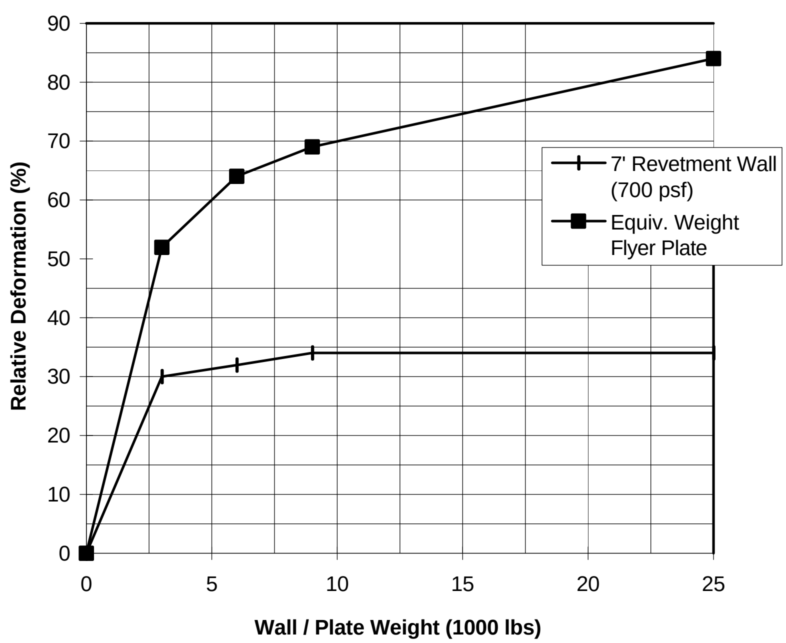

Figure 10d. WAU-17 Relative Deformation Curves, 18000 lb Donor.

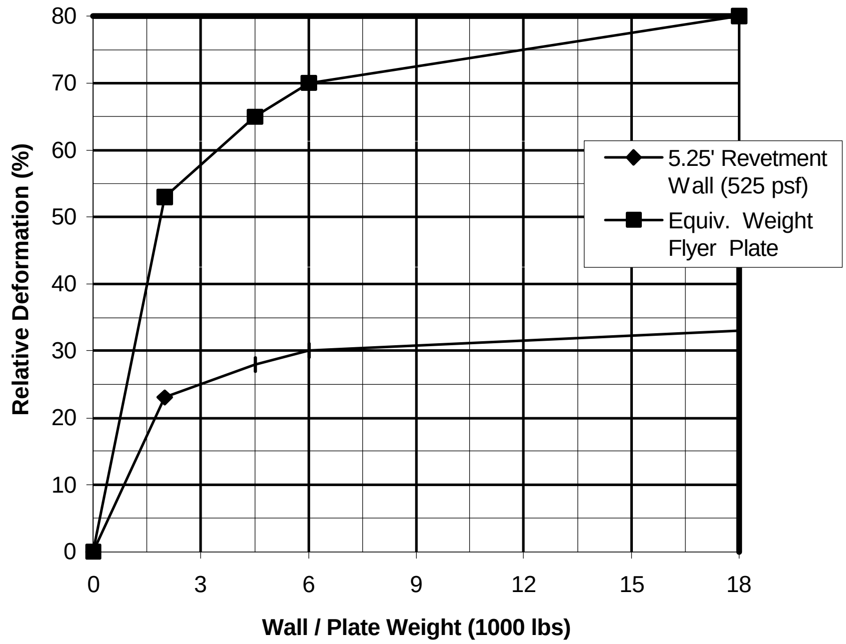

Figure 10e. WAU-17 Relative Deformation Curves, 5000 lb Donor.

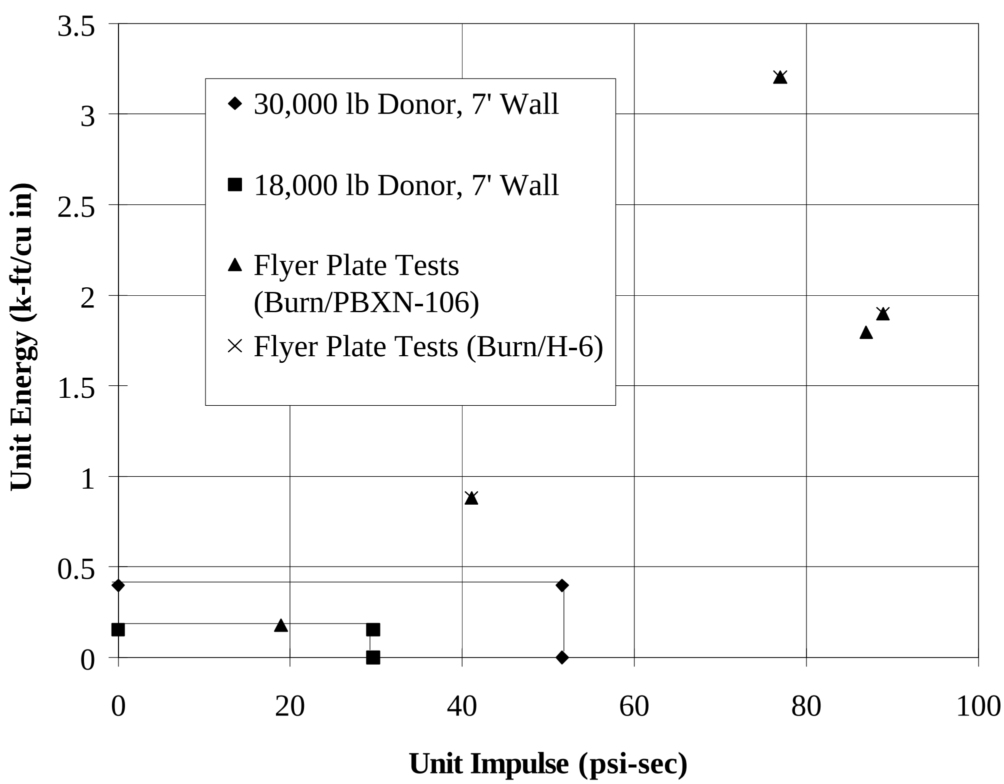

Figure 11. Mk103 Load Environment, Test Results vs. ARMCO Predictions.

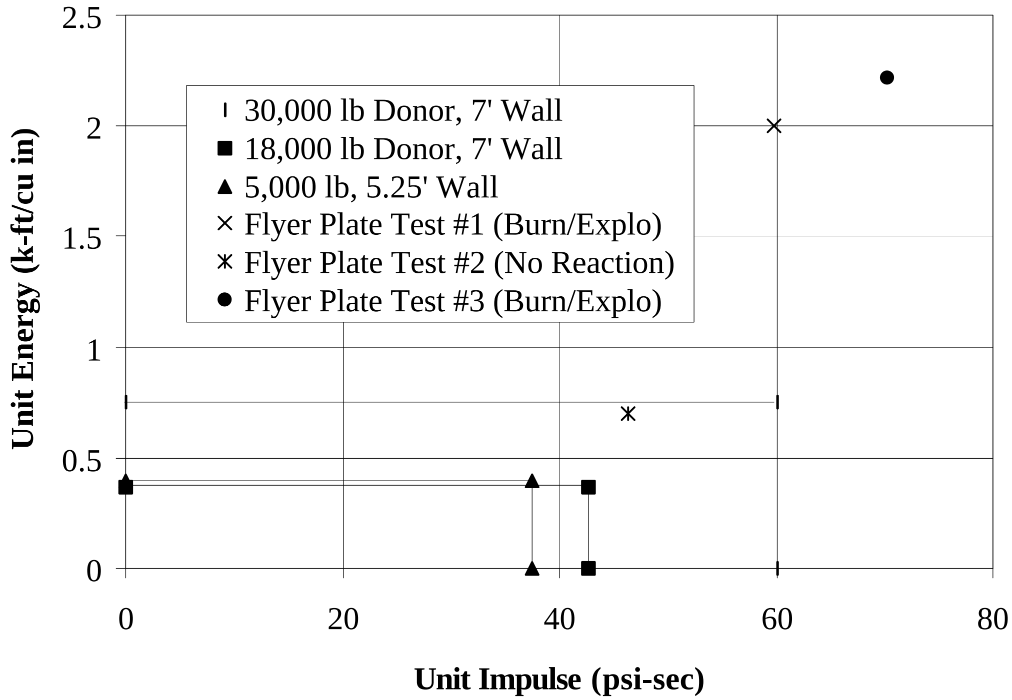

Figure 12. WAU-17 Load Environment, Test Results vs. ARMCO Predictions.