XM982 Excalibur Sympathetic Detonation Modeling and Experimentation (U)

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(U) ABSTRACT

(U) The XM982 Excalibur is a 155mm artillery projectile currently being developed with a unitary warhead under PM Excalibur at Picatinny, NJ. Bofors and General Dynamics Ordnance and Tactical Systems (GD-OTS) have developed the warhead and Raytheon is the system contractor. The unitary warhead consists of a heavy steel body with a polyethylene surrounded PBXN-9 explosive billet. The packaging container consists of a thin steel shell with foam and polyethylene support for the munition. Two sympathetic detonation configurations (diagonal and adjacent acceptors) were originally tested by GD-OTS. The adjacent acceptor configuration resulted in a violent response. Concerns over achieving the sympathetic detonation (SD) requirement resulted in additional ARDEC modeling efforts. Based on logistics requirements, a variety of practical packaging configurations using different spacing and buffer materials were modeled. The high rate continuum model CALE was used with appropriate material models to predict pressure histories in the sympathetic detonation test acceptor munitions. Several promising configurations were identified. A final configuration was downselected and modeled. Based on these promising modeling results, an engineering sympathetic detonation test was completed. The successful result of this test provides the basis for the final packaging configuration. System level sympathetic detonation testing will be completed during upcoming XM982 qualification testing.

(U) INTRODUCTION

(U) Modern warheads development necessitates consideration of a number of design aspects that have a pronounced impact on overall munition efficacy, including but not limited to, determining how sensitive a munition is when subject to various external insults. Insensitive munition (IM) testing is conducted in an attempt to differentiate between responses exhibited when ordnance is exposed to various external stimuli representative of ones most likely to be seen over its lifetime. These stimuli include fast and slow cook-off (FCO and SCO), bullet and fragment impact (BI and FI), shaped charge jet impact (SCJ) and sympathetic detonation (SD).

(U) One test which has typically proven difficult to pass, especially for munitions containing a high energy explosive with a high percentage of HMX or RDX, is the SD test. SD testing attempts to determine the level of violence of reaction exhibited by a live “acceptor” round when exposed to the impact shock and deformation produced from the detonation of a nearby “donor” round. The donor explosion phenomena propagates outward from the initial round and often causes the unintended detonation of adjacent rounds, hence the expression “sympathetic detonation”. SD subjects personnel and materiel in the vicinity to much greater damaging effects than a single detonating round otherwise might.

(U) The severity of reaction, as is evidenced by damage inflicted on a witness plate placed beneath the acceptor round, also manifests itself in other ways such as large pieces of unreacted explosive, lower blast pressures, and larger fragments distributed closer than they would have had the acceptor round fully detonated. The depth and breadth of the damage to a witness plate, is a primary indicator of whether the acceptor round detonated or reacted to a lesser degree.

(U) The document which describes the various degrees of reaction for all of the aforementioned IM tests is Mil-STD-2105C (STANAG 4396 also governs munition test procedures for SD). The Mil-STD defines five levels of reaction severity ranging from the most severe type I detonation to the least violent type V burning reaction. For XM982, the requirement for passing SD testing was that the acceptor round exhibit nothing more severe than a type II partial detonation.

(U) The XM982 incorporates two new design features on the projectile, primarily for passing both cook-off tests, but as will be shown later also impacted SD testing and modeling. The first of these features is a high density polyethylene (HDPE) sleeve that completely encapsulates the explosive billet. This sleeve was designed to melt at a lower temperature than the critical temperature of PBXN-9 and provide a path for gases to vent around the billet. The second feature that works hand in hand with the HDPE sleeve is a number of vent plugs, located radially around the warhead body, which are also designed to melt at a lower temperature than one at which the billet reacts. Working in conjunction with the melted HDPE liner, these vent plugs fall out and provide a path for the products of combustion, given off on heating, from the billet to the atmosphere. The technical approach is that if the pressure surrounding a heated billet is relieved, then the reaction of a heated billet should not be as severe as it otherwise would be in a pressurized case.

(U) Melt pour explosives have traditionally been used in artillery applications in the past. For example; composition B and TNT have been used on the 155mm M107 and TNT has been loaded in the 155mm M795. Although lower energy level melt pour explosives have traditionally been used in artillery applications, in the interest of increasing lethality some newer projectiles are loaded with higher energy explosives such as PBXN-9. An example of such a round is the developmental unitary warhead XM982 155mm artillery projectile.

(U) INITIAL TESTING

(U) GD-OTS, working as a subcontractor to Bofors and the system contractor Raytheon, and in conjunction with the PM Excalibur, designed and produced initial XM982 warheads for IM testing. In addition to these efforts, the packaging group at Picatinny Arsenal designed and procured new 8 inch diameter shipping containers.

(U) In the initial container design, the projectile was nested within a .375 inch thick high density polyethylene (HDPE) sleeve which was surrounded by .625 inches of 6 lb/ft^3 foam as seen in figure #1 below.

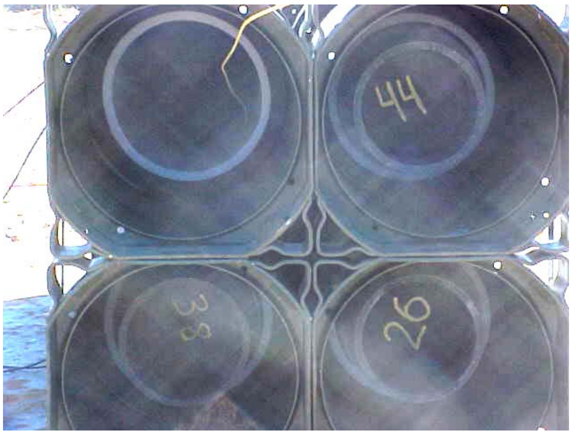
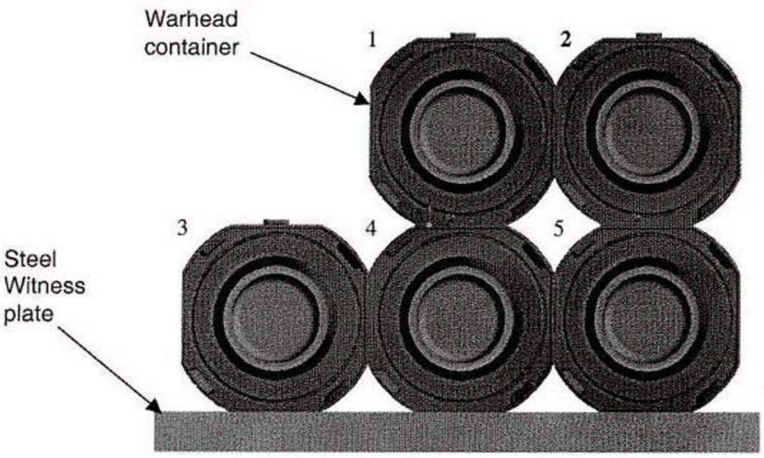


Figure #1 (U) Initial test packaged rounds without end caps

(U) This HDPE and foam next was designed not only to protect the projectile from environmental insults such as vibration, impact, and humidity, but to help mitigate the shock realized by a potential acceptor as well. Five rounds were stacked, in order to more accurately simulate confinement that might contribute to severity of reaction in an actual loaded configuration, and a witness plate placed below the acceptors to aid in determination of the level of reaction. The packaged configuration used for the two initial SD tests is seen in figure #2 below.



Arrangement of Test Assemblies (End View)

Position of Assembly	Test No. 1	Test No. 2
1	Slug	**Donor**
2	**Donor**	Slug
3	Slug	Slug
4	**Acceptor**	**Acceptor**
5	Slug	Slug

Figure #2 (U) Initial test configurations

(U) Since the time of transit between storage and the user represents the time of the projectile's life during which it is most likely to suffer from a physical insult resulting in an adverse reaction, SD testing is conducted with the projectile inside of the shipping container. In the first test, the diagonal case, the donor was placed in the number 2 position and the live acceptor was placed in the number 4 position diagonally downward and to the left of this donor. In the second test, that is the adjacent test case, the number 1 position was occupied by the donor while the acceptor still occupied the number 4 position. In both cases, all other positions were occupied by inert rounds.

(U) The results of the testing revealed that for the first test, the diagonal case, the acceptor warhead did not exhibit a type I reaction. It was, in fact, determined to have exhibited a type III reaction due to the lack of substantial damage to the witness plate, a number of large chunks of unreacted explosive, and the existence of relatively few large sized fragments. Figure #3 is a photo of the results of the first test.

Figure #3 (U) Test #1 unreacted PBXN-9 and large warhead case fragment

(U) The conclusion for the second test however, the adjacent acceptor case, indicated a type I detonation occurred. Evidence for the level of reaction, as can be seen by the high degree of damage of the second witness plate as compared with the first test witness plate in figure #4 below, was also supported by a lack of unreacted explosives and large fragments.

Figure #4 (U) Test #1 (diagonal) and Test #2 (adjacent) witness plate results

(U) INITIAL MODELING

(U) To quantify the strength of the shock that the acceptor round actually saw, ARDEC and GD-OTS modeled the SD test using the hydrodynamics codes CALE and HULL respectively. In order to consider the worst case scenario, a full diameter planar cross section taken through each round at a case thickness of .316 inches and through each container at .060 inches thick was modeled. Each container was located exactly 1 inch from the next with the donor round in the lower left corner and all the other rounds being inert acceptors. The donor round was set off at time zero and the subsequent shock and reaction products were allowed to propagate outward for approximately 200 µs, more than enough time for the shock to have impinged upon both the adjacent and diagonal rounds. Pressure time history data was recorded at various locations in the inert acceptor billets. The initial three configurations modeled included a projectile surrounded only by foam in the container, the projectile surrounded by a .375 inch HDPE sleeve inside of the container (the as tested configuration), and a projectile surrounded by an .375 inch HDPE sleeve within the container surrounded by yet another .375 inch thick HDPE sleeve. A plot of an early model setup, without an HDPE sleeve surrounding the warhead, is shown below.

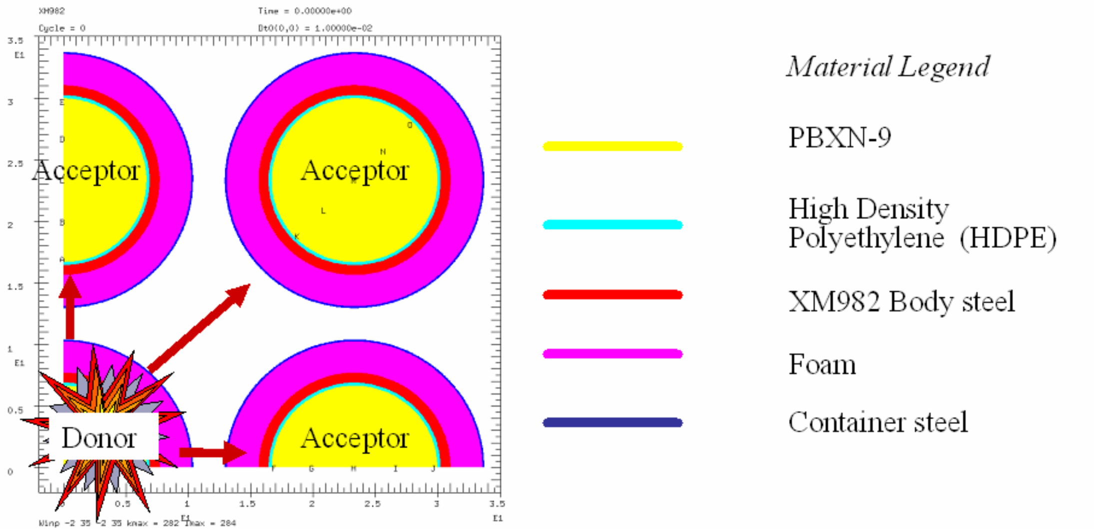


Figure #5 (U) Model setup

(U) The ARDEC Energetics and Warheads Division was tasked with examining the as tested container design, to see where improvements could be made that might increase the likelihood of passing the SD test. To help validate this effort, differences between the two-dimensional hydrocodes CALE (C based Arbitrary Lagrangian Eulerian) used by ARDEC and HULL (Eulerian) used by GD-OTS were examined. Two dimensional modeling was used as it is believed to yield an acceptable level of fidelity applicable to the geometry of this situation and the costs are considerably less, both computationally and financially, than three dimensional simulations.

(U) Conducting comparative modeling was necessary to see how well the different continuum modeling programs agreed so that results obtained from subsequent analysis done with CALE might be more fully trusted as being realistic. Figure #6, a plot from both CALE and HULL, shows the expanding reaction products and shock impacting the adjacent projectiles at approximately 76 µs.

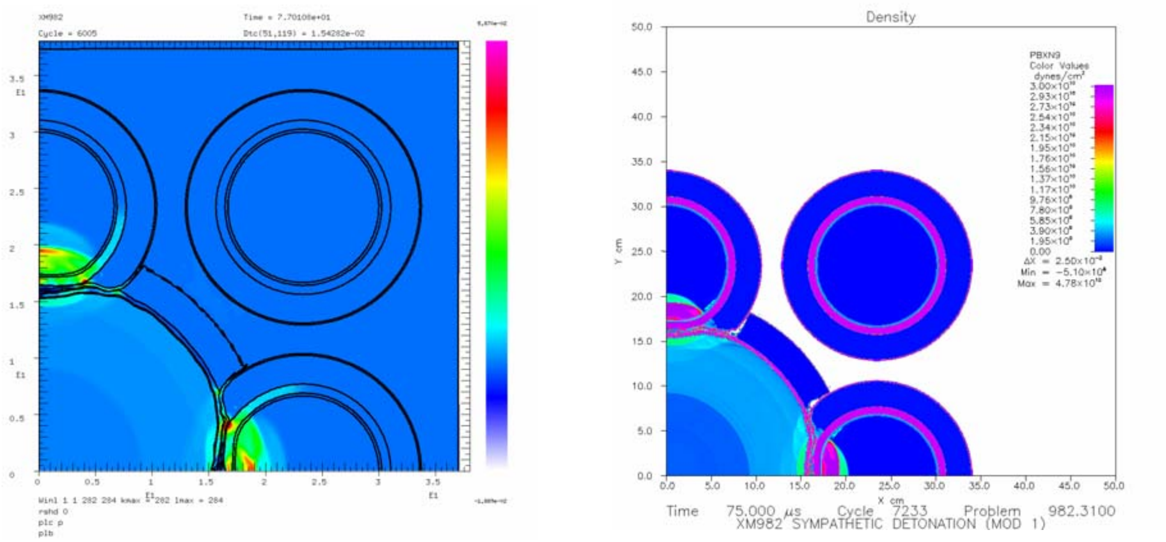


Figure #6 (U) CALE and HULL pressure distributions

(U) The pressures calculated by ARDEC at discrete locations were very close to those calculated by GD-OTS, the trend of diminishing pressures as a function of distance from the edge of the acceptor billet was exhibited by both. GD-OTS calculated a peak pressure of 32 kbars would be reached at 70 µs for the adjacent case and 24 kbars at 130 µs for the diagonal case whereas ARDEC calculated 38 kbars at 70 µs and 22 kbars at 122 µs for the adjacent and diagonal cases respectively.
(U) GD-OTS previously gathered model parameters for PBXN-9[2], with a density of 1.73 g/cm^3, from a 1991 U.S. Navy report, that included the Jones Wilkins Lee (JWL) equation of state (EOS). ARDEC modeled both the warhead case and the inert HE with a Gruneisen EOS while the shipping container and foam used a linear polynomial and Tepla-F EOS respectively. Only the warhead and shipping container were modeled using elastic plastic strength effects.

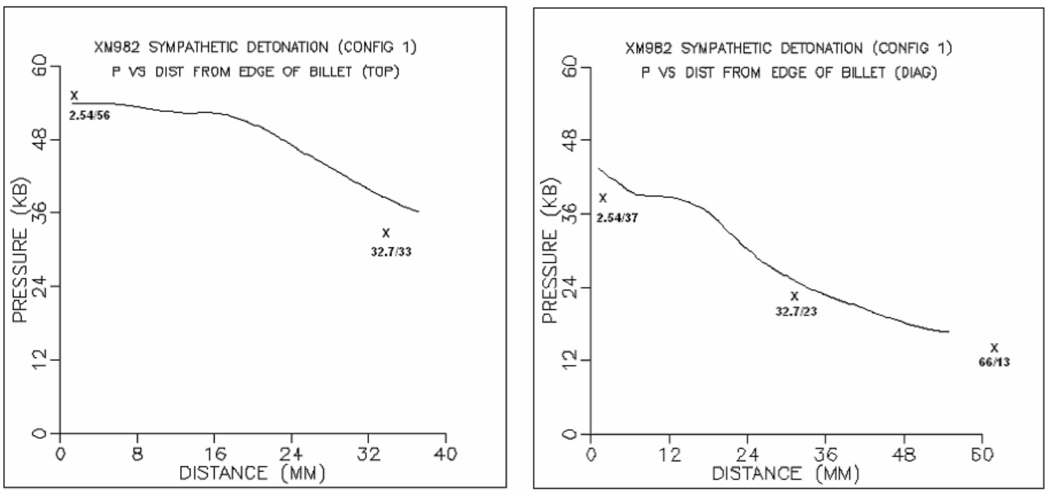


Figure #7 (U) Adjacent and diagonal pressure time histories (line GD-OTS, x – ARDEC)

(U) Although the results from both codes were in close agreement, as shown by the pressure curves in figure #7 below, the real value of these models is somewhat qualitative in nature, due to a lack of significant model validation via testing as well as inexact model fidelity. However, it is believed that the modeling results trends are representative of the shock and material deformation physics involved, and can this modeling approach could therefore be used in packaging design process in order to address SD.

(U) FOLLOW ON MODELING AND TESTING

(U) Proceeding on the premise that the further modeling could be used to investigate potential packaging design improvements, it was apparent that the shock imparted to the diagonal warhead (22kbars peak calculated in CALE), was not enough to cause detonation of the projectile while the shock(38kbar peak) realized by the adjacent warhead was strong enough to cause initiation. A solution configuration of the containers that would reduce the shocks to acceptable levels and allow the rounds to pass SD testing was sought. The effort focused on two primary areas: modifying the materials that occupied the space within the containers and increasing the distance between rounds in an attempt to sufficiently dampen the shock imparted to the acceptor projectiles.

(U) The immediate focus was on introducing materials that would attenuate the shock enough to reduce it to levels which would not cause initiation in the acceptor. Previous testing on other programs pointed to HDPE as a practical material whose use can result in significant reductions in shock pressures for relatively low weight gains. This was important for XM982, as the loaded shipping containers have a well defined maximum weight so that handling and manipulation by the soldiers in the field was still possible. It was for this reason that ARDEC focused on several variations utilizing HDPE as a primary material.

(U) The first four iterations were in fact, variations of using an HDPE sleeve as a buffer material. Initial iterations included the first two previously run, as well as .750 inch thick HDPE sleeves and .750 inch diameter HDPE blocking rods between the diagonal acceptors. It was found that after adding about .750 inches of HDPE, the pressures realized by the diagonal acceptor were higher than that which resulted from using less HDPE. It was hypothesized that the additional HDPE contributed to a focusing of the blast. After the first four variations of HDPE thicknesses, the next four iterations focused on increasing round to round spacing.

(U) Although the original shipping container was approximately 8 inches in diameter, the ARDEC packaging group also raised a potential option of adapting a larger 10 inch diameter container for use by the XM982. This larger container not only allowed for greater amounts of shock attenuating foam and HDPE but perhaps more importantly, they increased the center to center distance between rounds and provided an alternative method of reducing transmitted shock pressures. Three iterations with a ten inch container were modeled before one was identified that yielded appreciably lower results. However, issues with these larger containers include the need to adapt them for use on this round, large additional costs incurred because of the necessary tool up for manufacturing and, most importantly, they reduced the user's strategic configurable load (SCL): the amount of rounds on a pallet that they would ship to the field. Reducing the number of rounds on each SCL would necessitate more trucks to transport the same amount of required rounds and would have severely impacted the logistics of delivering the rounds to the user in the field. As a result, the larger container design was deemed much less attractive and all subsequent modeling reverted back to variations on the 8 inch container.

(U) In parallel with the SD modeling, other IM tests were also being conducted, including BI, FI, and FCO. More than one of these tests revealed that in locating the HDPE next to the warhead body resulted in an inability of the vent plugs to function properly since they were unable to exit the vent holes by virtue of being held in by the HDPE sleeve. It was for this reason that the decision was made to switch the order of the foam and HDPE and locate the foam next to the warhead body.

(U) Additionally, the modeling showed that by switching the order of the foam and HDPE, appreciably reduced adjacent acceptor shock pressures could be achieved. The lessons learned from the 10 inch container iterations were than incorporated into the 8" container modeling. The previous analyses showed that the use an alternating fill of thinner layers of foam and HDPE worked better than fewer thicker layers and that increasing the distance from round to round resulted in a decrease in transmitted shock pressure. Based on these considerations, an additional five configurations were modeled.

(U) The final five analyses began with an alternating assembly of foam and HDPE and increased the container to container spacing in one inch increments. The alternating layers, approximately .25 inches in thickness at a container spacing of 1 inch. This distance was increased until a container spacing of three inches was reached. Although this did not represent the absolute lowest pressure seen in any of the models, it was the only one which reduced the pressure to levels believed to be tolerable while at the same time, providing enough rounds on each SCL to be tolerable to the user. It was for this reason that it was determined to be the most valid candidate for follow on testing. The CALE model predicted that this final container design would result in transmitted shock pressures of 25kbars and 14 kbars for the adjacent and diagonal acceptors respectively. Figure #8 shows the actual shipping container as well as a plot of the physical boundaries of the model of this configuration.

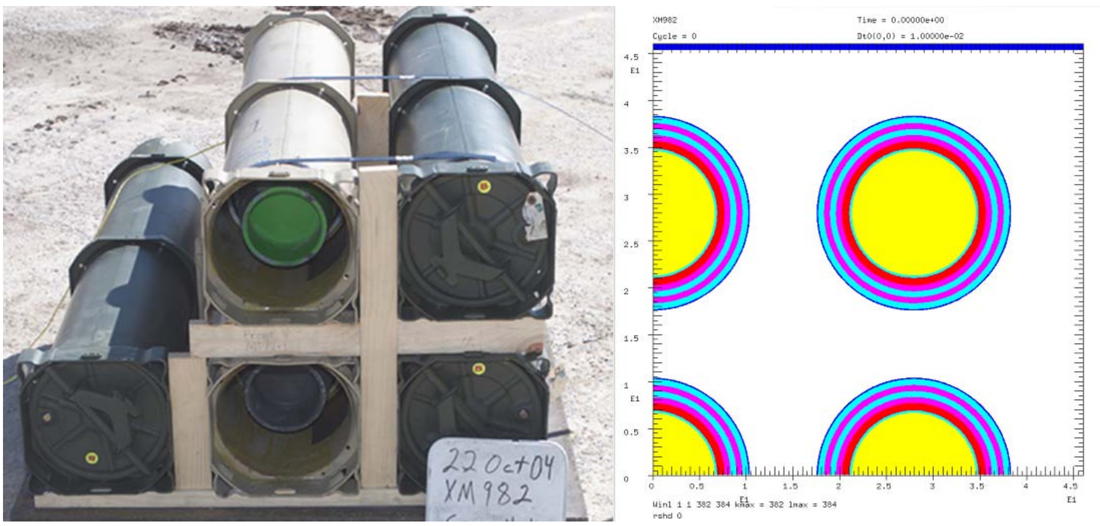


Figure #8 (U) Final test configuration and CALE model at time zero

A close up of a loaded container is shown below.

Figure #9 (U) Close up of a loaded shipping container final design

(U) The testing of the the last container design was conducted at Dugway Proving Ground (DPG) in Utah. Setup was similar to that previously conducted by GD-OTS with the exceptions previously mentioned and the addition of wood spacers on the container flanges, required to give the necessary round to round spacing.

(U) The final test revealed what was later judged to be a type III reaction. This was again apparent from the lack of severe damage to the witness plate, the large amount of unreacted explosive strewn about the test area, and a number of very large fragments. The witness plate while gouged and bent approximately .75 inch, was not damaged to a level corresponding to a detonation. In the area within approximately 25 to 50 feet of the test items, there were numerous large pieces of unreacted explosive. The photographs in figure #10 show both the unreacted explosive and the damage to the witness plate.

Figure #10 (U) Unreacted PBXN-9 and witness plate after latest configuration SD test

(U) In addition to the indications of a less severe reaction mentioned above, several large fragments of the acceptor warhead were recovered, including the nose cone with the fuze safe and arm (FSA) still attached, a large piece of the acceptor shipping container, a large section of the warhead with vent holes attached, and a portion of the base as shown in the following two figures.

Figure #11 (U) Large warhead case fragments after SD testing (base and vents)

Figure #12 (U) Recovered nose w/FSA and acceptor shipping container (front)

(U) CONCLUSIONS

(U) In total, ARDEC modeled 15 different configurations (see attached Table #1) of shipping container packaging designs in an attempt to enable XM982 to pass SD testing. Before this effort began, both adjacent and diagonal acceptor rounds had been tested but only the diagonal round exhibited a passing reaction. Clearly, the transmitted shock pressure and duration for the adjacent round in the initial configuration was high enough to allow a shock to detonation transition.

(U) The initial design in which the projectile sat within an HDPE sleeve surrounded by a foam barrier within the shipping container proved to be insufficient. The SD response was addressed by using high rate continuum modeling and container configuration design changes. Features of the container configurations investigated included round to round spacing, as well as barrier materials composition, order, and thickness within the container. Considering the high cost of testing developmental munitions, this modeling proved to be a relatively inexpensive tool with which to investigate design features. It is worth noting that the strength of the transmitted shock for some of configurations investigated was actually shown to be worse than that achieved by the original design! Although intuitively better, testing of these configurations would have been costly and futile.

(U) Through the use of shock mitigation techniques and iterative modeling via the hydrodynamics code CALE, ARDEC was successfully able to develop a design that not only enabled XM982 to pass SD testing, but did so while providing the user with an acceptable number of rounds per SCL and only minimally affecting the burden on his logistics resources.

(U) REFERENCES

1. J. Osborn and W. Kieffer, XM982 modeling presentation, "XM982 Sympathetic Detonation," GD-OTS Niceville 02, Oct, 2003.
2. Navy Letter, "PBXW-9 Type II (g) JWL EOS," 08 Feb, 1991.

Table #1 (U) Tabulated results for all modeled configurations

Config #	w/HDPE Rods	HDPE Sleeve	Diameter	# of rounds per SCL	Spacing	Pressure (kbars) Adj	Diag
1	No	None	8"	144	1"	56	37
2	No	.375"	8"	144	1"	38	22
3	No	.750"	8"	144	1"	21	55
4	Yes	.750"	8"	144	1"	21	39
5	Yes	.750"	10"	102	1"	22	16
6	No	.750"	10"	102	1"	22	15
7	No	HDPE/foam	10"	102	1"	17	13
8	No	.750"	8"	120	3"	22	16
9	No	.375"	8"	144	1"	34	22
10	No	.750"	8"	144	1"	27	24
11	No	.25"/layer	8"	144	1"	25	22
12	No	.25"/layer	8"	120	2"	26	16
13	No	.25"/layer	8"	120	3"	25	14
14	No	.750"	8"	120	3"	25	24
15	No	.750"	8"	???	4"	21	16

NOTES:

1) Configuration #2 was the original test configuration
2) Configurations #9-14 all used foam immediately next to the warhead vice HDPE
3) The final tested configuration was configuration #13