An Overview of AMO-CAT: DDESB's Explosives Safety Knowledge Improvement Program

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Abstract

A critical mission of the Department of Defense Explosives Safety Board (DDESB) is to develop standards and tools to ensure the safety associated with DOD explosives as they go through their life cycle of manufacturing, transport, storage, dismantling and demilitarization. In the 2000s, in an attempt to enhance the standards and develop new tools, DDESB embarked on a long term program of Explosives Safety Knowledge IMprovement Operation – REdux (ESKIMORE). At present most of the originally planned ESKIMORE work has been completed and reported on, but critical technology gaps and challenging issues remain to be addressed. This paper provides an overview of the current technology and information gaps identified, followed by a detailed description of a new explosives safety knowledge improvement program, Advanced Munitions Operations – Consequence Assessment Trials (AMO-CAT).

AMO-CAT is an integrated computational and testing program for development of new and/or enhancement of existing standards in support of explosives safety operations. The project is an attempt to integrate testing, advance computations, and engineering model development for explosives storage and demilitarization operations, protective construction, and risk assessment. Advance computations are of particular importance when full-scale testing is not practical. Phenomenology areas to be considered include blast and primary fragmentation, structural breakup and fragmentations, internal blast, mass fire, and underwater explosions.

This paper shall summarize the priority technology gaps being addressed under AMO-CAT, and how they will be realized. The testing and modeling efforts currently being conducted under AMO-CAT shall be summarized, as well as planned computational and empirical programs planned for the next five years. The ultimate goal of AMO-CAT is to enhance the state-of-the-art of explosives safety by utilizing a complimentary approach of testing and computational analysis to enhance understanding of explosion effects for ultimate incorporation into quantity-distance (QD) criteria and consequence assessment models. With full-scale testing being prohibitively expensive, it is

critical to develop empirically validated computational models to generate synthetic data to supplement the limited existing test data which is the basis of existing QD and explosion effects models.

1. Introduction

A critical mission of the DDESB is to develop standards and tools to ensure the safety associated with DOD explosives as they go through their life cycle of manufacturing, transport, storage, dismantling and demilitarization. In the 2000s, in an attempt to enhance the standards and develop new tools, DDESB embarked on a long term program of ESKIMORE. At present most of the originally planned ESKIMORE work has been completed and reported on, but critical technology gaps and challenging issues remain to be addressed. This paper provides an overview of the current technology and information gaps identified, followed by a detail description of a new explosives safety knowledge improvement program, AMO-CAT.

AMO-CAT has identified phenomenology areas requiring further study, with specific topics having been prioritized according to technology maturity and mission. Earth-covered magazines (ECMs) are common, and critical, facilities for storing ammunition and explosives (AE) across the DoD. A concerted effort was undertaken to establish a comprehensive summary of issues and knowledge gaps associated with these facilities, and to generated action plans to address all issues and provide solutions to these gaps in knowledge and/or criteria.

2. Project ESKIMORE

Explosives safety testing is a critical component of explosives safety. Explosives safety testing allows for knowledge/data gaps to be filled with actual test data to support various models and criteria. The DDESB has long had a focus on conducting explosives safety testing when feasible to provide critical data.

Project ESKIMO (Explosive Safety Knowledge IMprovement Operation) was a DDESB testing program that was conducted between 1971 and 1985. The goal of Project ESKIMO was to more accurately determine the minimum safe separation distance between ECMs storing high explosives. While previous ECM testing helped define ECM intermagazine distance (IMD) at the time (References 1 through 3) it was really Project ESKIMO that generated the ECM IMD criteria that we have today. A summary of the tests conducted as part of Project ESKIMO can be seen in Table 1 (References 4 through 10).

Table 1: Project ESKIMO Test Summary

Program	Number	Test Dates	Donor Magazine Type	Explosive Type	NEW (lb)	Comments
ESKIMO	I	December 8, 1971	Earth-Covered, Steel Arch	155 mm projectiles	200,000	Debris Data Airblast Data
	II	May 22, 1973	Open Revetment	M117 bombs	24,000	
	III	June 12, 1974	Earth-Covered, Steel Arch	M117 bombs	374,406	Airblast Data No Debris Data
	IV	September, 1975	Open, Hemispherical Stack	TNT	37,000	
	V	August, 1977	Open, Hemispherical Stack	TNT	75,000	
	VI	July 23, 1980	Mass Properties/Geometry of Earth-Covered Type IIB	MK 15 Torpedo Warheads	51,300	1/2 Scale Model Airblast Data Debris Data
	VII Roof	September 5, 1985	FOAMHEST	Primacord		
	VII Doors	September 12, 1985	Open, Hemispherical Stack	TNT	13,616	

In 2002, the DDESB established a testing program to support the improvement of consequence algorithms for the DDESB's risk-based explosive siting tool SAFER (Reference 11) and associated methodology defined within DDESB Technical Paper (TP) 14 (Reference 12), and refinement of U.S. explosives safety QD standards. In 2006, the program was formalized as a long-term DDESB project, titled Project ESKIMORE.

The ultimate goal of Project ESKIMORE was to provide data in explosion effects areas where data were lacking or completely absent. Three area of concern were identified at the initiation of the program. These concerns were:

- Issue 1: Secondary or donor (Potential Explosion Site (PES)) debris generation and density versus distance and azimuth
- Issue 2: Target building (Exposed Site (ES)) response to blast loading
- Issue 3: Target building (ES) protection against debris afforded to occupants

Project ESKIMORE consisted of three separate testing programs: SciPan, ISO, and SPIDER. Each program was designed so that the tests within the programs would address at least one of the concerns presented above.

The SciPan (abbreviation of Science Panel) test program consisted of five tests and was intended to address Issue 1 and Issue 2 of Project ESKIMORE. This program consisted of full-scale testing of a donor structure, shown in Figure 1, with non-fragmenting explosives with various target structures. The donor structure was common to all the tests, except for varying dimensions.

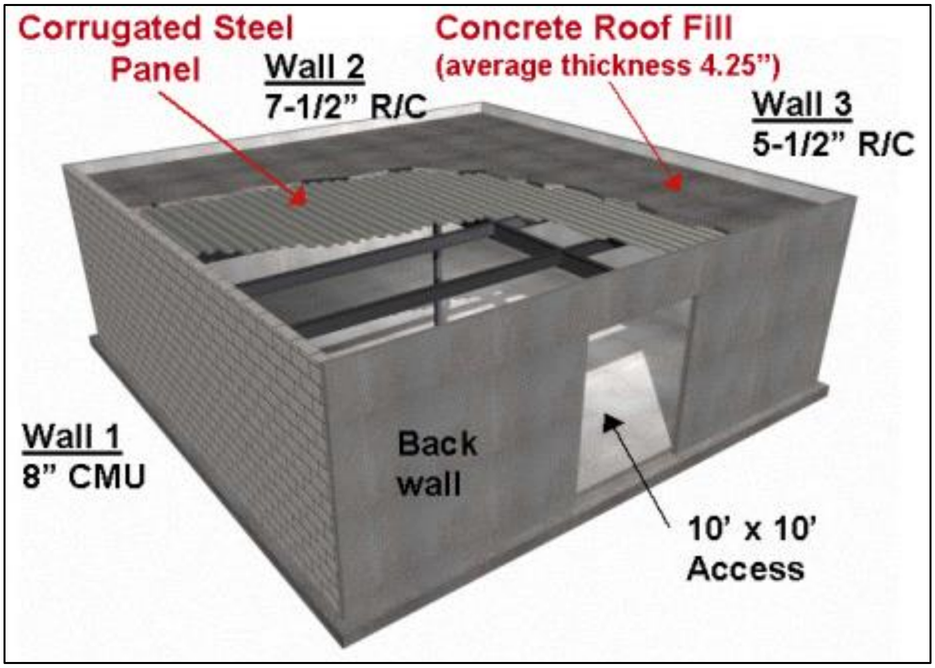

Figure 1: SciPan Donor Structure

Table 2 provides a summary of the key parameters for the SciPan tests (References 13 through 16).

Table 2: SciPan Test Program Summary

Program	Number	Test Date	NEW (lb)	PES (ft^3)	Density (lb/ft^3)	Target Structure	
						Target 1	Target 2
SciPan	1	Conducted 19 February 2003	27,005	36,864	0.73	5.5" Tilt-Up RC Wall/Wood Roof	7.5" Tilt-Up RC Wall/Wood Roof
	2	Conducted 9 July 2003	5,005	NA		5.5" Tilt-Up RC Wall/Wood Roof	7.5" Tilt-Up RC Wall/Wood Roof
	3	Conducted 6 April 2005	60,005	9,000	6.67	8" Unreinforced CMU/Wood Roof	8" Double Wythe Brick Wall/Wood Roof
	4	Conducted 27 August 2008	2,205	9,000	0.24	None	None
	5	Conducted 8 June 2011	6,601	9,000	0.73	None	None

The ISO test program consisted of seven tests and was intended to address Issue 1 of Project ESKIMORE. The ISO program originated within Project ESKIMORE because of the increasing use of ISO containers for explosives storage, especially in field storage and forward operating bases. All tests in the ISO program included a standard 8 ft wide by 20 ft long ISO container. An example of an ISO container used in this testing program can be seen in Figure 2. The ISO container in Figure 2 is from the ISO 4 test and was painted to help with identifying the debris origin.

Figure 2: Standard ISO Container (ISO 4)

Table 3 provides a summary of the key parameters for the ISO tests (References 17 through 20).

Table 3: ISO Test Program Summary

Program	Number	Test Dates	Explosive Type	NEW (lb)	Density (lb/ft^3)	Comments
ISO	1	Conducted 18 May 2006	ANFO	2,326	2.12	ISO Container on a Truck
	2	Conducted 21 March 2007	ANFO	8,819	7.52	ISO Container on a Truck
	3	Conducted 10 March 2009	105 mm projectiles	2,324	2.12	ISO Container on the Ground
	3Cal	Conducted 10 March 2009	105 mm projectiles	2,324	NA	Open Air
	4	Conducted 9 September 2010	C-4	2,205	2.12	ISO Container on the Ground
	4 Retest	Conducted 1 December 2010	C-4	2,205	2.12	ISO Container on the Ground

The Science Panel Impact Debris Evaluation and Review (SPIDER) test program consisted of four separate test series and was intended to address Issue 3 of Project ESKIMORE. The SPIDER test program was designed to determine the required kinetic energy for perforation of various wall and roof materials. The results of this test program are being used to update the values used in TP-14 for the kinetic energy absorbed by different wall and roof materials. In the SPIDER testing program, impactors were fired using a gun that was designed to launch the simulated fragments at pre-determined velocities for each test. SPIDER 1A and 1B impactors were launched using a black powder gun, while SPIDER 2 and 3 used a high velocity, compressed air gun. A sabot device was used to guide the impactors and to ensure that no pressure was leaked around the edges of the impactors during launch. High-speed cameras were utilized in the testing to measure initial velocity, exit velocity if the impactor perforated the target, and target response to the impactor. A schematic of the SPIDER test setup is shown in Figure 3.

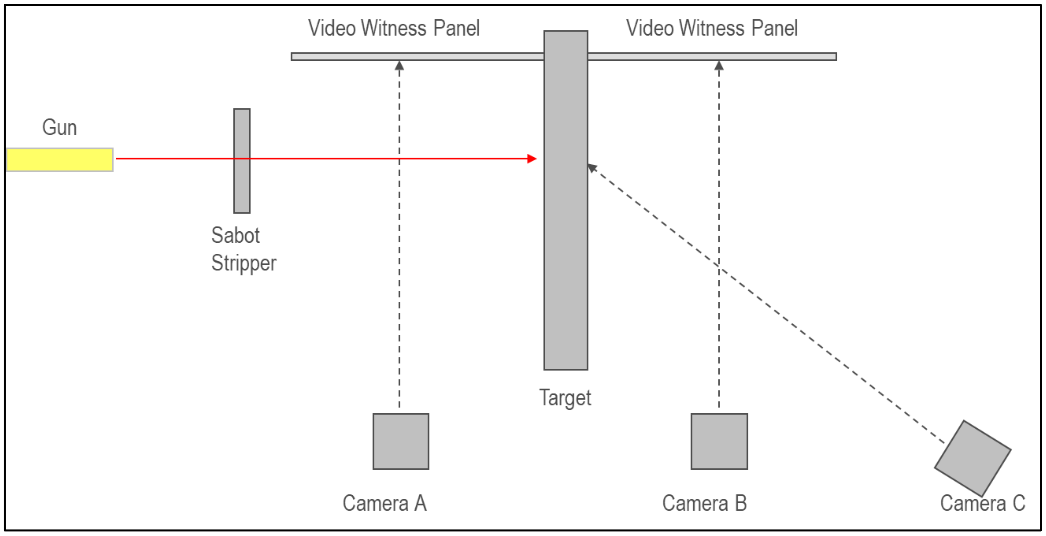

Figure 3: SPIDER Test Setup

Table 4 provides a summary of the key parameters for the SPIDER tests (References 21 and 22).

Table 4: SPIDER Test Program Summary

Test Program	Series Number	Test Dates	Impactors	Targets
SPIDER	1A	Conducted June 2004	Spherical steel & concrete	Roof materials
	1B	Conducted September 2004	Spherical steel & concrete	Roof materials
	2	Conducted May-September 2009	Spherical steel & concrete	Wall materials
	3	Conducted January 2015	Cylindrical steel & concrete	Wall materials

The DDESB has designated that Project ESKIMORE is complete and has since commissioned a new program to replace Project ESKIMORE: AMO-CAT.

3. AMO-CAT

AMO-CAT is an integrated computational and testing program for development of new and/or enhancement of existing standards in support of explosives safety operations. The project is an attempt to integrate testing, advance computations, and engineering model development for explosives storage and demilitarization operations, protective construction, and risk assessment. Advance computations are of particular importance when full-scale testing is not practical. Phenomenology areas to be considered include blast and primary fragmentation, structural breakup and response, mass fire, and underwater explosions.

A necessary and essential first task in development of a new program like AMO-CAT is identification and ranking of existing technology gaps. Table 5 lists phenomenology areas affecting explosives safety operations and their gap priorities. Gap rankings were calculated based on an extensive analysis that considered mission relevance, availability of suitable instrumentation, small and full-scale test data, maturity of technical understandings, capabilities of advance computational methods and engineering models. Note that closing of gaps does not necessarily mean testing alone. Rather, a careful analysis of available test data and computational codes in the phenomenology area of interest should be undertaken to develop an integrated plan that combines testing and computations in varying degrees. Sections 3.1 through 3.4 of this paper briefly summarize the phenomenology areas and specific topics that AMO-CAT aims to address.

Table 5. AMO-CAT Gap Priority Matrix

Phenomenology Area	Gap Priority (GP)
Blast and Primary Fragmentation	
Detonation and Fill Expansion	4
Quasi-Static Pressure (partially to fully vented and frangible vents)	3
Shock Pressure	4
Dynamic Pressure	3
Detonation Product Combustion	3
Case Breakup	4
Fragment Environment	3
Human Injury/fatality	2
Structural Breakup and Response	
Initial frag pattern (size, mass)/dynamic distribution	3
Fragment launch velocity	2
Effects on air blast	5
Interaction with Primary Frag	4
Effects of cover on ECM fragmentation and throw	2
ECM fragmentation pattern	3
ECM fragment launch velocity	2
Human injury and fatality	3
Mass Fire	
Internal Environment: Temp, Pressure, Impulse	3
Thermal Flux	2
Structural Breakup Fragmentation and debris throw	3
Human injury and fatality	2
Suppression techniques	5
Underwater Explosion	
Initial Blast Environment (Shock, Pressure,..)	4
Propagation in Water (clear, turbid, surf zone, bubbles)	4
Interaction with humans (swimmer, diver) and injury	1
Turbulence (Unresolved Flow)	4

Gap Priority Key	
1	Critical Gap - Top Priority - Must do
2	Significant Gap - High Priority - Should do
3	Gap - Normal Priority - Should do with partners
4	Enhancement Needed -Average/Normal priority
5	No need for effort currently - Adequate knowledge exists

3.1 Blast and Primary Fragmentation

The gap areas in Blast and Primary Fragmentation are human injury/fatality as the most critical gap with gap priority 2 (GP2) followed by Quasi-Static Pressure (fully vented and frangible vents), Dynamic Pressure, Detonation Product Combustion, and Fragment Environment, all ranked GP3. A large fragment database is available for various munitions based on testing. Also, analytical methods like DDESB's TP-16 (Reference 23) have been developed to define fragment environment for existing weapons. That said, there are large uncertainties in TP-16 results and new models need to be developed for new and emerging weapons.

In recent years, substantial effort has gone into testing and development of computational codes for case break up of existing and new weapons in confined spaces. This work has been primarily related to weapon effects on structures, but the computational codes developed can be leveraged to close the gaps for explosives safety, like human injury/fatality. Similarly, much progress has been made in recent years in the area of quasi-static and dynamic pressure and detonation product combustion. These programs are on-going which provide an opportunity for DDESB to collaborate with interested agencies for developments related to explosives safety.

The following program elements outline the steps for closure of technology gaps in Blast and Primary Fragmentation:

- Identification of appropriate computational codes and test data.
- Validation of computational codes with data appropriate for explosives safety.
- Generation of synthetic data using computational codes.
- Enhancement of confined blast software ConBlast or suitable replacement for gas pressure modeling improvements, such as pressure rise time, after burn effects, and blast through failing walls.
- Enhancement of TP-16 and/or reduction of uncertainties in TP-16 using synthetic data.
- Collaboration with other US government agencies and international partners in testing and computational analysis related to quasi-static, dynamic pressure and afterburning.
- Quantification of blast characteristics of very small quantities (< 1 lb) of Hazard Division (HD) 1.1 explosives and quantification of damage to conventional construction in confined or semi-confined environments (e.g., laboratories).

Recent efforts have been made to account for the rise time of the gas pressurization inside confined structures (Reference 24). The current design methodology for protective construction prescribed within UFC 3-340-02 (Reference 25) assumes an instantaneous rise time of the gas pressure, which can be quite conservative for some designs. In addition to quantification of the risk time, this work is also looking to develop an improved gas pressure model for use in protective design. Figure 4 is taken from Reference 24, and shows various calculated gas pressure histories plotted against the measured gas pressure history, which in this case is from NCEL TERA Test 3. Accounting for the rise time in the prediction method negates adding the unnecessary extra impulse in the early time blast history. Note that the shock waveform is including in the measured test data but is not included in the predicted/calculated gas pressure time histories.

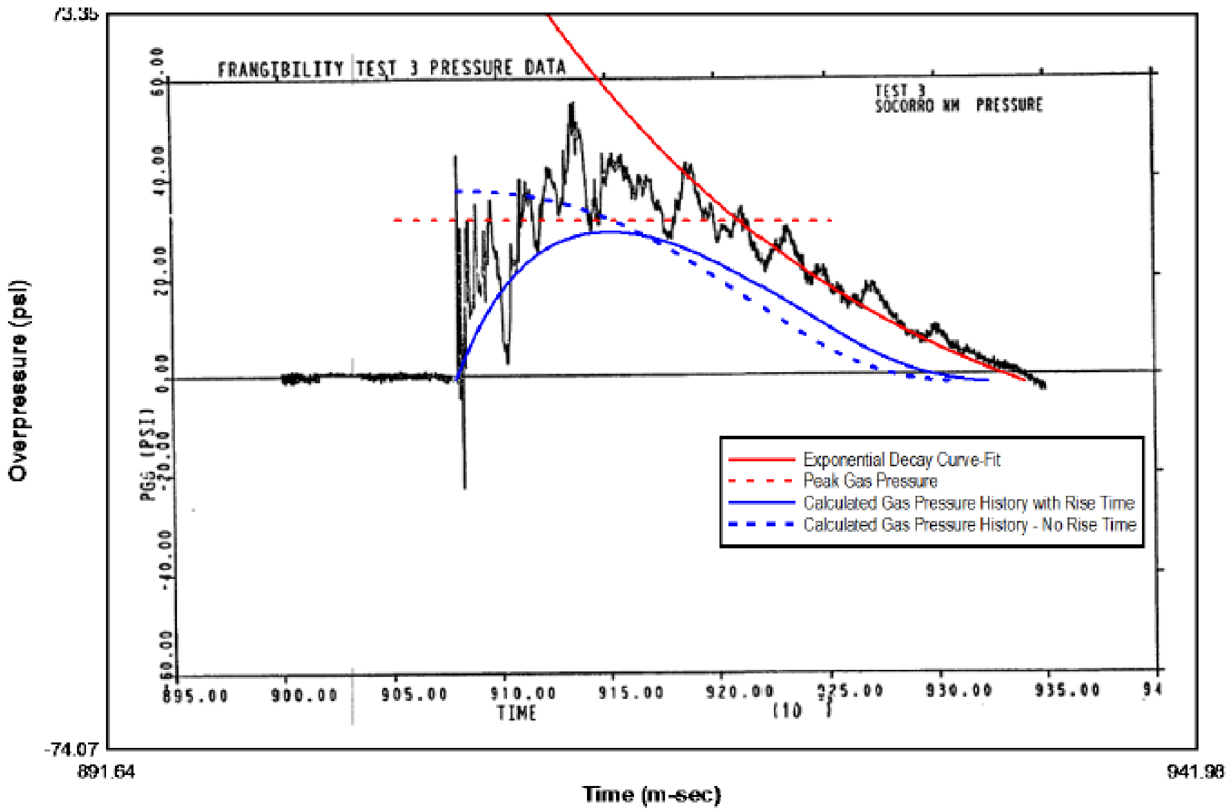

Figure 4. Comparison of Gas Pressure Calculation Methodologies

3.2 Structural Breakup and Response

Critical gaps (GP2) in this area are fragment launch velocity, effects of cover on ECM fragmentation and launch velocity. Other important gaps ranked as GP3 and somewhat related to GP2 ranked gaps are initial fragmentation pattern, dynamic mass distribution, and human injury/fatality.

The gaps listed above are the most challenging to close in terms of required funds, availability of test sites, and appropriate computational codes. The only viable approach in overcoming these challenges is to collaborate with international partners, Service safety centers, and any other interested parties. Conducting full-scale ECM tests at their maximum capacity of 500,000 lb is nearly impossible, but debris-focused tests are only necessary up to the point where debris still controls the hazard at inhabited building distance (IBD). Any testing will be planned with this threshold in mind. Data from previous full-scale and small-scale tests, in addition to future tests, will be used to develop capabilities in computational codes which can then be used to generate synthetic data in an attempt to close the gaps in this area. At present, computational modeling of earth cover and fragmentation of concrete are at the cutting edge of research.

The following program elements outline the steps for closure of technology gaps in Structural Breakup and Response areas:

ECM Program Element

- Review all applicable historical data on ECMs, to include previous testing, assessment of internal DDESB and Service basis of decisions on ECM criteria (e.g., Navy Type I and Type II SP&P ECMs), and the ECM test program plan developed under Project ESKIMORE.
- Conduct meetings with stakeholders and interested parties to identify all issues and knowledge gaps associated with ECMs and DoD ECM explosives safety criteria. Focus of meetings should be to identify deficiencies and generate plans to achieve solutions and ultimate end product.
- Develop plans for scaled and full-scaled testing, and development and validation of a suitable computational code.
- Generate data or computational capability to develop the end products identified in meetings with stakeholders.

Non-ECM Program Elements

- Review the database of scaled IBD vs. Charge Density to identify clean and reliable data for validation of computational codes. Important parameter is debris launch velocity.
- Conduct an initial assessment/validation of Computational Fluid Dynamic (CFD) and Computational Structural Dynamic (CSD) (if necessary) codes and compare/validate to applicable existing data.
- Determine all testing (scaled and/or full-scale) required to validate computational codes previously validated against available data.
- Generate synthetic data for debris launch velocity using validated codes. Utilize the best available trajectory prediction program to calculate IBDs for various PES types and loading densities/net explosive weight (NEW).

Figure 5 gives an example of ongoing coupled CFD/CSD numerical analyses being conducted modeling internal detonations in non-ECM structures (Reference 26). The primary focus of this particular effort is to accurately quantify debris break-up of the structures, particularly assessing the predicted mass distribution, velocity distribution, and angular distribution of the launched secondary debris.

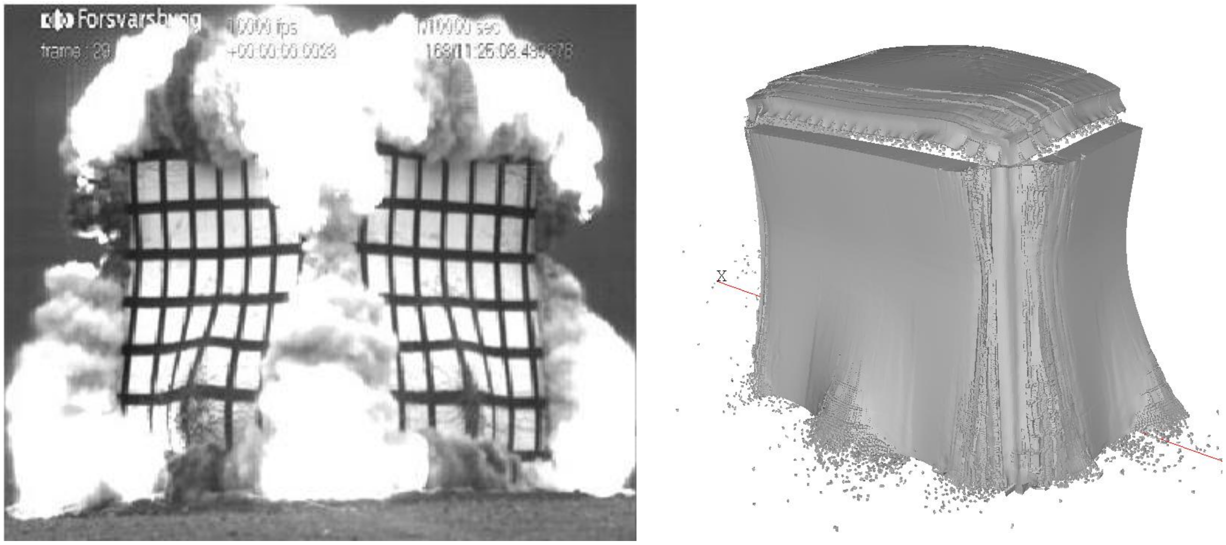

Figure 5. Kasun III test and simulation at 2.8 ms (16 155mm charges)

3.3 Mass Fire

Reference 27 provides a detailed description of technical gaps and issues related to Mass Fire. The solution presented is a four-year multi-series test program at both small and full-scale. However, many of the issues to be addressed through testing as proposed in Reference 27 can be addressed through computational approaches. The key is to identify suitable computational codes for combustion and structural response, verify and validate the codes and then use them to generate synthetic data for development of better standards and/or engineering models for risk based tools.

The following program elements outline the steps for closure of technology gaps in the area of Mass Fire:

- Review mass fire white paper (Reference 27) to determine which areas lend themselves to computational analysis or could benefit from test data in support of high explosives testing done in the past.
- Exercise CFD and CSD codes against existing mass fire data. Go/no-go decision needs to be made regarding availability of existing computational codes that can be used to generate reliable synthetic data. If unavailable, one can then determine what level of testing and algorithm developments are needed to develop appropriate codes and weigh the costs against the cost of proposed testing.
- Develop an integrated computational and testing approach to close critical gaps in mass fire as identified in Table **5**.

Figure 6 provides a comparison of past testing (Reference 28) and the modeling efforts associated with them (Reference 29). The predictive model on the right was not a coupled analysis, but rather employed a two-step process of performing CFD and CSD simulations in an iterative manner. The reason for this was two-fold: 1) the analysis was intended to be a rough initial estimate, and general proof of concept with known issues due to the lack of coupling, and 2) the CFD and CSD codes available and best equipped to handle each regime were not coupled to each other. There are multiple options for coupled analyses when modeling detonations, but the options are much more limited when modeling a deflagration event undergoing various phase changes. Recent efforts have been undertaken to model this scenario using an appropriate couple simulation model.

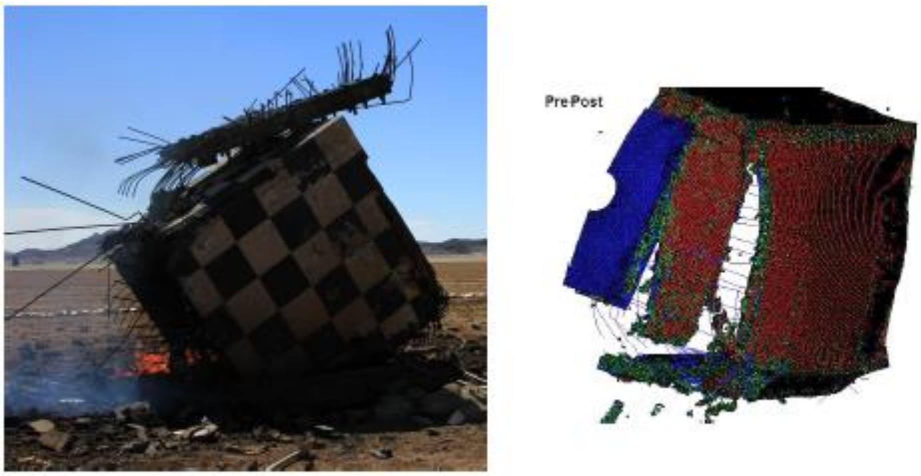

Figure 6. Experimental and Numerical Results of Confined Mass Fire

3.4 Underwater Explosion

The most critical gap in this area is interaction of underwater blast with humans. Limited human and animal testing were conducted by the UK in 1940s-1950s, but measurements do not have sufficient fidelity for model development. More recently, international organizations have conducted significant research, testing and modeling for effects on swimmers that may be directly relevant to the closure of the Underwater Explosion gap.

The following steps have been identified by the Underwater Explosion QD (UWEQD) working group as priority:

- Literature review of all relevant documents on underwater explosion and fragmentation
- Literature review of underwater explosion propagation test data
- Incorporation of applicable information into US DoD safety criteria, and identification of any remaining knowledge gaps.

4.0 ECM Explosives Safety Issues

The primary means of storage of AE in the DoD is through the use of ECMs. There are more than 20,000 ECMs within the DoD inventory, and a large percentage of those facilities were built in the 1950s and earlier. The fundamental purpose of an ECM is to prevent prompt propagation from the stored munition within in the event of an accidental explosion of an adjacent explosives storage facility. ECMs are desirable for storage, as the IMD between adjacent ECMs is significantly less than that required between non-ECM storage facilities.

As technology and knowledge of explosion effects, hazards generated from an explosive event, directional blast attenuation caused by ECMs, and structural response to blast loading has increased, the prescribed design response of ECMs has matured. The result is that many of the legacy ECM designs are not approved for new construction, and the current understanding of explosive hazards from ECMs may not be consistent with the expected consequences at IBD and the expected blast loading on adjacent ECMs at IMD.

Over the past 18 months, a number of avenues were utilized to generate a comprehensive list of issues, needs, knowledge gaps, and data requirements for ECMs across the DoD. A variety of personnel from the various Services provided input, comprised of end users, approval authorities at the Service and DDESB level, engineers, and scientists. As a result of the solicitation, it was readily apparent there were four aspects of ECMs that require further research and investigation to support further enhancement of explosives safety criteria:

1. Legacy Flat-Roof ECMs
2. ECM IMD Design Loads
3. ECM Debris Hazards
4. ECM Earth Cover Requirements

The first two focus areas investigate ECMs as an ES, while the third topic focuses on the debris hazard generated by an ECM as a PES. The fourth topic has potential to affect the ECM as both an ES and a PES. The first topic focuses on how to safely maximize the storage capacity of the thousands of legacy flat-roof ECMs currently in the DoD inventory. The second topic ensures that correct headwall and flat-roof design loads are being applied to all new ECM designs to satisfy the loading condition at minimum IMD separation distances. The third topic investigates the debris hazard generated by an ECM in the event of an accidental detonation, and the resulting debris IBD as a function of ECM direction (i.e., front, side, or rear). The fourth topic addresses defining a reasonable path forward in the event that the earth cover on top of the ECM becomes less than two feet due to erosion, as well as defining erosion prevention solutions that have a negligible impact on explosives safety. The proposed testing and numerical modeling efforts would be under the auspice of the DDESB’s AMO-CAT program.

4.1 Legacy Flat Roof ECMs

The two general ECM types are either arched ECMs or flat-roofed ECMs. The cross-section of the arch ECM is either constructed of thick corrugated steel panels or reinforced concrete panels, with a vertical rear wall and headwall on the rear and front, typically constructed of concrete. The flat-roofed ECMs were box structures of various sizes. When the top of an arched ECM is subjected to blast loading as an ES, the load path is transferred efficiently via arching mechanism. This has been demonstrated via testing in various programs over the years, particularly the Arco, NOTS, and ESKIMO test series (References 1 through 10). This arching mechanism to resist the roof load is not possible on flat-roofed ECMs, hence the roof itself must resist the load and provide a mechanism to transfer the blast load to the foundation. If a flat-roof ECM cannot be shown that it can adequately resist the applied roof blast load, then it must be sited as an aboveground magazine (AGM), and its sited NEW could be constrained by other adjacent A/E storage facilities, presumably ECMs.

Current flat-roofed ECMs approved for new construction are defined in DDESB Technical Paper No. 15 (Reference 30), and have been designed for both the 7-bar headwall load (101.5 psi, $13.9W^{1/3}$ psi-ms) and the flat-roof load (108 psi, $19W^{1/3}$ psi-ms) as prescribed in DoD 6055.09-M paragraphs V2.E5.5.2.4.2 and V2.E5.5.2.4.3 (Reference 31). However, the current design loads for flat-roof ECMs were not prescribed until this incorporated change was approved by the Board in 2000, and thus the older flat-roof ECMs were not designed with this blast load in mind. It should be noted that the current prescribed flat-roof load is primarily based on the 1980 ESKIMO VI test (Reference 9).

There are numerous variants of flat-roof ECMs built in the 1970s and earlier, but none were explicitly designed to the current blast load criterion. A common flat-roof ECM type built from the 1940s to 1970s is the Navy's Smokeless Powder & Projectile (SP&P) ECM. There are thousands of the SP&P ECMs in the DoD inventory, and the primary variants are the Type I, the Type IIA, and the Type IIB. They are large ECMs, typically 52 feet deep and ranging from 52 feet to 161 feet wide, and the reinforced concrete (RC) flat-slab roof is supported by interior RC columns.

Due to the large number of the SP&P ECMs in the DoD inventory, efforts were made to specifically investigate these ECM types and assess IMD for these ECMs that could give possible reprieve from AGM IMD. An extensive literature review and technical analysis was conducted to assess appropriate IMDs for these flat-roof magazine types. This resulted in the establishment of IMD hazard factors for the Type I, Type IIA, and Type IIB SP&P ECMs (Reference 32). The resulting IMDs for the SP&P ECMs are shown in Table 6.

Table 6. IMDs for Navy SP&P ECMs

To Exposed Site (ES)		PES			
		Existing ECM			
		S	R	FB	FU
Type I Smokeless Powder/Projectile Magazine	S	4.5	4.5	6	6
		6	6		
	R	4.5	4.5	6	6
		6	6		
	FU	6	6	6	11
	FB	6	6	6	6
Type IIA or Type IIB Smokeless Powder/Projectile Magazine	S	1.25	1.25	6	6
		2	2		
		6	6		
	R	1.25	1.25	6	6
		6	6		
	FU	6	6	6	11
	FB	6	6	6	6

Use up to 250K lb
Use up to 350K lb

To Exposed Site (ES)		PES			
		Existing ECM			
		S	R	FB	FU
ECM (Undefined)	S	1.25	1.25	4.5	4.5
		2	2	6	6
	R	1.25	1.25	2	2
	FU	6	6	6	11
	FB	6	6	6	6

Use up to 250K lb

4.2 ECM IMD Design Loads

The current ECM design loads, 7-bar headwall load (101.5 psi, $13.9W^{1/3}$ psi-ms) and the flat-roof load (108 psi, $19W^{1/3}$ psi-ms) as prescribed in DoD 6055.09-M, are primarily based on test data and are a function of specific PES-to-ES orientation configurations. Specifically, the 3-bar headwall load is based on the side-to-side separation distance of K1.25, the 7-bar headwall load is based on the front of the ES being located to the rear of the PES (rear-to-front orientation) at a separation distance of K2, and the flat roof load is based on the rear of the ES being in front of the PES (front-to-rear orientation) at a separation distance of K2. The blast design load criteria were largely generated from the ESKIMO test series, with the flat-roof load coming directly from the ESKIMO VI test results. DDESB TP-17 Revision 3 (Reference 33) and the corresponding Blast Effects Computer (BEC) v7.1 provide a prediction methodology for ECM overpressure and impulse out the front, side, and rear of an ECM. However, when calculating the resulting pressure and impulse at ECM IMD distances using BEC, it becomes apparent that the predicted pressure and impulse out the front of the ECM are higher than the prescribed design loads of DoD 6055.09-M. The prediction curves of TP-17 are simply a curve fit to all available data for that particular donor structure. Upon further investigation, much of the close-in data (say, $Z \leq 6$ ft/lb$^{1/3}$) is based on scaled test data. Additionally, the scale of some of this data are 1/10th, 1/50th, and 1/100th. The validity of applying these results to a full scale situation becomes very questionable. The fundamental issue is that there is very little test data at these distances, and the data that do exist were generated over 25 years ago.

4.3 ECM Debris Hazards

IBD from detonation of HD 1.1 in an ECM is defined as the distance where the hazardous fragment density is less than one hazardous fragment per 600 ft^2 and the overpressure drops below the acceptable overpressure threshold (generally 1.2 psi for NEW < 100,000 lb and 0.9 psi for NEW > 250,000 lb). A hazardous fragment is defined as a fragment having an impact energy of 58 ft-lb or greater. For all PES structures that can contribute to the fragment hazard, the debris criterion controls IBD for smaller NEW and the overpressure criterion controls for larger NEW. For NEW larger than 450 lb, the debris IBD is represented as a constant distance of 1250 ft. It has been recognized since at least 1990 (Reference 34) that this approximation is not adequate, as it is intuitive that the debris IBD would be larger for 10,000 lb than 1,000 lb in an identical structure, but the lack of empirical data has prevented much progress being made in this area. Over the past decade or so there has been tremendous progress made in this area (Reference 35) but there is still much work to do.

The crossover of IBD, transitioning from being controlled by debris to being controlled by overpressure, is a function of PES structure type. In the case of ECMs, the NEW that this occurs is also a function of direction: front, side, or rear. It should be noted that debris IBD is defined as less than 1250 feet for NEW less than 450 lb per Table V3.E3.T1, so the following points are only considering NEW > 450 lb. For the Front and Side directions, IBD is a constant 1250 feet until 45,000 lb, at which point overpressure controls IBD. For the Rear direction, IBD is a constant 1250 feet until 100,000 lb, at which point overpressure controls IBD. The directional, or “shotgun”, nature of the ECM causes both the debris and overpressure hazard to be greatly reduced out the rear direction. This mitigation is lessened out the sides of the magazine, while the mass of the soil cover on the sides and rear focuses the effects, both debris and overpressure, out the front direction. There are minimal test data on debris hazards from ECMs for NEW greater than 450 lb, but the data that do exist suggest that the 1250 ft value for debris IBD is inadequate for larger NEWs, and debris hazards may control IBD out the front for NEW larger than 45,000 lb at distances greater than 1250 ft.

4.4 ECM Earth Cover Requirements

The designation of “ECM” is inherently an explosives safety designation, as an AE storage facility that qualifies for this designation is afforded reduced explosives safety separation distances. This is particularly true for IMD, as the reduction in separation distance between ECMs is substantially less than AGMs, as shown in Table V3.E3.T6 of DoD 6055.09-M. For example, the side to side separation distance between ECMs is K1.25, whereas that same required distance between Barricaded AGMs is K6. For a storage facility sited for 500,000 lb, this is a difference of 100 feet versus 477 feet. More commonly, ECMs are built at the minimum side-to-side separation distance for the maximum sited value of 500,000 lb (100 feet), so if for some reasons those AE storage facilities are downgraded from their ECM designation to AGM, the sited value in each structure drastically drops down to 4,629 lb.

One potential cause, which has already been discussed, of an ECM being downgraded to an AGM is legacy flat-roof ECMs not having their roof adequately designed for the roof load. However, another issue which potentially affects all ECMs is the maintenance of a minimum of two feet of earth cover on top of the magazine. V5.E5.5.3.2 of DoD 6055.09-M states:

> *The earth fill or earth cover between ECMs may be either solid or sloped. A minimum of 2 ft [0.61 m] of earth cover shall be maintained over the top of each ECM. If the specified thickness and slope of earth on the ECM is not maintained, the ECM shall be sited as an AGM.*

The above paragraph indicates that if the earth cover erodes to 23 inches, then the facility must be classified as an AGM, which could have catastrophic implications of the storage capacity for the facility. Additionally, there is not clear guidance on what are acceptable erosion control techniques to use on top of ECMs without adversely affecting explosives safety

5. ECM Testing and Modeling Initiative

The various issues and knowledge gaps identified within the four general ECM Focus Areas were briefly discussed in Section 4. The path forward for each issue is briefly summarized in this section. Each focus area sub-topic has a plan of action associated with it to address that particular knowledge gap through testing and/or numerical simulation. Some of this work has been completed or will be completed soon, while other Focus Area sub-topics will be addressed in the future.

5.1 Focus Area 1: Legacy Flat-Roof ECMs

Calculations have demonstrated that the SP&P Type I, Type IIA, and Type IIB ECMs will not satisfy UFC 3-340-02 response criteria when analyzed under the prescribed flat-roof loads of DoD 6055.09-M. The response of the Type IIA and Type IIB ECMs is excessive, but are within the realm of possibility that there would not be a catastrophic roof failure under those loads. On the other hand, the Type I roof is minimally reinforced, is clearly designed for only dead and live loads applied downward, and does not have continuous reinforcement on either the top or bottom face of the slab.

The goal of this research area is to generate data to make the ECM IMD criteria defined in Table 6 the SP&P ECMs more realistic, as they may be conservative due to a lack of relevant information. Both paths forward entail advanced computational modeling of the EMCs under the applied loading, but the approach is different for the Type I and Type IIA/IIB based on their structural detailing. For the Type IIA/IIB ECM, the design was tested in ESKIMO VI, the roof response was measured, and thus provides a validation point for the numerical model. The analysis methodology prescribed in UFC 3-340-02 is acknowledged as conservative, so a combination of the tested results of a roof response that did not pass the deflection criterion can be used in conjunction with the numerical model to back-calculate an IMD load (scaled distance/NEW combination) that would have resulted in a deflection response satisfying UFC 3-340-02 criteria.

The SP&P Type I ECM numerical model is expected to have a shear failure at the concrete support under minimal loading, and thus can't be shown to satisfy UFC 3-340-02 criteria. However, the model will be run under a variety of roof loading scenarios and the response of the roof will be characterized, to include both deflection and velocity in the event of a catastrophic failure/complete detachment of the supports. The approach shall entail quantification of roof velocity and impact energy and impulse in an effort to determine the probability of propagation. If asset loss, but non-propagation, is an accepted response, then that could allow for reprieve from the Type I SP&P IMD criteria of Table 6.

Finally, after the numerical models have been vetted and results analyzed, updated IMD for the SP&P IMDs shall be proposed to replace Table 6 (if supported by the analytical results). In the event that the numerical modeling is not conclusive and/or there are still outstanding questions on the roof response, there is the option of conducting a test on an existing SP&P ECM to address these concerns. In order to generate the desired roof load while also minimizing the explosive amount as this would be conducted in an old depot/not on a DoD range, a High Explosive Simulation Technique (HEST) test would be conducted. A HEST test entails placing a layer of explosives on the ECM roof over a buffer material. The intent is to generate the desired blast wave on the roof (both peak pressure and impulse), while minimizing the amount of explosives material detonated. This testing option will be assessed based on the outcome of the numerical models and the response of the technical community and approval authorities to any proposal made to reduce IMD values prescribed in Reference 32.

- Focus Area 1.1: Numerical Modeling of SP&P Type IIA/IIB ECM
- Focus Area 1.2: Numerical Modeling of SP&P Type I ECM
- Focus Area 1.3: HEST Tests of SP&P Type I and/or Type IIA/IIB ECMs (Optional)

Initial analysis of the Navy SP&P Type I ECM has proven quite promising (Reference 36). The numerical simulation using LS-DYNA has shown that there is far more capacity in the roof than is predicted using the prescribed methodologies of UFC 3-340-02 to determine the blast load response. Figure 7 shows the deformation of the ECM under an applied blast loading scenario of the roof.

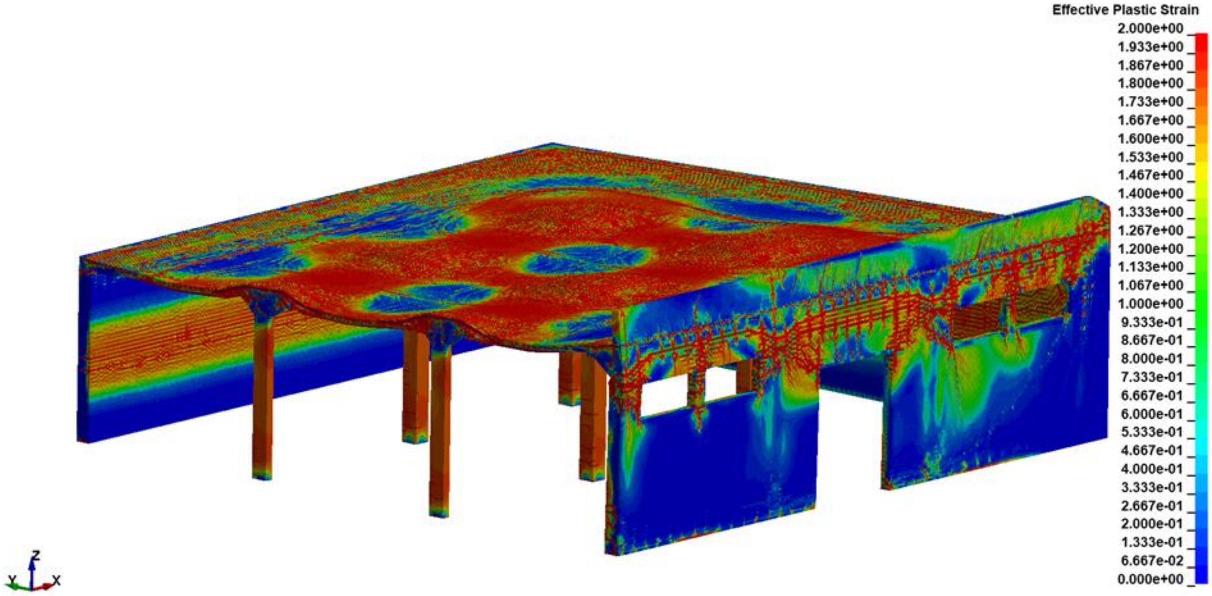

Figure 7. Navy SP&P Type I ECM deformation under roof blast load

5.2 Focus Area 2: ECM IMD Design Loads

This research area will be a phased approach, and will primarily focus on numerical modeling of existing test data that is the basis of the pressure and impulse values in TP-17 for ECMs at standoff distances less than K6 ft/lb$^{1/3}$. The hypothesis is that the data from very small scale tests may not be applicable since gravity (which wasn't scaled) is affecting the break-up response of the ECM and thus affecting the directional blast wave attenuation. It's also quite possible that the anomaly is in fact the ESKIMO VI data point, and that we should be prescribing a larger roof load for all new ECM designs. Whatever the conclusion of the study is, the execution method is a comprehensive numerical analysis of all of the data points in question.

At this point, it is still to be determined whether or not this would require a coupled analysis, or if a CFD analysis would suffice. It is anticipated that it would be preferable to start with just a CFD analysis for simplicity, but a coupled analysis could be done from the start if necessary. It is anticipated that some or all of the following test series listed below would be modeled. The ESKIMO VI and Modular Igloo Test (Reference 37) are necessary to model, while the rest of the test series will be prioritized by quality of waveform data recorded, thoroughness of test description, and range applicability.

- Various Kingery, et. al. model tests (small scale) (References 38 through 40)
- ESKIMO VI (1/2 scale)
- Modular Igloo Test (full scale)

The CFD (or coupled model) would not attempt to be a scale model, but rather the intent is to model the actual test set-up and provide the predictive results.

If test results can be duplicated, the next step is to conduct a series of "full scale" runs of the test data. A select number of scaled tests (maybe $1/10^{th}$ scale or $1/100^{th}$ scale) will be turned into full scale models (with the "actual" gravity) and rerun for comparison with the scaled test results (which did not scale gravity). If results are observed which confirm the suspected trend, and the blast loading is commiserate with the prescribed design loads in DoD 6055.09-M, then it would not be necessary to conduct tests to fill in data gaps. If there are still questions or data gaps, then it may be necessary to conduct tests to provide answers. It is anticipated that the full scale ECM tests of Focus Area 3.3 and Focus Area 3.4 will be fully instrumented and provide full-scale blast load data for both roof and headwall loads.

Any validation tests (outside of the multi-purpose full-scale tests of Focus Area 3.3 and 3.4) would likely be scaled in nature, and would be multi-purposed. They would also be designed to address data gaps in in secondary debris hazards from ECMs, as well as used as an opportunity to try out novel instrumentation techniques to assist with the debris and data collection effort for the eventual full-scale testing effort as part of this program. These optional scaled ECM tests will be addressed in Focus Area 3, ECM Debris Hazards.

- Focus Area 2.1: Numerical Analysis of Existing Scaled ECM IMD Blast Load Data
- Focus Area 2.2: Numerical Analysis of Equivalent Full-Scale ECM Tests

Figure 8 shows the ECM Front pressure and impulse data that is tabulated within DDESB TP-17. There is minimal data at very small scaled distances, and the data that do exist there are from small scale tests. As can be seen in Figure 8, the BEC predictions are curve fits to the data, and there is a slight incongruity with the prescribed blast loads. It is this discrepancy that will be investigated in Focus Area 2.

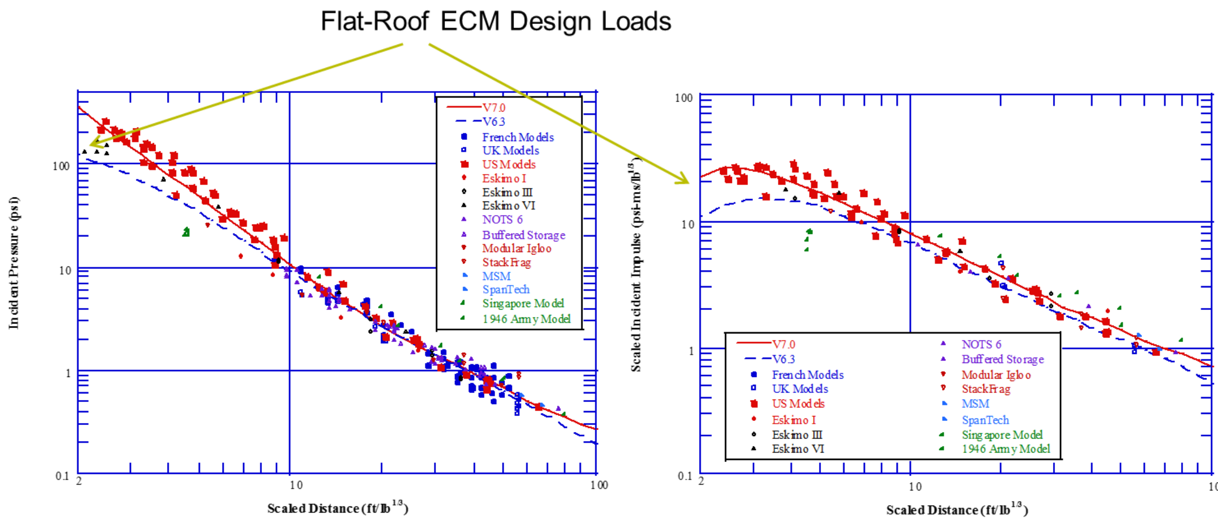

Figure 8. TP-17 ECM Front Data

5.3 Focus Area 3: ECM Debris Hazards

For the purposes of both definition of appropriate debris IBD and for development of accurate risk and consequence assessment models, the debris hazard from ECMs needs to be better understood and defined. As previously mentioned, much progress has been made in recent years with respect to quantifying the debris hazard from heavy concrete/masonry PES types as well as light PES types such as ISO containers. However, there is still a paucity of data when it comes to debris hazards from ECMs.

The first step in addressing this issue is to calculate the debris IBD for every ECM debris test conducted, plot as a function of NEW for front, side, and rear directions, compare with current QD, and assess for data gaps and deficiencies. Attempts should be made to include any accident data on these plots as well (if available). The initial analysis will aid in selecting the optimal NEW for a full-scale test. ECMs have a maximum storage capacity of 500,000 lb NEW, but IBD is controlled by overpressure at that NEW value, so determination of debris IBD is less of a concern. Hypothetically, there will be an NEW corresponding to where the overpressure IBD crosses over the debris IBD for the front, side, and rear. It is the front direction that is of primary concern, but side and rear are also of value. Furthermore, it is anticipated that the debris IBD at this crossover point will be some distance larger than 1250 ft.

It remains to be seen if there is value in conducting scaled ECM tests prior to a full scale test. Two general concerns of scaled testing are: 1) cost does not directly scale, and 2) the results may generate more questions than answers. Another specific concern is that a series of scaled ECM tests conducted in the past five years (References 41 & 42) have demonstrated that the break-up mechanism of ECMs at different scales (where the earthen fill was not scaled) were substantially different. Obviously the debris throw and trajectory does not scale, but a previous assumption was that if the launch conditions were defined in a scale test, those conditions could be extrapolated to full scale. It should be noted that the previous assumption of scalability did not apply to mass distribution, as inertial effects on initial break-up and shatter upon impact are gravity dependent. However, the results of the scaled ECM test conducted in References 41 and 42 raise concern that if the breakup is substantially different, the velocity distribution, horizontal launch angle distribution, vertical launch angle distribution, and general timing of break-up effects won't scale. It is anticipated that the efficacy of conducting scaled ECM tests as a part of Focus Area 3.2 will depend on the results of Focus Areas 2.1 and 2.2, as well as results from other concurrent ECM testing.

The culmination of this program is envisioned as conducting multiple full-scale ECM tests. This will generate a robust debris data set, quality high-speed video coverage, full-scale blast data at locations defining ECM design loads, and various other sensor information describing the response. The donor ECM should represent ECMs that have been commonly built in recent years and will be built in the future. The best representative for this is some variant of the Modular Storage Magazine. The pre-cast construction reduces cost and the internal geometry is ideal for today's storage layouts (arch ECMs waste space due to the curvature in the ECM). Ideally, two tests can be conducted at two different NEWs. There will be a large mobilization cost to conduct the test, so a second test would be conducted at a substantial discount if done in conjunction. The donor ECM for Test #2 could be an acceptor ECM for Test #1. It is envisioned that there will be other surrogate acceptors on site in order to calculate the actual applied blast loading on adjacent ES ECMs spaced at IMD.

- Focus Area 3.1: Debris IBD Investigation of Existing Test Data
- Focus Area 3.2: Scaled ECM Test Series (Optional)
- Focus Area 3.3: Full Scale ECM Test #1 – IMD Blast Loads and Debris Collection
- Focus Area 3.4: Full Scale ECM Test #2 – IMD Blast Loads and Debris Collection (Optional)

A comprehensive study has been completed over the past few years that compiled all relevant debris data by PES type, and sought to develop debris IBD curves (Reference 43). The curve for the front of ECMs is shown in Figure 9. As can be seen in the figure, there is very minimal data beyond 450 lb, and the current DoD 6055.09-M IBD criteria may not align with what data is available.

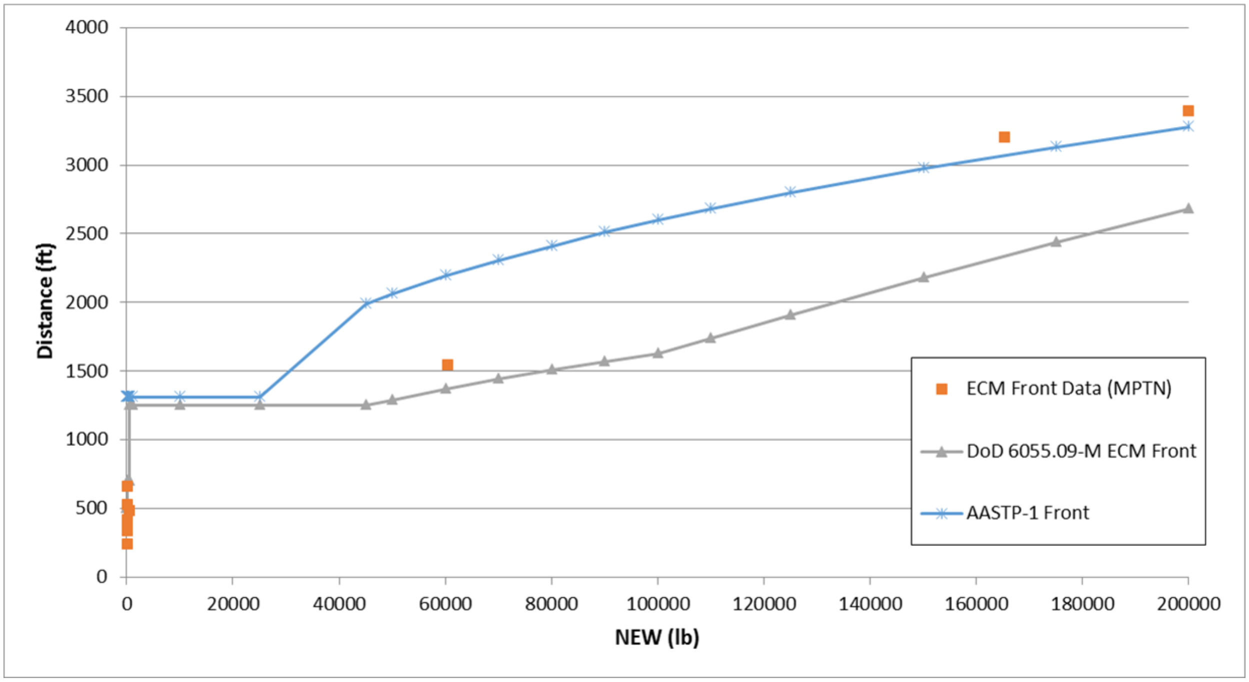

Figure 9. Debris IBD (MPTN) ECM Front

5.4 Focus Area 4: ECM Earth Cover Requirements

The earth cover on an ECM performs multiple functions. First, as a PES, the near-field blast wave of an ECM is highly directional, with the energy release being primarily focused out the front due to the door and headwall having the lightest areal mass of all the surfaces. This pressure focusing is intrinsically tied to the IMD K-factors for ECMs defined in DoD 6055.09-M, as the current IMDs and associated design blast loads are all based on testing, all of which had ECMs with two feet of earth cover. As an ES, the earth cover performs two functions. First, the mass of the earth acts to benefit the structural response of the ECM via inertial effects under the applied blast loading in the event of an accidental detonation. For flat-roofed ECMs, this is explicitly accounted for in the design calculations. Arched ECMs do not have design blast loads for the roof/arch, as they have been shown adequate at minimum IMD via testing. The tested arched ECM designs all did have two feet of earth cover on them, which undoubtedly benefited the response under the applied blast load. Secondly, the presence of earth cover helps to protect the magazine contents from potential impacts of lobbed debris and fragments in the event of an accidental detonation to an adjacent structure. This is not a defined criterion anywhere in explosives safety regulations, but this inherent protection is still provided.

Soil erosion is an inevitable occurrence in many locations, and many ECMs will inevitably see their minimum soil cover drop below 24 inches after some duration. There is no rational argument that states the physical characteristics of an ECM responding to an accidental detonation, either as a PES or ES, are drastically altered when the minimum soil cover drops from 24 inches to 23 inches, but DoD 6055.09-M is a criteria-based manual where clear guidance of thresholds and minimums must be established. The first part of this study, Focus Area 4.1, will assess the change in ECM response, both as a PES and as an ES, when the earth cover is not a minimum of 2 feet. This will be realized through a combination of testing and numerical modeling. The end product is uncertain at this point, but it could be one of two things: 1) a defined buffer zone (say, greater than 20 inches) where the facility can still be classified as an ECM, or 2) implemented criteria where the required IMD become a linear interpolation between that of an ECM and that of an AGM between 24 inches and some lower bound value (say, 12 inches).

The second technology improvement associated with this focus area, Focus Area 4.2, is defining acceptable ECM erosion control methods for explosives safety applications. Erosion control solutions are readily available, but there has always been concern that some of the solutions could adversely increase the debris hazard in the event of an accidental explosion in the ECM. Since solutions have not been clearly defined there is a DoD requirement to define which erosion control solutions are acceptable to use on ECM earth cover from an explosives safety perspective.

A secondary, but related, concern was raised during meetings with ECM stakeholders. Concerns have been raised regarding a series of best practices in ECM construction, particularly related to the fill material. Specific guidance on stone size is provided for the fill, but other guidance is either missing or ambiguous at best. The secondary objective of Focus Area 4.2 is to identify design or construction issues and questions related to this topic, and identify best practices or responses to these questions to provide to the Service Safety Centers.

- Focus Area 4.1: ECM Earth Cover Alternative Criteria
- Focus Area 4.2: ECM Erosion Control Solutions and Best Practices

Work has begun in both of the above focus areas. A preliminary effort is underway to identify viable erosion control solutions for ECMs. Additionally, the US Army Corps of Engineer Research and Development Center (ERDC) has drafted a multi-phase test program to begin addressing the concerns associated with Focus Area 4.1 (Reference 44). The Phase 1 tests of this effort were conducted in summer of 2018.

5.5 Schedule/Timeline

The schedule and execution of the ECM Testing and Modeling program described herein is dependent upon multiple factors, but a general schedule has been developed for each of the focus area. The schedule shown in Figure 10 is tentative at the moment, but is fairly representative of the planned timeline. As can be seen in Figure 10, some focus area sub-tasks have been completed or are currently ongoing, while many efforts have yet to begin. Some examples of ongoing work have been briefly discussed in previous sections.

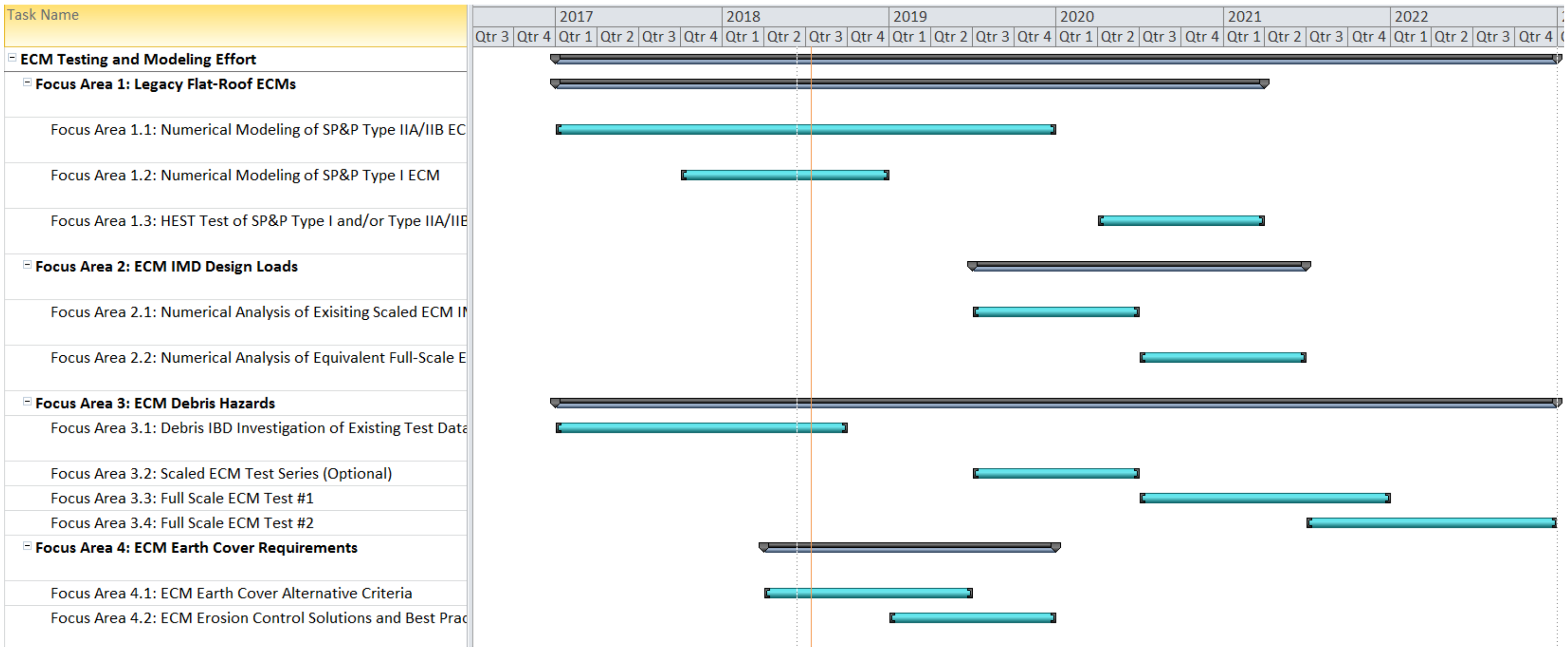

Figure 10. Proposed Timeline for ECM Modeling and Testing Effort Under AMO-CAT

6. Summary

AMO-CAT has been established as is an integrated computational and testing program for development of new and/or enhancement of existing standards in support of explosives safety operations. An extensive review has been conducted to develop gap priority rankings that consider technology maturity, knowledge gaps, and alignment with the mission of the DDESB.

In addition to the comprehensive knowledge gap assessment across multiple aspects of explosives safety that AMO-CAT has generated, a focused effort looking specifically at ECMs has been developed. This has resulted in an ECM Testing and Modeling program to address four focus areas that have been defined based on input from stakeholders across multiple disciplines within explosives safety. A multi-year plan to address these ECM issues has been developed, and shall be achieved through a combination of testing efforts and advanced computational modeling.

The ultimate goal of AMO-CAT is to advance the knowledge base of explosives safety, enhance criteria, and to develop an optimal balance of providing safety to personnel, maintain mission capability, and minimize land encumbrance across the DoD.

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