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How Not to Site Plan: Common Pitfalls and Mistakes in Hazards Analyses

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Abstract

Explosives safety site planning often requires planners and engineers to provide protection from explosives hazards when standard Quantity-Distance (QD) criteria cannot be met. Properly identifying and quantifying explosives hazards as well as selecting effective mitigation strategies is a challenge. Mischaracterizing hazards can lead to improper proposed solutions.

Common mistakes as well as best practices are presented. Topics include improper extrapolation of common equations, improper use and placement of barricades, improper understanding and use of Substantial Dividing Walls (SDW), and improper application or interpretation of available test data. Basic examples are provided for each topic.

1. Introduction

Explosives safety site planning often requires planners and engineers to provide protection from explosives hazards when standard QD criteria cannot be met. Properly identifying and quantifying explosives hazards as well as selecting effective mitigation strategies is a challenge. Mischaracterizing hazards can lead to improper proposed solutions.

2. Identifying Hazards – Use of Equations

Many references exist to help site planners quantify hazard distances for blast effects. U.S. Department of Defense (DoD) sanctioned references include DoD 6055.09-M (Reference 1), Unified Facilities Criteria (UFC) 3-340-02 (Reference 2), Department of Defense Explosives Safety Board (DDESB) Technical Paper (TP) 16 (Reference 3), and UFC 3-340-01 (Reference 4).

The issue at hand is the range of applicability of the equations in these references. The equations presented in each of the listed references are empirical in nature, meaning they are tied to test data. The available data used to generate the equations are generally sparse due to cost of testing and limitations of testing methods and equipment. For example, an equation for predicting debris perforation into wood targets may be based on only a few data points. These data points cannot possibly represent a complete range of wood material types and thickness, nor a full range of impactor shapes, masses, and velocities.

Engineers and planners are often led to use empirical equations to estimate hazards or mitigations. Understanding the range of applicability as well as any other constraint for an empirical equation is critical to ensuring that unintended and incorrect extrapolation does not occur.

2.1. Fragmentation Distance

A first example of misrepresenting an empirical equation involves the DoD standard for hazardous fragment distance (HFD) as presented in Reference 1. The HFD is the prescribed standoff distance for the public such that the density of "hazardous fragments" will be acceptably low. This is not the same as the maximum fragment distance (MFD), which is the greatest predicted distance for any single fragment associated with a particular explosion.

By U.S. siting criteria, the HFD for any explosive weight larger than 450 lb is 1,250 ft. For explosive weights less than 450 lb, the HFD is calculated using an empirical equation based on test and accident data (see Figure 1).

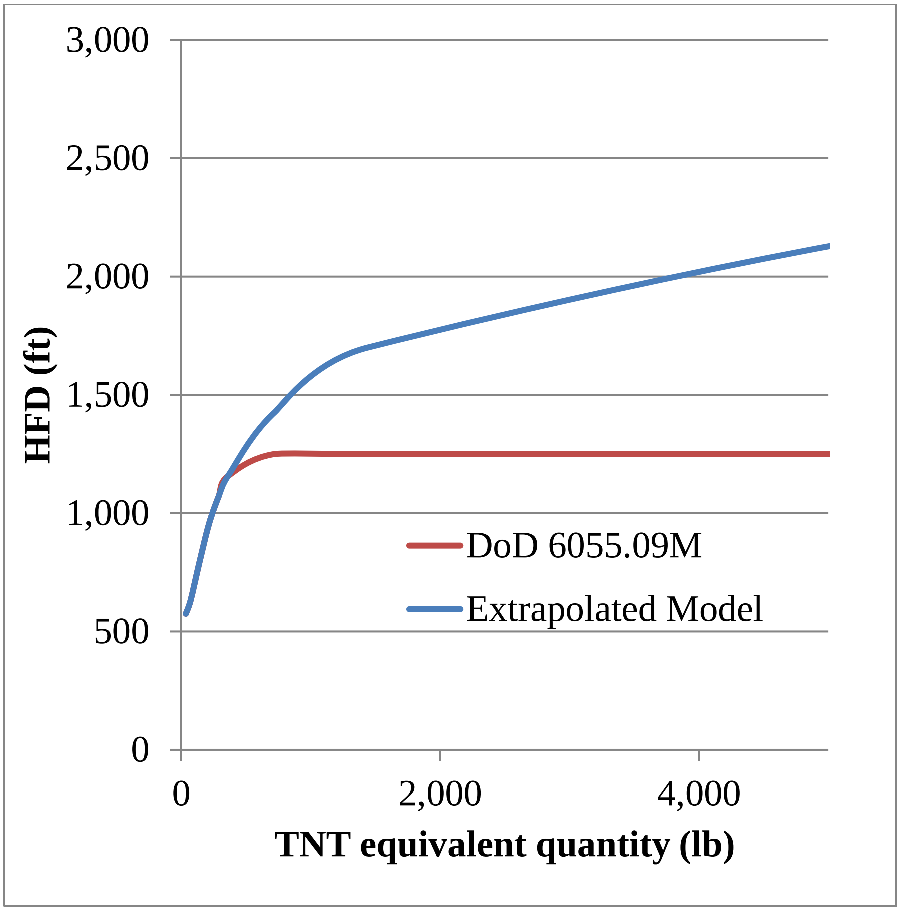

Figure 1 - HFD Extrapolation - Low Explosive Weights

In 2014, APT was tasked to peer-review a hazard assessment model that was being sold to emergency responders throughout the U.S. as a fast-running model for explosives hazards. The software claimed to be using approved DoD methods. The model appeared to provide conservative HFD estimations for low explosive weights, and extremely conservative HFD estimations for large explosive weights (see Figure 2).

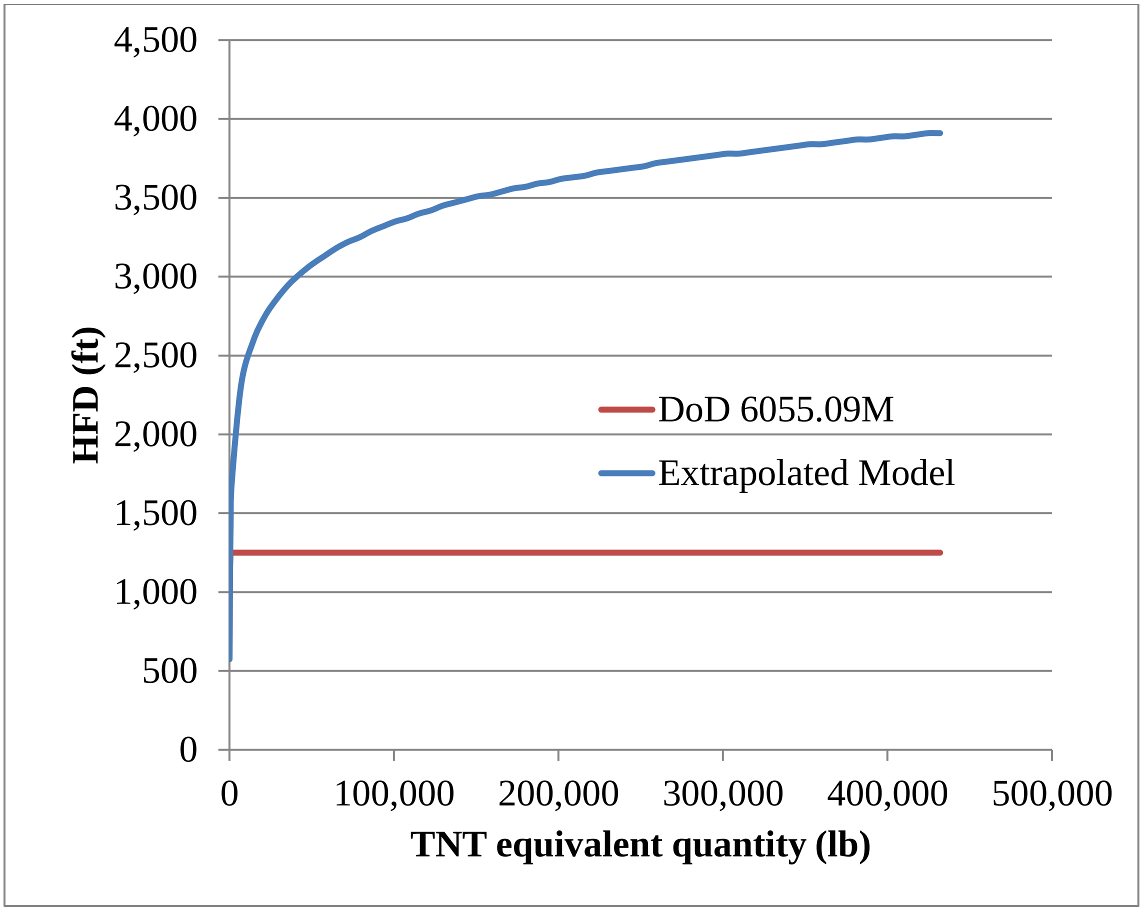

Figure 2 - HFD Extrapolation - High Explosive Weights

Upon review, it was discovered that the software designers extrapolated the HFD equation from Reference 1 beyond the intended limit of 450 lb. The resulting extrapolated HFD model appeared to be continuous and provide conservative results, and was, therefore, not questioned further by the software designers.

However, this equation was never intended to be used beyond 450 lb of explosives. The results, though conservative, require extreme standoff distances. And the results were falsely promoted as being in accordance with accepted DoD methods.

2.2. <u>Fragment Perforation</u>

A second common example of misrepresenting an empirical equation involves estimating fragment perforation. Essentially every DoD reference for debris penetration and/or perforation of steel fragments into various types of metal, glass, or polycarbonate is based on methodology known as Thor constants (References 3, 4, and 5). These empirical equations are based on test data and are widely accepted. The issue with these methodologies is that they are often presented without corresponding ranges of applicability for target thickness or impact velocity or mass.

Review of the ranges of limitations for the equations (Reference 6) shows that while many of the equations have wide ranges of applicability for striking velocity and target thickness, they are limited in the range of the mass of the steel fragment impactor. Other than steel targets, which are applicable for a steel fragment mass of up to approximately 2 ounces, all other target types are applicable for steel impactors only up to 0.5 ounces or less. The reasoning for this is likely that the models are intended for primary fragments (e.g., munitions casings), which are typically small.

The issue is that these equations are commonly applied to larger fragments, such as secondary debris from structures. Planners and engineers are typically attempting to model the "worst-case" scenario, which leads the analyst to estimate the largest theoretical fragment. Users can be led to use Thor equations on the edge or beyond the range of applicability in the pursuit of conservatisms, when in fact the equations may not be conservative (or correct).

To remedy this issue, alternative sources should be researched for use with larger fragments. UFC 3-340-02 (Reference 2) is intended for the response of structures and may better account for larger steel fragments such as secondary debris. The equations within UFC 3-340-02 are also empirical but are not directly tied to Thor constants.

3. Identifying Hazards - Overconservative Assumptions

In pursuit of safety, conservatism is commonly required in hazard assessments. This conservatism can be used to provide a factor of safety for unknowns or other assumptions. While this practice is useful and accepted, caution must be taken to ensure that unrealistic requirements are not imposed.

Any single conservative assumption can be generally understood, along with its potential impact on the resulting calculation. However, when multiple layers of conservatism are applied, it is more difficult to assess the impact of individual assumptions. If multiple assumptions of conservatism are made by the analyst, or imposed by the approval authority, hazards can be severely overrepresented, even to the point of being unrealistic or impossible. Likewise, mitigation options can have unrealistic and costly requirements developed in order to reduce or remove the assumed hazard.

An example of this is illustrated by debris hazards, specifically the flight range and striking velocity of individual fragments. An analyst may seek to determine how far a fragment may travel or what type of barricade would be required to mitigate the fragment. For these calculations, some representation of the fragment mass and velocity is required. For both variables, a larger value is generally more hazardous and is therefore assumed or required (i.e., what is the worst-case scenario).

Debris velocity can describe the velocity at either the moment of launch or the moment of impact. If the fragment has traveled hundreds of feet prior to impact, the velocity can be significantly reduced, depending on the details of the scenario. A conservative assumption can be made that the impact velocity is equal to the launch velocity. This assumption may be made if the launch velocity is available and there is uncertainty in the impact velocity. The launch velocity can sometimes be obtained via testing and the use of high-speed cameras or other equipment (e.g., Doppler radar). It can also be calculated for some scenarios using empirical equations (Reference 3).

It is common to assume that the velocity of all fragments launched from a single component or article is the same. This is an assumption of Reference 3 for each analyzed section of a munition casing. This assumption simplifies the analysis but may apply "worst-case" conservative values to all individual fragments, which in reality travel at varying speeds. This assumption is further strained for secondary structural debris. Secondary debris for a scenario can vary widely in velocity due to the nonuniformity of many variables such as material type, size, and support constraints.

The mass of the debris also typically varies from very small to potentially very large fragments. This is due to the breakup mechanics of the material (e.g., crushing fracturing of concrete or tearing and rupturing of steel). In nearly all scenarios, it is required to account for the largest theoretical fragment as the controlling hazard.

In some scenarios, it is not correct to account for the highest theoretical velocity and largest theoretical mass simultaneously. This combination can create improbable, if not impossible, hazard scenarios.

A recent example of this occurred while designing a barricade intended to mitigate low-angle fragments from a missile warhead at a contractor-operated maintenance facility. The review authority was aware of arena testing data available for the warhead and requested that the information be used to design the barricade. The test report identified an "estimated" fragment launch velocity of 5,000 feet per second. This velocity is very high, but still within the range of potential values for primary fragments originating from a warhead casing. The arena test also collected fragments within the test fixture as well as several fragments that perforated the test fixture. Of these, the warhead front plate was recovered, with a mass of 48.6 lb.

The review authority requested that the warhead plate be considered as the design fragment. Being that the only velocity mentioned in the report was the estimated 5,000 feet per second speed for an unspecified fragment, the review authority also requested that this worst-case velocity be considered. It is important to note that this estimated velocity was a launch velocity and would be greatly reduced if the impact location was at distance.

At this point, the calculations could be made for the fragment and a mitigation strategy could be developed. However, it is important to view the scenario from the perspective of whether the resulting design fragment is realistic. Nearly all fragment perforation calculations are based in some way on kinetic energy (see References 1-4). In these calculations, the velocity term is squared or otherwise magnified to a greater extent than the mass, as in the standard equation for kinetic energy. Therefore, conservative assumptions related to the velocity have a far greater effect on the fragment perforation hazard than do equivalent conservative assumptions for the mass.

$$Kinetic\ Energy = \frac{1}{2} mass \times (velocity)^2$$

In the scenario described, the kinetic energy for the requested design fragment is 1.90E+07 foot-pounds of energy. Without comparing this value to other benchmark cases, it could be easy to progress with the calculations and design for the subject fragment. However, upon further inspection, it can be seen that this value is incredibly large and wholly unrealistic. To put the value in perspective, this estimated kinetic energy is equal to that of a fully-loaded concrete truck (66,000 lb) traveling at a speed of 92.5 miles per hour. This is an immense amount of kinetic energy that cannot be imparted to a single plate during an open detonation by the energy contained within the warhead.

In this scenario, because the mass of the fragment is measured and known, it is reasoned that the worst-case launch velocity is overestimated. This is a realistic finding for a fragment representing the thickest portion of the fragment casing. The impulse imparted into the fragment casing at the time of the explosion would be expected to propel thinner/lighter fragments faster than thicker/heavier fragments.

Discussion with the review authority led to a reduction in the estimated impact velocity of the design front plate fragment. As a conservative backup, other fragment sizes and shapes, representing the average instead of the maximum mass, were analyzed at the full 5,000 feet per second worst-case velocity.

4. Mitigation - Barricades

Barricades, whether earthen berms or concrete walls, are perhaps the most common blast hazard mitigation technique. Barricades have significant advantages in terms of cost and constructability, but also have limitations that are not always recognized. DoD site planning criteria (Reference 1) differs from that of the U.S. commercial sector (Reference 7) and international criteria such as NATO siting criteria (Reference 8).

DoD criteria recognize that barricades can be used for fragment mitigation as well as blast overpressure attenuation but establish limitations on the applicability of these protective features. Blast overpressure attenuation can be accounted for, but only directly nearby the barricade and is dependent upon the barricade size (see Reference 1, Section V2.E5.4.2.5). The criteria clearly state that the attenuation is not applicable to far field exposures such as inhabited building distance (IBD) or public traffic route distance (PTRD).

By DoD criteria, fragment mitigation from the barricade is only applicable to low-angle debris for intermagazine distance (IMD) and intraline distance (ILD). No credit or reduction is given to IBD and PTRD for barricades. Similar criteria are found in NATO manuals (Reference 8). This is because the fragments that reach IBD or PTRD ranges are not low-angle fragments that would be intercepted by barricades. Rather, the debris that overwhelmingly control the HFD for both IBD and PTRD are fragments that are launched at angles of at least 5 to 10 degrees. These fragments come from the upper portions of the donor structure walls or donor structure roof. They can also be generated by the top exposed half of the munition.

Figure 3, generated using the TrajCan software (Reference 9), illustrates a typical range of variables for secondary debris launched from a donor structure in an accidental explosion. This example shows combinations of debris mass (1, 5, 10 and 25 lb), launch velocity (100-500 fps) and launch angle (10-80 degrees). The fragments that travel to typical IBD ranges of 1,250 feet and beyond are those with the largest mass and velocity, as well as launch angles greater than 10 degrees. Barricades designed per DoD criteria are not intended to intercept debris at launch angles greater than 2 degrees.

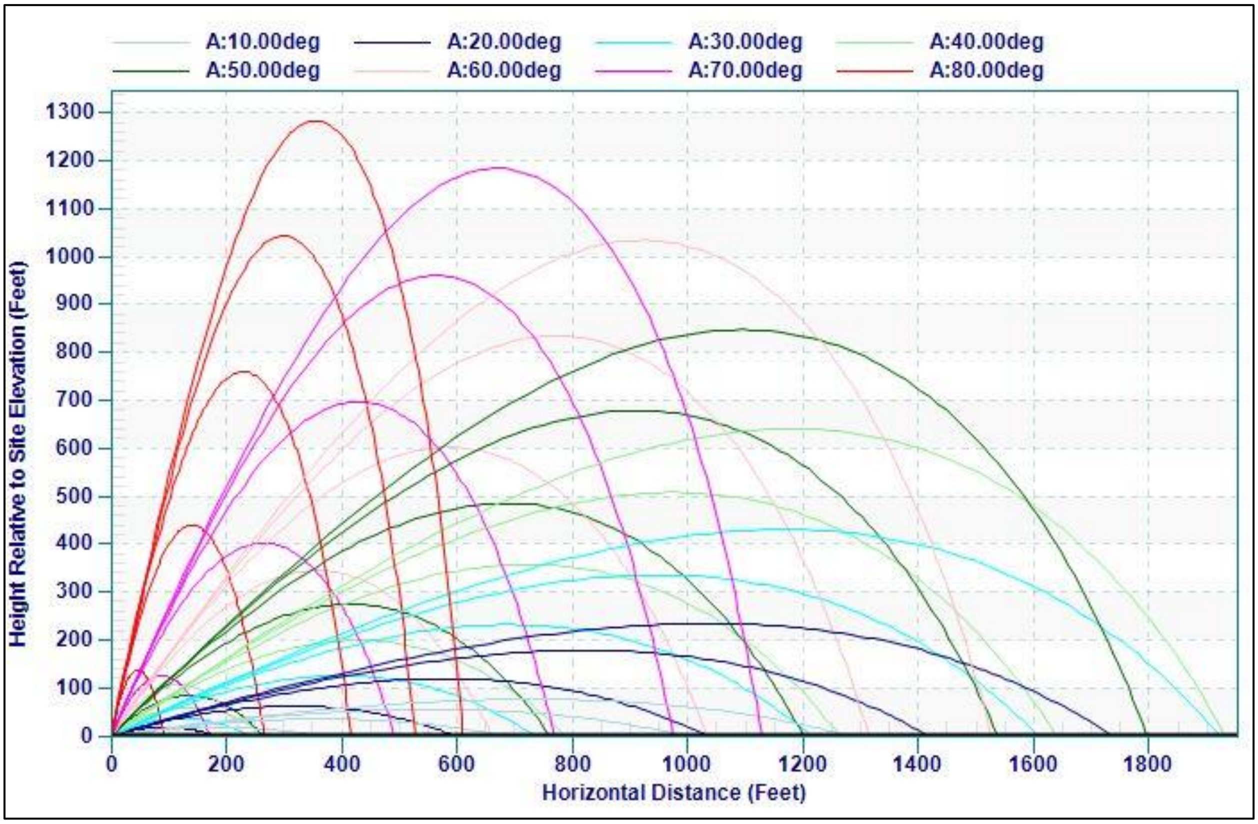

Figure 3 - TrajCan simulation of debris reaching IBD

APT has inspected multiple contractor-owned contractor-operated (COCO) sites that have been required by review and approval authorities to build large barricades with the intent of reducing the IBD. In two scenarios, the exposure in question was a highway located approximately 1,100 feet from the donor structure; each donor structure had a sited explosive limit of less than 30,000 lb. In one of the scenarios, a 600 ft long, 25 ft tall earthen berm was constructed. In the second scenario, a multi-million-dollar concrete wall 400 ft long and 25 ft tall was constructed.

In both scenarios, it is understood that the intent is to provide protection, and that having a barricade is almost always better than not having a barricade. The point of this discussion is that enormous, expensive barricades are not likely mitigating the hazard that is driving the requirement, thus requiring such barricades is contrary to DoD criteria manuals that dictate the site planning.

Barricades are versatile and cost-effective in mitigating some blast and fragment hazards. However, they should not be required or utilized in scenarios in which they do not effectively reduce the hazard being analyzed.

5. Mitigation – Substantial Dividing Walls

Substantial dividing walls (SDW) are pre-approved blast mitigation features that can be incorporated into site plans if all applicable criteria are met. The governing document for SDWs is a DDESB Memorandum dated Jan 2003 (Reference 10). This document provides minimum construction requirements for SDWs as well as restrictions and limitations on the applicable types and quantities of explosives. SDWs are intended primarily to prevent prompt propagation of explosives between adjacent bays but can also be designed in select circumstances to provide personnel protection.

Essentially, an SDW is a robust concrete wall (minimum of 12 inches thickness) with proper steel reinforcement and support constraints. Structures that utilize SDW criteria are required to meet minimum ventilation criteria for detonation scenarios.

The usefulness of this type of pre-approved mitigation feature has led to wide application. Due to the implementation of the criteria at so many locations, many people have been exposed to the benefits of these criteria.

However, widespread implementation does not ensure widespread understanding of the criteria and their limitations. Unfortunately, it is common for almost any concrete wall with a robust appearance to be labeled as an SDW. This issue is compounded because many of the production and test facilities used in the U.S. were constructed prior to the establishment of the SDW criteria. Many existing structures include robust walls with significant capacity for explosives hazard mitigation, yet they do not meet all of the SDW criteria.

The most common structural deficiencies that prevent legacy structures from utilizing the SDW criteria are:

1. Lack of proper shear reinforcement. Unfortunately, legacy structures were not required to have the same type and amount of shear reinforcement as is currently required. This lack of shear reinforcement is difficult to overcome and commonly disqualifies even very robust concrete walls from utilizing the SDW criteria.

2. Lack of sufficient venting for detonation scenarios. Many legacy structures were originally designed to have only a single frangible venting surface and otherwise contain the hazard as much as possible in the other directions. This attempt to provide additional safety actually disqualifies many structures from consideration for SDW criteria for detonation scenarios.

3. Confinement of deflagration effects within a common structure. Deflagration events for Hazard Divisions 1.3 and 1.4 do not require a minimum venting area but do require that the firebrand and other thermal effects do not transfer from one side of the SDW to the other. Some operations structures have a layout of several adjacent parallel bays that share a common front passageway or hallway. In the event of a deflagration scenario, the fire will exit one bay but may not blowout the frangible hallway. In this scenario, the fire is actually confined and channeled into adjacent bays, opposite to the intent of the SDW criteria. In these scenarios, even if the construction details meet SDW standards, the SDW criteria may not be approved.

6. Mitigation – Earth Covered Magazines

The earth-covered magazine (ECM) is another example of a widely implemented hazard mitigation option that can be misunderstood. These common structures are effective at reducing the IMD required between storage facilities, and therefore can provide significant reductions in required land when used in large quantities. ECM design types must meet specific criteria (Reference 1) and must be DDESB-approved for use.

Due to the widespread implementation across nearly every DoD explosive storage location, commercial industry sites, and throughout the world at many foreign sites, many people have been introduced to this facility type. However, a surprisingly common misconception is that ECMs are preferred and add safety because the magazines (are believed to) actually contain the explosives effects. This misconception is reinforced due to the robust construction of the ECM.

In reality, the robust construction of any ECM is designed to protect the contents from external loads such as the detonation of an adjacent magazine. No ECM design considers internal loads from an internal detonation. While it is true that these robust structures would contain the effects of some quantity of explosives, this quantity is surprisingly small. Test series Navajo and Hastings (Reference 11) showed that explosives quantities as little as 20 lb can destroy the roof of an ECM. It may not launch the roof as debris, but it will cause the roof to collapse.

Another misconception of ECMs is that the site planning criteria is always preferable over equivalent above-ground magazine (AGM) criteria. ECM criteria do provide reduced IMD and ILD criteria and should be considered if many storage magazines are required, high explosives quantities are required, and space is restricted. However, if few magazines are required and moderate explosives quantities are requested, the significant additional cost for ECMs may not be justified. This is particularly true if IBD is the controlling factor in the site plan.

Figure 4 compares DoD IBD criteria for AGMs and the various sectors of an ECM. On this logarithmic plot, it can be seen that the ECM IBD is less than that of the AGM for net explosive weights (NEW) less than 450 lb or larger than 30,000 lb. However, between these values, the ECM and AGM criteria for IBD are equivalent.

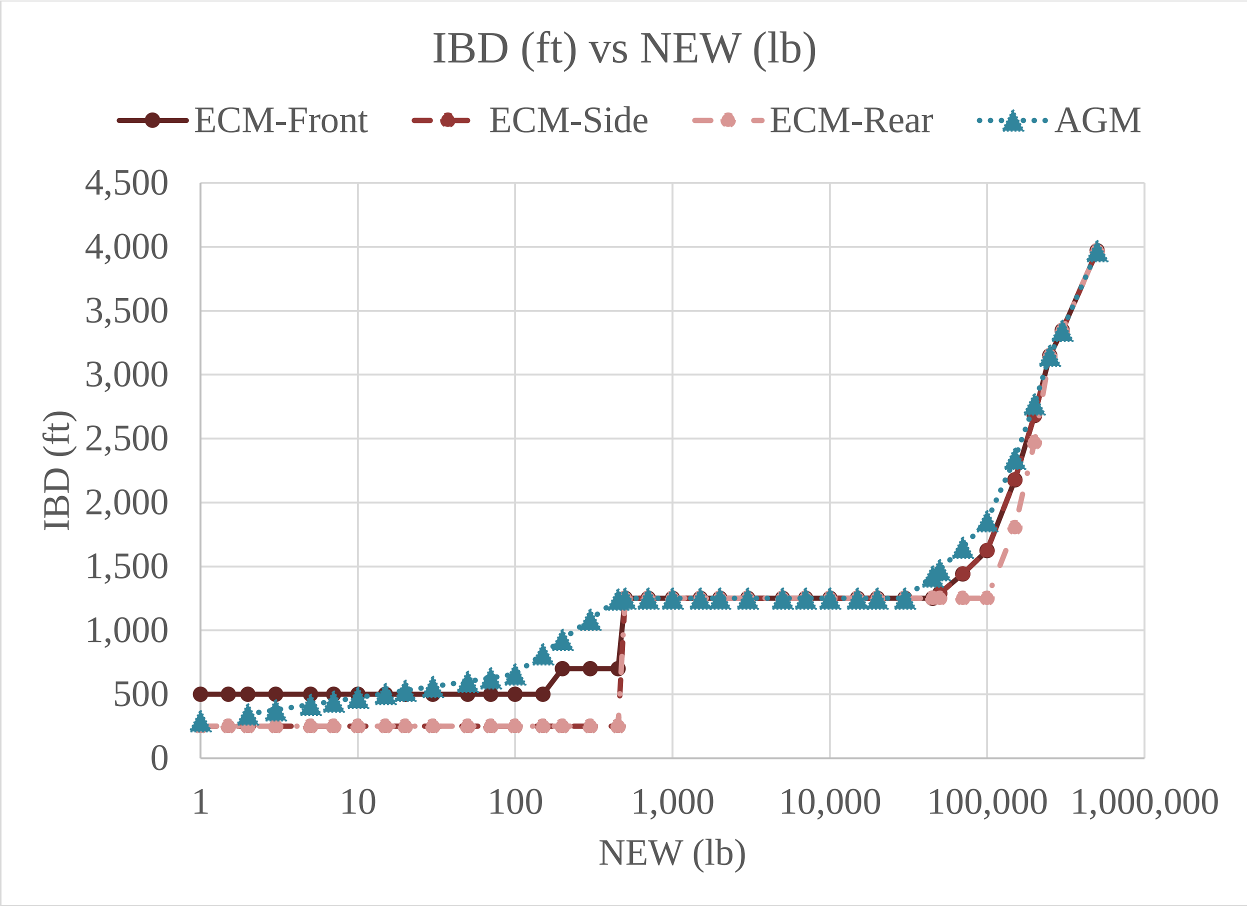

Figure 4 - U.S. DoD ECM vs AGM criteria

7. Conclusion

Properly identifying explosives hazards and properly designing mitigation strategies can ensure that excessive cost is not incurred for impractical considerations. This can also help ensure that impractical or unnecessary structures are not designed and implemented. Understanding the intents and limitations of various explosives safety criteria can aid in selecting effective mitigation strategies.

References

1. DoD Ammunition and Explosives Safety Standards, DoD 6055.09-M, 4 August 2010, Incorporating Change 1, August 31 2011.
2. Unified Facilities Criteria 3-340-02, Change 2, “Design and Analysis of Hardened Structures to Conventional Weapons Effects”, September 2014.
3. Department of Defense Explosives Safety Board Technical Paper (TP) 16 Revision 5, “Methodologies for Calculating Primary Fragment Characteristics”, Department of Defense Explosives Safety Board, 19 December 2016.
4. United Facilities Criteria 3-340-01, “Structures to Resist the Effects of Accidental Explosions”, Change 2, September 2014.

5. U.S. Army Armament Research and Development Center Ballistic Research Laboratory ARBRL-TR-02561, "Compilation of Mass, Velocity Region Graphs for Penetration of Metallic Barriers by Steel Fragments as Predicted by the THOR Equations", May 1984.
6. Handbook for Blast Resistant Design of Buildings, Donald O. Dusenberry, Wiley Publishing, January 2010.
7. Army-Navy Explosives Safety Board, Technical Paper No. 1, "The Present Status of the American Table of Distances," Washington, D.C., 1 July 1945.
8. Allied Ammunition Storage and Transport Publication (AASTP)–1, Change 3, "Manual of NATO Safety Principles for the Storage of Military ammunition and Explosives," May 2010.
9. Chrostowski, J.D., Gan, W., Cao, L., "TRAJ_CAN White Paper", ACTA Technical Report No. 15-954/02, December 2015.
10. DDESB-KT Memorandum of 15 January 2003, Subject: "Updated Guidance for Substantial Dividing Walls (SDW)".
11. Reeves, H., and Robinson, W. T., "Hastings Igloo Hazards Tests for Small Explosive Charges," Memorandum Report ARBRL-MR-03356, U.S. Army Ballistic Research Laboratory, MD, May 1984.