Updated Blast Effects and Consequence Models in DDESB Technical Paper 14

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Abstract

The U.S. Department of Defense Explosives Safety Board (DDESB) has established an approved quantitative risk assessment (QRA) methodology for evaluating and accepting risks associated with explosives storage and activities. This methodology is defined in DDESB Technical Paper (TP) 14, Approved Methods and Algorithms for DoD Risk-Based Explosives Siting. The currently approved version of TP 14, Revision 4a, was published in March 2017, however that update represented only administrative/editorial changes to TP 14 Revision 4, which was published in July 2009. Significant updates to the blast effects and consequences algorithms of TP 14 have been underway incorporating empirical results and analytical modeling techniques generated over the past decade, and have resulted in a draft version of TP 14 Revision 5.

A general overview is provided of the methods and algorithms within TP 14 Revision 5 that estimate the blast effects from an accidental explosion, and the associated consequences to personnel and assets. While the ultimate purpose of TP 14 is to quantify the annual risk to personnel from explosives operations, the additional terms for estimation of risk, probability of event, exposure, and the inherent uncertainty in the calculation, shall not be addressed within this paper. Significant updates incorporated into Revision 5 shall be addressed, with accompanying background with references for the basis of improvement and the ultimate effect on the end result. These improved models are in areas including, but not limited to, new potential explosion site (PES) types, new exposed site (ES) types, improved pressure & impulse attenuation curves, improved blast ingress models, updated direct blast effects models, improved glass hazard logic, new primary fragment routines, improved PES secondary debris mass distribution, improved debris launch velocity models, updated debris throw models, improved debris perforation models, and more advanced human vulnerability models to blunt impact by debris.

While the current version of TP 14 (Revision 4a) is implemented with the software tool SAFER v3.1, the next version of TP 14 (Revision 5) shall be implemented with the Risk Based Explosives Safety Siting (RBESS) module which will reside within the Explosives Safety Siting (ESS) software, which is a QD siting software sponsored by the DDESB.

Introduction

The U.S. Department of Defense Explosives Safety Board (DDESB) has established an approved quantitative risk assessment (QRA) methodology for evaluating and accepting risks associated with explosives storage and activities. In the explosives safety community, QRA represents an alternative path for regulator acceptance to the long established deterministic method of quantity-distance (QD), where a singular distance as a function of explosives weight is determined acceptable. This methodology is defined in DDESB Technical Paper (TP) 14 [Ref. 1], and considers probability of event as a function of activity type, exposure of various population groups, and consequences given the occurrence of an event. The Department of Defense (DoD) QRA model is based on recent advances in modeling of explosion effects and structural response, and it provides comprehensive risk and consequence calculations. The QRA model defines criteria for acceptable risk levels to both individuals and population groups. The methodology is intended to be both fast running and all-encompassing, as it needs to be applicable for all explosives activities and scenarios. The use of TP 14 has been approved by DoD and has been incorporated in DoDM 6055.09 [Ref. 2].

This paper provides details of the explosion effects and consequence algorithms of TP 14. It presents updated effects and consequence models that will be published in the next version of TP 14. This paper shall detail the consequence models from the various hazard mechanisms from an explosives event, as well as the relation to injury and fatality. While the current version of TP 14 (Revision 4a) is implemented with the software tool SAFER v3.1 [Ref. 3], the next version of TP 14 (Revision 5) shall be implemented using the Risk Based Explosives Safety Siting (RBESS) module within the Explosives Safety Siting (ESS) software [Ref. 4], which is a QD siting software sponsored by the DDESB.

DDESB Technical Paper 14 Overview

The official U.S. DoD explosives safety risk-based siting methodology is defined in DDESB TP 14. TP 14 defines the underlying logic and algorithms used in DoD risk-based explosives safety analyses, for both production of DDESB site plans as well as risk management purposes. The currently approved version of TP 14 is Revision 4a, and is implemented in the risk analysis tool Safety Assessment for Explosives Risk (SAFER) Version 3.1. An important distinction is made in that TP 14 defines the currently approved DDESB QRA methodology (TP 14 Revision 4a), while this methodology is implemented via the approved DDESB QRA tool (SAFER Version 3.1).

The basic formulation of the risk equation in TP 14 is that *Risk* is the product of *Likelihood*, *Consequences*, and *Exposure*. While the general application of the *Risk* equation and implementation of the risk management process has been detailed elsewhere, this the paper shall focus on the *Consequence* term. The *Consequences*, or probability of fatality given the event occurs and a person is present, are calculated by combining the potentially harmful effects generated by the event. The architecture of the methodology is a 26-step process to quantify the risk associated with an explosives operation, as shown in Figure 1.

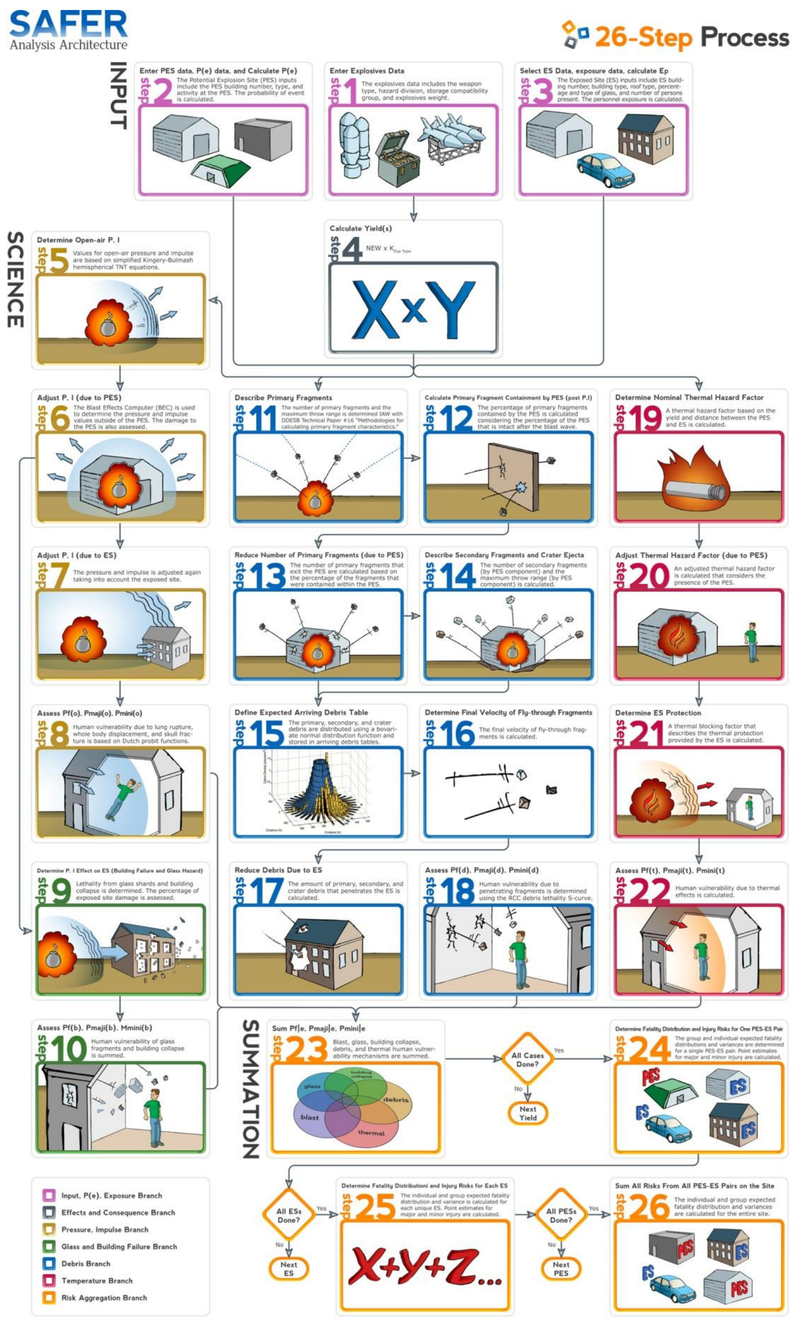

Figure 1 – TP 14 26-step risk process

The sequential steps shown in Figure 1 are organized in six Groups, additional details of which are provided in Table 1. Group 1 can generally be thought of as the "Input" steps, Groups 2 – 5 can be thought of as the "Science" steps, and Group 6 can be thought of as the "Summation" steps. The focus of this paper shall be on the "Science" steps, providing detail on the algorithms and methodologies utilized to quantify probabilities of injury and fatality, as well as the background data and analysis used to generate these methods.

Table 1 – Six Functional Groups of TP 14

Group 1	Steps 1-4	Situation Definition, Event and Exposure Analyses Includes inputs that describe the situation (potential explosion site and exposed site) and calculates P_e, exposure, and yield
Group 2	Steps 5-8	Pressure and Impulse Branch Calculates the magnitude of the fatality mechanisms of pressure and impulse
Group 3	Steps 9-10	Structural Response Branch Calculates the magnitude of the fatality mechanisms of building collapse and broken windows (overall building damage)
Group 4	Steps 11-18	Debris Branch Calculates the magnitude of the fatality mechanisms for multiple types of flying debris
Group 5	Steps 19-22	Thermal Branch Calculates the magnitude of the fatality mechanism heat for HD 1.3 scenarios only
Group 6	Steps 23-26	Aggregation and Summation Aggregates the total magnitude and risks of all fatality mechanisms, calculates the desired measures of risk, and assesses overall uncertainty

TP 14 Revision 5 Update

Since the original publication of TP 14 Revision 4 in 2009, there have been numerous advances in numerical techniques to quantify probability of injury and fatality due to the various explosion effects hazard mechanisms. Additionally, multiple explosives tests have been conducted investigating theses phenomena which have been published in various media. The DDESB has led a continuous effort to update the state-of-the-art in this area, and multiple improvements in prediction methodologies have been made. Where appropriate, the algorithms within TP 14 have been updated and a draft Revision 5 of this document has been produced. While not yet published, these prediction methodologies and supporting information used to generate these models shall be discussed herein. Note that while the TP 14 Revision 4a was published in 2017, the changes from the 2009 TP 14 Revision 4 were primarily administrative/editorial in nature, as there were no fundamental changes to the underlying consequence algorithms. The term “TP 14 Revision 4” shall be used throughout this paper in reference to the consequence algorithms that were established in the 2009 publication and remain in the currently approved TP 14 Revision 4a.

While there have been numerous changes throughout the document, there are a specific number of major updates that have been undertaken since the last revision. The areas of major updates are as follows:

- Window response and glass injury/fatality models
- Secondary debris mass distribution
- Explosion produced debris effects
- Explosion produced debris consequences

Group 2 Steps: Pressure and Impulse Branch

Steps 5-8 of the TP 14 architecture determine the blast effects (pressure and impulse) generated by the combination of the net explosive weight (NEW), potential explosion site (PES), and munition type modeled in the scenario, as well as the injury and fatality consequences resulting from those effects. Steps 5-7 calculate the final pressure and impulse acting upon persons accounting for any attenuation caused by the PES, exposed site (ES), and/or munition type, while Step 8 determines the probability of injury and fatality from that applied blast load.

The blast wave properties as a function of distance are well-known for explosive charges in the open, and are commonly estimated using the Kingery-Bulmash equations which assume a hemispherical charge of TNT in the open. While these equations are widely accepted and have been shown to scale appropriately for large and small charge weights alike, they require modification when the explosive composition is not TNT, when the explosive material resides within a cased munition (which is the vast majority of the cases in the DoD), or when the NEW is located inside a structure. To properly model this, the algorithms within TP 14 utilize the blast attenuation methodology defined within DDESB TP 17 (Ref. 5) and implemented by the Blast Effects Computer (BEC) version 7.1 The blast wave attenuation curves are implemented via a two-step process, with the first step accounting for the attenuation caused by the explosive material and/or the munition type, and the second step accounts for the attenuation cause by the PES. The structural attenuation is a function of the construction type, with lighter structures (e.g., light frame steel) providing little to no attenuation and heavier structures (e.g., concrete) providing greater attenuation. Directional effects generated by the structure are also accounted for, as the attenuation to the front, side, and rear of an earth-covered magazine (ECM) are quite different, particularly close-in.

The attenuation curves are generated based on fits to available test data, and account for the pressure and impulse attenuation independently. Based on the particulars of the scenario and the scaled distance, an equivalent hemispherical weight of TNT is defined for pressure and a separate one is defined for impulse. This is a vast improvement over using a scalar value for TNT-equivalence, as that value is typically different for pressure and impulse and changes as a function of scaled distance. An example of the curve fit generated within TP 17 for the peak incident pressure as a function of scaled distance for a concrete operating building is shown in Figure 2.

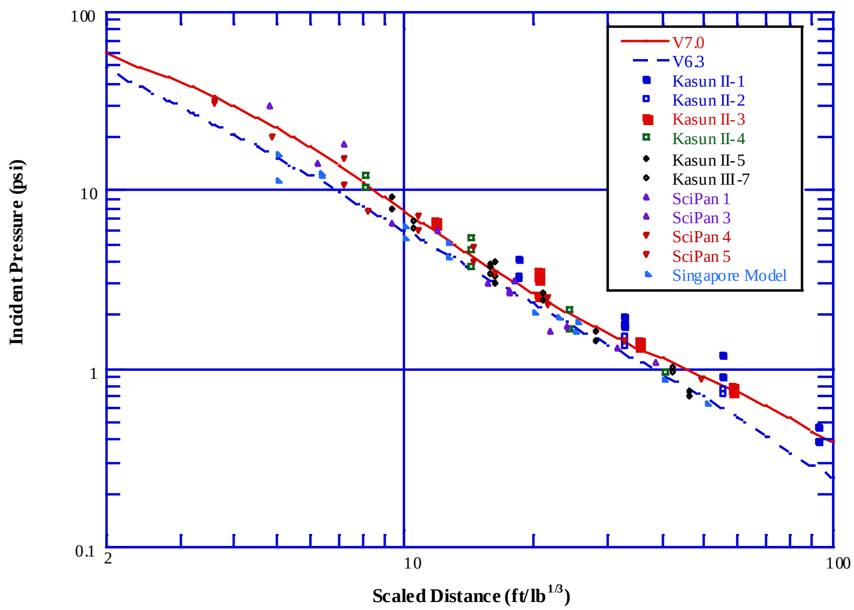

Figure 2 – Aboveground Structure Concrete – Pressure Comparison

Once the incident pressure and impulse at the distance of interest are known, the final step before determining the consequences to personnel is to quantify the blast load that personnel are subjected to. If personnel are in the open, then it is simply the pressure and impulse calculated as previously described, but if the persons of interest are inside a structure, the protection afforded to the occupants by the structure must be accounted for. Any opening to the structure will allow for leakage pressure to enter and build up inside the facility. A nominal small percentage of the facility is assumed to have opening due to HVAC and other potential perforations, but the vast majority of openings in any structure is provided by the presence of windows. The underlying assumption of the methodology is that the windows break almost instantaneously and allow for the blast wave to enter through the opening. The filling pressure inside the building is determined based on a procedure defined within UFC 3-340-02 (Ref. 6), which defines the pressure-time history via an incremental procedure. To create the algorithm for TP 14, this procedure was performed for all relevant parameters, and then generic curve fits were developed. The end result is a method to calculate the peak pressure and impulse applied to occupants inside a facility.

Once the pressure and impulse acting upon an individual is calculated, TP 14 quantifies the probability of injury and fatality to the individual for those direct pressure effects. In determining probability of fatality, three potential fatality mechanisms are considered: lung rupture, whole body displacement, and skull fracture. Similarly, determination of major and minor injury assesses the following vulnerabilities: soft tissue injuries, whole body displacement, and skull fracture. Soft tissue injuries examine injury potential to the lungs, the gastrointestinal tract, the larynx, and ear drum.

Probabilities of consequence from the individual sources are determined by using either pressure impulse diagrams or probit functions, depending on the particular injury/fatality mechanism.

The aggregation of consequences is performed using a conditional summation from the separate source mechanisms, which for probability of fatality is lung rupture, whole body displacement, and skull fracture. For determination of major and minor injury probabilities, a conditional summation is performed on the various soft tissue injury mechanisms prior to performing a conditional summation on the probability of injury due to soft tissue response, whole body displacement, and skull fracture.

Group 3 Steps: Structural Response Branch

After determination of the consequences to personnel from direct blast effects, the next calculation within TP 14 is the injury and fatality caused to personnel by glass hazards from the windows and structural damage from the building. Determination of building damage and window breakage is primarily performed through the use of pressure-impulse (P-I) diagrams. An example of a P-I diagram is shown in Figure 3, which consists of a series of isometric curves that define a specific damage or response level for the structure or component of interest.

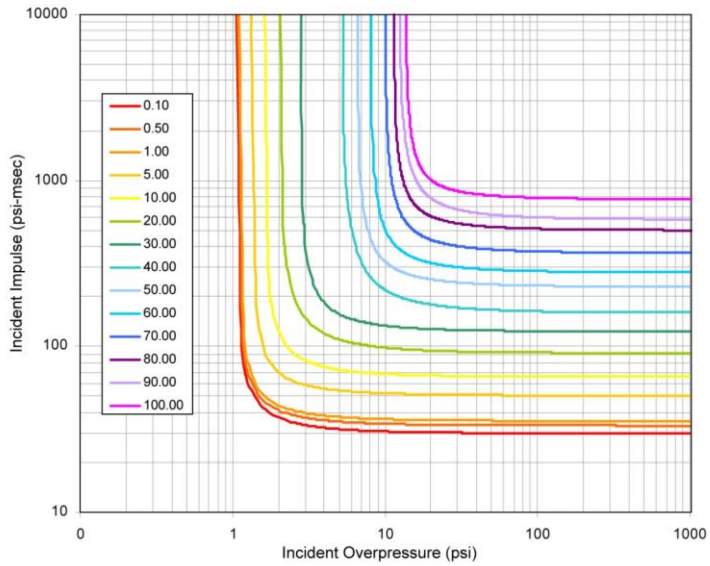

Figure 3 – P-I Diagram Example

The building damage P-I diagrams represent composite P-I damage curves, and were developed by aggregating the damage curves for the primary and secondary structural components on each building surface as a function of the applied load (i.e., reflected or incident) and then averaged over the entire structure (Ref. 7). This was done for all 21 different ES types within TP 14 Revision 5. Relations for probability of injury and fatality were developed as a function of building damage for each ES, which accounted for multiple factors. These factors included assessments of hazard due to roof failure, wall component velocity upon failure, and consequences associated with collapse, all of which greatly varied with construction type. For example, 60% damage for a light metal building might have a minimal probability of fatality associated with it, whereas that same damage level for a much stronger structure such as a heavy reinforced concrete facility would have a much higher probability of injury and fatality. Of course it must be kept in mind that it would take a much larger pressure and impulse for the heavy concrete structure to reach that damage level.

A baseline assumption of the TP 14 model is that persons who are injured receive prompt medical attention. So while glass hazards can generally produce a large amount of injuries, the likelihood of a fatality associated with window breakage is much lower. In cases where fatality due to window breakage becomes likely, there are typically other blast hazard mechanisms generating high probability of fatalities as well.

The injury and fatality due to window breakage is a multi-step process. The first step is to determine the probability that window breakage occurs. Since the strength properties of glass have been shown to be highly variable, it is most appropriate to assess breakage in terms of probability. After a breakage probability has been established, the area hazarded inside the facility must be determined, which is highly dependent upon the amount of windows, or percent glass, on the perimeter of the facility. Another fundamental assumption that TP 14 uses is that persons located beyond the first 12 feet of the facility perimeter wall are protected from glass hazards. This is to account for interior walls or partitions inside the facility which will protect personnel in the center of the building not exposed to window hazards and is shown in Figure 4a. For facilities less than 24 feet wide, this protected area is ignored. Next, the hazard area needs to account for the percent glass on the perimeter. The baseline injury and fatality equations within TP 14 assume windows covering one-third of the facility perimeter (G_p = 11.11%), with the consequences being scaled as a function of the actual percent glass. As can be seen in Figure 4b, a glass percentage of 11.11% or less will result in an area with minimal glass hazard to personnel.

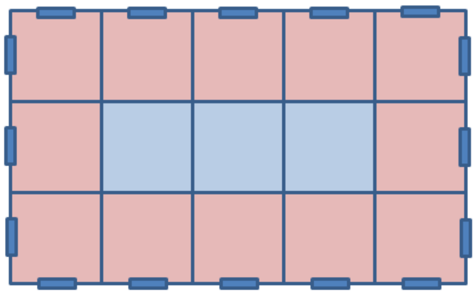

Figure 4a – Window Perimeter Area

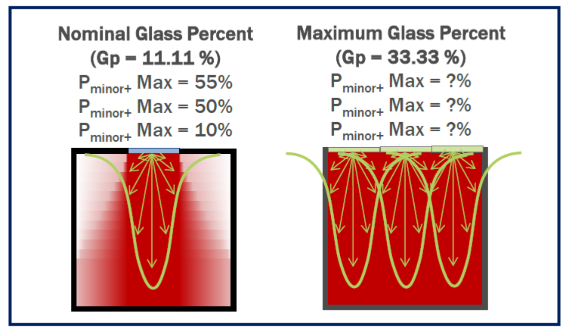

Figure 4b – Glass Shard Throw Distribution

There are four window type options within TP 14 Revision 5: annealed, tempered, dual pane (both panes annealed), and laminated annealed (interior pane laminated). Each window type has a different probability of breakage diagram as well as injury/fatality algorithms. The injury/fatality algorithms were developed for the baseline assumption of 11.11 glass percent on the face of the exterior (4 ft by 4 ft windows over one third of the façade) and employed a physics-based Monte Carlo throw model that varied relevant parameters to determine probability of hit on a standing or sitting person (Ref. 8). The target person was modeled by region, and relationships of shard size, shard velocity, and hit area were used to determine probability of injury and fatality. This was done for the annealed, tempered, and dual pane windows since the injury mechanism is penetration. The laminated annealed windows were handled slightly different, as the injury/fatality mechanism for that window type is blunt trauma.

Finally, as was the case with the direct effects from pressure and impulse, the structural response branch concludes with a conditional summation of the consequences resulting from the glass hazard and building collapse. The probabilities of fatality, major injury, and minor injury are aggregated to produce a probability of consequence for this branch.

Group 4 Steps: Debris Branch

Due to the numerous phenomenological aspects that need to be accounted for, representing the debris hazards from an accidental detonation is the most complex aspect of modeling explosion effects. Incidentally, the debris branch also represents the most comprehensive update in moving from TP 14 Revision 4 to Revision 5.

The debris branch of TP 14 comprises eight steps (Steps 11-18) that account for the probabilities of injury and fatality occurring from all types of launched debris generated by the event. Types of debris accounted for are primary fragments from the metal munition casing (which can be steel or aluminum), secondary debris from the donor structure (which can be steel or concrete), and crater ejecta (modeled as concrete due to similar density to rock). Primary fragments have extremely high velocities, on the order of 5,000 to 8,000 feet per second, and are typically very small in mass, with the vast majority of the fragments usually having a mass of less than 0.35 ounces. Secondary debris typically have a lower initial velocity than primary fragments, with that velocity being dependent upon the loading density, or the amount of NEW in the PES divided by the internal volume. One can imagine the extreme scenario with a steel donor structure completely filled with explosives generating secondary debris velocities comparable to that of primary fragments. Secondary debris will include much larger fragment sizes, though the range will be from maybe hundreds of pounds down to fractions of an ounce, depending on the structure type and the loading density. The distribution of fragments in this sense is referred to as the mass distribution, and is also a function of loading density. High loading densities will generate a large number of small pieces, while small loading densities will generate a small number of large pieces (nominally). Depending on the soil or foundation beneath the PES, crater ejecta is either soil, rock, or concrete, and both the amount of material thrown and the initial velocity are a function of the NEW.

Defining all of the fragments within the mass distribution for a specific debris type is not feasible for a fast-running model, so TP 14 performs a simple discretization of the continuous mass distribution into ten mass bins. These mass bins have defined bin limits, as shown in Table 2, and are different for steel, aluminum, and concrete debris. The definition of the mass bin limits was developed as a function kinetic energy of that specific debris type falling at terminal velocity (Ref. 9). Given that all debris eventually needed to be translated to hazardous effects on persons which are calculated as a function of kinetic energy, this simplified the process of assessing hazards from multiple debris hazards. These kinetic energy bins, also shown in Table 2, are defined as logarithmic half orders of magnitude.

Table 2 – KE/Mass Bin Format

Bin #	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
KE Min (ft-lb)	100K	30K	10K	3K	1K	300	100	30	10	3
KE Average (ft-lb)	173K	54K	17K	5K	1.7K	547	173	54	17	5
KE Max (ft-lb)	≥ 300K	100K	30K	10K	3K	1K	300	100	30	10
Fragment Upper Limit Mass (steel) (lb)	57.7	25.3	10.3	4.50	1.83	0.801	0.325	0.142	0.0577	0.0253
Average Fragment Mass (steel) (lb)	35.7	14.9	6.34	2.66	1.13	0.473	0.199	0.0852	0.0379	0.0142
Fragment Lower Limit Mass (steel) (lb)	25.3	10.3	4.50	1.83	0.801	0.325	0.142	0.0577	0.0253	0.0104
Fragment Upper Limit Mass (concrete) (lb)	122.1	53.6	21.7	9.54	3.87	1.70	0.687	0.302	0.123	0.0538
Average Fragment Mass (concrete) (lb)	75.4	31.5	13.4	5.61	2.38	1	0.42	0.18	0.08	0.03
Fragment Lower Limit Mass (concrete) (lb)	53.6	21.7	9.54	3.87	1.70	0.687	0.302	0.123	0.0538	0.0218
Fragment Upper Limit Mass (aluminum) (lb)	98.9	43.4	17.6	7.72	3.13	1.37	0.556	0.244	0.0989	0.0434
Average Fragment Mass (aluminum) (lb)	65.3	27.3	11.5	4.58	2.04	0.872	0.368	0.154	0.0647	0.0258
Fragment Lower Limit Mass (aluminum) (lb)	43.4	17.6	7.72	3.13	1.37	0.556	0.244	0.0989	0.0434	0.0176

The number and launch velocity of primary fragments are a function of the munition type selected. In the likely event that the NEW analyzed consists of multiple items, assumptions are made on the stack geometry of the munitions. This stack geometry is important as only the portions of munition casing on the exterior of the stack are considered to contribute to the debris hazard. This is based on previous test data and accepted methodologies suggesting that fragments on the interior of the stack are either thrown down/inward or are launched with a minimal velocity due to the multiple collisions experienced inside the stack.

Once the number/mass distribution of the primary fragments and launch velocity is determined, the containment and/or mitigation provided by the PES must be accounted for. This consists of two separate checks. The first is assessment of the damage to the PES caused by the internal detonation. In the event that the NEW was quite small and the PES experiences minimal or no damage, then the PES may contain the vast majority of the primary fragments. This will be dependent upon the PES type, as a reinforced concrete PES with thick walls will prevent primary fragments from leaving the structure if undamaged; the same cannot be said of an undamaged pre-engineered metal building. In the event that the NEW was large enough to cause complete destruction of the PES and launch all of the mass as secondary debris, then there is still the possibility that the PES can affect the primary fragments. The assumption made is that in the case of the heavy PES structures (concrete and reinforced masonry), the walls and roof (assuming they meet a minimal thickness) will impede the velocity of the primary fragments, resulting in those fragments departing with a velocity restricted to that of the secondary debris. Again, lighter structures, such as the pre-engineered metal building, will not have any effect on the launch velocity of the primary fragments.

The determination of secondary debris characteristics differs for the various PES types, and is largely a function of loading density. The improvements to this methodology in Revision 5 are significant as they incorporate information and data generated primarily over the past decade from a series of tests conducted to investigate these very phenomena (Ref. 10 – 21). These extensive testing efforts essentially provided information where very little existed previously – quantitatively defining the mass distribution for secondary debris. This is an absolutely critical part of the equation, as poor representation of the mass distribution can affect the debris hazard predictions by an order of magnitude, in either a conservative or unconservative manner, depending on the error in the mass distribution estimate. In addition to the mass distribution improvements, these tests also provided information as to the horizontal azimuthal distribution generated from these square/rectangular donors, particularly from the heavier PES types (e.g., concrete and masonry). Finally, much more accurate information was gathered on launch velocity for secondary debris in some of the recent tests. The secondary debris launch velocity prediction methodology is primarily based on the Debris Launch Velocity (DLV) equations (Ref. 22), which were initially developed based on a series of controlled experiments. This general methodology was found applicable to the more recent large scale testing, and for donor construction types not originally considered during development of the DLV.

As previously mentioned, the mass distribution for secondary debris is a function of the loading density. Despite the vast amount of knowledge gained in recent years on this topic from the aforementioned test series, there are still large data gaps and areas of uncertainty. For this reason, development of the mass distribution for secondary debris consisted of two separate steps. The first is to define the nominal mass distribution for a given PES type, which would be based on a loading density with the largest amount of empirical data available to establish the greatest degree of confidence given the information available. The nominal mass distribution for the various PES types is not always at the same loading density, given the available test data differed by PES type. The second step is to define the dynamic nature of the mass distribution, or rather how the nominal mass distribution changes with a varying loading density. Ideally this is developed with empirical or analytical information available describing the structural break-up at the extreme high or extreme low loading density, but for cases where no information was available for a specific PES type an analogous comparison was made to those PES types with this information. Additionally, where minimal information was available, the dynamic change of the distribution was made less aggressive; or rather the change in mass distribution from the nominal was minimized. Table 3 provides the mass distribution for the PES types having a standard concrete mass distribution in TP 14 Revision 5. The standard concrete mass distribution is applicable concrete roof and wall components with a thickness of less than 8 inches. The nominal mass distribution is defined at a loading density of 0.733 lb/ft^3, while the low and high distributions are defined at 0.244 lb/ft^3 and 6.667 lb/ft^3, respectively. The percentage of mass for each structural component is defined for each mass bin. A simple linear interpolation is made between entries if necessary to match the actual loading density of the PES analyzed.

Table 3 – TP 14 Revision 5 Standard Concrete Mass Distribution (% Total Mass)

	Density (lb/ft^3)	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10	Bin G
High	6.667	0.00	0.00	0.00	0.65	0.74	1.75	1.50	1.91	1.95	3.33	88.17
Nominal	0.733	0.00	0.43	2.49	5.63	5.81	5.82	4.52	4.66	4.62	5.24	60.78
Low	0.244	9.28	10.47	12.67	13.04	8.12	6.34	4.80	4.42	3.21	2.07	25.58
Y_{100} equivalent	Y_{100} equivalent	12.47	14.07	17.03	17.52	10.91	8.52	6.45	5.94	4.31	2.78	0.00

One aspect not previously discussed is the development of Mass Bin G. This is an improvement made from the Revision 4 methodology, and it was determined that it was a crucial consideration that needed to be incorporated.

Testing of concrete structures at high loading densities (Ref. 11, 18, and 19) has demonstrated that a significant portion of the concrete mass is essentially pulverized, and is converted to debris mass below the lower limit of Mass Bin 10. There were multiple instances where this was demonstrated, and much discussion was had prior to accounting for this effect. Ultimately, it was argued that the debris model would be grossly conservative for high loading densities if not accounted for, so it was included. The establishment of Mass Bin G accounts for the initial mass of the structure that was pulverized to very small debris/dust such that mass is conserved, but does not include it in the debris throw calculations because it does not travel to a range of concern due to the aerodynamics involved, nor does it have sufficient kinetic energy upon impact at distance to cause injury. The end result is that the debris model does a much better job of matching the total piece count when compared to concrete test data with high loading densities.

One of the biggest challenges in developing the TP 14 methodology is how to convert complex debris trajectory calculations for a variety of debris masses into a fast-running model. TP 14 Revision 4 defined bi-variant normal distributions for each debris type to represent the downrange debris density functions. The assumed trajectory of debris was treated as leaving the PES either vertically (high-angle debris) or horizontally (low-angle debris). The low-angle debris (e.g., secondary debris from a wall) was further discretized into fly-through or side-impact debris, which assigned the debris as either being hazardous to persons the entire horizontal trajectory (fly-through) or hazardous to persons only upon impact because of the “lobbed” nature of the trajectory (side-impact).

While the Revision 4 method is a valid approach and has been compared with test data, the Revision 5 methodology took a more physics-based approach to the debris model which introduced a bit more complexity. Given the mass bin framework established within TP 14, probability density functions for specific debris types (mass bin and debris source) were established ahead of time as a function of only launch velocity.

The debris probability density functions (PDFs) were generated via Monte Carlo simulations for each defined scenario. Each source of debris required different assumptions and distributions on shape factors, drag coefficients, material density, mass distribution over the mass bin limits, and launch conditions, so a total of 25 different departing debris sources were considered. Each debris source then required development of ten debris PDFs (or seven in the case of primary fragments), one for each mass bin. The exception to this was for primary fragments, as it was determined that development of debris PDFs for the larger mass bins was not necessary. Table 4 defines the general debris types considered and the corresponding mass bins that debris PDFs were developed for.

Table 4 – TP 14 Revision 5 Departing Debris Types

Debris Material	PES Component / Stack Launch Direction	ES Surface	Model Output	Mass Bins
Concrete	Wall	Wall	Probability	1 to 10
			KE Ratio	1 to 10
		Roof	Probability	1 to 10
			KE Ratio	1 to 10
	Roof	Roof	Probability	1 to 10
			KE Ratio	1 to 10
Secondary Steel	Wall	Wall	Probability	1 to 10
			KE Ratio	1 to 10
		Roof	Probability	1 to 10
			KE Ratio	1 to 10
	Roof	Roof	Probability	1 to 10
			KE Ratio	1 to 10
Primary Steel	Horizontal	Wall	Probability	4 to 10
			KE Ratio	4 to 10
		Roof	Probability	4 to 10
			KE Ratio	4 to 10
	Vertical	Roof	Probability	4 to 10
			KE Ratio	4 to 10
Primary Aluminum	Horizontal	Wall	Probability	4 to 10
			KE Ratio	4 to 10
		Roof	Probability	4 to 10
			KE Ratio	4 to 10
	Vertical	Roof	Probability	4 to 10
			KE Ratio	4 to 10

For each source of debris, a primary discretization factor was the general launch angle that the debris parted the PES, whether the launch angle was primarily horizontal or vertical. For example, the wall of the PES is primarily launched horizontally, while the roof is launched vertically. Similarly, the primary fragments from the side of the stack are launched horizontally and the primary fragments from the top of the stack are launched vertically. The launch angle distribution for each scenario is assumed to be a normal distribution, and a mean launch angle and standard deviation are assigned as a function of the material and direction the debris is being launched.

In the end, the concern is primarily how the debris arrive at the ES, whether it impacts the wall or the roof, and the impact kinetic energy as it hit the target. The kinetic energy is measured normal to the impact surface, as a high velocity fragment impacting an ES roof with a "glancing blow" is far less of a concern that a fragment impact with an identical velocity traveling straight down. Initial analyses determined that vertically launched debris presents a trivial hazard on ES walls, due to both the low probability of impact as well as a minimal kinetic energy normal to the impact surface. At distance, it was determined that horizontally launched debris could present a hazard to the ES roof (e.g., the trajectory of a golf shot with a driver), so that scenario is considered. Figures 5 and 6 show the hit probability and impact kinetic energy ratio for a horizontally launched steel primary fragment from Mass Bin 6 (average mass is 0.473 lb) for the ES wall and ES roof, respectively. Kinetic energy (KE) ratio is used as the method to normalize the results and define it as a function of launch velocity for that specific debris mass.

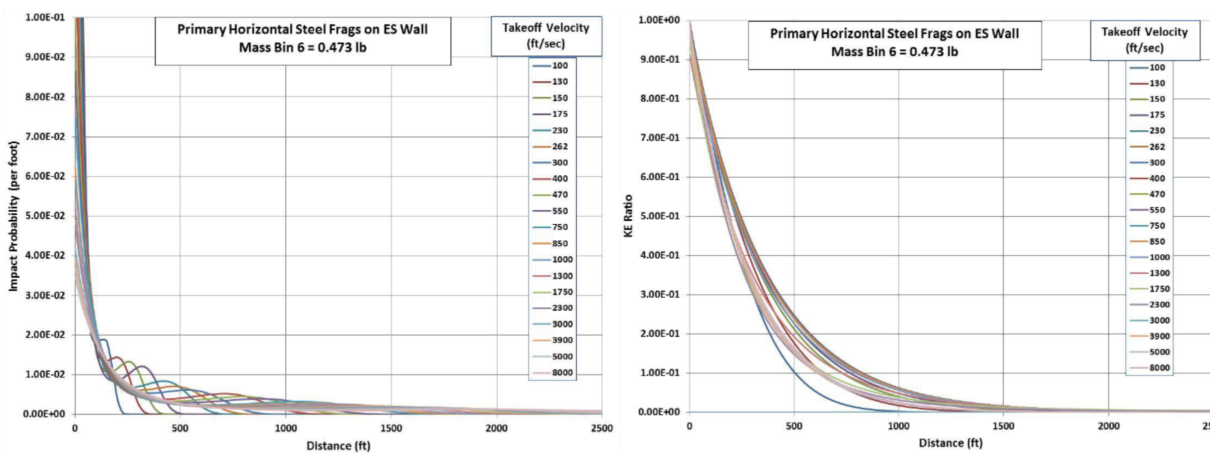

Figure 5 – Probability of Impact and KE Ratio on ES Wall

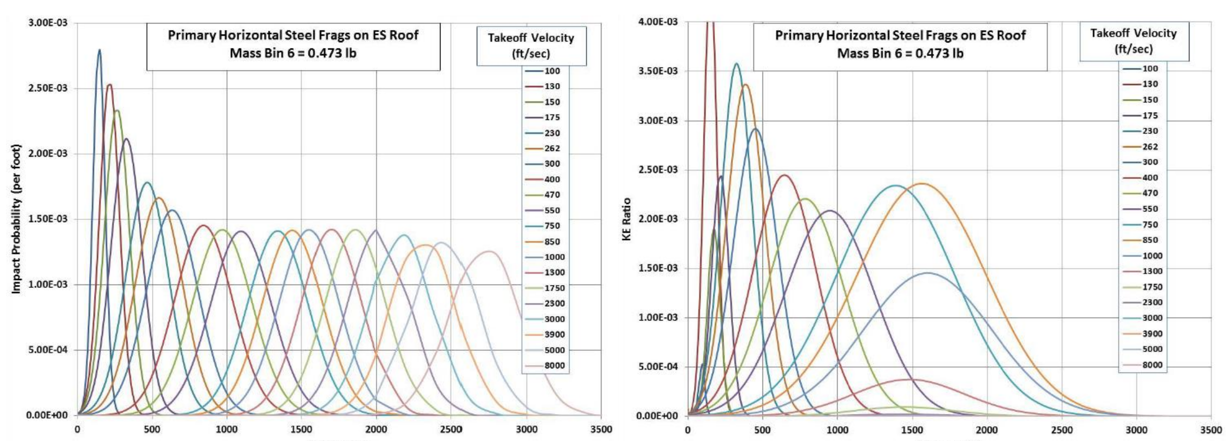

Figure 6 – Probability of Impact and KE Ration on ES Roof

Once the arriving debris hazard at the ES is defined, a determination needs to be made with respect to the perforation resistance that the walls and roof provide the occupants. The perforation resistance of the various ES components is defined as a function of kinetic energy, and the amount of energy required to perforate the component is referred to as the delta kinetic energy, or *ΔKE*. An undamaged component will stop all debris with an impacting kinetic energy below the *ΔKE* of the component, and for impacting debris with a kinetic energy greater than the *ΔKE* of the component, the debris is modeled as perforating the component and entering the facility with a kinetic energy reduction equivalent to the *ΔKE* of the component. The *ΔKE* for the ES wall and roof components were initially defined in early versions of TP 14 via analytical models and empirically based prediction equations, but test series over the years (Ref. 23 and 24) have generated greater fidelity in the perforation resistance of conventional construction wall and roof components, particularly with respect to the dependency on impactor material type (e.g., steel versus concrete debris).

Finally, once the debris field hazard to personal inside an ES is fully defined with respect to probability of hit for each debris type and the associated kinetic energy, probabilities of injury and fatality can be defined. Consequence levels from impacting debris are determined probabilistically and the severity is a function of the body part impacted (head, thorax, abdomen, or limbs). The exposed personnel also have an assumed distribution of population mix (male, female, and/or children), an assumed mix of standing vs. sitting, and a probability of orientation to the debris (front, side, or top). The size of the body part and consequences given a hit to that body part as a function of kinetic energy are defined for each scenario, and the plots for fatality and major injury are modeled as shown in Figure 7. Also shown in Figure 7 are the major injury and fatality prediction curves that TP 14 Revision 4 is based on, which is independent of body hit area. It should be noted that with the assumption of prompt medical attention, fatality due to debris impacts to limbs is not considered. The debris consequence logic combines the effects of these considerations and generates a probability of fatality, probability of major injury or greater, and a probability of minor injury or greater.

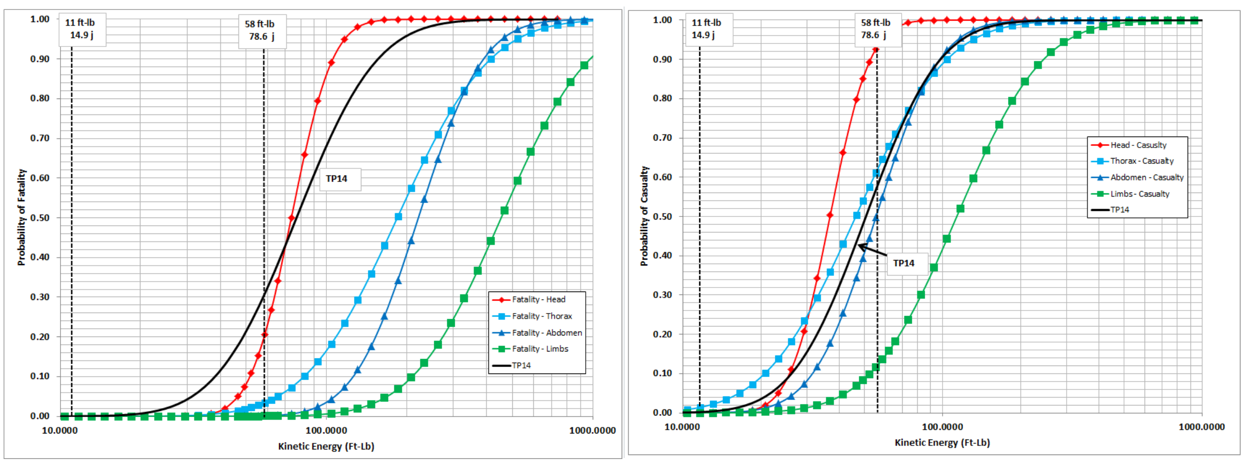

Figure 7 – Probabilities of Fatality and Major Injury as a Function of Impact Area

<u>Group 5 Steps: Thermal Branch</u>

The thermal branch within TP 14 is quite simplistic. The methodology is primarily a rough estimate of the thermal hazards associated with the deflagration of HD 1.3 material. The thermal hazards are not calculated when associating the risks associated with HD 1.1 material, as the thermal hazard never controls the risk with the current assumptions for HD 1.1. Additionally, only the thermal hazards are considered when assessing the risk for HD 1.3 material. This can be unconservative for storage of HD 1.3 in heavily confined structures, as a rapid pressurization of the structure could occur resulting in a catastrophic rupture with a significant fragment hazard. Because of this potential hazard, TP 14 provides guidance that if the sited facility has potential to act in this manner, the analyst should consider treating the NEW as HD 1.1 to conservatively capture the debris hazard. Within the DoD, there is currently ongoing work looking to address this particular hazard, which can hopefully provide better guidance as to how it is treated in both quantity distance siting and risk-based analyses (Ref. 25, 26, & 27).

The thermal branch within TP 14 accounts for thermal blocking provided by some PES types, as well as thermal protection provided by some ES types. The primary injury and fatality mechanism is due to the radiant heat generated from the material deflagration, which is primarily based on propellant burn equations. The injury and fatality is related to scaled distance from the HD 1.3 material that is being analyzed. There is one final check that is performed, and that is to determine if the ES is within the fireball radius, which is a function of the quantity of material. If the ES is within the fireball radius, the probability of fatality is treated as 1.

Additional TP-14 Revision 5 Enhancements

TP-14 Revision 5 will also feature other improvements and changes that have not been previously discussed. A large portion of these improvements are focused on user flexibility within the model. TP-14 Revision 5 has included the ability to import custom PES and ES types. These changes are meant to be utilized by users that have unique facilities that do not conform to any of the pre-defined PES and ES types. Custom PES and ES types will be meant for use by experience users that have extensive knowledge in the building model development of TP-14 Revision 5. Also, any custom PES or ES will have to be approved by the appropriate authority for use in a QRA.

Another change from TP-14 Revision 4 to TP-14 Revision 5 is the munition types used in the model. TP-14 Revision 5 has transitioned to using generic munition types instead of the specific munition types previously defined. The generic munition type models were developed based on average characteristics of applicable munition types within the DDESB TP 16 database (Ref. 28). Table 5 presents the munition types used in TP-14 Revision 5 and TP-14 Revision 4.

Table 5 – Munition Types in TP 14 Revision 5 and Revision 4

TP-14 Revision 5	**TP-14 Revision 4**
Steel munition of any NEW	MK82
Aluminum munition of any NEW	M107
Bulk/Light Case	MK83
Bulk Propellant	MK84
Bare Explosives	AIM-7
User-Defined/Custom Munition	M1 105mm projectile
	40 mm projectile
	Bulk/Light Case
	Bulk Propellant

TP-14 Revision 5 will also include the ability to import custom munition types, much like custom PES and ES types. Like custom PES and ES types, custom munitions are only meant for knowledgeable users and will require approval from the appropriate authority for use.

TP-14 Revision 5 will use a unique method for handling HD 1.2 explosives compared to previous versions of the document. For HD 1.2.1 and HD 1.2.3 explosives, the methodology will require two separate runs. The first run will use the maximum credible event (MCE) for the PES and treat the explosives as HD 1.1 with the MCE as the NEW in the analysis. The second run will use the total NEW in the PES and will treat the explosives as HD 1.3. The highest risk generated from the two analyses will be used to compare to criteria. This change in methodology will now require the MCE as an input for HD 1.2.1 and HD 1.2.3 explosives. Also, the user's manual for TP-14 Revision 5 will also provide instructions on how to complete an analysis with HD 1.3 explosives stored in a facility that provides confinement. The user will be instructed to use a X% TNT equivalent NEW and run the analysis as an HD 1.1 analysis. These instructions are necessary because previous versions of TP 14 have only modeled HD 1.3 material to generate thermal hazards. However, it has been shown that HD 1.3 explosives under confinement can result in explosive events that violently rupture and generate debris.

Another new addition to TP-14 Revision 5 is asset protection methodology. TP-14 Revision 5 will be able to approximate the damage and associated cost to repair/replace an asset given an event. The asset protection methodology will allow an ES to be entered as an asset and will also allow a building with no exposed personnel to be added as an asset. All existing ES types can be considered to be assets, but additional building types have been included in TP-14 Revision 5 for use in only the asset protection methodology. These new assets, along with a brief description, can be seen below:

- Tent – Represents an 8 ft tall by 16 ft by 16 ft canvas structure with metal supports. This structure is meant to be temporary and expediently assembled.
- ISO Container – Represents a metal asset with corrugated metal walls and a sturdy brace structure. ISO containers are typically 8 ft wide by 8 ft tall by 20 ft long, this asset model represents the typical ISO container used for shipping.
- Hardened ISO Container – Represents a metal asset with sturdy metal walls and a sturdy brace structure. ISO containers are typically 8f t wide by 8 ft tall by 20 ft long, this asset model represents the typical ISO container used for shipping that is equipped with thicker metal walls.
- Hardened Aircraft – Represents a small aircraft with a fuselage diameter of roughly 6 ft and a wing span of approximately 40 ft. This asset is assumed to have a sturdy design able to handle loads in excess of 10 Gs.
- Hardened Vehicle – Based on a lightly armored 8 ft wide by 16 ft long by 6.5 ft tall vehicle. This vehicle would be capable of traversing most terrains and would be of similar construction to a Jeep or Hummer.
- Box Truck – Represents an 8 ft wide by 24 ft long by 10 ft tall vehicle. The cab of the vehicle is a standard truck cab and the back of the box truck is a wood or aluminum box structure. This represents a typical box style moving truck.
- Power Line System – Represents a typical wood pole and cable power transmission system constructed throughout the USA.
- Radar Tower - Does not specifically represent a dome or dish type structure. Instead, the vulnerability model was developed on typical design loads for ground-based radar systems

The TP-14 asset protection methodology uses the expected damage calculated from the model to estimate an expected replacement cost. This is accomplished using cost/damage curves like the curves for stationary vehicles and box trucks shown in Figure 8.

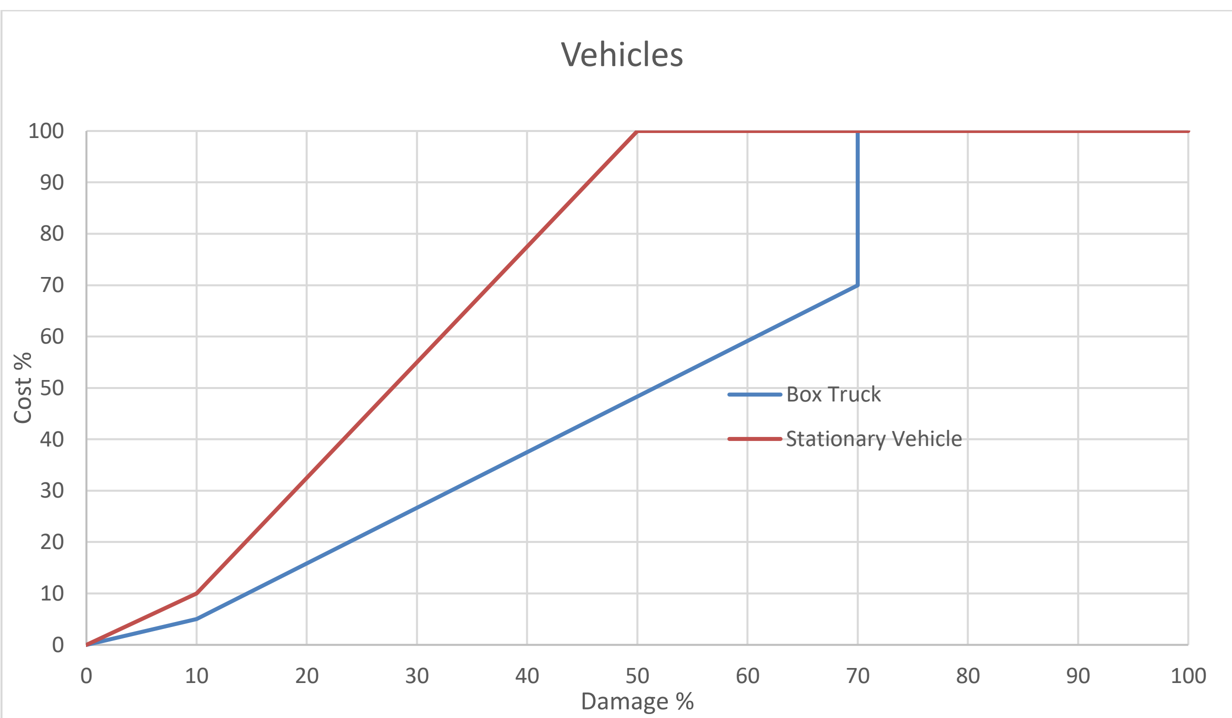

Figure 8 – Cost/Damage Curves: Stationary Vehicle and Box Truck

Summary of TP 14 Consequence Algorithms

The TP 14 Revision 5 consequence algorithms represent a significant update in the state-of-the-art with respect to modeling explosion effects and consequences in a fast-running tool. The calculated consequence portion within TP 14 is combined with exposure, probability of event, and uncertainty to generate the approved quantitative risk assessment model for DDESB risk-based explosives safety site plans. The individual and group risk are calculated in accordance with prescriptive guidance and compared to the appropriate criterion for determination of acceptance.

In addition to use within this specific quantitative risk assessment models, these algorithms can be used for other consequence or risk assessment purposes by only considering the consequence term. Effects of individual mechanisms (e.g., blast, debris, etc.) can be examined, or the final outputs of probability of injury and fatality can be used. The ultimate goal is to promulgate awareness and usage of these methods and algorithms to enhance explosives safety across the DoD and international explosives safety communities.

Conclusion and Way Forward

The draft update to TP 14, in the form of Revision 5, is currently being finalized. The currently approved version of the QRA model is TP 14 Revision 4a, which is implemented in the DDESB approved QRA tool SAFER Version 3.1. Ultimately, this improved QRA model defined in TP 14 Revision 5 will be implemented in the QRA tool of the Risk Based Explosives Safety Siting (RBESS) module which resides within the DDESB's automated site planning tool, the Explosives Safety Siting (ESS) software (Ref. 29, 30, & 31). ESS is the DoD's enterprise software for explosives safety site plan preparation and QD analysis. Incorporation of the TP 14 Revision 5 methodology within the QRA tool RBESS of ESS will allow for rapid risk assessments in conjunction with QD analyses already being performed. These risk assessments will allow use of these TP 14 explosion effects and consequence models for both quantitative and qualitative risk analyses, as well as general quantification of hazards and consequences given the occurrence of an event. Ultimately, the purpose of these fast-running models is to provide high fidelity results with minimal effort to supply decision makers with information on risk to make informed decisions.

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