International Explosive Safety Symposium & Exposition
San Diego, CA, August 6-9, 2018

(U) Metrics Analysis for the Improved Evaluation Methodology of the Hazard Severity of Fragments Projected from Deflagrating Warheads

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(U) Abstract

(U) While warhead developers have a fundamental understanding of the damage a detonating munition inflicts from intended warhead fragmentation [2], there appears to be some inconclusive evidence regarding the damage a fragment can inflict from a lower order, accidental deflagrating munition. Both the Safety community and the Insensitive Munition (IM) community attempt to characterize this phenomena, utilizing generic characterization methods such as mass vs. throw distance, mass quantity density statistics, etc. However, it is not clear how much of a physical science basis some of these methods have. A fragment's geometry, along with its exterior / terminal ballistics characteristics, should not be overlooked when evaluating its hazard potential.

(U) The U.S. Army conducted a hazardous fragment study to analyze the methods in which fragments projected from munitions (e.g. warheads) are evaluated and characterized for their projection energy and level of threat they pose to soldiers and their materiel. This study was initiated due to the result of concerns raised by the community, questioning the validity of the current metric (20J) used by the IM community to differentiate between a benign burning reaction and a semi-violent deflagration. The purpose of the study was to determine if the current 20J kinetic energy at 15m requirement is appropriate, if the previous 79J at 15m metric was more appropriate, or perhaps if evidence proves an even more appropriate metric or criterion.

(U) This paper discusses the research conducted to investigate the origins of the current/previous metrics used to categorize a fragment's level of hazard, including blunt injury and skin penetration tests performed as far back as the 1800's. The equations used to develop the original mass-distance curves that were used to evaluate fragment energy were recreated and analyzed by the U.S. Army, are referenced in this paper, and discussed in a 'sister' paper, 'Aeroballistics Calculations for the Insensitive Munitions Hazardous Fragment Criterion, K. Miers, et. al.' [1]. Several errors were discovered in the original ballistics equations of the existing energy-based methodology, such as it improperly being based on launch energy, instead of impact energy. The updated curves are discussed on this paper, and discussed in [1]. Furthermore, the U.S. Army identified an advanced methodology to improve the evaluation of fragment hazard levels. This paper discusses the newly proposed 'energy density' methodology that is currently under evaluation for future use as a standard requirement, as well as the metrics under consideration by the U.S. Army for final implementation.

(U) The criterion of interest indicates the maximum distance a fragment of a given mass could travel before it would be hazardous, presumably to a person standing, at 15m [1,2,6,] This paper discusses the events that led to the review and improved revision of the method and metrics used to evaluate the hazard severity of a munition fragments. This paper sets the stage for its sister paper [1] which discusses in detail the exterior ballistic trajectory code that was written and validated, the equations of motion utilized in the code, coupled with the appropriate modeling assumptions (e.g. shape factors, drag coefficient data, etc.), the trajectories calculated forward or backward in time, the univariate optimization routines utilized to perform the maximum distance calculations, etc. Inherent characteristics and limitations of such curves (e.g. fragment size, geometry) are explained, and the advantages and disadvantages of several suggested criteria and their implementation are reviewed.

(U) The U.S. Army successfully identified the origins of the current/previous metrics used to evaluate the hazard severity of fragments from deflagrating munitions. The original equations used to formulate the curves used for this methodology were recreated, examined, corrected and successfully reformulated. Finally, a new methodology was developed and proposed for review and assessment, and current ballistics, lethality and non-lethality investigations are on-going to determine the appropriate metric suitable for measuring the hazard levels of a fragment projected from a deflagrating munition. This paper will discuss these metrics and how they will be incorporated into the new methodology.

(U) BACKGROUND AND OBJECTIVES

(U) AOP-39 [5] is the NATO document that provides guidance for the development, assessment and testing of Insensitive Munitions (IM). This document has recently been reviewed and revised by the NATO IM Working Group to reflect the latest developments in IM progression, as well as improvements to the methods in which munitions are evaluated for their sensitivity. One of the major updates to this document is the munition Response Descriptors section, which defines the six munition response types (Detonation, Partial Detonation, Explosion, Deflagration, Burning, No Reaction). Each of these responses are defined, using both qualitative and quantitative measures, which assist evaluators in their decision-making process to assign a response level to a particular munition. It is imperative that these measures are relevant, reasonably attainable, scientifically accurate, and based on historical evidence and technical data.

(U) In the fall of 2015, the NATO IM Working Group began the review and revision of the Response Descriptors. One major topic of importance included the relevance of the quantitative metric governing hazardous fragment projection of munitions. Per AOP-39 [5], for a Type IV (Deflagration), ‘At least one piece (e.g., casing, packaging or energetic material) travels (or would have been capable of travelling) beyond 15m and with an energy level greater than 20J based on the distance versus mass relationships in figure B-1’; and for a Type V (Burn), ‘No piece (e.g., casing, packaging or energetic material) travels (or would have been capable of travelling) beyond 15m and with an energy level greater than 20J based on the distance versus mass relationships in figure B-1. This criterion is being used by the IM community to distinguish between Type IV and Type V responses. After an IM test, fragments are measured for their weight and distance thrown from reaction origin. Based on their mass-distance relationship, if this critical distance is exceeded, the munition is assigned a Type IV. If this distance is not exceeded, the munition is assigned Type V (as long as other criterion are satisfied, such as absence of blast overpressure and witness plate gouging).

(U) During the review of this criterion, the NATO IM Working Group posed several questions, including: Where did the metric '20J' come from? -- Why did we switch from 79J to 20J? – Where did '79J' come from? -- Why is the 15m (50ft) significant? -- Are these the best metrics? -- What methods are we using to measure these metrics? -- Is there a better method to measure these metrics? Unfortunately, at this initial meeting, no member nations were able to answer any of these questions. Only speculations were thrown about by even the most senior participants.

(U) In the spring of 2016, per the Proceedings of the 5th Response Descriptors Working Group Meeting [9], MSIAC, NATO Headquarters, Brussels, Belgium, 11-12 April 2016, 'The third briefing was also related to the fragment projection topic and was given by Mr. Pudlak (US). This was offered in response to Action Item 3 that was assigned to all nations at the prior meeting. Mr. Pudlak provided a considerable amount of background information, basically historical, on the origin of the hazardous/lethal fragment factors and how they relate to the fragment energy levels currently in use for IM and HC. This information was nearly identical to the background research information given by Mr. van der Voort at the beginning of his presentation. Mr. Pudlak highlighted the key issue from his analysis – the comparison of launch vs. impact energy. At this point a more detailed explanation was provided that related to the launch/impact energy and how this relates to the 20 vs. 79J issue.' [9]

(U) Historical Research. The first question(s) in which to investigate were: 'W*here did the 20J metric come from*?', and '*Why did we switch from 79J to 20J*'?

(U) AOP-39 Ed 2 (2009) and MIL-STD-2105C (July 2003) both utilized 79J as the threshold.
(U) AOP-39 Ed 3 (2010) and MIL-STD-2105D (April 2011) both utilized 20J as the threshold.
*MIL-STD-2105 is the US DoD Hazard Assessment Tests for Non-Nuclear Munitions.

(U) In the late 1800's, Colonel Journee (French Infantry Officer) established the 15ft-lb & 58ft-lb criterion. His work considered the upper and lower bounds of what a man could endure from recoil of a rifle.

- 15ft-lb (20J) was set as the maximum recoil suitable for a military rifle.
- 58ft-lb (79J) recoil energy was estimated to provide significant bruising/damage to typical male shoulder.

Weapon System	Muzzle Recoil Energy (ft-lbs)
Lee-Enfield Rifle	12.75 ft-lbs
.45 Cal. Rifle	14.40 ft-lbs
.30 Cal Garand	15.18 ft-lbs
Springfield '03 Rifle	14.98 ft-lbs

Computed Recoil Energy	Limitation
Less than 15 ft-lb (20.3 Joules)	Unlimited Firing
15-30 ft-lb (20.3 – 40.7 Joules)	200 rounds / day / shooter
30-45 ft-lb (40.7 – 61.0 Joules)	100 rounds / day / shooter
45-60 ft-lb (61.0 – 81.4 Joules)	25 rounds / day / shooter
Greater than 60 ft-lbs (81.4 Joules)	No Shoulder Firing

Table 1. TOP 3-2-504 – Daily Firing limit for safety of hand and shoulder weapons

(U) As an example, a typical shotgun produces 25 ft-lb to 35 ft-lb of recoil, and a typical elephant gun produces ~52 ft-lb of recoil. "The recoil energy of the Lee-Enfield rifle is well below the maximum energy of recoil advisable for a military rifle, which should not exceed 15 ft-lbs, --1909 British Textbook of Small Arms.

(U) Historical Literature:

- Burns and Zuckerman, 1941, 3/32" steel ball study
  - 20J is optimum energy to wound a man
- Beyer, "Wound Ballistics", Office of the Surgeon General, 1962
  - Journee - 58 ft-lb rule (79J)
    - Pistol / Rifle calibers: 4.5mm - 21.2mm
    - Projectile weights: 3 grams - 56 grams
    - Unjacketed, full-jacketed (copper German silver, steel), lead core bullets: Lead, zinc, aluminum
- Sperazza, "Handbook for Human Vulnerability Criteria", 1976
  - Journee – Levels required for wounding soft tissue and bone
    - 15 ft-lb to penetrate soft tissue
    - 36 ft-lb to crack bones
    - 115 ft-lb to assure fracture of large bone (e.g. femur)
    - Determined 58ft-bs rule
- USARIEM, "Technical Report T04-05", 2004 Weapon Recoil Health Hazard Study
  - 93% of volunteers experienced significant shoulder bruising when asked to fire 15 rounds of ammo w/ recoil of 59ft-lbs (well within firing rate of limitation of the TOP).

(U) Examples of projectiles and their associated energy:

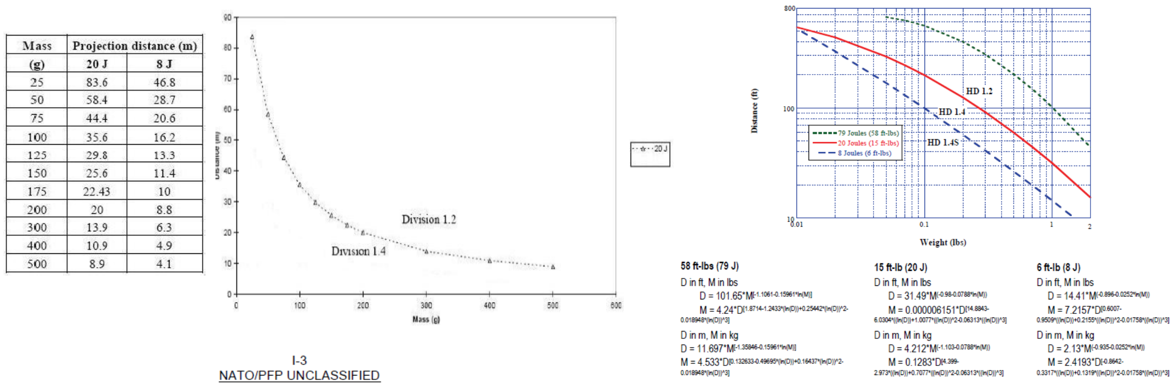
- Paintball 300ft/s – 12J
- 0.177 cal pellet 900ft/s– 21J
- Football 50mph – 112J
- Baseball 90mph – 120J
- 40mm non-lethal grenade 200ft/s – 150J

(U) It can easily be seen from the data above that 20J may not be an accurate metric for measuring a munitions 'lethality' or 'hazardousness'. Now that we have a better understanding of where the 20J and 79J metrics come from, and how they compare to commonly used objects of similar energy, we need to determine if one of these metrics are more accurate than the other, or if there is a more appropriate number not being considered, or if there is a better method of measurement than currently being utilized.

(U) DISCUSSION

(U) Understanding the Current Methodology. *How did we acquire 20J?* The current AOP-39 Ed 3 utilizes the 20J curve as seen below in Figure 1 (left). This curve is built from data points representing masses of IM-interest, in the range of 50g-500g. This curve is actually a derivation from the plot on the right, which is found in TB 700-2, which is the US DoD Standard for

Ammunition & Explosives Hazard Classification Procedures. Notice that both the 20J and 79J curves are superimposed on this chart, as well as a lower threshold, 8J. These three curves are used by the US DoD Safety Community to differentiate the Hazard Classification of munitions. It is evident that both of these curves come from this plot, however, it is not clear why we have switched to 20J, from 79J.

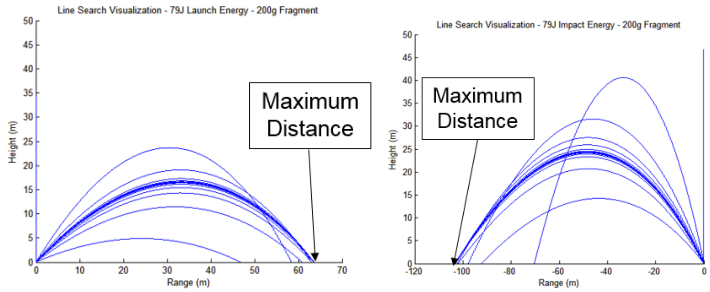


Mass	Projection distance (m)	
(g)	20 J	8 J
25	83.6	46.8
50	58.4	28.7
75	44.4	20.6
100	35.6	16.2
125	29.8	13.3
150	25.6	11.4
175	22.43	10
200	20	8.8
300	13.9	6.3
400	10.9	4.9
500	8.9	4.1

(U) Figure 1. The 20J Curve, as it appears in AOP-39 (left) and TB-700-2 (right)

(U) Understanding how the curves work. In order to evaluate which curve is more relevant for fragments associated with munition sensitivity/hazardousness, it was important to understand how the curves were built, and what inputs/assumptions were utilized. To begin, the guidance (AOP-39, MIL-STD-2105D) states that 'At least one piece (e.g. casing, packaging, or energetic material) travels (or would have been capable of travelling) beyond 15m and with an energy level greater than 20J based on the distance versus mass relationships.' This would indicate that we are to measure the fragment's energy at *impact*. Unfortunately, there was no documentation to review which would explain the creation of the curves. The originators of the curves were contacted for explanation of inputs/assumptions made to create the curves. The 20J curve was then recreated by ARDEC and matched quite well. Unfortunately, the same assumptions were made to create the 79J curve, but they did not exactly match. Nevertheless, after analysis, it was discovered that both the 20J & 79J curves were built with *launch energy basis, not an impact energy basis*. This raised a flag as this is not what is intended in the guidance. The 20J curve, for example, based on launch energy, uses is a curve fit for max projection distance of 20J fragments *at launch* as a function of mass. It works based on calculating the maximum distance a given mass can travel when launched at 20J. Therefore, it does not calculate the fragment's impact energy, but rather it compares its travel distance to the maximum distance its mass could travel with 20J launch energy. If the fragment is less than the maximum distance the fragment could have flown with 20J, then it must have less than 20J at impact (due to factors like air drag). Actual impact energy cannot be determined based on mass and distance without a known trajectory. Only minimum impact energy required to reach the given distance can be calculated accurately.

(U) Creating the Impact Energy-based curves. Point-mass trajectories can be run backwards in time. Thus the line search technique can be used, starting at the origin with a fixed impact velocity, to adjust the impact angle until the maximum distance backward is reached. Figure 2 demonstrates how the impact energy curve calculation is similar to the launch energy curve calculation but backwards.



(U) Figure 2. Visualization of a line search algorithm to quickly find the maximum throw distance for a fixed launch energy (left) and for a fixed impact energy (right).

(U) This technique finds the same maximum as the previously described technique (which tries to find a combination of launch angle and velocity that yields the largest range at which a 79J impact can occur). It also runs into the same problem – at a sufficiently low mass, the maximum range at which the impact criterion is satisfied goes off to infinity, or at least outside the range of validity for the drag coefficient data. This is due to terminal velocity coming into play. Figure 3 shows the results of this methodology to generate 20J and 79J impact energy curves.

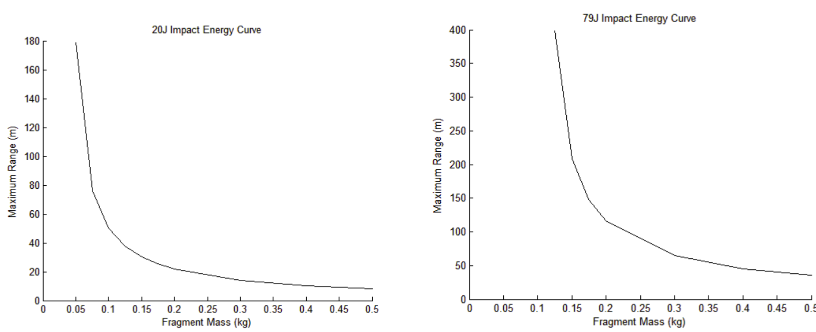


Figure 3. Calculated impact energy curves

(U) It should be noted that the curves appear to go off to infinity for the smaller masses. For IM evaluation purposes, this would appear to be an issue, more so for the 79J curve than the 20J curve. For example, the 20J curve would allow a 0.05g to travel ~160m. However, a fragment of 0.05g travelling 160m would most likely not represent a munition reacting in the Deflagration regime, but rather in an Explosion-Detonation regime. Further analysis of historical data may help draw a 'ceiling', or horizontal line across the left side of the curve, eliminating those fragments from this evaluation.

(U) Further Improved Methodology – 15m (50ft) threshold. As mentioned above, the threshold, per AOP-39, is worded such that energy of the fragments should be measured at 15m. While the section above explains the improvements made to the original curve(s) to address energy at impact, not at launch, the curve still required improvements to address energy at a specific distance (i.e. 15m). Adjustments made to the curve were of substantial improvement for the impact-based curves. By adjusting the curve to only address impact (with no specified distance), the curve(s) appeared to go off to infinity for smaller, faster masses. By adjusting the impact-based curves to include 15m, the curve flattens out and converges, failing the smaller, faster masses; and produced a 'cut-off' for larger, slower masses. Figure 4 illustrates a 20J at 15m for steel fragments.

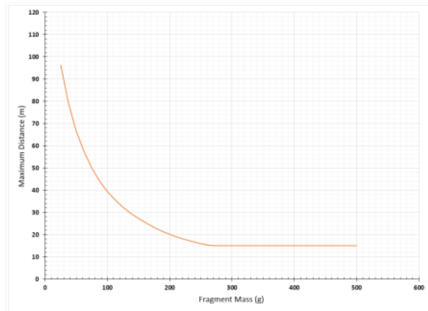
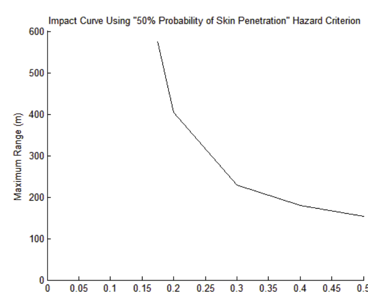


Figure 4. 20J @ 15m curve for steel fragments.

MSIAC presented a 20J at 15m curve using TRAJCAN with similar results [8].

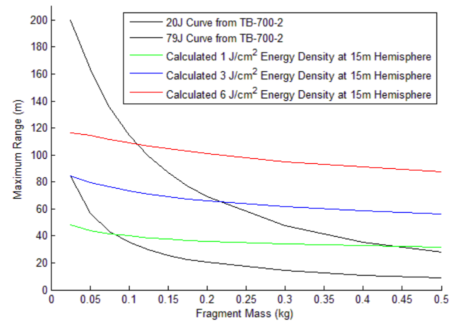
(U) Further Improved Methodology – Energy Density based Curve. While utilizing an Impact Energy based curve is an improvement to the Launch Energy based curve, it should be noted that energy alone is not the best method in which to evaluate impact severity for human hazardousness. As mentioned above, a pellet gun threatens the 20J threshold, and a football/baseball produces ~5X+ that of the 20J threshold. While these sport projectiles would be assigned a Type IV with this energy based criteria, they are no match for acceptable wartime hazards. This is primarily due to the fact that the energy based methodology does not take into account surface area of the mass's impact. To compare actual *applied* energy amongst projectiles, the impacting surface area – mass relationship must be considered. This is why it was proposed to implement an Energy Density Methodology (J/cm^2).

(U) The following curve in Figure 5 is an Impact Energy Density based curve with a threshold of 7.9 J/cm^2. This metric (7.9 J/cm^2) was selected as an example, as it is the Probability of Skin Penetration criterion given AASTP-1. While the method is a better method to utilize, the metric does not meet the regime of IM Burning/Deflagrating munitions. A more suitable metric must be selected for this method to be utilized for IM fragment evaluation.



(U) Figure 5. 7.9 J/cm^2 Energy Density Curve

(U) Prior research indicates that a range of 1 J/cm^2 – 6 J/cm^2 may be more appropriate for the IM Type IV/V fragment evaluation. These are metrics that have been identified for similar safety concerns used in other industry and government products/processes. Figure 5 illustrates how the Energy Density curves associated with these metrics plot in comparison to the 20J & 79J Launch Energy based curves. Notice that the Energy Density based curves alleviate some of the larger, slower moving masses, and restrict some of the smaller, faster moving fragments. It should be noted that these curves may coincide with the theory mentioned before that a 'ceiling', or horizontal line, could be drawn across the Impact Energy based curves to eliminate the super small fragments travelling at super high velocities from this evaluation.



(U) Figure 6. Example Energy Density Curves superimposition

(U) The Energy Density curves must also be adjusted for the 15m threshold. Figure 6 illustrates such for the 1J/cm^2, 3J/cm^2, & 6J/cm^2 curves, and Figure 7 illustrates the 7.9J/cm^2 curves.

(U) Figure 7 includes all of the curves mentioned in this paper, illustrating how each methodology/metric compares to one another. The original 20J & 79J launch-based curves are plotted in black, and it can be seen how they compare with the impact based curves. More importantly, the improvement to the 20J & 79J curves by adjusting them to reflect 15m can been compared. It can be seen how the Energy Density curves are much flatter, taking the fragments mass into account. Notice that the 7.9J/cm^2 skin penetration model does not apply so well for the mass-distance relationships of IM Type IV/V fragments. The lower energy density curves do match quite well, however. Non-lethality research indicates that 1.6J/cm^2 might be an appropriate number for blunt injury, however, further investigation is required to determine a metric that appropriately incorporates both blunt and penetration impacts, perhaps lying somewhere between the 7.9J/cm^2 and 1.6J/cm^2.

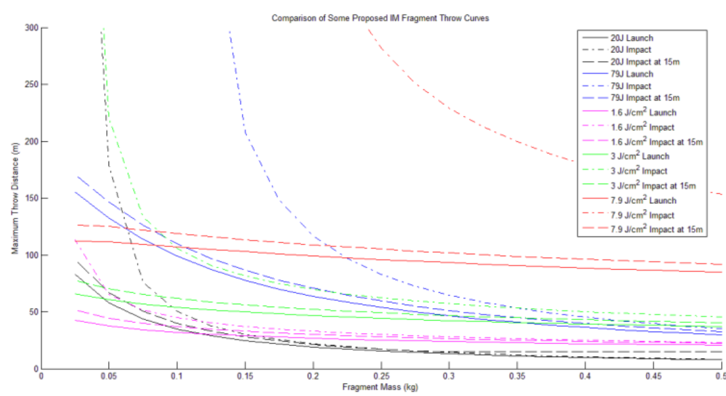


Figure 7. Superimposition of all curves.

(U) Current status of on-going work to improve the IM fragment evaluation methodology. To implement the Energy Density methodology, further lethality/non-lethality work needs to be conducted to determine a technically justifiable metric to utilize for implementation. Additionally, as taking into account the impacting surface area of the fragment/mass is the prevailing reason for the Energy Density methodology being more accurate than an energy only based methodology, it is imperative that the impacting surface area of the fragment is accurately measured/assumed. For uniform/symmetric fragments, this is easily done, however, for asymmetric fragments, this can be a challenge. Several methods of measuring/assuming the surface area have been proposed:

- (U) Automated 3-D optical measurement devices can measure icosahedrons quickly and precisely.
- (U) Generic fractional volume categories (frag-in-a-box) can be assigned. The volume fraction in which a fragment shape occupies inside of a cube it fits in, for example:
  - Cubical fragment – A cube occupies 4/4 of a cube's volume in which it fits inside.
  - Convex fragment - A sphere occupies ~3/4 of the cube's volume
  - Concave fragment – An 'hour glass' occupies ~2/4 of the cube's volume.
  - Length/Diameter – A long, thin rod/strip ~1/4 of the cube's volume.

(U) Penetration and blunt impact characteristics, as well as aerodynamic flight/orientation must be taken into account (e.g. tumble, Frisbee, etc.). For example, research indicates that a long, thin rod/strip may tend to fly in an orientation that causes the least drag resistance. Therefore, the surface area of the point / sharp edge may be appropriate to use for its evaluation.

(U) The current curve is built based on assumptions such as a chunky, tumbling, steel fragment. This, however, is not an accurate method for fragments with different characteristics, such as: density, shape, stability, etc. Therefore there must be several curves in which to reference when evaluating unique fragments. For example, Figure 8 illustrates four 20J at 15m impact based curves, of which each represents fragments of various densities associated with material commonly found on modern-day munitions systems. These four densities represent the majority of fragment material typically evaluated during IM tests, including: tungsten, steel, aluminum, and HDPE. These four curves should be replicated for other factors, such as fragment shape, and flight orientation. While creating several curves for this evaluation would appear to be more complex than utilizing one generic curve, these curves can be superimposed on one plot for the user, and only the curve representing the fragment of interest need be utilized. The upfront work goes into creating the curves. Once created, it will be quite simple for the user.

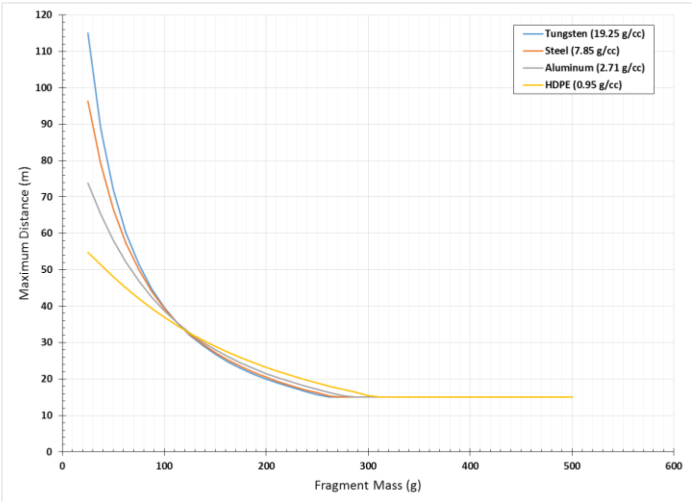


Figure 8. (U) New AOP-39 Mass-Distance curve

(U) The NATO IM Working Group has verbally accepted to implement this methodology, pending an appropriate metric is provided. As for now, the Working Group has voted to implement the 20J Impact Energy based curve as the first improvement.

(U) SUMMARY AND CONCLUSIONS; FUTURE WORK

(U) Summary and Conclusions

(U) During the review and revision of the Response Descriptors within AOP-39 [5], the IM NATO Working Group questioned the validity of the hazardous fragment criterion which is one major factor for differentiating between a Type V Burning response and a Type IV Deflagration response. The initial question was with respect to the 20J energy threshold at the time, and whether the older 79J metric was more appropriate, or if another metric would be more appropriate than both. The US Army DoD took the action to investigate the history of the criterion, and evaluate which maybe more appropriate. After extensive investigation, the US determined that the question itself was invalid. Neither 20J, nor 79J, actually mean much without incorporating the mass's impact force with relation to the impacting surface area. The US developed and presented an Energy Density methodology to the NATO IM Working Group as a potential new criterion to adopt for the IM hazardous fragment evaluation. This methodology was accepted by the group, however, a metric (numerical value) must be technically justified before implementation.

(U) Additionally, the IM NATO Working Group questioned where the 20J and 79J curves came from, and how they were derived. After inspection of the curve, and investigation of its origins, the US found the originators of the curve and discovered that there is no existing documentation for the creation of the curve. So the US back-calculated the curve using the masses-distance relationships associated with the curve, and successfully mimicked the 20J curve. Unfortunately, the same inputs/assumptions used for the 20J curve did not produce an exact match for the 79J curve. Some speculations were made regarding this matter, however no concrete evidence found. Moreover, during evaluation/manipulation of the factors included in the curve, it was discovered that the curves did not represent the criterion called out in AOP-39. The curves were built based on launch energy of 20J, not impact energy of 20J. The US adjusted the curves to reflect such, only to find further issues with the use of such curves (convergence issues). Fortunately, by tying in the 15m factor, the convergence issues were resolved, and furthermore a 'ceiling' has been proposed to omit non-Type IV/V type fragments from the evaluation.

(U) Future Work

(U) The NATO IM Working Group concurred with potential future implementation of the Energy Density Methodology, pending an appropriate metric is provided. Additionally, the surface area measurement/identification methodology must be complete in order to develop the associated curves to support the evaluation procedure. The final deliverable will be approximately 16 curves superimposed on one plot, with a legend for the user to reference the appropriate curve for the fragment of interest. This work is currently on-going at ARDEC and seeking funding to leverage the expertise of lethality/non-lethality SMEs at ARL and ARDEC. Until then, the Working Group voted to implement the 20J at 15m impact energy based curve as the first improvement.

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