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Projection Criteria for Insensitive Munitions and Hazard Classification

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The origin of projection criteria for Insensitive Munitions and Hazard Classification was investigated. The distance-mass relations were reproduced using TRAJCAN trajectory analysis by using launch energies of 8, 20 and 79J and calculating the maximum impact distance reached by a natural fragment (steel) launched from 1 m height. The analysis shows that at the maximum throw distances, the impact energy is generally much smaller than the launch energy. For the launch energies of interest, the height reached by the projectiles is not enough to reach the terminal velocity before impacting the ground. Using maximum distance projections, new distance-mass relations were developed that match the criteria based on impact energy at 15m and beyond rather than launch energy. For near vertical projections the impact distance does not provide any information about the launch energy or impact energy. High velocity shallow trajectories can result in high impact energies, but collected data may be unrealistic due to ricochet effects. The smallest projectile masses in the distance-mass relations are in the transition region from penetration injury to blunt injury. For this reason, blunt injury dominates the assessment of injury or lethality. State of the art blunt injury models predict only minor injury for a 20J impact. For a 79J blunt impact, major injury is likely to occur with a small probability of a lethality. MSIAC recommends changing the distance-mass relation that distinguishes a munitions burning response to a 20 J impact energy criterion at 15 m.

INTRODUCTION

The AOP-39 Edition 2 [1] used a 79J criterion to define a burn response: for a Type V (burn) no projections with an energy more than 79J or with a mass of greater than 150g beyond 15 m was allowed. The latter is equivalent to 8J which is inconsistent with 79J. Due to this inconsistency the AOP-39 criteria were changed in Edition 3 [2]; the 79J criterion was replaced by the 20J criterion from the UN Orange Book [3]. AOP-39 Ed. 3 Annex I provides a criterion for a Type V (burn) that no projectiles travel (or would have been capable of travelling) beyond 15m and with an energy level greater than 20J based on the distance versus mass relationships provided.

A study has been conducted on the origin of projection criteria for Insensitive Munitions and Hazard Classification. In the UN Orange Book, the 20J criterion is introduced in the context of the external fire (bonfire) test as a criterion for hazard classification to distinguish between HD1.2 and HD1.4. An additional energy criterion of 8J is defined to distinguish between HD1.4 and HD1.4S. The UN Orange Book does not include the 15m criteria as part of the external fire (bonfire) test criteria. The UN Orange Book additionally warns that the distance-mass relations are based upon metallic projections: “Non-metallic projections will produce different results and may be hazardous as well. Hazards from non-metallic projections should also be considered. The type V response descriptors have recently raised questions within the Insensitive Munitions community. MSIAC performed a survey to collect these questions [4]. Issues raised by Insensitive Munitions European Manufacturers Group (IMEMG) were described by Arnold [5]. In particular, issues of launch energy versus impact energy, the influence of projectile shape and material and the potential lack of consistency with other NATO manuals were expressed as concerns.

LAUNCH ENERGY VS. IMPACT ENERGY

In order to investigate the launch energy vs. impact energy issue, calculations have been performed with the TRAJCAN software [6]. Various fragment materials, shapes, masses, launch angles, and launch velocities can be analysed in batch. The drag coefficient is generally a function of the Mach number. The software integrates the equations of motion for a 2D trajectory under the influence of gravity and air drag.

The following fragment types were considered:

- Natural fragment (steel): density: ρ_s = 7903 kg/m^3, shape factor: B = 0.33 (TP16 legacy steel fragment).
- Natural fragment (aluminium): density: ρ_{al} = 2710 kg/m^3, shape factor: B = 0.33 (TP16 legacy aluminium fragment).
- Fuzes: tumbling cylinder with a length/diameter ratio of 3.05 and a density of 3423 kg/m^3. These average values have been obtained after inspection of various types of fuzes described in AOP-8 [7]. The ten selected fuzes are applicable to various calibre munitions (20 to 155 mm) and weapon types. The length/diameter ratios varied between 2.8 and 3.4, while the average density varied between 2444 and 4404 kg/m^3.
- 2mm thick square plate: A large variety of packaging and barrier material exists. As an example we consider steel square plates of 2 mm thickness. In tumbling motion the plate has an average projected area of 50% of the frontal area.

The following calculation settings and assumptions have been made:

- Three launch energies (E_0 = 8J, 20J and 79J);
- Eleven fragment masses from 25g to 500g, according to the UN orange book: 25, 50, 75, 100, 125, 150, 175, 200, 300, 400 and 500;
- The launch height (h_0) is set equal to 1m;
- The terrain is a flat horizontal surface;
- Relevant constants (gravity: g = 9.81 m/s^2, density of air: ρ_a = 1.225 kg/m^3);
- Wind effects are not taken into account;
- Fragments reach their final location in a single trajectory without ricochet.

The maximum throw distances were calculated by varying the launch angles. When the launch and impact are at the same height, and the drag force is neglected, the maximum throw distance occurs at a 45º launch angle. Both a non-zero launch height and the presence of air drag decrease that angle. The plotted impact distance results are presented in figure 1, along with the plotted distance-mass relationships for 8J and 20J from the UN Orange book. The results clearly show that the distance-mass relations in the UN orange book are based on natural fragments (steel) kinetic energy level of at launch, not at impact. Table 1 provides a the numerical values for natural fragments (steel), including the calculated impact energies. The results clearly show that the impact energies reduce dramatically as the fragment size decreases. This effect increases with increasing launch energy. This is also evident in Figure 2, which presents plots comparing launch energy to impact energy at maximum distance for natural fragments (steel). The terminal kinetic energy associated with the free fall terminal velocity is also plotted, showing that the impact conditions at maximum range are always below the terminal kinetic energy.

INFLUENCE OF PROJECTILE SHAPE AND MATERIAL

Figure 1 also shows TRAJCAN calculation results for other fragment shapes and materials. Fuzes reach very similar distances as natural fragments (steel). For fuzes there are two competing effects. The tumbling cylindrical shape with a length/diameter ratio of 3 has a relatively small projected area compared to the natural fragment shape. On the other hand the average density of a fuze is low compared to the density of a natural fragment (steel), which causes a fuze to have a relatively large projected area. However, the two competing effects

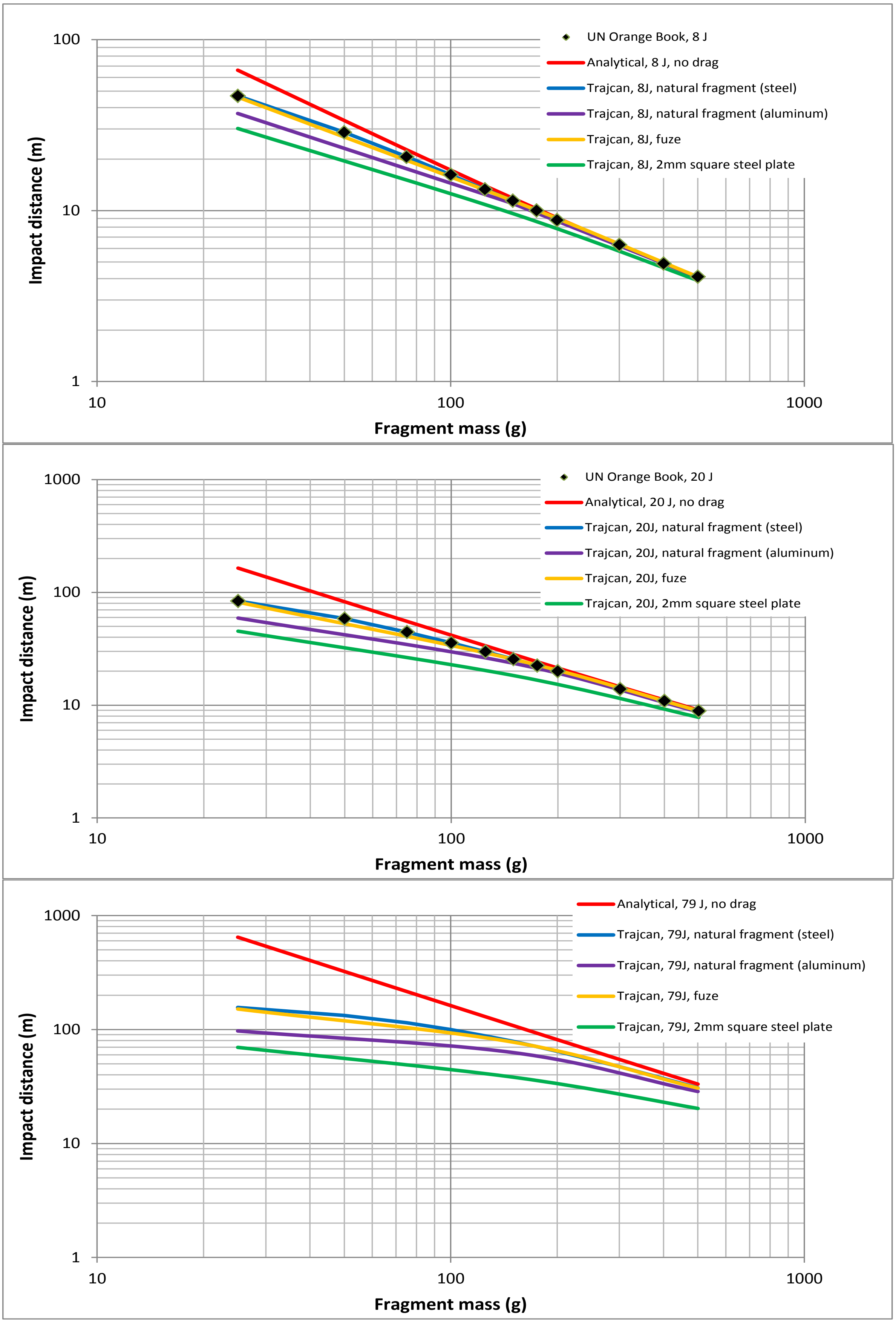


Figure 1. Impact distance versus fragment mass for three launch energies (8, 20 and 79J). UN Orange book data, analytical solution (no drag), and TRAJCAN results for natural fragments (steel and aluminum), fuzes, and 2mm square steel plates.

Table 1. UN orange book data together with TRAJCAN calculation results for natural fragments (steel). Tables for launch energies of respectively:

8J Launch Mass (g)	Initial velocity (m/s)	UN distance (m)	TRAJCAN maximum distance (m)	TRAJCAN launch angle (º)	TRAJCAN impact energy (J)
25	25.30	46.8	46.9	41	4.48
50	17.89	28.7	28.7	42	6.5
75	14.61	20.6	20.7	43	7.47
100	12.65	16.2	16.2	43	7.92
125	11.31	13.3	13.3	43	8.49
150	10.33	11.4	11.4	42	9.18
175	9.56	10	9.9	42	9.22
200	8.94	8.8	8.9	42	9.83
300	7.30	6.3	6.3	41	10.9
400	6.32	4.9	4.9	39	11.8
500	5.66	4.1	4.1	39	12.9

20J Launch Mass (g)	Initial velocity (m/s)	UN distance (m)	TRAJCAN maximum distance (m)	TRAJCAN launch angle (º)	TRAJCAN impact energy (J)
25	40.00	83.6	84.0	39	6.44
50	28.28	58.4	58.5	42	11.1
75	23.09	44.4	44.4	42	14.1
100	20.00	35.6	35.7	43	16.1
125	17.89	29.8	29.8	43	17.9
150	16.33	25.6	25.6	43	18.2
175	15.12	22.43	22.5	43	18.6
200	14.14	20	20	43	19.5
300	11.55	13.9	14	43	21.4
400	10.00	10.9	10.9	42	23.1
500	8.94	8.9	8.9	41	24.8

79J Launch Mass (g)	Initial velocity (m/s)	UN distance (m)	TRAJCAN maximum distance (m)	TRAJCAN launch angle (º)	TRAJCAN impact energy (J)
25	79.50	N/A	156.3	34	8.7
50	56.21	N/A	132.9	41	19
75	45.90	N/A	114.6	40	27.2
100	39.75	N/A	99.8	41	34
125	35.55	N/A	88.0	42	39.8
150	32.46	N/A	78.7	42	44.5
175	30.05	N/A	70.9	42	49.3
200	28.11	N/A	64.4	43	54
300	22.95	N/A	47.3	43	64
400	19.87	N/A	37.2	43	69.3
500	17.78	N/A	30.8	43	75.8

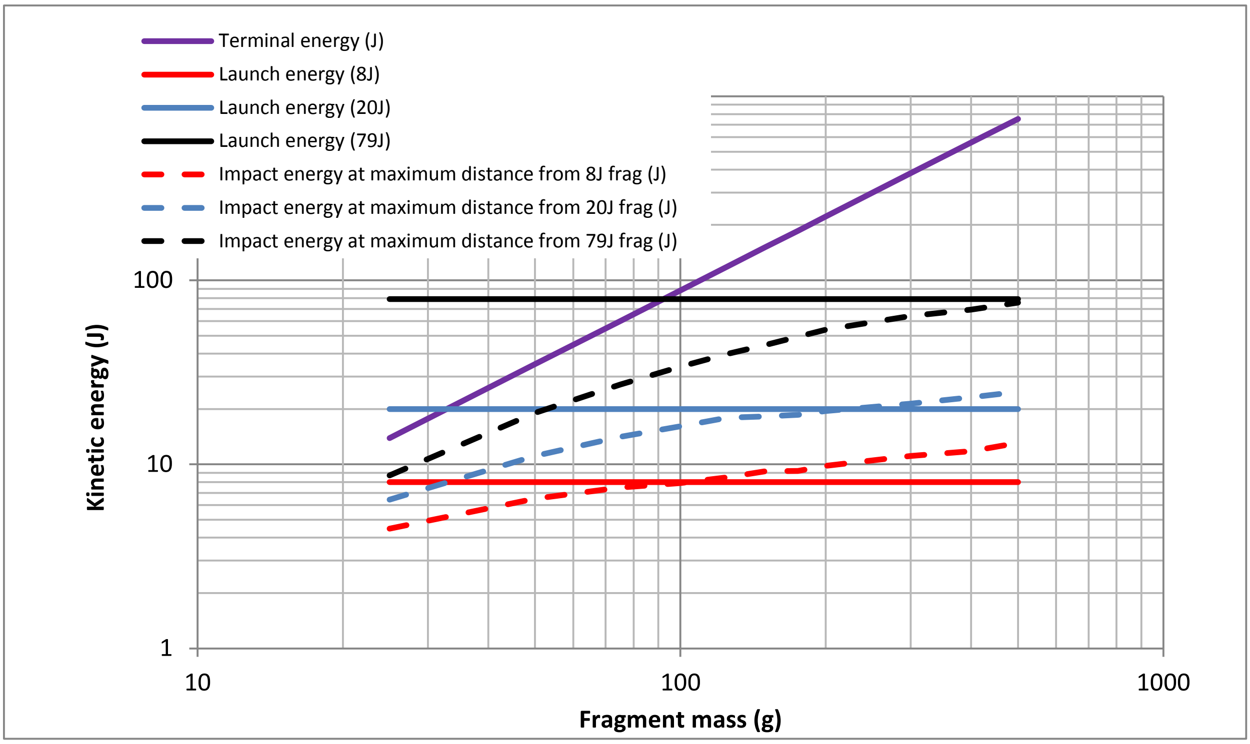


Figure 2. Comparison of launch energy, impact energy at maximum distance, and the terminal energy for natural fragments (steel).

average density of a fuze is low compared to the density of a natural fragment (steel), which causes a fuze to have a relatively large projected area. However, the two competing effects tend to cancel each other as seen from the results. Aluminium natural fragments and 2mm thick square steel plates reach significantly smaller impact distances than natural fragments (steel) launched with the same energy. This means that for these fragment types, the distance-mass relation is significantly more stringent.

INFLUENCE OF LAUNCH ANGLE

In this paragraph we will discuss the influence of launch angle on the impact conditions. Figures 3 and 4 show the impact distance and impact energy as a function of launch angle for one particular natural fragment (steel) mass (100 g). Curves are shown for launch energies of 8, 20 and 79J, as well as for 200J. Note that the maxima in the impact distance curves correspond to the distance-mass relations for 8, 20 and 79J at 100g in Figure 1. Suppose that during an IM or HC test a 100g natural fragment (steel) is observed at 30 m distance (grey dashed line). There are now three possibilities:

1. The fragment was launched with a moderate launch angle. This is typically the most likely option. Its impact distance can be compared with the maxima of the 8, 20 and 79J curve to draw a conclusion about the launch energy.
2. This fragment was launched with a near vertical launch angle. The impact distance does not provide any information about the launch energy or impact energy, although the latter will never be larger than the terminal energy. It is important, during IM and HC tests, to verify the presence of such projections with high speed video.
3. The fragment was launched with a shallow launch angle (possibly even negative) and a launch energy much larger than one would conclude based on option 1. However, fragment recovery lengths may be unrealistically long due to ricochet effects.

IMPACT ENERGY AT 15m

The Insensitive Munitions Type V criteria are related to a fire fighter at a distance of 15m. It is therefore most relevant to consider the impact energy from fragments at this distance. For that reason, distance-mass relations have been calculated to match the energy criteria at impact

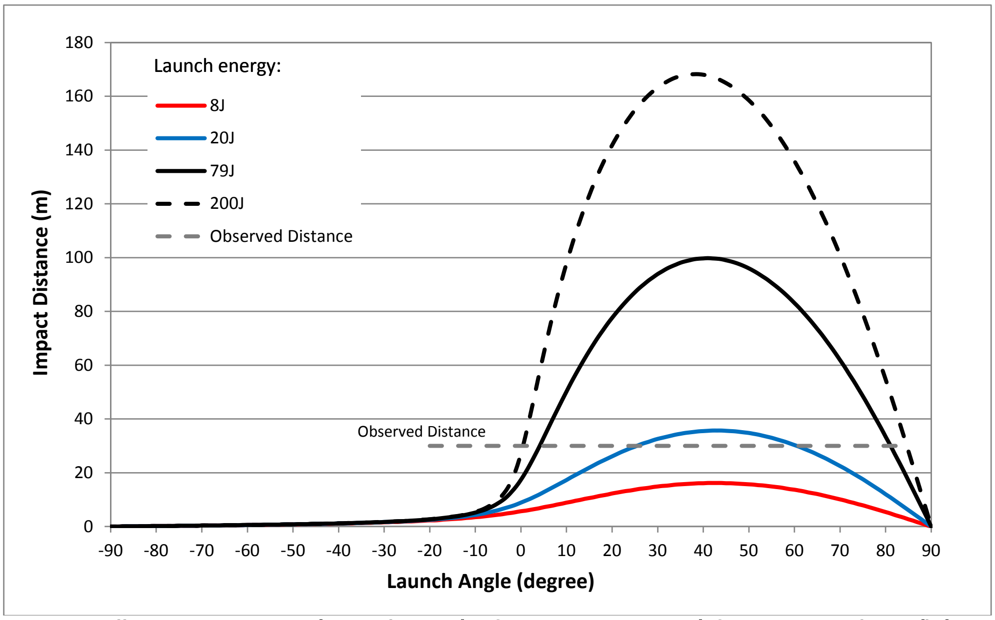


Figure 3. Impact distance versus launch angle for 100 g natural fragments (steel) launched from 1 m height with launch energies of 8, 20, 79 and 200J.

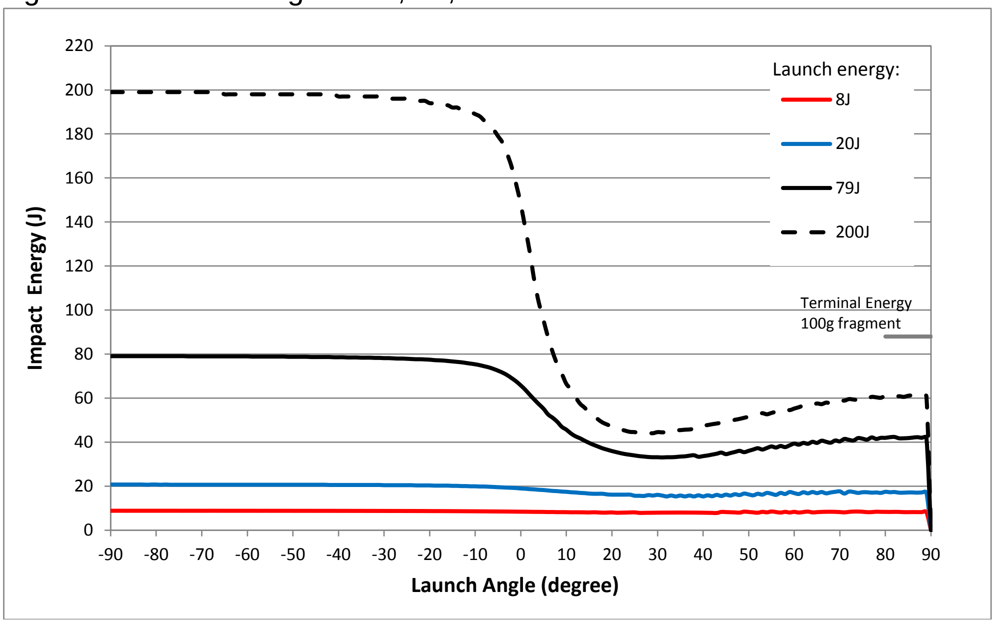
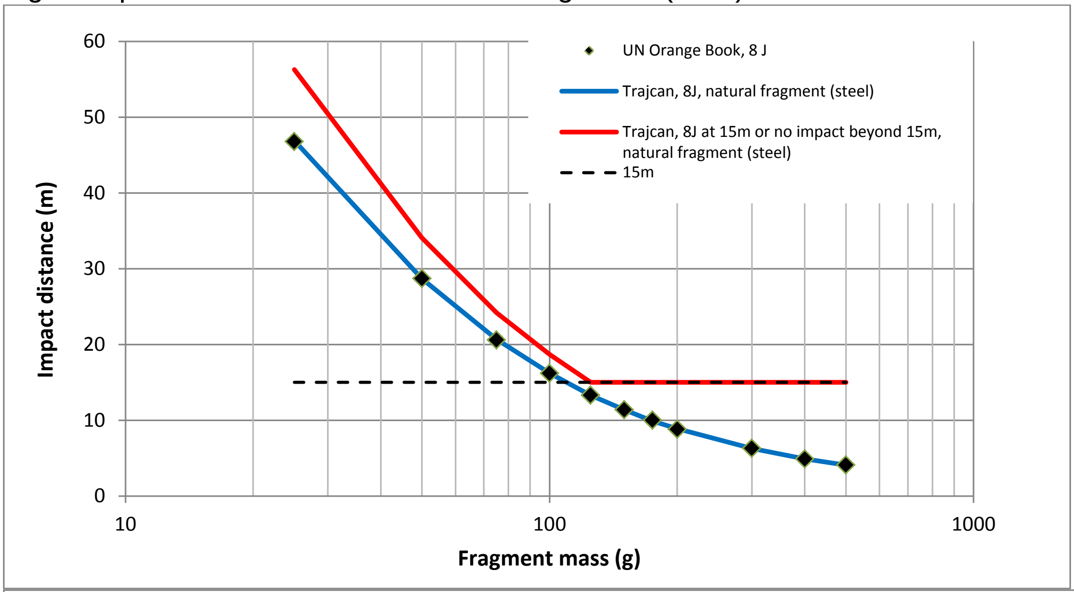


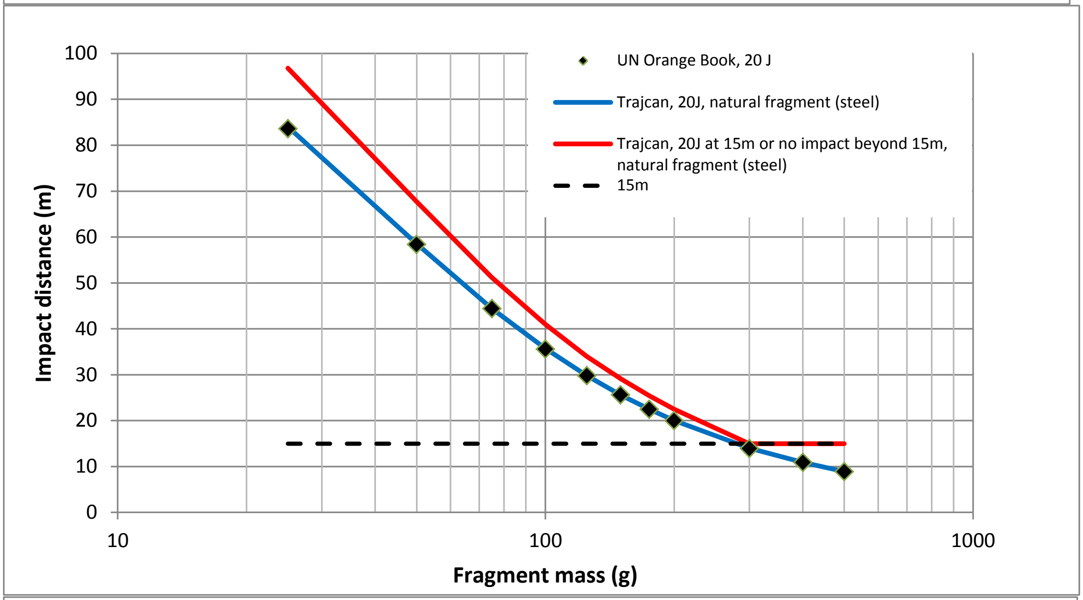
Figure 4. Impact energy versus launch angle for 100 g natural fragments (steel) launched from 1 m height with launch energies of 8, 20, 79 and 200J.

instead of at launch. The new mass distance relations have been determined as follows:

- Matching the impact energy at 15m: Using maximum distance trajectories, the launch energy E_0 was increased so that the energy criterion E_c = 8, 20 or 79J is reached at 15m. However, the maximum distance is not always 15m or greater for heavier fragments.
- Matching the impact distance: For heavier fragments that do not reach 15m using the energy criterion, the launch further energy is increased so that the maximum fragment impact takes place just before 15m at ground level. Note that the impact energy for these cases is larger than the energy criterion, but in principle that is not a problem because the fragments do not actually reach 15m (or beyond).

Figure 5 presents the results for natural fragments (steel).





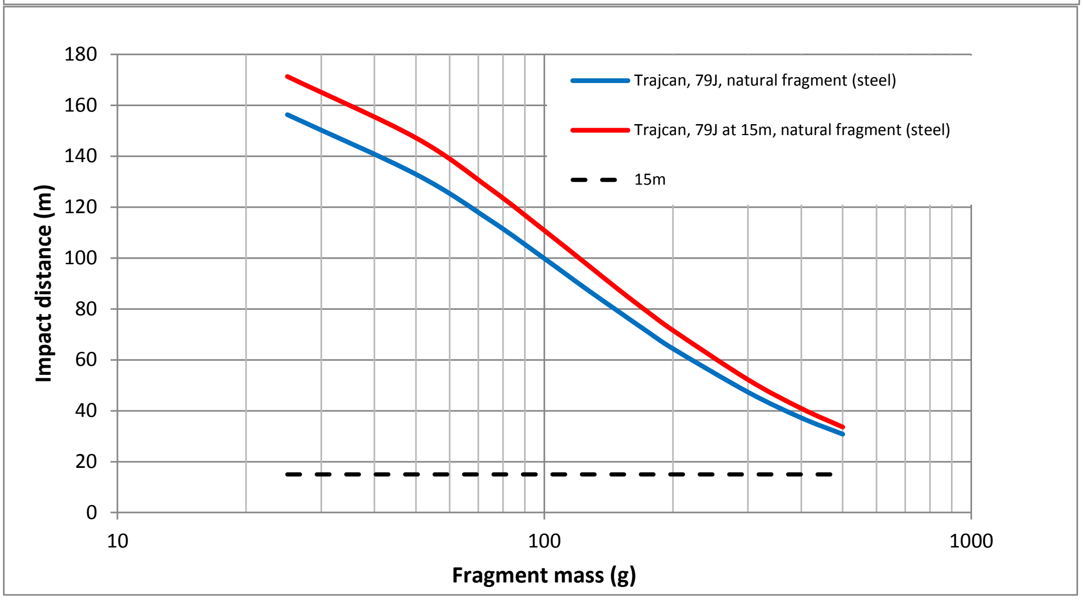


Figure 5. Lethality, major injury and greater, minor injury and greater, versus impact energy for a frontal exposure.

INJURY AND LETHALITY CRITERIA

For small fragments, injury and lethality effects are primarily due to penetration by fragments. For larger fragments, injury and lethality effects are primarily due to blunt impact energy. The smallest projectile masses in the distance-mass relations (25g to 100g) are in the transition region from penetration injury to blunt injury, as presented in figure 6 [8,9]. Lethal penetration injury for a 25g fragment occurs as a matter of coincidence at about 20J. The 20J energy criterion would still be sufficient to avoid (lethal) penetration injury for fragments larger than 25g, so injury due to blunt impact dominates in this case. A relation between lethal blunt injury and impact energy is described in the NATO Manual on Explosives Safety Risk Analysis AASTP-4 [11]. This model was extended to predict major and minor injuries, and incorporated into the Safety Assessment for Explosives Risk (SAFER) computer program [12]. Major injury is defined as injury requiring hospitalization. Bio-mechanical modelling as a function of impactor mass, velocity and body part impacted were used for the developed blunt trauma models for fatality and major injury [13]. MSIAC reproduced the resulting lethality, major injury, and minor injury models in SI units. Making the conservative assumption that a person is impacted at the front, we then calculated the probability given an arbitrary hit at the body using projected areas of the various body parts as a weighted average. The results in Figure 7 show that for a 20J blunt impact, lethality and major injury are not expected, but the probability of minor injury is high. For a 79J blunt impact there is a small probability of lethality (2.32%) with major injury likely to occur (36.8%). These estimates of the lethality, major injury, and minor injury are given an arbitrary hit for a frontally exposed person. They do not address how likely that hit is to occur.

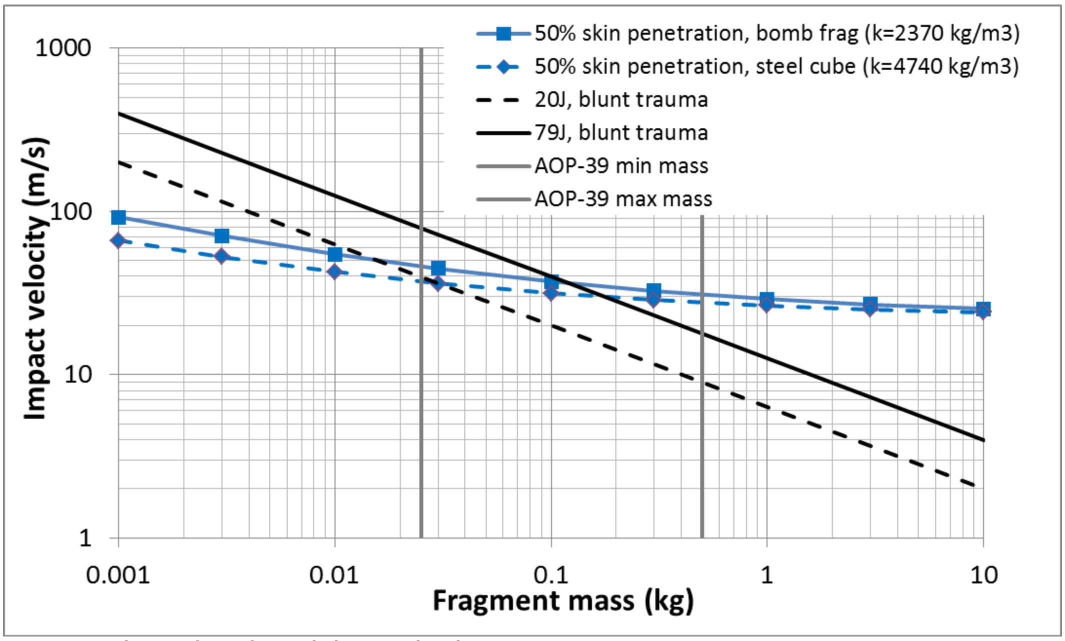


Figure 6. Overview of various injury criteria. .

HIT PROBABILITY

In IM testing, the weapon type of interest and its response varies largely. Also there are differences in the test configuration (e.g. horizontal or vertical shell orientation), the amount of tested ammunition and the type of packaging material. In other words, the source is not well known. Based on the number of projectiles that are collected after a test we can estimate the hit probability at a specific distance. For this purpose we make the following rough assumptions: 1) The angular distribution of fragments is uniform. Each launch angle is equally likely and 2) The trajectories between the event and the location of interest (e.g. exposed person at 15m) are well approximated by straight lines. Further information about mass-distance, and velocity distribution are not necessary in that case. The hit probability (P_{hit}) then follows from the launched number of projectiles (N) multiplied by the ratio between the area of a person (S= 0.56 m^2) and that of a hemisphere around the event with the distance to the

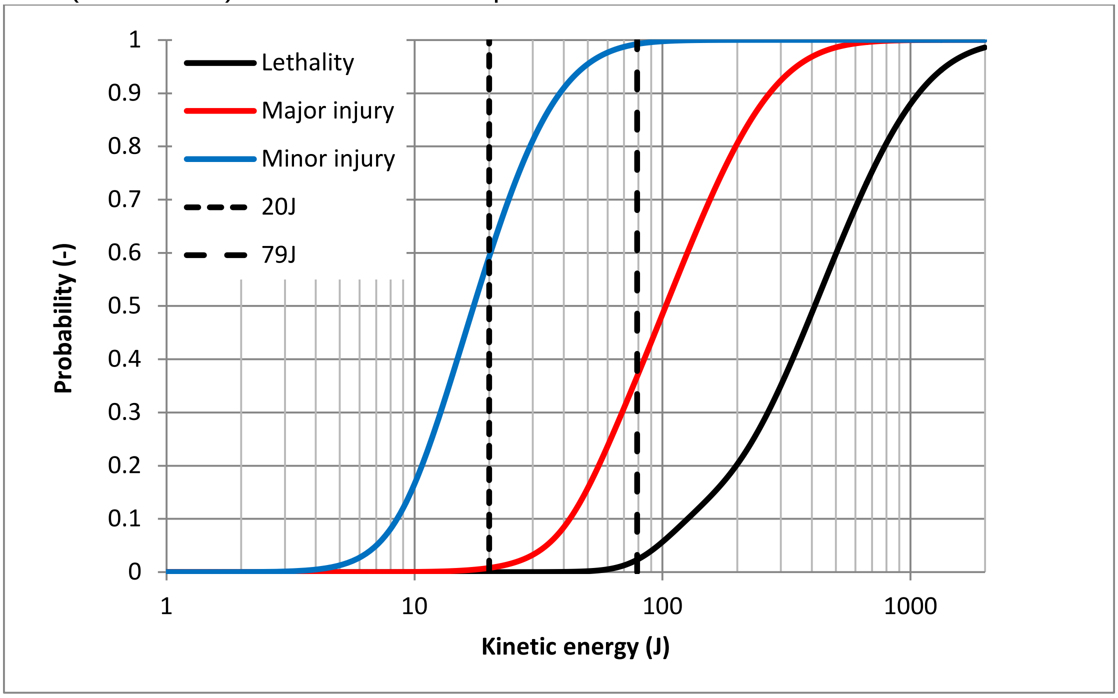


Figure 7. Lethality, major injury and greater, minor injury and greater, versus impact energy for a frontal exposure.

person as the radius (R).

$$P_{hit} = 1 - e^{-\frac{N \cdot S}{2 \cdot \pi \cdot R^2}} \qquad (1)$$

When we set the limiting hit probability at 15m to 1%, we find the limiting number of collected projectiles to be N = 25. This means that if we collect any more than 25 projectiles that meet the given injury or lethality criteria, we have a greater than 1% probability of a projectile that meets the criteria actually hitting a single person.

CONCLUSIONS

A study has been conducted on the origin of projection criteria for Insensitive Munitions and Hazard Classification. The distance-mass relations from the UN Orange book were reproduced with the software TRAJCAN, assuming the maximum impact distance reached by a natural steel fragment launched from 1 m height. The analysis also showed that the fragment shape and material have a significant influence on the throw distances. For fuzes, comparable impact distances have been predicted as for natural fragments (steel).

Further analysis showed that at the maximum distance, the impact energy is generally much smaller than the launch energy. This is an issue, as the latter energy is often used as a criterion. For the launch energies of interest (8, 20 and 79J), the height reached by the projectiles is not enough to reach the terminal velocity and energy before impacting the ground. The most relevant energy to know with respect to hazard is that of impact, possibly with an exposed fire fighter at 15m distance. For this reason, new distance-mass relations were developed that match the criteria based on impact energy, instead of launch energy.

For near vertical projections the impact distance does not provide any information about the launch energy or impact energy, although the latter will never be larger than the terminal energy. It is important, during IM and HC tests, to verify the presence of such projections with high speed video. An impact distance may also be reached by high velocity shallow trajectories. This will often appear to be unrealistic due to ricochet effects.

To assess the hazard of projections to persons, both penetration and blunt injury have to be taken into account. State of the art blunt injury models predict only minor injury for a 20J impact. For a 79J blunt impact there is a small probability of lethality and major injury is likely to occur. These conclusions can be drawn for a standing person with a frontal exposure to the event, and given that the body is hit once. Lethal penetration injury by smaller projections may take place at lower energy levels. The smallest projectile masses in the distance-mass relations (25g to 100g) are in the transition region from penetration injury to blunt injury. An assessment based on blunt injury alone is not conservative in this region. The 20J criterion is however sufficient to avoid lethal penetration injury for steel fragments larger than 25g.

It has been suggested to harmonize the projection criteria with the definition of the Inhabited Building Distance (IBD) in AASTP-1. This means that the 20J criterion would be changed into a 79J criterion and that the hit probability would be limited to 1%. A rule of thumb was developed to ensure a hit probability below 1% at 15m; the total number of projectiles counted between the 20J and 79J distance-mass relation should be 25 or less. This rule of thumb assumes that each launch angle is equally likely and that trajectories are well approximated by straight lines up until 15m. It is however not straight forward how to scale a test result to realistic, full scale, accident scenarios. MSIAC recommends changing the distance-mass relation that distinguishes a munitions burning response to a 20 J impact energy criterion at 15 m. Maintaining 20J as an energy value is necessary to guarantee projectile related non-lethal effects and minimal probability of major injuries, which one would expect from a burning reaction. Furthermore, we recommend distinguishing between projectile shapes and materials; at least between steel and aluminium projections. Including a hit probability to the projection criteria is not recommended because of the aforementioned scaling issues.

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