U.S. ARMY

DEVCOM ARMAMENTS CENTER

U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND ARMAMENTS CENTER

(U) IMPLEMENTATION OF IMPROVED METRICS FOR HAZARDOUS FRAGMENT EVALUATION FOR BOTH INSENSITIVE MUNITIONS & HAZARD CLASSIFICATION PURPOSES

JANUARY 21-23, 2026

(U) International Explosives Safety Summit (IESSE)

(U) Phoenix Convention Center
Phoenix, Arizona, USA

(U) Daniel J. Pudlak

PURPOSE

FSA – I gave this talk in San Diego at the 36th IESSE in August 2018.

- **The purpose for presenting this again is to serve as a lead-in to my following presentation (next) that discusses the new / proposed methodology for evaluating hazardous fragments for IM & HC test & evaluation purposes.**

U.S. ARMY

Intent

DEVCOM ARMAMENTS CENTER

- '**Improved Metrics**' discussed in this paper have been adopted by the NATO / IM communities via AOP-39.
  - Intention - familiarize / inform the HC / Safety community(ies) with:
    - ✓ *Corrections* we've made to the math behind the 8J, 20J & 79J curves that we all use
    - ✓ *Improvements* we've made to math behind the 8J, 20J & 79J curves that we all use
    - ✓ *Additional New Curves* that we've incorporated to take into account modern-day armament material.

- '**Improved Methodology**' paper (following presentation) discusses the new / proposed 'Energy-Density' methodology.
  - Brings forth a *more scientifically* accurate method of evaluating the severity / hazardousness of fragments, rather than the 'Energy' methodology that we all currently use.
  - This has not yet been adopted by the IM community, but…
    - Purpose is to *solicit help to finalize the methodology for incorporation into the IM & HC / Safety evaluation processes.*

U.S. ARMY

Current Type IV Response Descriptor

DEVCOM ARMAMENTS CENTER

Per MIL-STD-2105D / **AOP-39(3)**:

- "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 vs mass relationships in figure 1."

Resultant questions from Response Descriptor CWG back in 2012 timeframe.

- Where did 20J come from?
- Why did we switch from 79J to 20J?
- Why is 15m (50ft) significant?
- Are these the best metrics?
- What method are we using to measure these metrics?
- Is there a better method to measure these metrics?

*Note:

- 79J in AOP-39 Ed 2 (2009) and MIL-STD-2105C (July 2003)
- 20J in AOP-39 Ed 3 (March 2010) and MIL-STD-2105D (April 2011)

U.S. ARMY

Where did 20J & 79J come from?

DEVCOM ARMAMENTS CENTER

Colonel Journee, French infantry officer established 15ft-lb & 58 ft-lb criterion in 1800's

– "Considered the **upper and lower bounds of what a man could endure** from recoil of a rifle".
  - **15 ft-lb (20J**) was set as the **maximum recoil suitable for a military rifle**
  - **58 ft-lb (79) recoil energy** was estimated to provide **significant bruising/damage to typical shoulder**

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

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

15 ft-lbs (20J) →

58 ft-lbs (79J) →

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

» **Shotguns produce 25 ft-lb to 35 ft-lb of recoil**

» **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 foot pounds." --1909 British Textbook of Small Arms

U.S. ARMY

Energy as a Measure of Personnel Hazard

DEVCOM ARMAMENTS CENTER

- Since then, 20J & 79J have been referenced and used for numerous applications
  - Testing standards, injury thresholds, toy/weapon limits, etc.

- Currently we use the fragment’s mass and distance to calculate its energy.
  - Found that many projectiles are not lethal, or even very hazardous with 20J/79J.

- Examples of projectiles and their associated energy:
  - Paintball 300ft/s – **12J**
  - 0.177 cal pellet (air gun) 900ft/s– **21J**
  - Baseball 90mph – **120J**
  - 40mm non-lethal grenade 200ft/s – **150J**

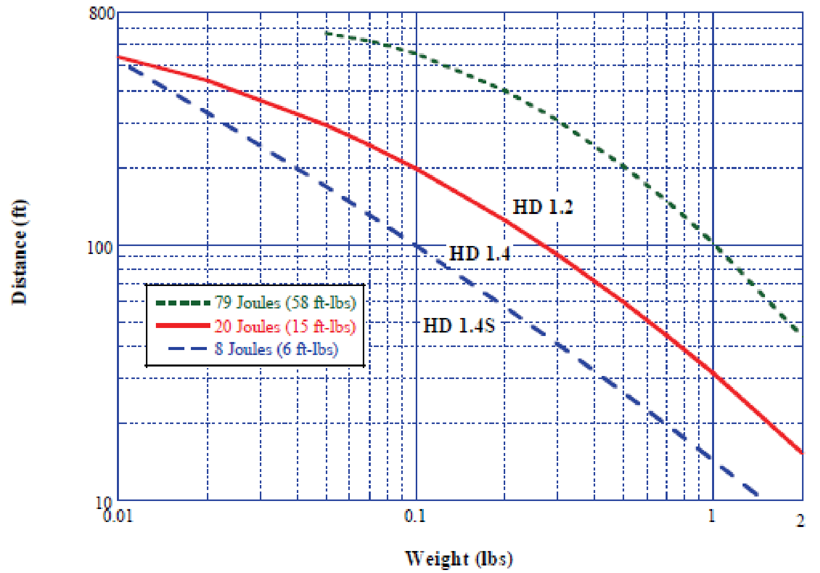
UNCLASSIFIED

U.S. ARMY

Where did our 20J & 79J curves come from?

DEVCOM ARMAMENTS CENTER

TB 700-2
NAVSEAINST 8020.8C/TO 11A-1-47



58 ft-lbs (79 J)

D in ft, M in lbs

$D = 101.65*M^{[-1.1061-0.15961*ln(M)]}$

$M = 4.24*D^{[1.8714-1.2433*(ln(D))+0.25442*(ln(D))^2-0.018948*(ln(D))^3]}$

D in m, M in kg

$D = 11.697*M^{[-1.35846-0.15961*ln(M)]}$

$M = 4.533*D^{[0.132633-0.49695*(ln(D))+0.16437*(ln(D))^2-0.018948*(ln(D))^3]}$

15 ft-lb (20 J)

D in ft, M in lbs

$D = 31.49*M^{(-0.98-0.0788*ln(M))}$

$M = 0.000006151*D^{[14.8843-6.0304*((ln(D))+1.0077*((ln(D))^2-0.06313*((ln(D))^3]}$

D in m, M in kg

$D = 4.212*M^{(-1.103-0.0788*ln(M))}$

$M = 0.1283*D^{[4.399-2.973*((ln(D))+0.7077*((ln(D))^2-0.06313*((ln(D))^3]}$

6 ft-lb (8 J)

D in ft, M in lbs

$D = 14.41*M^{(-0.896-0.0252*ln(M))}$

$M = 7.2157*D^{[0.6007-0.9509*((ln(D))+0.2155*((ln(D))^2-0.01758*((ln(D))^3]}$

D in m, M in kg

$D = 2.13*M^{(-0.935-0.0252*ln(M))}$

$M = 2.4193*D^{[-0.8642-0.3317*((ln(D))+0.1319*((ln(D))^2-0.01758*((ln(D))^3]}$

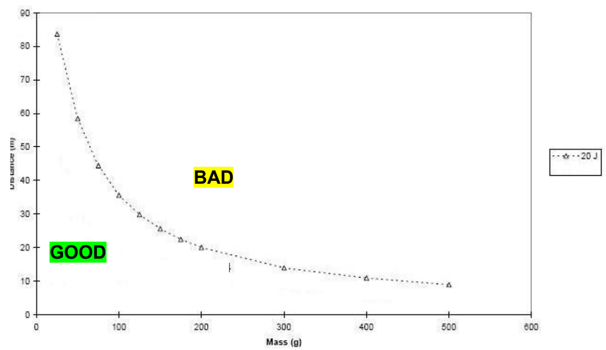
Figure 5-17 Relationship of Projection Kinetic Energy and Hazard Division

Current Metrics & Method

- <u>Current Metric:</u>
  - $E_{Fragment} > 20J$ beyond 15m → TYPE IV
  - $E_{Fragment} < 20J$ beyond 15m → TYPE V

- <u>Current Method</u>
  - Measurement of fragment location, orientation, weight, and condition.
  - **Mass and Distance** are then used to determine if fragment energy was over 20J.
    - *Handy frag energy calculator
  - If the fragment's energy is:
    - above the curve, TYPE IV
    - below the curve, TYPE V

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.S. ARMY

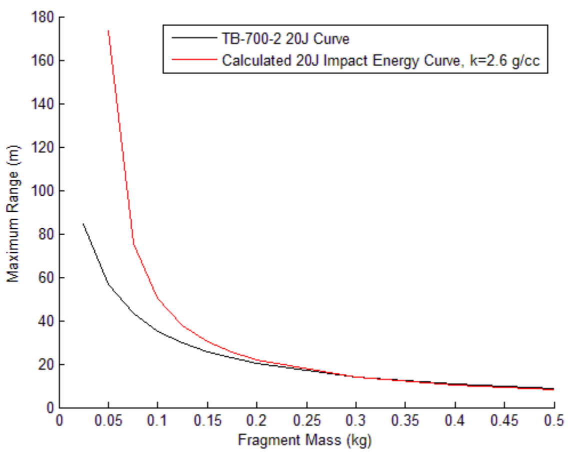
So what's the problem?

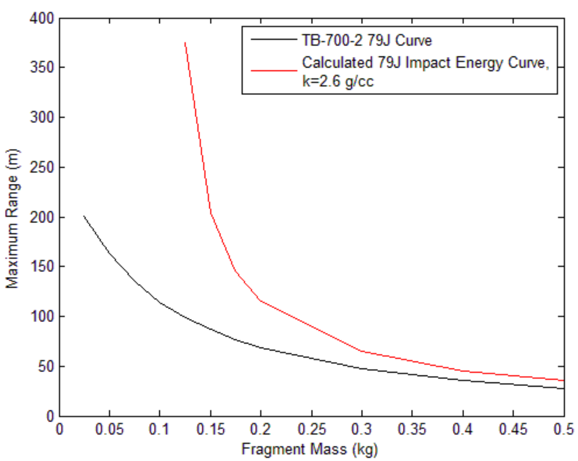
DEVCOM ARMAMENTS CENTER

<u>Problem #1:</u>

- **Current curve** we use was formulated with a **<u>Launch Energy Criterion</u>**
  - <u>Works based on:</u>
    - **Calculating the max distance a given mass can travel *<u>when launched with 20J.</u>***
      - However, AOP-39 guidance indicates *<u>we should be measuring **Impact Energy**</u>*.

- **<u>Solution #1:</u>**
  - We reformulated both curves under consideration (20J & 79J) *<u>based on **Impact Energy Criterion**</u>*





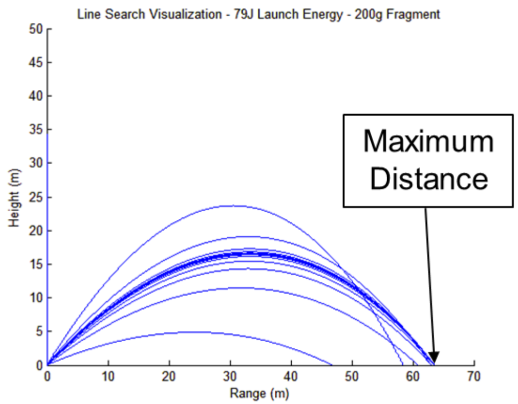
U.S. ARMY

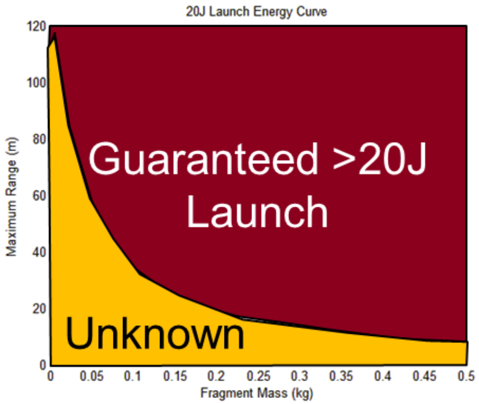
First, Let's Looks at Launch Energy Criterion

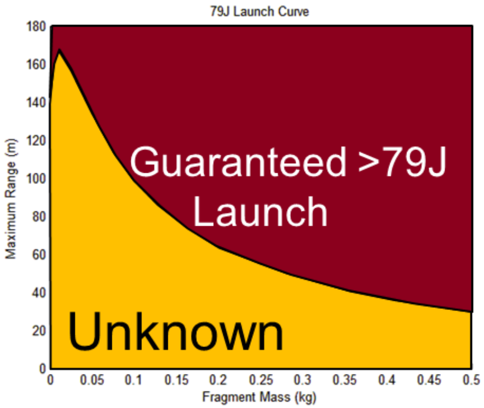
DEVCOM ARMAMENTS CENTER

How does it work?

- Each point on the launch energy curves calculated using a line search forward in time from launch
  - **Finds maximum distance a fragment of that mass could travel, *<u>having been launched at 20J.</u>***







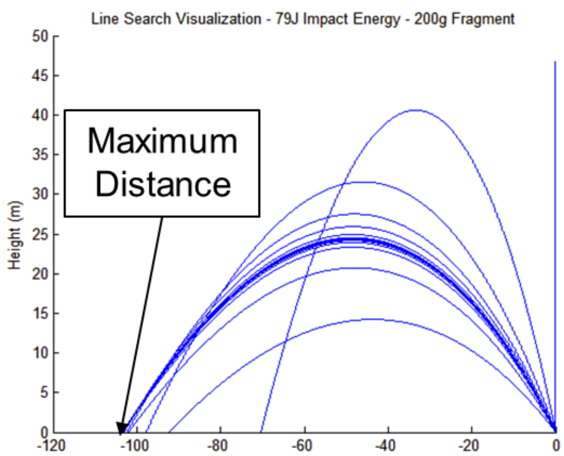
What other issues are there with this criterion?

- **Fragments that land past this max distance *<u>are guaranteed hazardous</u>***
- **Fragments that do not exceed this distance *<u>may or may not be hazardous</u>***
  - <u>For example</u>: high energy fragments launched vertically or directly at the ground
- All curves calculated from starting height of zero. A starting height changes the curves!
- Ricochet can be modeled (questionable accuracy)

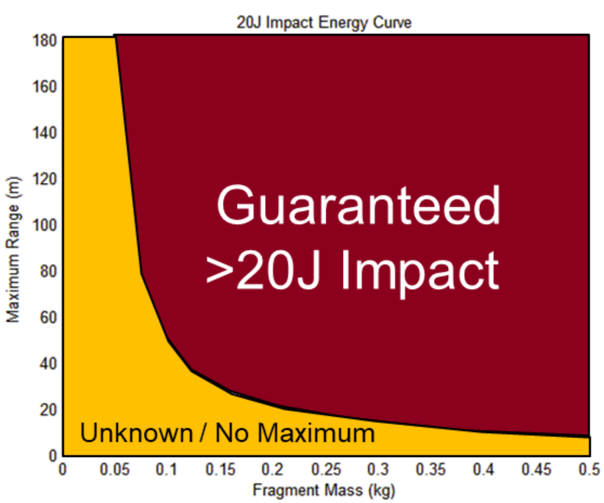
U.S. ARMY

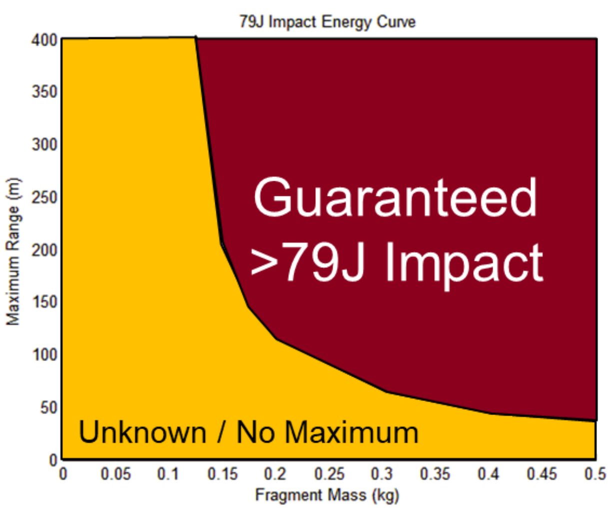
Now, Let's Look at Impact Energy Criterion

DEVCOM ARMAMENTS CENTER



- Each point on the Impact Energy curves calculated using a line search backward in time from impact
  - Finds maximum distance a fragment of that mass could travel, having impacted at 20J
- Fragments that land past this distance are guaranteed hazardous
- Fragments that do not exceed this distance may or may not be hazardous
  - For example, high energy fragments launched vertically or directly at the ground
- The curve goes off to infinity for small fragments



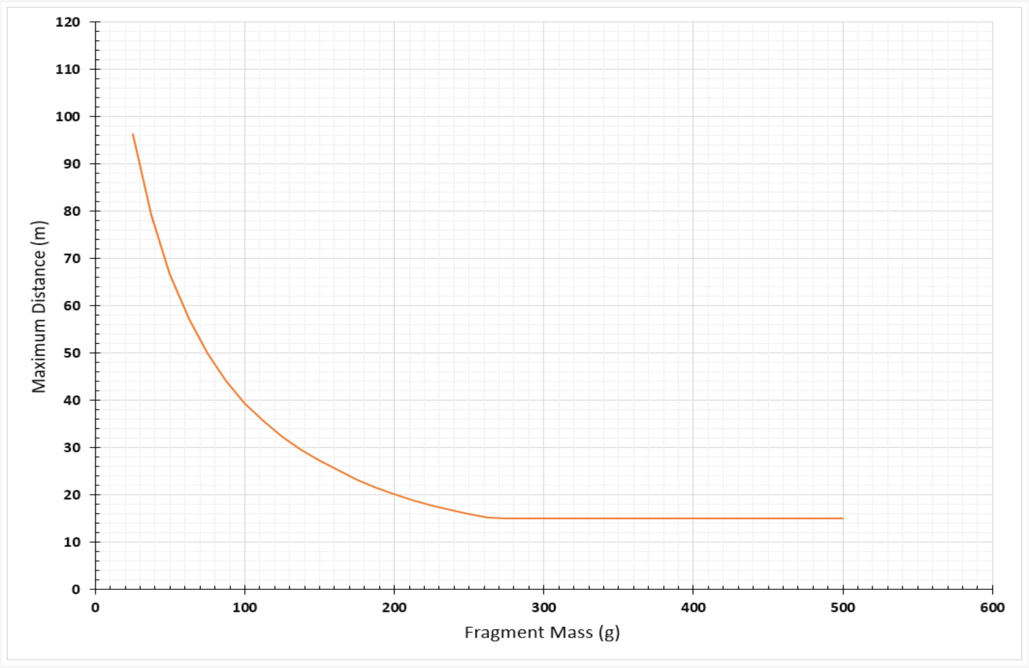


What else is wrong with the curve?

Problem #2:

- **Current curve** doesn't take into account 15m.

- **Solution #2:**
  - Incorporated 15m in 20J Impact Energy @ 15m curve.

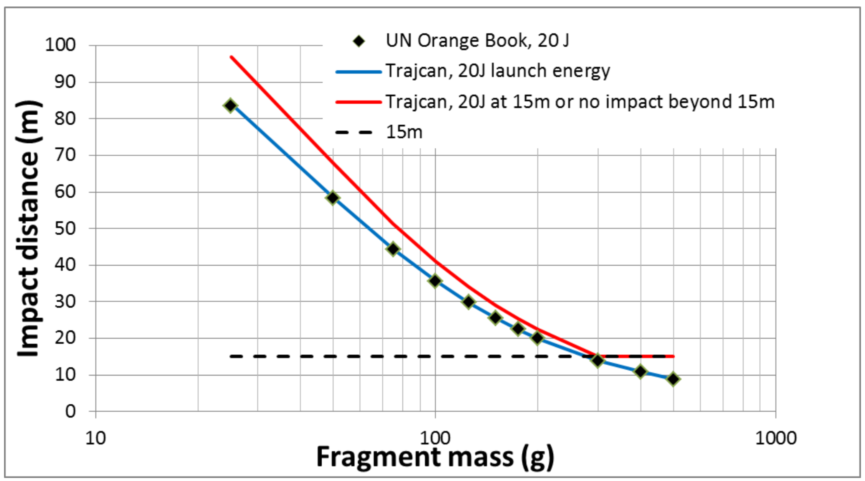


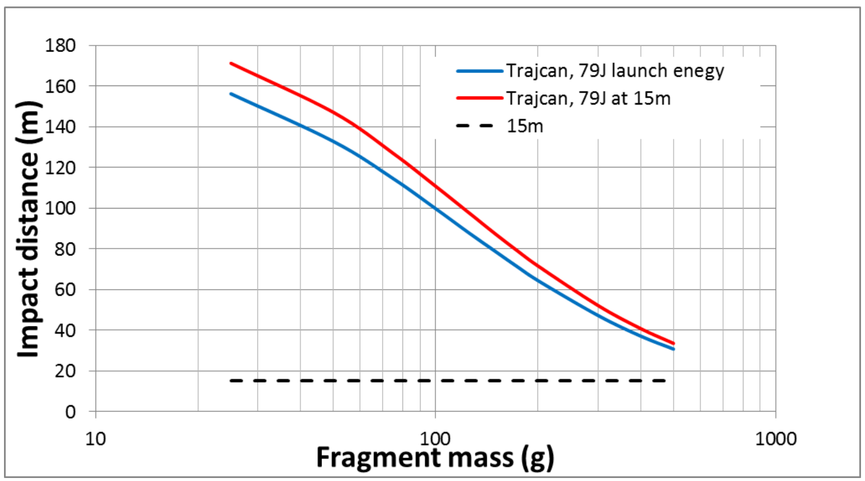
U.S. ARMY

TRAJCAN

DEVCOM ARMAMENTS CENTER

- **MSIAC TRAJCAN results agree**
  - Martijn Van der Voort incorporated 15m in 20J Impact Energy @ 15m curve.

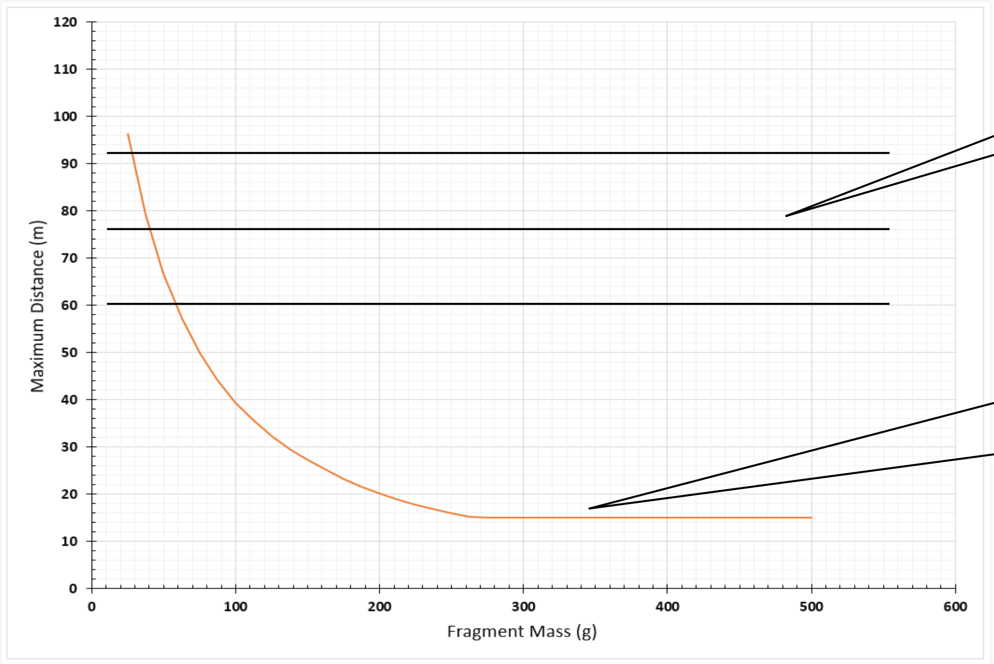




2016 INSENSITIVE MUNITIONS & ENERGETIC MATERIALS TECHNOLOGY SYMPOSIUM, NASHVILLE, TX, **PROJECTION CRITERIA FOR INSENSITIVE MUNITIONS AND HAZARD CLASSIFICATION,** Martijn M. van der Voort, Ernest L. Baker, Emmanuel Schultz and Michael W. Sharp, *Munitions Safety Information Analysis Center (NATO), Brussels, Belgium.*

What else is wrong with the curve?

- Curve still may not converge enough for Type IV/V fragments
  - Further investigation required to bound upper/lower limits



Arbitrary lines represent potential 'ceiling' for non-Type/IV/V frags

Flattens out due to masses so large that cannot impact with at least 20J by virtue of its mass.

U.S. ARMY

How Does Impact Energy @ 15m work?

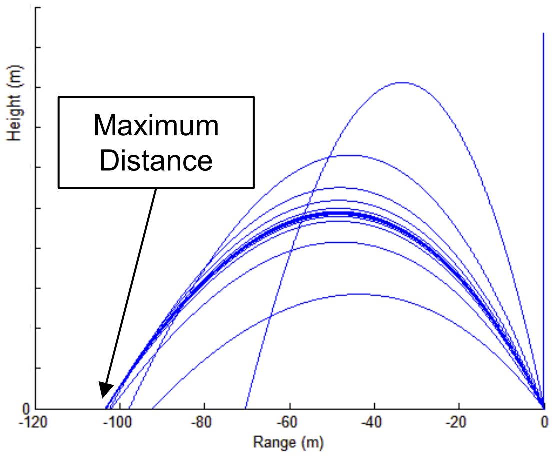
DEVCOM ARMAMENTS CENTER

Impact Energy @ 15m:

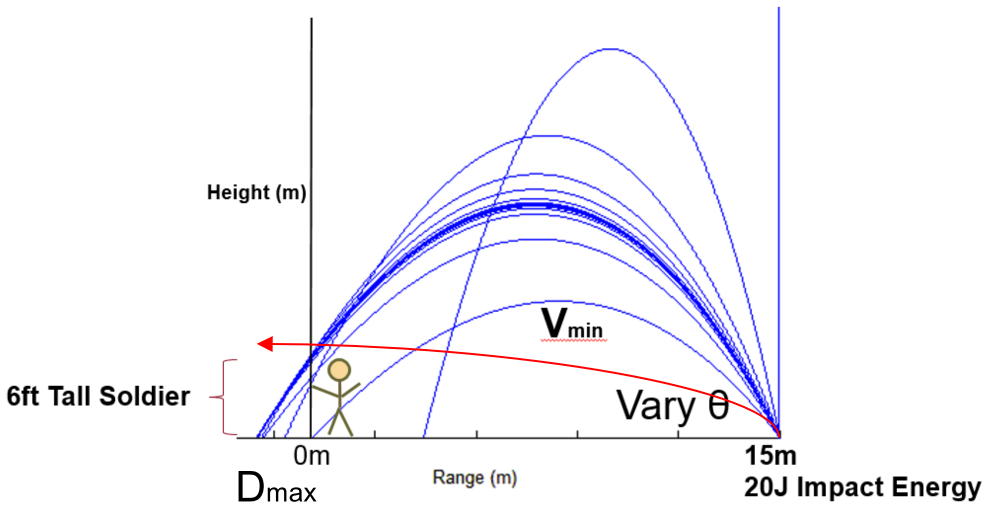
- Find V_{min} of 15m, 20J Impact
- Use V_{min}, Increase θ to find D_{max}
- Use D_{max} to find E_{max}

Conservative approach indicates 20J at 15m, Higher than 20J beyond 15m.

Impact Energy



Impact Energy @ 15m



U.S. ARMY

Does that resolve all issues?

DEVCOM ARMAMENTS CENTER

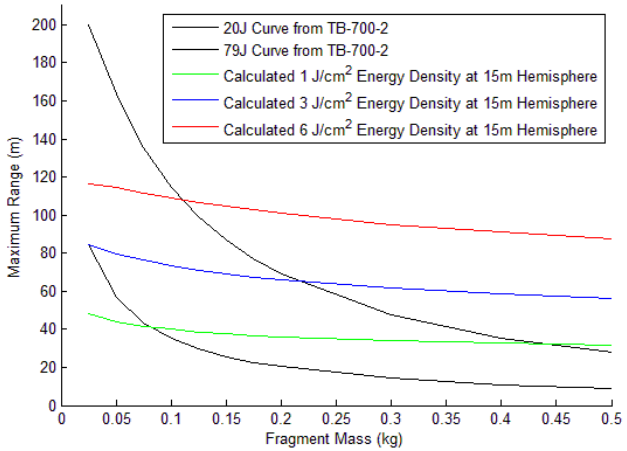
Problem #3

- Energy (J) alone is not a good measure of impact
  - Does not take into account the energy applied per the presented area
- Energy Density (J/cm^2) is a better measure of impact
  - Does take into account the energy applied per the presented ar
- Example:
  - 32g, 2” diameter, object fired at 150f 33.4J
  - 3.5g, 2” diameter, object fire produces 8J
  - Both objects J/cm^2
  - The is the presented area of the objects

Plug – We will discuss Energy Density during the next presentation.

Solution:

- ARDEC formulated Energy Density curves for
  - 1 J/cm^2,
  - 3 J/cm^2
  - 6 J/cm^2



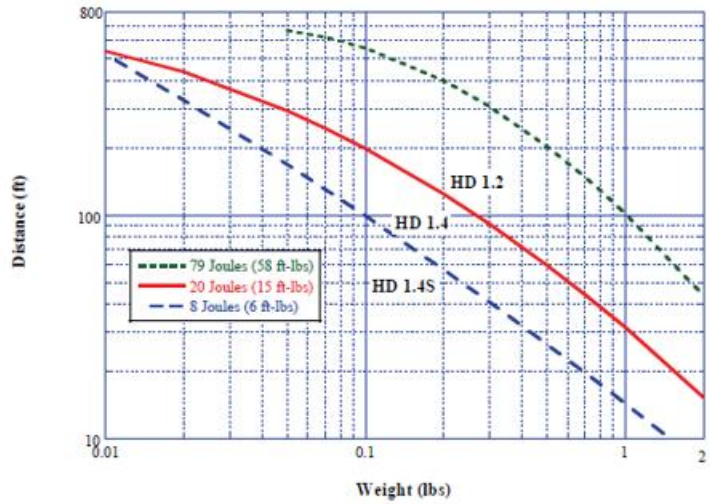
U.S. ARMY

Final Fix

DEVCOM ARMAMENTS CENTER

Old / Current Curves from TB 700-2

TB 700-2
NAVSEAINST 8020.8C/TO 11A-1-47



58 ft-lbs (79 J)

D in ft, M in lbs

$D = 101.65*M^{[-1.1061-0.15961*\ln(M)]}$

$M = 4.24*D^{[1.8714-1.2433*(\ln(D))+0.25442*(\ln(D))^2-0.018948*(\ln(D))^3]}$

D in m, M in kg

$D = 11.697*M^{[-1.35846-0.15961*\ln(M)]}$

$M = 4.533*D^{[0.132633-0.49695*(\ln(D))+0.16437*(\ln(D))^2-0.018948*(\ln(D))^3]}$

15 ft-lb (20 J)

D in ft, M in lbs

$D = 31.49*M^{(-0.98-0.0788*\ln(M))}$

$M = 0.000006151*D^{[14.8843-6.0304*((\ln(D))+1.0077*((\ln(D))^2-0.06313*((\ln(D))^3]}$

D in m, M in kg

$D = 4.212*M^{(-1.103-0.0788*\ln(M))}$

$M = 0.1283*D^{[4.399-2.973*((\ln(D))+0.7077*((\ln(D))^2-0.06313*((\ln(D))^3]}$

6 ft-lb (8 J)

D in ft, M in lbs

$D = 14.41*M^{(-0.896-0.0252*\ln(M))}$

$M = 7.2157*D^{[0.6007-0.9509*((\ln(D))+0.2155*((\ln(D))^2-0.01758*((\ln(D))^3]}$

D in m, M in kg

$D = 2.13*M^{(-0.935-0.0252*\ln(M))}$

$M = 2.4193*D^{[-0.8642-0.3317*((\ln(D))+0.1319*((\ln(D))^2-0.01758*((\ln(D))^3]}$

Figure 5-17 Relationship of Projection Kinetic Energy and Hazard Division

U.S. ARMY

Ballistic Trajectory Modeling – Background

DEVCOM ARMAMENTS CENTER

Equations of Motion (Vector Form)

$$\frac{d\mathbf{V}}{dt} = -\frac{\rho S C_D}{2m}|\mathbf{V}|\mathbf{V} + \mathbf{g}$$

$$\frac{d\mathbf{x}}{dt} = \mathbf{V}$$

F=ma with air drag

Equations of Motion (Scalar Form)

$$\frac{dV_x}{dt} = -\frac{\rho S C_D}{2m} V V_x = -\frac{\rho S C_D}{2m} V_x \sqrt{V_x^2 + V_y^2}$$

$$\frac{dV_y}{dt} = -\frac{\rho S C_D}{2m} V V_y - g = -\frac{\rho S C_D}{2m} V_y \sqrt{V_x^2 + V_y^2} - g$$

$$\frac{dx}{dt} = V_x$$

$$\frac{dy}{dt} = V_y$$

(Modeling approximations)

Shape factor data

$$m = kS^{3/2}$$

If the fragments from a given weapon are assumed to be geometrically similar, the mass m and presented area A are related by M = kA$^{3/2}$. Values of k, called a shape factor or ballistic density, may be determined from weight and presented area measurements on fragments recovered from tests of particular weapons. Although the value of k differs from one weapon to another, for forged steel projectiles and fragmentation bombs the average value of 660 grains/in.^{3} (2.60 g/cm^3) has been recommended, while for demolition bombs the value 590 grains/in.^{3} (2.33 g/cm^3) has been applied.

(from Zaker, DDESB-TP-12)

(2.60 g/cm^3)

Drag Coefficient Data

TABLE I DRAG COEFFICIENTS FOR IRREGULAR FRAGMENTS

MACH NUMBER	DRAG COEFFICIENT
0	0.80
0.75	0.88
0.90	1.09
1.15	1.26
2.00	1.14
4.00	1.08
>4.00	1.08

Note: Drag coefficient varies linearly between Mach Number entries

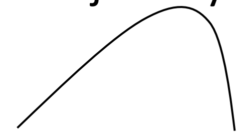
In Design Considerations for Toxic Chemical and Explosives Facilities; Scott, Ralph A., et al.; ACS Symposium Series; American Chemical Society: Washington, DC, 1987.

(from Swisdak, "Fragmentation Effects: An Overview")

Numerical Solver

- MATLAB ode45 (variable-timestep Runge-Kutta)
- Validate with flat fire solutions / ensure same results obtained for very small constant timestep
- Can run backwards or forwards in time
- Launch height usually zero
- Stop integration when trajectory ordinate becomes negative

Trajectory



Curve Generation / Other Analysis

Ballistic trajectory calculations like these are where the TB-700-2 curves came from

U.S. ARMY

DEVCOM ARMAMENTS CENTER

Final Fix

- Previous curves (TB 700-2) incorporate air drag coefficient based merely on steel
  - Chunky Steel drag

Final Fix

- Previous curves (TB 700-2) incorporate air drag coefficient based merely on steel
  - Chunky Steel drag

- For fragments of different density than steel, effect of drag should be taken into account accordingly.

  - Generically speaking, can group into fractions of steel, ex:
    - ¾ density of steel
    - ½ density of steel
    - ¼ density of steel

Final Fix

- For accuracy, we should just use the densities of common materiel found in modern-day armaments that we would find on the test site post-test.
  - Tungsten (19.25 g/cc)
  - Steel (7.85 g/cc)
  - Aluminum (2.71 g/cc)
  - HDPE (0.95 g/cc)

U.S. ARMY

DEVCOM ARMAMENTS CENTER

Final Fix

- For accuracy, we should just use the densities of common materiel found in modern-day armaments that we would find on the test site post-test.
  - Tungsten (19.25 g/cc)
  - Steel (7.85 g/cc)
  - Aluminum (2.71 g/cc)
  - HDPE (0.95 g/cc)

$$V = V_0 \exp\left(-\frac{\rho_{air} S C_D}{2m} x\right) = \sqrt{\frac{2E_0}{m}} \exp\left(-\frac{\rho_{air} \frac{3}{2}\left(\frac{m}{\rho_{frag}}\right)^{2/3} C_D}{2m} x\right)$$

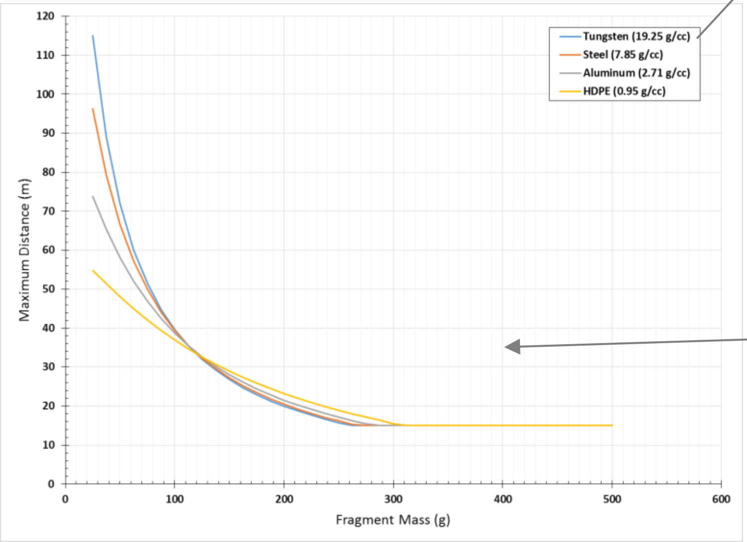
U.S. ARMY

Final Fix

DEVCOM ARMAMENTS CENTER

- For accuracy, we should just use the densities of common materiel found in modern-day armaments that we would find on the test site post-test.
  - Tungsten (19.25 g/cc)
  - Steel (7.85 g/cc)
  - Aluminum (2.71 g/cc)
  - HDPE (0.95 g/cc)

$$V = V_0 \exp\left(-\frac{\rho_{air} S C_D}{2m} x\right) = \sqrt{\frac{2E_0}{m}} \exp\left(-\frac{\rho_{air} \frac{3}{2}\left(\frac{m}{\rho_{frag}}\right)^{2/3} C_D}{2m} x\right)$$



*Curves provided to NATO IM Working Group for inclusion into newest version of AOP-39.

U.S. ARMY

New Curves in AOP-39

DEVCOM ARMAMENTS CENTER

AOP-39

Note the handy-dandy mass-distance chart (below) that we (AIMB) use for quick reference.

Mass (g)	Projection Distance (m)			
	Tungsten 20J	Steel 20J	Aluminum 20J	HDPE 20J
25	114.98	96.33	73.86	54.76
50	72.01	66.77	58.18	48.14
75	51.42	49.93	46.88	42.09
100	39.62	39.41	38.72	36.94
125	32.04	32.31	32.67	32.61
150	26.78	27.23	28.05	28.96
175	22.93	23.42	24.43	25.87
200	19.98	20.48	21.53	23.23
225	17.66	18.12	19.14	20.95
250	15.77	16.18	17.14	18.95
275	15.00	15.00	15.39	17.18
300	15.00	15.00	15.00	15.50
500	15.00	15.00	15.00	15.00

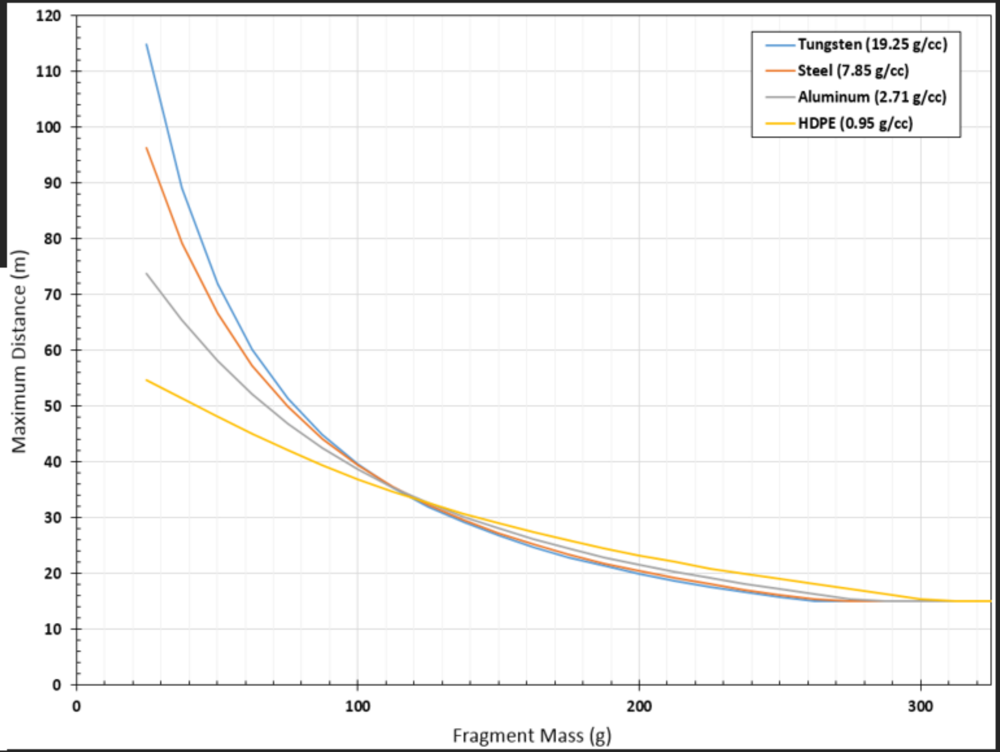


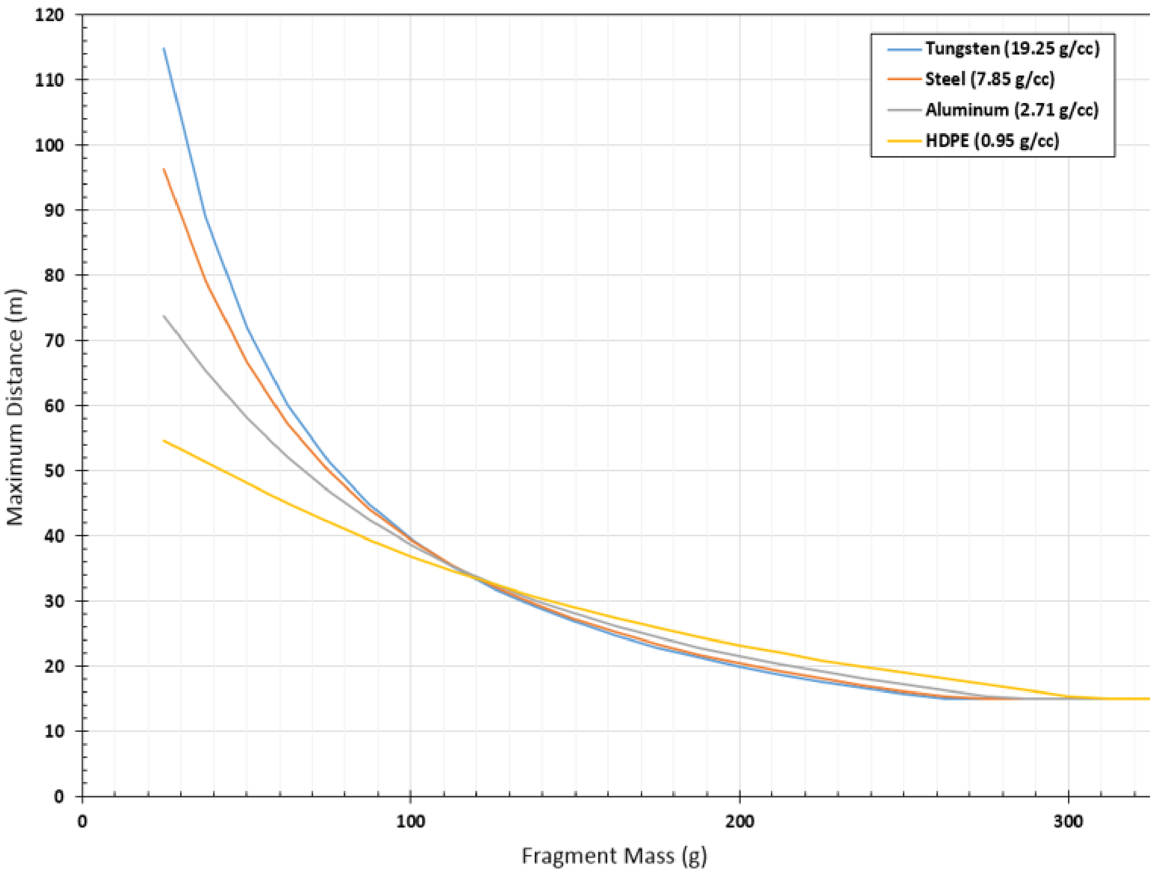
Figure A-1: Projection distance of a fragment with an energy of 20 J at 15 m depending on its mass and its nature.

U.S. ARMY

Final Fix

DEVCOM ARMAMENTS CENTER

- For simplicity, this is all you need, however.



Conclusion

- Inherent issue with Mass-Distance curve for Pass/Fail Criteria
- Best we can do is fix current curve, and improve criteria
- ARDEC reformulated the curve with Impact Energy Criterion
- MSIAC reformulated Impact Energy Criterion @ 15m
  - Much more conservative approach than previous curve
- New / Fixed curves adopted by IM community → *Suggest HC follow-suite*
- The 20J vs 79J argument is irrelevant
  - Energy Density is better method to measure impacts/injury than energy alone
    - Literature and Lethality Experts suggest 1.6 J/cm^2 for our IM realm of Type IV/V fragments / injuries
    - Still needs work before implementation
    - NATO Response Descriptor Working Group (RDWG) Decision for incorporation into IM.

Questions?

Back-up Slides

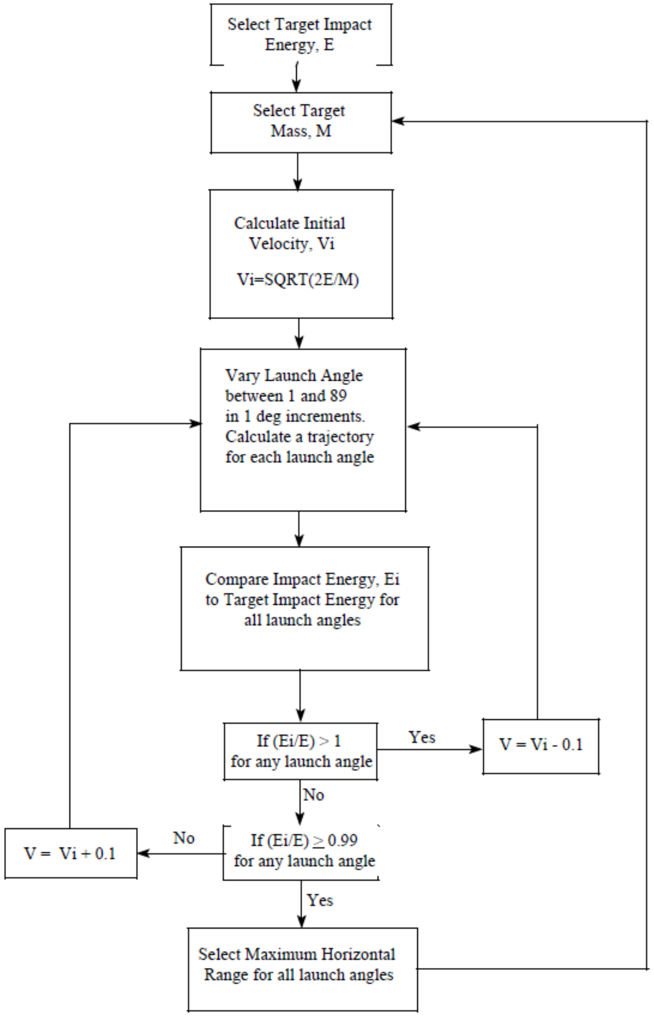
UNCLASSIFIED

U.S. ARMY

Status of Current Response Descriptors

DEVCOM ARMAMENTS CENTER

- What are we currently doing?
  - "Type IV (Deflagration)" if fragments found further than TB-700-2 20J curve
  - We spoke to the originators of the TB-700-2 curves, were provided with the following methodology
    - See flow chart they provided
    - Limits the maximum impact energy to 20J
    - The maximum impact energy *is* the launch energy (unless item is on a stand)
    - "at 15m" caveat not considered in their calculation
  - The TB-700-2 20J curve definitely represents maximum distance a fragment could be thrown at 20J launch energy



The 20J and 79J curves in both TB-700-2 and the UN Orange Book represent launch energy as a result of a mistake in the calculations

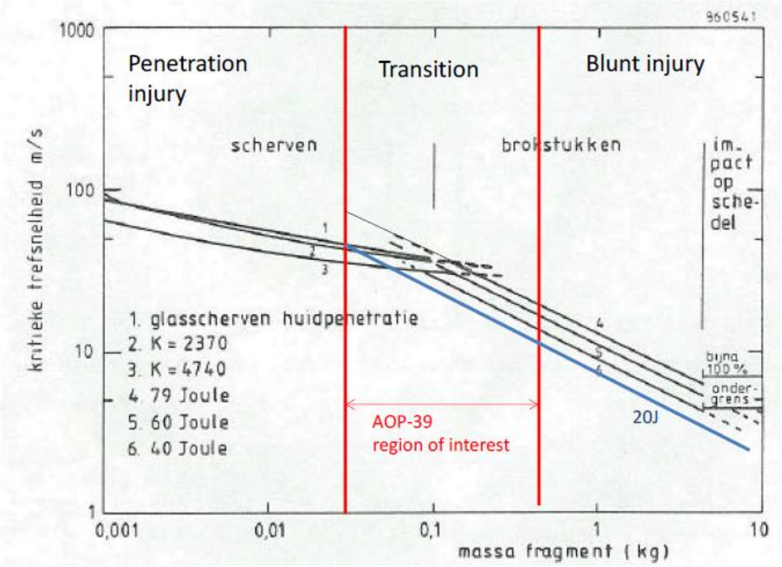
U.S. ARMY

Skin Penetration vs. Blunt Trauma

DEVCOM ARMAMENTS CENTER

- According to MSIAC:
  - Energy/Area more relevant for skin penetration
  - Energy more relevant for blunt trauma
  - Fragments in region of interest are big enough to start causing blunt trauma injuries at relatively low velocities
  - Furthermore, blunt trauma injuries will be caused at lower velocities thus a skin penetration criterion is not conservative

- It is conceivable that steel fragments of the sizes in AOP-39 can be thought of as relatively dangerous at relatively slow speeds
- Intuitive considerations regarding absorption of the impact energy
  - Partitioning of impact energy between projectile and target (energy absorbing structural deformation)
  - Distribution of force over impact surface
- US lethality experts should be consulted on what criterion makes sense for the fragments in this range

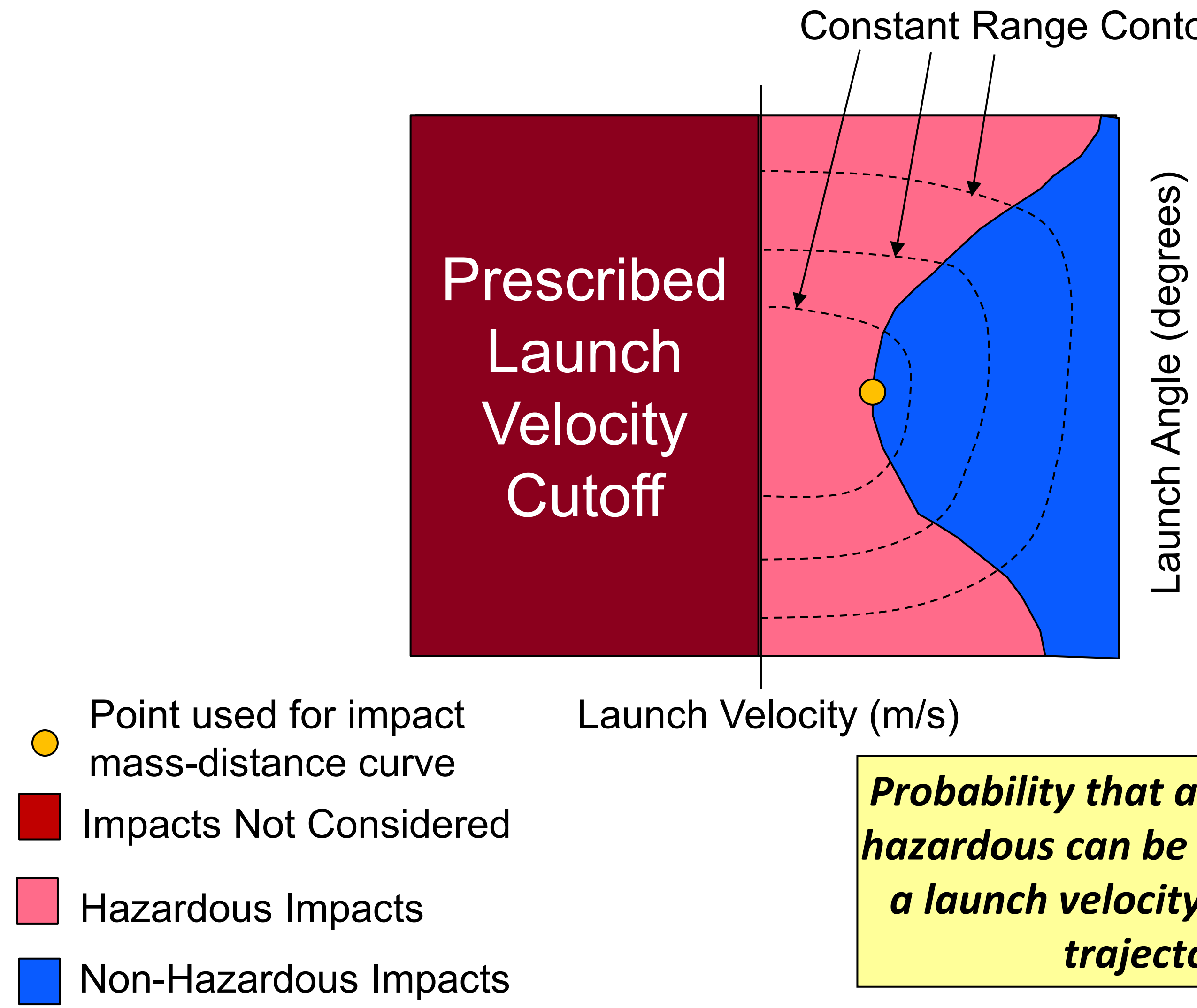


From Martijn van der Voort, "**ANALYSIS OF THE IM TYPE V RESPONSE DESCRIPTOR**"

U.S. ARMY

Uncertainty Reduction Strategies - Probability Methodology

DEVCOM ARMAMENTS CENTER



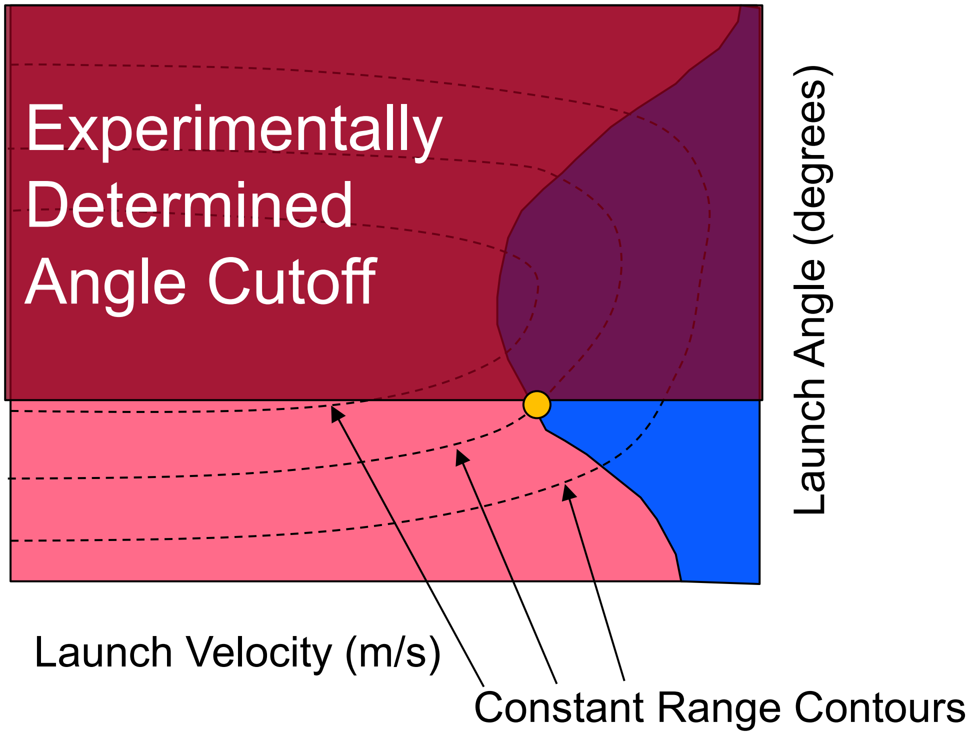
Fragments just under the curve have a (quantifiable) higher probability of being hazardous than fragments further below the curve

Probability that a fragment under the curve is hazardous can be computed (~ratio of areas) if a launch velocity cutoff is prescribed and all trajectories equally likely

U.S. ARMY

Uncertainty Reduction Strategies - Angle Cutoffs (Experimental)

DEVCOM ARMAMENTS CENTER



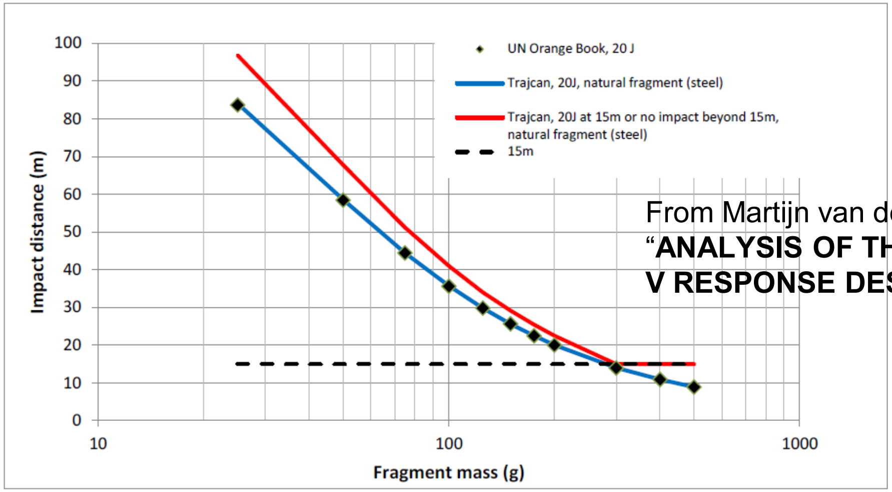
Perhaps orthogonal cameras or witness screens of some sort could provide angle/velocity cutoff information

- New lower point used for impact mass-distance curve
- Impacts Not Considered
- Hazardous Impacts
- Non-Hazardous Impacts

If it can be photographically determined that the largest launch angle out of all the debris does not exceed a given value, the curve is lowered (fidelity of the measurement is gained)

Impact Energy at 15m (MSIAC Proposal) (Cont'd)

- MSIAC proposal is an **impact energy at 15m** criterion
  - This is different from an **impact energy** criterion (e.g., doesn't go off to infinity)
- Methodology
  - Find minimum possible launch velocity to hit person standing at 15m with a 20J impact
  - Using that velocity, adjust the launch angle until the maximum distance is found, this is the point used for their mass-distance curve
  - A fragment which lands above their curve has a higher velocity than the minimum velocity possible to reach a person standing at 15m with 20J
  - Therefore it **guarantees a person at 15m would be hit with at least 20J if the launch angle were lowered**



From Martijn van der Voort, "**ANALYSIS OF THE IM TYPE V RESPONSE DESCRIPTOR**"

Pro: Guarantees hazardous impact at 15m if above curve, conservative lethality criterion reduces unknown region below curve

Con: Not much different from launch energy, lethality criterion may be too conservative