U.S. Army Research, Development and Engineering Command

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

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TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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Current Type IV Response Descriptor

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 versus mass relationships in figure 1."

  - 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)

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Where did 20J & 79J come from?

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

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Energy as a Measure of Personnel Hazard

- 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**

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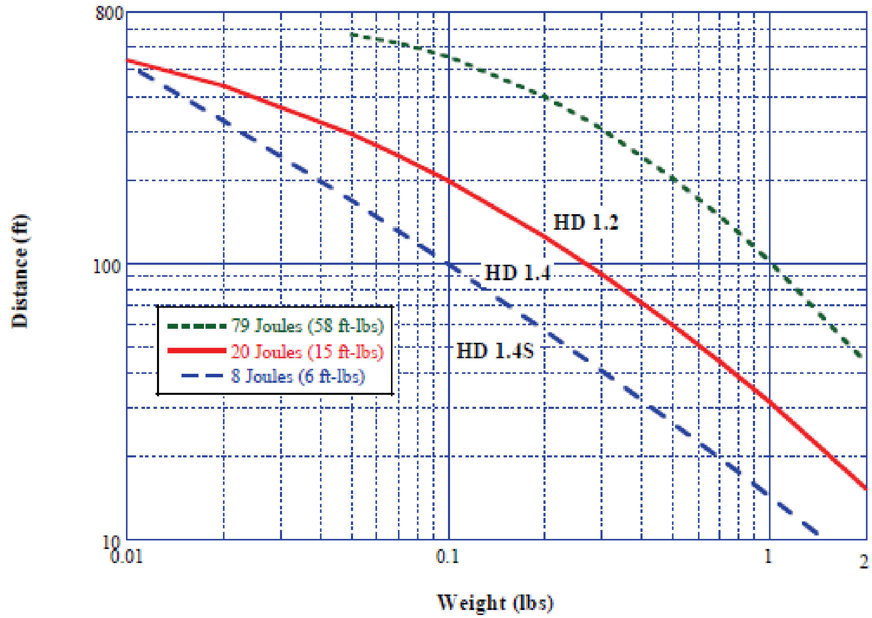
Where did our 20J & 79J curves come from?

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

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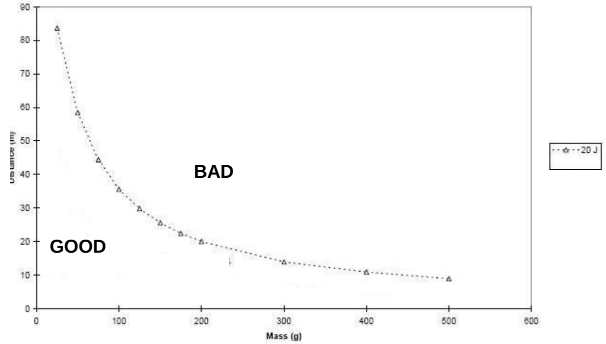
Current Metrics & Method

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



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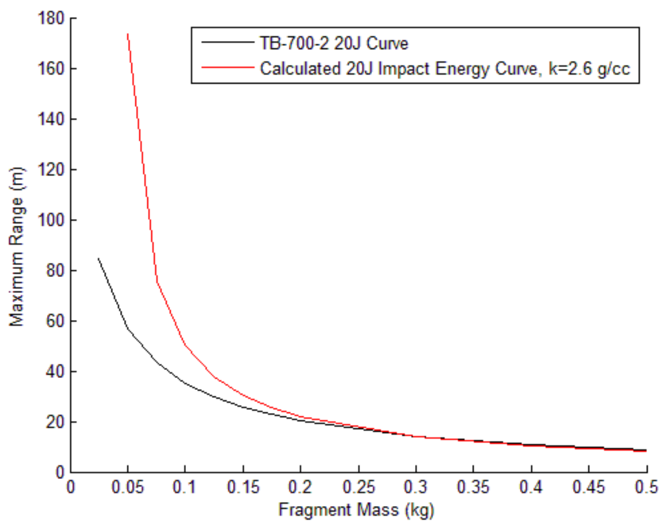
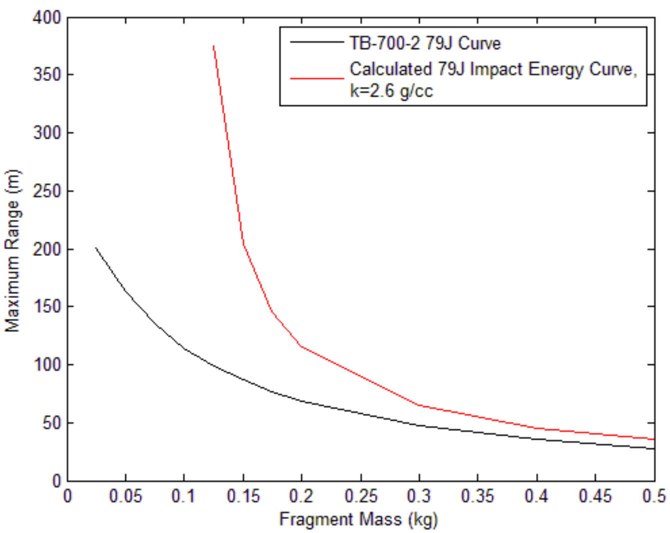
So what's the problem?

- **Problem #1:**
  - – **Current curve** we use was formulated with a **Launch Energy Criterion**
    - Works based on **calculating max distance given mass can travel when launched with 20J**.
    - AOP-39 guidance indicates we measure Impact Energy.

- **Solution #1:**
  - – We reformulated both curves (20J & 79 J) based on Impact Energy Criterion





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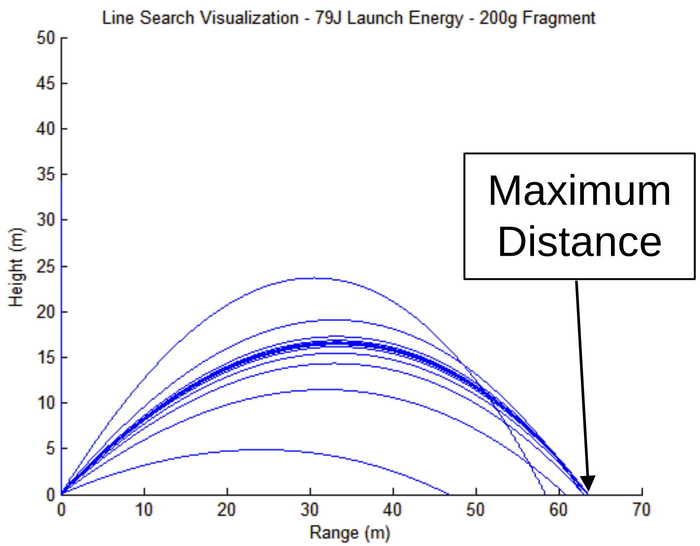
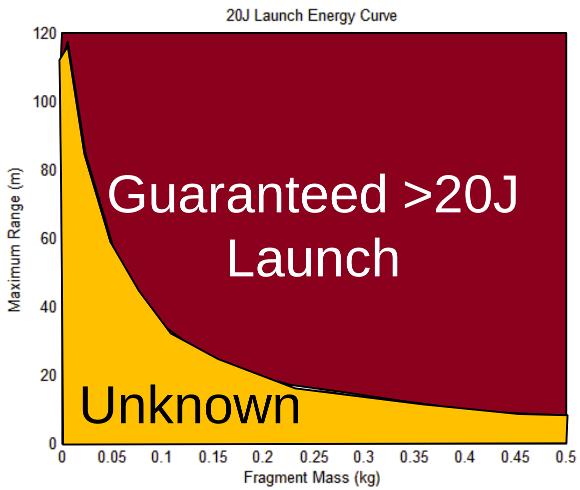
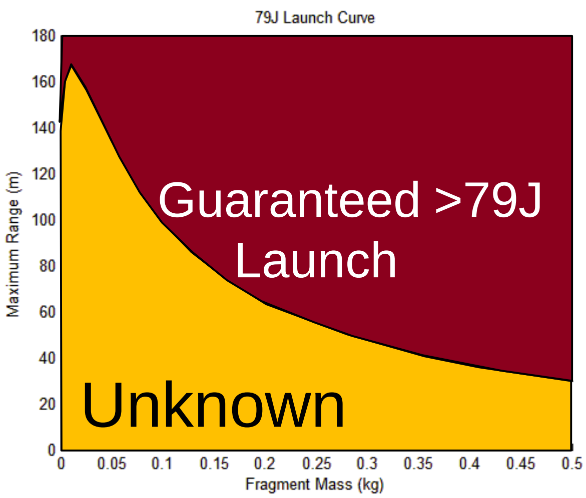
How does Launch Energy Criterion work?



- 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, having been launched 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
  - All curves calculated from starting height of zero. A starting height changes the curves!
  - Ricochet can be modeled (questionable accuracy)





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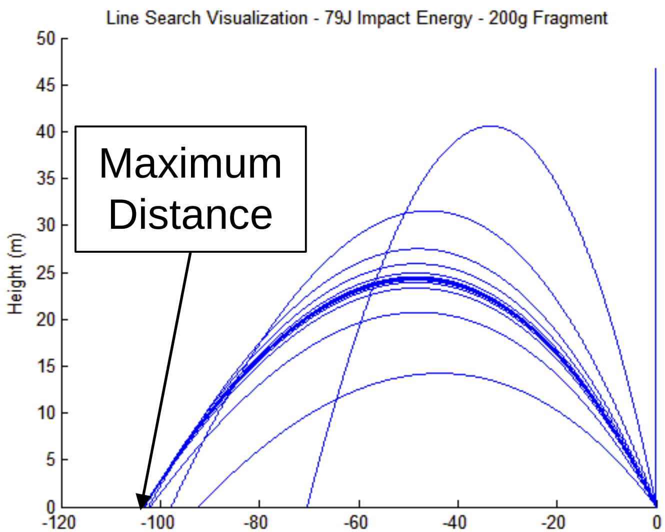
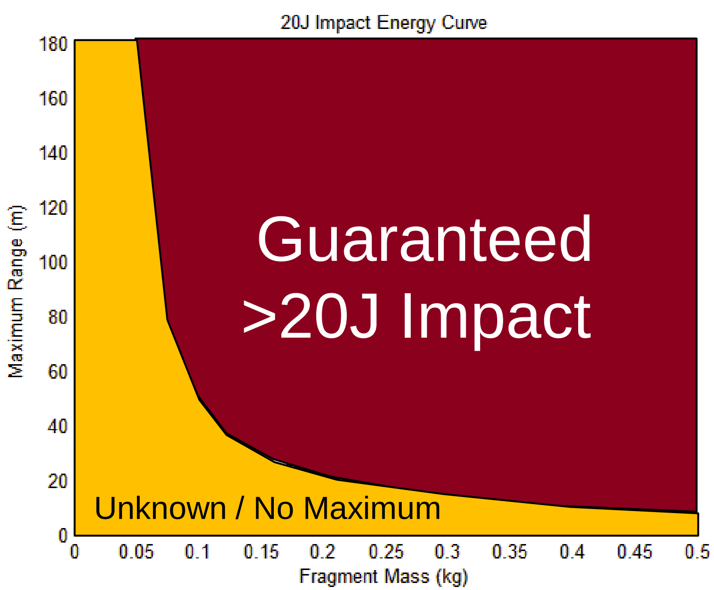
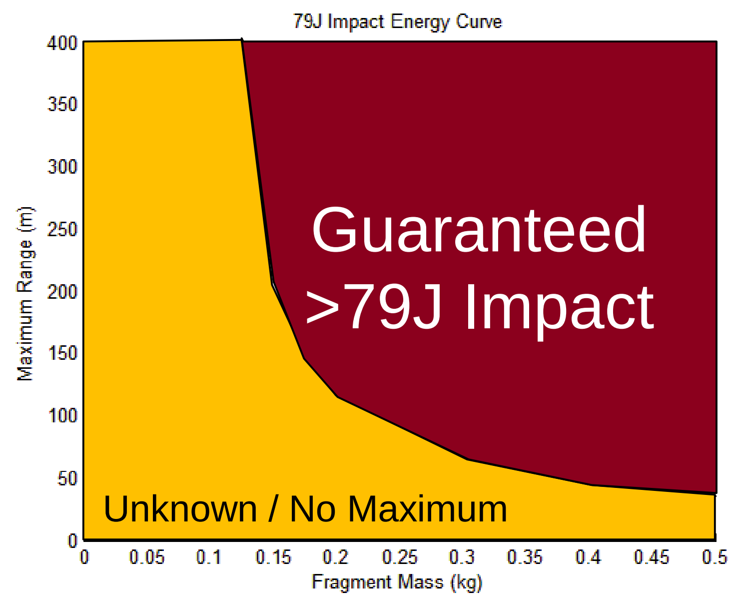
How does Impact Energy Criterion Work?



- Each point on the launch 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



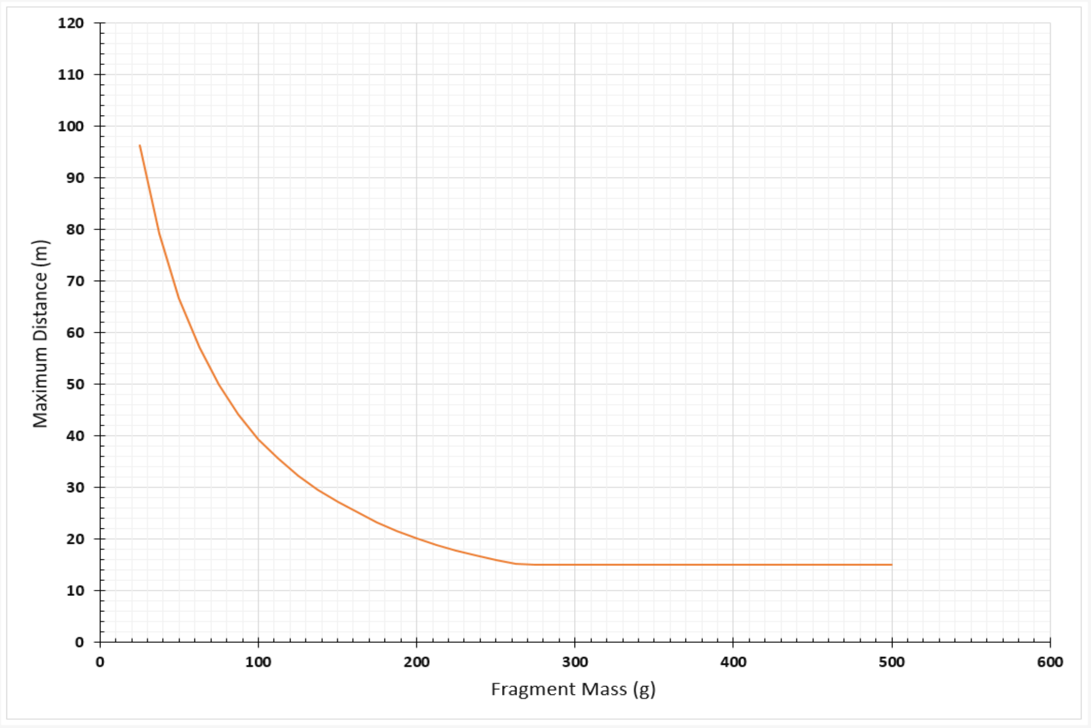


What else is wrong with the curve?

Problem #2:

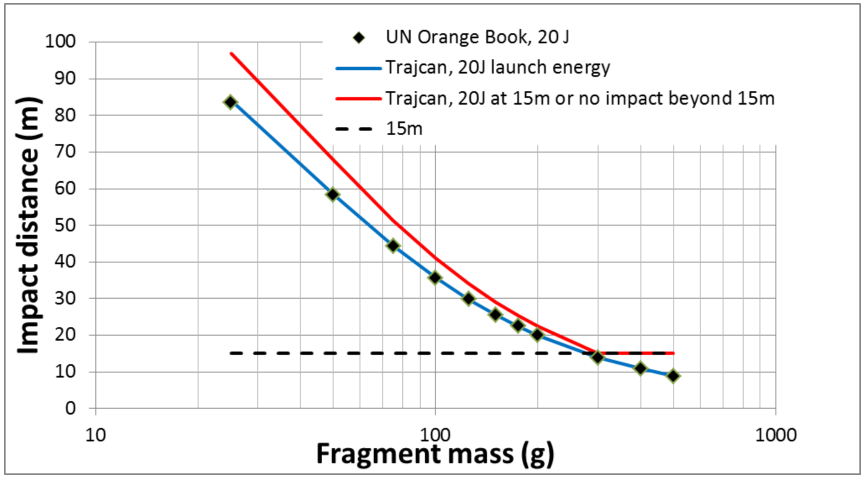
– **Current curve** doesn't take into account 15m.

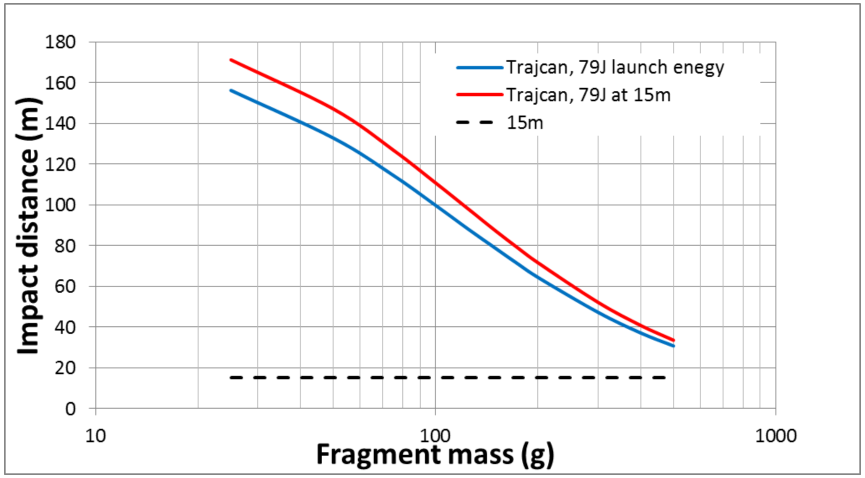
- **Solution #2:**
  – Incorporated 15m in 20J Impact Energy @ 15m curve.



TRAJCAN

- **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.*

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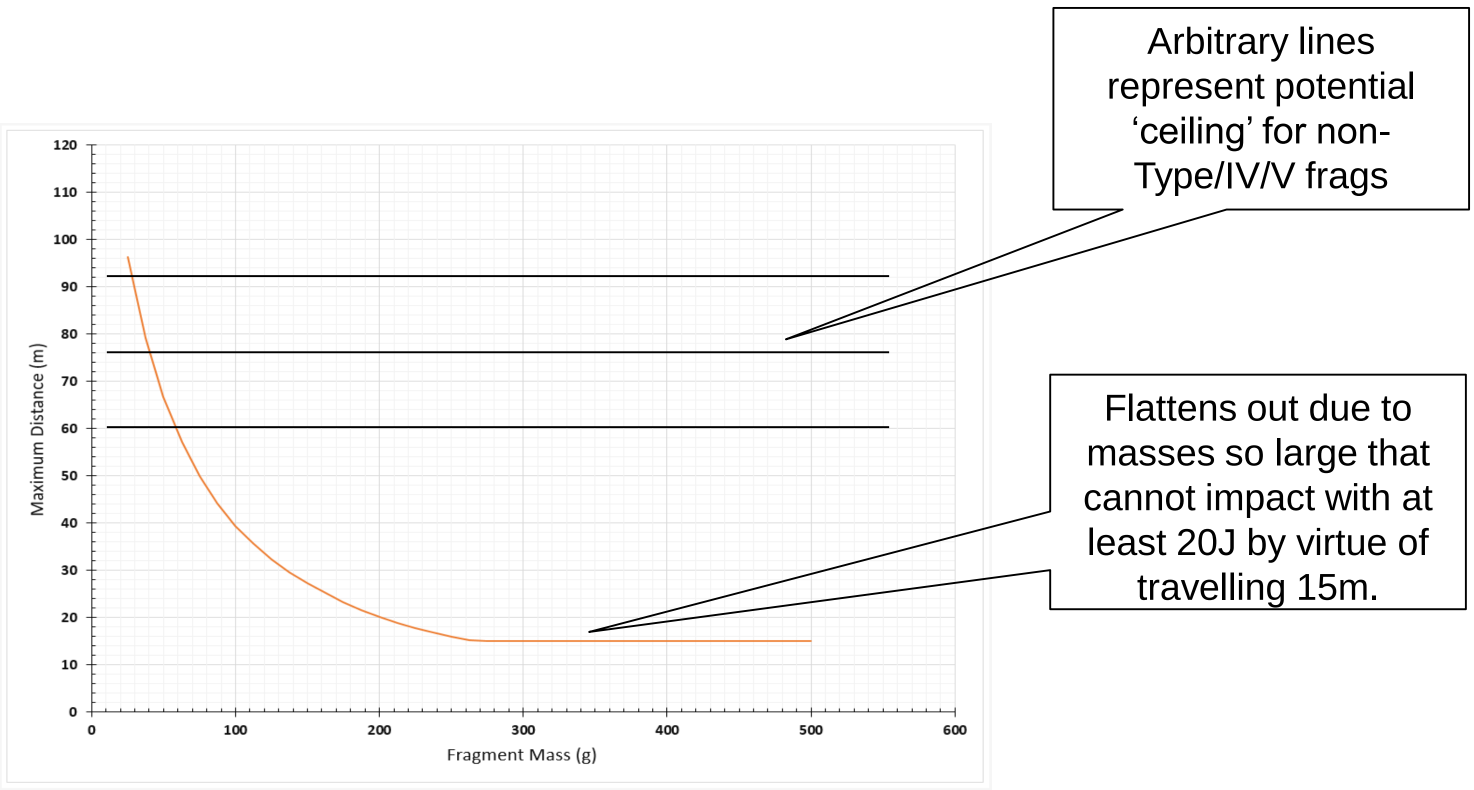
What else is wrong with the curve?

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



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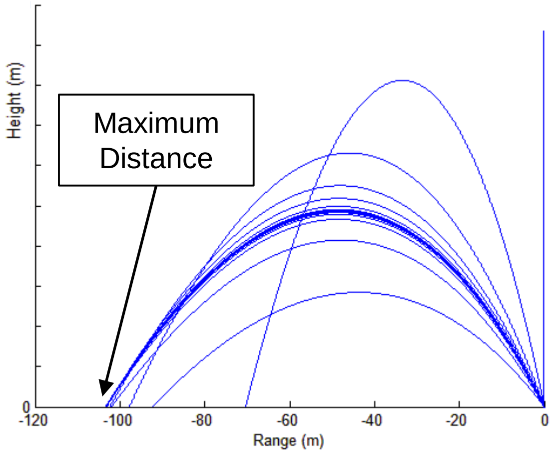
How Does Impact Energy @ 15m work?

Impact Energy @ 15m:

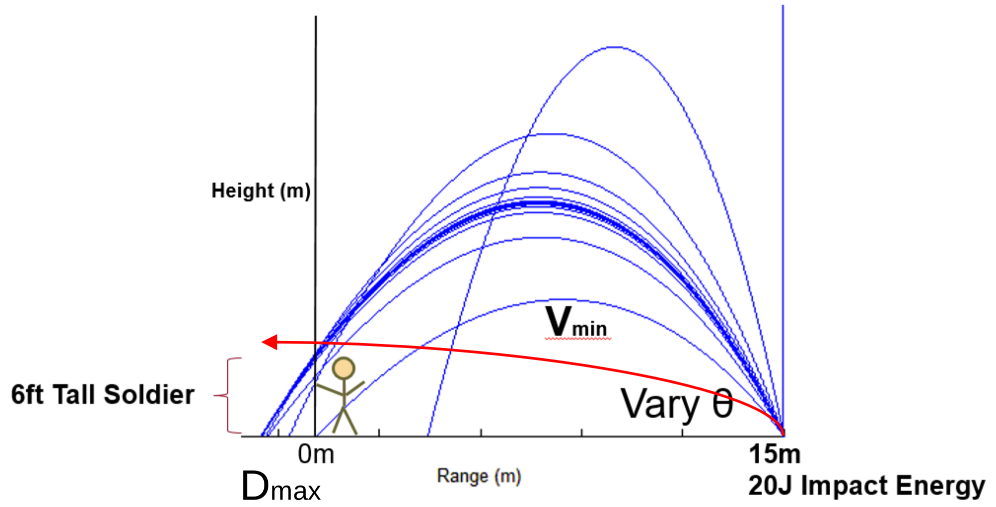
- Find V_{min} of 15m, 20J Impact
- Use V_{min}, Increase θ to find D_{max}
- Use D_{max} to find E_{max}

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

Impact Energy



Impact Energy @ 15m



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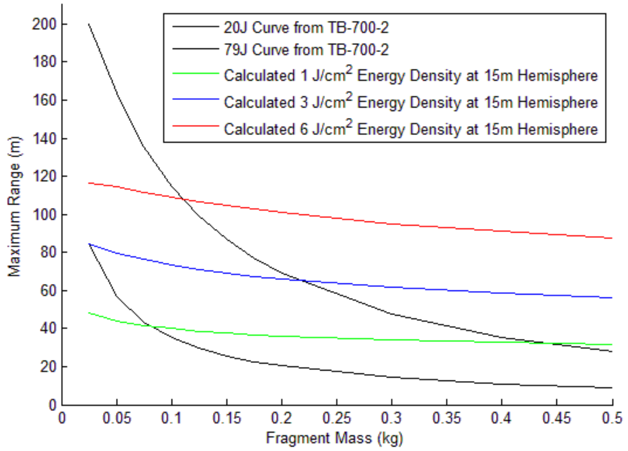
Does that resolve all issues?

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 area
- Example:
  - 32g, 2" diameter, object fired at 150fps produces 33.4J
  - 3.5g, 2" diameter, object fired at 230fps produces 8J
  - Both objects produce ~3.8J/cm^2
  - The key attribute is the presented area of the objects

Solution:

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



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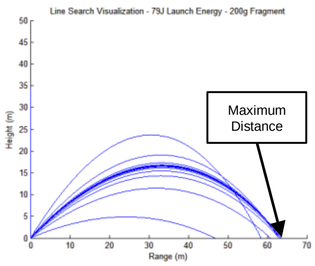
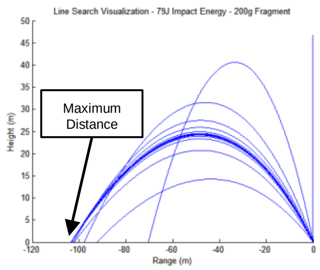
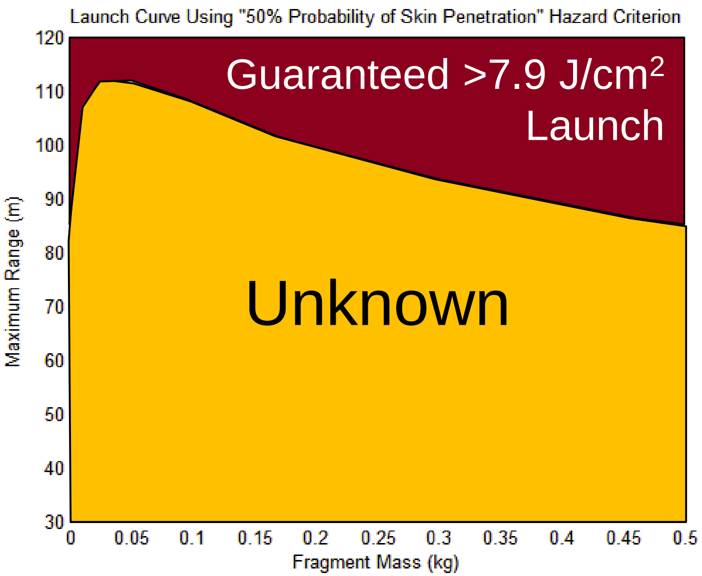
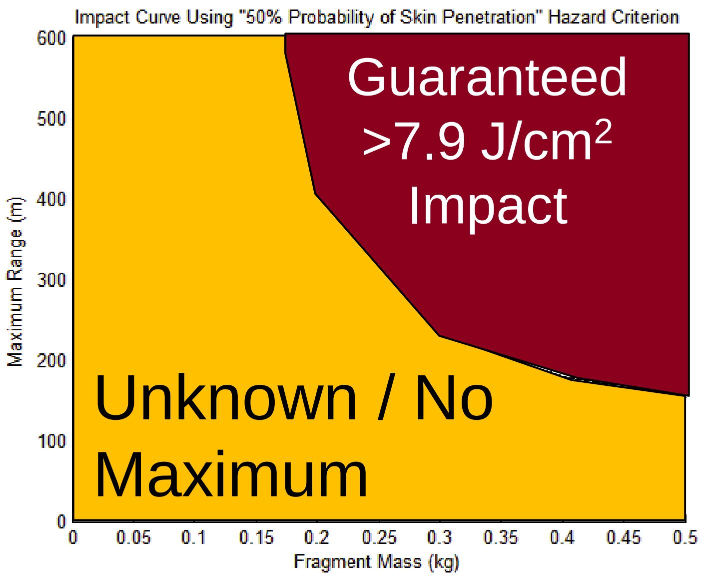
How does Energy Density Work?





- Energy Density can be used with either the:
  - Launch Energy Criterion or
  - Impact Energy Criterion
- Major difference is that mass is computed as a function of presented area:
  - mass=k*(presented area)^(3/2)
    - k=2600 kg/m^3
- The issue with using 7.9 J/cm^2, which is the 50% skin penetration model, distances are too large for IM purposes.





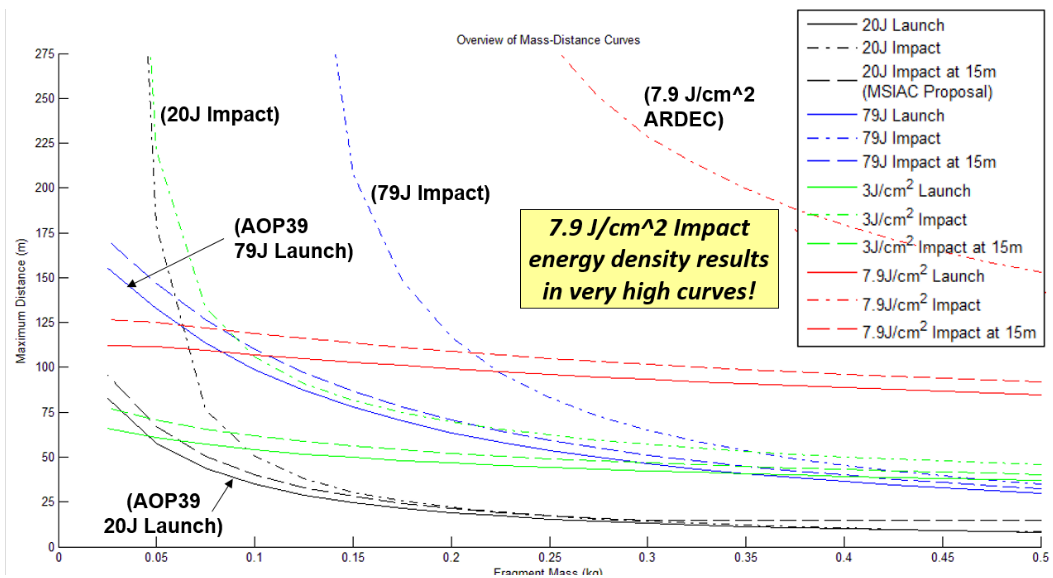
What is the solution?

Problem #4:

- What is an **acceptable metric for** using the **Energy Density Criterion**?
- What is an appropriate metric to use as threshold for hazardous fragment in the realm of IM Type IV/V fragments?

Solution #4:

- Lethality & safety experts suggest **7.9 J/cm^2** is more relevant to **penetration injury/impacts**.
- Literature research suggests **1.6 J/cm^2** appropriate for human injury based on **"Blunt Theory"**.



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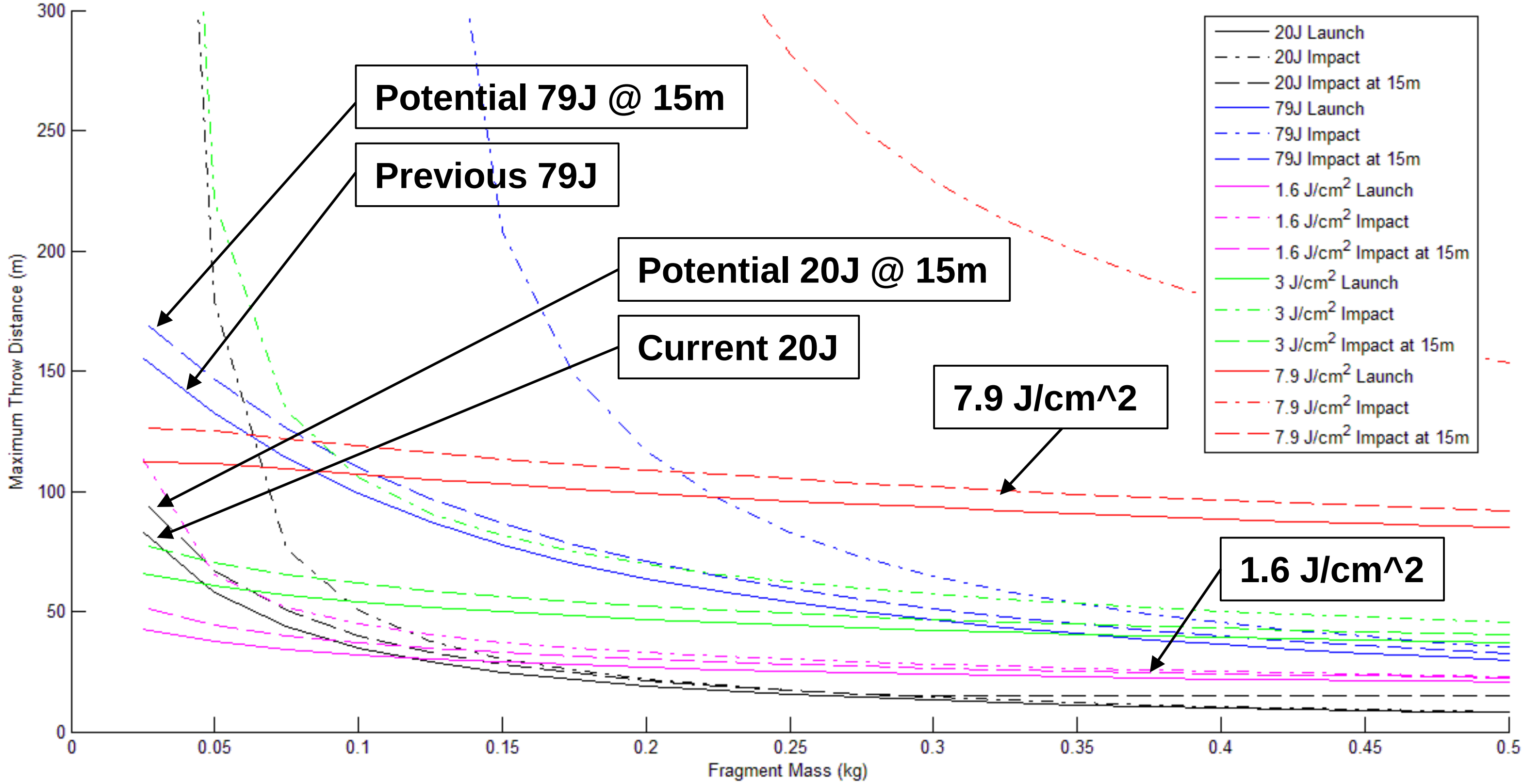
Comparison of Candidate Solutions



- Impact energy curves go off to infinity for small mass (terminal velocity)
- Impact energy at 15m curves are very close to launch energy curves

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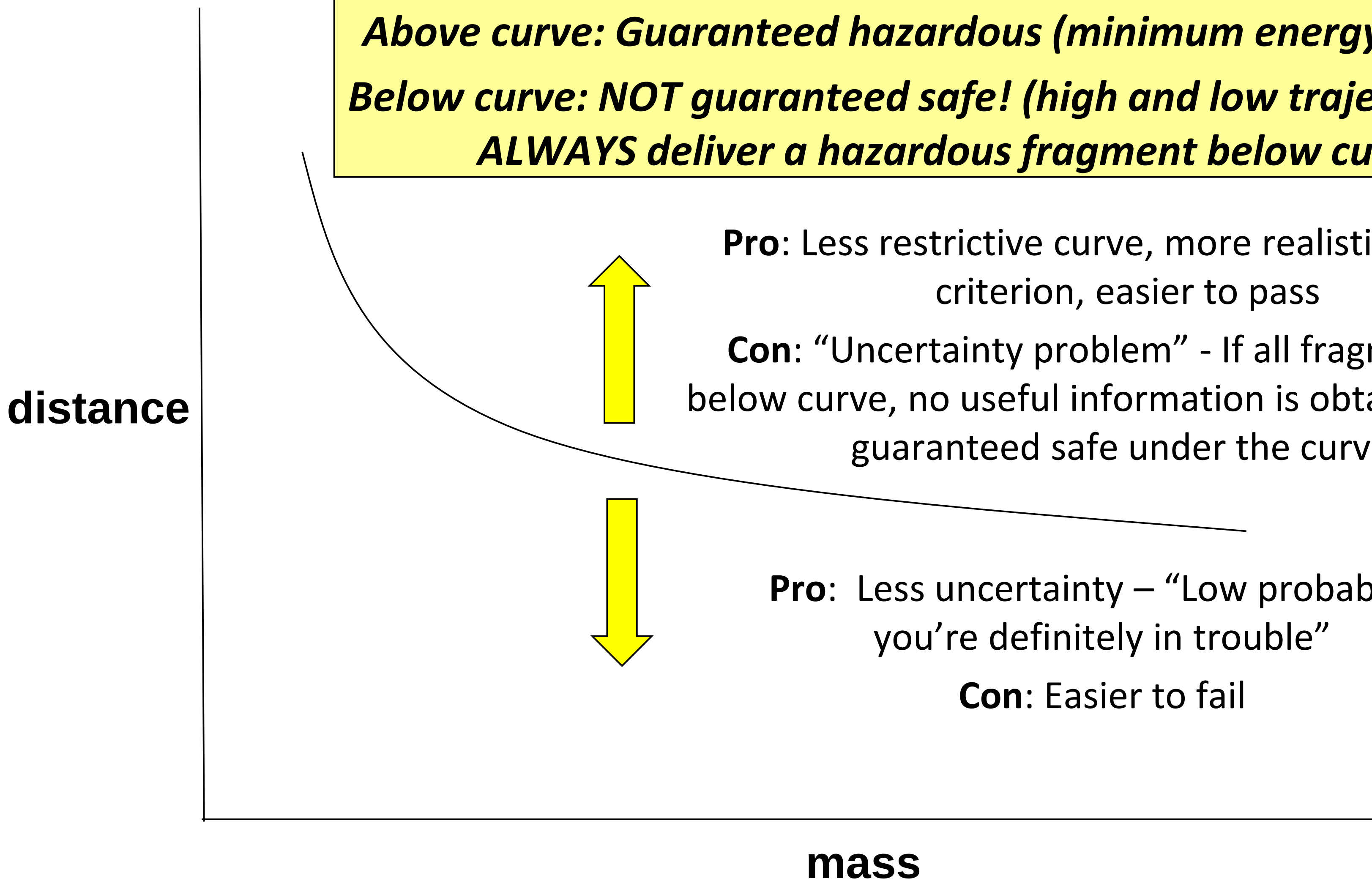
The Problem with Mass-Distance Curves

Curves represent a maximum throw distance

Above curve: Guaranteed hazardous (minimum energy to reach)

Below curve: NOT guaranteed safe! (high and low trajectories can ALWAYS deliver a hazardous fragment below curve)



Pro: Less restrictive curve, more realistic lethality criterion, easier to pass

Con: "Uncertainty problem" - If all fragments fall below curve, no useful information is obtained – NOT guaranteed safe under the curve!

Pro: Less uncertainty – "Low probability you're definitely in trouble"

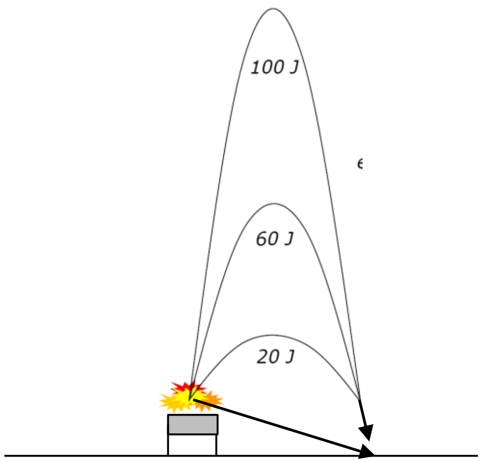
Con: Easier to fail

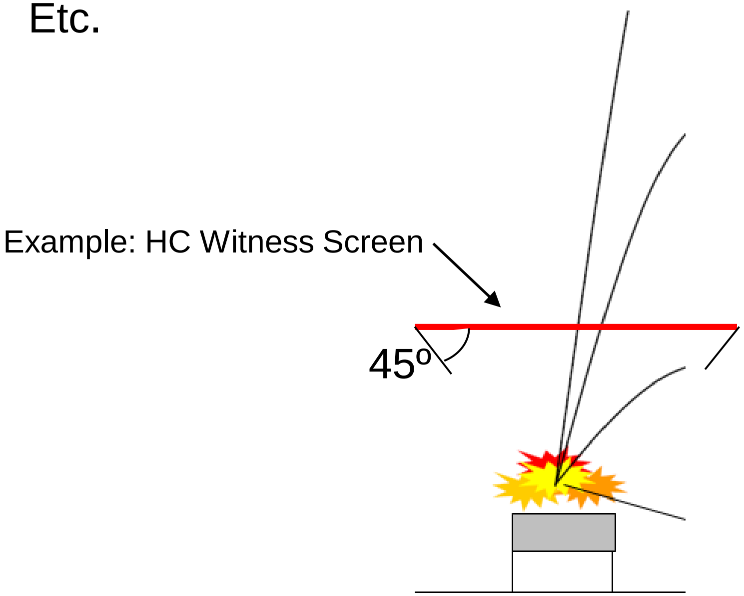
The Problem with Mass-Distance Curves

Risk: Frags under curve may have extremely high/low trajectories and may have travelled with high velocity/energy

Mitigation:

- Accept – We currently accept this risk
- Confirm trajectories utilizing equipment
  - HC witness screens
  - Cameras
  - Etc.





Portfolio of Curves

- Current curves assume chunky, tumbling, steel fragment
  - Not accurate evaluation for characteristic-unique fragments
    - Must consider other factors:
      - Density
      - Shape
      - Stability
      - Etc.

- Should be several curves to reference when evaluating unique fragment

- A set curves superimposed on one graph, each incorporating density, shape, and stability. User references specific curve for unique fragment.

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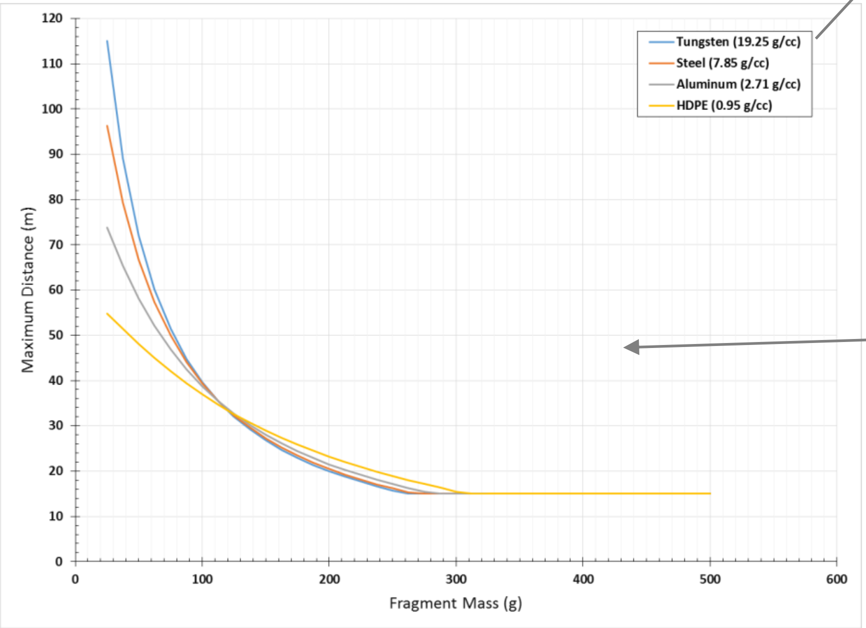
For example: Density

- For fragments of different density than steel, effect of drag can be taken into account using the previous methodology.
  - Can group into four categories:
    - ¾ density of steel
    - ½ density of steel
    - ¼ density of steel

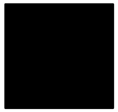
$$V = V_0 \exp\left(-\frac{\rho_{air} S C_D}{2m} x\right) = \sqrt{\frac{2E_0}{m}} \exp\left(-\frac{\rho_{air} \frac{3}{2}\left(\frac{m}{\rho_{frag}}\right)^{2/3} C_D}{2m} x\right)$$



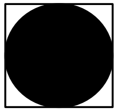
*Curves provided to NATO IM Wokring Group for inclusion into revised AOP-39

Future Work – Surface Area Meas.

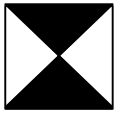
- **Energy Density Methodology**
  - *Impacting Surface Area of Fragment* must be accurately measured/assumed
  - Not easy for asymmetric fragments
  - Several methods proposed:
    - Automated 3-D optical measurement device – icosahedron
    - Generic fractional volume categories (frag-in-a-box)
      - <u>Cubical fragment</u>
        - » Cube occupies 4/4 of a cube's volume



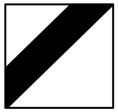
      - <u>Convex fragment</u>
        - » Sphere ~3/4 of the cube's volume



      - <u>Concave fragment</u>
        - » Hour glass ~2/4 of the cube's volume.



      - <u>Length/Diameter</u>
        - » Long, thin rod/strip ~1/4 of the cube's volume.



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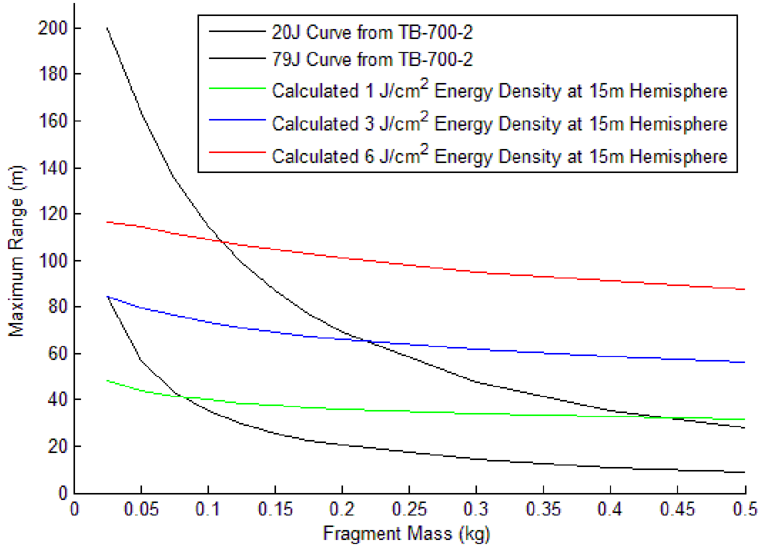
Future Work – Metrics

- **Technically identify and justify Energy Density Methodology**
  - Leverage with SMEs
    - ARDEC
      - Aero ballisticians
      - Lethality Division
      - Non-Lethality Division
      - System Effectiveness
      - Biomedical Engineering
    - TBRL
    - ARL
      - SLAAD



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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
- 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
- NATO Response Descriptor Working Group (RDWG) Decision

Questions?

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Back-up Slides

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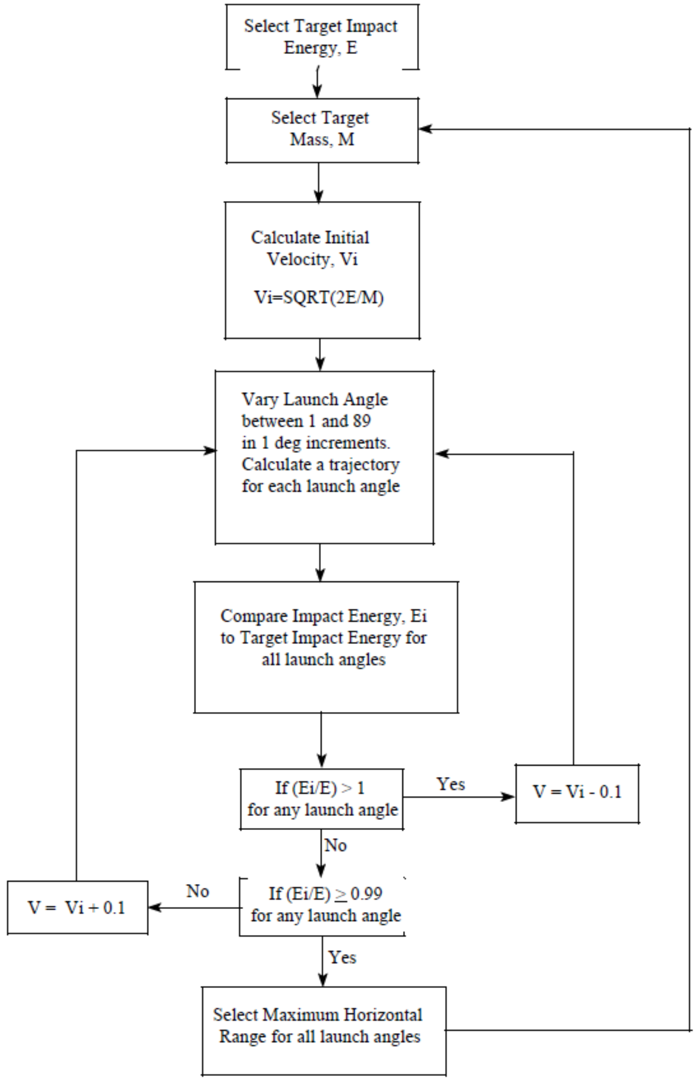
Status of Current Response Descriptors

- 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

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Ballistic Trajectory Modeling – Background

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

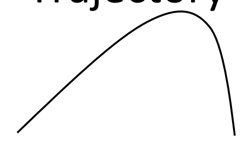
In Design Considerations for Toxic Chemical and Explosives Facilities; Scott, Ralph A., et al.; ACS Symposium Series; American Chemical Society: Washington, DC, 1987.

(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

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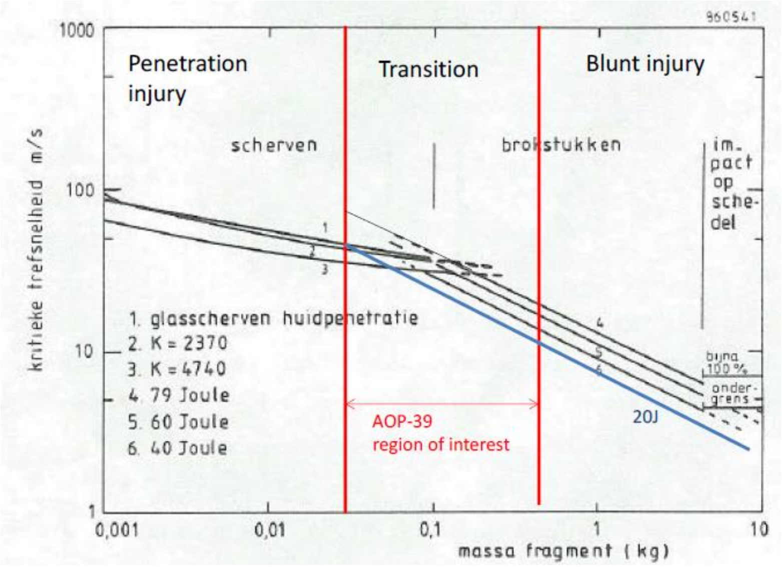
Skin Penetration vs. Blunt Trauma

- 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**"

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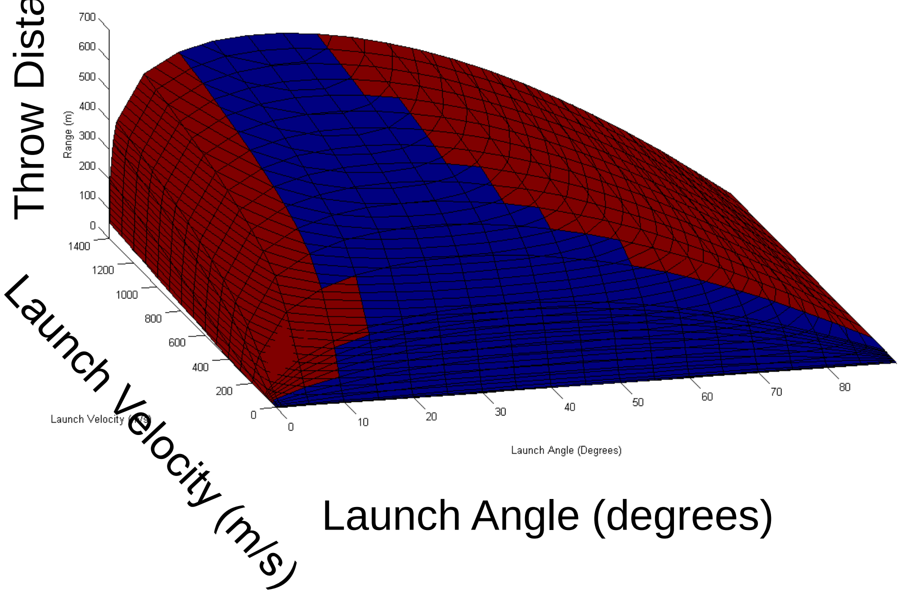
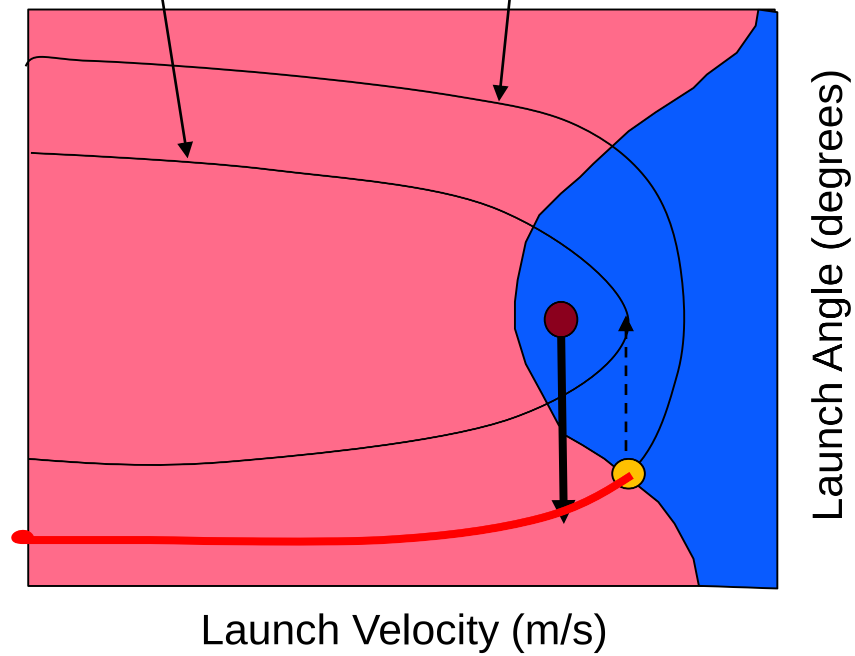
Impact Energy at 15m (MSIAC Proposal) (Cont'd)

Red = hazardous impacts
Blue = nonhazardous impacts
(Charts apply to a given mass)



Range > 15m contour (point on the mass-distance curve)

Range=15m contour



- Minimum velocity for hazardous impact at 15m
- Fragment found above MSIAC proposed curve
- Hazardous Impacts
- Non-Hazardous Impacts

Fragments which land above MSIAC curve are guaranteed to hit 15m with a hazardous fragment if the launch angle were lowered

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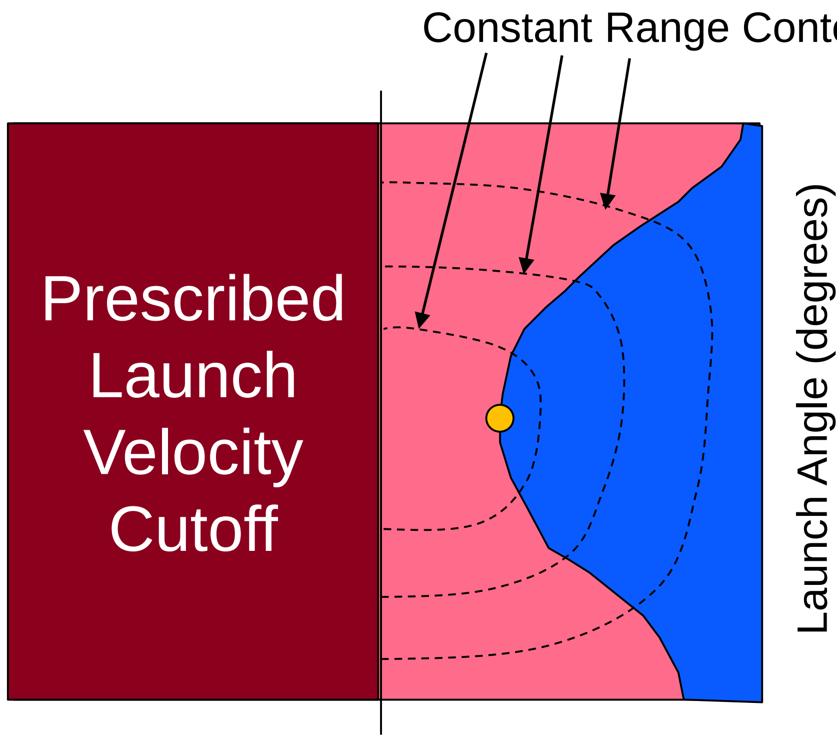
Uncertainty Reduction Strategies - Probability Methodology

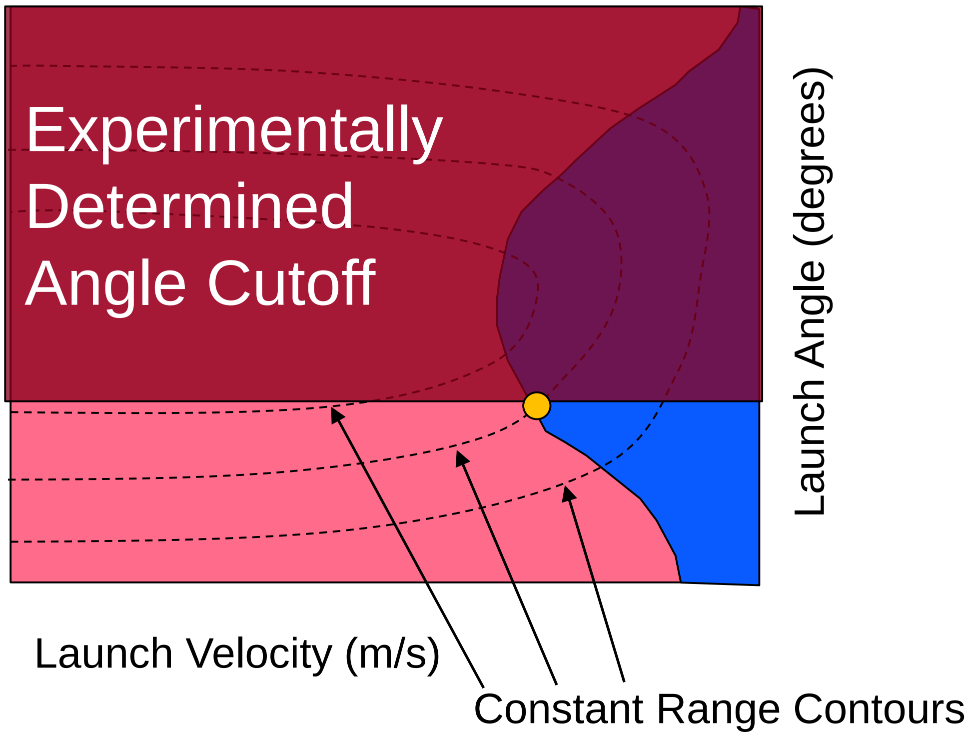


Fragments just under the curve have a (quantifiable) higher probability of being hazardous than fragments further below the curve

- Point used for impact mass-distance curve
- Impacts Not Considered
- Hazardous Impacts
- Non-Hazardous Impacts

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

Uncertainty Reduction Strategies - Angle Cutoffs (Experimental)



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)

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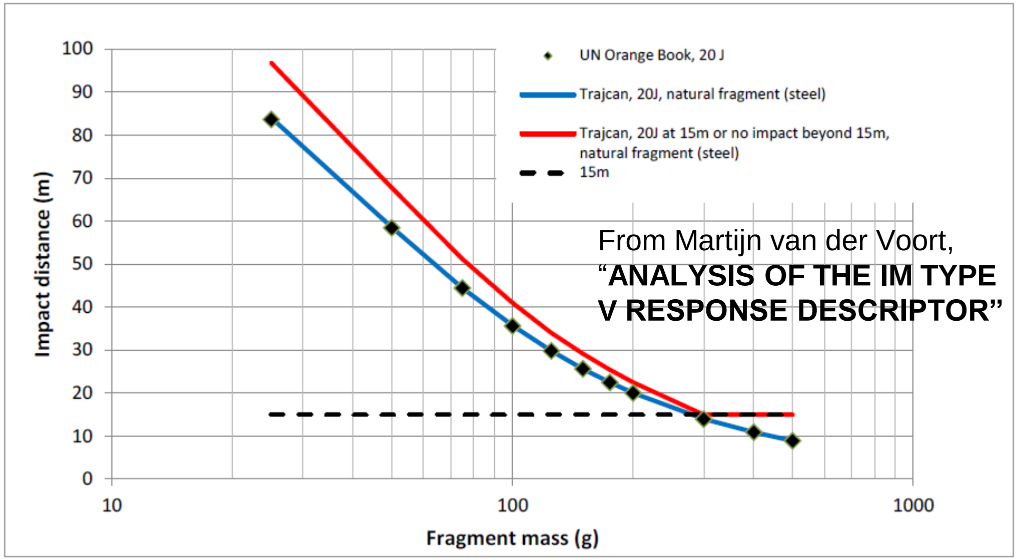
Impact Energy at 15m (MSIAC Proposal) (Cont'd)

- 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**



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

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