Updated Blast Effects and Consequences Models in DDESB TP-14 Revision 5

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Introduction

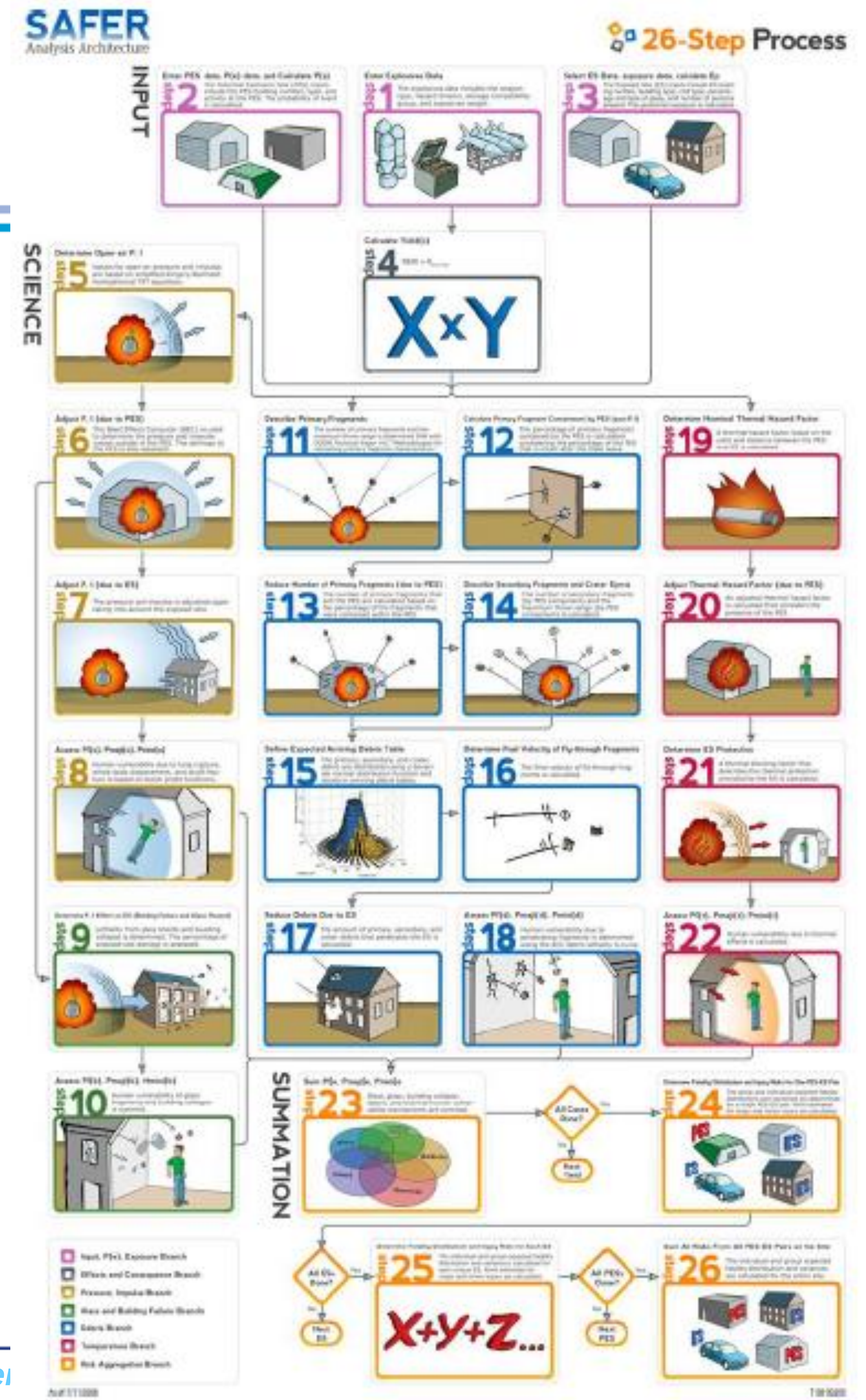
- The U.S. Department of Defense Explosives Safety Board (DDESB) has established an approved quantitative risk assessment methodology (QRA) for evaluating and accepting risks associated with explosives storage and activities
  - Equivalent alternative to Quantity-Distance (QD) siting
  - Approved QRA model defined in DDESB Technical Paper (TP) 14
- This brief provides details of the explosion effects and consequence algorithms of TP 14, focusing on recent updates to the methodology

What is DDESB Technical Paper 14?

- DDESB TP 14 presents the underlying logic and algorithms used in the DDESB approved QRA methodology for risk-based explosives safety siting
  - –Method is implemented in the approved QRA tool SAFER v3.1
  - –Current approved version is Revision 4, but a draft Revision 5 has been developed and improvements shall be briefed herein
  - –In future years, the DDESB-approved QRA tool will be the Risk Based Explosives Safety Siting (RBESS) tool within the DDESB's Automated Site Planning software ESS
- Within the context of TP 14, risk is defined as follows:
  - –*Risk = Likelihood * Consequence * Exposure*
  - –$Risk = P_f = P_e * P_{f|e} * E_p$
- This presentation shall focus on the $P_{f|e}$ term of the equation, which can also be termed as "*the probability of fatality given the event occurs and a person is present*"

TP 14 Architecture

- TP 14 employs a 26-step process
  - –The first step is to admit that you have a QD violation…
- The architecture is defined by a logical flow that starts at the scenario input, accounts for all of the potential harmful effects generated by an explosion, and quantifies both the individual and group risk
- The individual Steps are bunched into a series of six Groups
- Focus of this brief is the "Science" Groups, 2 through 5

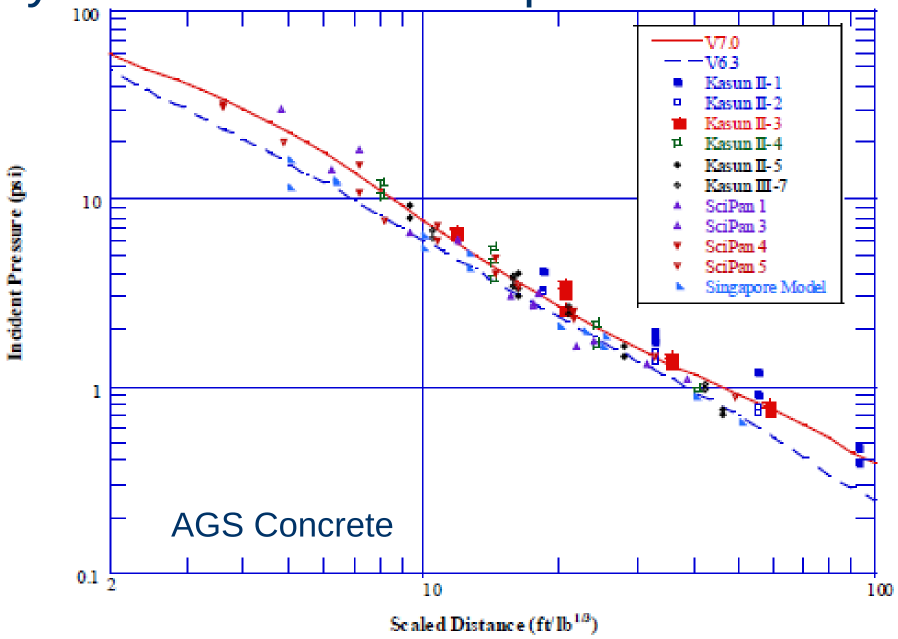


TP-14 Revision 5 Update

- Since the publication of TP-14 Revision 4 in 2009, there have been numerous updates to blast effects modeling
  - Improved numerical simulation techniques
  - Multiple explosives safety tests conducted
- Many of these improvements have been incorporated into TP-14 Revision 5, with the more critical ones being:
  - Window response and glass injury/fatality models
  - Secondary debris mass distribution
  - Explosion produced debris effects
  - Explosion produced debris consequences
- This briefing details the Revision 5 methodology, including many of these algorithm enhancements

Group 2 Steps: Pressure & Impulse Branch

- The Group 2 steps calculate the pressure and impulse acting upon exposed persons and the resulting consequences from these primary blast effects
- Blast wave parameters at a given distance are baselined as a function of Kingery-Bulmash TNT based equations, but then require modification to account for the different explosive material, casing effects, and attenuation provided by the structure the explosive event occurs
- Blast wave prediction methodology of DDESB TP-17 Revision 3 is implemented in TP-14 Revision 5

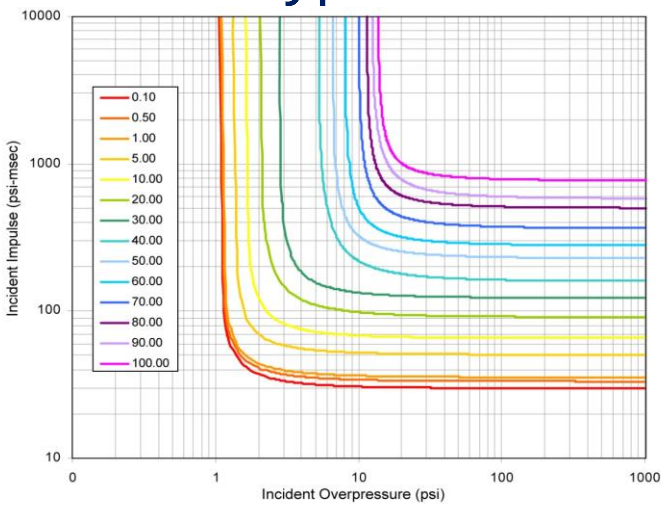


Group 2: Direct Blast Effects

- Pressure and impulse calculated at distance of exposed site (ES)
  - –If person in the open blast effects are directly applied to calculate consequences
  - –For persons in buildings, attenuation by structure is calculated
- Leakage pressure into building calculated using methodologies prescribed in UFC 3-340-02, "Structures to Resist the Effects of Accidental Explosions"
- Injury and fatality mechanisms due to direct blast are then calculate for each system vulnerability
  - –Fatality: lung rupture, whole body displacement, & skull fracture
  - –Major & Minor Injury: soft tissue damage, whole body displacement, & skull fracture
    - Soft Tissue Damage: lung, gastrointestinal tract, larynx, ear drum rupture

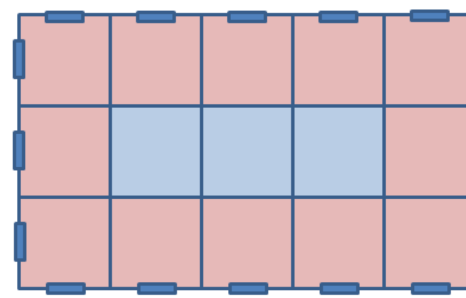
Group 3 Steps: Structural Response Branch

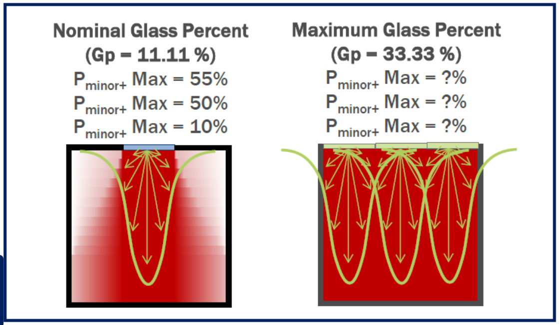
- Pressure-Impulse (PI) diagrams are used to quantify building damage
- Composite PI diagrams were developed for each of the 21 ES structure types by analyzing component response and then averaging over the entire structure
- Damage is then equated to injury and fatality as a function of ES type



Group 3: Window Hazard Models

- Determination of hazards from windows is a multi-step process
  - –Determine pressure and impulse from Group 2 steps
  - –Calculated breakage probability as a function of window type (annealed, tempered, dual pane, & laminated annealed)
  - –Determination of internal hazard area
  - –Scale from nominal glass hazard (11.11%)
- Additional factors such as emergency response and presence of curtains are considered, as well as multi-hit effects that can elevate the consequence





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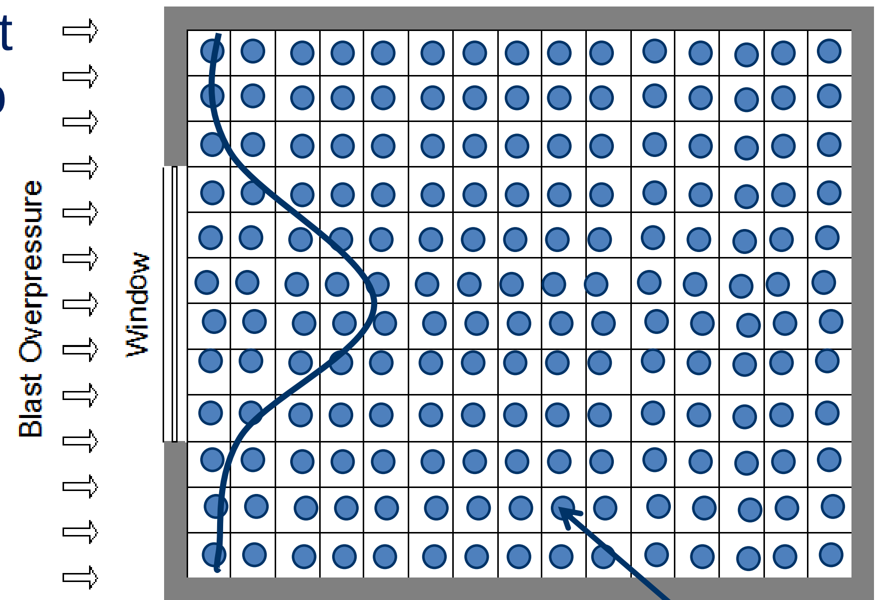
Group 3: Window Model Background

- Window models are an engineering fit to the physics-based analysis used to develop them
- Statistical distribution of glazing properties set and breakage probabilities established
- Shard mass distribution and velocity profile at breakage determined *
- Shard flight and impact location on target calculated
- Based on impact area (e.g., artery, eye, head, etc.), probability of minor injury, major injury, and fatality established

*Laminated windows treated as blunt force trauma



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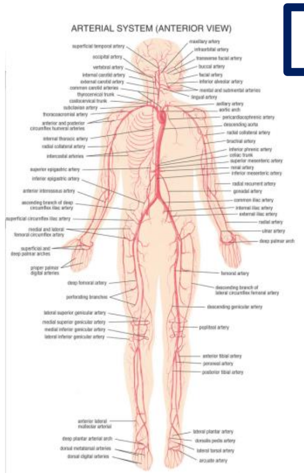
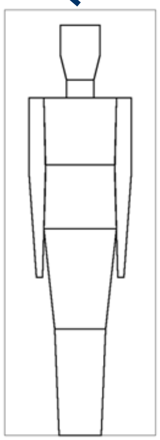


Standing Human Element



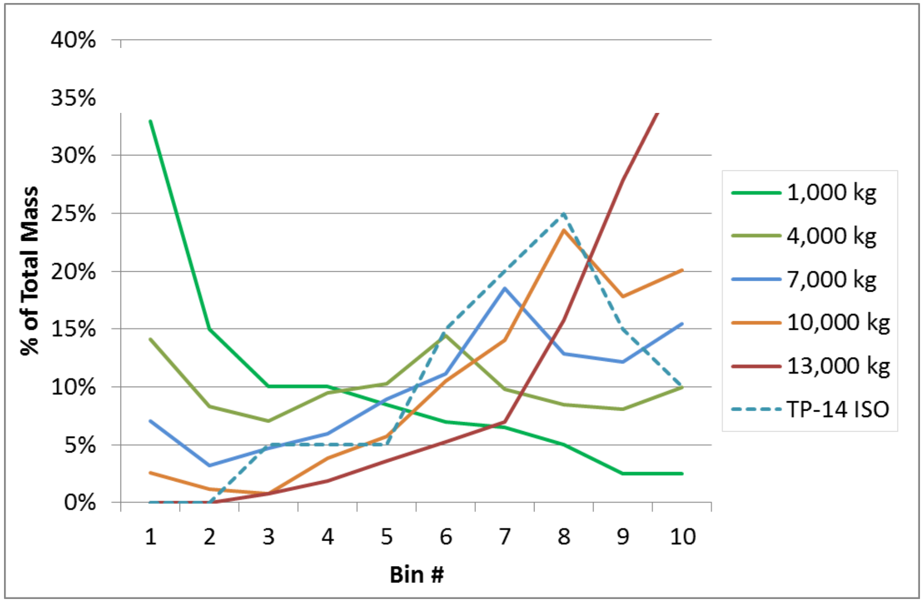
Group 4 Steps: Debris Branch

- End goal of quantification of debris effects is to discretize arriving debris into one of 10 kinetic energy (KE) bins
  - –Injury and fatality from debris is defined as a function of KE
- Essential first step is to discretize all primary and secondary mass into one of ten mass bins

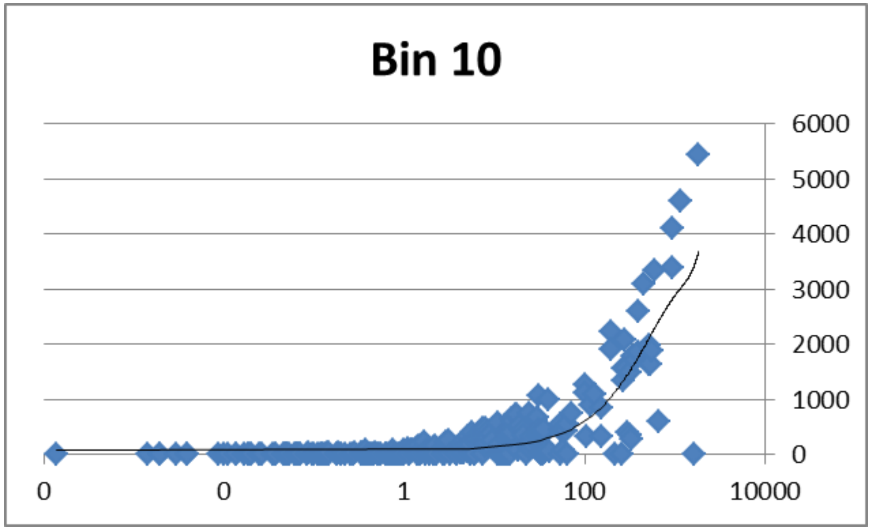
Bin #	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
KE Min (ft-lb)	100k	30k	10k	3k	1k	300	100	30	10	3
KE Average (ft-lb)	173k	54k	17k	5k	1.7k	547	173	54	17	5
KE Max (ft-lb)	≥ 300k	100k	30k	10k	3k	1k	300	100	30	10
Fragment Upper Limit Mass (steel) (lb)	57.7	25.3	10.3	4.50	1.83	0.801	0.325	0.142	0.0577	0.0253
Average Fragment Mass (steel) (lb)	35.7	14.9	6.34	2.66	1.13	0.473	0.199	0.0852	0.0379	0.0142
Fragment Lower Limit Mass (steel) (lb)	25.3	10.3	4.50	1.83	0.801	0.325	0.142	0.0577	0.0253	0
Average Fragment Mass (concrete) (lb)	75.4	31.5	13.4	5.61	2.38	1	0.42	0.18	0.08	0.03
Fragment Upper Limit Mass (aluminum) (lb)	98.9	43.4	17.6	7.72	3.13	1.37	0.556	0.244	0.0989	0.0434
Average Fragment Mass (aluminum) (lb)	65.3	27.3	11.5	4.58	2.04	0.872	0.368	0.154	0.0647	0.0258
Fragment Lower Limit Mass (aluminum) (lb)	43.4	17.6	7.72	3.13	1.37	0.556	0.244	0.0989	0.0434	0

Group 4: Mass Distribution

- The primary fragment (munition casing) mass distribution has been developed from generic munition types; is a function of size of the item
- Improvements in secondary debris (donor structure) mass distribution has been greatly aided by vast test data generated over the past decade
- Mass distribution is dynamic, in that it is a function of explosive weight
  - Higher explosive weight ➔ larger number of smaller pieces

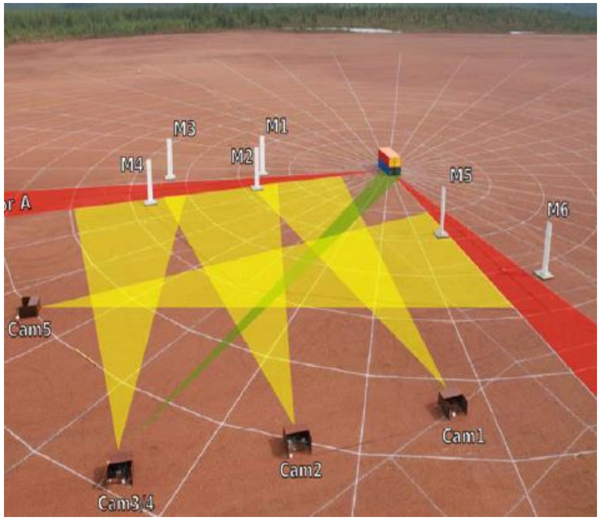


Generic Munition Item

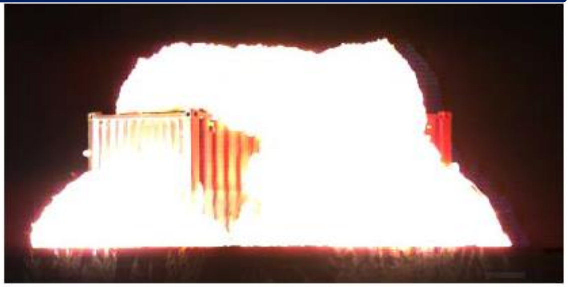


Group 4: Initial Velocity

- Initial velocity for secondary debris is defined as a function of loading density for each PES type
  - –Initial velocity increases with loading density
- Primarily use DLV formula with adjustments in TP-14 Rev 5
- Velocity functions developed via numerical simulation and analysis of test data



Klotz Group ISO container tests



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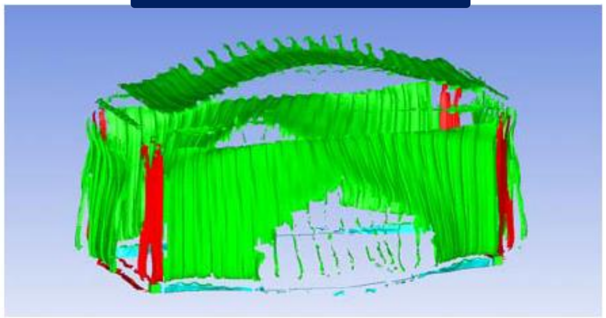

Group 4: Improved PDF Methods

- The approach is to perform drag-corrected trajectory simulations based on the TP14 fragment mass bin definitions
  - –Each simulation involves many trials; each trial varies key fragment parameters
  - –After each trial, the wall and roof impacts on an ES at various downrange distances are recorded
- After a simulation, the wall/roof trial impacts are used to develop FRMs as a function of distance:
  - –Probability of wall impact per lineal foot & mean KE
  - –Probability of roof impact per lineal foot & mean KE

Bin #	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
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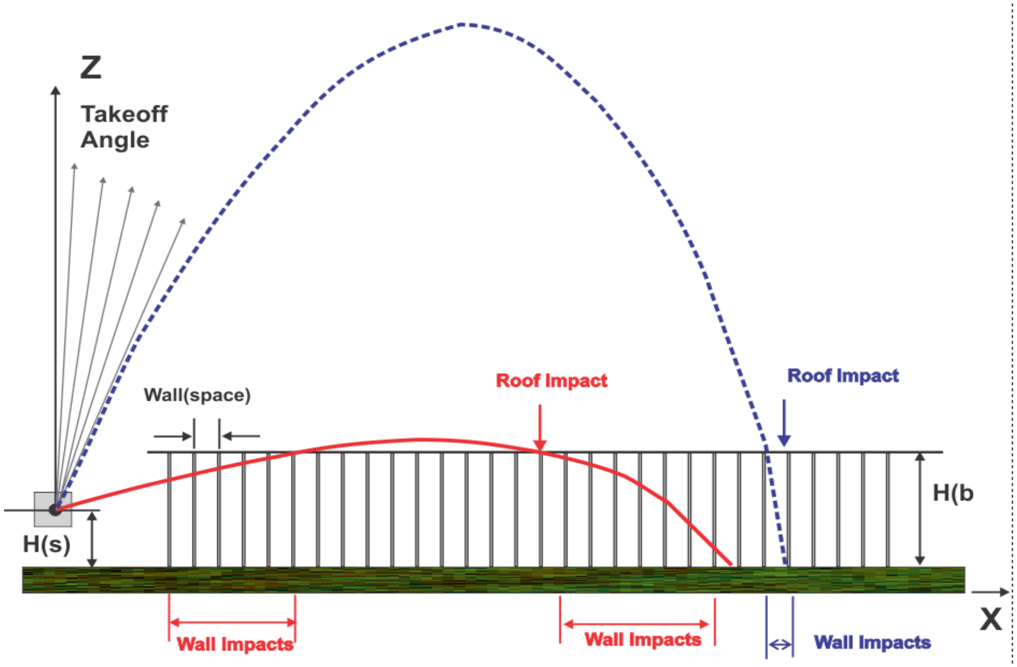

Group 4: Sample Problem – Concrete Building

- Potential Explosion Site (PES) = concrete building; wall & roof fragments
- Constant fragment parameters
  - Considered 10 average values defined by TP14 "concrete" mass bins
  - Takeoff Velocities ➔100 – 3,000 ft/sec
- Random parameters
  - Fragment shape = box with aspect ratio ranging from 1 to 2 (between its 3 sides)
  - Drag Coefficient = based on tumbling box as a function of velocity
- Wall-Specific Parameters
  - Fixed Takeoff Height = 7.5 feet
  - Takeoff angle distribution = normal
    - Mean = +5 deg (upwards)
    - Standard Dev = 6 deg
  - Number of Monte Carlos = 5,000
- Roof-Specific Parameters
  - Fixed Takeoff Height = 15 feet
  - Takeoff angle distribution = normal
    - Mean = 90 deg (upwards)
    - Standard Dev = 6 deg
  - Number of Monte Carlos = 20,000

Table 13. SAFER KE/Mass Bin Format

Bin #	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
KE Min (ft-lbs)	100k	30k	10k	3k	1k	300	100	30	10	3
KE Average (ft-lbs)	173k	54k	17k	5k	1.7k	547	173	54	17	5
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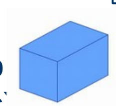

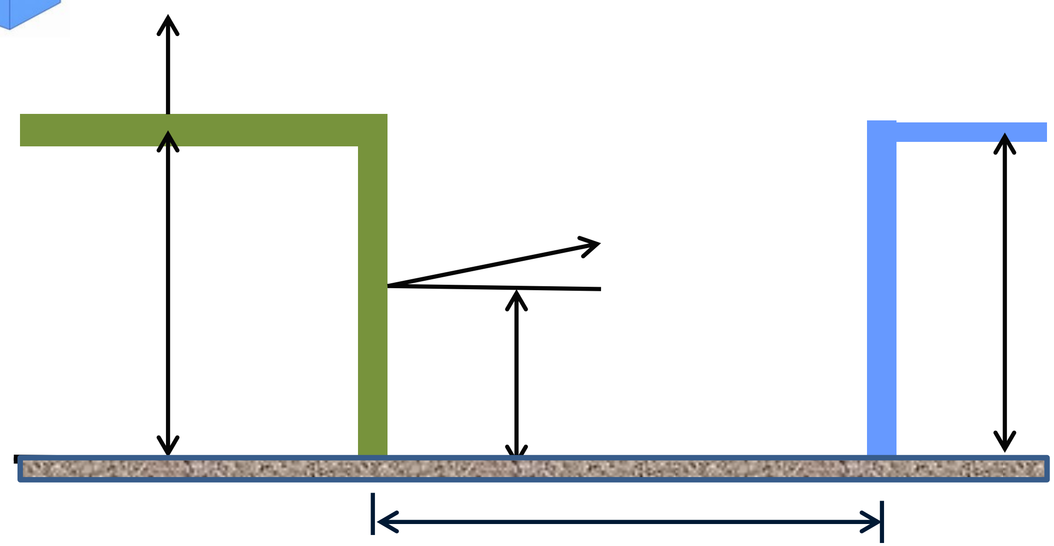

- ES-Specific Parameters
  - ES Height = 15 ft
  - PES to ES distance (X) = variable

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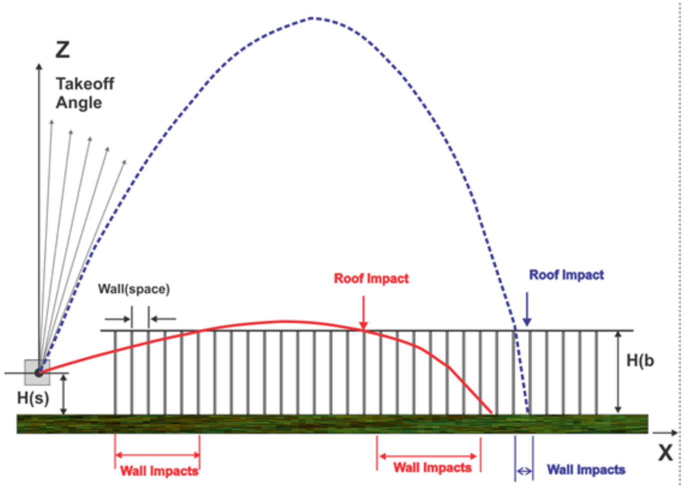
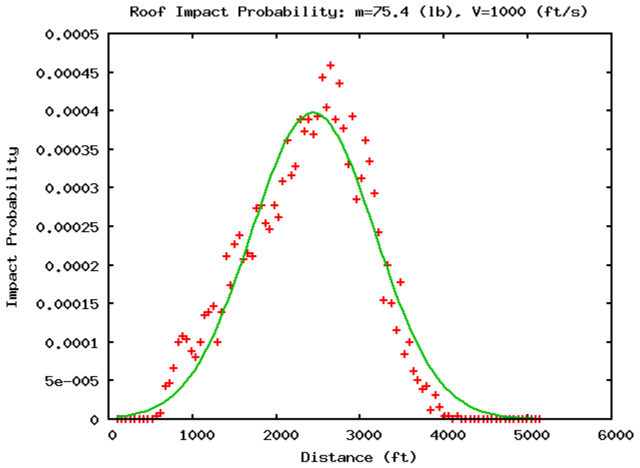
Group 4: PDF Technical Approach

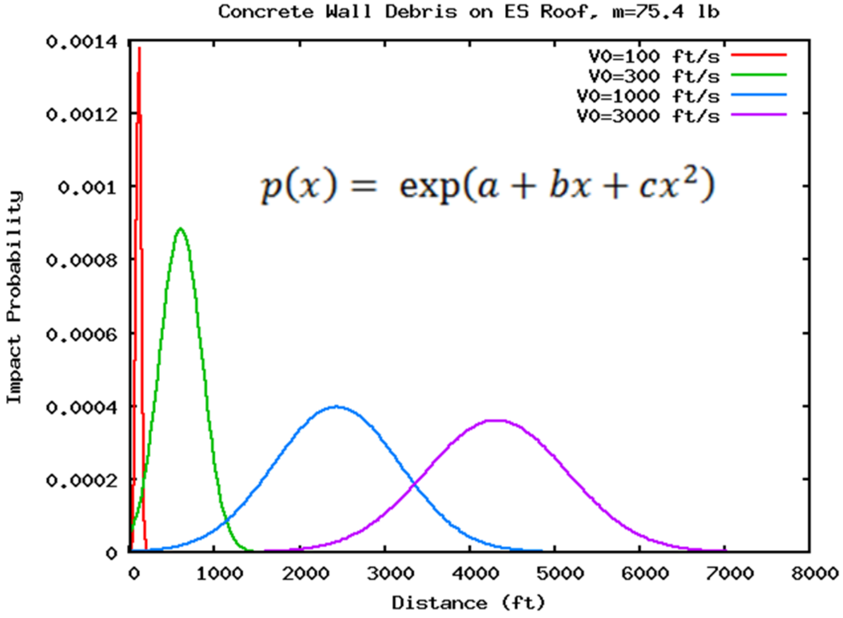
- Fast Running Models (FRMs) are developed based on simulated fragment impact data from a software program developed for this specific purpose.
  - –Internally the trajectories are computed using the same integration algorithm in TRAJ_CAN
- Each FRM is in the form: $f(x)=\exp(a+b*x+c*x^2+d*x^3)$ where a, b, c and d are model parameters, x is the distance, and f is either impact probability or kinetic energy ratio.
- The parameters are determined through least-squares fitting to data generated by Monte Carlo simulations.





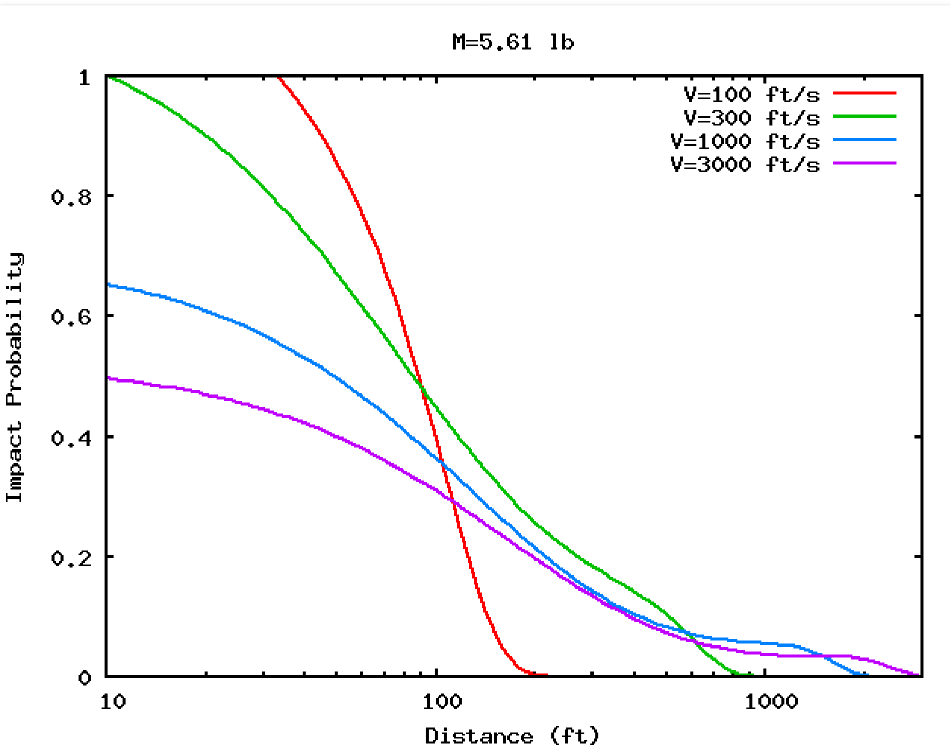
Group 4: PDF Technical Approach

- For each combination of the discrete parameters, FRM curves are generated for a series of takeoff speeds (up to 8,000 ft/s for primary fragments).
- FRM results are interpolated between two speeds.
- 320 tables are generated, corresponding to the combinations of 2 outputs × 8 debris source/types × 10 mass bins × 2 impact surfaces.
- Each table will have sufficient number of speed data points to ensure interpolation quality (typically about 15).



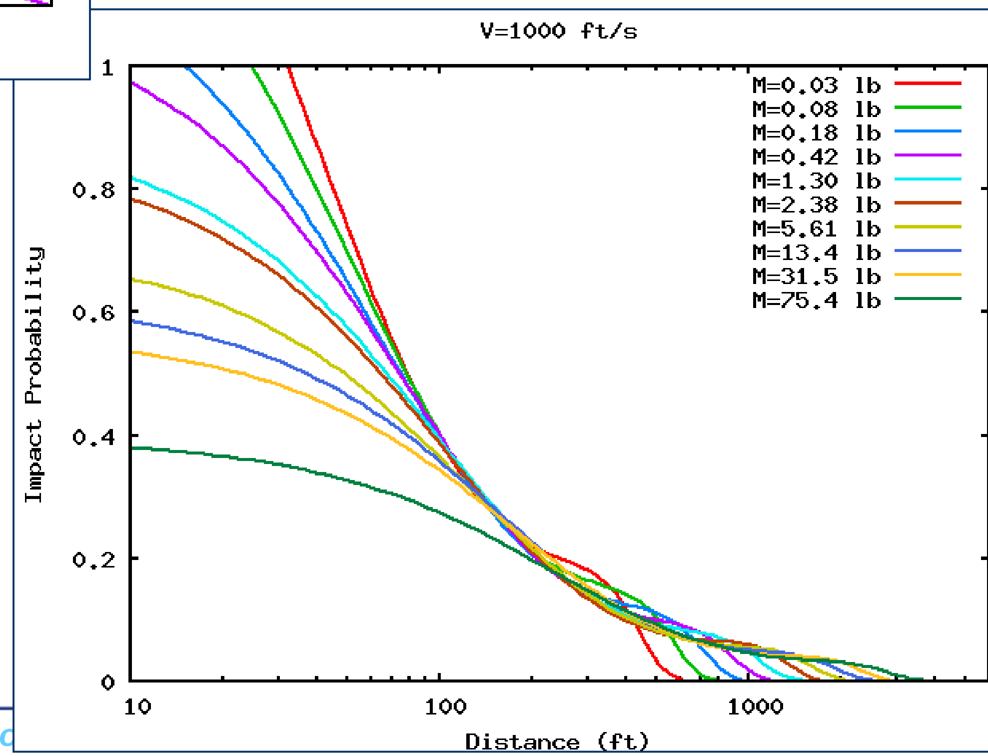
Takeoff Speed (ft/s)	Curve-fit Coefficients (m=75.4 lb)		
	a	b	c
100	-1.4834E+01	1.5113E-01	-6.8927E-04
300	-9.9983E+00	9.8167E-03	-8.1146E-06
1000	-1.3285E+01	4.4658E-03	-9.1419E-07
3000	-2.1349E+01	6.2156E-03	-7.1961E-07

Group 4: Results Example

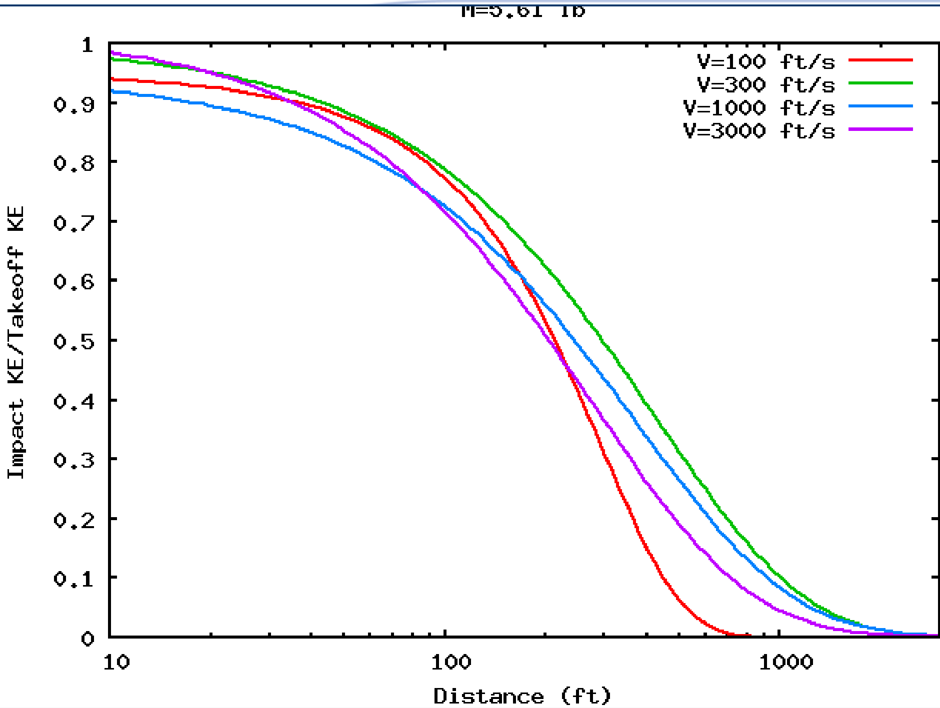


PES Wall PDF on ES Wall vs. Velocity (M = 5.61 lb)

PES Wall PDF on ES Wall vs. Mass (V =1,000 ft/s)

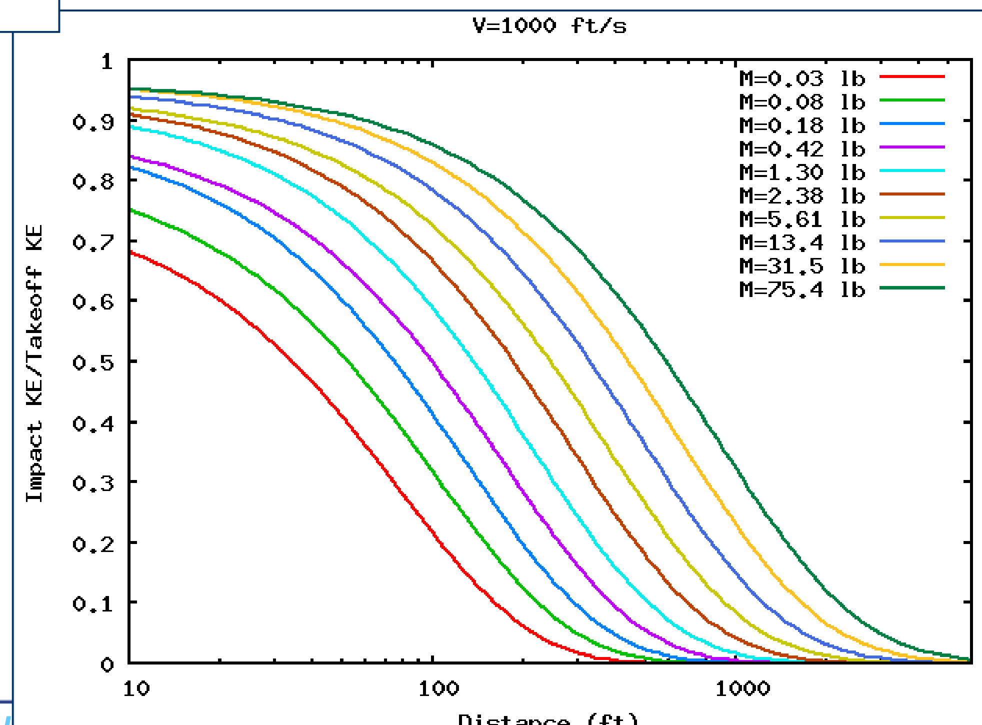


Group 4: Results Example



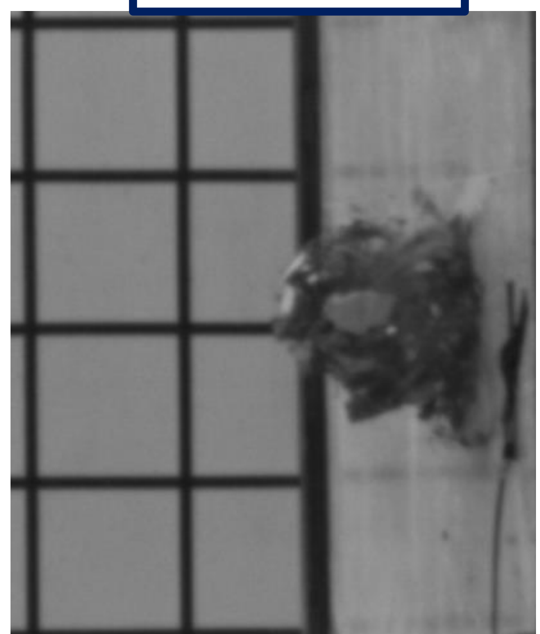
PES Wall KE on ES Wall vs. Velocity (M = 5.61 lb)

PES Wall KE on ES Wall vs. Mass (V =1,000 ft/s)



Group 4 Steps: Debris Branch

- Once the debris density distribution at the ES for all debris sources and types is determined, the protection afforded by conventional wall and roof construction must be determined
- Perforation resistance/reduction in debris velocity is defined as a function of kinetic energy for each component (delta KE)
  - Values have been determined by extensive testing (SPIDER series) and modeling efforts to approximate delta KE values



SPIDER Tests

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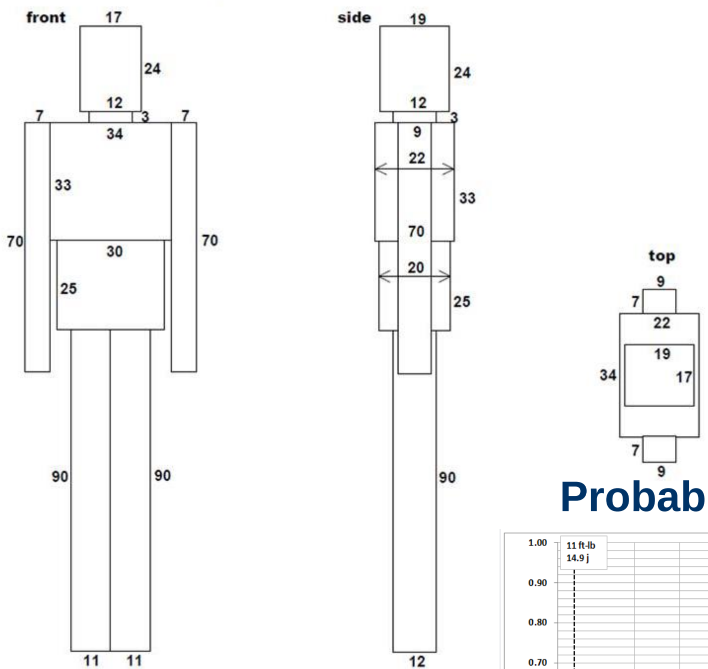
Group 4: Debris Impact Injury and Fatality

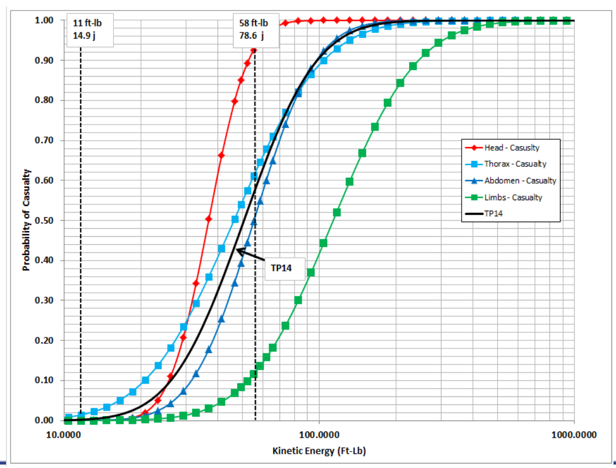
- Probabilities of injury and fatality are computed as a function of KE and hit area
  - –Head, thorax, abdomen, and limbs
- Distributions of personnel size, orientation, and location assumed

Position Standing / Prone

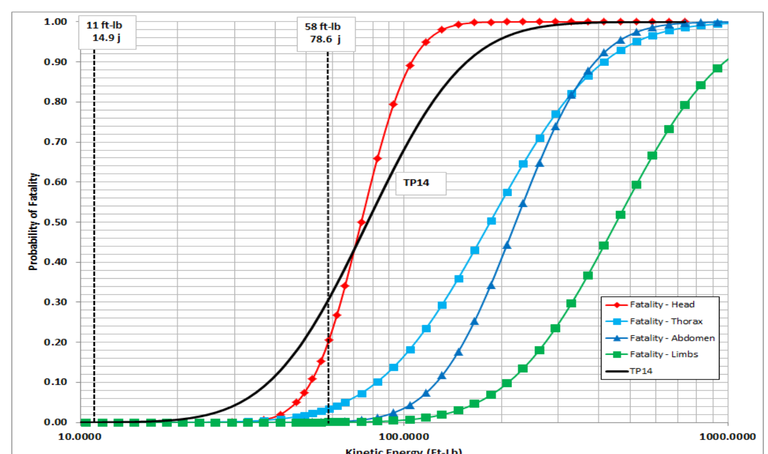


Exposed Impact Areas in the Standing Position

Probability of Major Injury+



Probability of Fatality



Group 5 Steps: Thermal Branch

- The thermal effects and consequence routine in TP-14 Revision 5 is only intended for HD 1.3 material and is quite simplistic
- Effects models are largely based on gun propellant
- Three step process for determining thermal effects
  - Quantify protection provided by PES and/or ES
  - Determine injuries and fatalities due to radiant heat effects as a function of quantity of material and distance
  - Perform final check of fireball radius to determine fatalities
- Thermal consequences are not calculated for HD 1.1 material; only thermal consequences are calculated for HD 1.3 material

Conclusions and Way Forward

- TP-14 Revision 5 is currently being finalized
- The QRA methodology will be officially released when the corresponding tool (RBESS) is fully implemented within ESS
- While TP-14 has been developed specifically for quantitative risk assessments associated with risk-based explosives safety siting, the consequence algorithms, $P_{f|e}$, can be used independently to support qualitative risk assessments, strictly consequence assessments, or other comparative studies to support optimization of funding allocation to support safety enhancements