Modeling Reactive Metal Fragment Effects in Endgame Simulations

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Defense Systems Information Analysis Center

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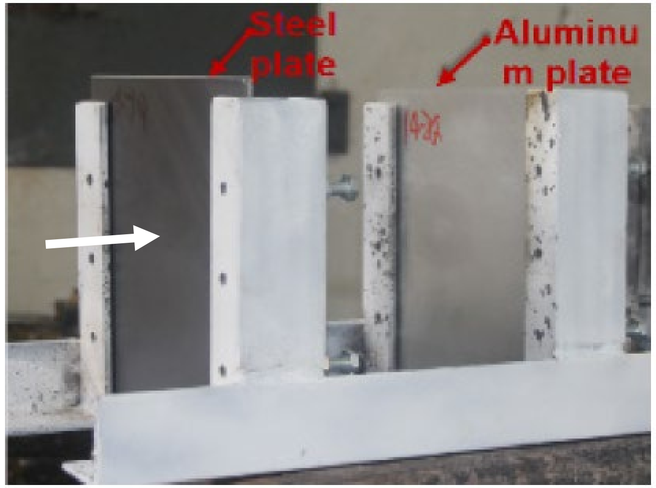
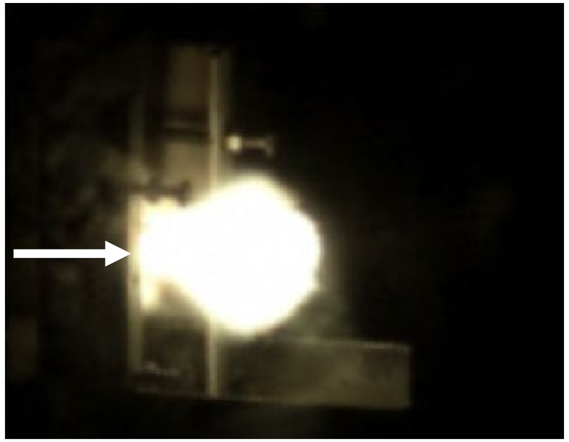
Reactive Metal Fragments (RMFs)

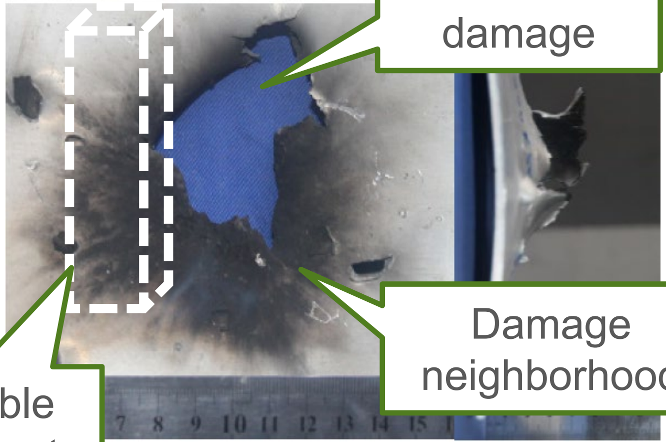
- Powder mixtures pressed and sintered into solid fragments.
- Example: PTFE + aluminum + tungsten. Density: 7.84 g/cm^3.
- Ballistic impact heating triggers chemical reaction.
- Energy release per unit mass can exceed TNT.
- Damage potential: kinetic energy + chemical energy.

RMF Impact Effects

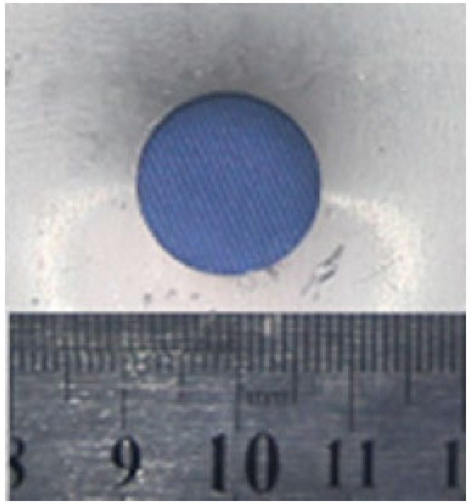


Peng, J., B. H. Yuan, X. Y. Sun, Y. J. Chen, and H. Chen. "Research on Penetration Behavior and After Effects of Coated Reactive Fragments Impacting Steel Targets. *International Journal of Multiphysics,* vol. 14, no. 1, p. 39, 2020.



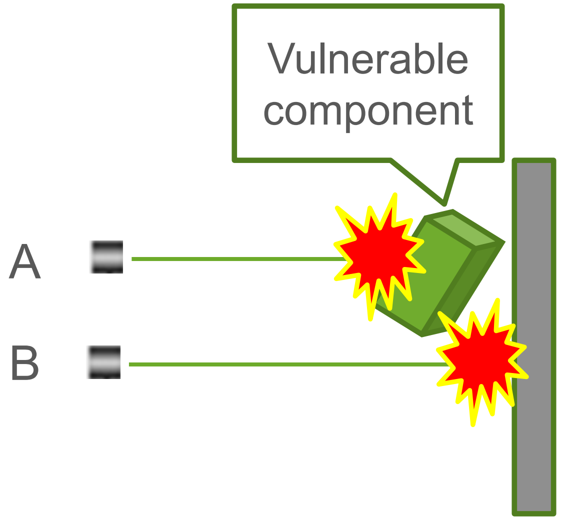


Reactive Fragment



Inert Fragment

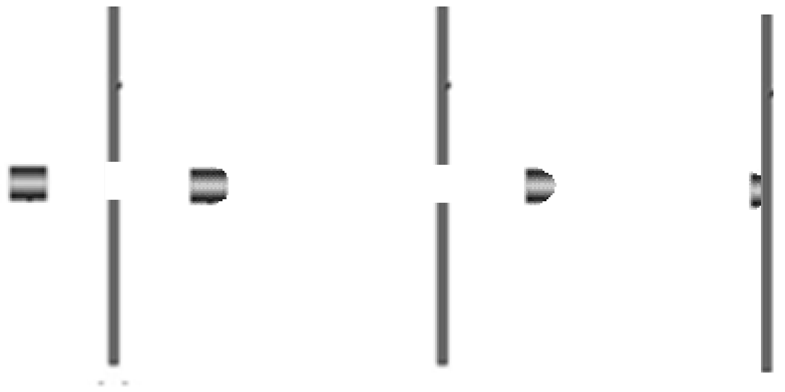
Additional Damage Mechanisms Modeled for RMF



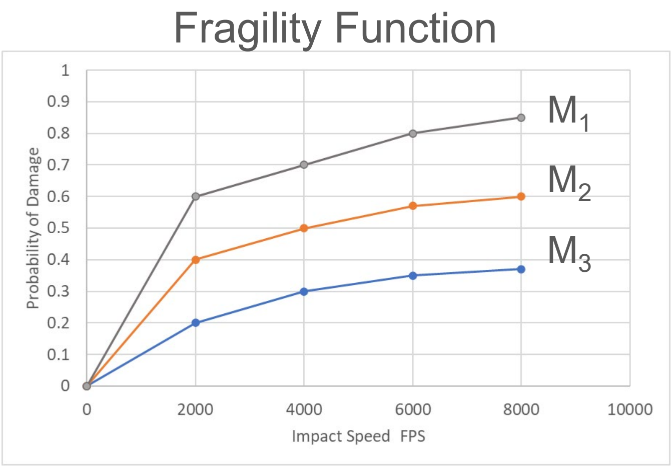
- Shotline A – intersects the component
  - Kinetic energy (KE) damage effect
  - Chemical energy enhancement
- Shotline B – *misses* the component
  - Chemical energy damage effect

RMF Endgame Shotline Modeling

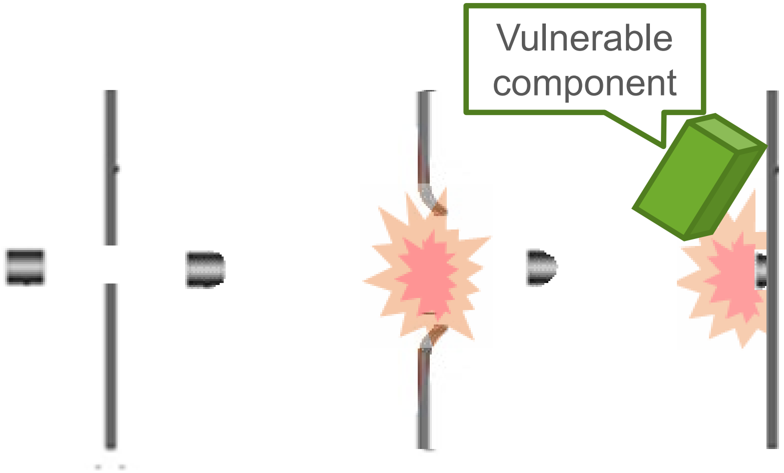
Inert



- Well-established penetration algorithms:
  - FATEPEN
  - JTCG PEH
  - PROJPEN
- Well-established fragility functions:
  - F (mass, velocity)
  - F (frag energy)
  - Etc.

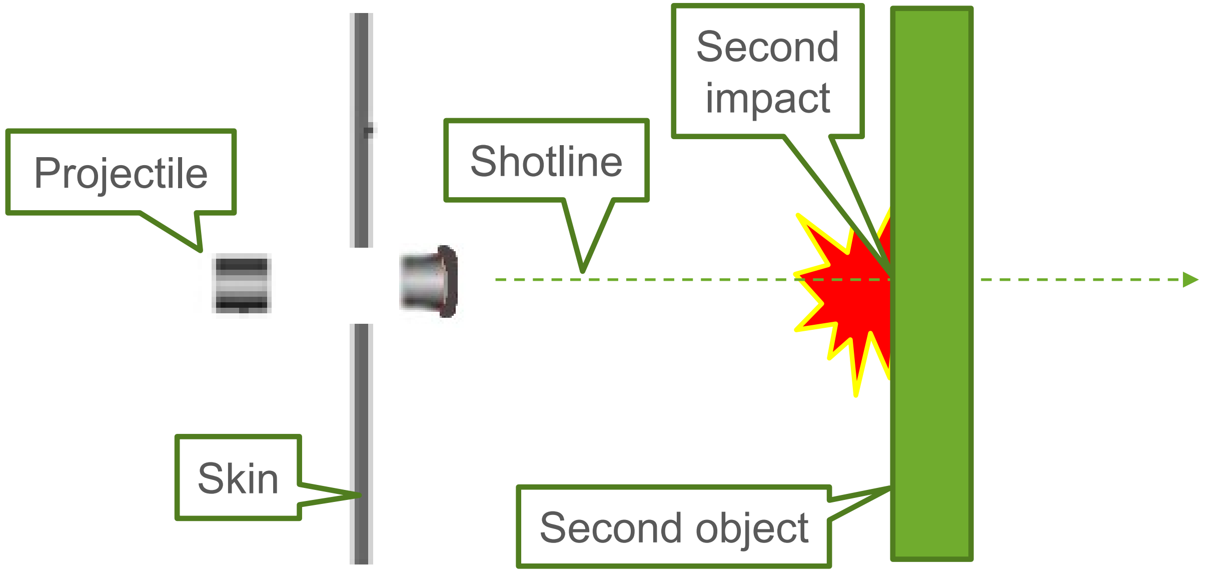


RMF



- Required algorithms:
  - Penetration algorithm
  - Energy deposition algorithm.
  - Modified fragility functions.
  - Indirect-hit damage model.

Simplified RMF Model



Penetration Algorithm

- Penetrates thin skin intact
- Stops on second impact

Energy Deposition Algorithm

- Released on second impact

Modified Fragility Function

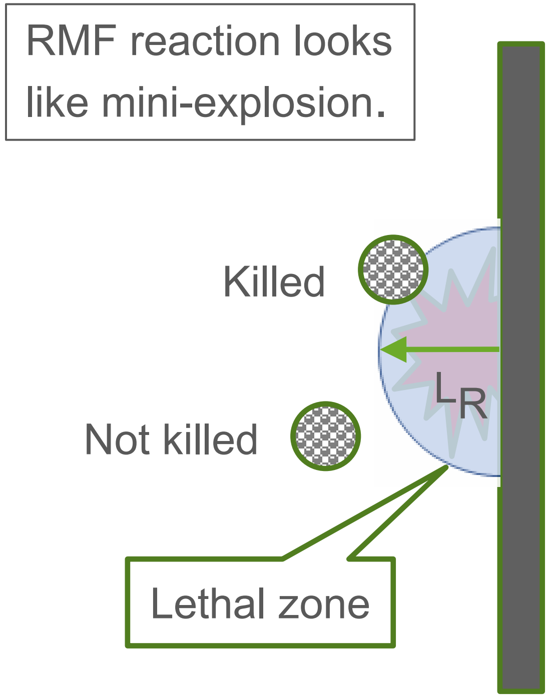
- $P_K = 1.0$

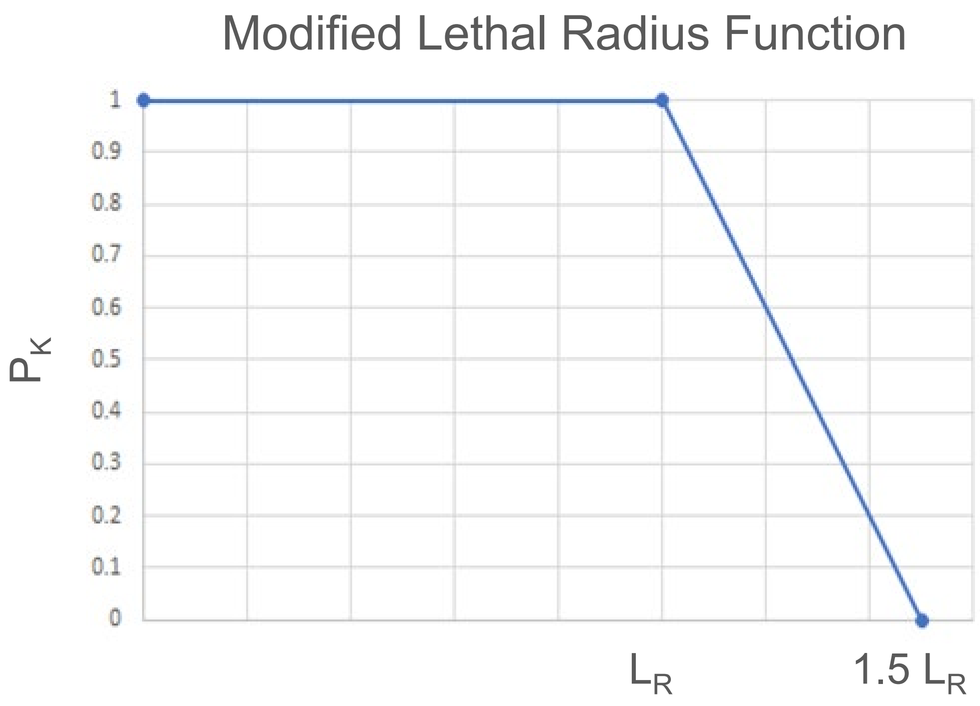
Indirect-Hit Damage Model

- Lethal radius

Simplified RMF Model Off-Shotline Effects

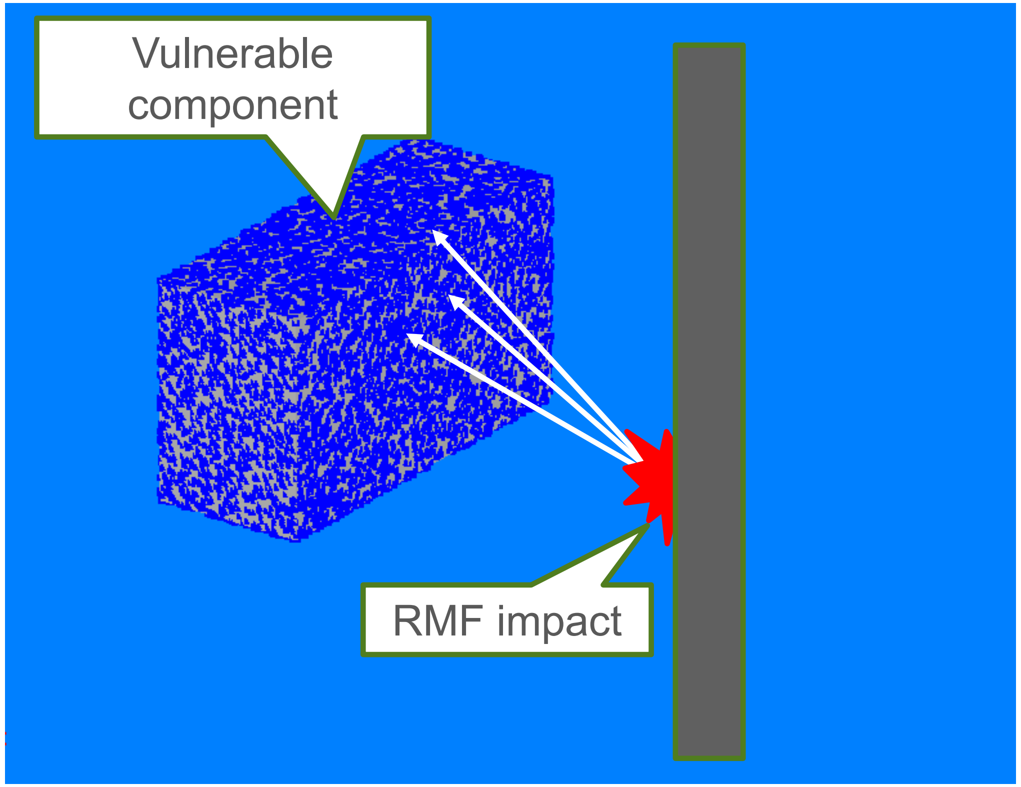
Impulsive loading effects → Lethal radius model



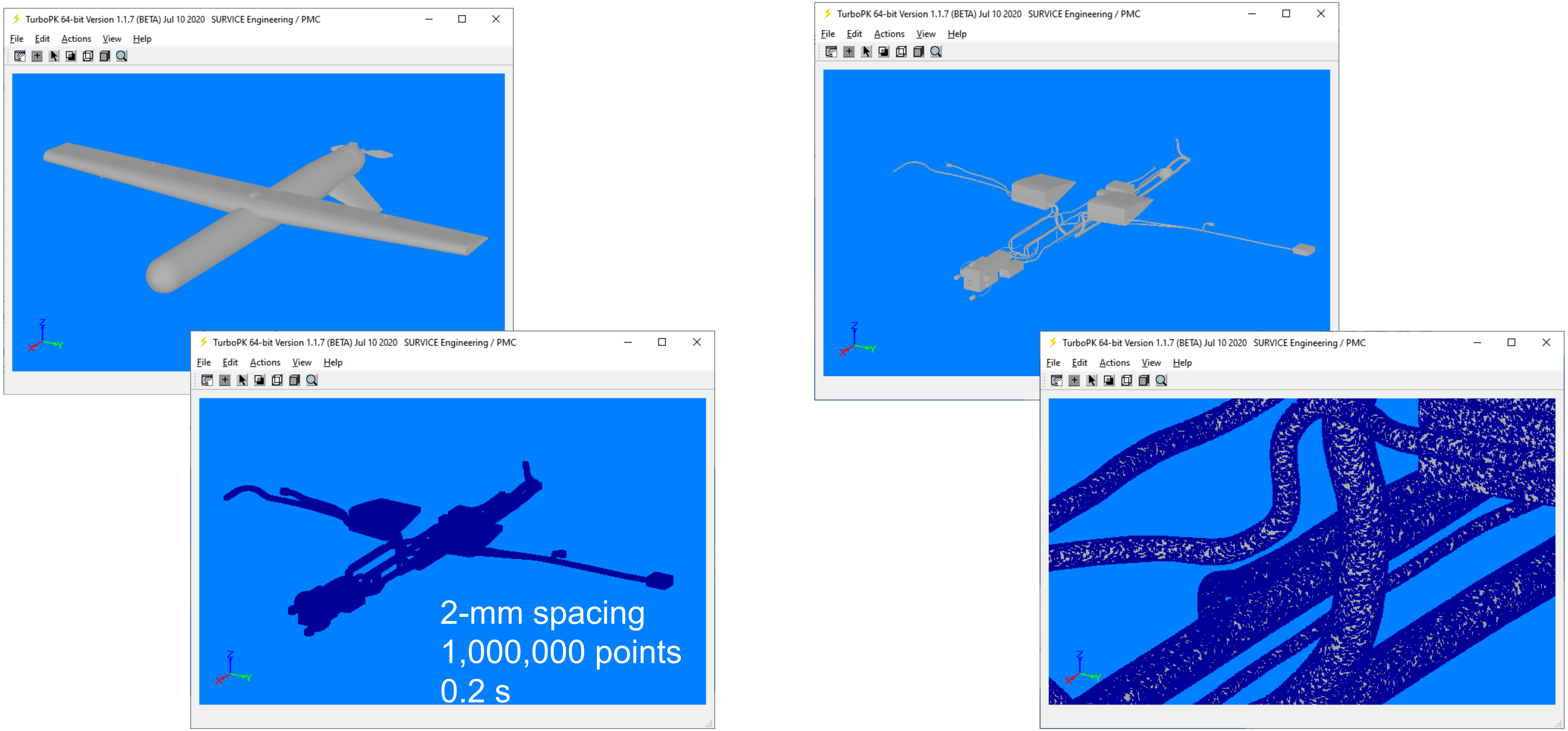


How to Determine if a Component Is Inside the Lethal Radius

- Cover each vulnerable component's surface with points.
- Determine those with direct line of site from reaction point to surface point.
- Calculate distance from reaction point to each surface point.
- Test distances vs. lethal radius.
- Key idea: KD-Tree data structure for fast "Radius Search."

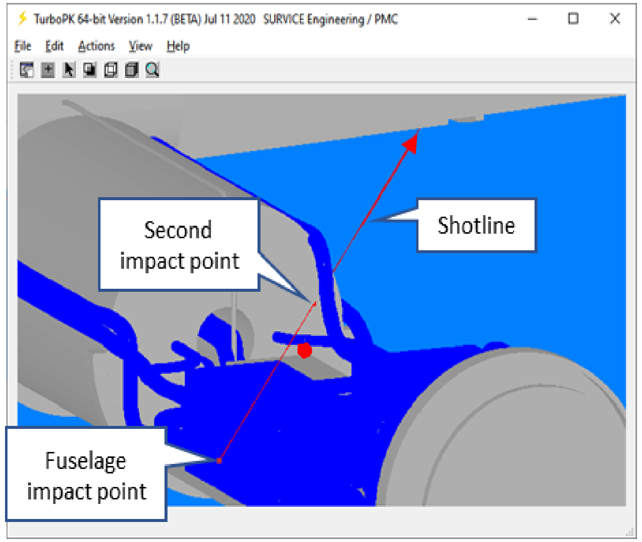


Surface Point Creation

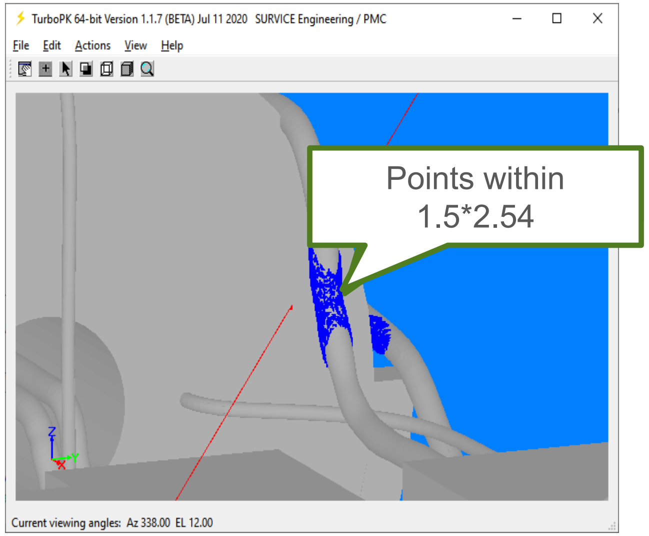


Shotline Processing Steps

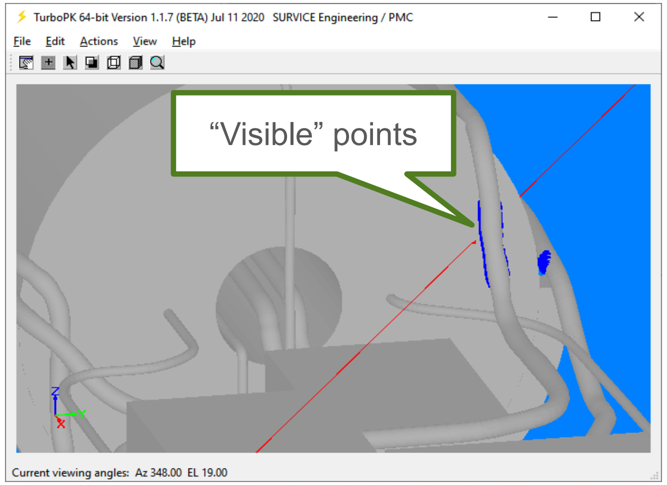
All surface points.



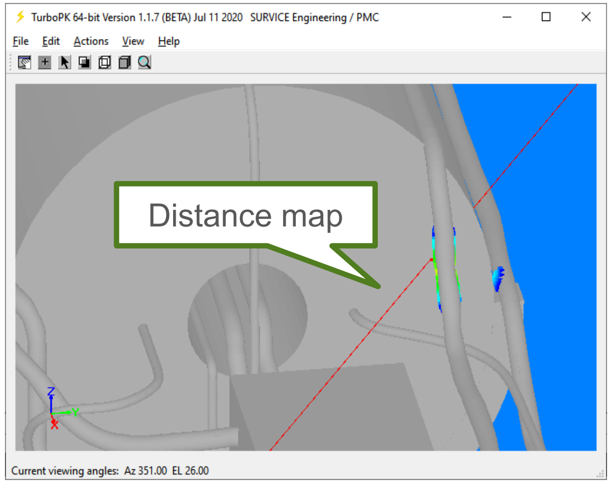
KD-Tree radius search.



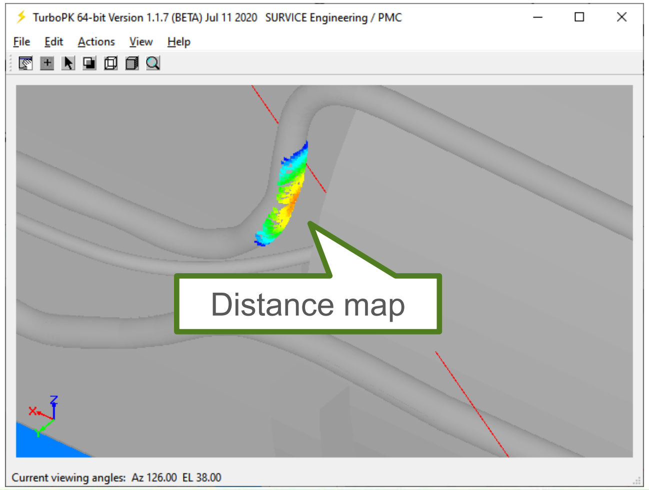
Ray-trace determines "visibility."



Distance map.

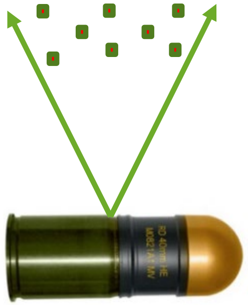


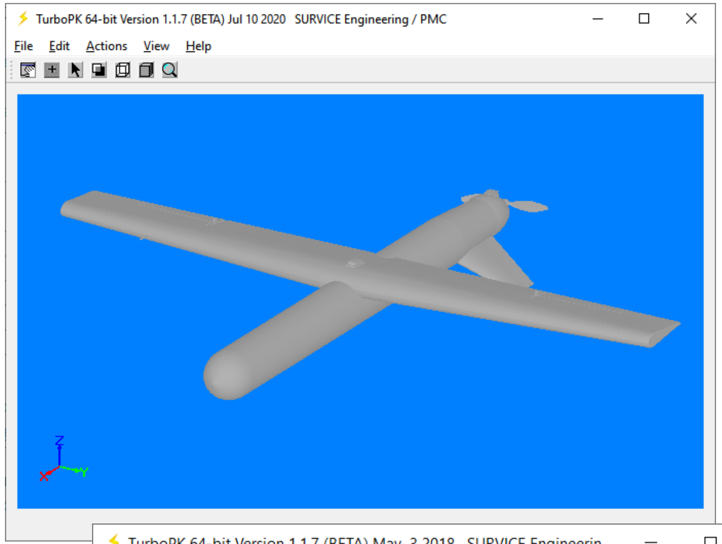
Distance map – rotated view.



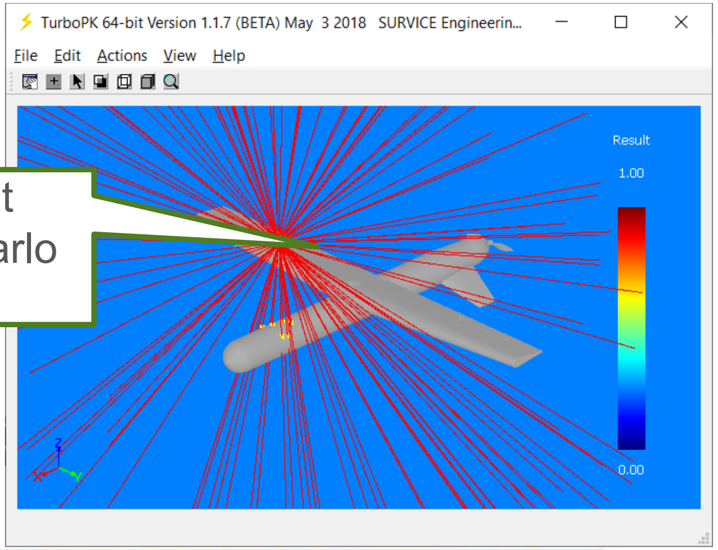
Example Endgame: 40-mm Air Burst Projectile vs. Drone

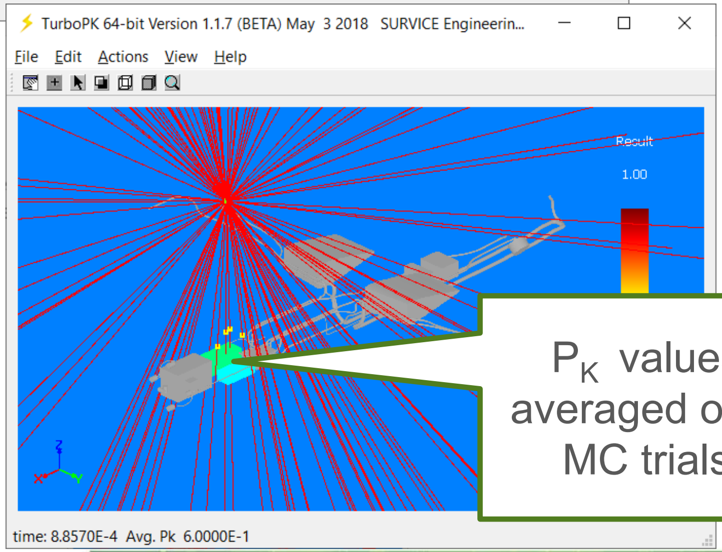
- 120 fragments, 20 grains each
- 4,000-fps ejection speed
- 20-deg side spray





Point burst
20 Monte Carlo trials

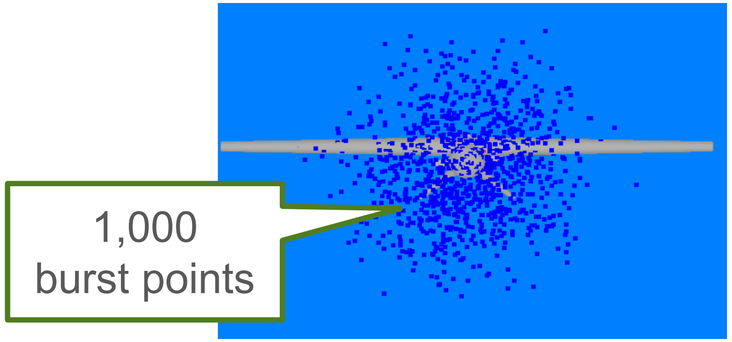




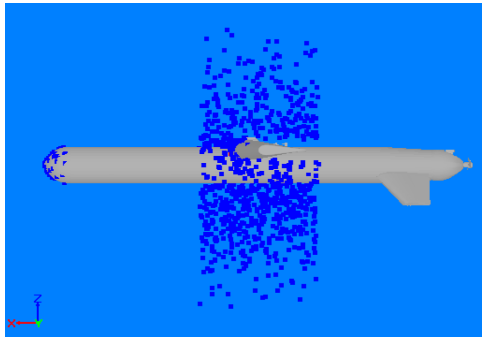
P_K values averaged over MC trials

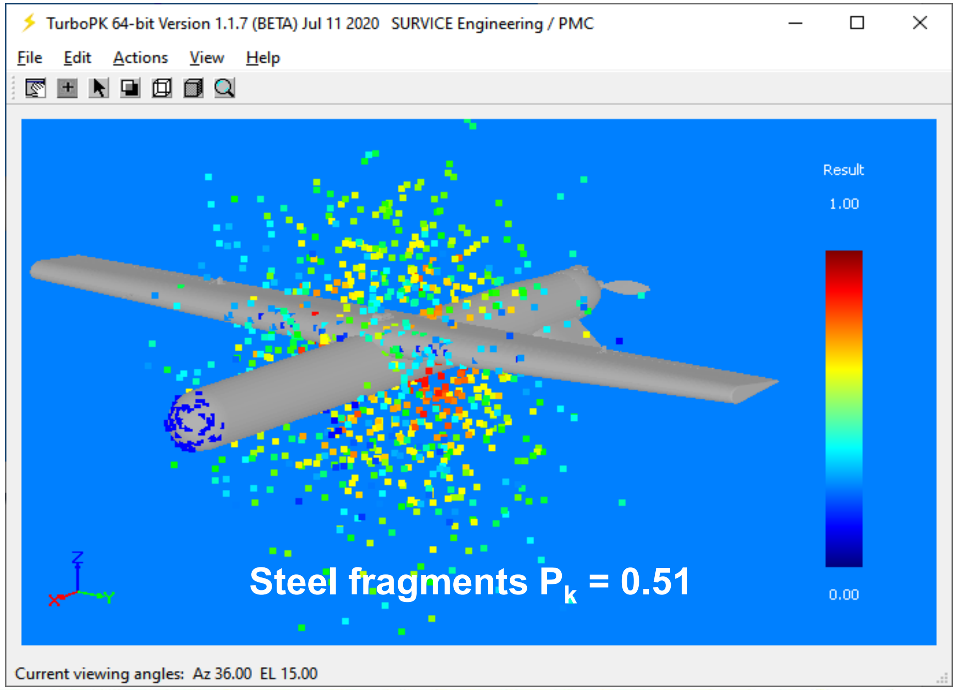
Example Endgame: 40 mm vs. Drone

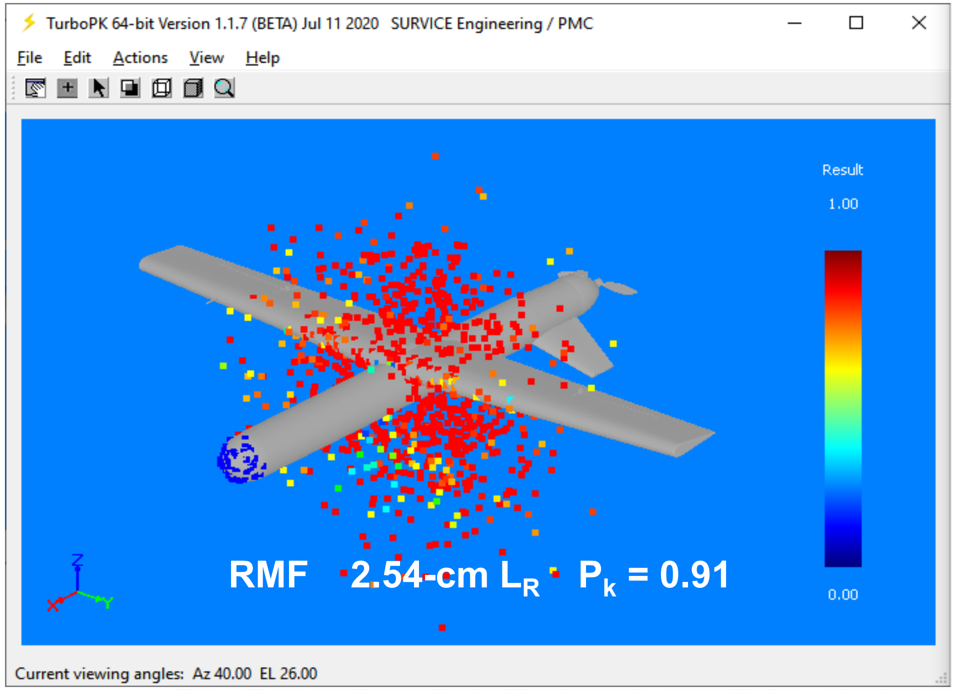
Head-on, 0.5-m CEP



±0.0015-s timing error

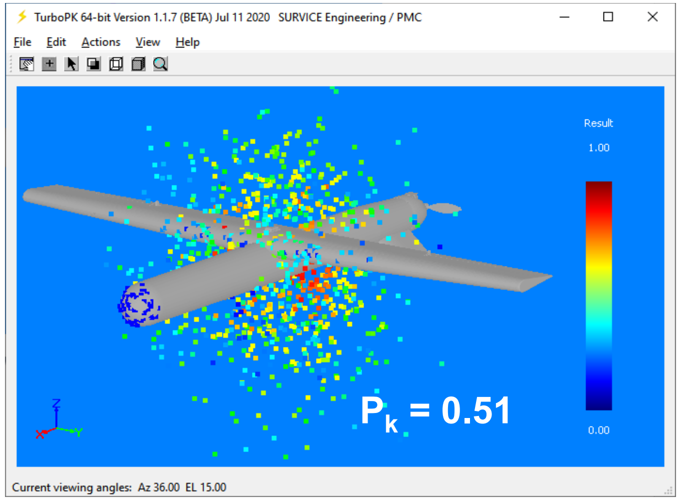






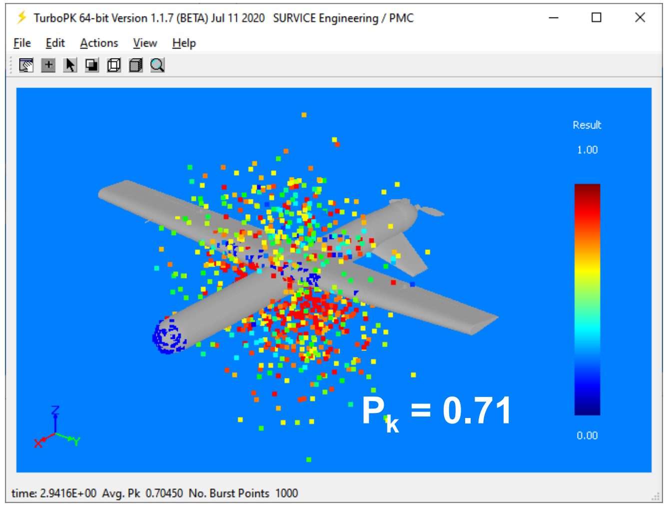
Example Endgame: 40 mm vs. Drone

Steel



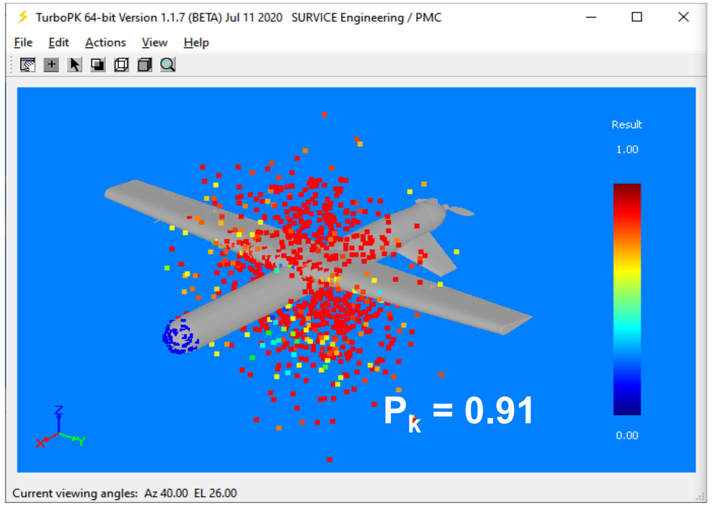
- KE only

RMF Lethal Radius 0.0



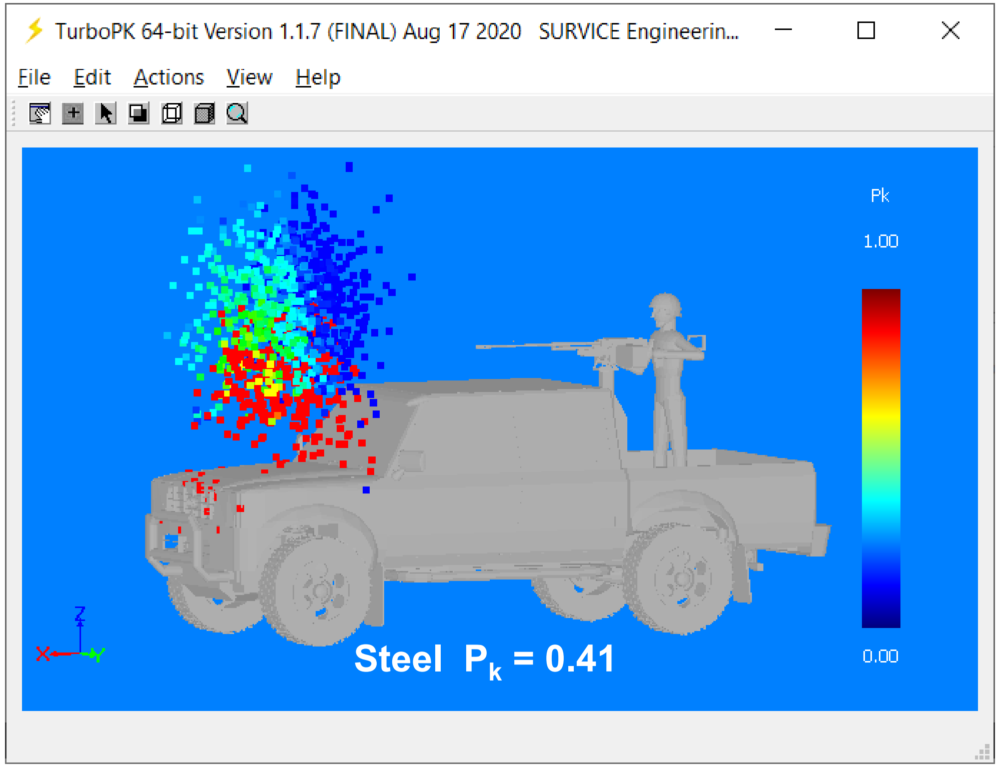
- KE + CE → $P_{K/H}$ = 1.0

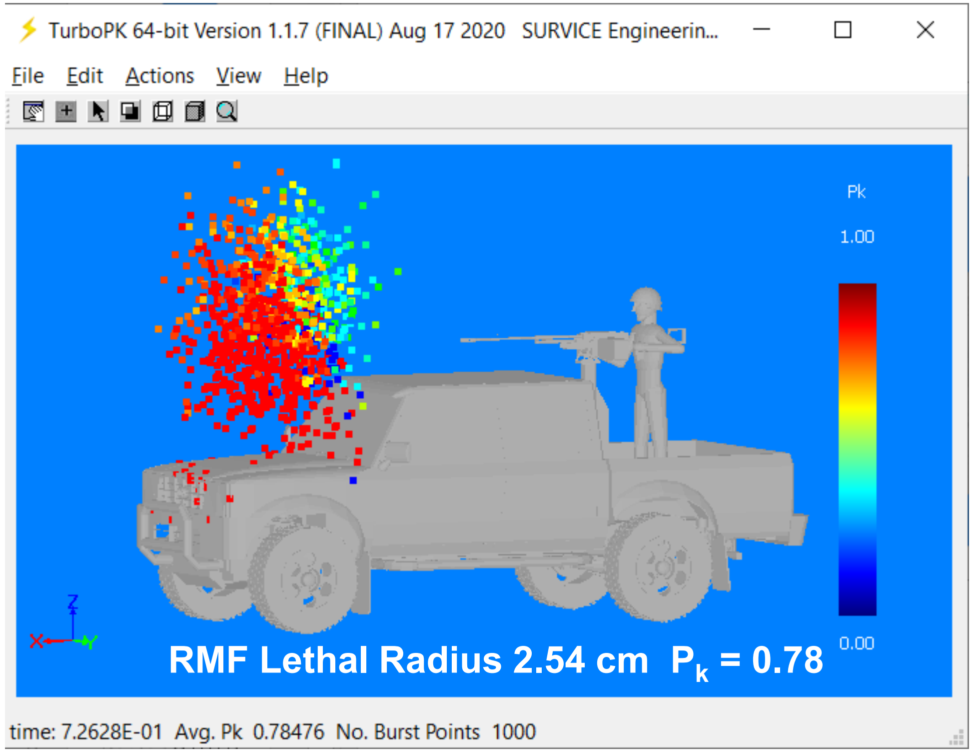
RMF Lethal Radius 2.54



- KE + CE → $P_{K/H}$ = 1.0
- Lethal radius effect

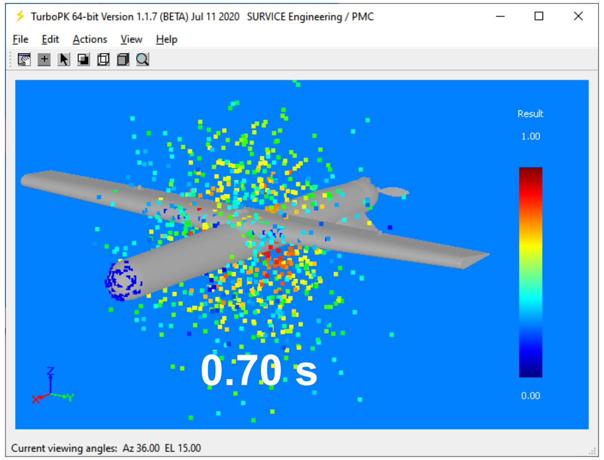
Example Endgame: 40mm vs. Truck

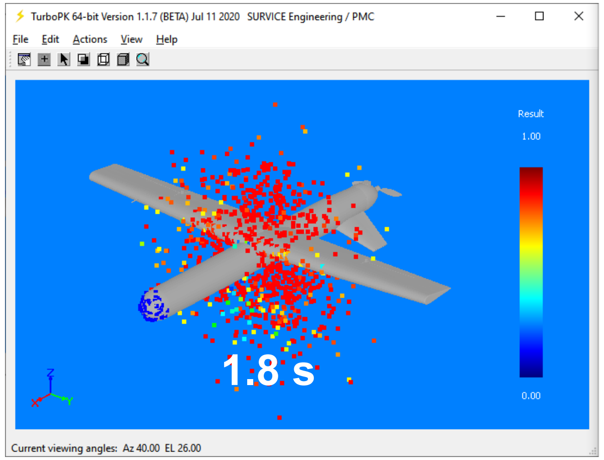


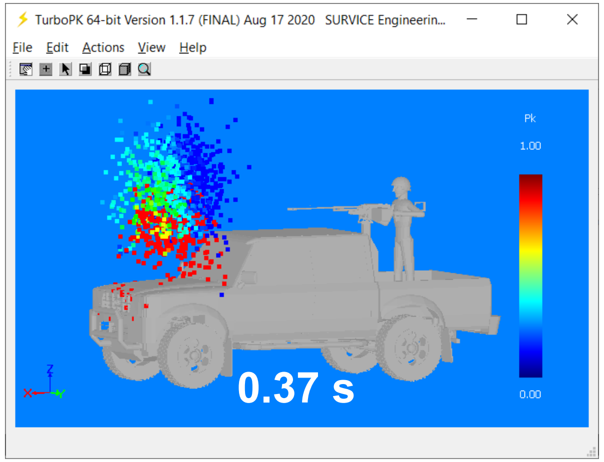


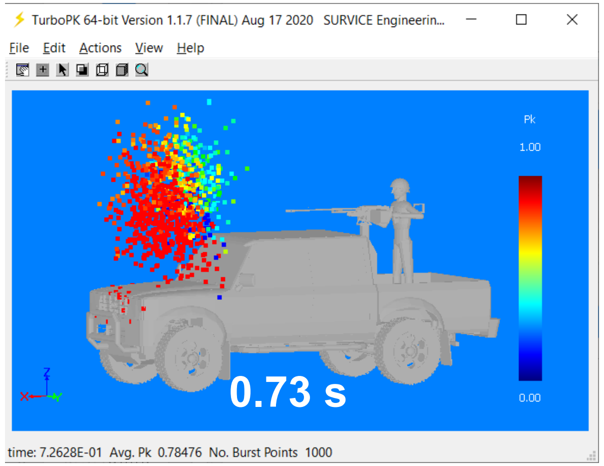
Example Endgame Run Times

- 1,000 burst locations, 20 sample point bursts at each
- (1,000 × 20 × 125 = 2.5 · 10^6 shotlines)
- Fully parallelized + KD-Tree = speed



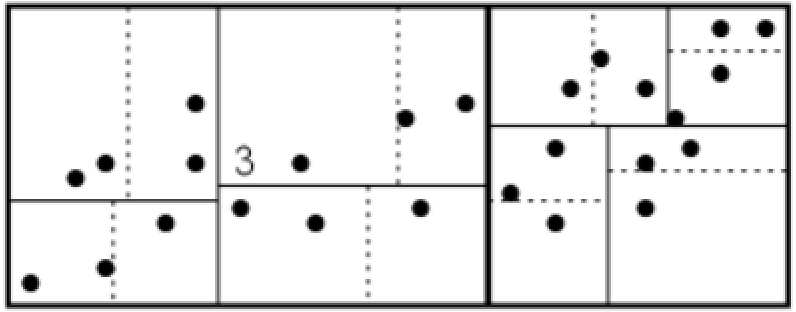




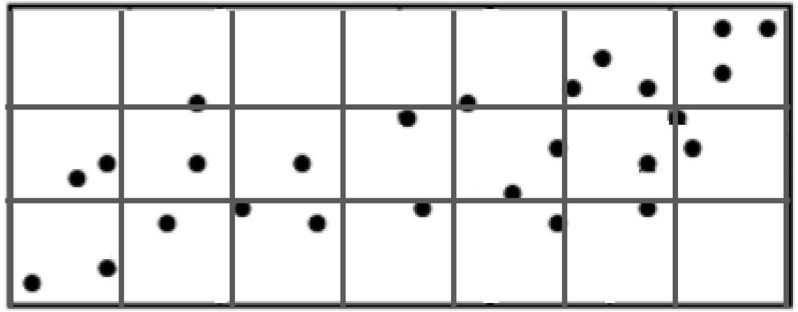


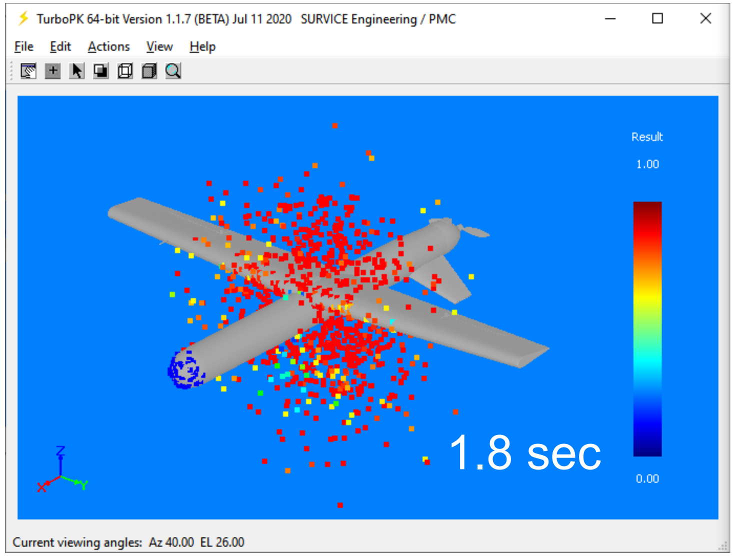
Alternative Point Structures

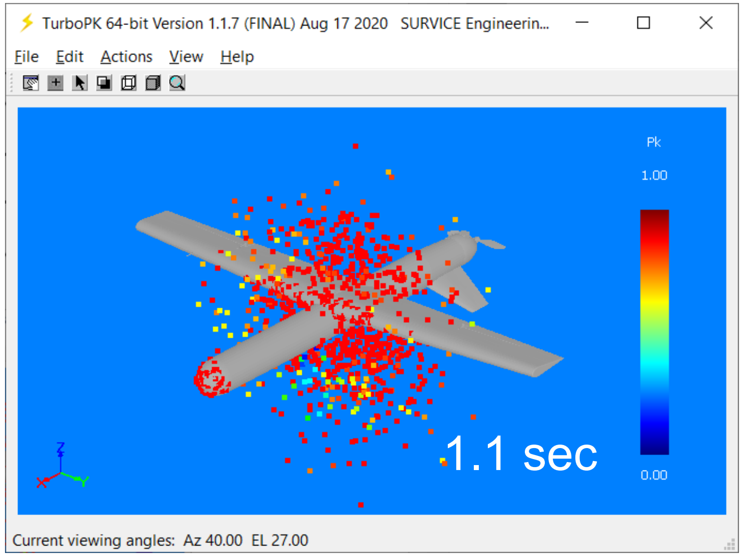
KD-Tree



Uniform Grid

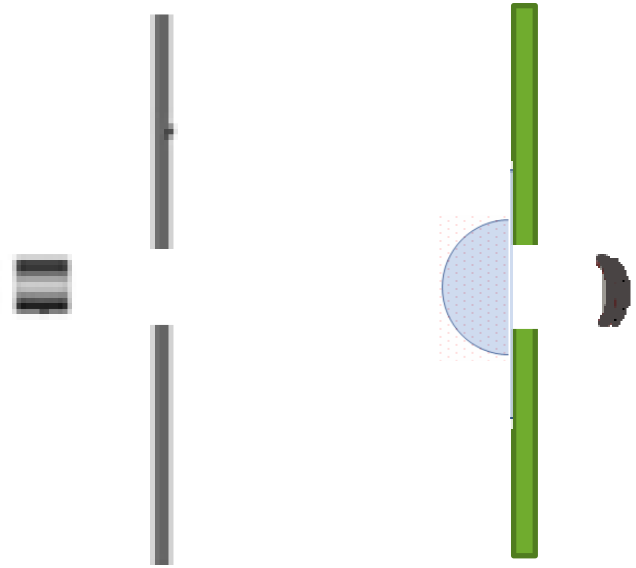






- R-trees, BVH, Morton Curves, Hilbert curves, Peano curves….

More Complicated RMF Model



Penetration Algorithm

- RMF treated as steel
- V_{50} increased by x%

Energy Deposition Algorithm

- Proportional to KE loss
- Minimum speed value for any reaction

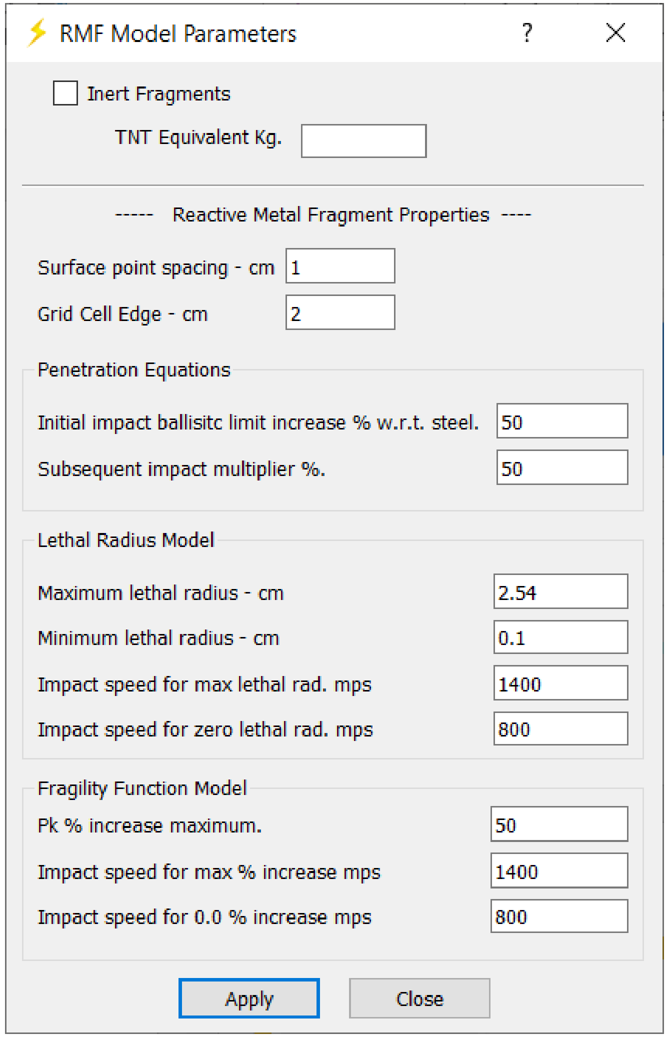
Modified Fragility Function

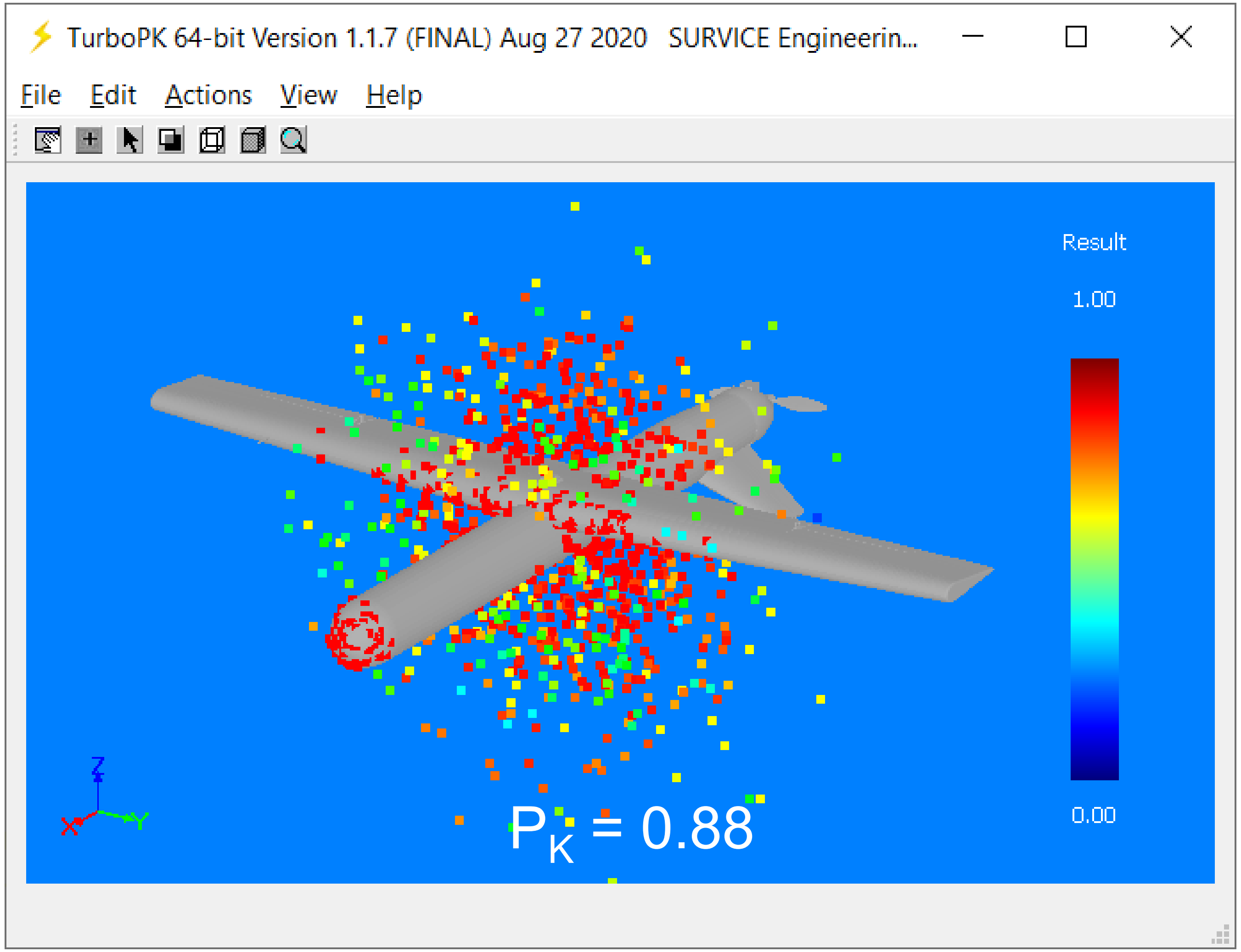
- Baseline fragility functions
- Linear increase based on KE loss

Indirect-Hit Damage Model

- Baseline lethal radius
- Impact V for baseline
- Minimum speed value for LR = 0.0
- (KE loss)/(baseline KE) LR reduction

More Complicated RMF Model





Summary

- **Demonstrated a methodology for treating RMF impacts.**
- **It shows large potential gains in P_K for RMF.**
- **It is fast. “Radius Search” data structures are key.**
- **Need quantification of lethal radii.**
- **Lots of work to do:**
  - Per component lethal radii
  - Penetration model for RMF
  - Energy deposition model for RMF
  - Countermeasures
  - Etc.