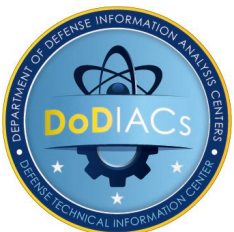


Modeling Reactive Metal Fragment Effects in Endgame Simulations

Patrick Buckley
SURVICE Engineering
pat.buckley@survice.com
pat@pmc-inc.com



DSIAC is a DoD Information Analysis Center (IAC) sponsored by the Defense Technical Information Center (DTIC), with policy oversight provided by the Office of the Under Secretary of Defense (OUSD) for Research and Engineering (R&E). DSIAC is operated by the SURVICE Engineering Company.

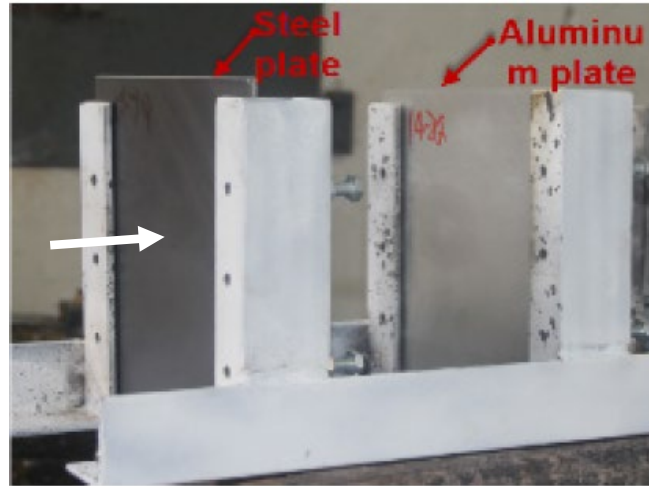
Distribution A; Approved for Public Release; Distribution Unlimited

Disclaimer: The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of any agency of the U.S. government. Examples of analysis performed within this article are only examples. Assumptions made within the analysis are not reflective of the position of any U.S. government entity.

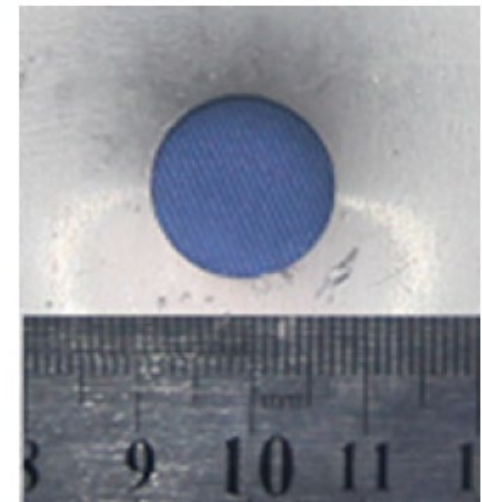
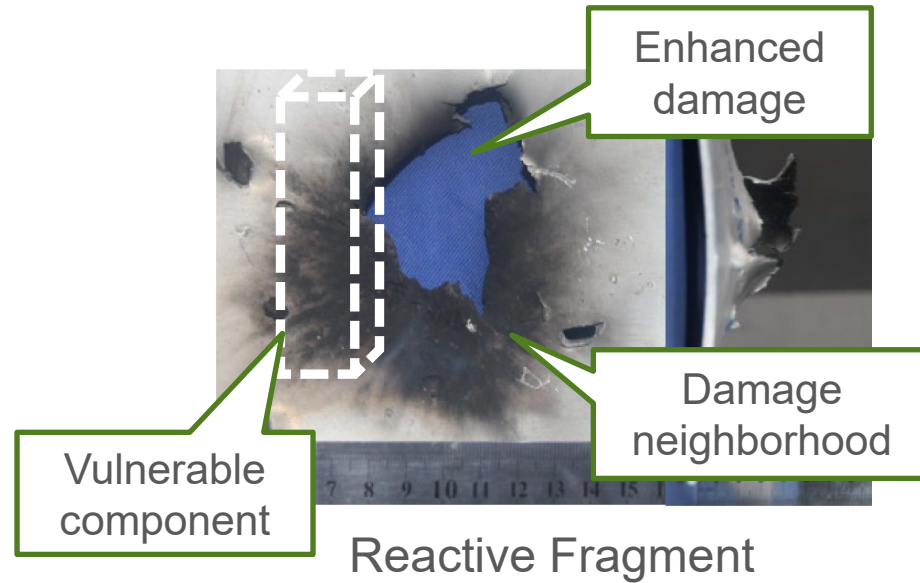
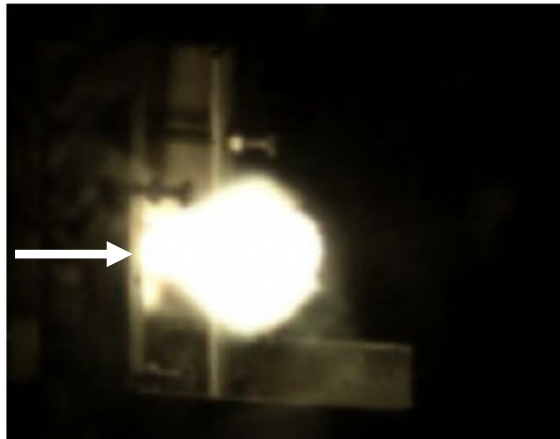
Reactive Metal Fragments (RMFs)

- 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.

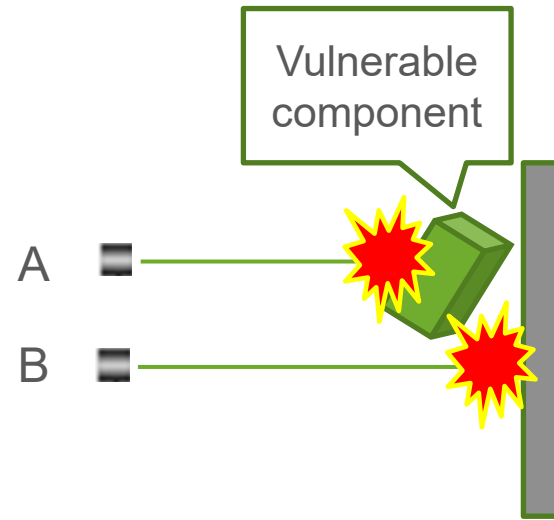
RMF Impact Effects



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.

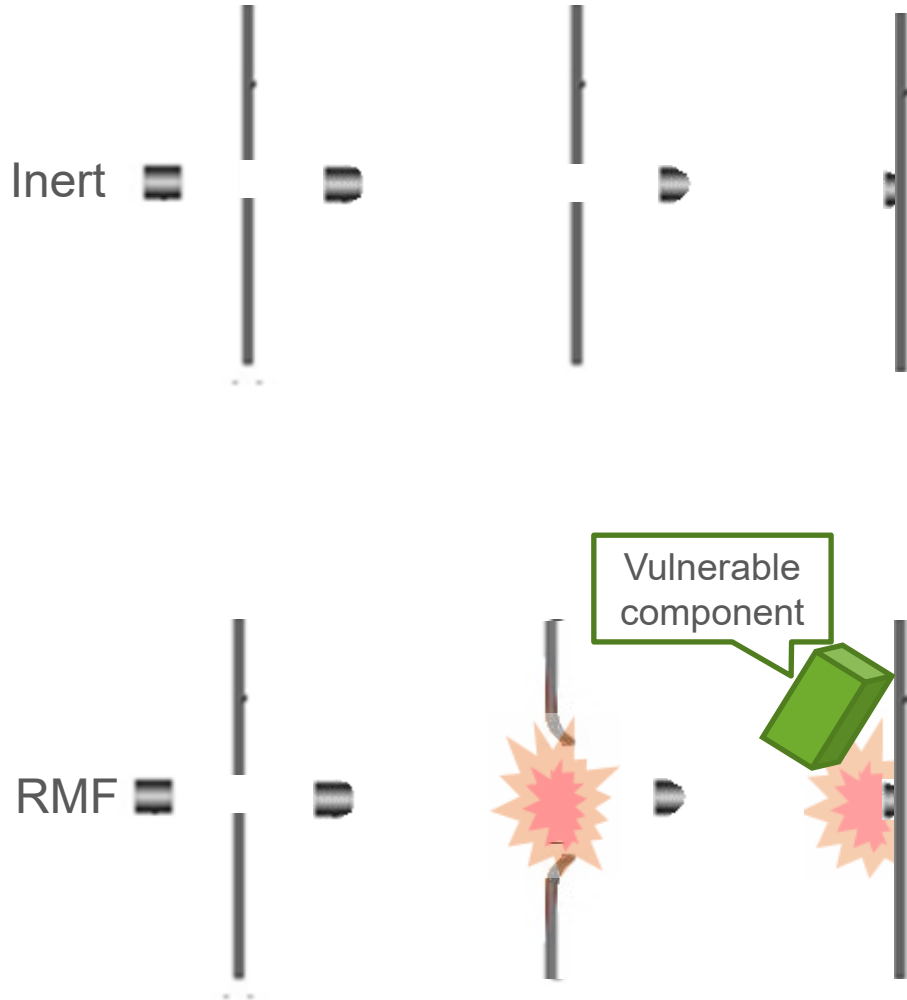


Additional Damage Mechanisms Modeled for RMF

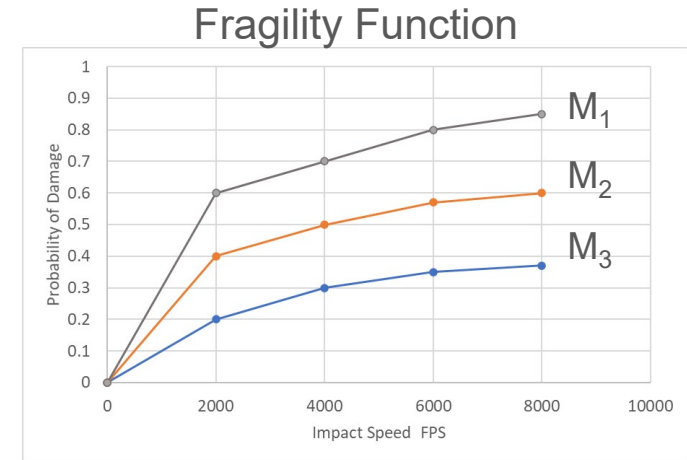


- Shotline A – intersects the component
 - Kinetic energy (KE) damage effect
 - Chemical energy enhancement
- Shotline B – *misses* the component
 - Chemical energy damage effect

RMF Endgame Shotline Modeling

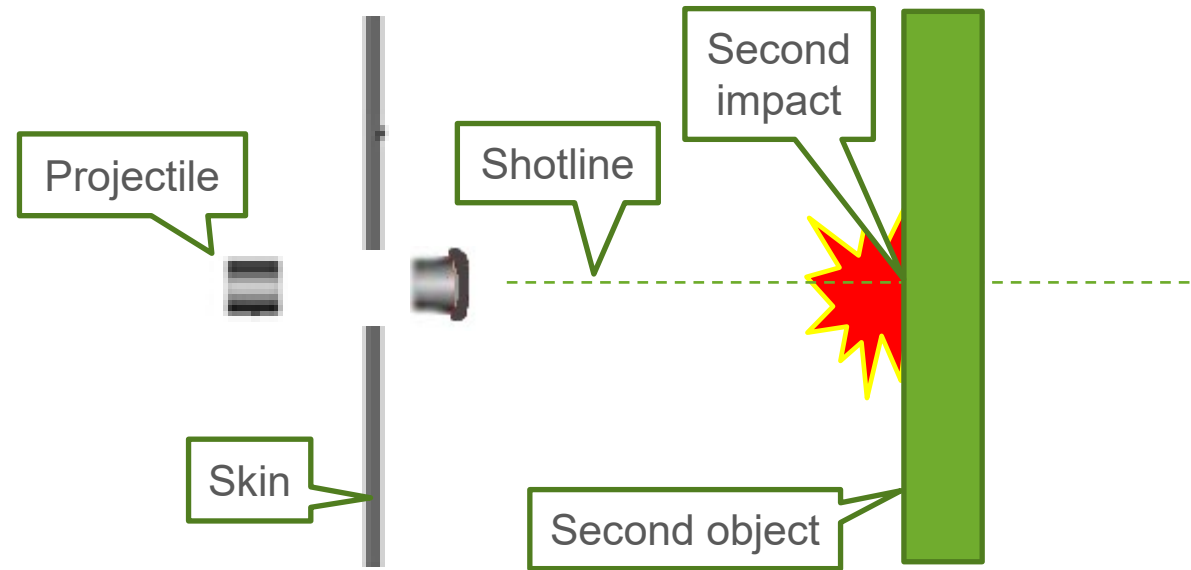


- Well-established penetration algorithms:
 - FATEPEN
 - JTCG PEH
 - PROJPEN
- Well-established fragility functions:
 - F (mass, velocity)
 - F (frag energy)
 - Etc.



- 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

- $P_K = 1.0$

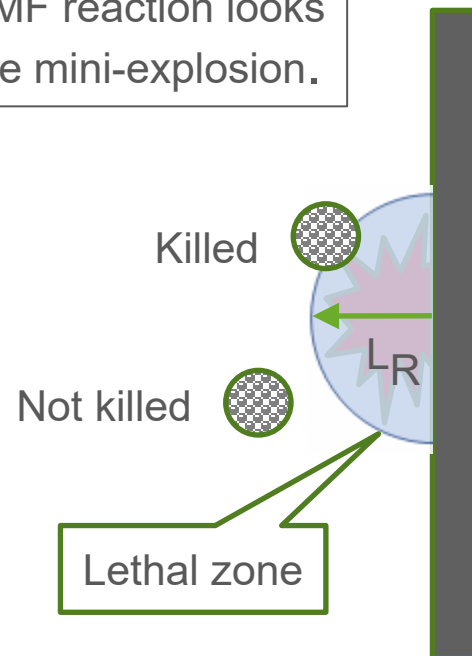
Indirect-Hit Damage Model

- Lethal radius

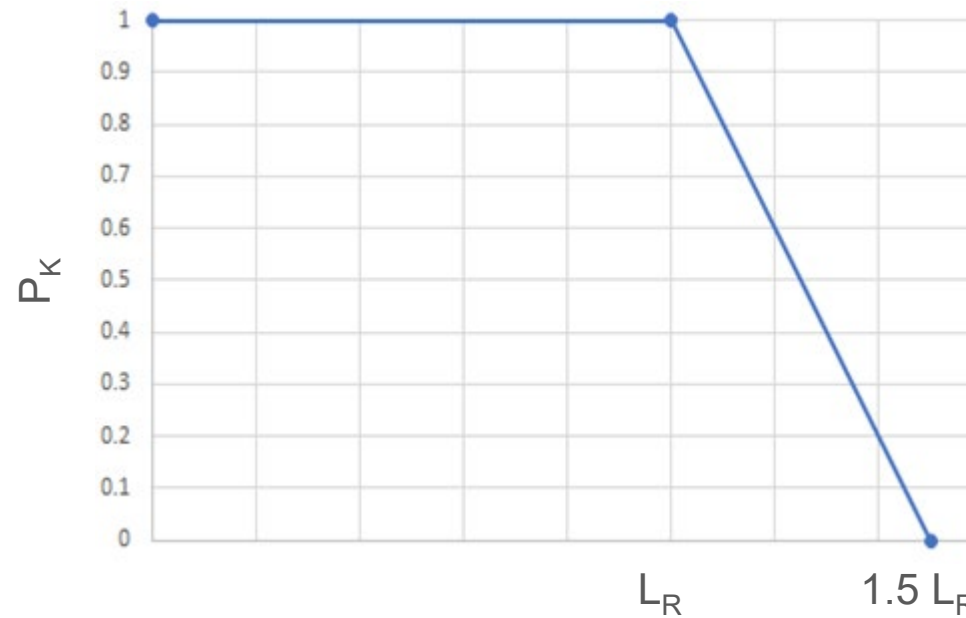
Simplified RMF Model Off-Shotline Effects

Impulsive loading effects \longrightarrow Lethal radius model

RMF reaction looks like mini-explosion.

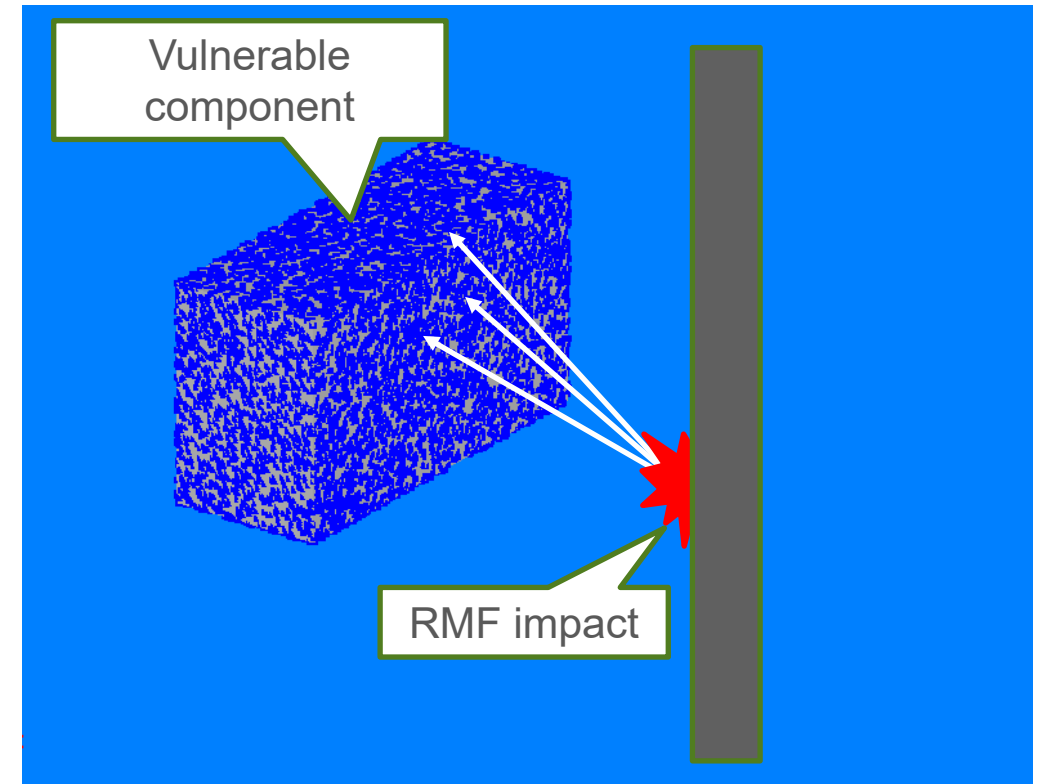


Modified Lethal Radius Function

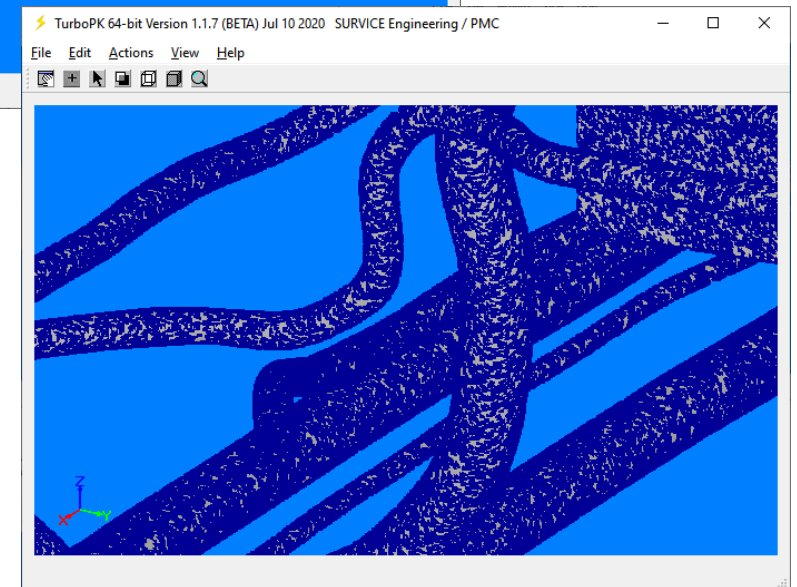
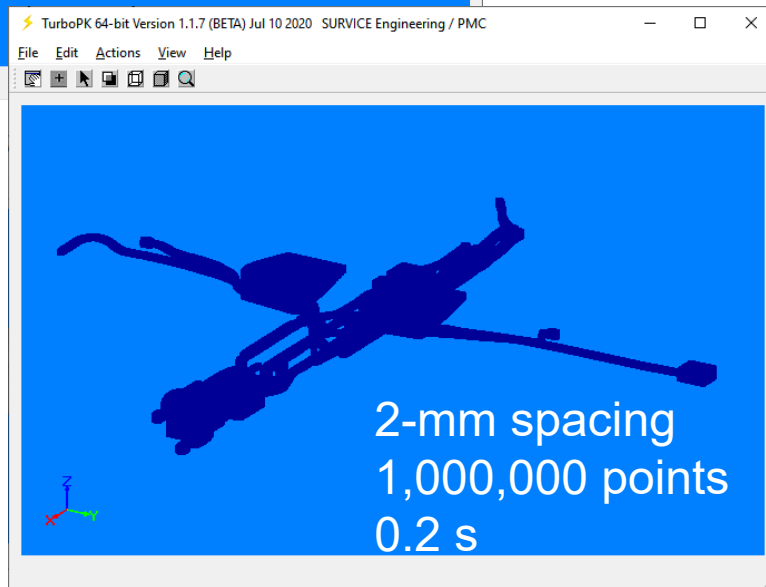
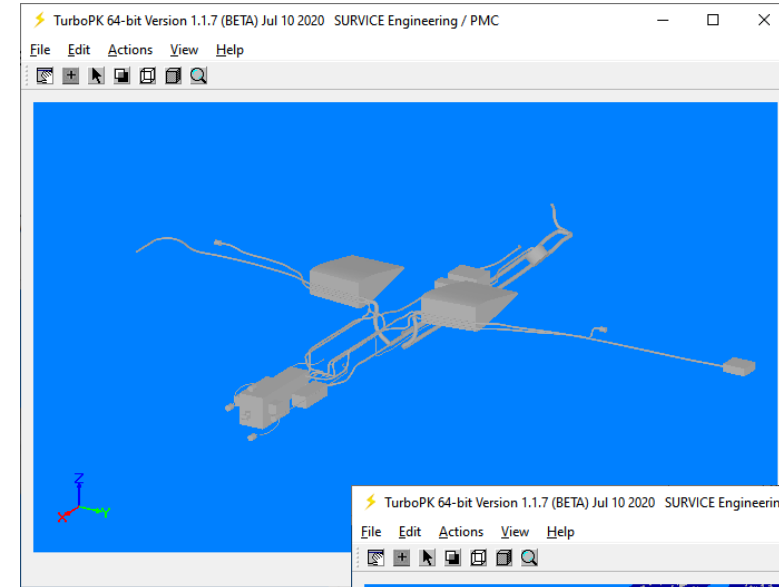
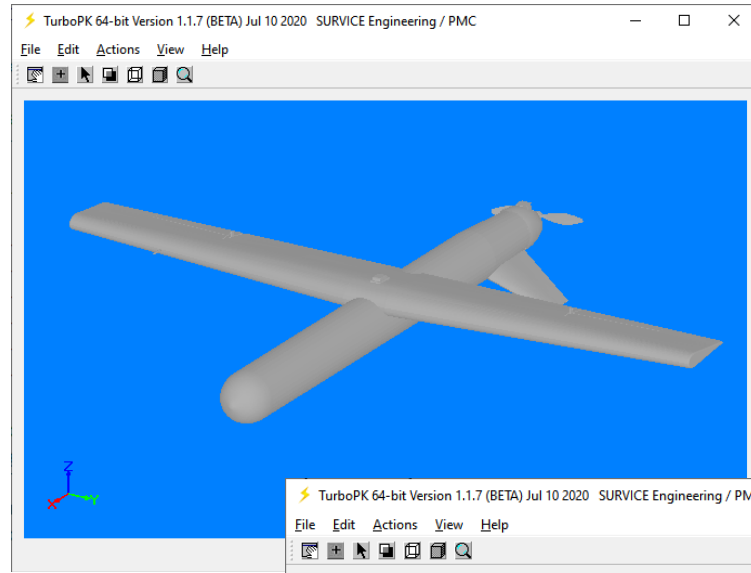


How to Determine if a Component Is Inside the Lethal Radius

- 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."

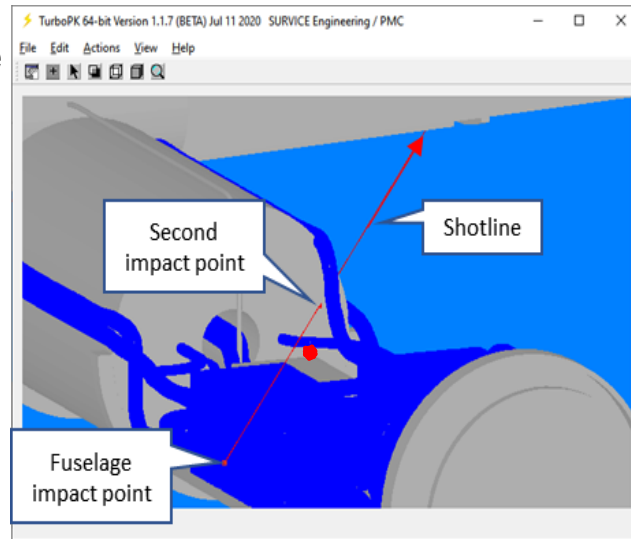


Surface Point Creation

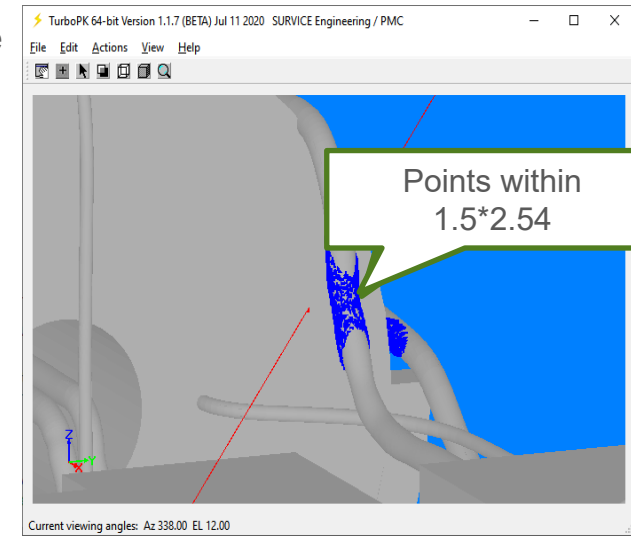


Shotline Processing Steps

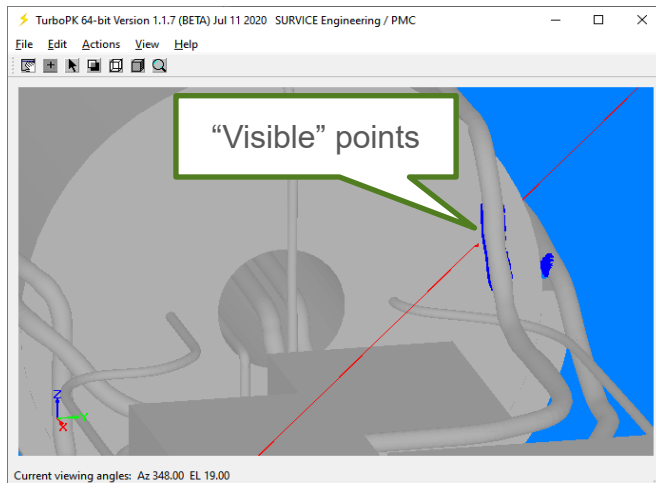
All surface points.



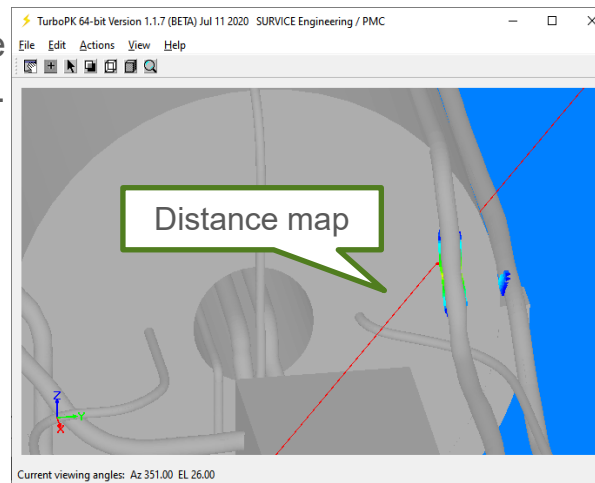
KD-Tree radius search.



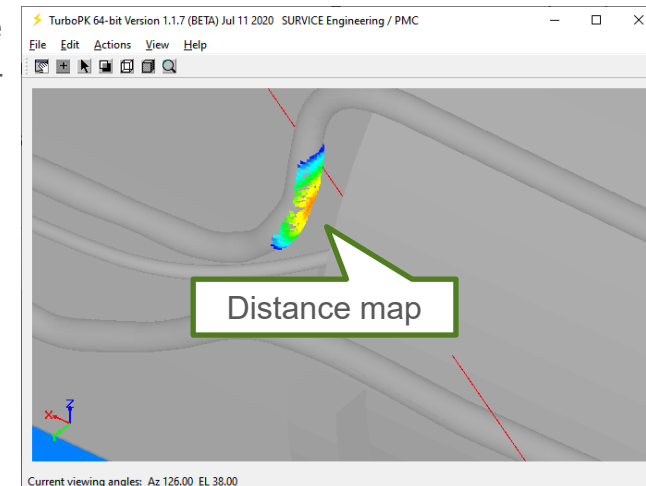
Ray-trace determines "visibility."



Distance map.

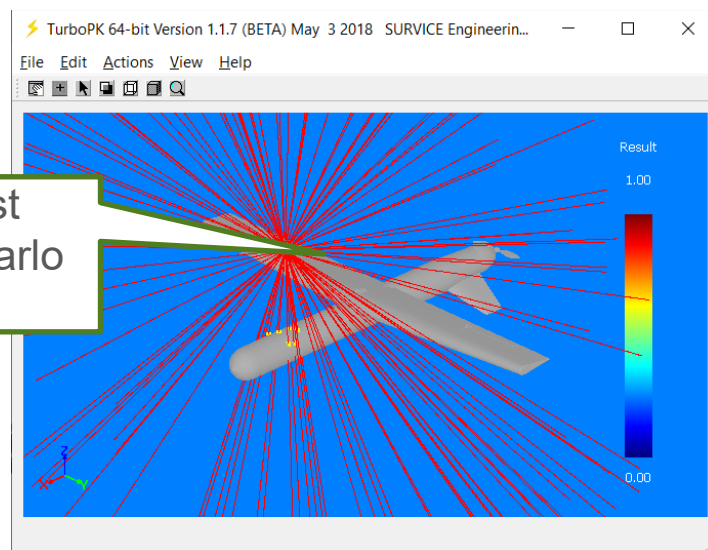
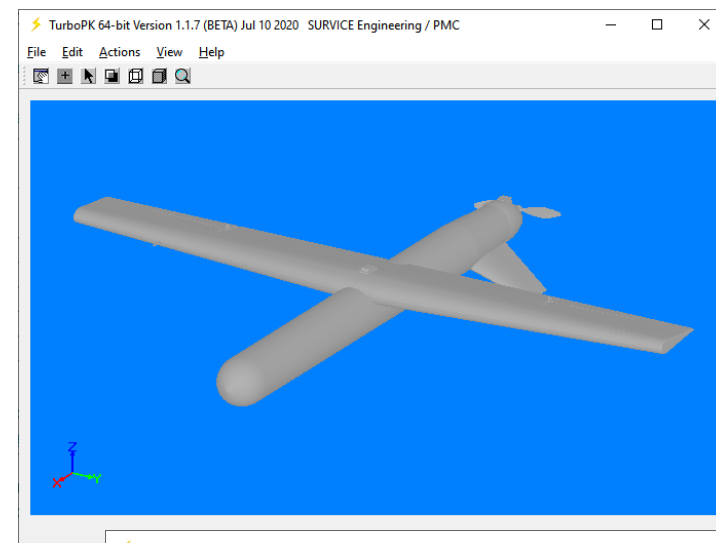
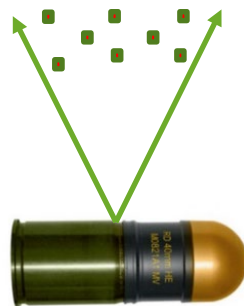


Distance map – rotated view.

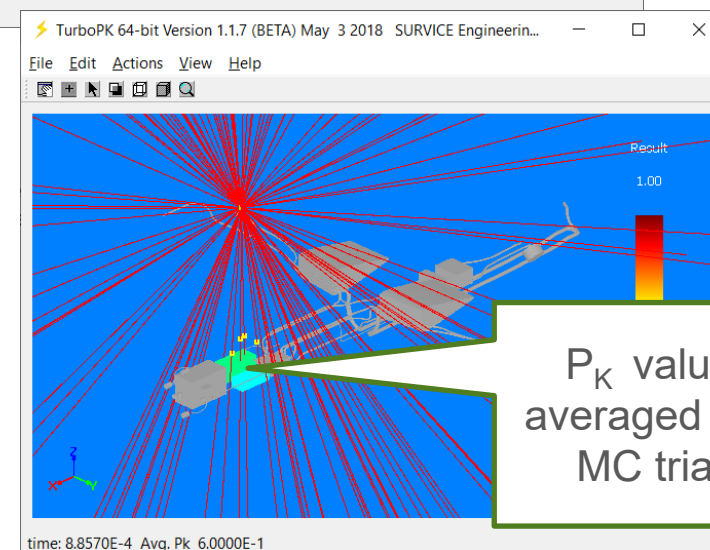


Example Endgame: 40-mm Air Burst Projectile vs. Drone

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



Point burst
20 Monte Carlo
trials



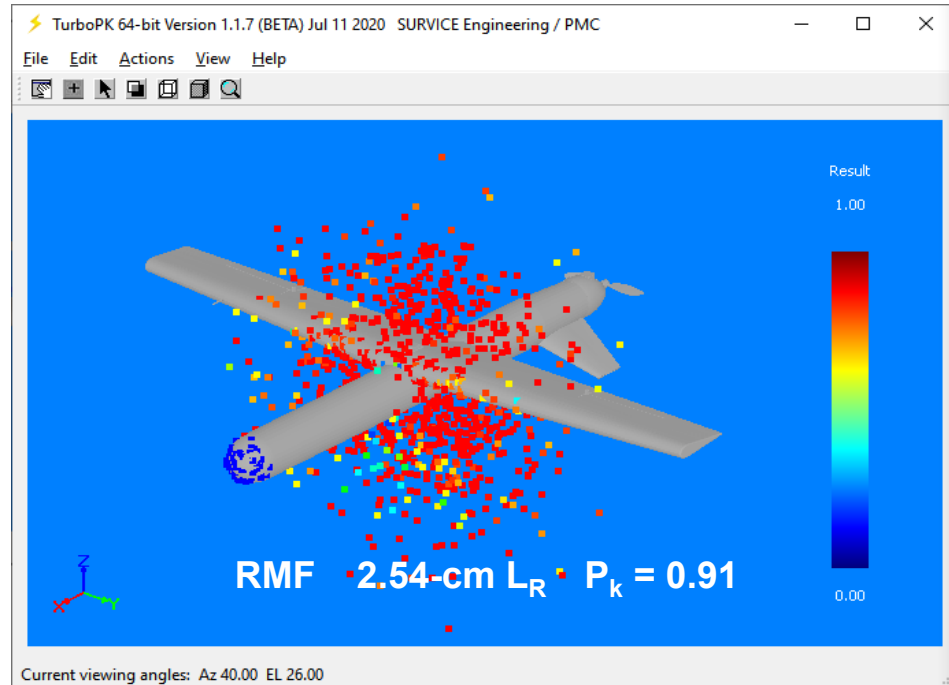
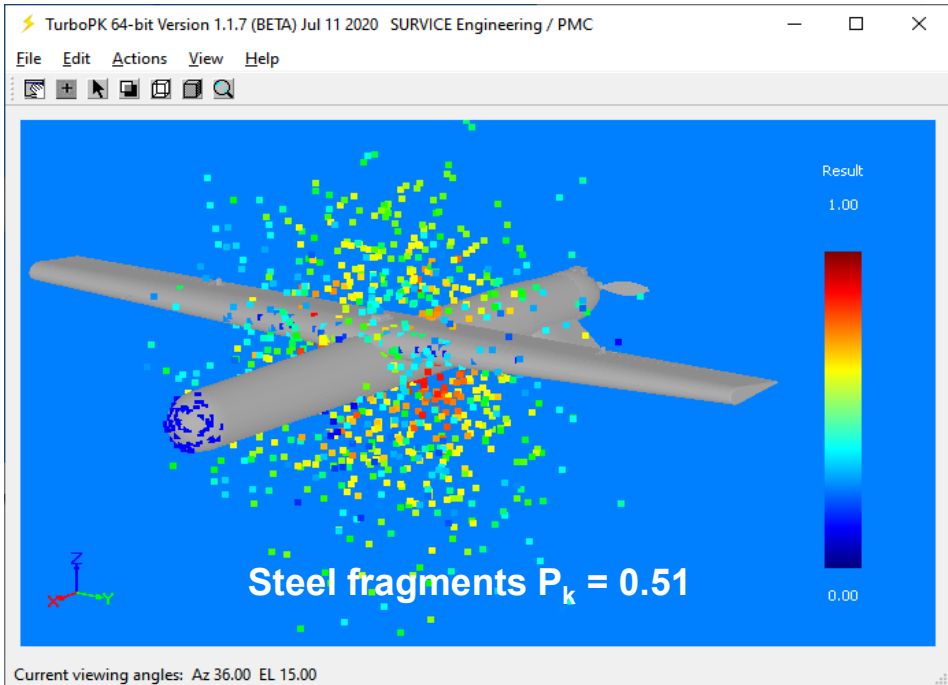
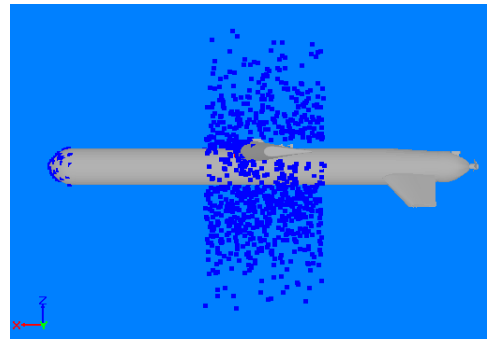
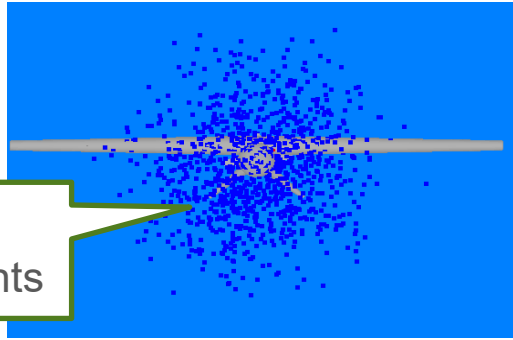
P_K values
averaged over
MC trials

Example Endgame: 40 mm vs. Drone

Head-on, 0.5-m CEP

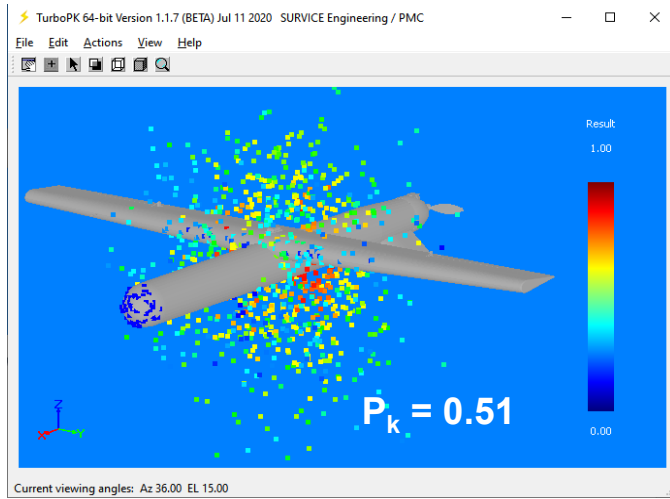
± 0.0015 -s timing error

1,000
burst points

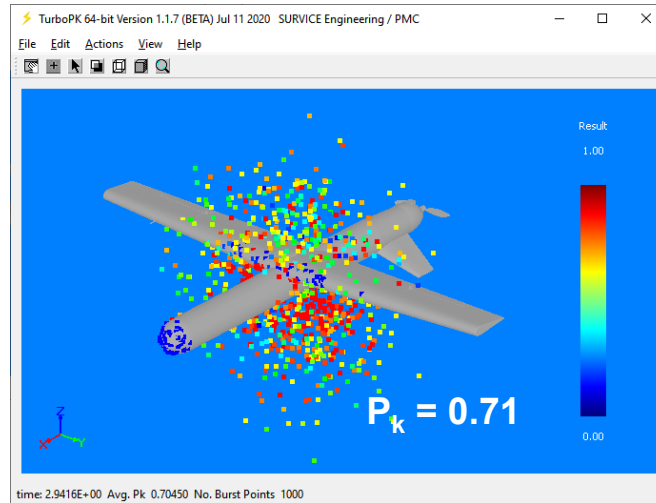


Example Endgame: 40 mm vs. Drone

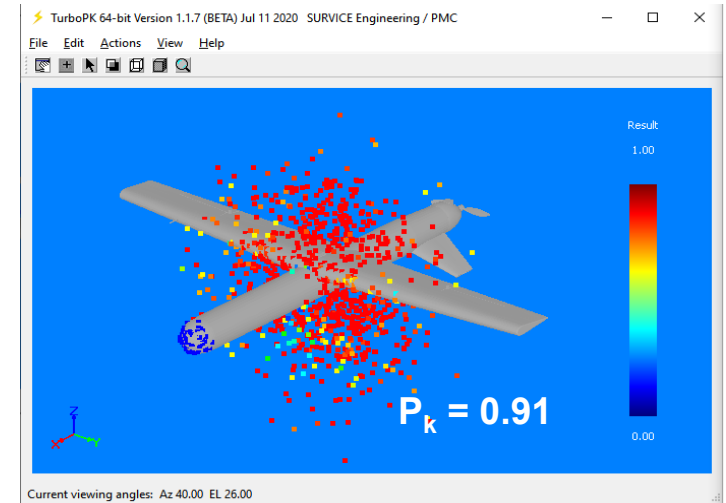
Steel



RMF Lethal Radius 0.0



RMF Lethal Radius 2.54

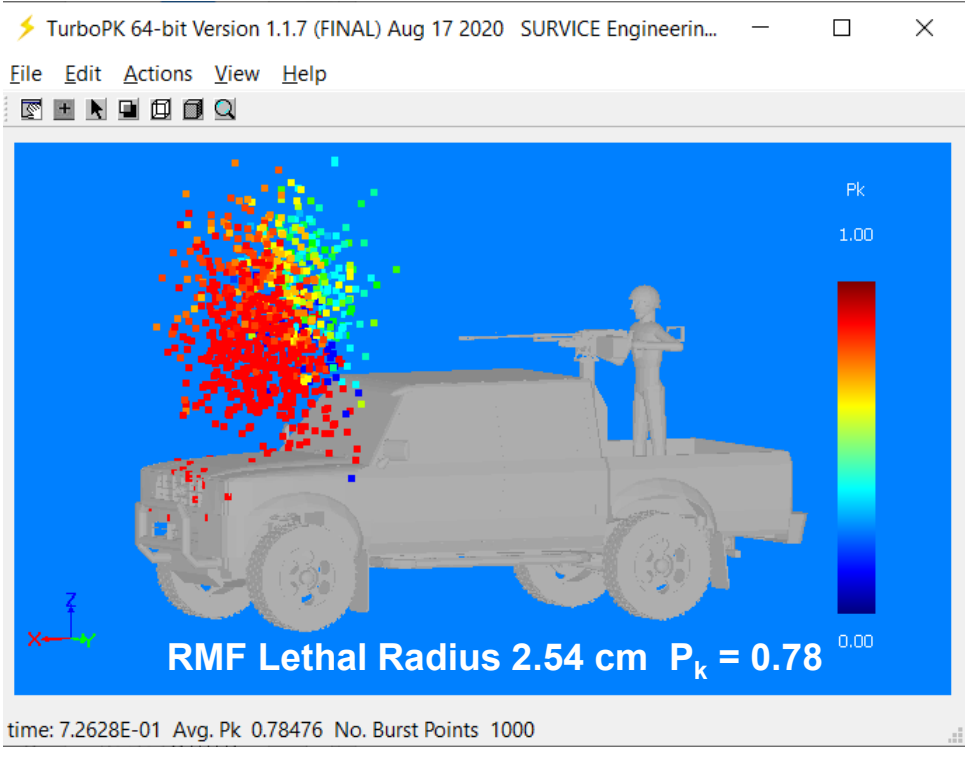
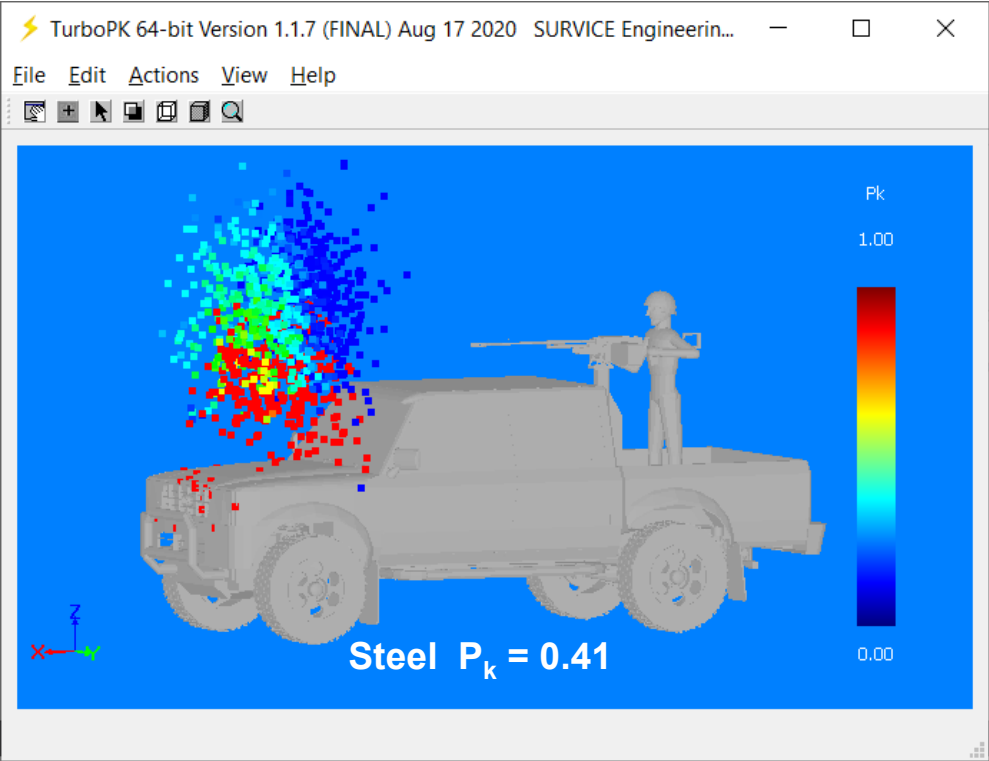


- KE only

- KE + CE $\rightarrow P_{K/H} = 1.0$

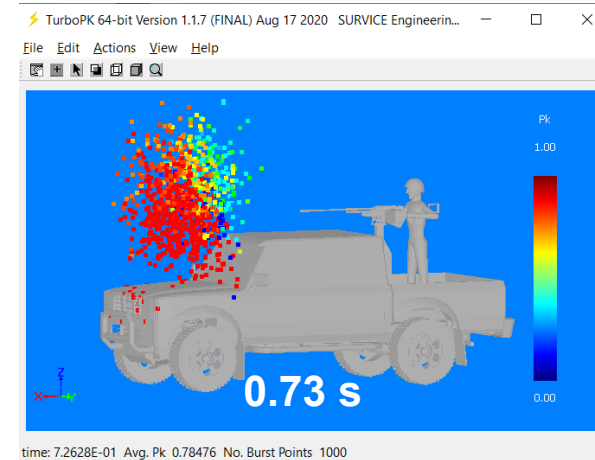
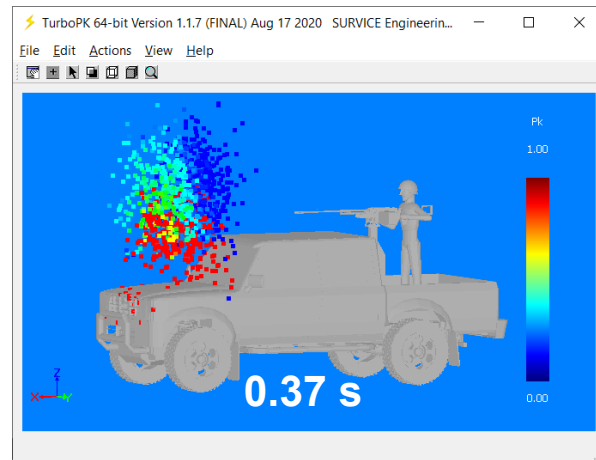
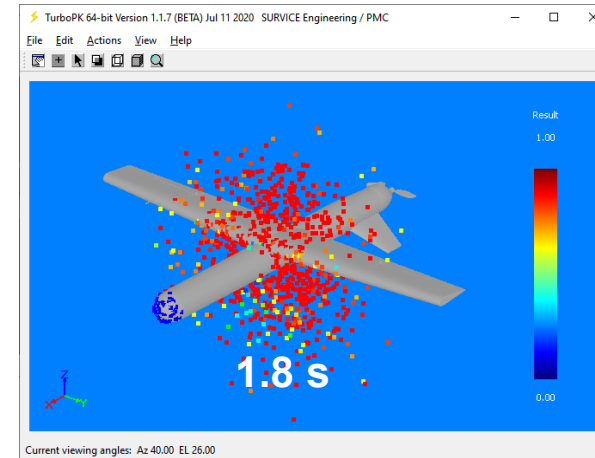
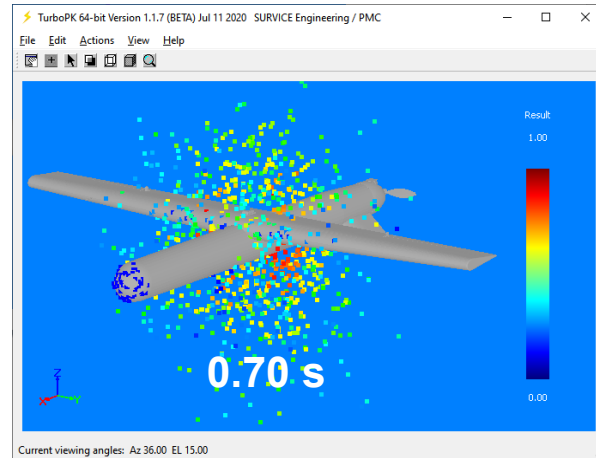
- KE + CE $\rightarrow P_{K/H} = 1.0$
- Lethal radius effect

Example Endgame: 40mm vs. Truck



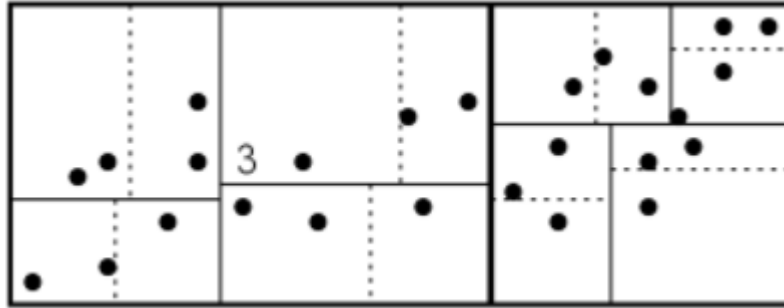
Example Endgame Run Times

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

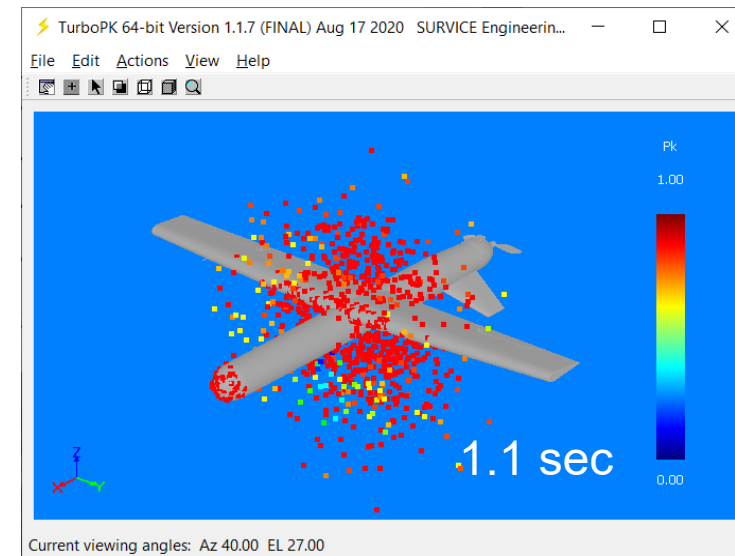
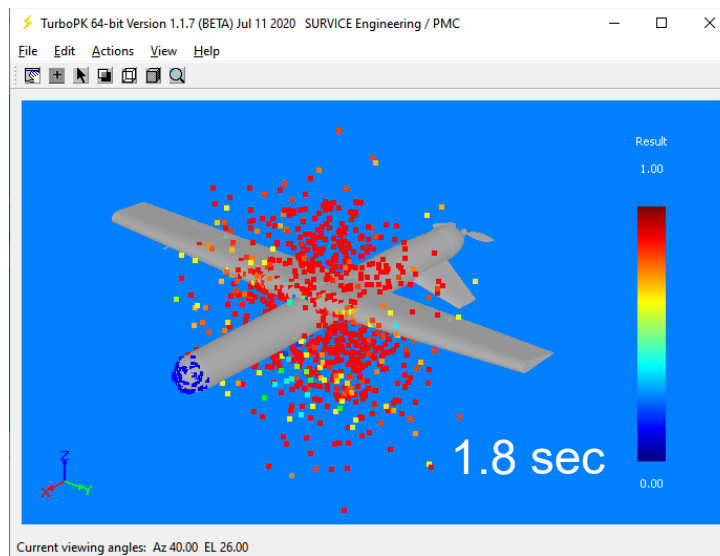
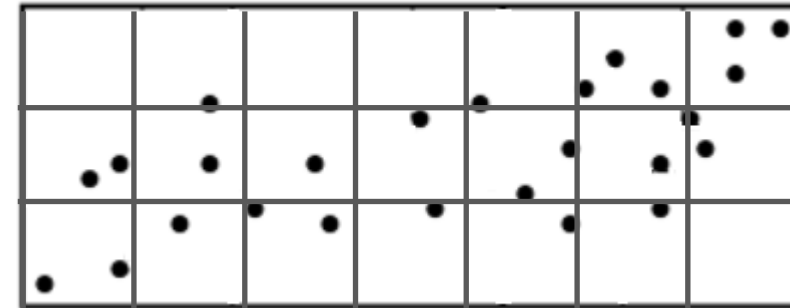


Alternative Point Structures

KD-Tree

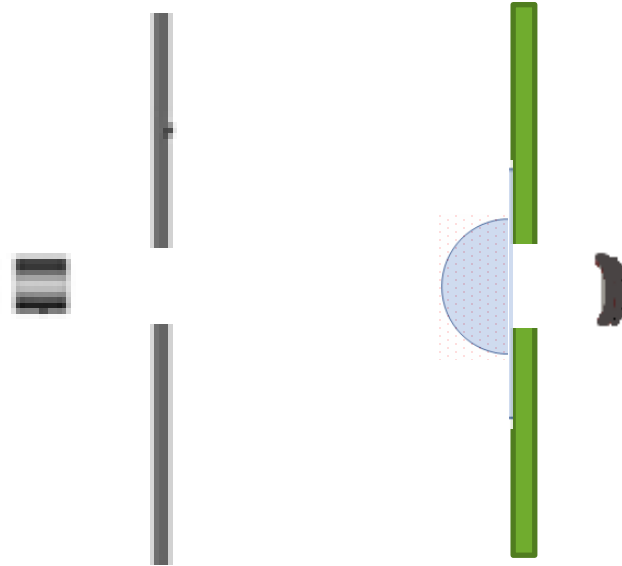


Uniform Grid



- 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
- $(KE \text{ loss}) / (\text{baseline KE})$
LR reduction

More Complicated RMF Model

RMF Model Parameters

Inert Fragments
TNT Equivalent Kg.

----- Reactive Metal Fragment Properties -----

Surface point spacing - cm
Grid Cell Edge - cm

Penetration Equations

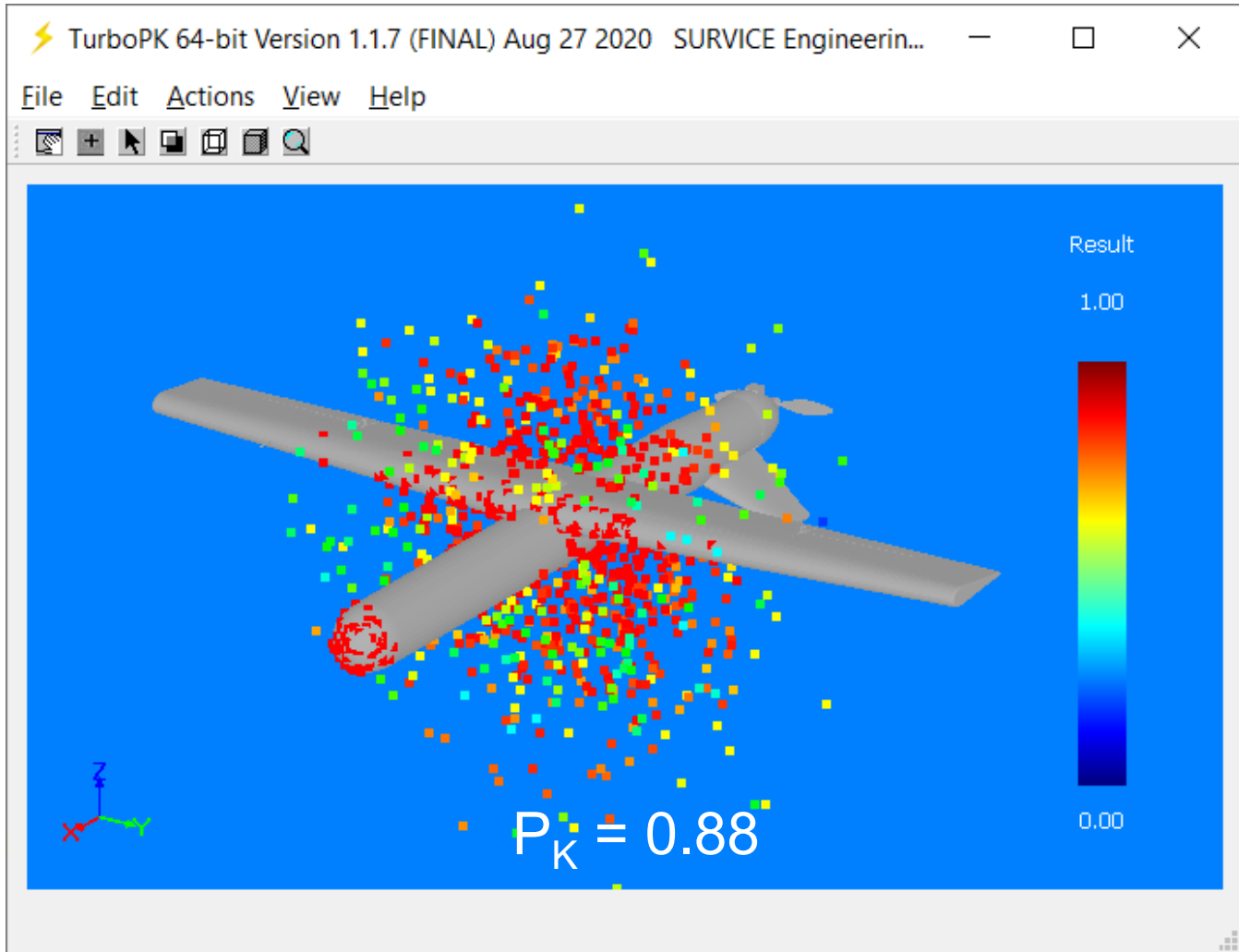
Initial impact ballistic limit increase % w.r.t. steel.
Subsequent impact multiplier %.

Lethal Radius Model

Maximum lethal radius - cm
Minimum lethal radius - cm
Impact speed for max lethal rad. mps
Impact speed for zero lethal rad. mps

Fragility Function Model

Pk % increase maximum.
Impact speed for max % increase mps
Impact speed for 0.0 % increase mps



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.