



Options and Uncertainties for Nuclear Mitigation in the 2025 Hypothetical Asteroid Threat Exercise Scenario

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The Delta V Criteria: Shifting Technical Risk

- The velocity threshold criteria were intended to be simple and conservative:
 - For a uniform impulse from ablation of the burst-facing surface:
 - If $\Delta v < 0.1 v_{\text{esc}}$, the object is very unlikely to disrupt.
 - If $\Delta v > 10 v_{\text{esc}}$, the object is very likely to strongly disrupt.
- A lot of previous work has assumed a high-speed trajectory, not rendezvous
 - Limited control of height of burst
 - Proximal operations have a high-risk of premature impact
- The hypothetical threat object size range and orbit make it difficult to adhere to the delta V heuristics for stand-off bursts
 - Up to a dozen impulses required in some cases
- This scenario allows rendezvous, which make proximal operations viable
 - Surface bursts couple much more energy to the target
 - Energy deposition is highly localized

Hypothesis: A Single 1 MT Burst in Close Proximity Could Strongly Disrupt the Hypothetical Threat Object.

- 2024 PDC is of comparable size, mass to the PDC 2011 conference venue, if substantially weaker.
- A 1 MT surface burst on Earth makes a transient crater of a size comparable to the threat object.
 - 300-500 m diameter
 - 50-100 m depth
 - Glasstone and Dolan, pp. 253-257
- A 1 MT surface burst on the threat object is not expected to make a smaller crater.
 - lower surface gravity, no air,
 - expected to be weaker than the rock under load used above.
- Koa crater on Eniwetok Atoll is a potential near neighbor



Top: Romanian Palace of Parliament, courtesy Wikipedia

Bottom: : Landsat image of Eniwetok Atoll, showing some of the craters Glasstone and Dolan's model was derived from. (NASA/USGS)

The Koa Crater in the Eniwetok Atoll is a Potential Near Neighbor

- Described in “Nuclear Cratering Experience at the Pacific Proving Grounds” (UCRL-12172)
 - Yield = 1.3 MT
 - Final crater diameter: 1.1 km
 - Transient crater diameter 400-500 m
 - Excavation depth: 41 m
- Extensive studies of the crater were done by the USGS PEACE Program in the 1980’s. (USGS Open-File Report 86-419 & etc.)

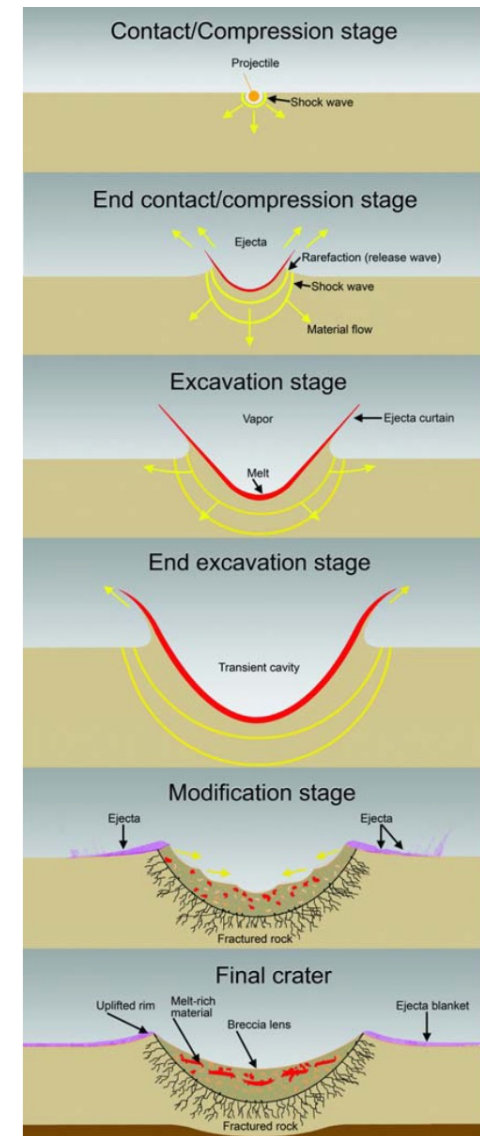
Top: Landsat image of Eniwetok Atoll, showing the Mike and Koa craters. (NASA/USGS)
Bottom: Frontispiece, UCRL-12172



The Amount of Material Displaced in a Strong Disruption Should be Predicted to be at Least that of a Similarly Sized *Transient* Crater.

- The transient crater is that which exists at the end of the excavation stage on Earth.
 - Third frame from the bottom
 - It is deeper and narrower than the final crater.
 - Over geologic time on Earth, the transient crater slumps, becoming wider and shallower.
- The modification process does not apply to our scenario, so we use the transient crater, not the final crater.
- We propose these dimensions as a lower bound.
- We hypothesize that if the device is big enough to move at least that much material on Earth, it should do so in space.

Image by B. French and D. Krings, LPI



Glasstone and Dolan Scaled Crater Predictions Suggest Disruption of 2024 PDC by a Near-Surface Burst is Possible.

- Transient crater dimensions for $Y = 1$ kt are experimentally determined
 - Dimensions can be scaled to other yields
 - $d(Y) = d(1\text{kt}) * Y^{1/3}$
 - Scaled predictions validated against experiments
- Cube root scaling example:
 - Scaled DOB = $DOB / Y^{1/3} = 0 / 1000^{1/3} = 0$
 - $30 \text{ m} < D(1\text{kt}, \text{HOB}=0) < 50 \text{ m}$
 - $300 < D(1\text{kt}) * 1000^{1/3} < 500 \text{ m}$
- Predicted transient crater $D > D$ threat object
 - lower surface gravity,
 - target expected to be weaker

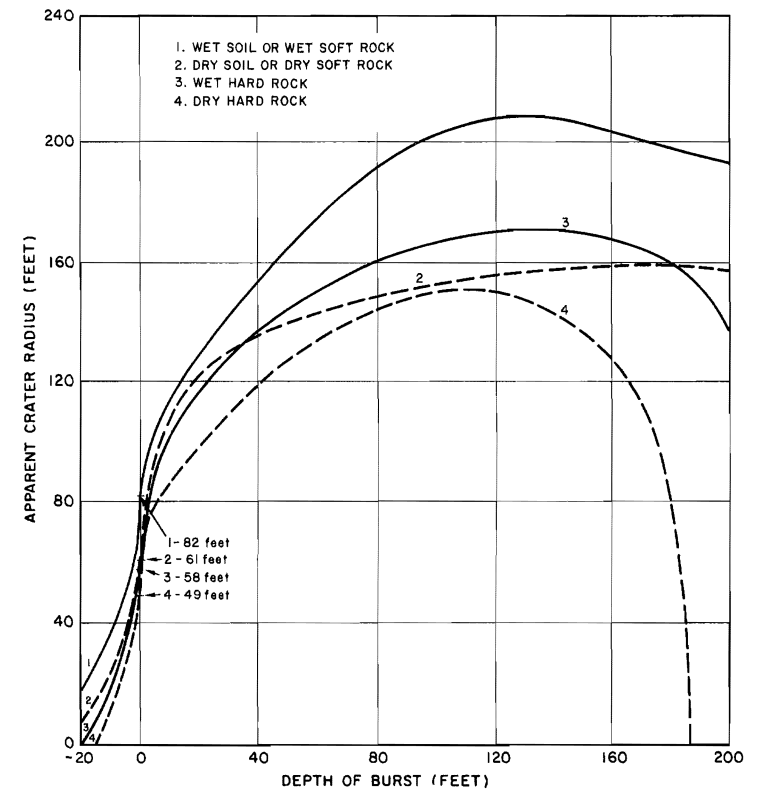


Figure 6.72a. Apparent crater radius as a function of depth of burst for a 1-kiloton explosion in (or above) various media.

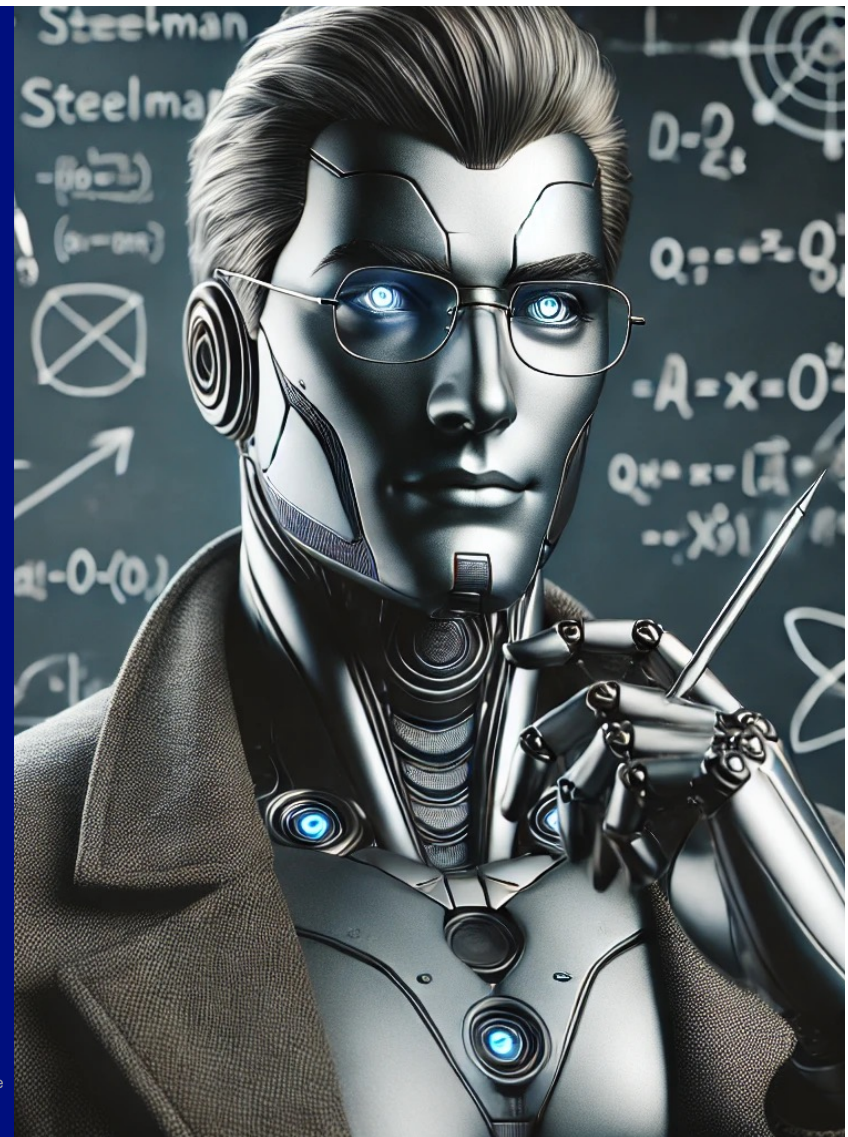
Mitigation Outcome Requirements Used in This Work

A community standard definition may be beneficial

- The initial target parameters should over-predict the difficulty of disruption
- No remaining fragment should be larger than Tunguska
 - We use $d = 30$ m, the lower end of Tunguska diameter predictions
- Q_m^* vs Q_D^*
 - Energy required to mitigate to our preferred specifications
 - Energy required to disrupt so that the largest fragment is 50% of initial
- Fragments should be left with sufficient velocity to miss Earth
 - Not well-posed
 - Solar wind effects on smaller particles
 - What amount of disrupted mass at what size distribution is tolerable?

Cautious Simplification Through a Steel Man Argument

- A rhetorical technique to address the strongest form of an argument.
- We believe 2024 PDC to be structurally weaker than solid SAE 304 stainless steel.
- We can model 2024 PDC as solid steel, which has well-known constitutive properties.
- If a steel target disrupts, we believe the attempt would likely also disrupt 2024 PDC.



Steel vs. S-type Asteroid: 2-3 Orders of Magnitude Stronger

	Yield	Tensile	Shear
S-type	0.2-5 MPa	< 10 MPa	< 10 MPa
SAE 304	294 MPa	200 Mpa	370 MPa

- We don't know the internal properties of 2024 PDC, or most asteroids, very well.
- The disruption threshold is dependent on these properties
- Specific cases that involve gravity regime cratering may be less sensitive to target strength
 - These cases involve high energies

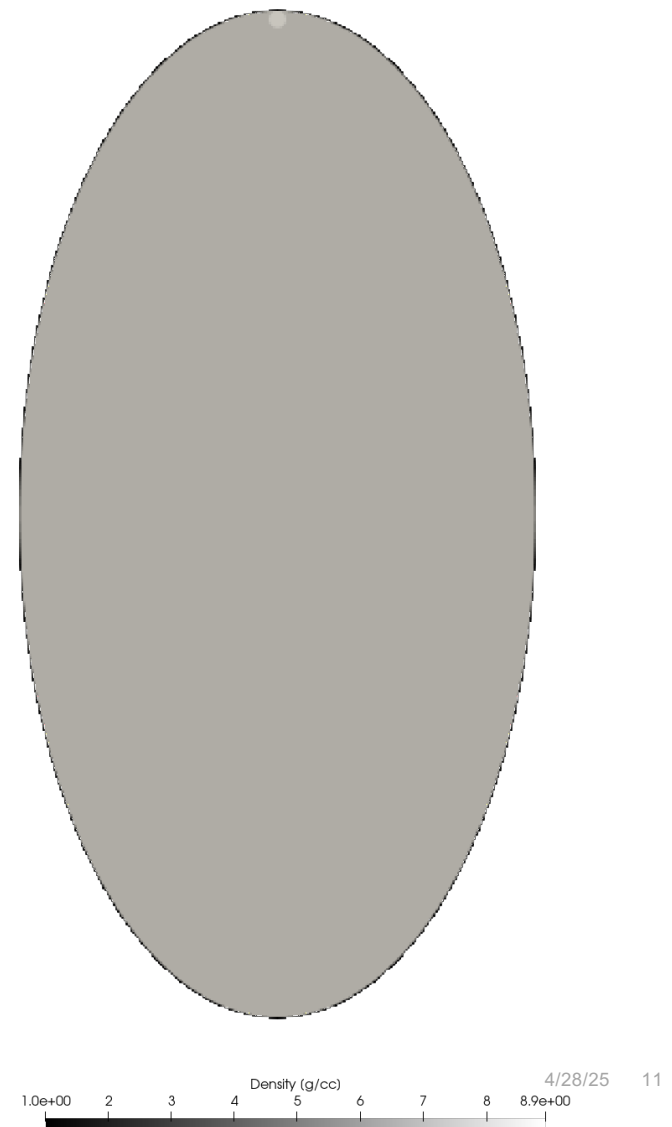


The Pagosa Hydrocode

- Pagosa is a 1-3D Eulerian finite difference code
- Fixed mesh (non-AMR)
- Used to study high-velocity impacts and high explosives phenomena.
- Weseloh et al. (2010)
- Verification and validation for crater modeling by Heberling et al. (2017)
- Was tested in the Stickle et al. (2019) code benchmarking study prior to DART.

2024 PDC Epoch 2 Steel Man Model Input

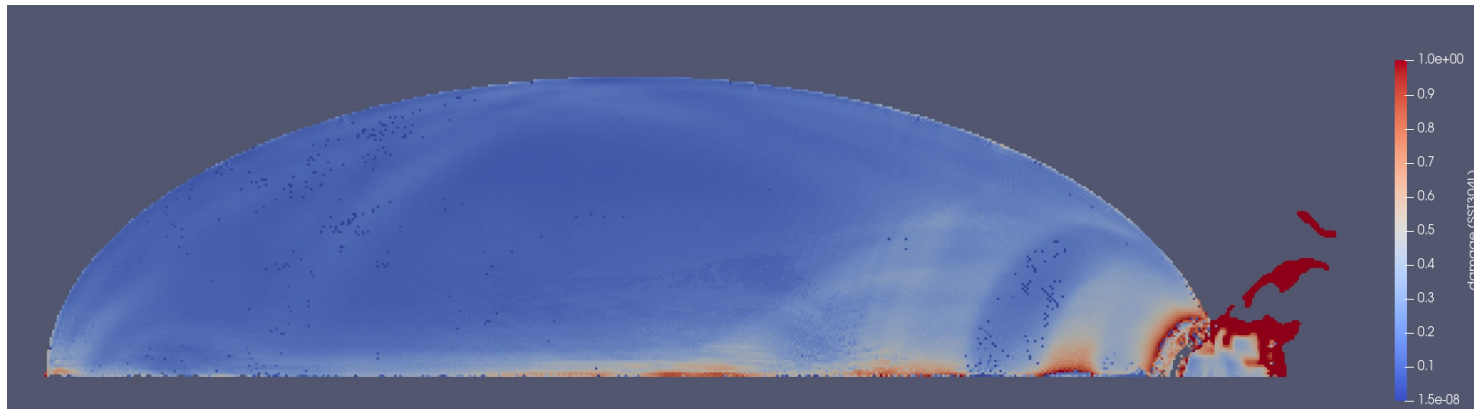
- Pagosa:
 - Hydrodynamics only, no x-rays.
 - $dx = 50$ cm fixed mesh
 - 2d-axisymmetric
- Energy pill has variable internal energy sourced into a copper sphere:
 - $d = 2$ m, Mie-Gruenisen Copper EOS
 - 1 ton TNT $< Y < 500$ kt TNT
 - At the surface along the long axis, partially buried
- Threat object
 - 95th percentile ellipsoid (121m x 124 m x 236 m)
 - Homogeneous Sesame EOS 4272
 - Preston-Tonks-Wallace strength
 - Yield stress: 0.002944 Mbar
 - Johnson-Cook damage
 - spall stress: 0.05861 Mbar



2024 PDC Epoch 2 Steel Man Model Results

Yield (kt)	Disrupted ?	Q^*_D Achieved?	$dV > 100$ cm/s ?	Energy Imparted
500	Yes, $t < 0.4$ s	Yes, $t < 0.2$ s	Yes, $t < 0.1$ s	170 kt deposited, ~50 kt does work on solids
200	TBD	TBD	TBD	60 kt deposited, ~ 30 kt does work on solids
100	TBD	TBD	TBD	30 kt
10	No	No	No	3.7 kt
1	No	No	No	0.55 kt
0.001	No	No	No	~10 lbs TNT

2024 PDC Epoch 2 Steel Man Model Results: Non-Disruption Cases

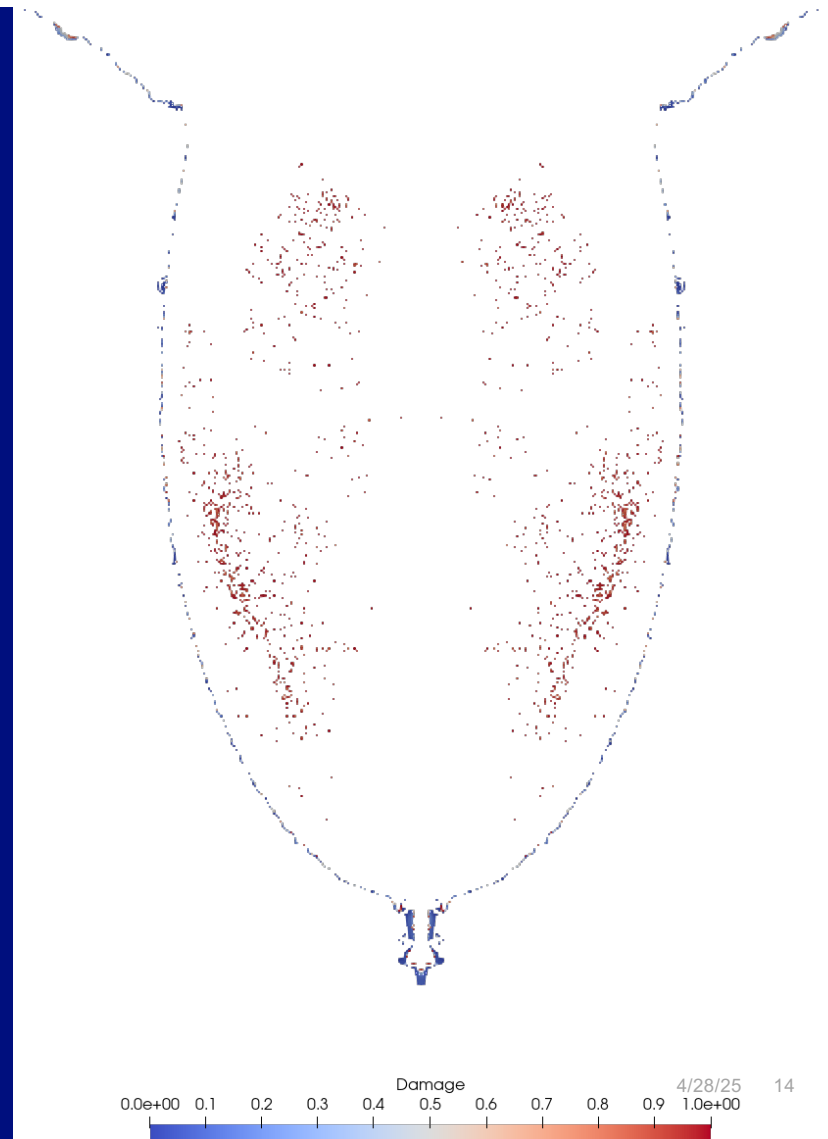


Yield (kt)	First shock crossing	Time shock attenuated to -pfail < P < yld str., -0.05861 < P < 0.002 Mbar	Damage at time of attenuation
10	t = 0.0383 s	t > 0.07 s	TBD
1	t = 0.0387 s	t = 0.0676	minimal
0.001	t = 0.0412 s	t = 0.0412	minimal

2024 PDC Epoch 2 Steel Man Model Results

- A single 500 kt – 1 Mt contact burst appears sufficient to strongly disrupt a steel object of the same volume as the 95th percentile case of 2024 PDC.
- It should be sufficient to disrupt any instantiation of 2024 PDC.
- Parameter studies are ongoing to constrain a lower bound estimate of the energy required to mitigate, for completeness, does not drive mission design.

Contiguous portions of the steel target subject to the 500 kt blast with damage < 1 are meter-scale or smaller at late time.



2024 PDC Epoch 2 Geologic Model Input

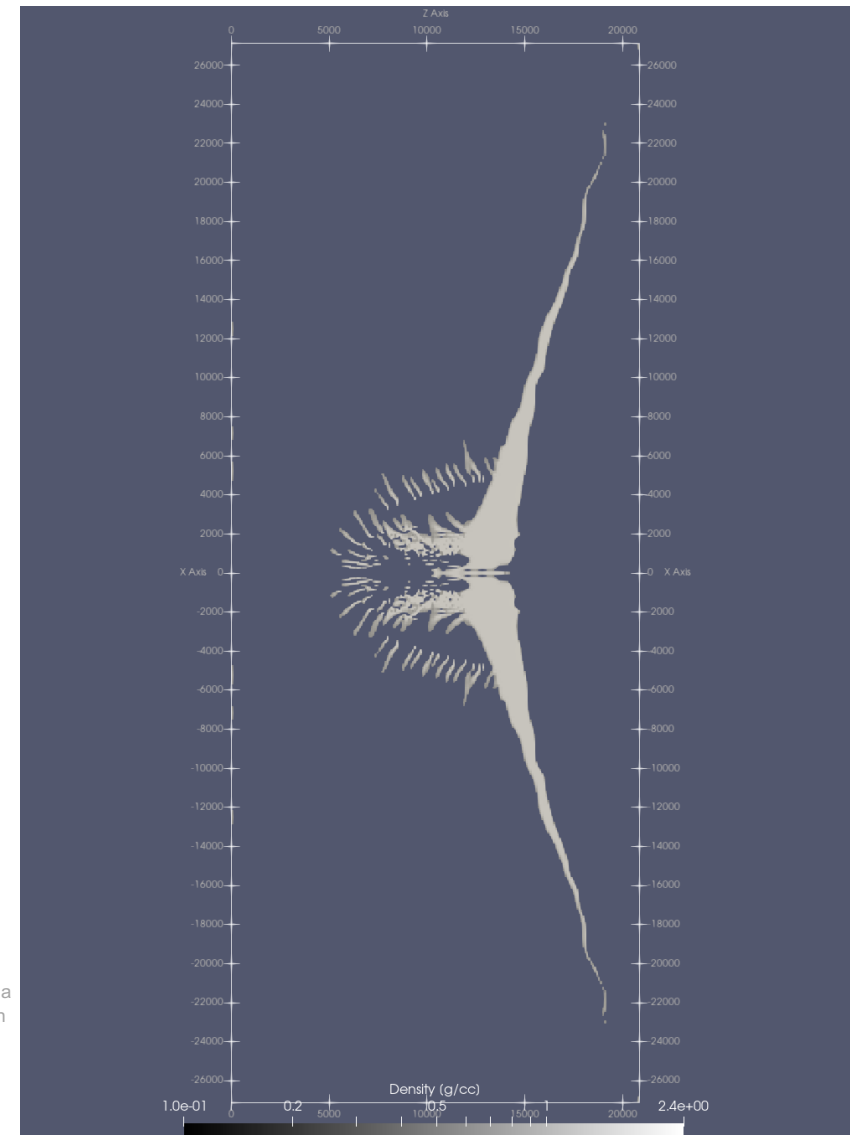
- Pagosa:
 - Hydrodynamics only, no x-rays.
 - $dx = 50$ cm fixed mesh
 - 2d-axisymmetric
- Energy pill is 500 kt internal energy sourced into a copper sphere
 - $d = 2$ m
 - Mie-Gruenisen EOS
 - At the surface along the long axis, partially buried
- Threat object
 - 95th percentile case
 - SESAME Nevada Alluvium EOS
 - Porosity implicit in the EOS to include PdV work.
 - Kospall strength model, cohesion \sim yield strength.
 - Homogeneous material.



2024 PDC Epoch 2 Geologic Model Results

- As expected from the steel man models, all cases strongly disrupt.
- 95th percentile case model suggests strong disruption by $t = 1.0$ s
 - One Tunguska-sized contiguous piece
- Craters made by explosions this size are in the gravity regime.
 - May be less sensitive to details of target strength.

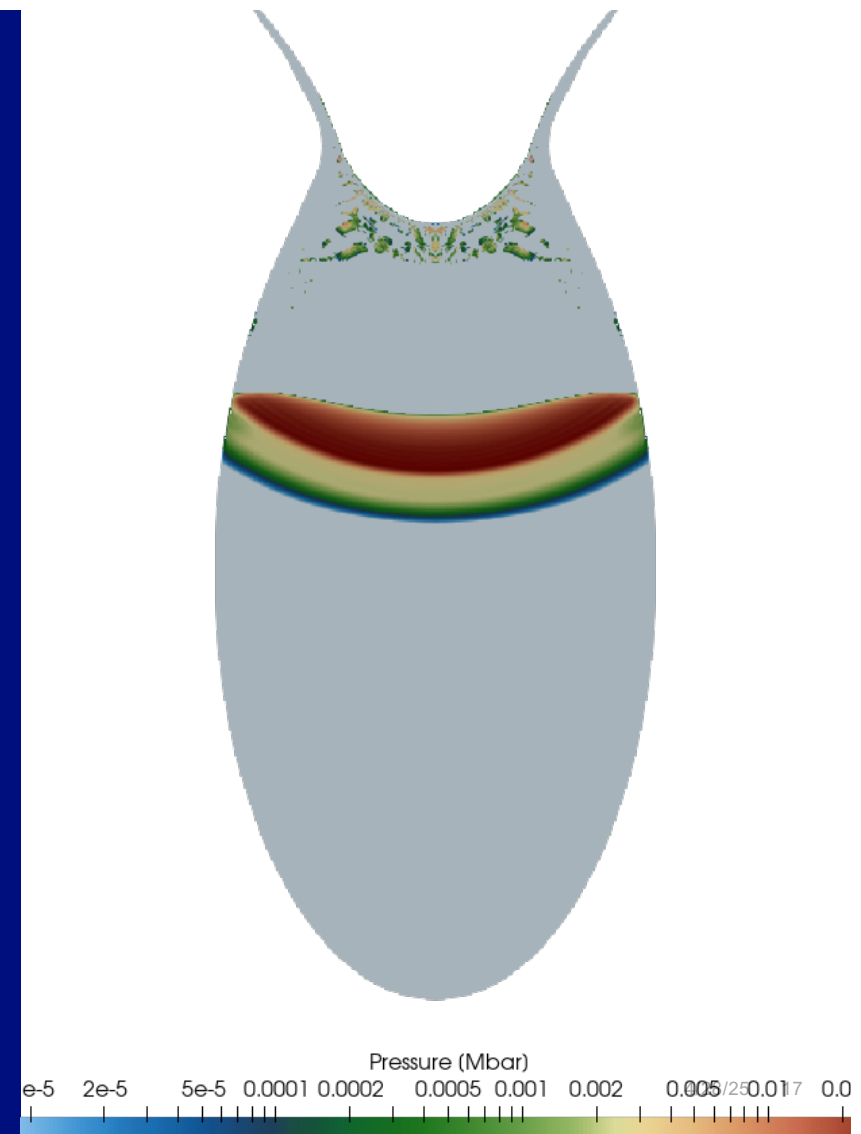
Right: Hydrodynamics simulation of a 500 kt energy pill tangent to the 95th percentile threat object.



Potential Applications

- Disruptions are insensitive to:
 - B-plane direction
 - perihelion timing
- As a main option:
 - 2032-2039, per Barbee et al. (this meeting)
- Reserve options (upon main option failure)
 - Post Northward IBD: 2034-2039
 - Post Southward IBD: 2035-2039
 - Post Southward Partial IBD: 2035-2039
 - Post KI Backup Dates: 2037-2039

Right: A cross-section of a shock wave traveling through a disrupting steel target. Pagosa 500 kt steel simulation at $t=0.01$ sec.



Remaining Questions

- Mission options for contact binaries
 - 2+ devices placed carefully?
- Time required for dispersal of decameter scale fragments
- A specific consensus definition of mitigation outcome requirements
 - based on expected ground effects?

Right: A cross-section of a disrupting steel target, colored by damage, thresholded to $D < 1$. Pagosa 500 kt steel simulation.

