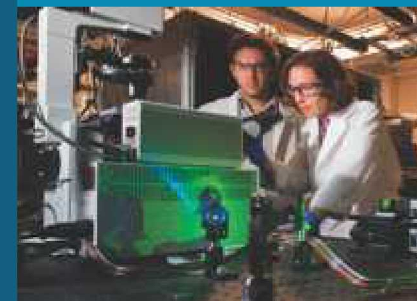
SAND2019-4104C

Mesoscale Modeling and Debris Generation in Hypervelocity Impacts



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HVIS 2019.04.19

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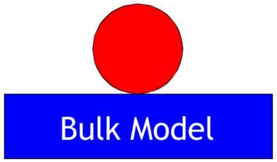
Overview

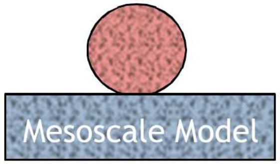
Background and Motivation

Hydrocode Input Development

Bulk (Isotropic) Model
- Overview
- Results

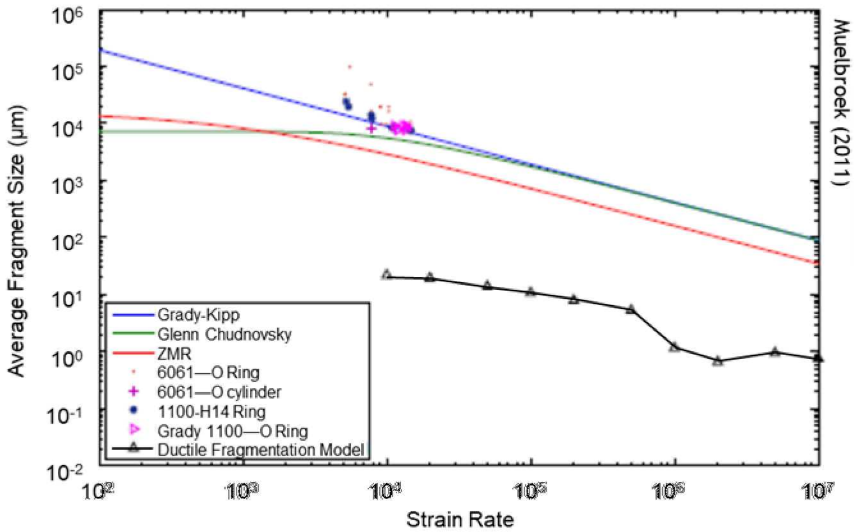


Mesoscale Model
- Overview
- Results



Summary

Background and Motivation



- Electro-optical/infrared (EO/IR) signatures from hypervelocity impacts originate from small, hot debris
- System-level hypervelocity impact modeling relies on sub-grid fragmentation theories to predict micro-debris
- Little data exists to validate micro-debris models, especially at higher strain rates

Goal of this study:

- Use the CTH shock physics code to investigate differences in the predicted strain rate at failure (as a proxy for fragment size) and material temperature when explicitly modeling mesoscale grain structure versus using a traditional bulk approach to asses the potential impact on EO/IR source and signature generation

$$S = \left(\frac{\sqrt{24}K_c}{\rho c\dot{\varepsilon}}\right)^{2/3}$$

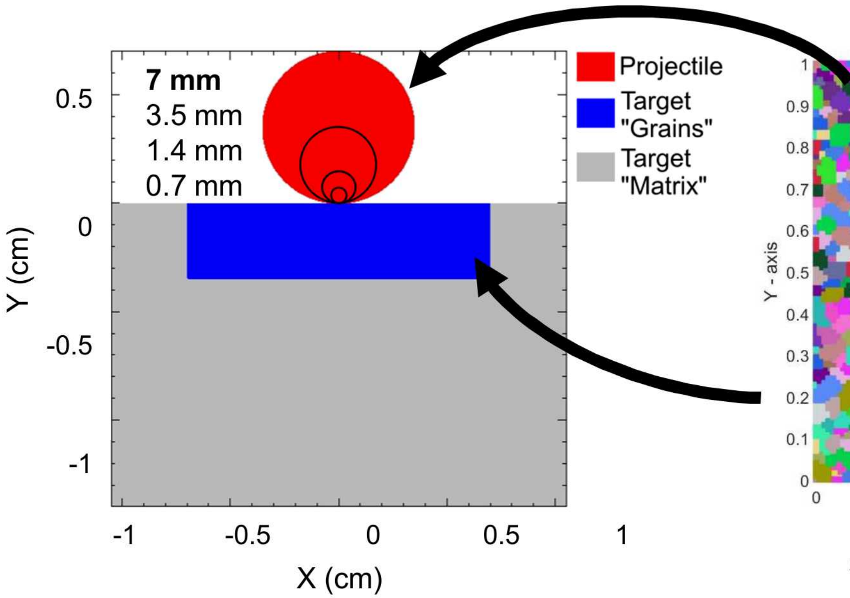
Grady-Kipp Fragment Size
(dominated by fracture toughness)

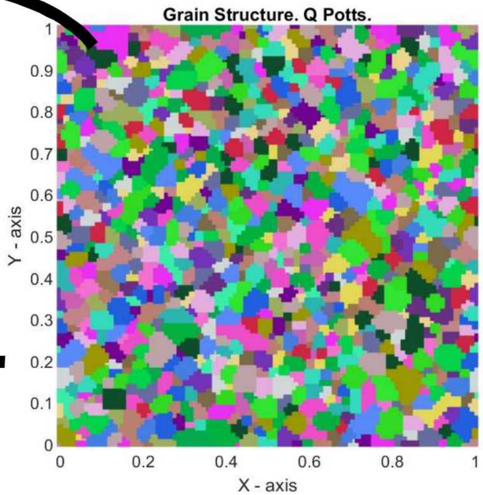
$$P = \sigma A T^4$$

Radiative Power Output

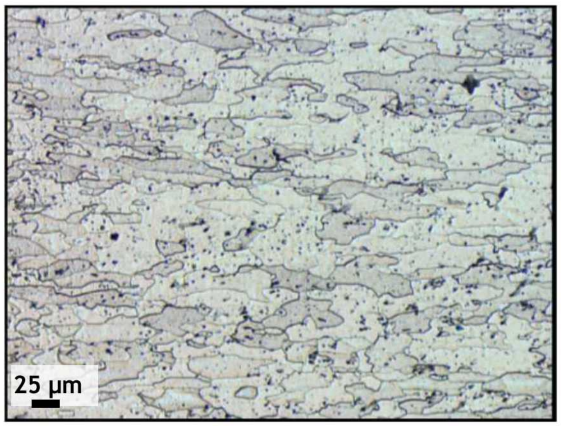
CTH Input Development

- 2D CTH model
- Aluminum sphere on aluminum plate, impacting nominally at 4 km/s
- SESAME equation of state with Johnson-Cook strength, Johnson-Cook fracture, and Grady-Kipp fragmentation
- Cell structure generated in MATLAB from 2D grain growth model for a unit cell
  - Scaled the unit cell so that grains are ~14 μm in diameter
  - Eight grain types (eight different material initializations) in both projectile and target
- **Future work** would expand effort to 3D CTH models and the exploration of grain aspect ratio



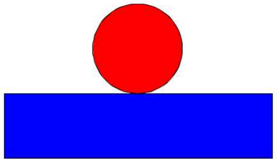


MATLAB unit cell output



Pure aluminum imaged by Clemex Vision image analyzer

Bulk (Isotropic) Model Overview



Recall: Goal is to assess effects of grain structure on strain rate at failure and material temperature

Bulk (Isotropic) Model:

Standard simulation method

- No grains simulated
- Baseline for comparison with mesoscale models

Explore underlying physics through tests of:

- Resolution
- Projectile Size
- Impact Speed

Assess effects primarily in the projectile (most interesting results result in finite-thickness objects)

Major Findings:

Increasing resolution increases strain rate, but convergence is observed in temperature

- 3.5 μm resolution was chosen for remainder of sims

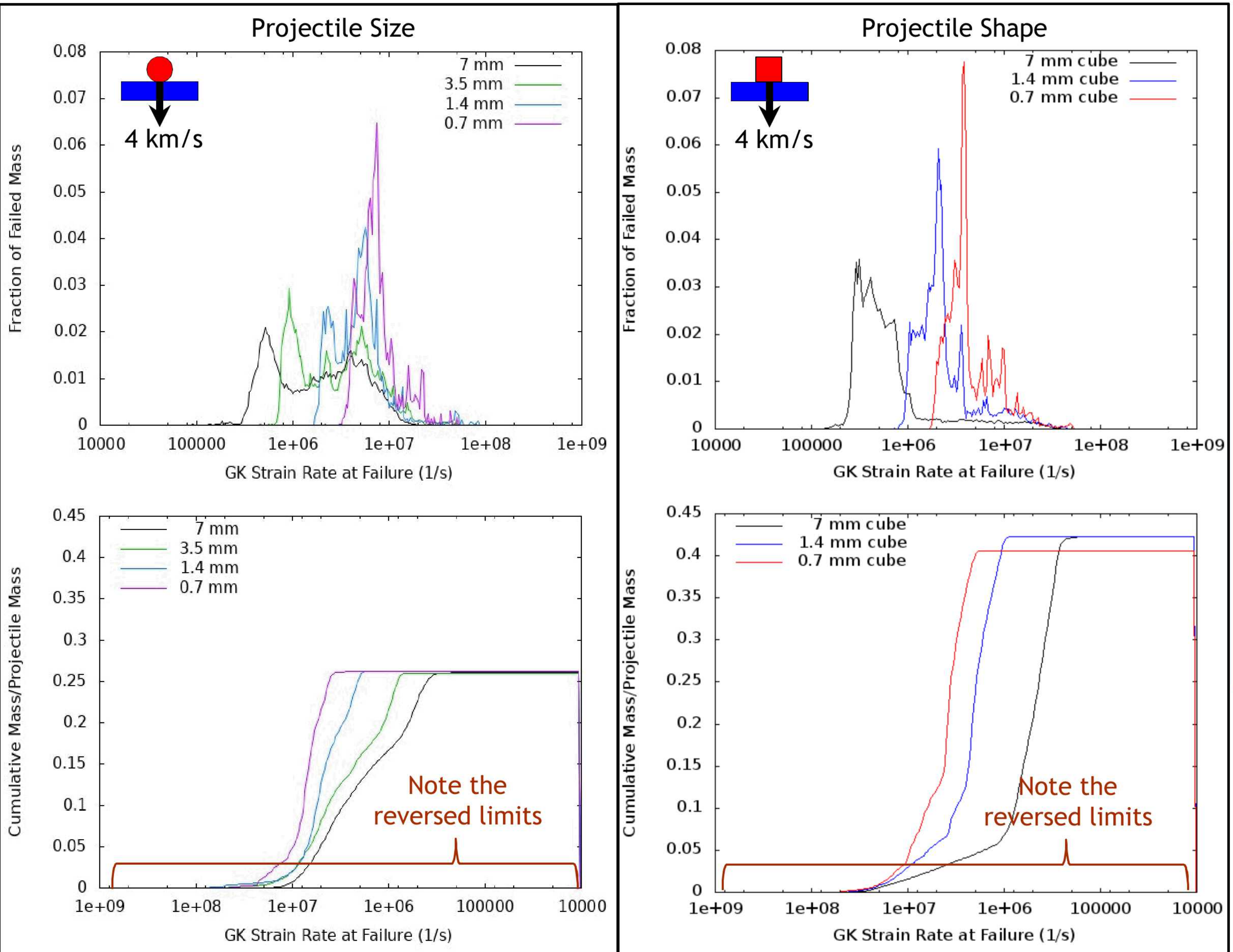
Strain rate histograms have a bimodal distribution

- The onset of the first peak and the separation between peaks is dependent on projectile size
- 1^{st} peak appears to be driven by transit time across object (i.e, by a length scale, in this case projectile diameter)
- 2^{nd} peak appears to be related to sound speed

Reducing projectile size and/or increasing velocity, shifts to higher strain rates

For a given velocity, peak temperatures and temperature distributions are similar between all projectile sizes

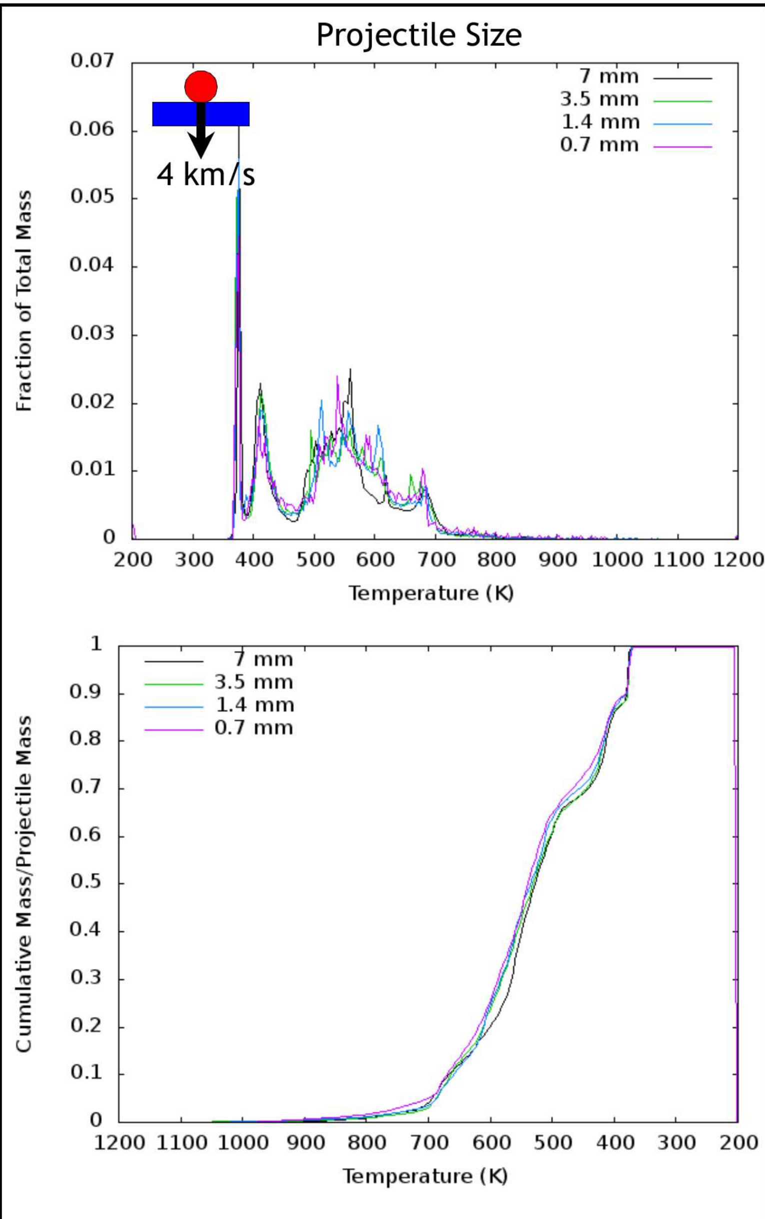
Bulk Model Results: Comparisons of Strain Rate at Failure

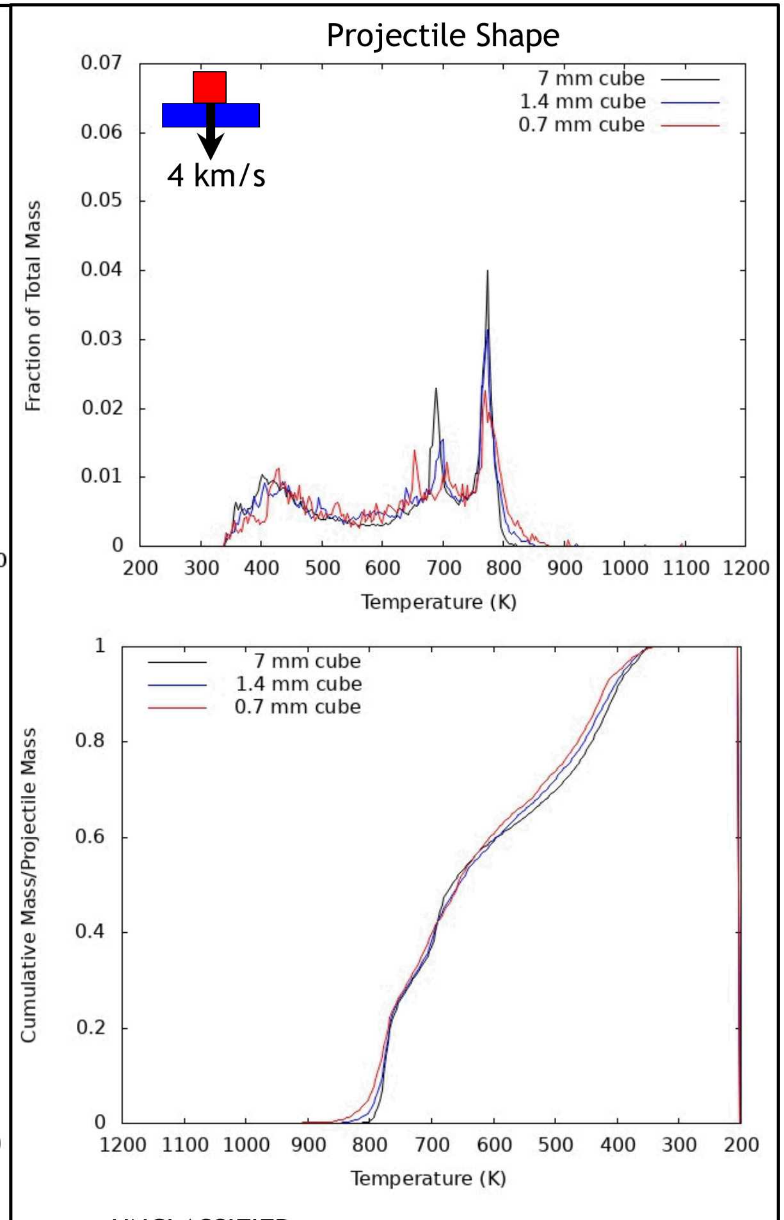


Projectile **size** and **shape** control bimodal distribution of strain rates.

Smaller projectiles produce **higher strain rates** (smaller fragment sizes)

Bulk Model Results: Comparisons of Material Temperature

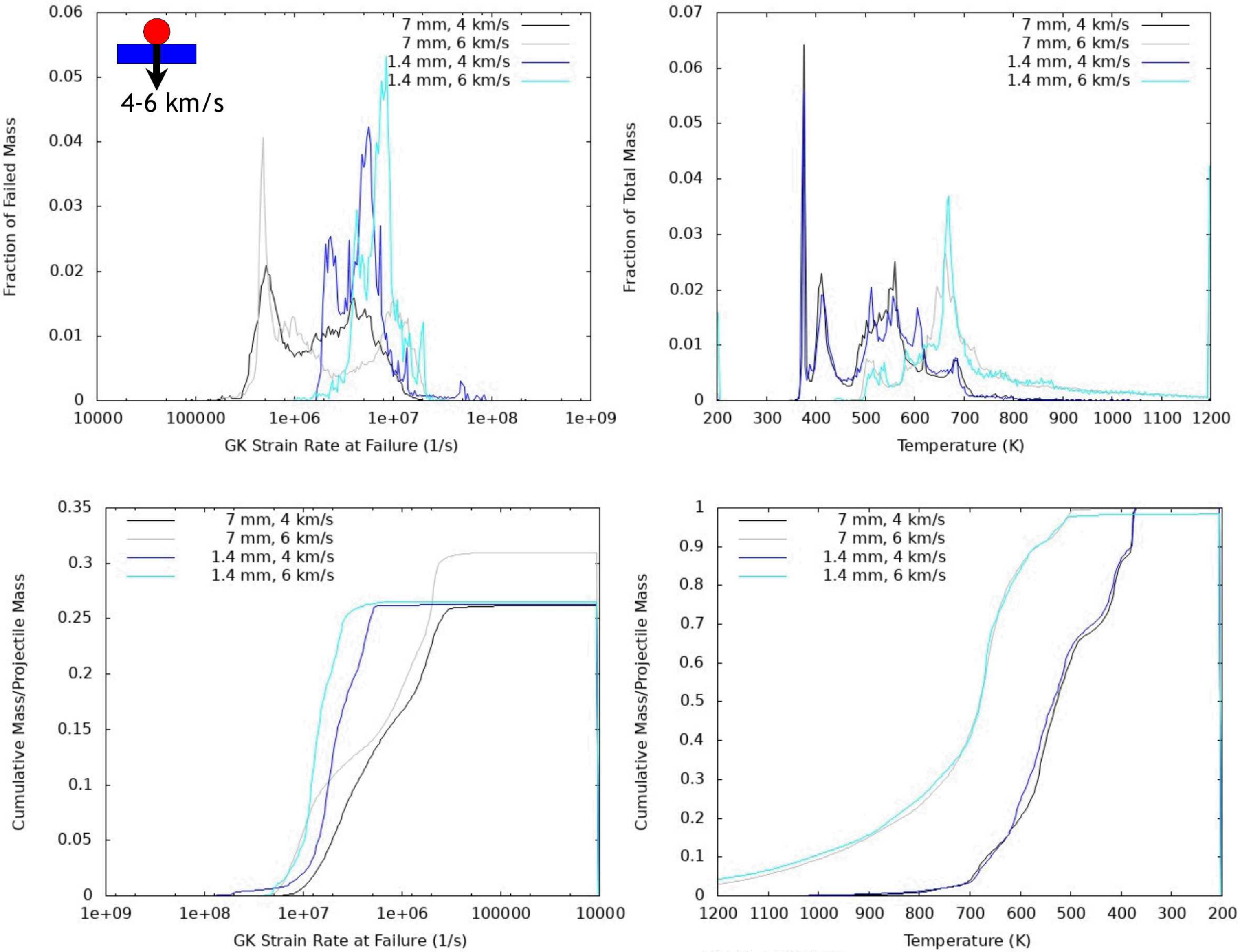




Cube (face-on) projectiles produce **higher temperatures** and therefore **higher expected EO/IR signatures**.

Finite targets (more realistic targets) may produce strain rates and temperatures that are similar to cube projectiles.

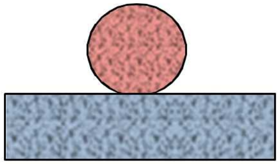
Bulk Model Results: Impact Velocity on Strain Rate & Temperature



Increased impact speed results in higher strain rates and temperatures (**smaller fragments**).

Impacts at the same speed result in similar temperature distributions regardless of impactor size.

Mesoscale Model Overview



Recall: Goal is to assess effects of grain structure on strain rate at failure and material temperature

Mesoscale Models:

Explore the effects of modeling individual grains within a material

Vary grain properties such as:
- Strength and fracture properties
- Interface properties (slip)
- Void space

Note: Results will be shown for the 7 mm diameter projectile (500 grains across)

Major Findings:

The range of results when modeling grains in a consistency study encompassed bulk model results and indicates acceptable agreement between methods

Attempts to change material properties or interfaces of grains had minor effects
- Shift toward lower strain rates, decrease or smoothing of 2^{nd} peak
- Shift toward higher material temperatures

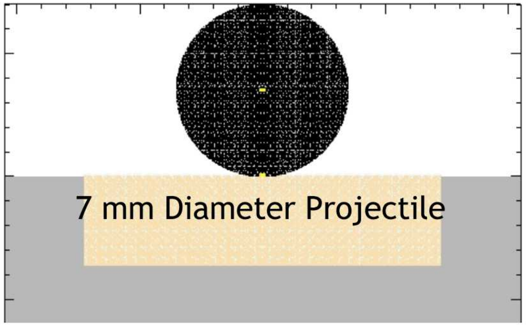
Interfaces between grains (by void in this study) had major effects
- Dampening pressure wave through grains
- Overall shift to higher strain rate at failure and material temperature
- Significant decrease in 1^{st} strain rate peak

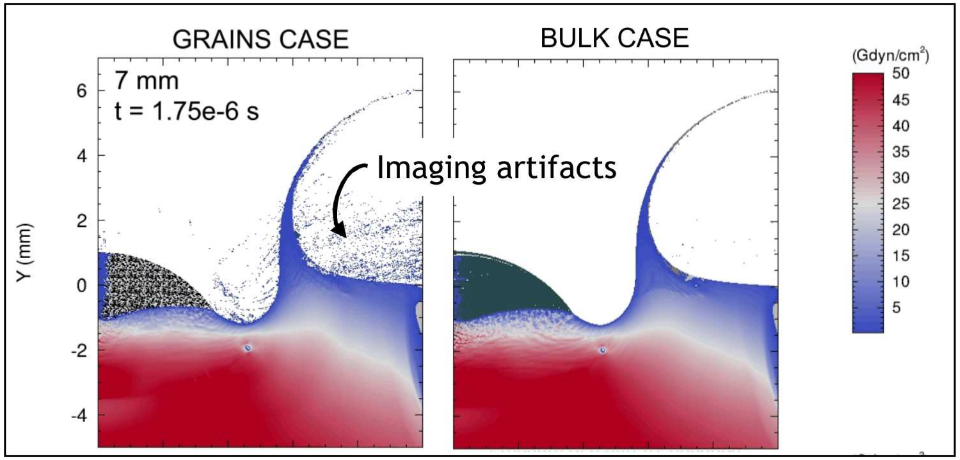
Mesoscale Model Results

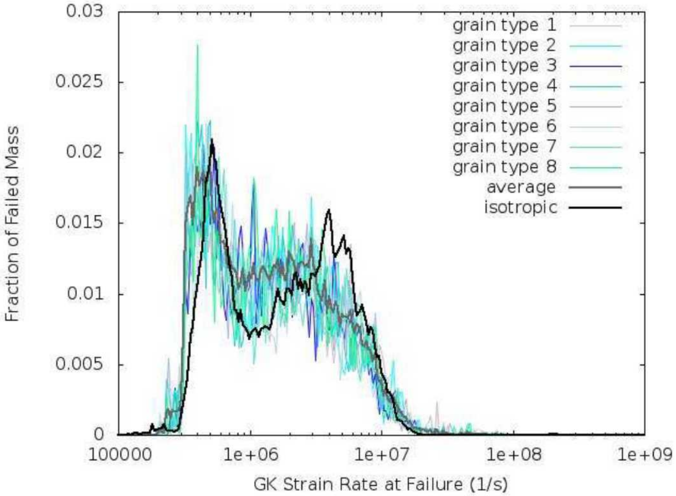
Consistency Study

- Compare a mesoscale grains case in which all grain types are composed of the same material as the bulk model
  - Each grain type is individually initialized in the code

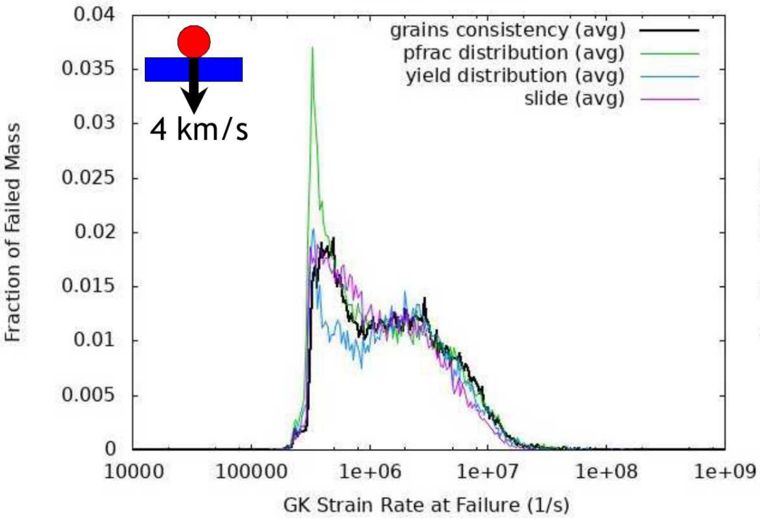
- Differences between the averaged grain type results and the bulk model are attributed to numerical effects
  - Plots of pressure for each case are nearly identical except for imaging artifacts
- Consistency study average used for comparisons

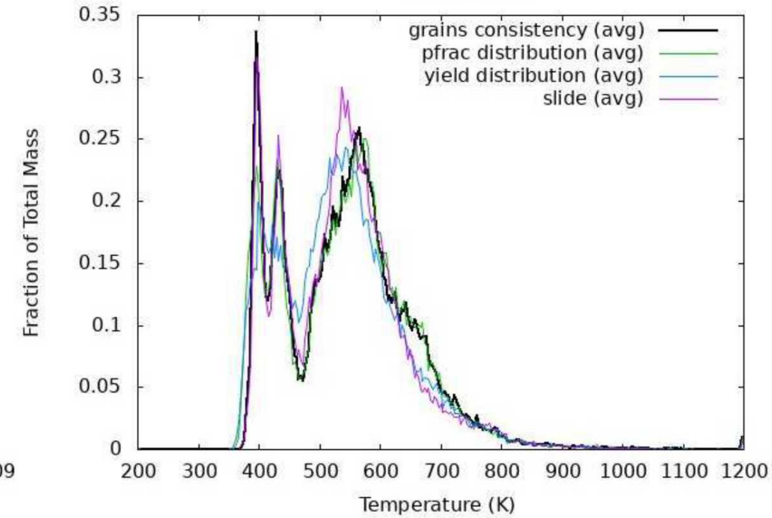


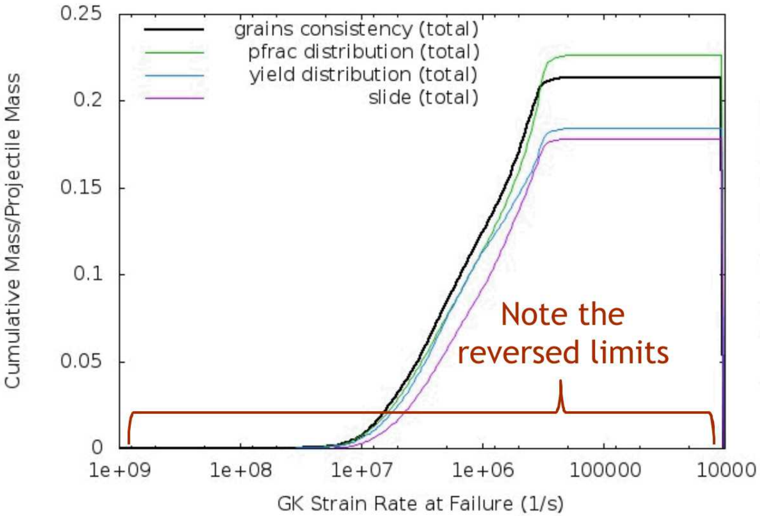


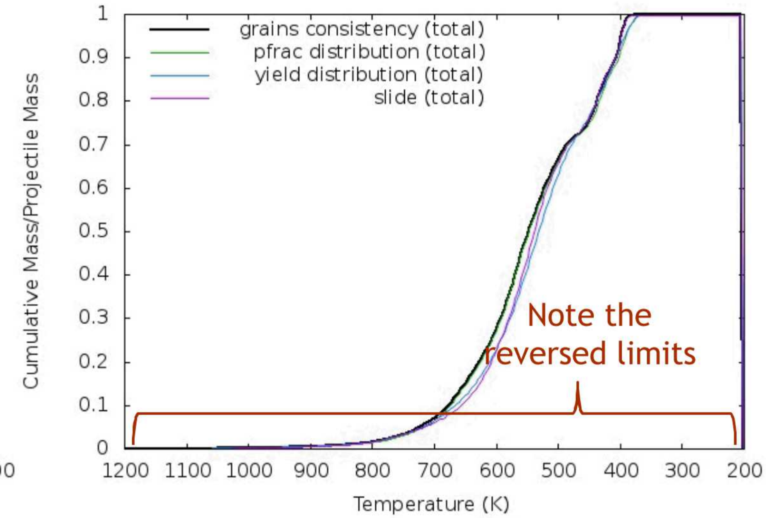


Mesoscale Model Results: Comparison of Studies (Strain Rate & Temperature)



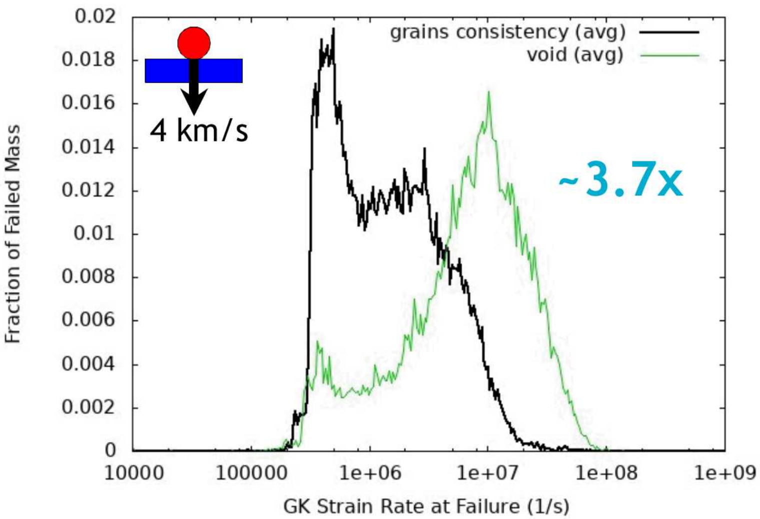


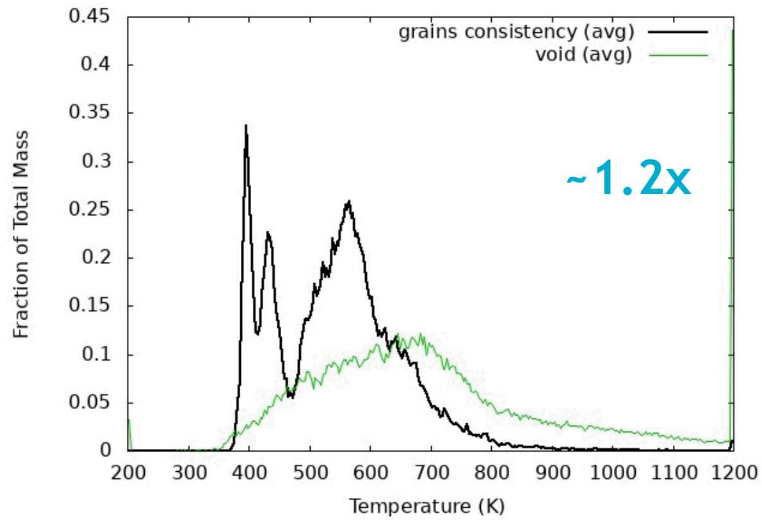


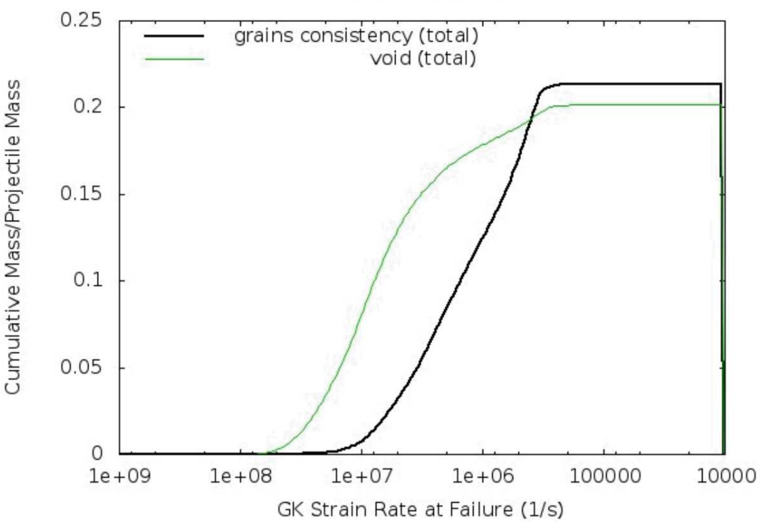


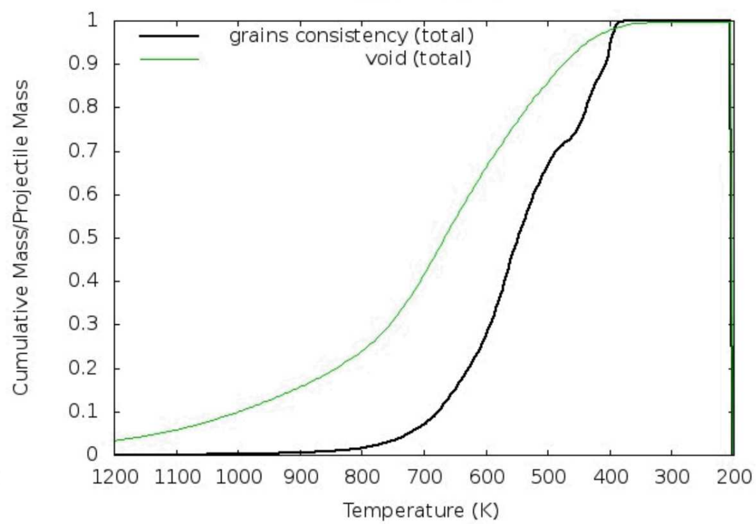
- A distribution of spall strengths (centered on that of Al), **pfrac**, resulted in an increase of low strain rates.
- A distribution of **yield** strength between grains decreased low strain rates but did not affect higher strain rates.
- Allowing slip (**slide**) between grains had inconclusive results because of grain configuration and/or algorithm

Mesoscale Model Results: Effect of Material Interfaces (Strain Rate & Temperature)







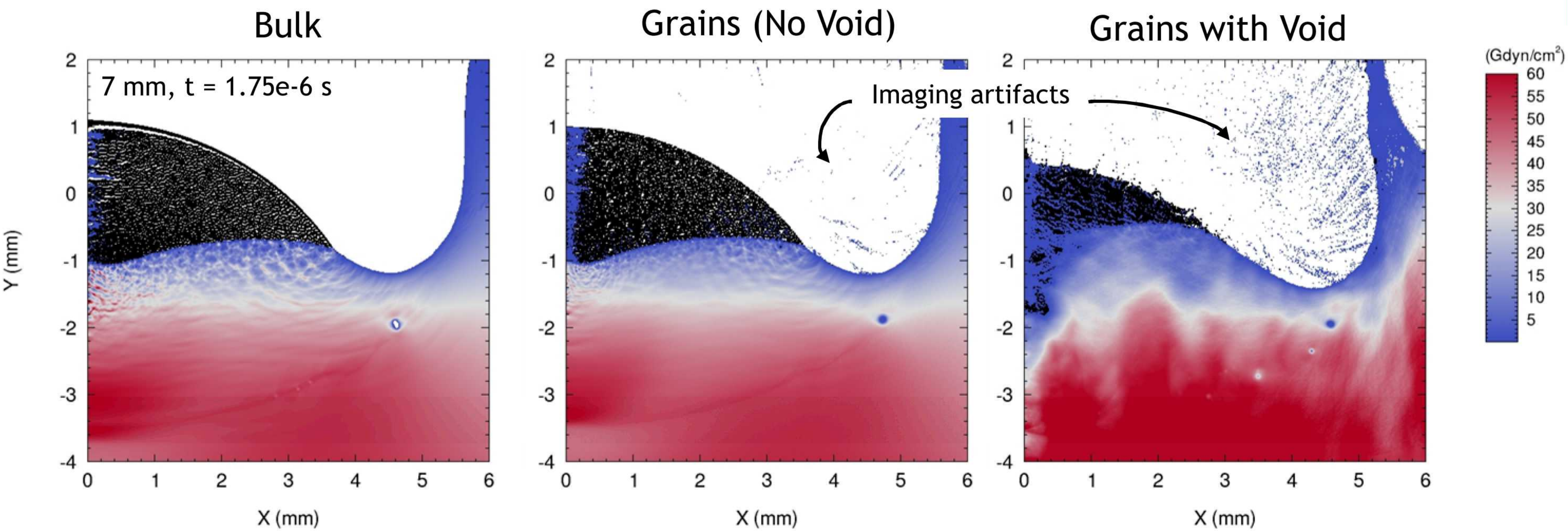


Interfaces between grains drastically increase strain rate (~3.7x) and temperature (~1.2x)

Interfaces achieved here by replacing a single grain type void (12.5% void is high for real metals)

However, study could be repeated with other types of interfaces

Mesoscale Model Results: A Closer Look at Interfaces

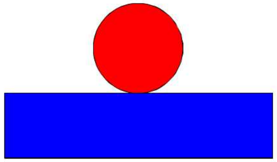


Implication

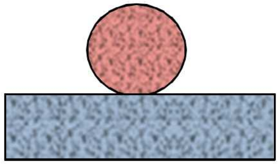
- Simply adding grains does not change the pressure profile from the bulk case
- Interfaces between grains (here modeled as void space) drastically dampens the shockwave, but results in locally higher pressures and temperatures that could affect EO/IR signatures

Summary

- Study compared the effects of modeling grain structure to the traditional bulk material modeling in 2D CTH models, but could be expanded to incorporate 3D models or different grain aspects



- **Bulk models** allowed for exploration of the underlying physics and served as a baseline case
  - Bimodal strain rate histograms result from projectile shape and size
  - A reduction in projectile size or an increase in velocity results in higher strain rates at failure, but only an increase in velocity significantly affects material temperatures



- **Mesoscale models** explicitly simulated a material grain structure
  - Changes in material properties within individual grains resulted in only minor effects (primarily only an increase in low strain rates at failure)
  - The introduction of interfaces between grains resulted in a substantial shift to higher strain rates and temperatures
    - Here void space was used, but other structures (inclusions, dislocations, etc.) likely have similar effects

Interfaces between grains appear to control local, microscale strain rate at failure and material temperature

- Higher strain rates produce smaller fragments (needed to compare with observed impacts)
- Higher temperatures result in higher EO/IR signatures
- ***Future studies could determine a correction factor that would account for interface effects in bulk material simulations***

Backups

Background and Motivation

Grady-Kipp Fragment Size

Spall dominated by:

Fracture toughness

$$S = \left(\frac{\sqrt{24}K_c}{\rho c \dot{\varepsilon}}\right)^{2/3}$$

K_C dependent on T

Flow stress

$$S = \left(\frac{1.2Y}{\rho \dot{\varepsilon}^2}\right)^{1/2}$$

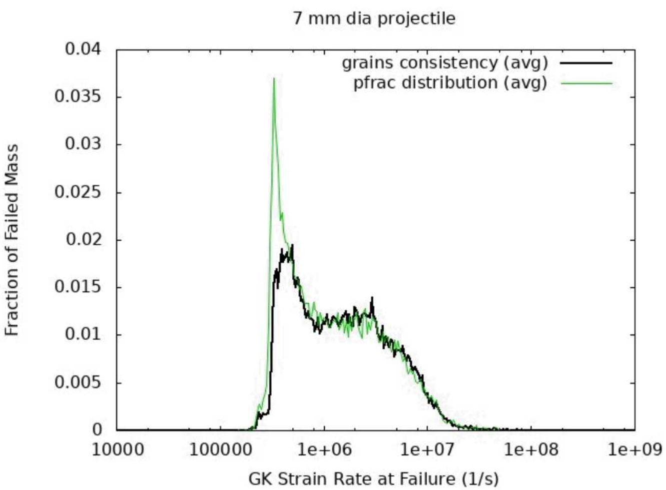
Liquid spall
(above melt temp)

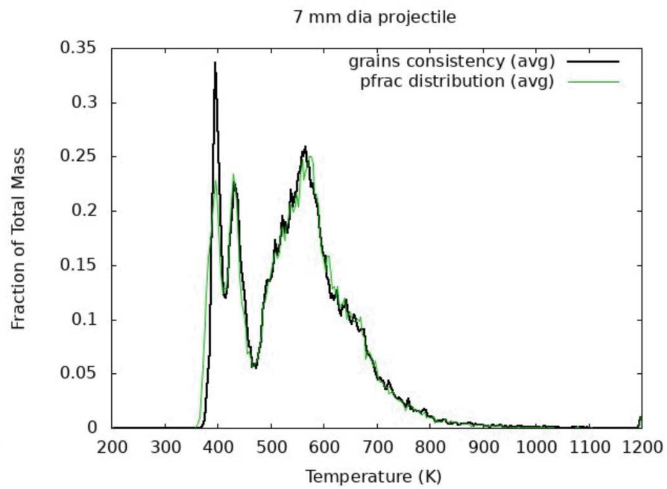
$$S = \left(\frac{48\gamma}{\rho \dot{\varepsilon}^2}\right)^{1/3}$$

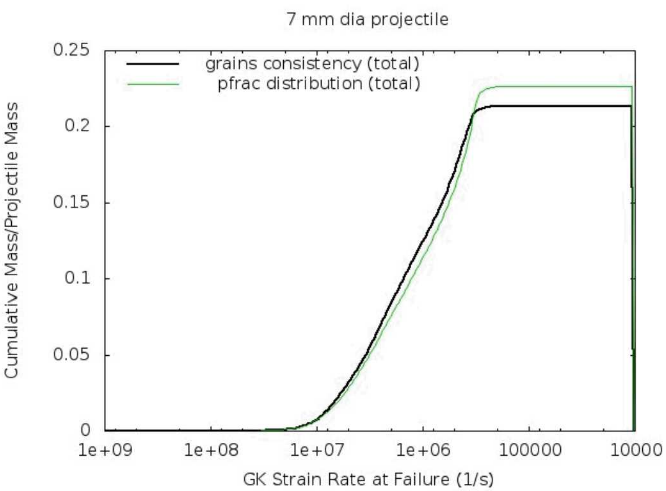
Radiative Power Output

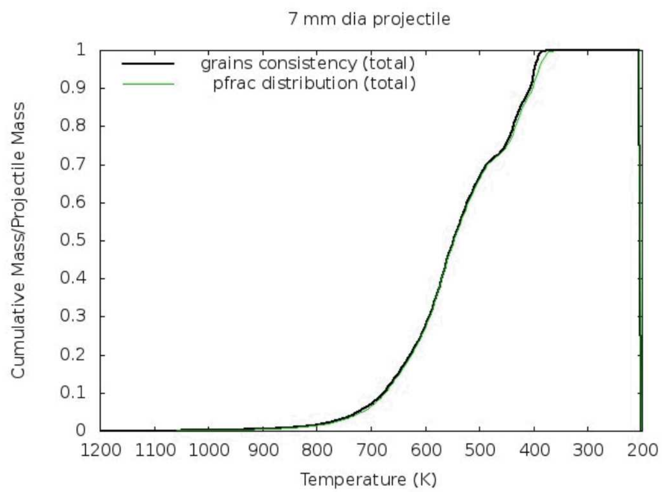
$$P = \sigma A T^4$$

Fracture Study







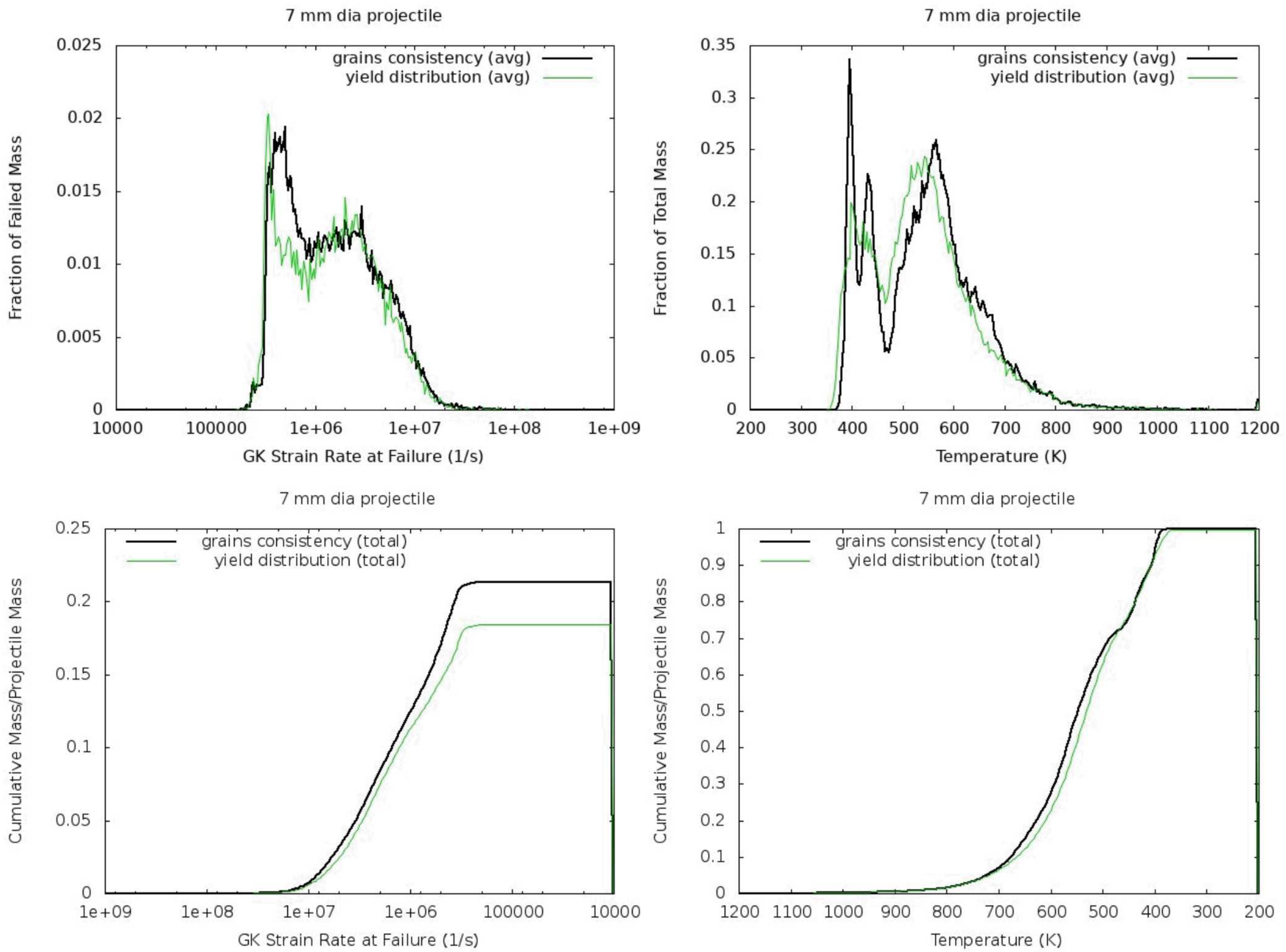


We varied fracture strength in a normal distribution (based on fracture strength in various aluminum alloys) within each grain type material.

Fracture strength affects the lowest strain rates and may be due to reduced transit time across grains (rather than the whole projectile).

Yield Study (Projectile)

$$Y = (A + B\varepsilon_p{}^n)(1 + C \ln \dot{\varepsilon}_p{}^*)(1 - T^{*m})$$



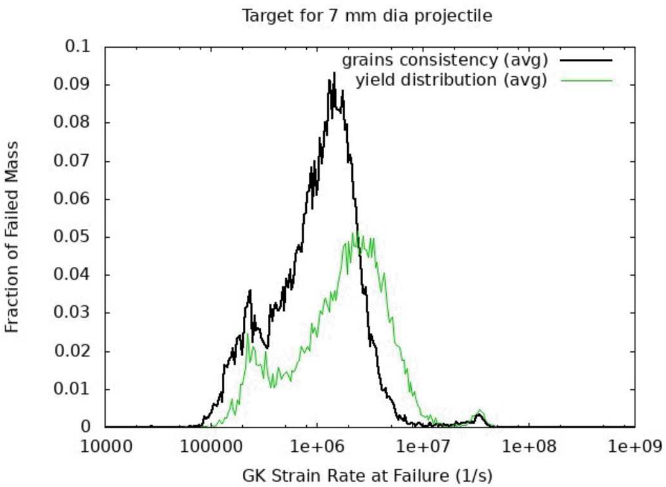
- ε_p is the equivalent plastic strain
- $\dot{\varepsilon}_p$ is the plastic strain rate
- *T* is the homologous temperature, $(T\text{-}T_{room})(T_{melt}\text{-}T_{room})$
- *A*, *B*, *C*, *m*, and *n* are all material const.

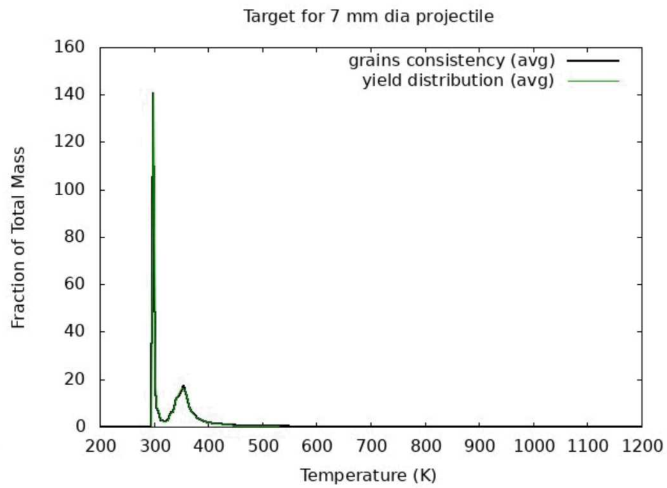
We varied A and B using the same pfrac distribution as in the fracture study

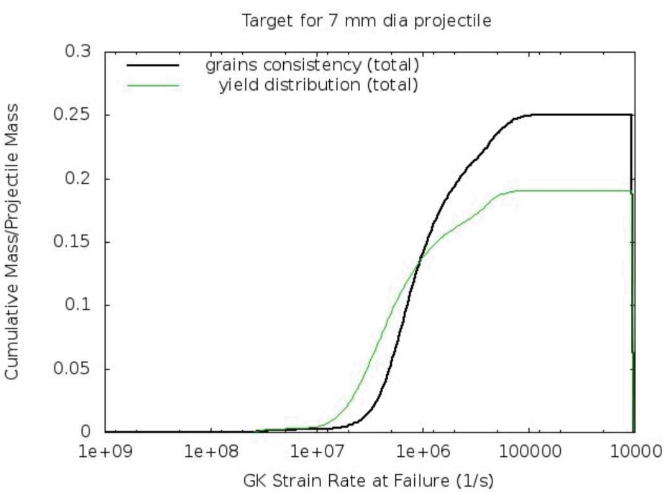
Yield strength variations resulted in **less overall strain** and slightly **lower temperatures** in the projectile.

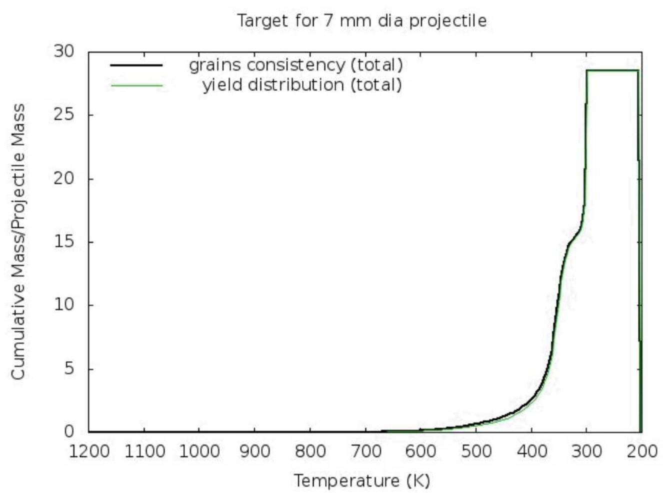
Yield Study (Target)

$$Y = (\mathbf{A} + \mathbf{B}\varepsilon_p{}^n)(1 + C \ln \dot{\varepsilon}_p{}^*)(1 - T^{*m})$$







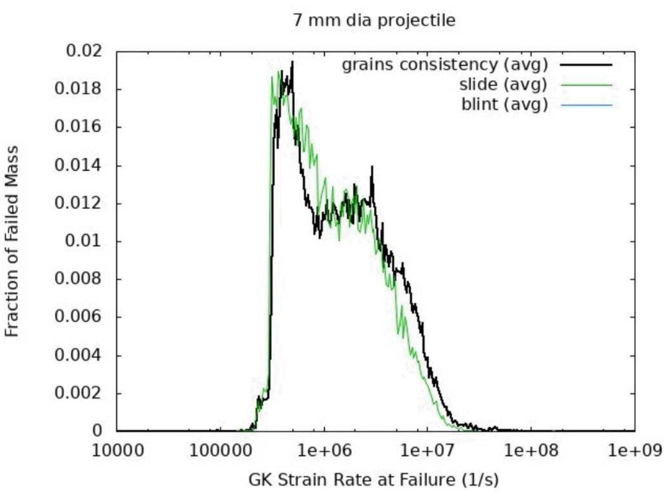


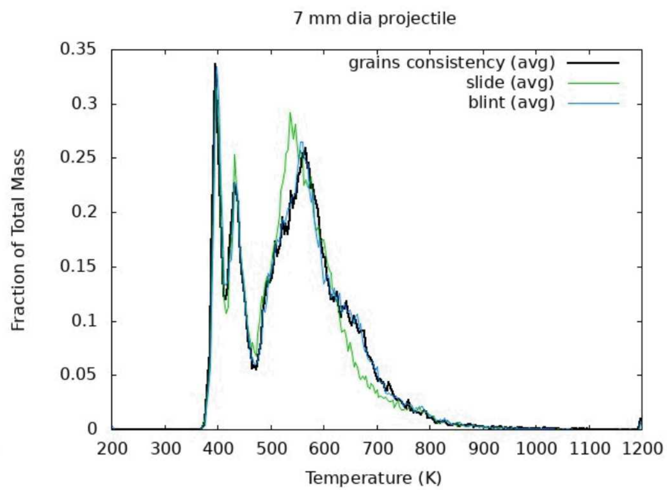
- ε_p is the equivalent plastic strain
- $\dot{\varepsilon}_p$ is the plastic strain rate
- *T* is the homologous temperature, *(T-T*$_{room}$*)(T*$_{melt}$*-T*$_{room}$*)*
- *A*, *B*, *C*, *m*, and *n* are all material const.

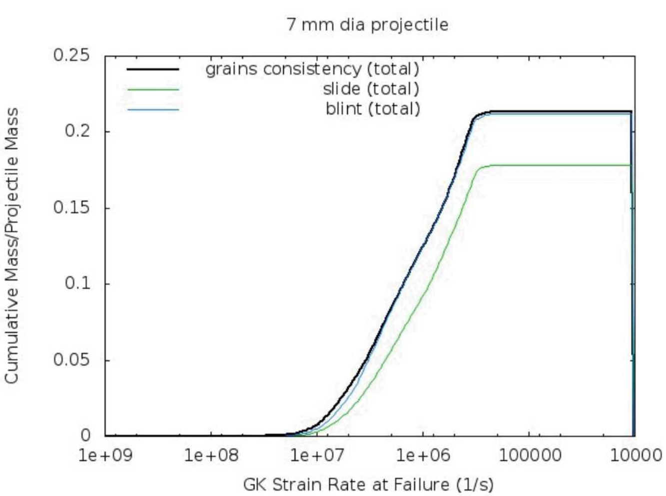
We varied A and B using the same pfrac distribution as in the fracture study

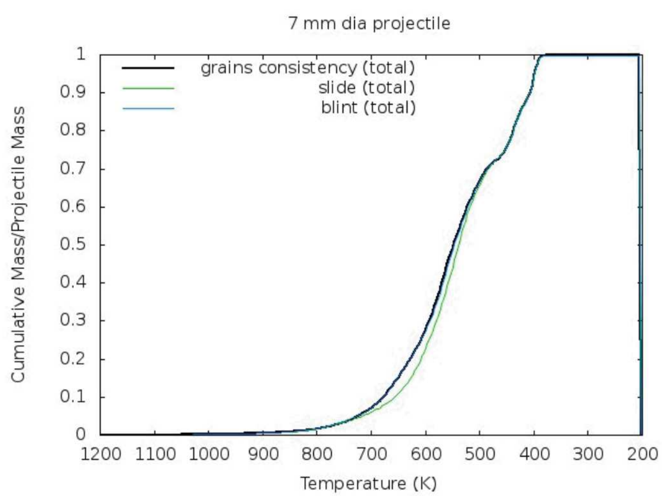
Yield strength variations resulted a slight shift toward **higher strain rates** in the target, but **no change in temperature**.

Slip Study





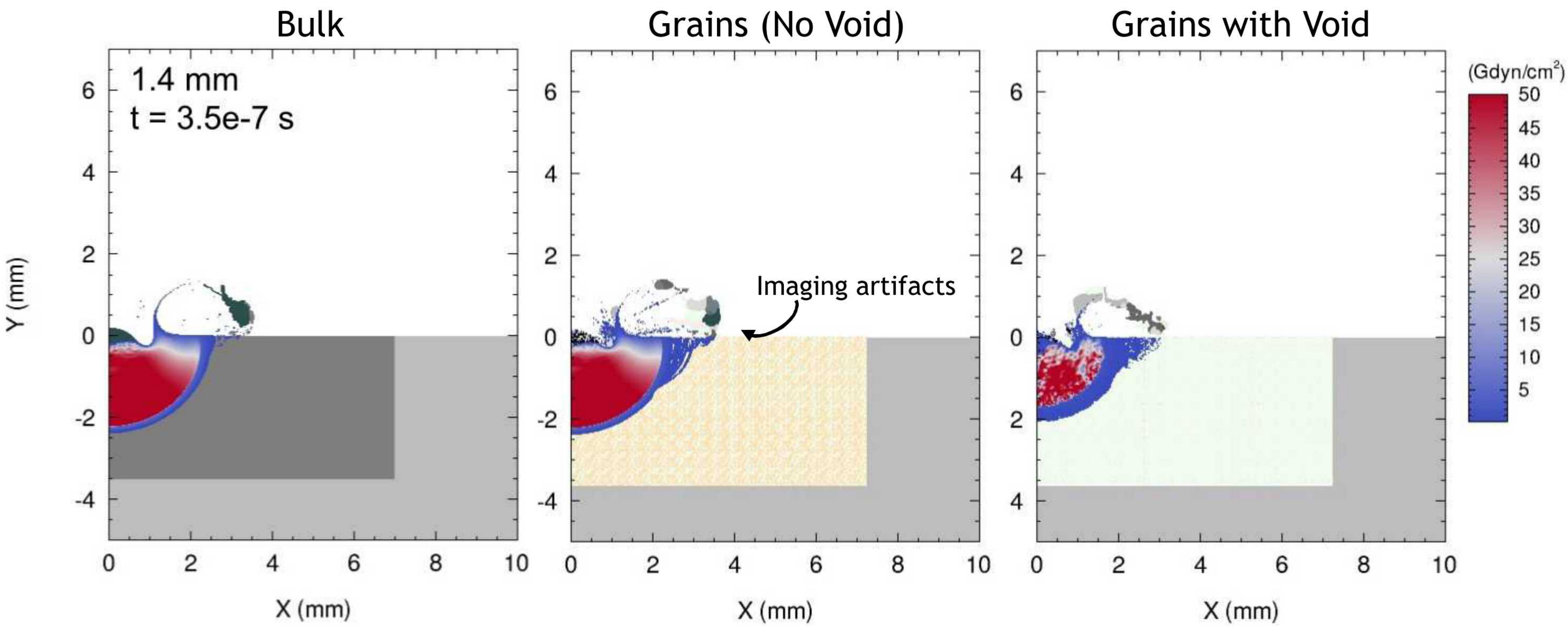




We tested two slip algorithms in CTH: SLIDE and BLINT.

Neither algorithm had a clear or dominant effect on the resulting strain rates or temperatures. Potential causes are that the grains boundaries perfectly match each other, so the materials could not slip past each other. Algorithm subtleties may also have affected results.

Mesoscale Model Results: A Closer Look at Interfaces



Note: 1.4 mm projectile (100 grains) shown for clarity

Implication

- Simply adding grains does not change the pressure profile from the bulk case
- Interfaces between grains (here modeled as void space) drastically dampens the shockwave, but results in locally higher temperatures that could affect EO/IR signatures