LA-UR-16-29201

Title: Phenomenological Studies of Macroscale Failure in Metals

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Intended for: Report

Issued: 2016-12-06

Phenomenological Studies of Macroscale Failure in Metals

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TCG-IV Fall Meeting

November 28-29, 2016

Picatinny Arsenal, Bldg 3022, 2nd Floor Conference Room

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Abstract

Highlights of recent phenomenological studies of metal failure are given. Failure leading to spallation and fragmentation are typically of interest. The current 'best model' includes the following:

o - a full history stress in tension
o - nucleation initiating dynamic relaxation toward a tensile yield function
o - failure dependent on strain, strain rate, and temperature
o - a mean-preserving 'macrodefect' is introduced when failure occurs in tension
o - multifield theoretical refinements

Model parameters are determined using flyer plate data for free surface velocity, and shell fragmentation. Examples for copper and steel are shown at various size scales. Time scaling with the local mass appears to be an important way to obtain parameters valid over a wide range of problem scales.

Acknowledgments

Los Alamos National Laboratory is operated by Los Alamos National Security LLC, for the U.S. Department of Energy's National Nuclear Security Administration. Support for this work from both the DOE and from the U.S. Department of Defense is gratefully acknowledged.

Thanks for technical support go to Curt Bronkhorst, Carl Cady, Carl Trujillo, Rusty Gray, and Frank Addessio. Thanks also to Mike Burkett for believing it could be done, and to Ian Fleming for giving it all an honest test.

Highlights

- Full History Stress in Tension
- Nucleation with Dynamic Relaxation to Tensile Yield Function
- Failure Criteria: Both Volumetric (I_1) and Deviatoric (J_2)
- Upon Tensile Failure: Mean-Preserving Macro-Defect
- Multifield Theory: Partitioning of Pressure and Work
- Model Parameters via Flyer Plate & Filled Hemi data
- Cu and 4340 @ RC32, RC54

Nomenclature: Multifield State Vector

$$(m, \mathbf{u}, e, v, \boldsymbol{\sigma}, *)_{\mathrm{r}}$$

r-field: (mass, velocity, internal energy, specific volume, stress, history variables)

$\boldsymbol{\sigma}$	Total Stress
$\boldsymbol{\epsilon}$	Total Strain
ϵ_p	Plastic Strain
$\sigma_e = \sqrt{3J_2}$	Equivalent Stress
$\sigma_m = \frac{1}{3}I_1$	Mean Stress
$\eta = \dfrac{v}{v_\circ}$	Expansion
$\delta = \eta - 1$	Dilatation
$\phi = 1 - 1/\eta = \delta/\eta$	Porosity (Relative to $v_\circ$)
K	Bulk Modulus
G	Shear Modulus
ν	Poisson's Ratio
$e = \tilde{e}[v, T]\ ; p = \tilde{p}[v, T]$	Caloric and Thermal EOS's determine pressure and temperature (p, T)

Stress Rate

- The stress can be expressed

$$\boldsymbol{\sigma} = K\epsilon_{kk}\mathbf{I} + 2G\left(\boldsymbol{\epsilon} - \tfrac{1}{3}\epsilon_{kk}\mathbf{I}\right)$$

- the rate form, in polar axes, is

$$\begin{aligned}\dot{\boldsymbol{\sigma}} &= K\dot{\epsilon}_{ii}\mathbf{I} + 2G\left(\dot{\boldsymbol{\epsilon}} - \tfrac{1}{3}\dot{\epsilon}_{ii}\mathbf{I}\right) \\ &\quad + \dot{K}\epsilon_{ii}\mathbf{I} + 2\dot{G}\left(\boldsymbol{\epsilon} - \tfrac{1}{3}\epsilon_{ii}\mathbf{I}\right)\end{aligned}$$

- and the strain rate is approximated by $\dot{\boldsymbol{\epsilon}} = \frac{1}{2}\left(\boldsymbol{\nabla}\mathbf{u} + \boldsymbol{\nabla}\mathbf{u}^T\right)$

Full History Stress

- We define the full r-material stress $\boldsymbol{\sigma} \doteq -p\mathbf{I} + \int_0^t \widehat{\boldsymbol{\sigma}} d\tilde{t}$

- Where p is the positive part of the hydrodynamic pressure, and

$$K = \begin{cases} 0, & \text{if } p > 0 \ ; \\ K_0, & \text{otherwise.} \end{cases} \qquad K_0 = 2G\left[\frac{1+\nu}{3(1-2\nu)}\right]$$

- In this way, the history stress carries the entirety of the tension, and the EOS pressure carries the entirety of compression.

- Hence the wave speeds are correct (up to the accuracy of the EOS); and dynamic tensile flow is permitted.

Nucleation with Dynamic Tensile Relaxation

- Nucleation condition is a simple function of density

$$\mathcal{P}_n = \frac{\delta}{\delta_n}$$

- Relaxation goes according to a local rate

$$\dot{\sigma}_m = K\dot{\delta} - b\omega \times \mathtt{MAX}\left(0, \sigma_m - Y^*\right)$$

- and a local Gurson-like Tensile Yield Function

$$Y^* = Y(1 - \phi)\mathrm{e}^{-a\phi}$$

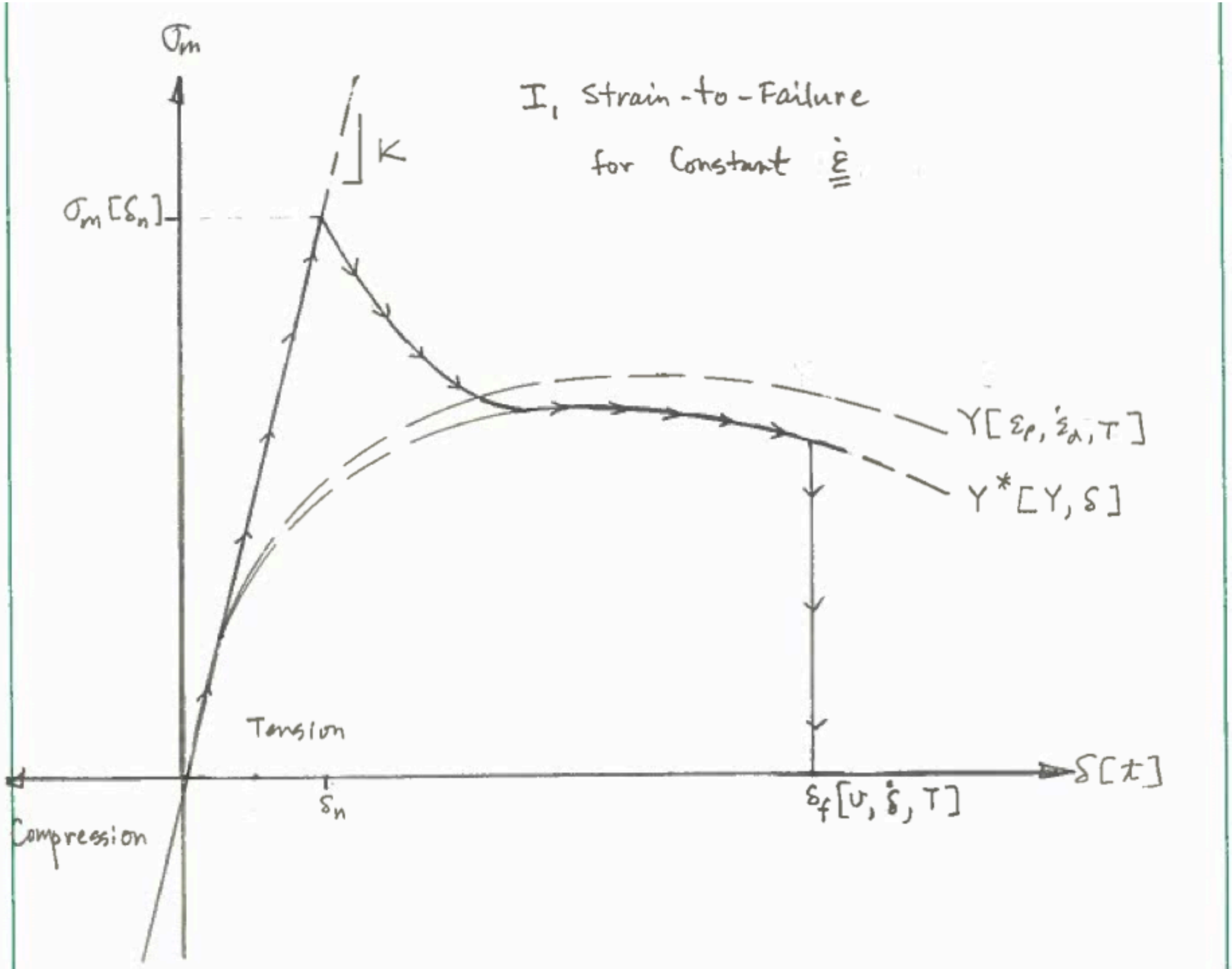
- hence the nucleation—relaxation part of the model is very much in the same class with TEPLA.

Rate Scaling

- We find that both the tensile relaxation rate and the volumetric straining rate are best scaled by the same factor. That is

$$\omega = \frac{c_h}{\sqrt[3]{mv}} \equiv \frac{\text{homogeneous sound speed}}{\text{material mass length scale}}$$

- This rate, times the integration timestep, is the CFL number associated with the mass.



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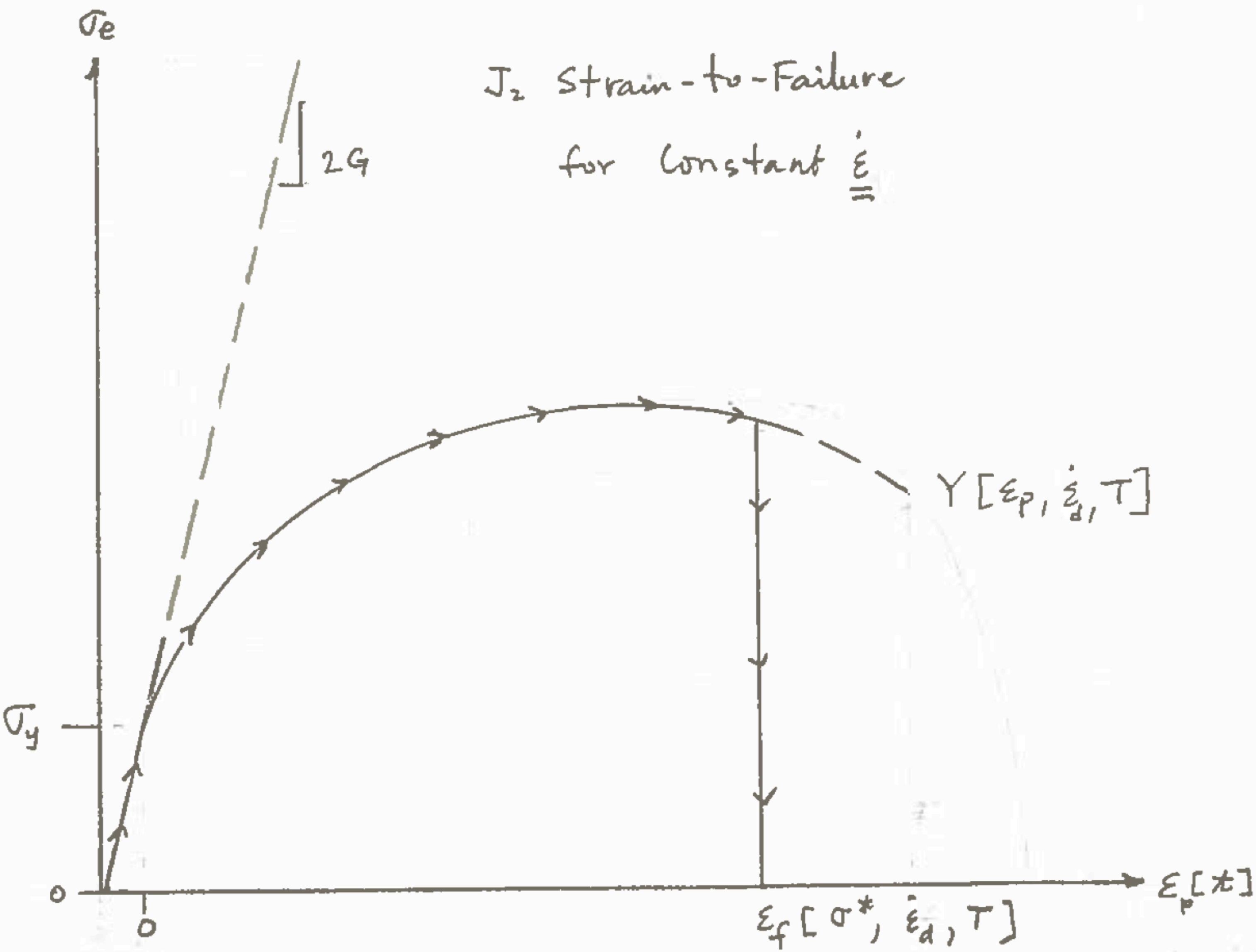


σe
J2 Strain-to-Failure
for Constant ε̇
2G
Y [εp, ε̇d, T]
σy
0
0
εp [t]
εf [σ*, ε̇d, T]

Multifield Theory for Pressure and Work

- The rate form for the equilibration pressure furnishes a model for the evolution of the specific volume:

$$\rho_{\mathrm{r}}\dot{v}_{\mathrm{r}} = \left(\theta_{\mathrm{r}}\beta_{\mathrm{r}}\dot{T}_{\mathrm{r}} - f^{\theta}_{\mathrm{r}}\sum\theta_{\mathrm{s}}\beta_{\mathrm{s}}\dot{T}_{\mathrm{s}}\right) - f^{\theta}_{\mathrm{r}}\sum v_{\mathrm{s}}\Gamma_{\mathrm{s}} + f^{\theta}_{\mathrm{r}}\boldsymbol{\nabla}\cdot\mathbf{u}$$

$$f^{\theta}_{\mathrm{r}} = \theta_{\mathrm{r}}\kappa_{\mathrm{r}}\Big/\sum\theta_{\mathrm{s}}\kappa_{\mathrm{s}}$$

- The work rate is then:

$$\dot{e}_{\mathrm{r}} = -\left(p+q\right)\dot{v}_{\mathrm{r}}$$

- And the first iteration of a pressure equilibration solution gives the pressure:

$$p = \left(\sum f^{\theta}_{\mathrm{s}}\tilde{p}[v_{\mathrm{s}}, T_{\mathrm{s}}]\right)\times\left(1-\theta_{\mathrm{v}}\right)$$

Failure Consequences

- When at least one Failure Probability exceeds one, the material mass is failed.

$$\mathcal{P} = \texttt{MAX}\left(\frac{\epsilon_p}{\epsilon_f}, \frac{\delta}{\delta_f}\right)$$

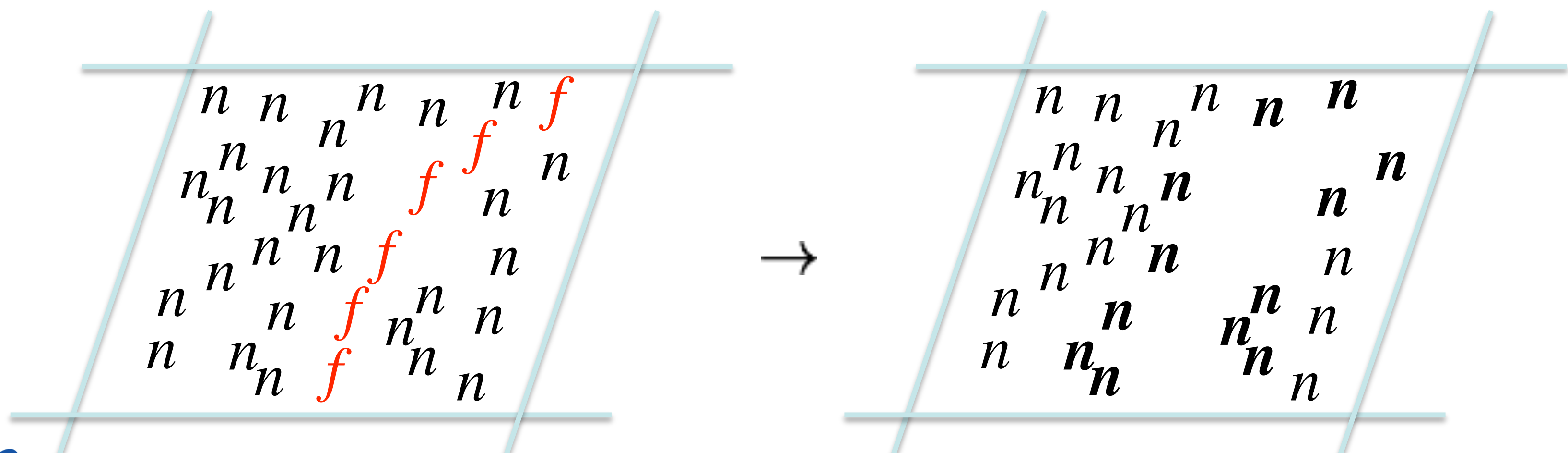
- If the mass fails in tension we replace the mass with a mean-preserving macro-defect.
- Any mass that fails in compression simply becomes a nonviscous material (as if it had melted).

Mean-Preserving Macro-Defect

- A mean-preserving macro-defect is a ‘hole’ in the discrete data that is the result of a sudden, local, *unresolved* tensile failure.
- The failed mass is transferred to its nearest neighbors in a *locally weighted* fashion, such that the *mean* mass, momentum, internal energy, stress and flow strain are all preserved.
- Importantly, in this physical process, the stress and flow strain of neighboring masses both get ‘diluted’ (reduced in proportion to the failed mass).
- The defect can appear instantly, or at a finite rate.

Macro-Defect Schematic

- Let *f* and *n* signify failed and non-failed material points, in some arbitrary region of space.
- After redistribution of the state, only the modified non-failed points remain, and are signified by ***n***. The mean mass, momentum, energy and stress in the region are unmodified.



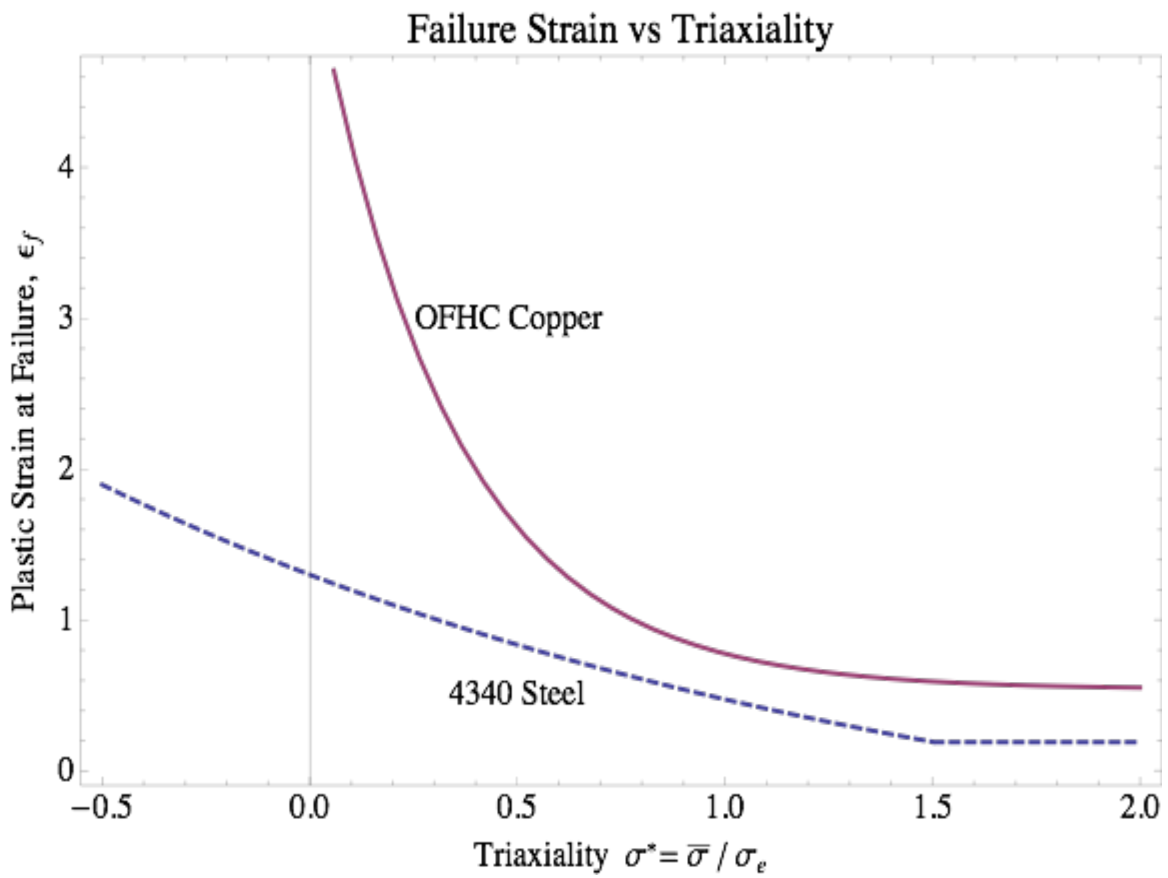
Macro-Defect continued…

- The mean-preserving macro-defect model is ripe for embellishment.
- The local data can be used to approximate the direction of an impending failure surface.
- This directionality can be used to improve the post-failure stress state that is redistributed with the mass.

Shear (J_2) Strain-to-Failure

$$\epsilon_f = \left(D_1 + D_2 \mathrm{e}^{-D_3 \sigma^*}\right)$$

Classical Hancock-MacKenzie triaxiality function:



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Johnson & Cook extended Hancock & MacKenzie for the J_2 (deviatoric) failure flow strain

- JC added Thermal and Rate terms, which we retain, along with a floor on the failure strain:

$$\epsilon_f = \mathtt{MAX}\left(\epsilon_{fmin}, D_1 + D_2 \mathrm{e}^{-D_3 \sigma^*}\right) \times R_R \times R_T$$

$$R_R = \left(\frac{1 - \mathtt{MIN}[0, D_4 \dot{\epsilon}^*]}{1 + \mathtt{MAX}[0, D_4 \dot{\epsilon}^*]}\right)$$

$$\dot{\epsilon}^* = \mathtt{SIGN}\left(|\dot{\epsilon}_d|, \mathbf{\nabla} \cdot \mathbf{u}\right) / \omega$$

$$R_T = (1 + D_5 T^*)$$

$$T^* = \left(\frac{e - e_{stp}}{e_{melt} - e_{stp}}\right)$$

Volumetric (I_1) Strain-to-Failure

- We find that the failure dilatation typically increases with increasing temperature, and decreases with the dilatation rate.
- Hence thermal and strain rate effects act in opposing directions.
- In Copper we find that spall occurs with sudden tension in cold material; both spall and shear failure are suppressed in material that is only slightly warm.
- Flyer plate data at various strain rates is helpful in determining the nucleation condition, tensile flow rate, and the balance between thermal and strain rate effects on failure.

The I_1 failure strain, for the tensile case, is new

- It is analogous to the J_2 failure strain, in terms of the dilatation:

$$\delta_f = \delta_\circ \times \left(\frac{1 - \texttt{MIN}[0, D_6 \dot{\delta}^*]}{1 + \texttt{MAX}[0, D_6 \dot{\delta}^*]} \right) \times (1 + D_5 T^*)$$

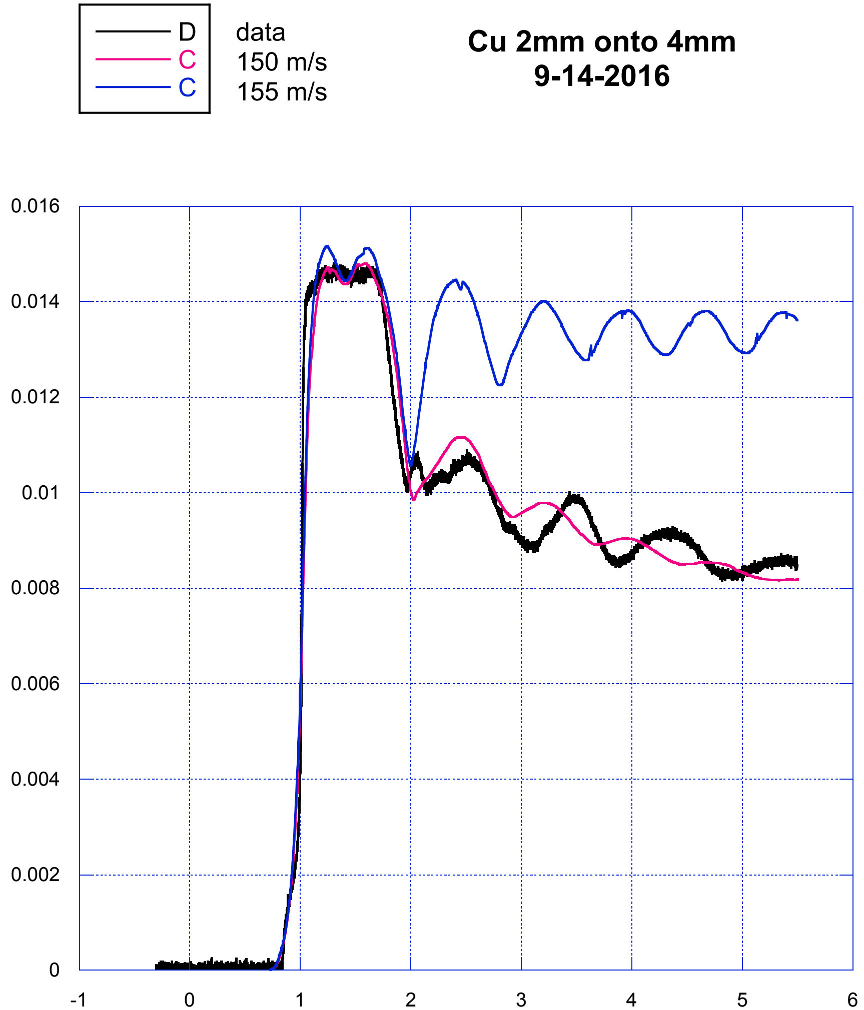
$$\dot{\delta}^* = \frac{\dot{W}}{(\omega W)}$$

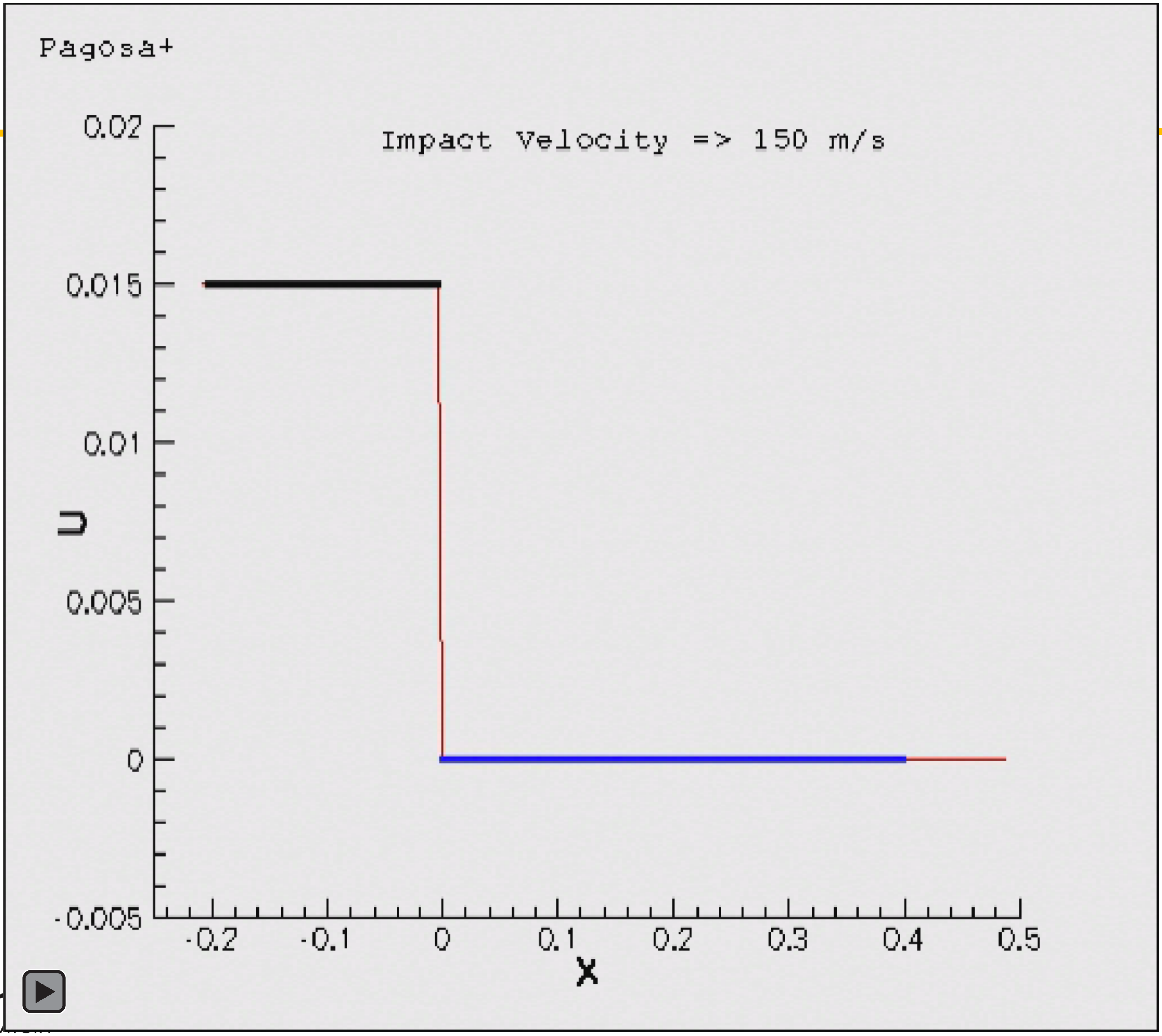
$$= \frac{(\eta \log \eta)(\nabla \cdot \mathbf{u})}{\omega(1 - \eta + \eta \log \eta)}$$

Numerical Method

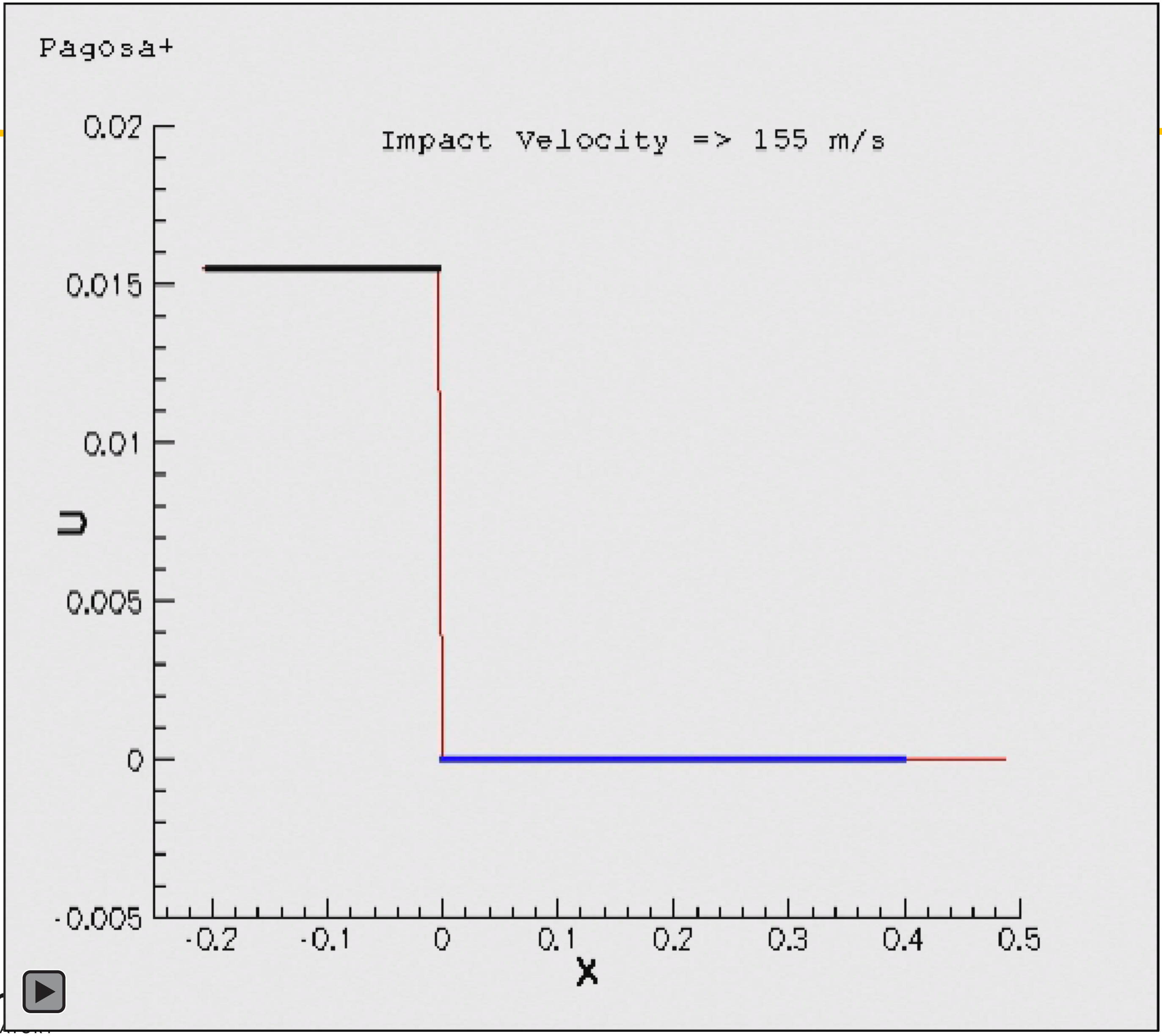
- Fieldwise choice of frame: Eulerian (fluids) or Lagrangian (solids). We call this a Mixed Frame calculation.
- Eulerian transport via interface tracking on a grid; Lagrangian transport via material mass points displaced by center-of-mass velocity (à la FLIP + Material Point Method, with pointwise tensor viscosity).
- A fixed grid furnishes the common frame of reference for exchanges of mass, momentum and energy among fields.
- Fluxes are space-time centered in classical TVD fashion.
- Stable for $c\Delta t/\Delta x < 1$, where c is the maximum signal speed.

Flyer Plate Data Determines (most) Model Parameters.   Example: Copper





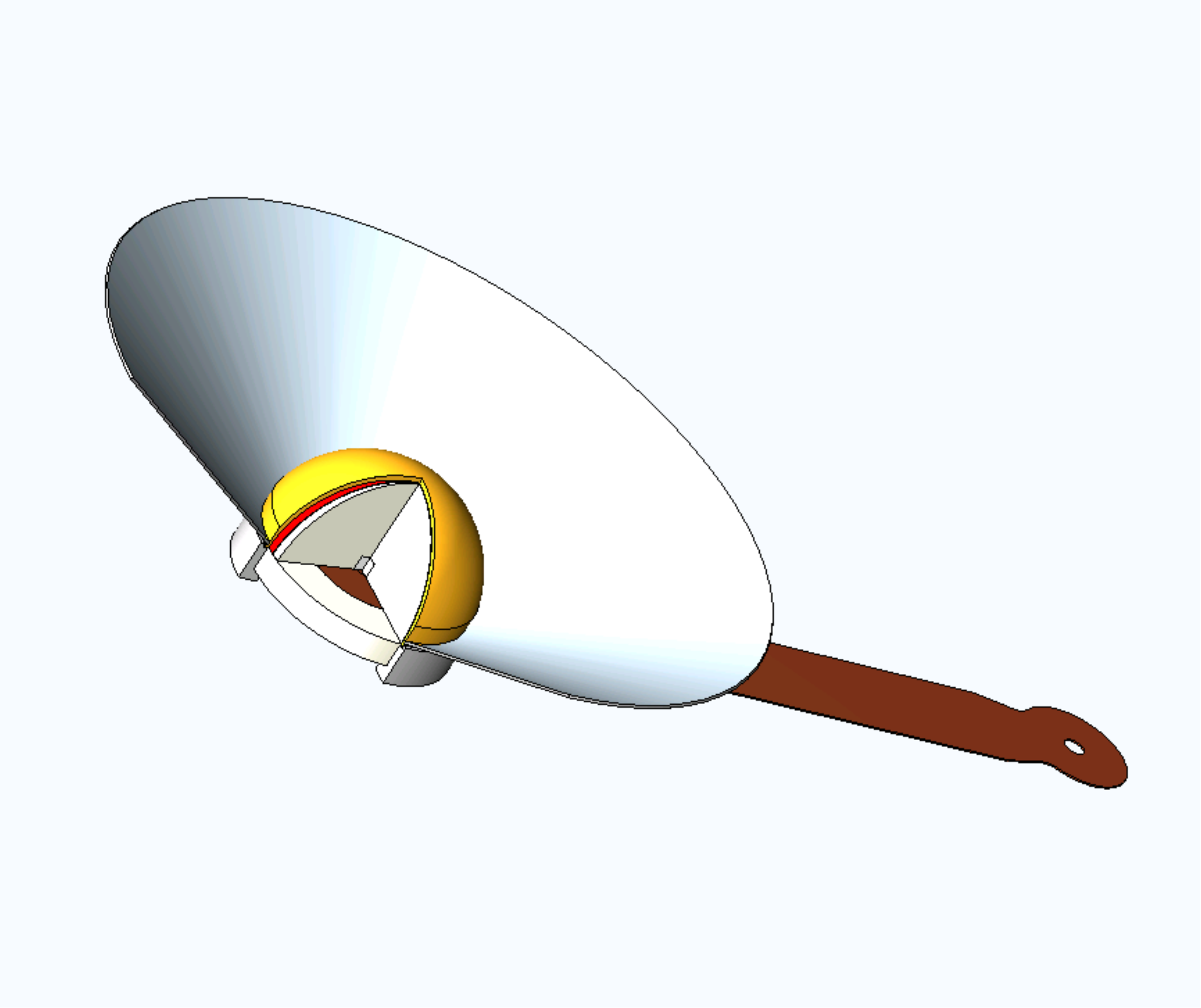
Pagosa+
Impact Velocity => 150 m/s
0.02
0.015
0.01
0.005
0
-0.005
U
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
X


Pagosa+
Impact Velocity => 155 m/s
0.02
0.015
0.01
0.005
0
-0.005
U
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
X

Fragmentation Experiment

- 4 cm ID Hemispherical Shell, wall thickness h = 0.2 cm
- Filled with PBX 9501, center initiated.
- 4340 in four heats: As Quenched, 2H @ (325, 450, 525) C =>
- RC hardness: (54.2, 47.5, 41.3, 32.1)
- X-Ray of expanding fragment cloud center.
- Area frequency measured via computer graphic imagery.

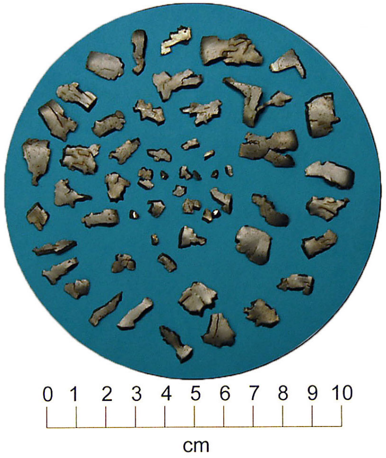
Filled Hemispherical Shell



4340 responds to temper

525°C 2 hrs
RC 32

450°C 2 hrs
RC 41

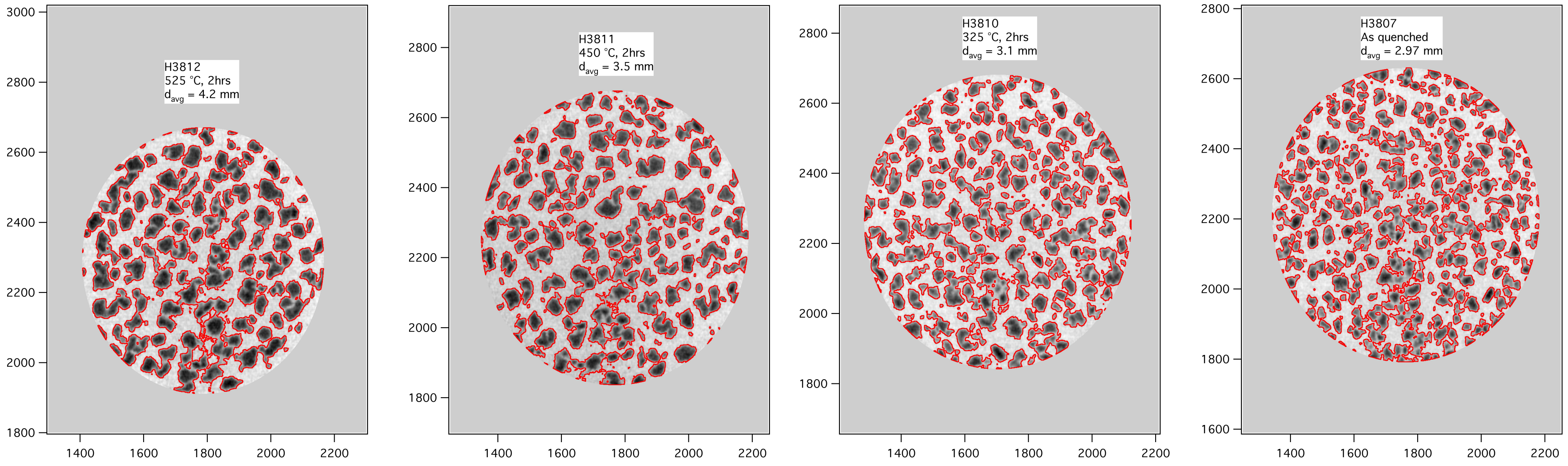


325°C 2 hrs
RC 48

As Quenched
RC 54

- All shots were "water recovery"

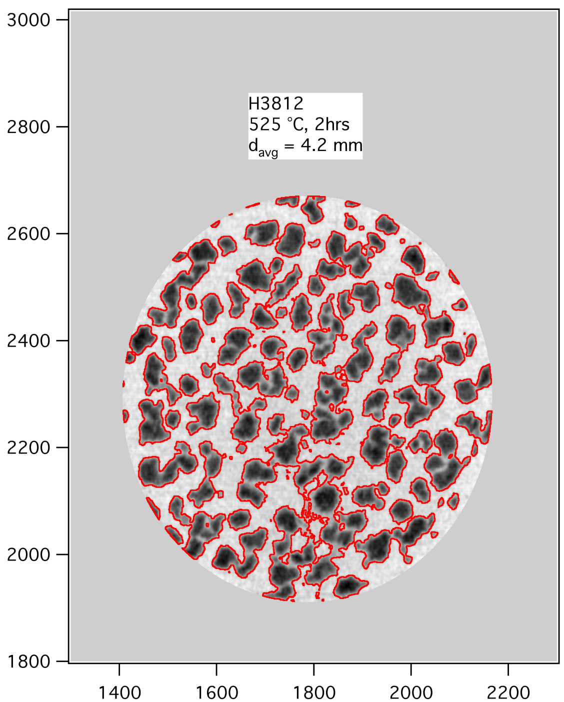
Fragments expanding in air are smaller



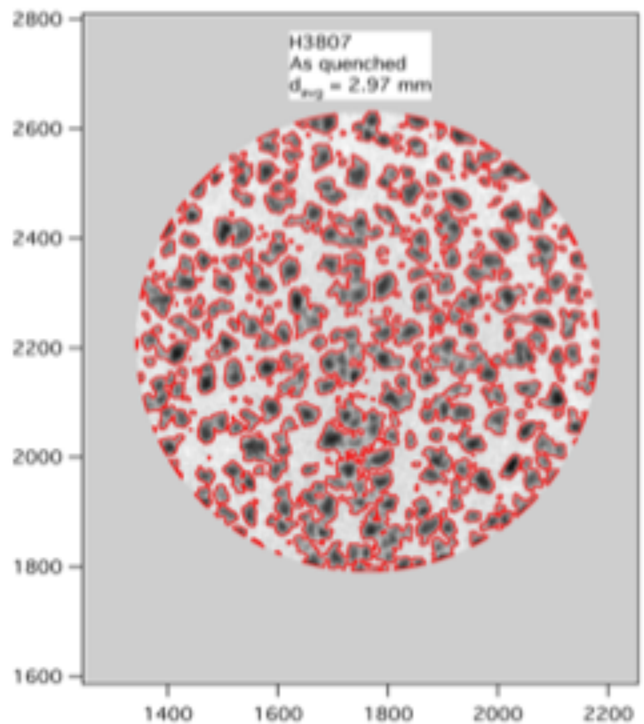
- Although smaller, fragment sizes observed radiographically follow the same trend

Area Fractions by Image Processing

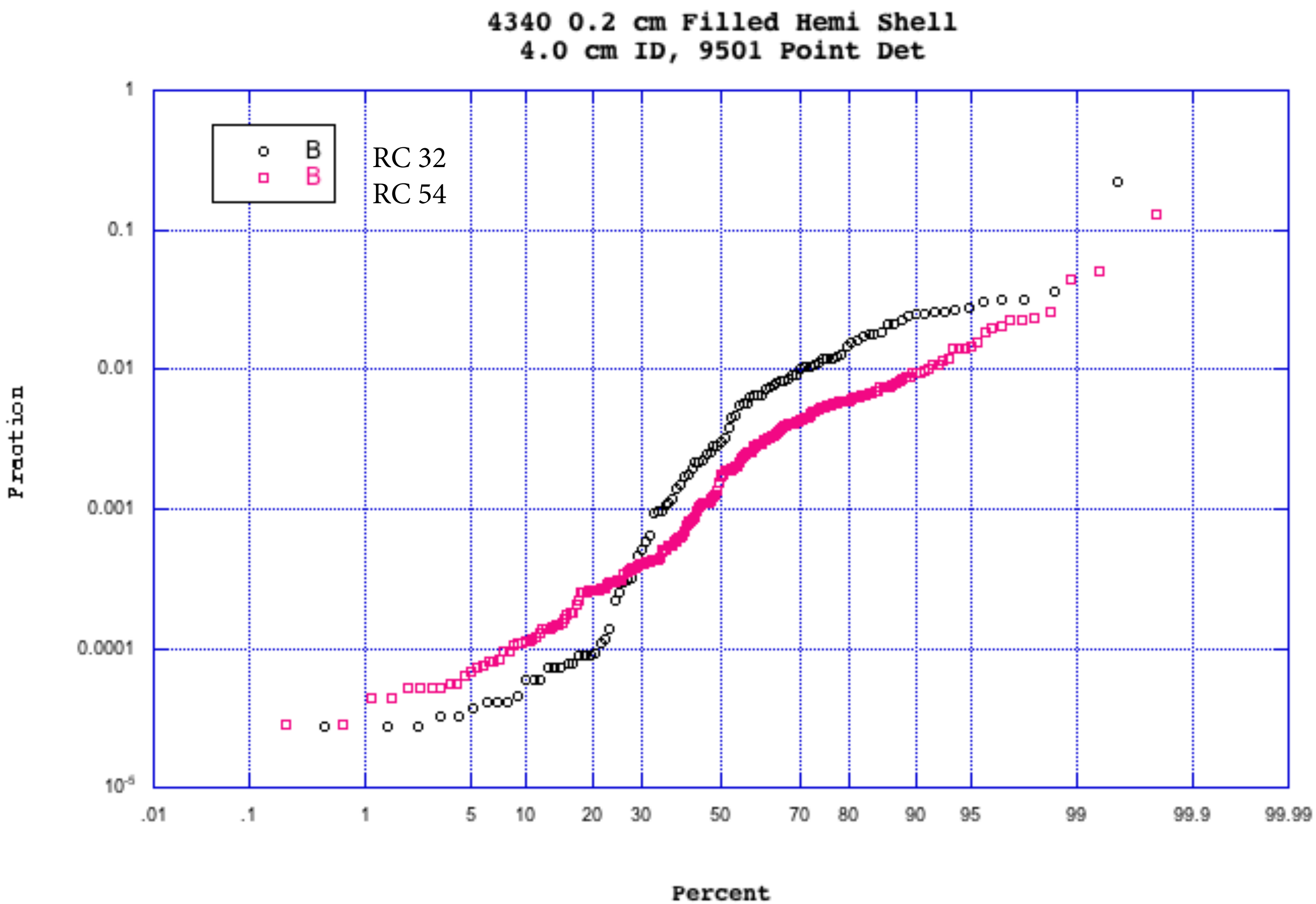
RC 32

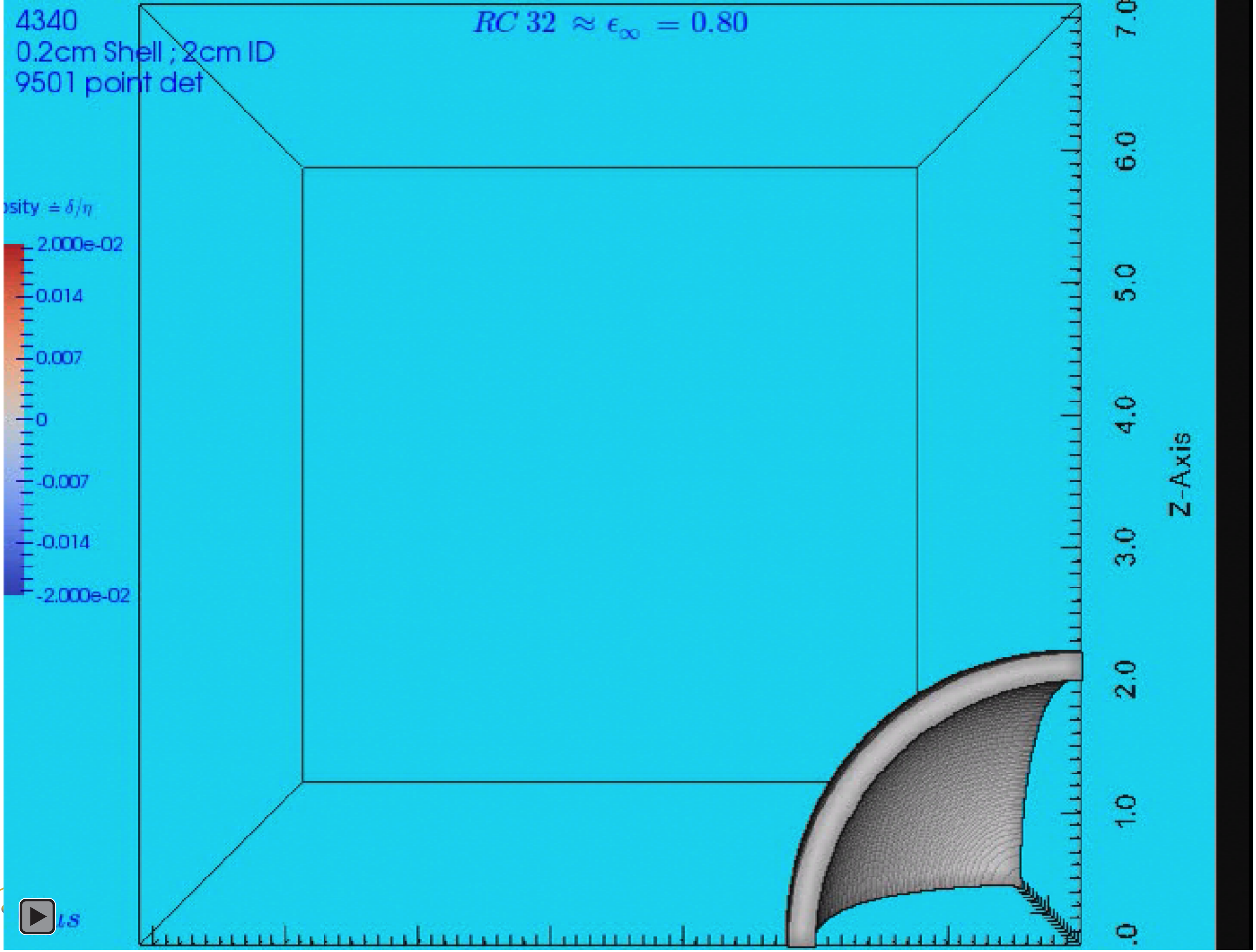


RC 54



Radiographic Area Fraction Data





4340
0.2cm Shell ; 2cm ID
9501 point det
$RC\ 32 \approx \epsilon_{\infty} = 0.80$
osity $\doteq \delta/\eta$
2.000e-02
0.014
0.007
0
-0.007
-0.014
-2.000e-02
Z-Axis
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0

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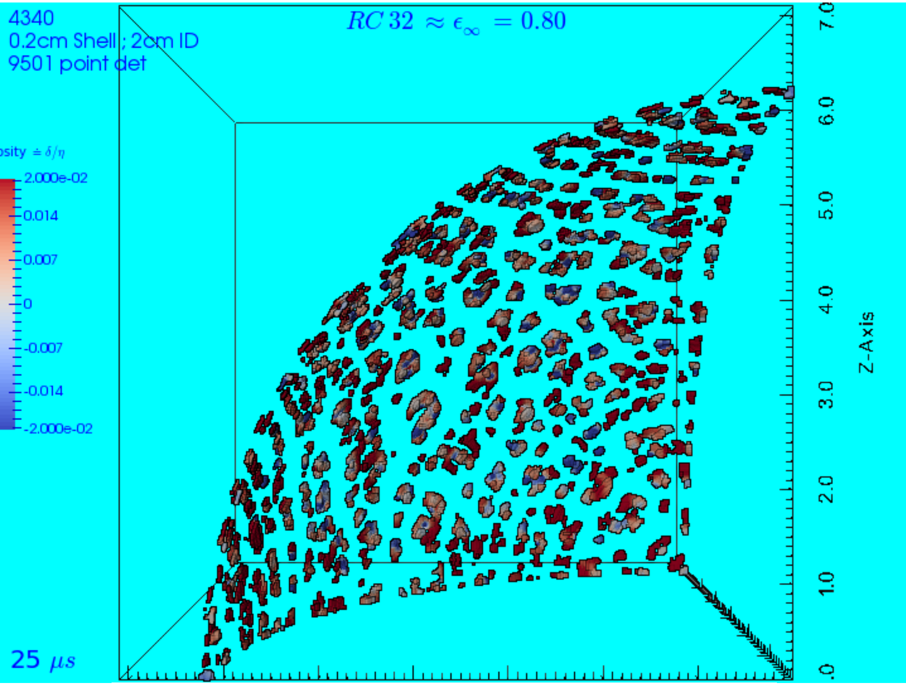
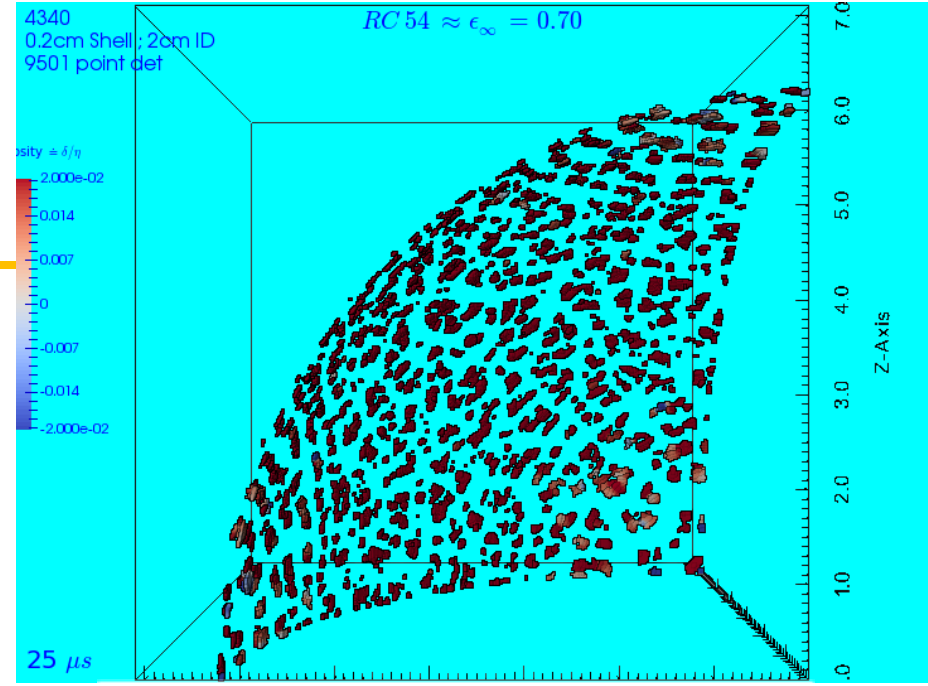
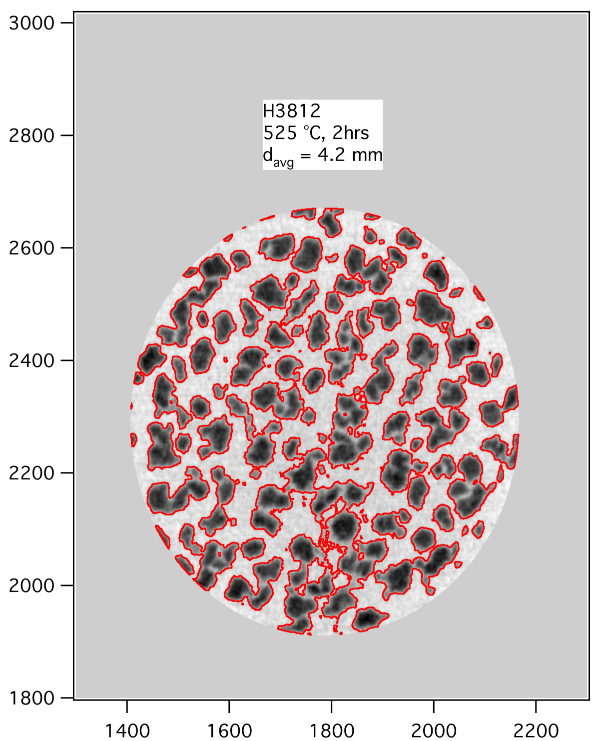
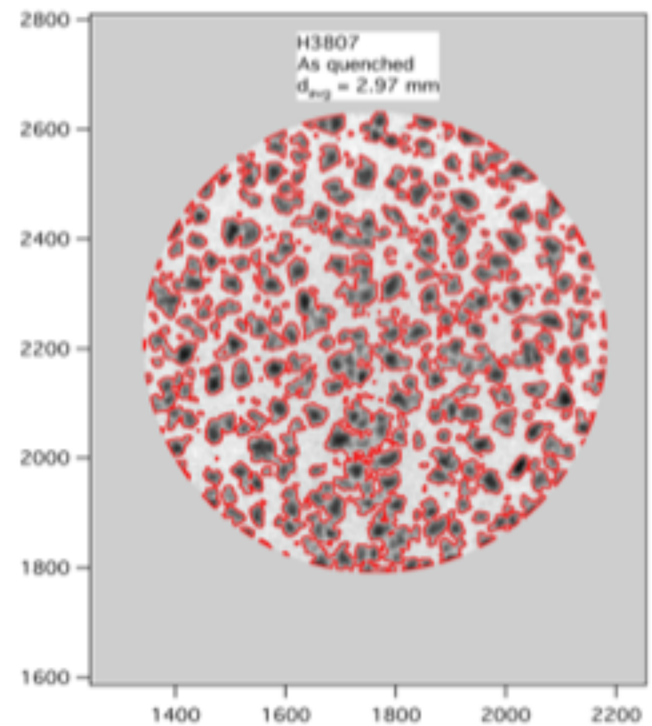
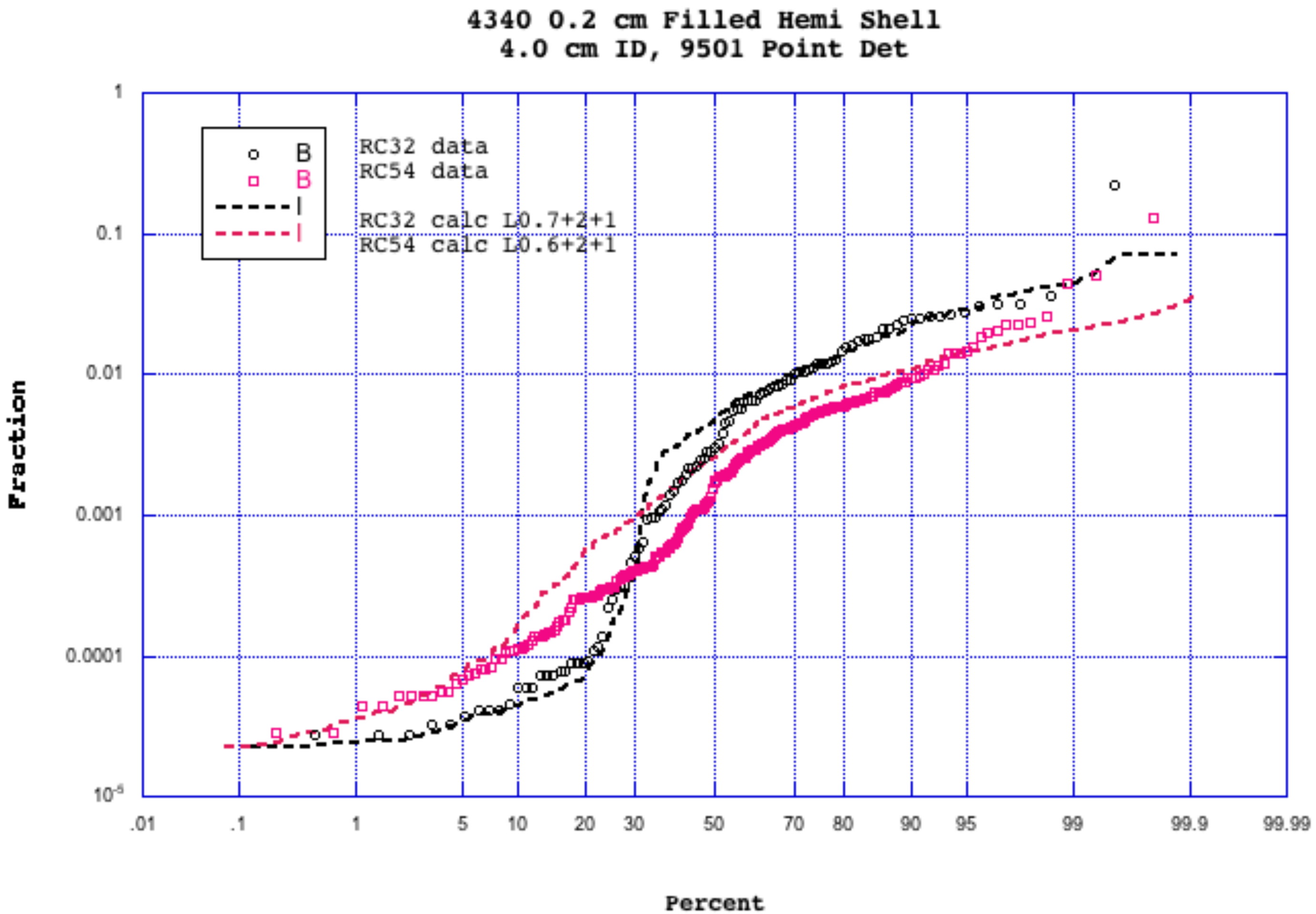

4340
0.2cm Shell ; 2cm ID
9501 point det
$RC\,32 \approx \epsilon_\infty = 0.80$
2.000e-02
0.014
0.007
0
-0.007
-0.014
-2.000e-02
25 μs
Z-Axis
0.
1.0
2.0
3.0
4.0
5.0
6.0
7.0


4340
0.2cm Shell ; 2cm ID
9501 point det
$RC\,54 \approx \epsilon_\infty = 0.70$
2.000e-02
0.014
0.007
0
-0.007
-0.014
-2.000e-02
25 μs
Z-Axis
0.
1.0
2.0
3.0
4.0
5.0
6.0
7.0


H3812
525 °C, 2hrs
d_{avg} = 4.2 mm
3000
2800
2600
2400
2200
2000
1800
1400
1600
1800
2000
2200


H3807
As quenched
d_{avg} = 2.97 mm
2800
2600
2400
2200
2000
1800
1600
1400
1600
1800
2000
2200

Area Fraction and Scaled Mass Fraction

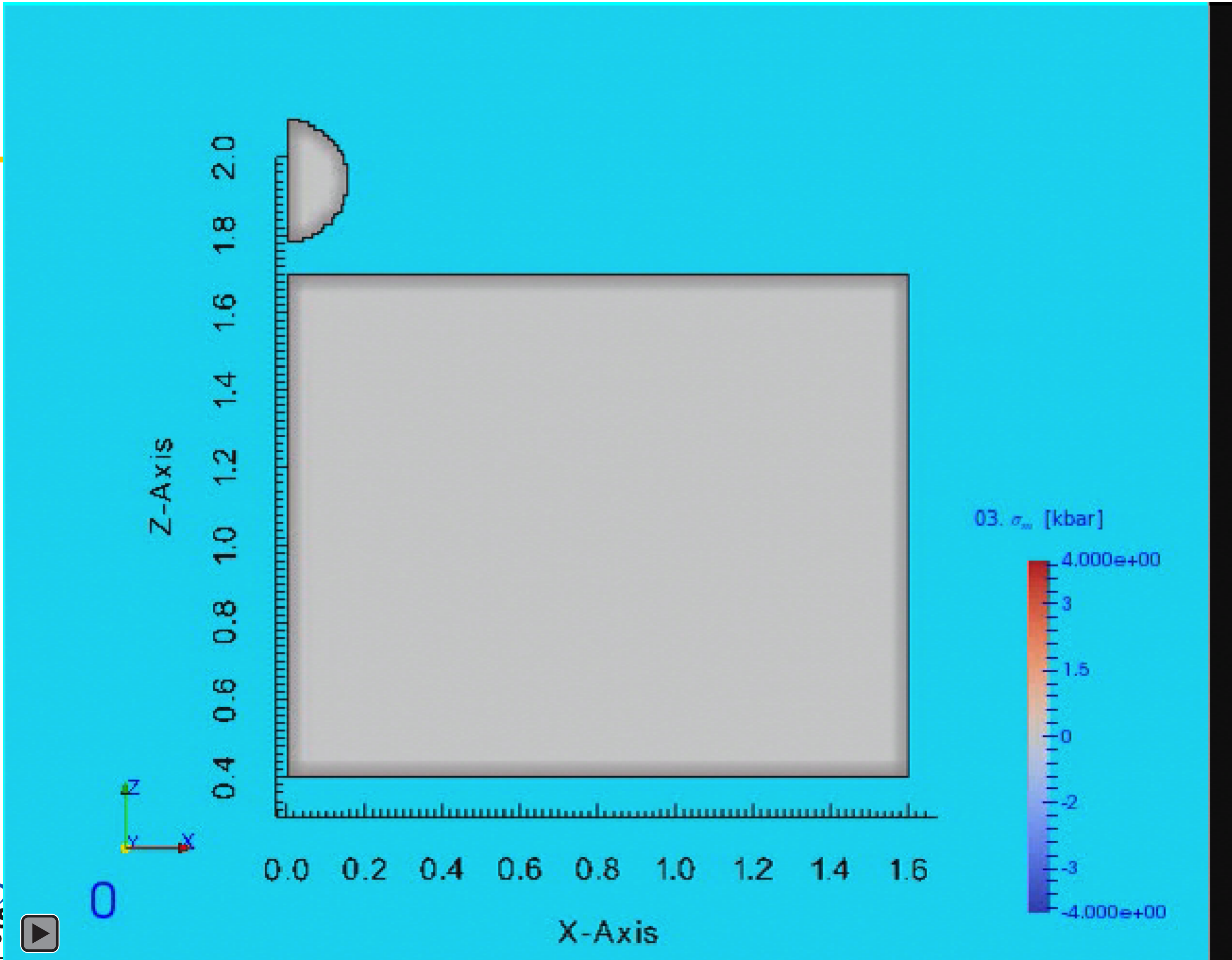


Conclusions

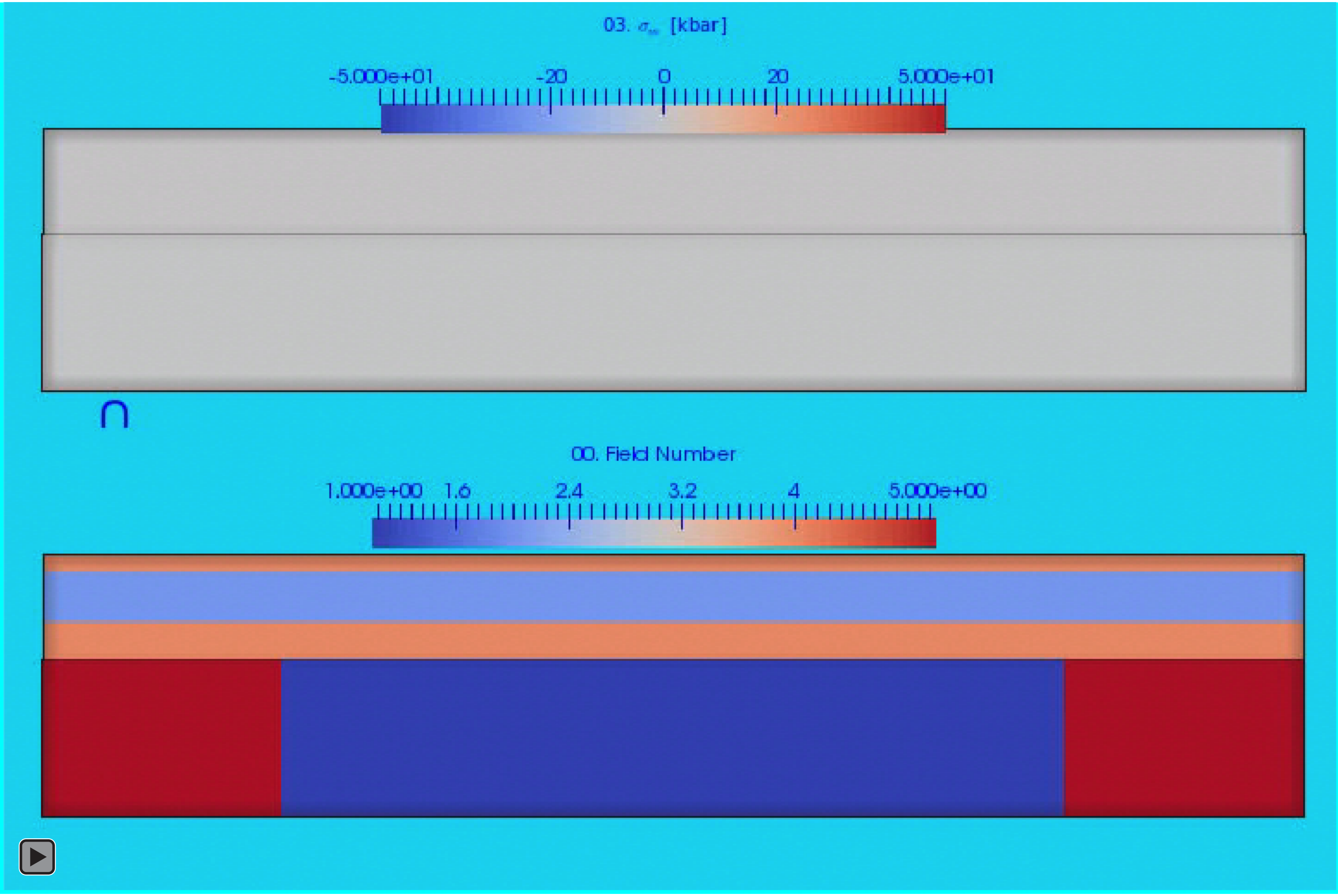
- Failure Probability studies have been resumed with a new multifield model; plus an advanced numerical solution scheme (Marker-Lagrangian Solid, Grid-Eulerian Fluid).
- A new Multifield "Debris-Free" method has been introduced, and is ripe for embellishment.
- Phenomenology for Isotropic Hardening and Failure Probabilites can yield realistic macroscale fragmentation statistics.
- A monotone high-order integration scheme is prerequisite.
- Additional validation is needed, and is ongoing, for other materials of interest.

We thank you for your attention.

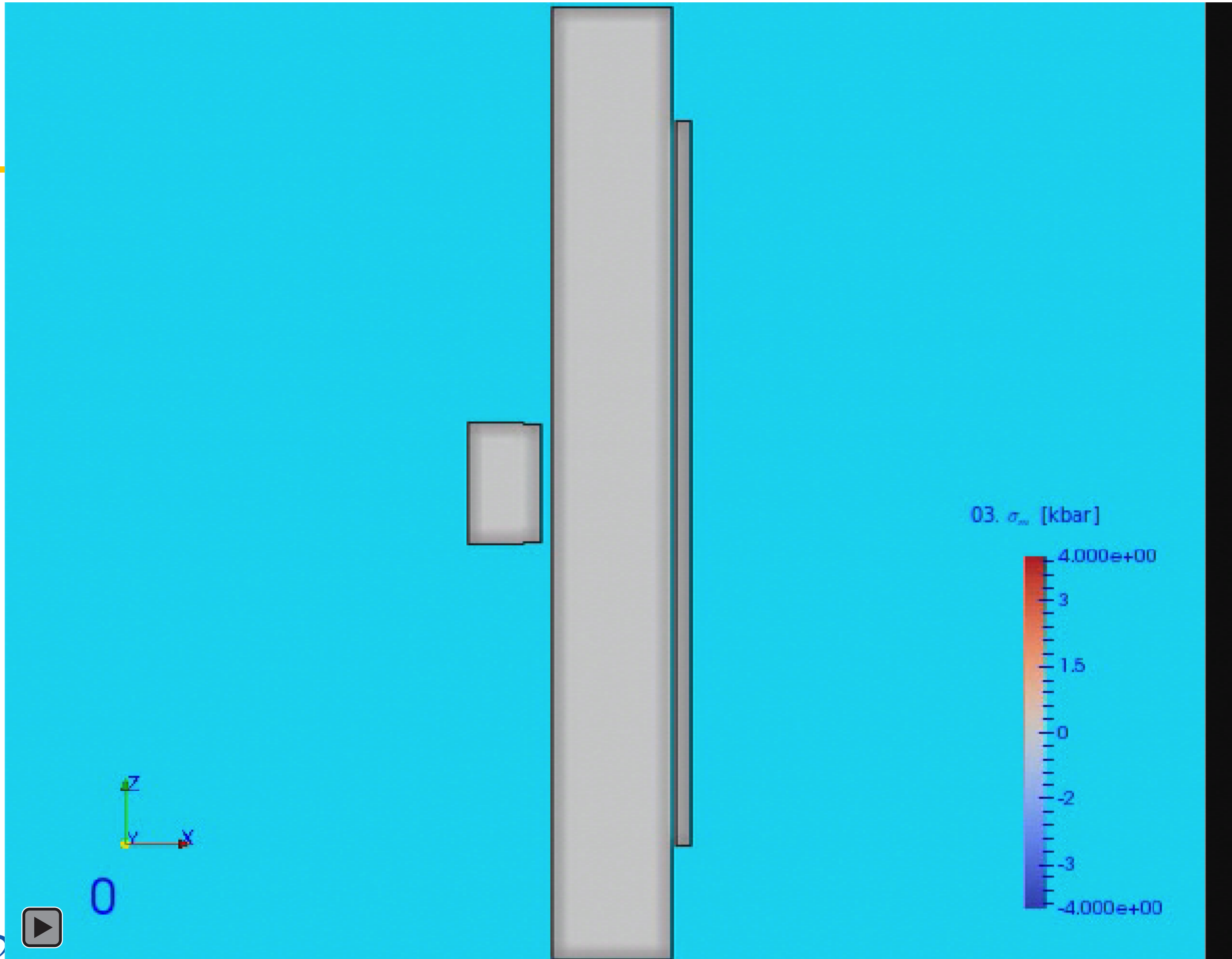
Questions?

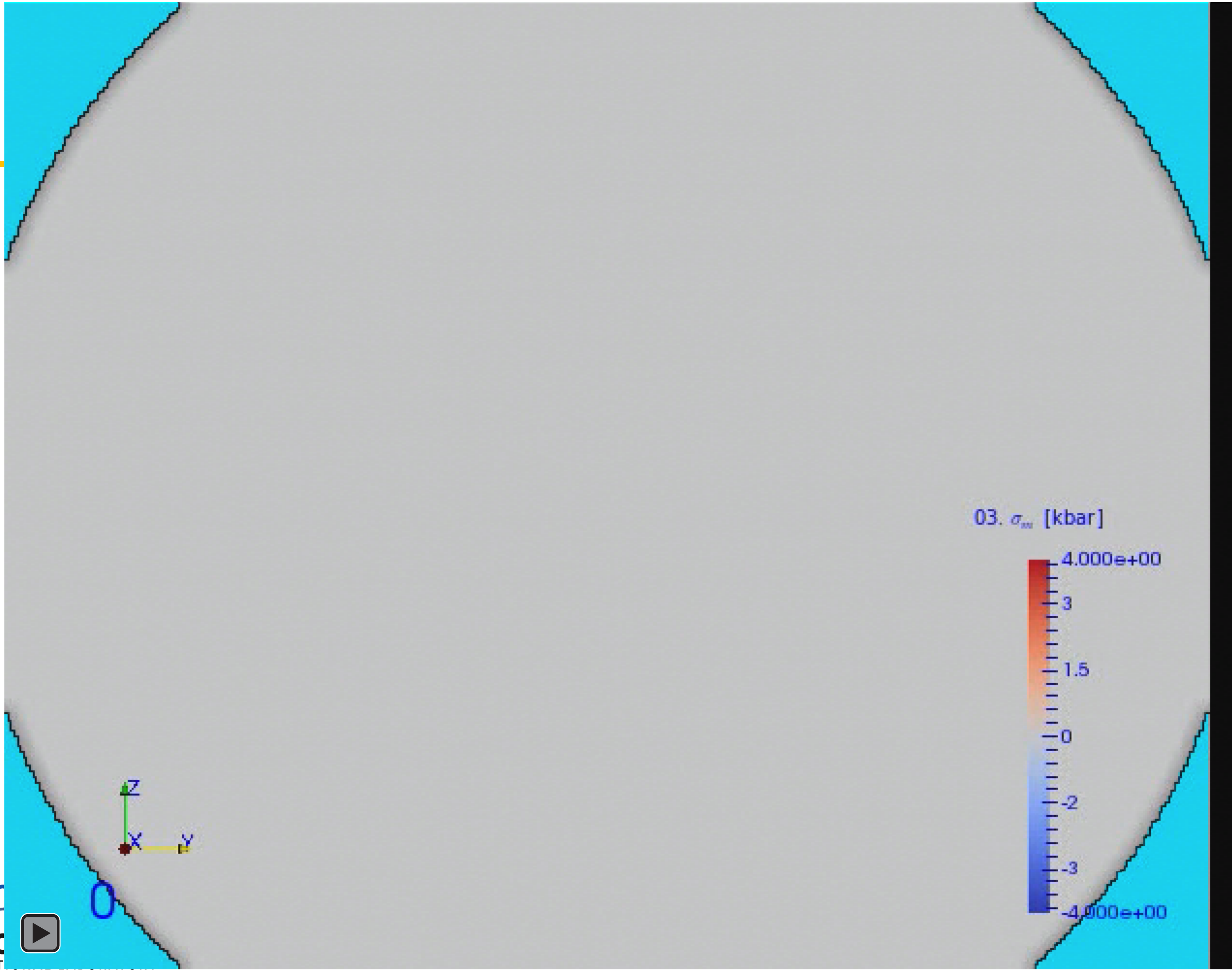


Z-Axis
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
X-Axis
03. σ [kbar]
4.000e+00
3
1.5
0
-2
-3
-4.000e+00
Z
Y
X
0



03. σ [kbar]
-5.000e+01
-20
0
20
5.000e+01
00. Field Number
1.000e+00
1.6
2.4
3.2
4
5.000e+00


03. σ [kbar]
4.000e+00
3
1.5
0
-2
-3
-4.000e+00
Z
Y
X
0


03. σm [kbar]
4.000e+00
3
1.5
0
-2
-3
-4.000e+00
Z
X
Y
0

Computed Fragment size frequencies

- Frequencies are determined using a standard cluster counting algorithm (Hoshen-Koppleman), using ParaView.
- This is fair because material points separated by more than one grid cell act independently.

HM failure model, by the numbers: SAE 4340

RC	*Drawn@ 2 hours*	*Elongation*	*D1*	*D_2*	*D_3*
30	***700 C***	***0.19***	***-0.8***	***2.10***	***-0.500***
32	***575 C***	***0.18***	***-0.8***	***2.03***	***-0.485***
41	***450 C***	***0.15***	***-0.8***	***1.83***	***-0.437***
48	***325 C***	***0.13***	***-0.8***	***1.69***	***-0.398***
54	***As Quenched***	***0.10***	***-0.8***	***1.48***	***-0.332***