Strain Amplitude Volume Fraction Method for Evaluation of Fatigue Durability

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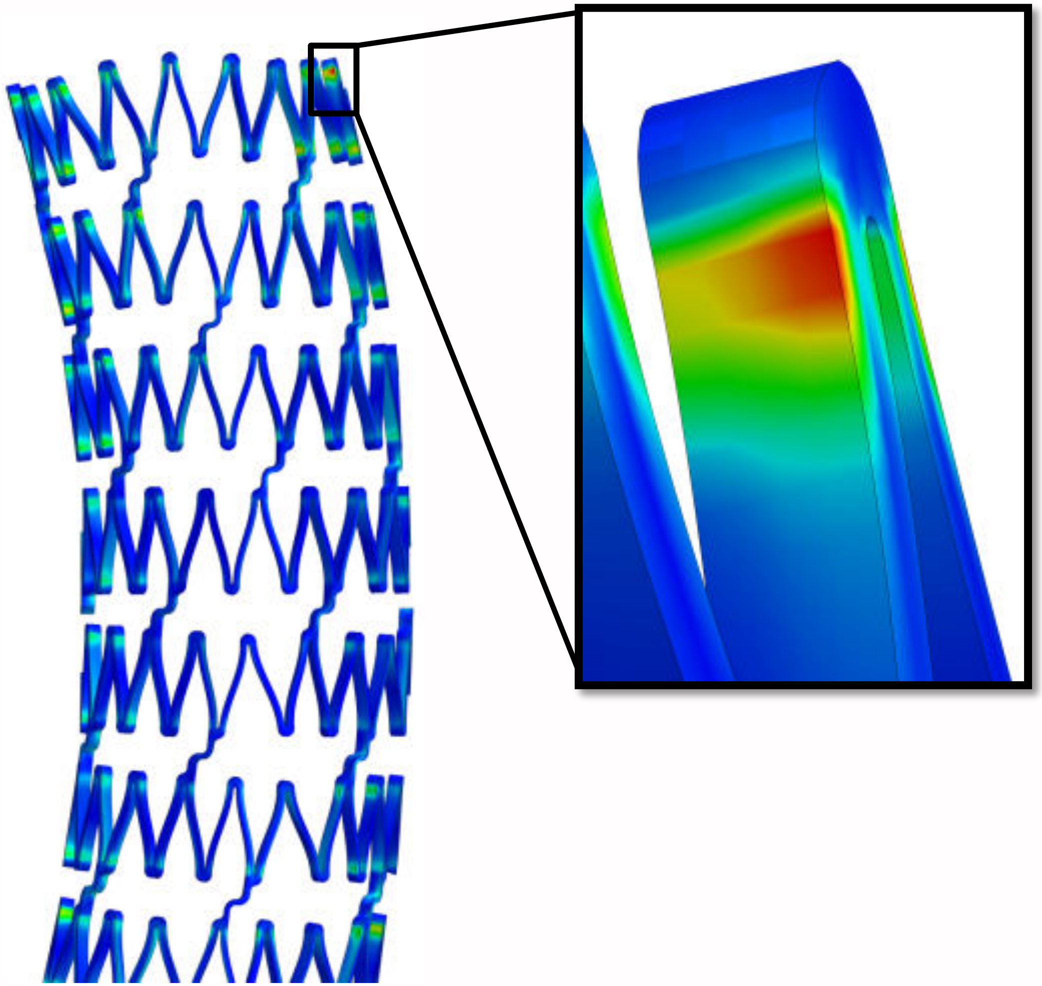
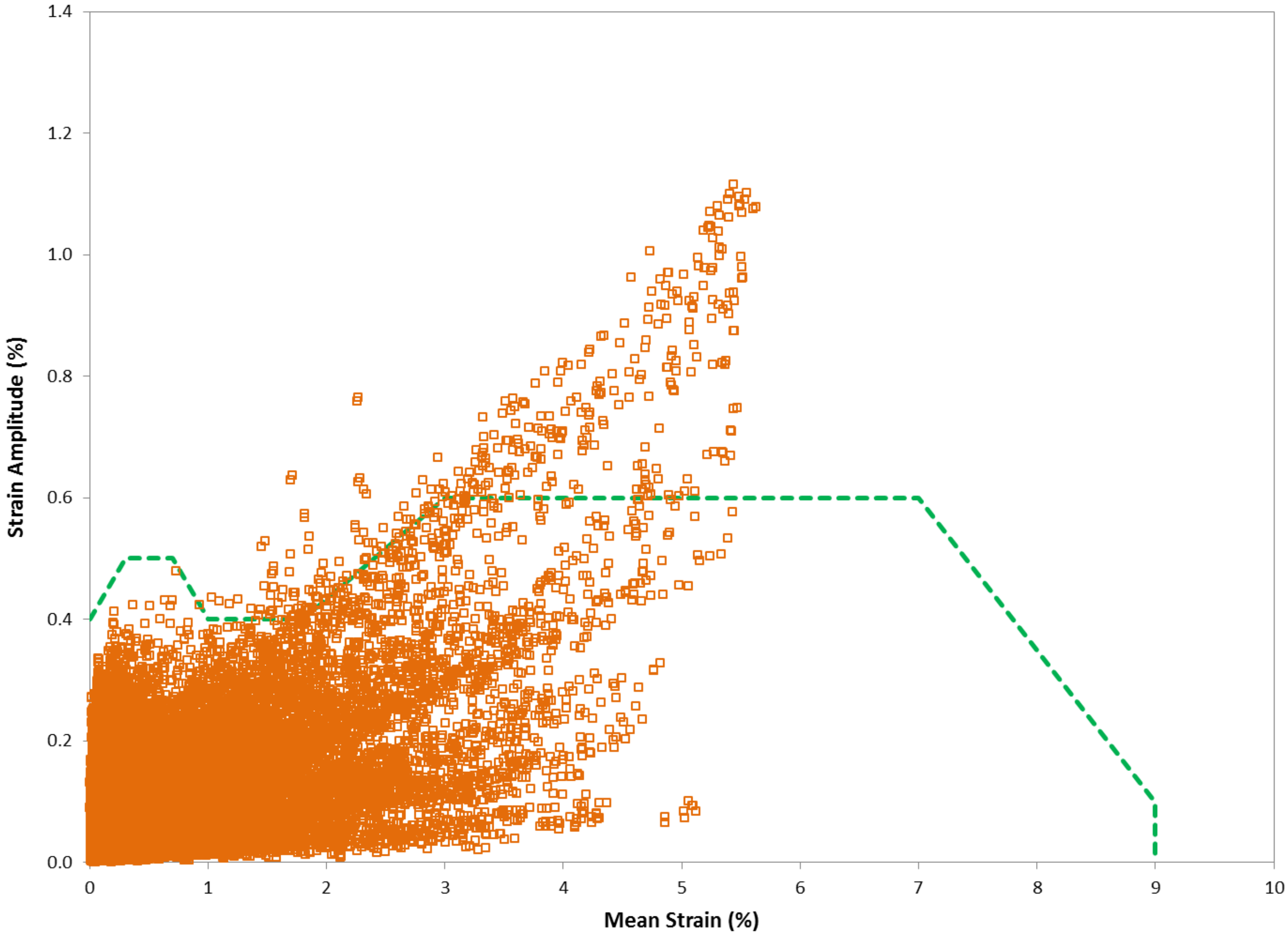
Stress/Strain Field



Example Case: Diamond Specimen



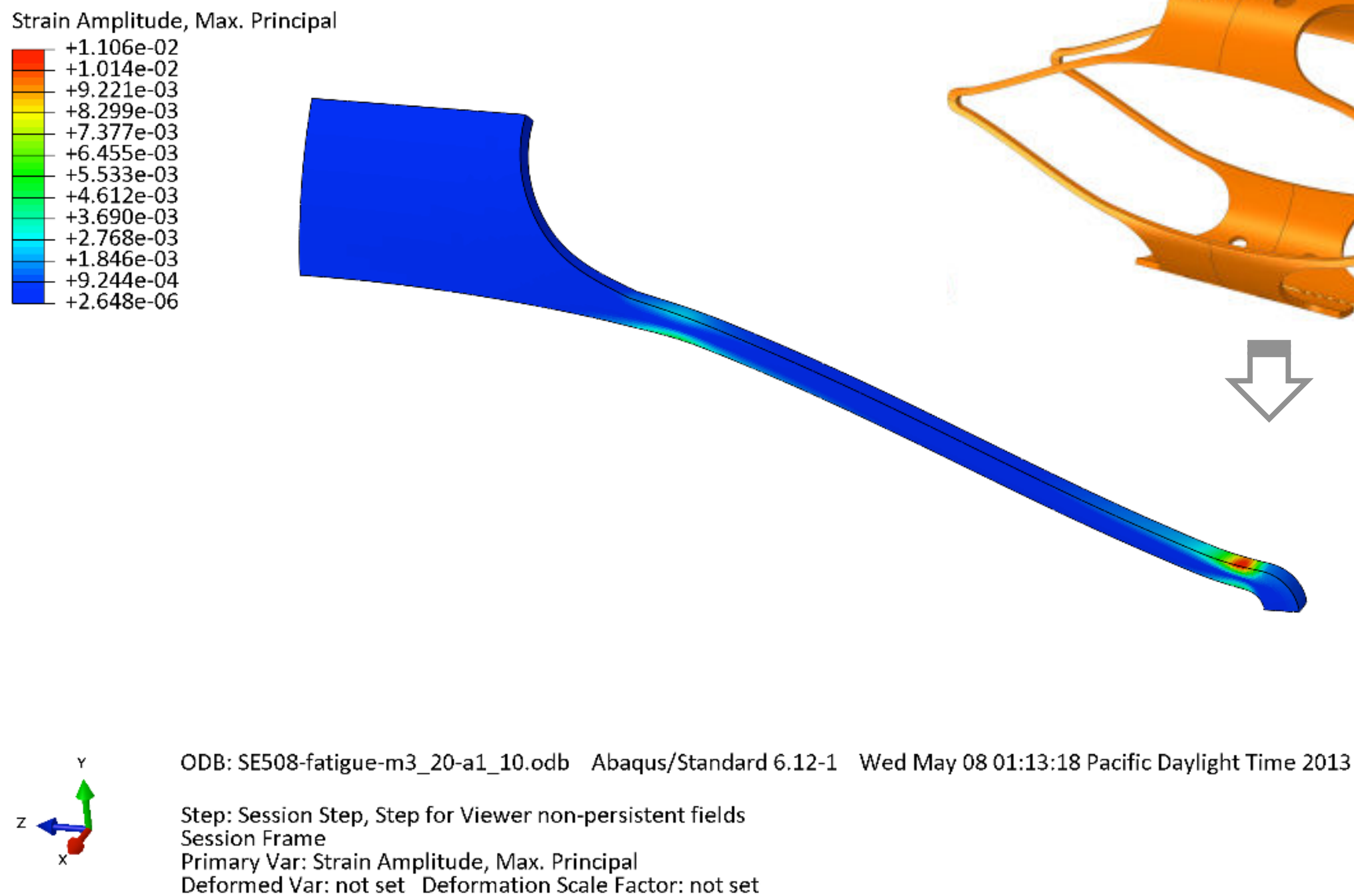
Hazard Probability

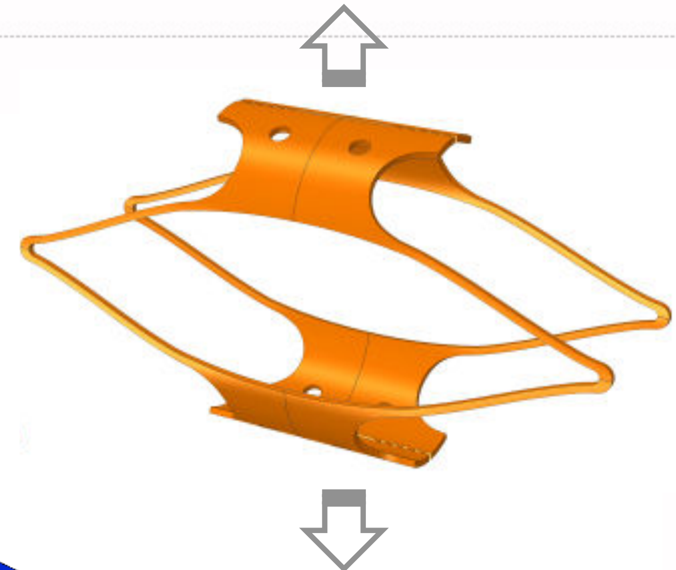
Volume fraction of inclusions

Critical strain region probability

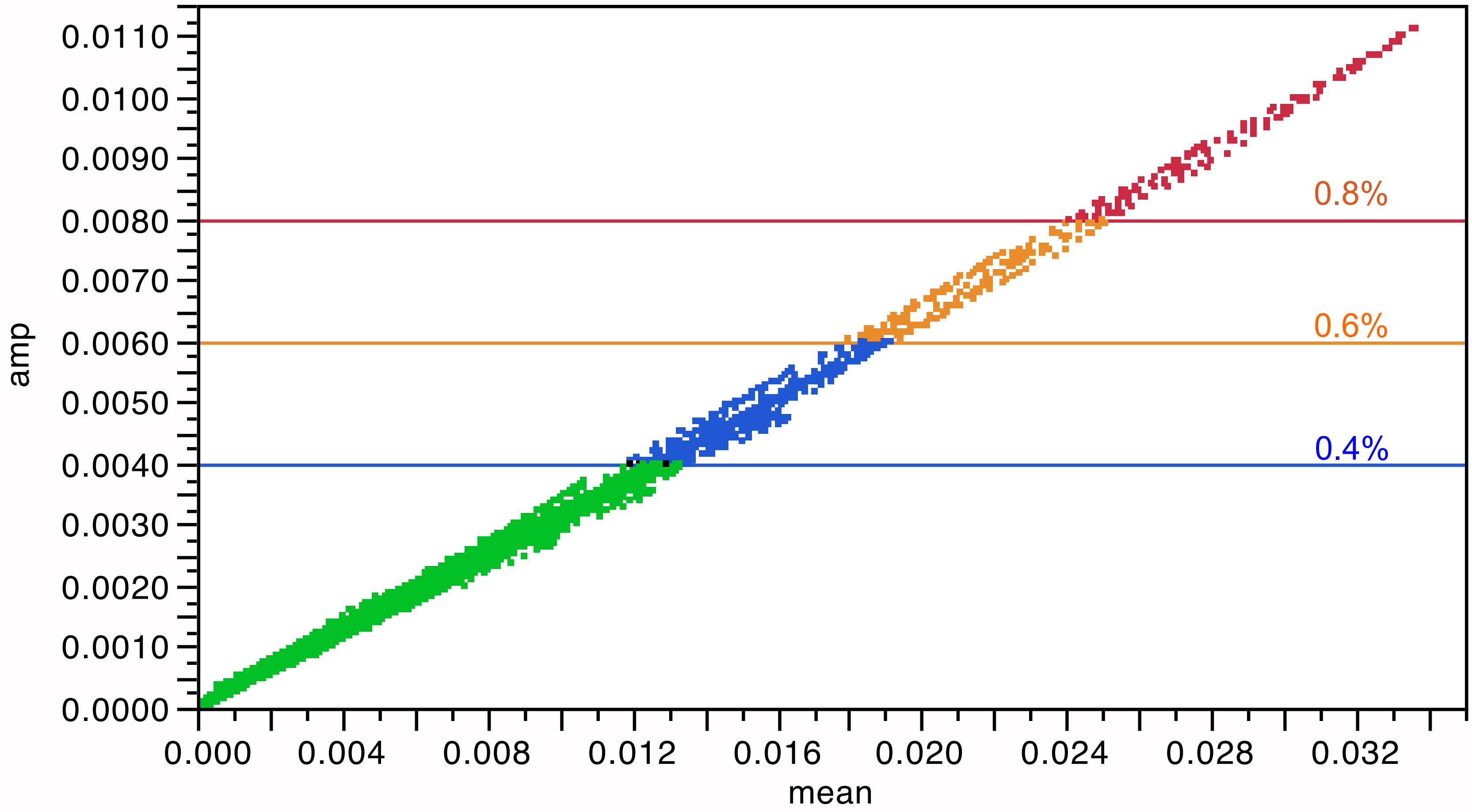
Putting everything together

Example Case: Diamond Specimen

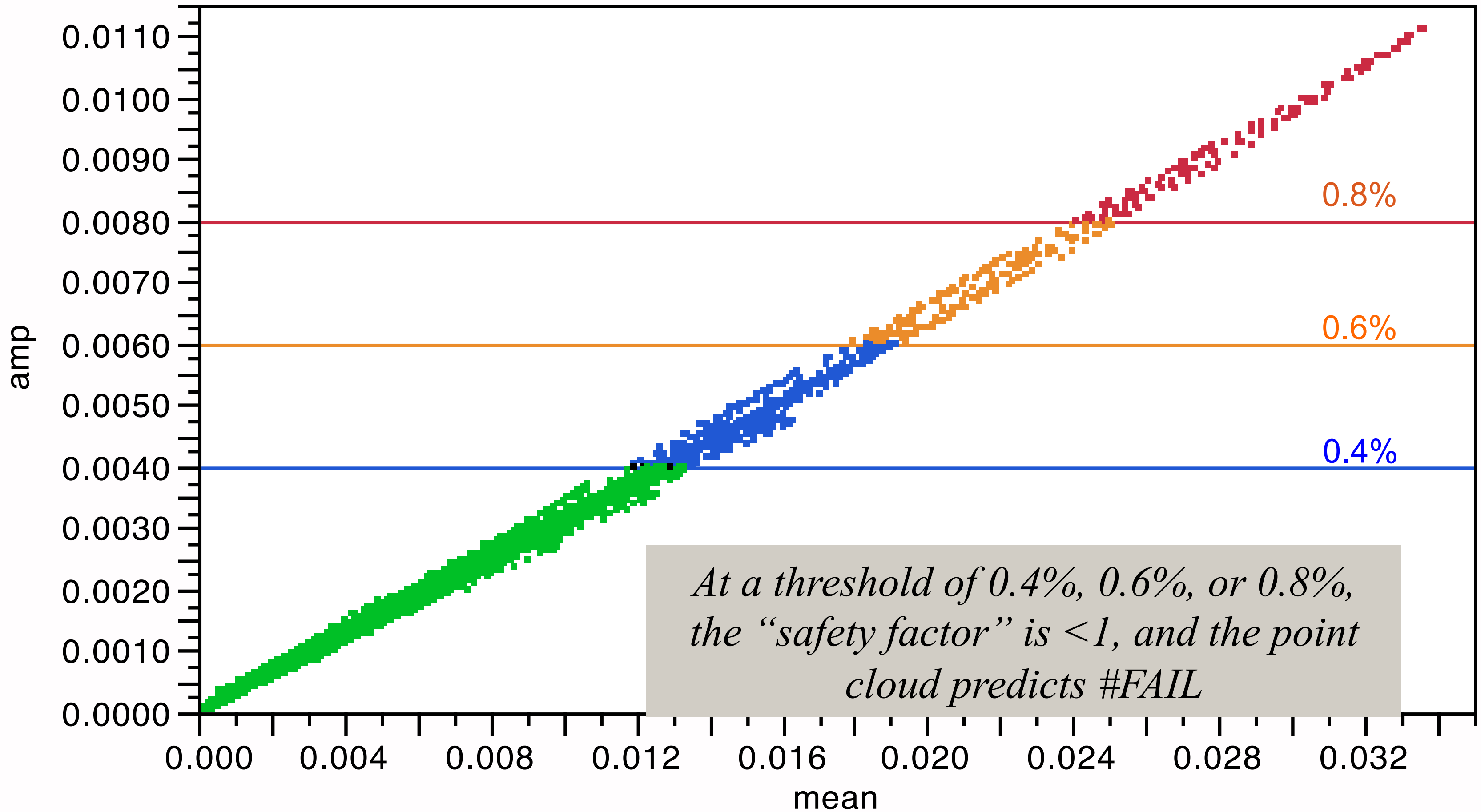




Point Cloud

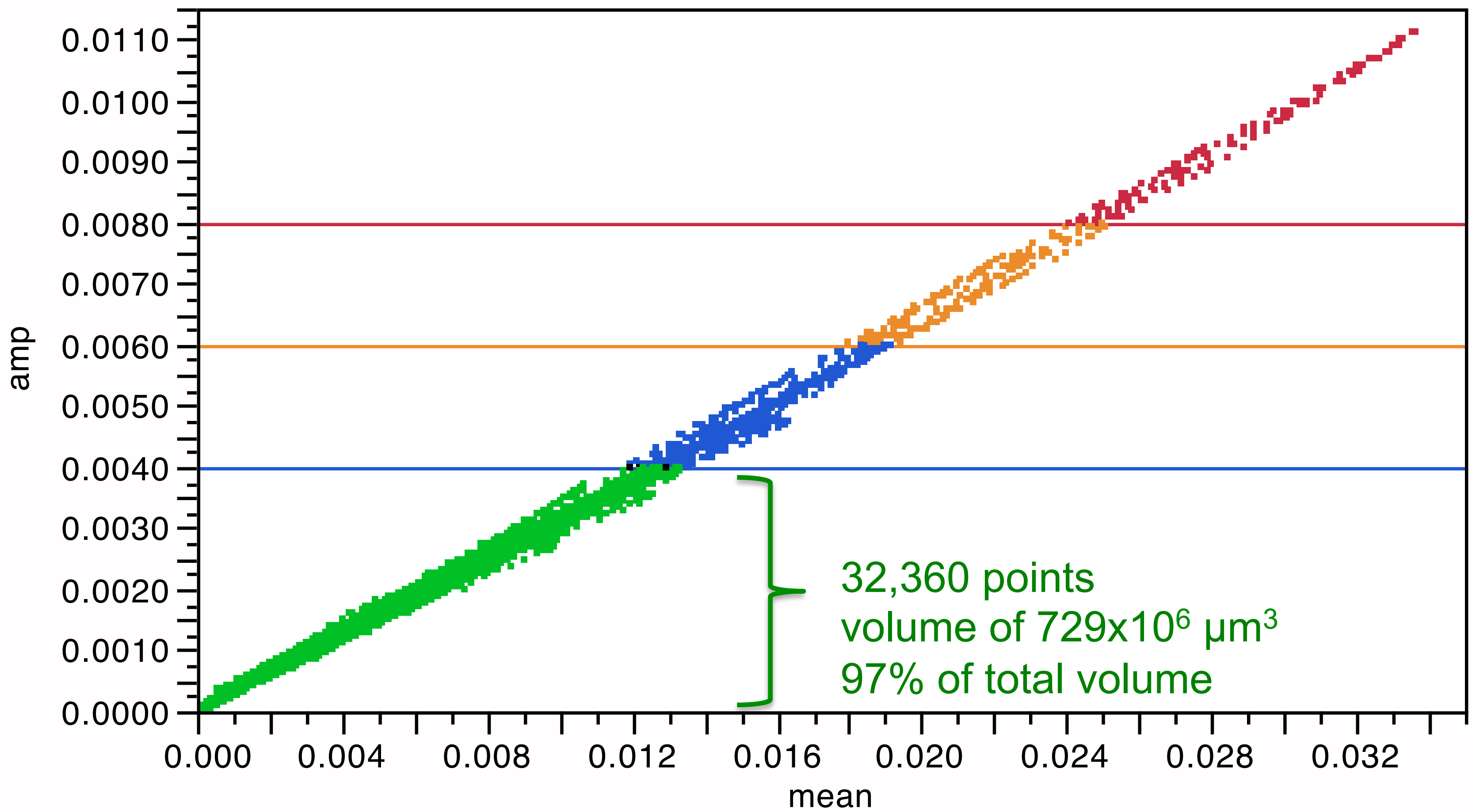

0.0110
0.0100
0.0090
0.0080
0.0070
0.0060
0.0050
0.0040
0.0030
0.0020
0.0010
0.0000
amp
0.8%
0.6%
0.4%
0.000
0.004
0.008
0.012
0.016
0.020
0.024
0.028
0.032
mean

Point Cloud and Safety Factor: Binary result "PASS" or "FAIL"

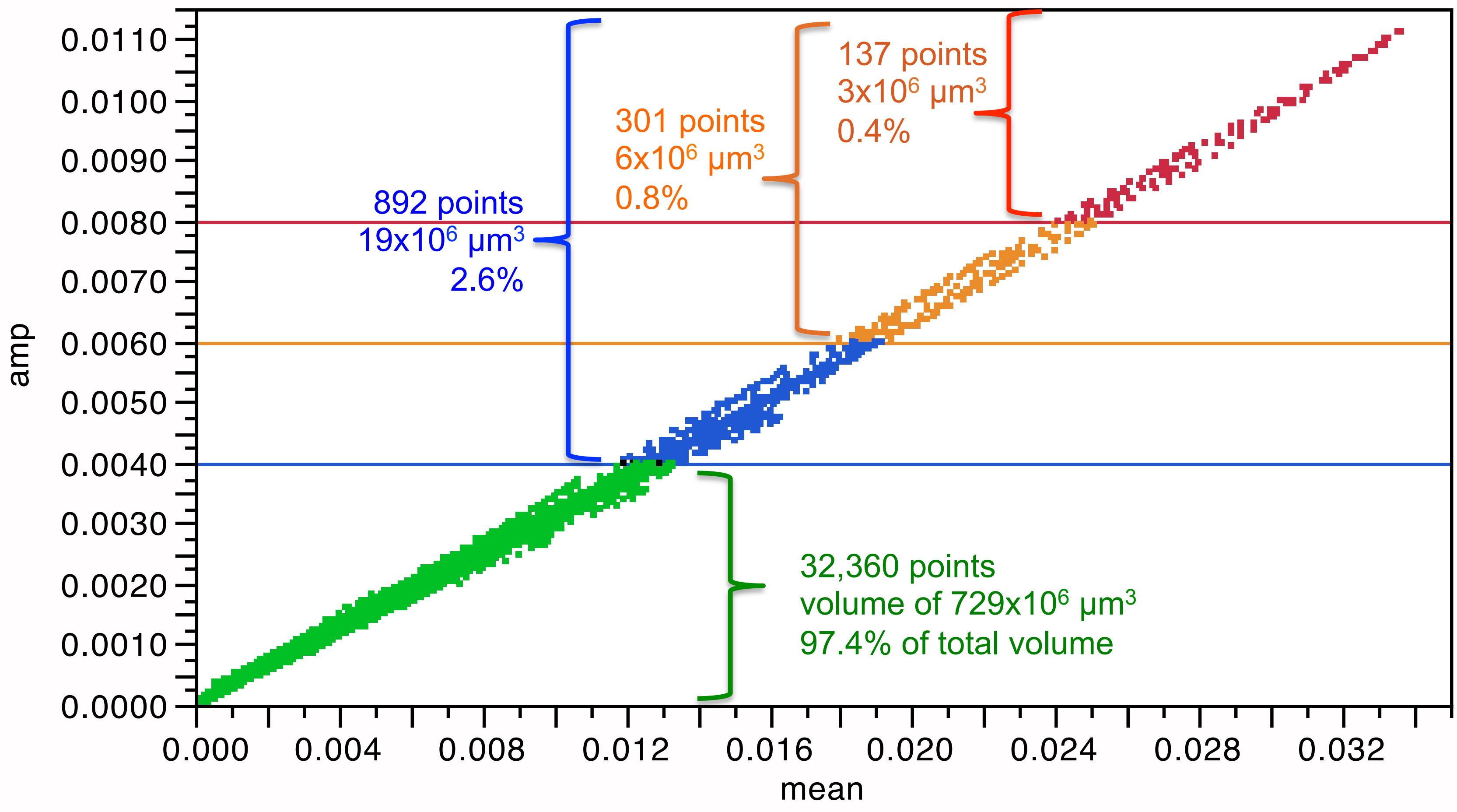


At a threshold of 0.4%, 0.6%, or 0.8%, the "safety factor" is <1, and the point cloud predicts #FAIL

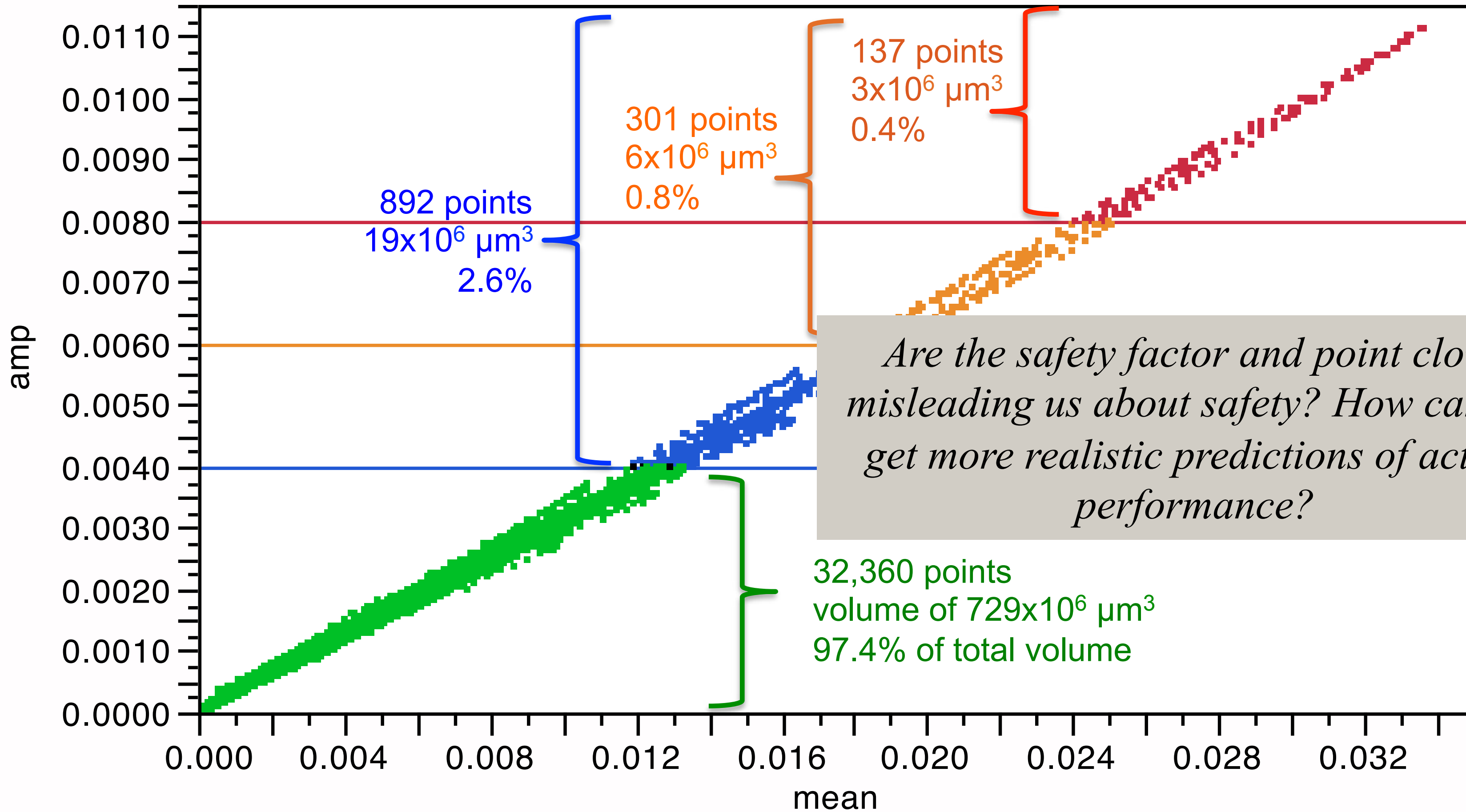
Point Cloud Limitations



Point Cloud Limitations



Point Cloud Limitations



Are the safety factor and point cloud misleading us about safety? How can we get more realistic predictions of actual performance?

Strain Amplitude Volume Fraction

- Define a relevant strain amplitude threshold: ε_{limit}
- Calculate strain amplitude for all integration points
- Calculate the volume of material for all element having a strain amplitude exceeding the threshold: $\sum V\varepsilon_{limit}$
- Calculate the total volume of material in the model: V_{total}
- The Strain Amplitude Volume Fraction: $SAVF = \dfrac{\sum V\varepsilon_{limit}}{V_{total}}$

Hypothesis 1

Hazard probability at any location depends on coincidence of (ε_{amp} > threshold) AND (presence of an impurity)

$$P_{hazard} = P(A \cap B) = P(A) \cdot P(B)$$

P(A) = Probability of an impurity at a location = Volume fraction of impurities detected in the material

P(B) = Probability of strain amplitude exceeding threshold at the same location = Volume fraction of elements exceeding threshold in a finite element analysis model

Hazard Probability

Volume fraction of inclusions

Critical strain region probability

Putting everything together

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Volume fraction of inclusions: Considerations

- ASTM F-2063 requires:
  - Voids and nonmetallics ≤ 2.8% area fraction at 500X
  - Oxide and Carbide particles ≤ 39.0 μm
  - Oxide and Carbide ≤ 500 PPM (by mass)

- None of these provide meaningful information about the volume percent of inclusions in typical materials

- So let's try to figure this out using some new methods…

Volume fraction of inclusions: Methodology

- SEM micrographs, tubing transverse sections, 500X
  - 10 micrographs for typical VAR material
  - 10 micrographs for typical high-purity VAR material

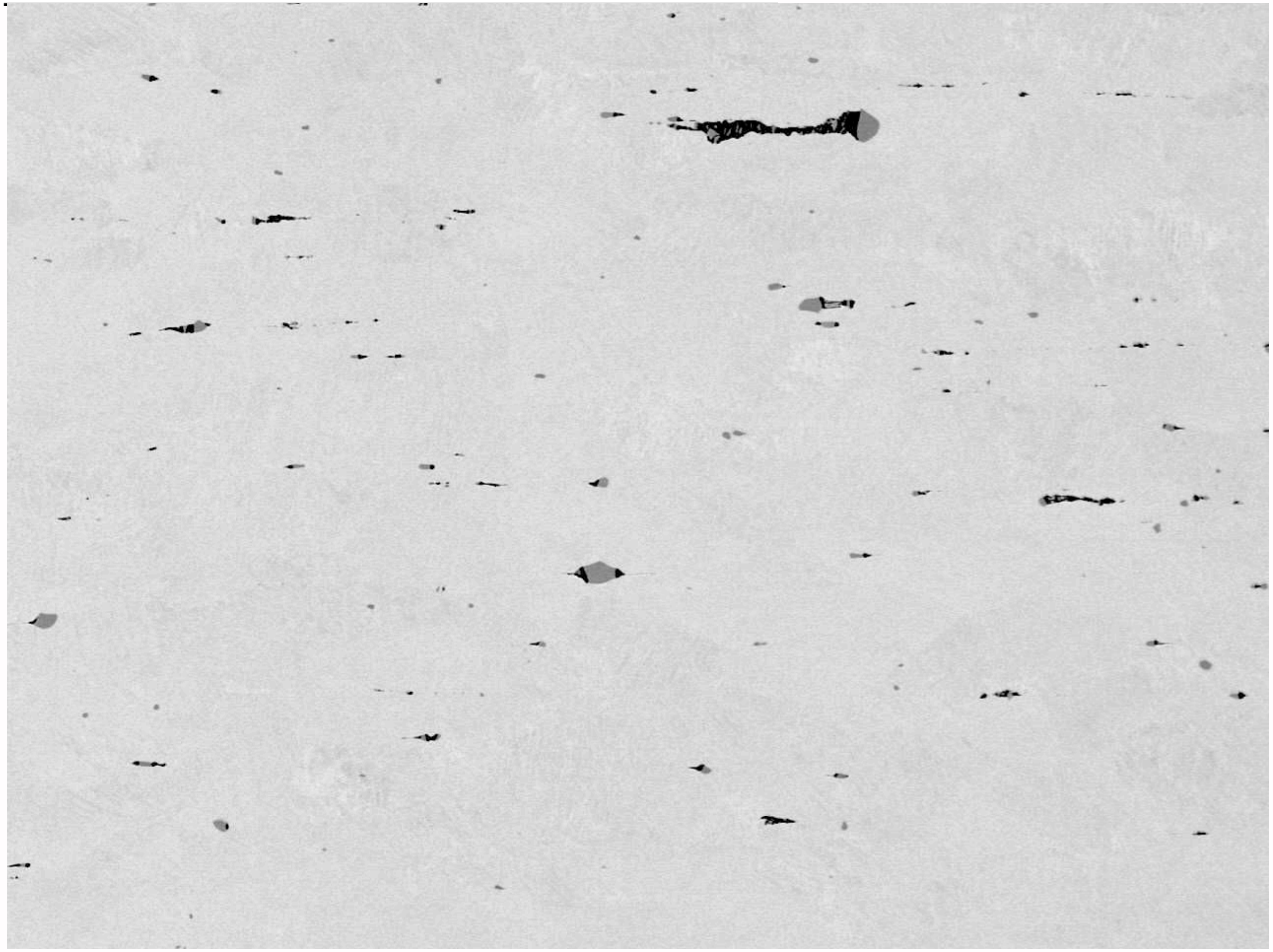
- An image processing algorithm was used to isolate particles in each image, and quantify their size in μm^2

- The volume of each particle was estimated as follows:
  - if particle area $\leq 25\ \mu m^2$, depth = $(\text{particle area})^{1/2}$
  - if particle area $> 25\ \mu m^2$, depth = $5\ \mu m$

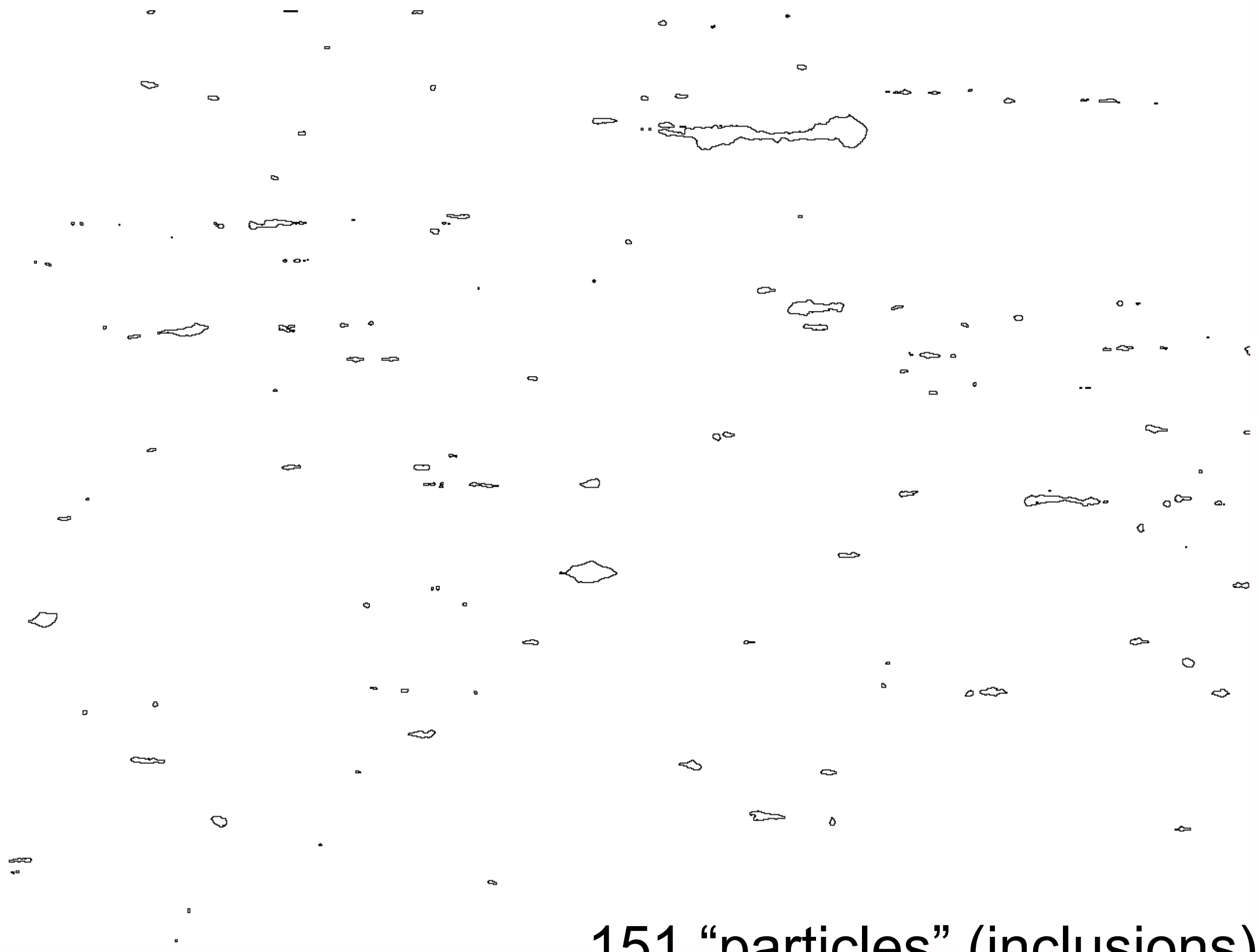
- The volume fraction of particles was calculated assuming each cross section accounts for $5\ \mu m$ depth

Typical raw image – VAR material

264.46x198.35 µm (1280x960); 8-bit; 1.2MB



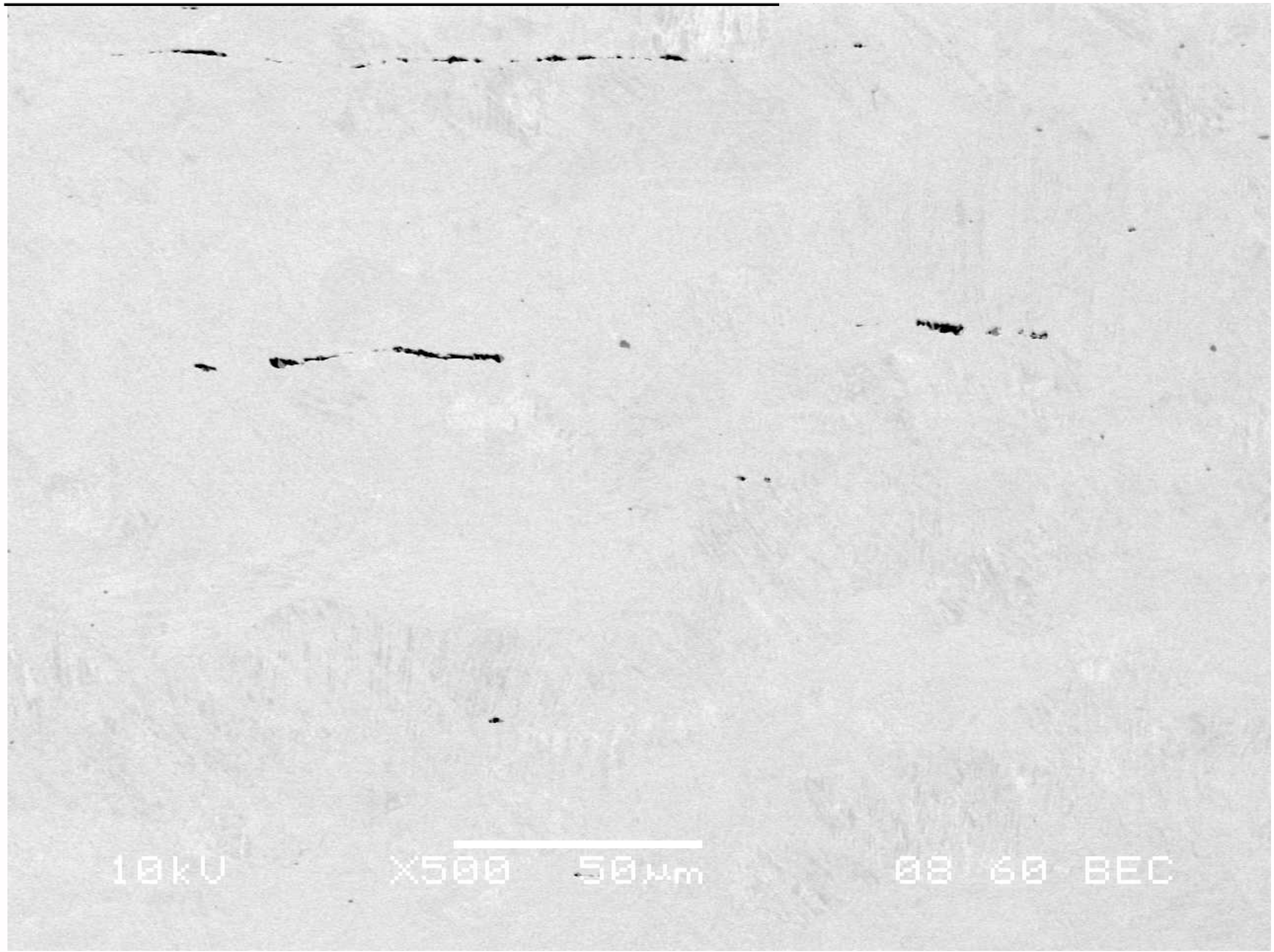
Typical particle detection – VAR material



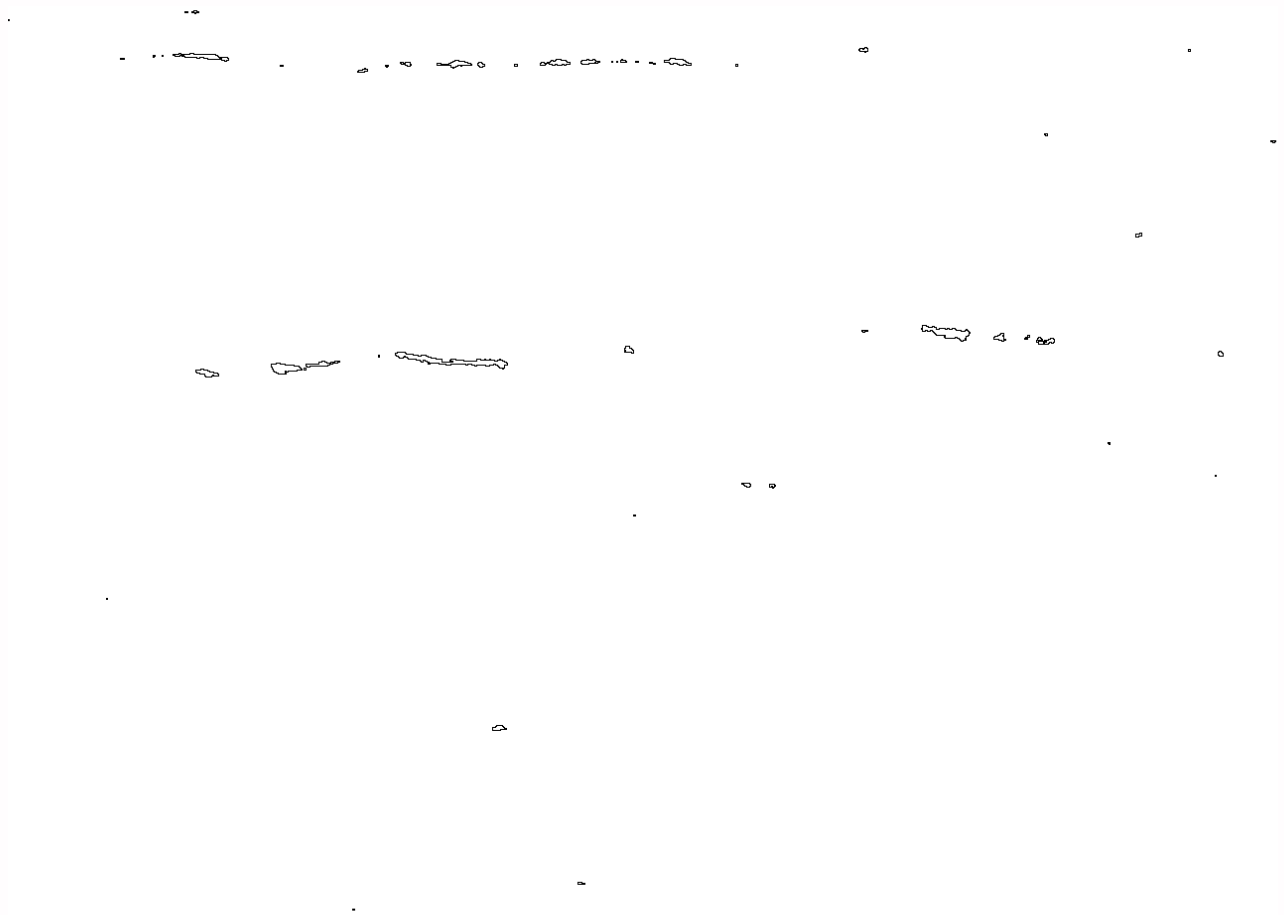
151 “particles” (inclusions) detected

Typical raw image – high purity VAR

264.46x198.35 µm (1280x960); 8-bit; 1.2MB

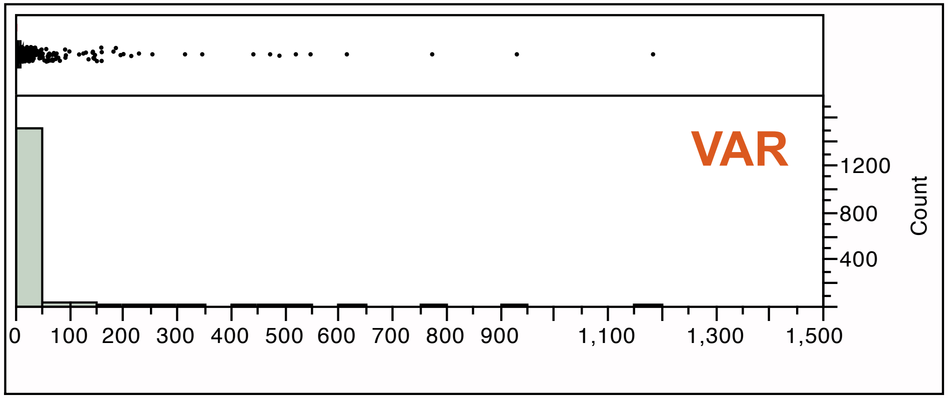


Typical particle detection - ELI



55 “particles” (inclusions) detected

Volume Histograms for VAR, High Purity VAR



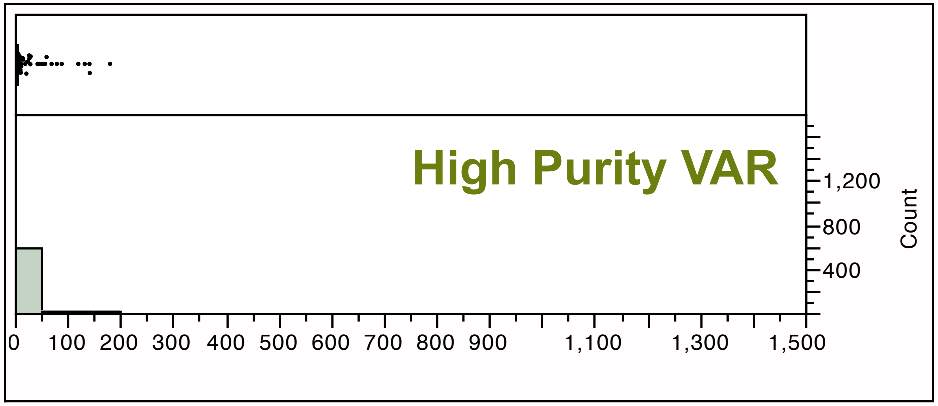
Quantiles

100.0%	maximum	1185.67
99.5%		477.427
97.5%		77.238
90.0%		12.326
75.0%	quartile	3.697
50.0%	median	0.730
25.0%	quartile	0.130
10.0%		0.025
2.5%		0.009
0.5%		0.009
0.0%	minimum	0.009

Summary Statistics

Mean	10.793
Std Dev	58.644
Std Err Mean	1.485
Upper 95% Mean	13.706
Lower 95% Mean	7.881
N	1560.000

N=1,560
μ=10.8
σ=59



Quantiles

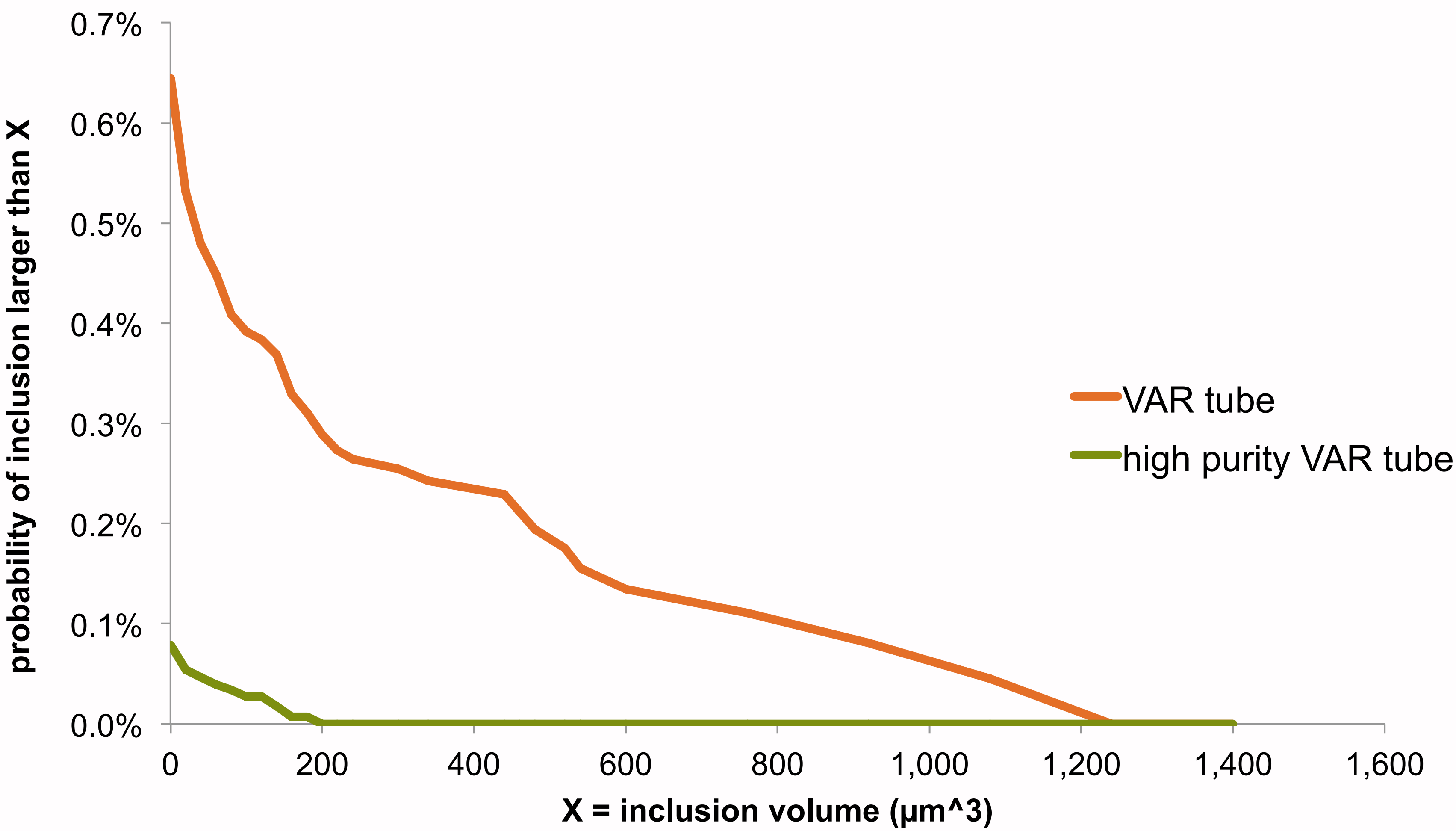
100.0%	maximum	181.000
99.5%		142.010
97.5%		29.986
90.0%		4.772
75.0%	quartile	1.342
50.0%	median	0.200
25.0%	quartile	0.046
10.0%		0.009
2.5%		0.009
0.5%		0.009
0.0%	minimum	0.009

Summary Statistics

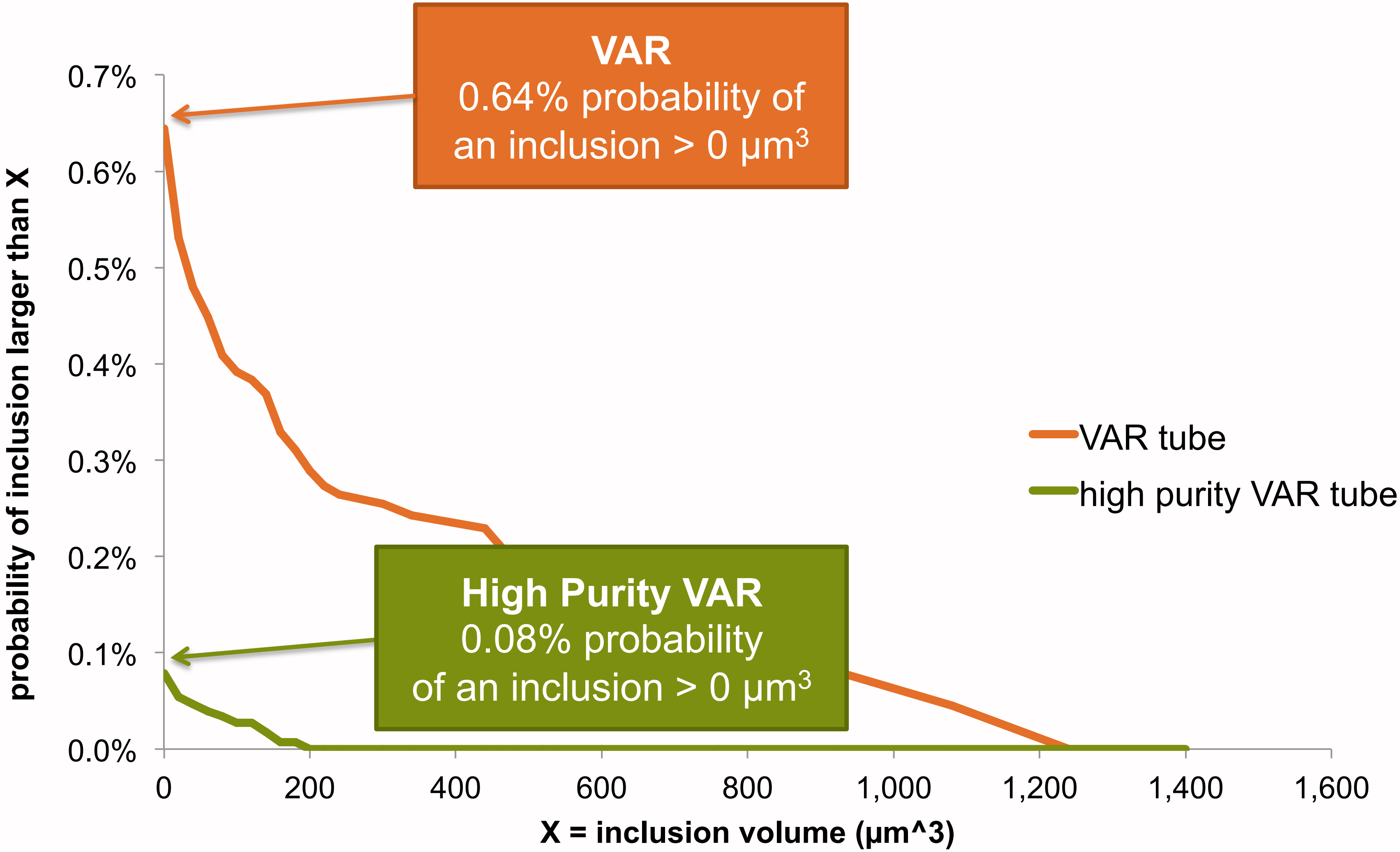
Mean	3.562
Std Dev	15.616
Std Err Mean	0.650
Upper 95% Mean	4.839
Lower 95% Mean	2.286
N	577.000

N=577
μ=3.6
σ=16

Cumulative probability for inclusions by volume



Cumulative probability for inclusions by volume



Hazard Probability
Volume fraction of inclusions
Critical strain region probability
Putting everything together

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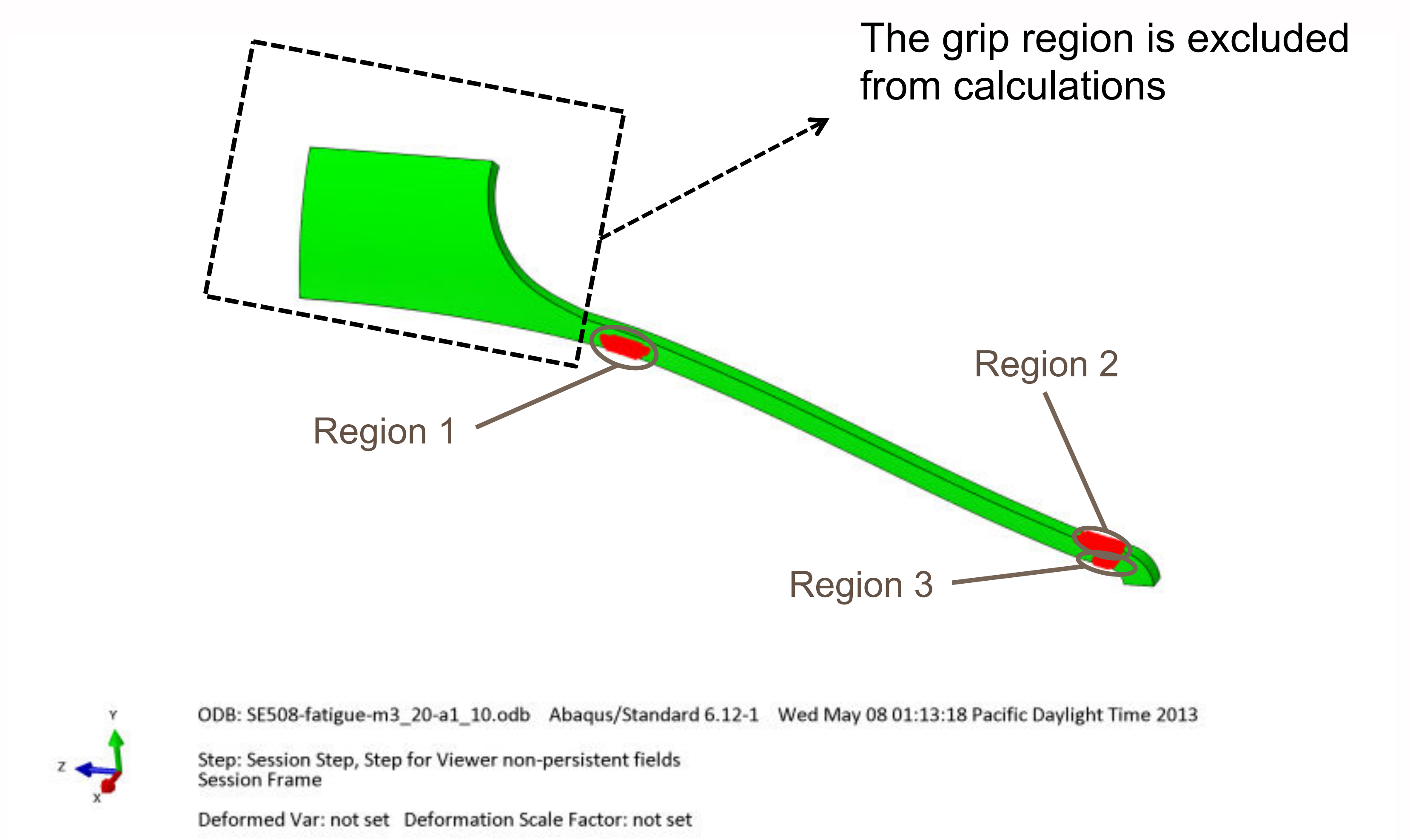
Critical strain region volume

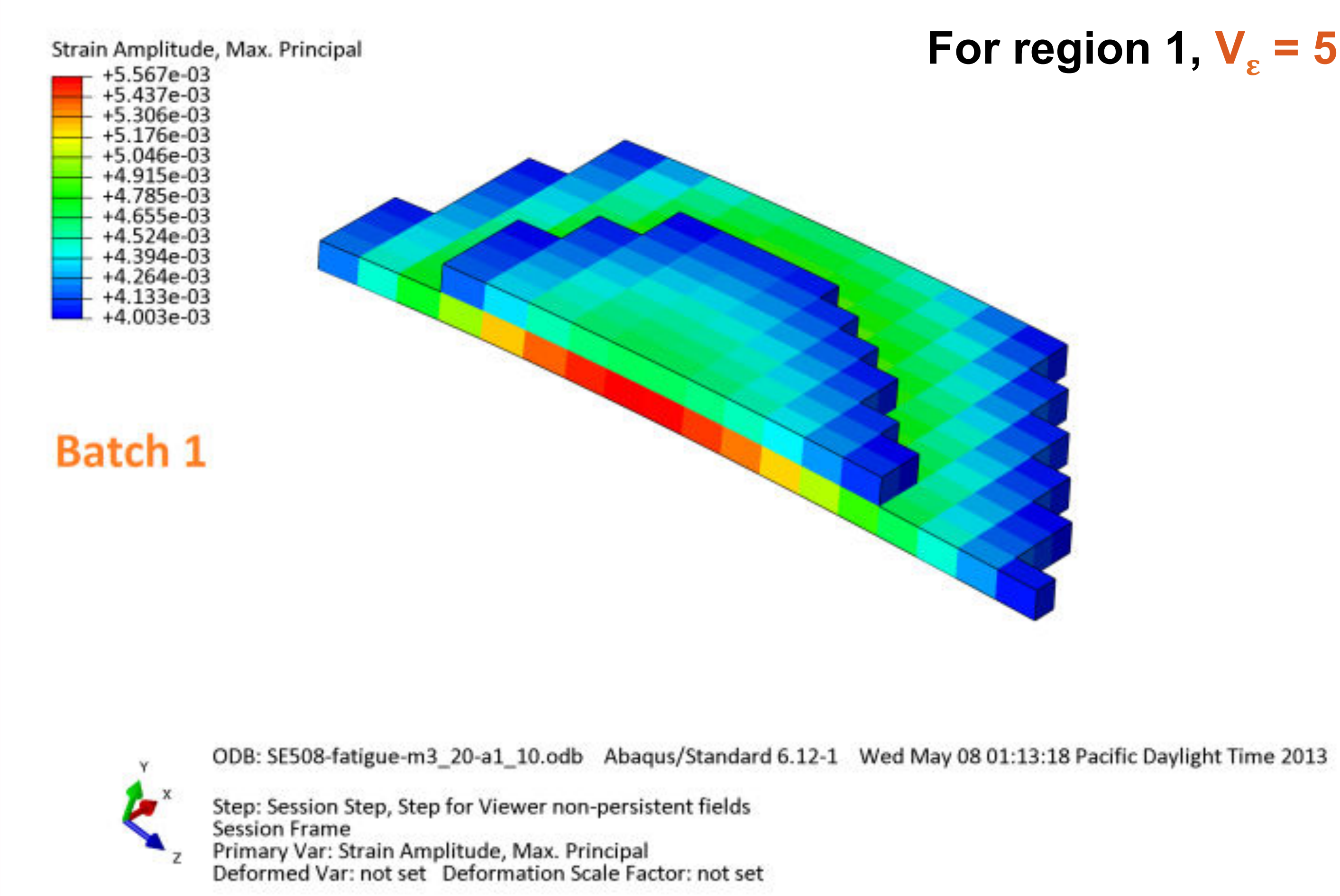
- An algorithm was developed
  - to identify contiguous regions of elements with a strain amplitude exceeding a defined threshold…
  - and measure the volume of each of these regions
- The algorithm has been implemented as an Abaqus Python script
- The critical strain regions are illustrated on the following slides

Critical strain region volumes:
Case 1, strain threshold = 0.4%



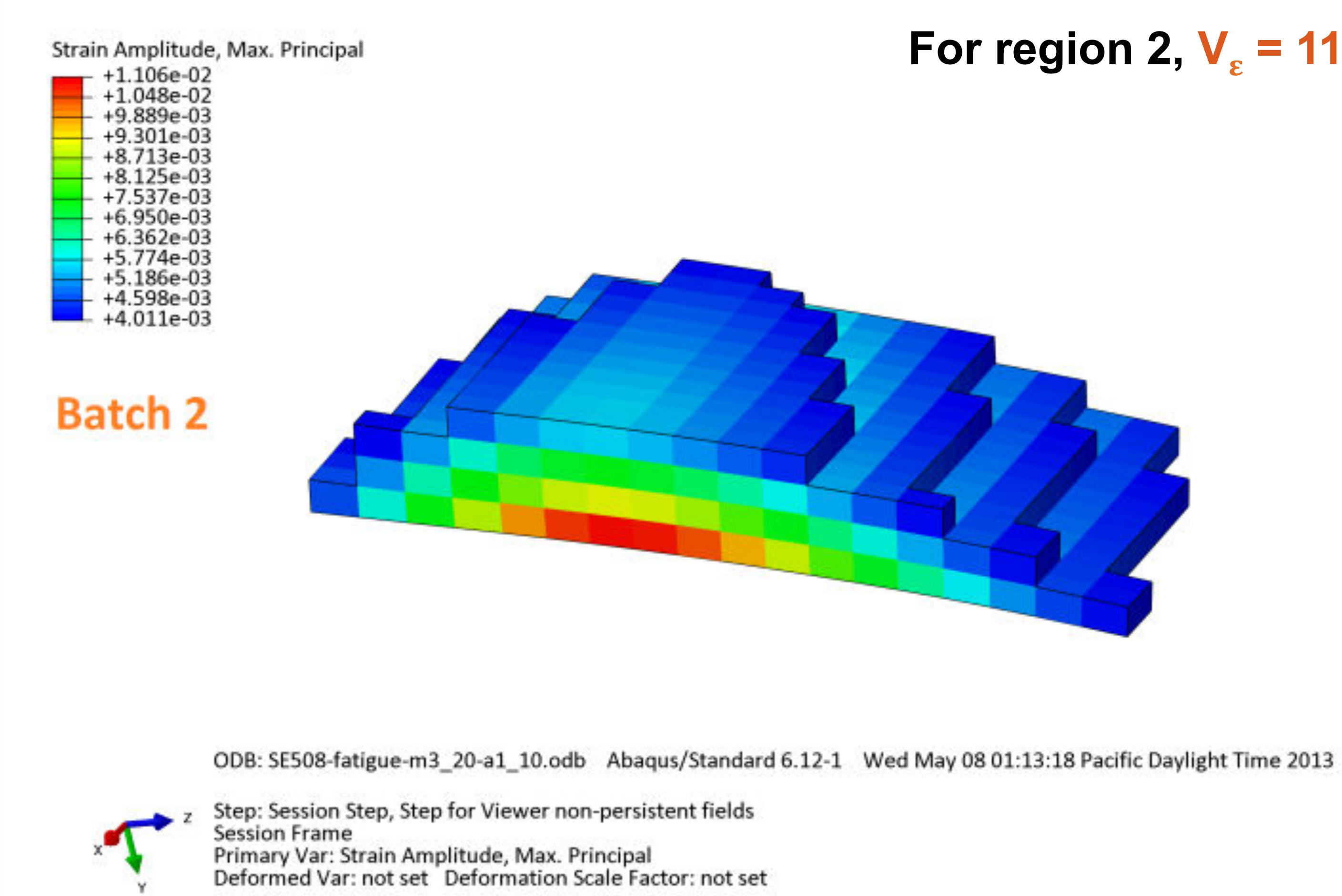
Critical strain region volume 1:
Case 1, strain threshold = 0.4%

For region 1, V_ε = 5,671,500 μm^3



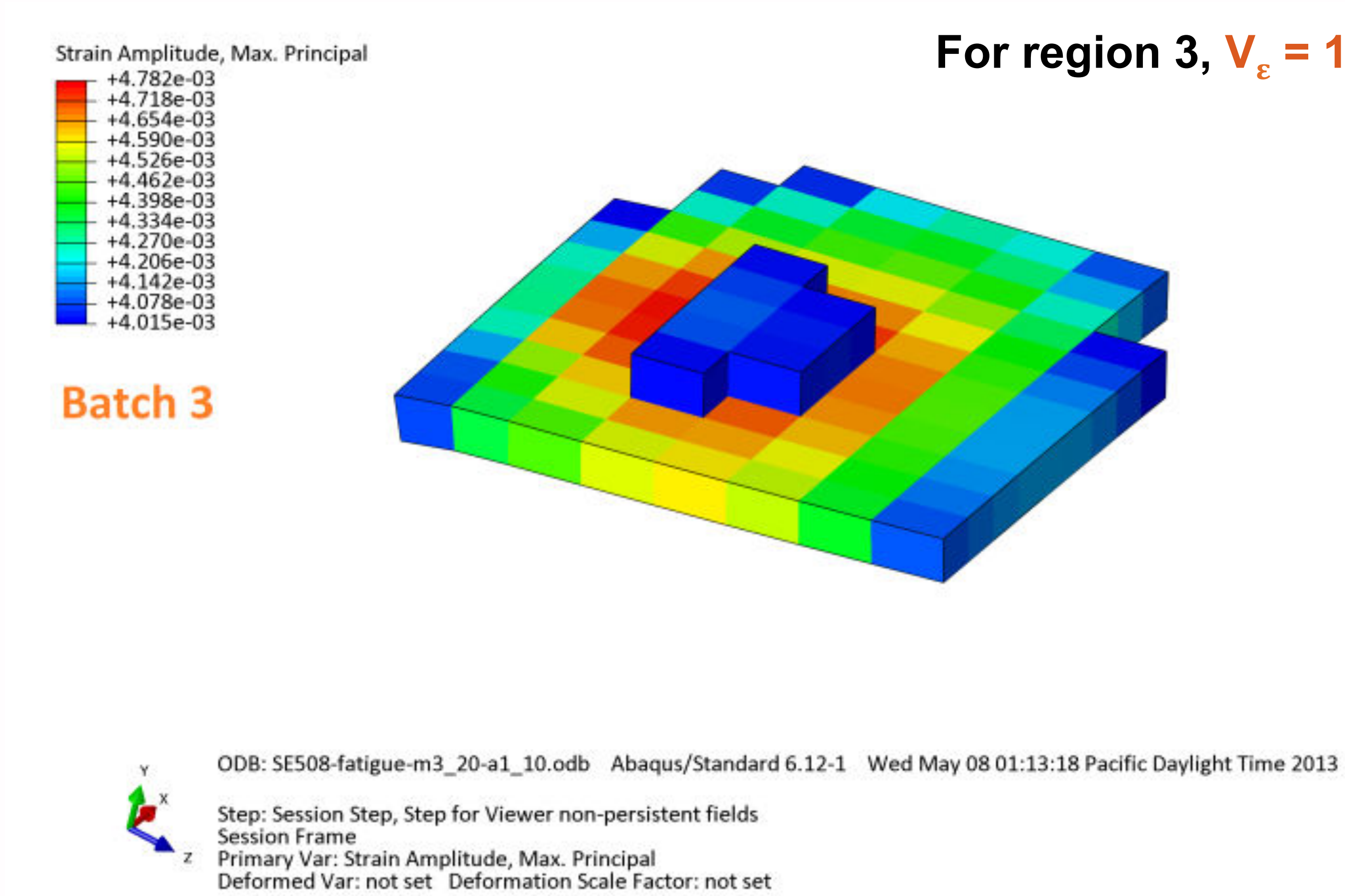
Critical strain region volume 2:
Case 1, strain threshold = 0.4%

For region 2, V_ε = 11,702,000 μm^3

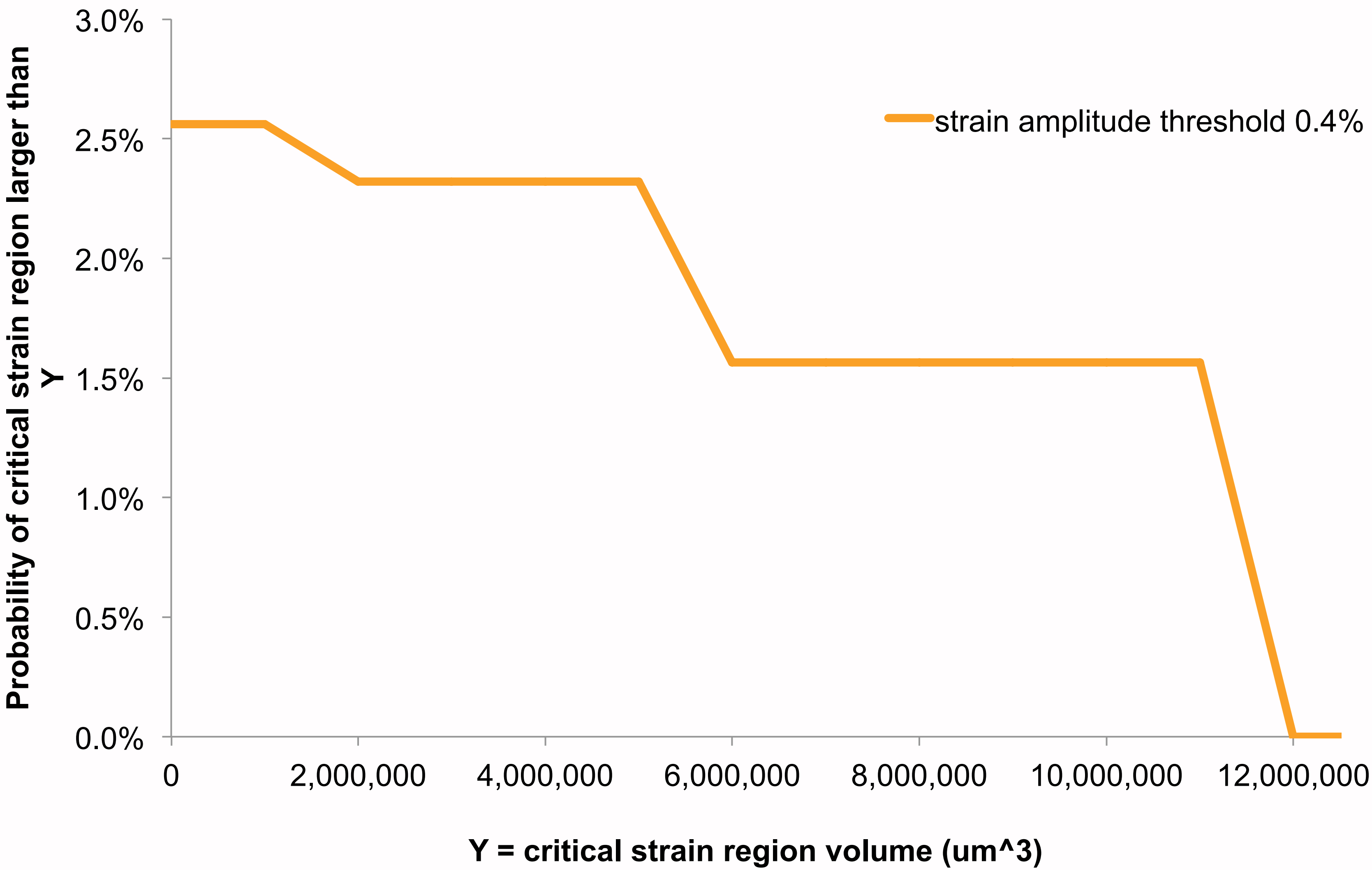


Critical strain region volume 3:
Case 1, strain threshold = 0.4%

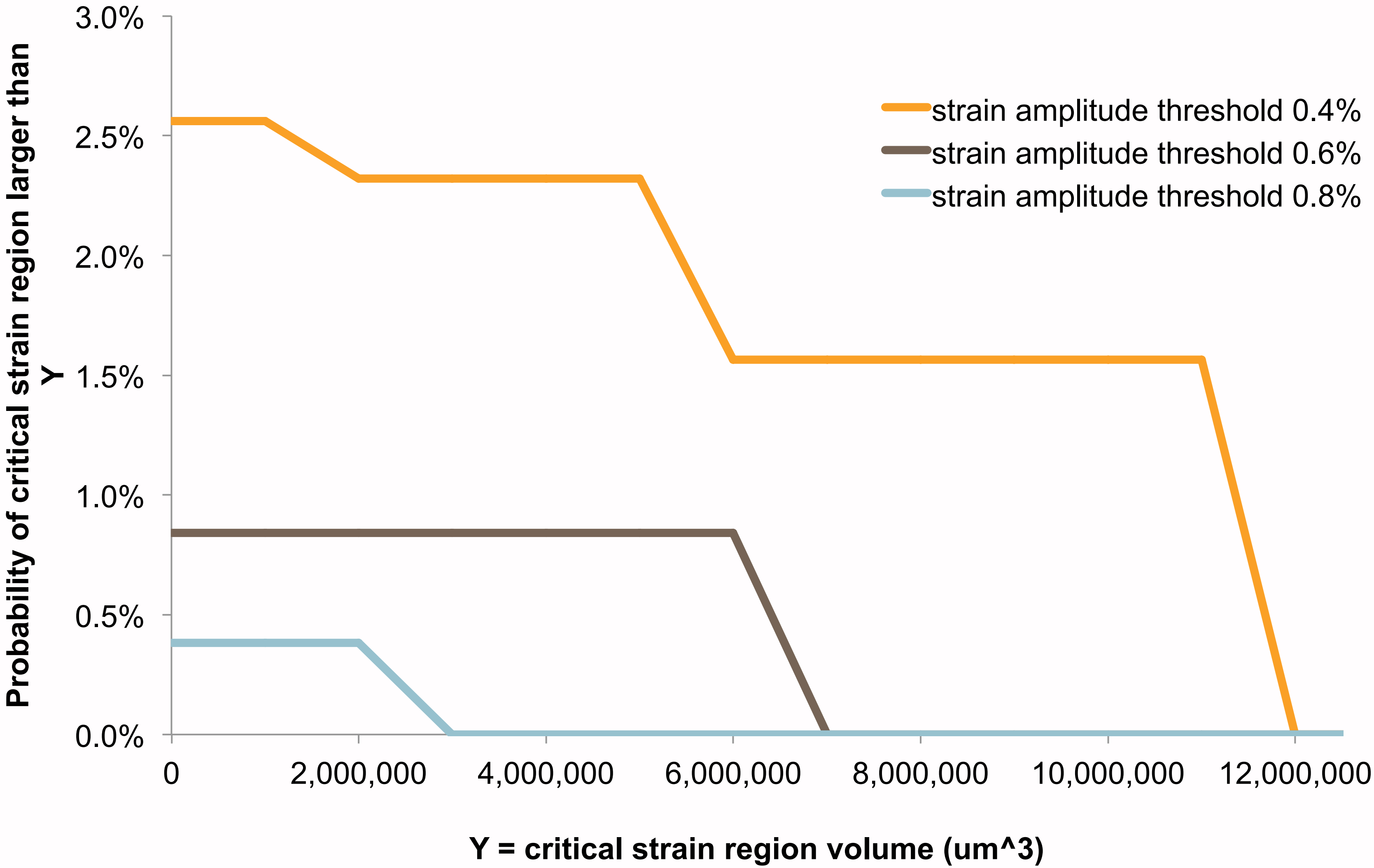
For region 3, V_{ε} = 1,791,300 µm³



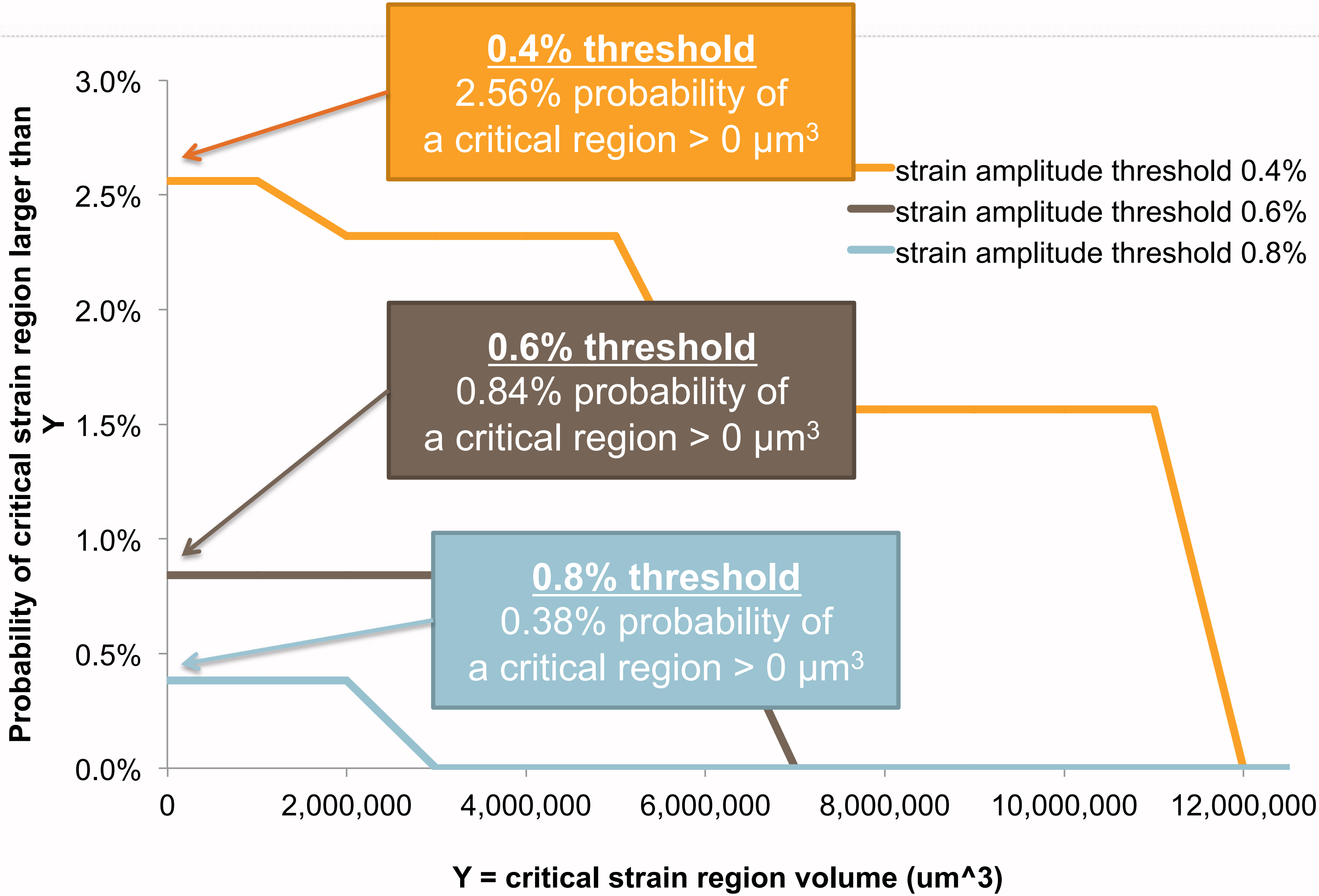
Probability vs. critical strain region size



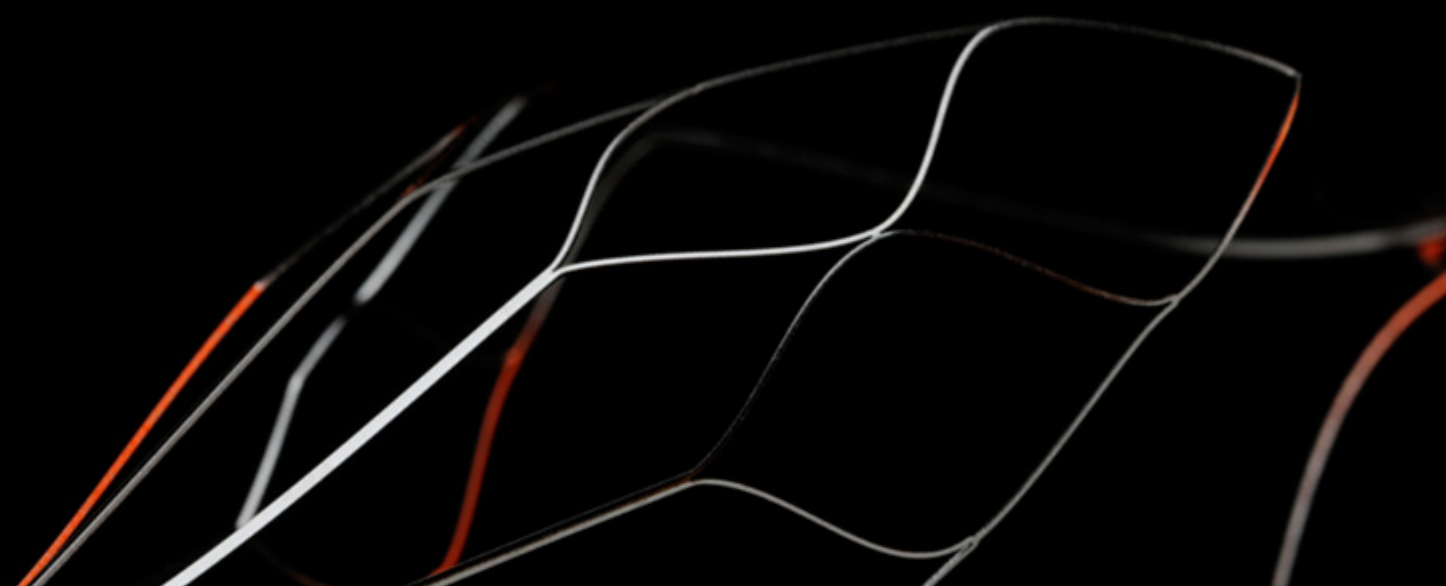
Probability vs. critical strain region size



Probability vs. critical strain region size



Hazard Probability
Volume fraction of inclusions
Critical strain region probability
Putting everything together



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Hazard Probabilities: VAR Material

VAR Material		unit	Threshold 0.4%
Probability of an inclusion larger than zero	[1]	%	0.64%
Probability of a critical strain region larger than zero	[2]	%	2.56%

Hazard Probabilities: VAR Material

VAR Material		unit	Threshold 0.4%
Probability of an inclusion larger than zero	[1]	%	0.64%
Probability of a critical strain region larger than zero	[2]	%	2.56%
Hazard probability for model ([1] * [2])	[3]	%	0.02%
Hazard probability for the model, PPM ([3]*10^6)	[4]	PPM	164

Hazard Probabilities: VAR Material

VAR Material		unit	Threshold 0.4%
Probability of an inclusion larger than zero	[1]	%	0.64%
Probability of a critical strain region larger than zero	[2]	%	2.56%
Hazard probability for model ([1] * [2])	[3]	%	0.02%
Hazard probability for the model, PPM ([3]*10^6)	[4]	PPM	164
Number of repeating features in device	[5]	N	180
Hazard probability for the device	[6]	%	2.95%
Hazard probability for the device, PPM	[7]	PPM	29,491

Hazard Probabilities: VAR Material

VAR Material		unit	Threshold 0.4%	Threshold 0.6%	Threshold 0.8%
Probability of an inclusion larger than zero	[1]	%	0.64%	0.64%	0.64%
Probability of a critical strain region larger than zero	[2]	%	2.56%	0.84%	0.38%
Hazard probability for model ([1] * [2])	[3]	%	0.02%	0.01%	0.00%
Hazard probability for the model, PPM ([3]*10^6)	[4]	PPM	164	54	24
Number of repeating features in device	[5]	N	180	180	180
Hazard probability for the device	[6]	%	2.95%	0.97%	0.44%
Hazard probability for the device, PPM	[7]	PPM	29,491	9,677	4,378

Hazard Probabilities: High Purity VAR Material

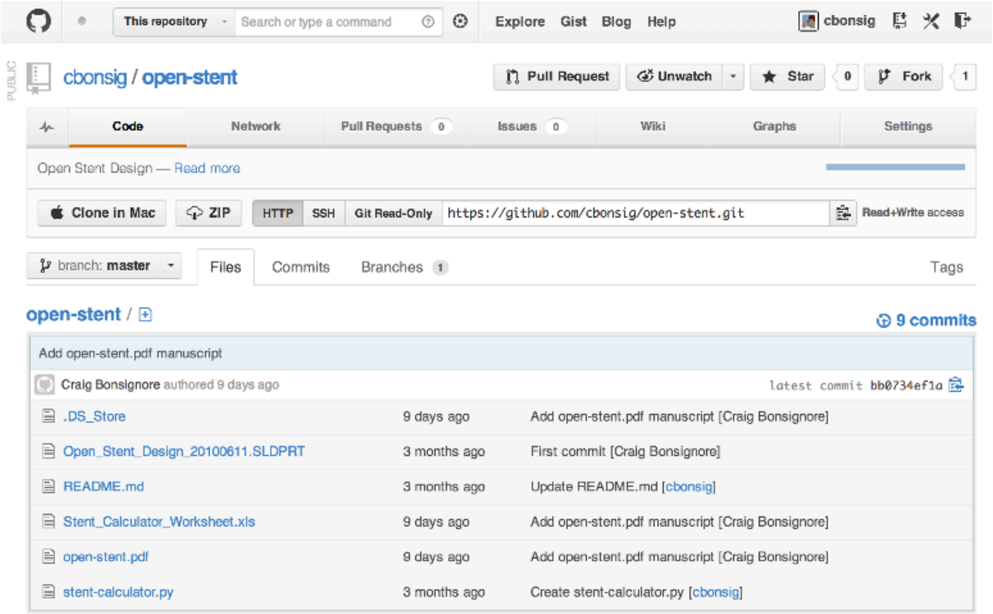
High Purity VAR Material		unit	Threshold 0.4%	Threshold 0.6%	Threshold 0.8%
Probability of an inclusion larger than zero	[1]	%	0.08%	0.08%	0.08%
Probability of a critical strain region larger than zero	[2]	%	2.56%	0.84%	0.38%
Hazard probability for model (inclusion >0 coincident with strain region >0) ([1] * [2])	[3]	%	0.00%	0.00%	0.00%
Hazard probability for the model, PPM ([3]*10^6)	[4]	PPM	20	7	3
Number of repeating features in device	[5]	N	180	180	180
Hazard probability for the device	[6]	%	0.37%	0.12%	0.05%
Hazard probability for the device, PPM	[7]	PPM	3,686	1,210	547

Future Improvements

- Extend script to consider strain amplitude threshold as a function of mean strain
- Improve speed of script, and automate analysis
- Extend hazard analysis to incorporate probability as a function of critical strain region size and inclusion size
- Confirm these predictions vs. physical testing results

Abaqus Python Code for critical strain regions

- Python code, this presentation, and related resources are shared publically on GitHub
- https://github.com/psaffari/strain-amplitude-region
- “Fork it”, try the code, contribute improvements!

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