# AGR-5/6/7 Fuel Fabrication Status and Schedule

## Part 2: *Preliminary quantitative 3-D analysis*

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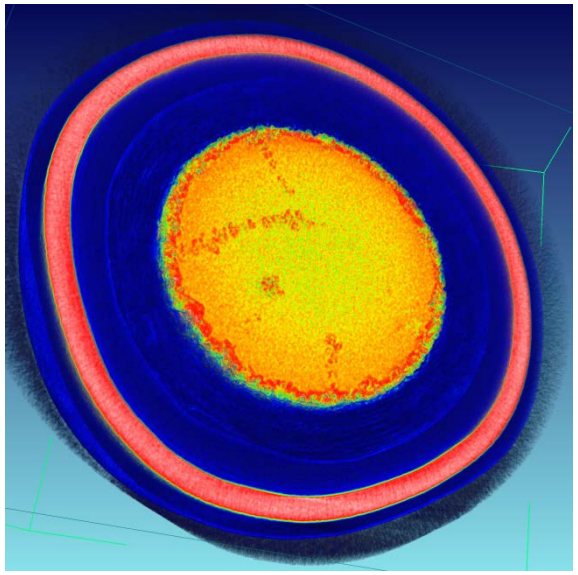
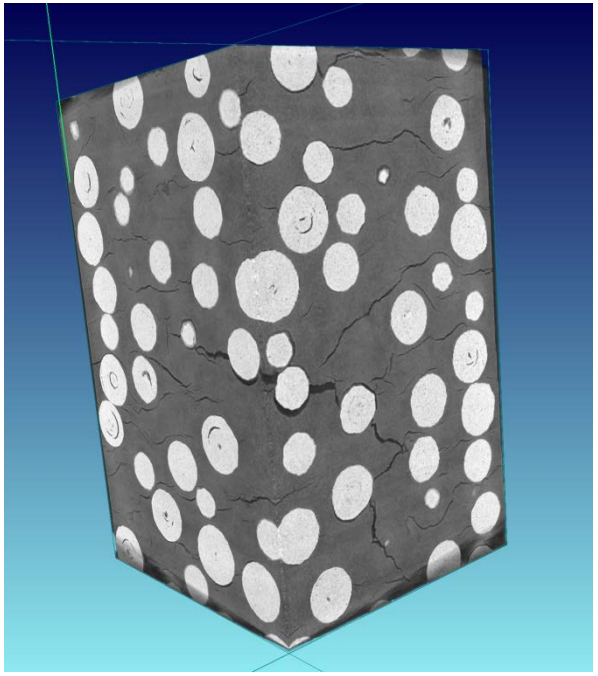
**Advanced Reactor Technologies**
**Advanced Gas Reactor TRISO Fuels Program Review**
**DOE Headquarters, Germantown, MD**
**June 8 to 9, 2016**





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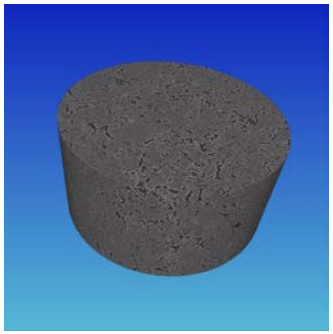
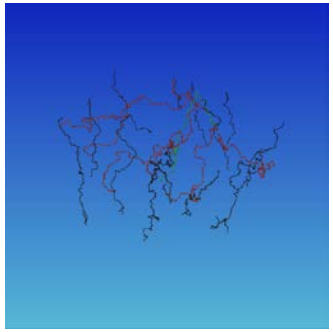
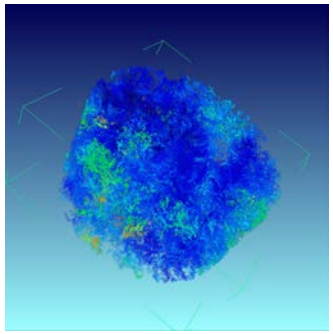
# Overview

Acknowledgement:

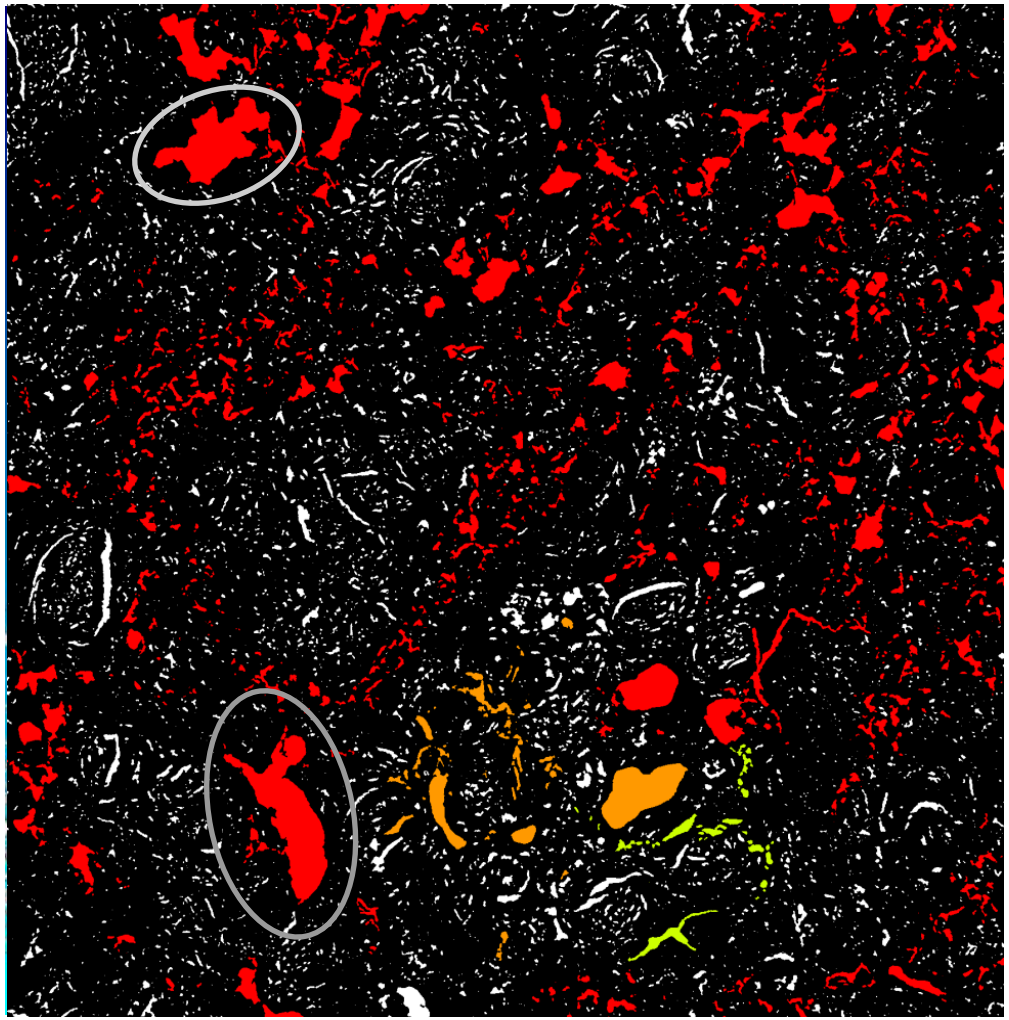
*Leveraging analysis capabilities developed for ART Graphite Program*

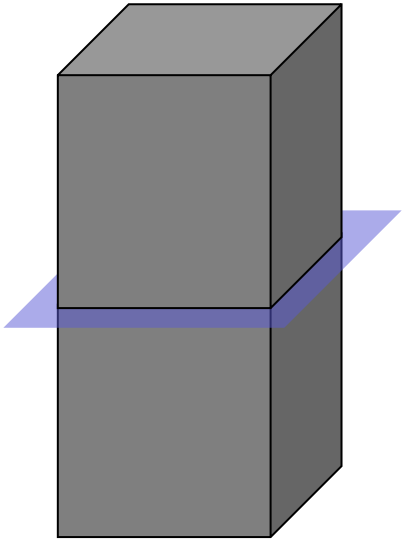
- What are benefits of 3-D analysis? Costs?
- Preliminary Analyses
  - Show what is possible for
    - Compacts
    - Individual TRISO particles
- Future plans/Potential application areas
- Summary

## *Visual Example #1*

# *Why use 3-D imaging and analysis?*

*We assume curvature and consequently limit connectivity*

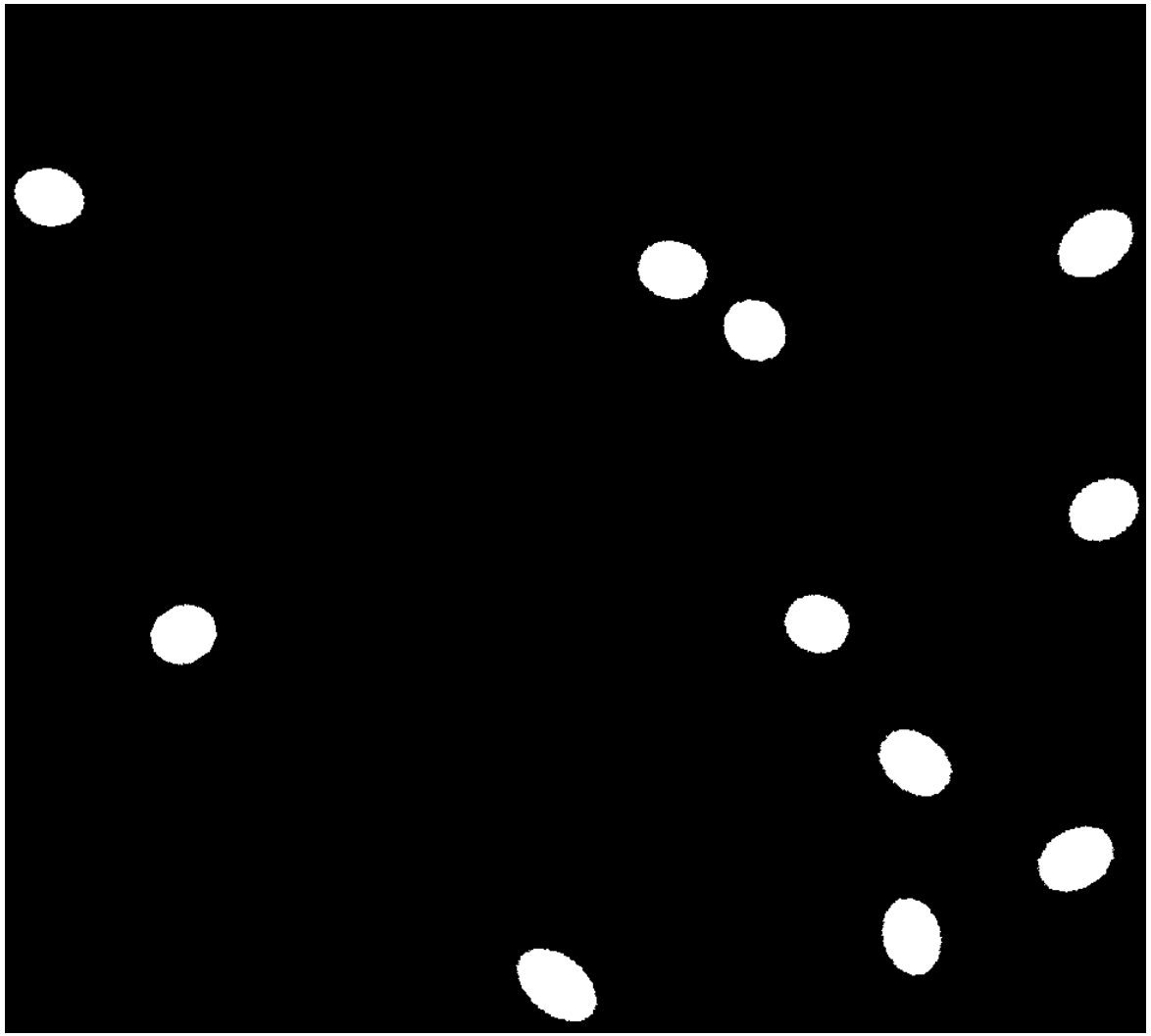


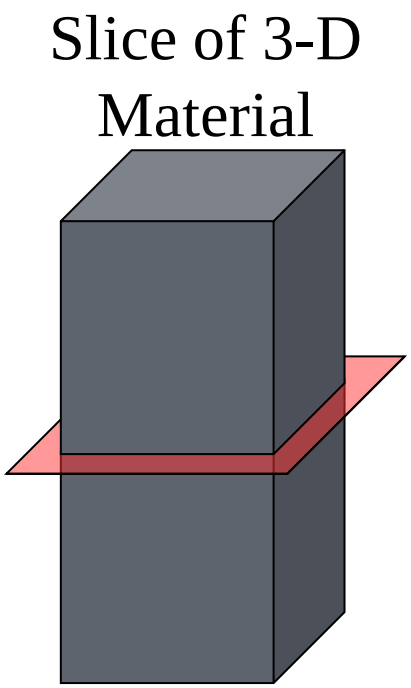


## *Visual Example #2*

# *Why use 3-D imaging and analysis?*

*We often make assumptions regarding the shape of objects*





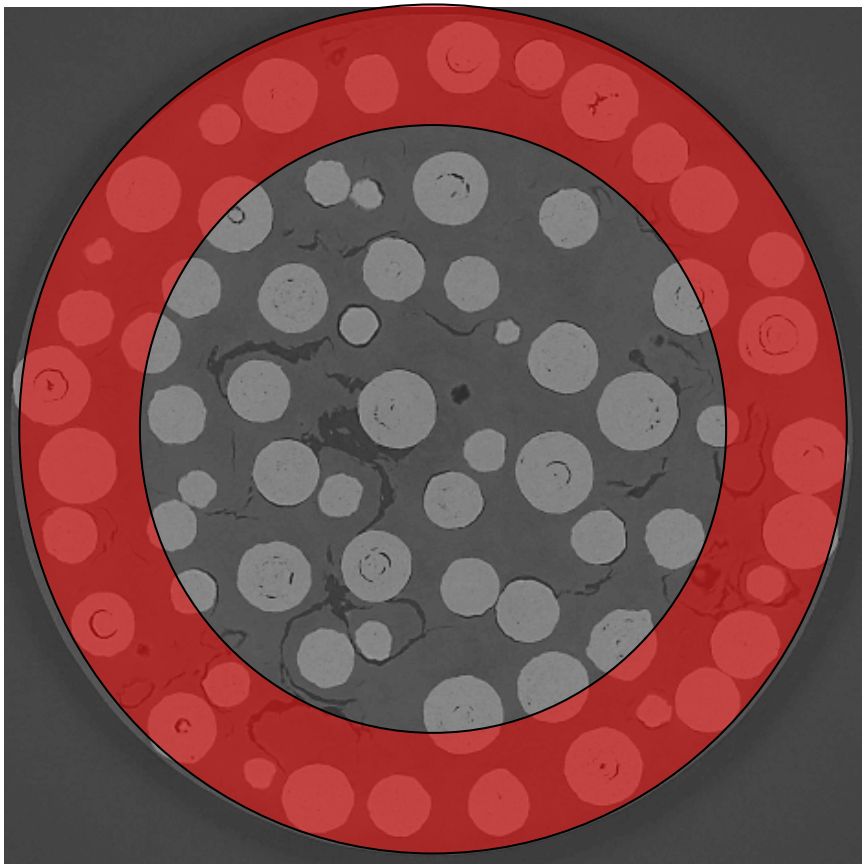
# Surrogate Compact

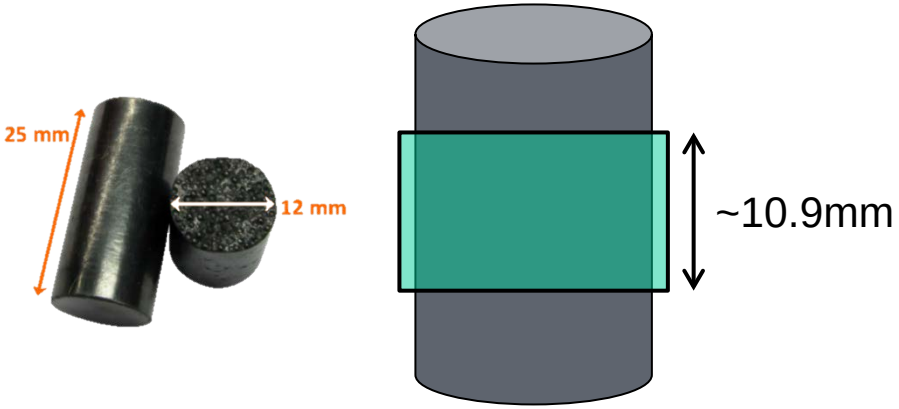
## EARLY COMPACT:

- Surrogate Compact
- Alumina Particle Surrogate
- Resin material has changed

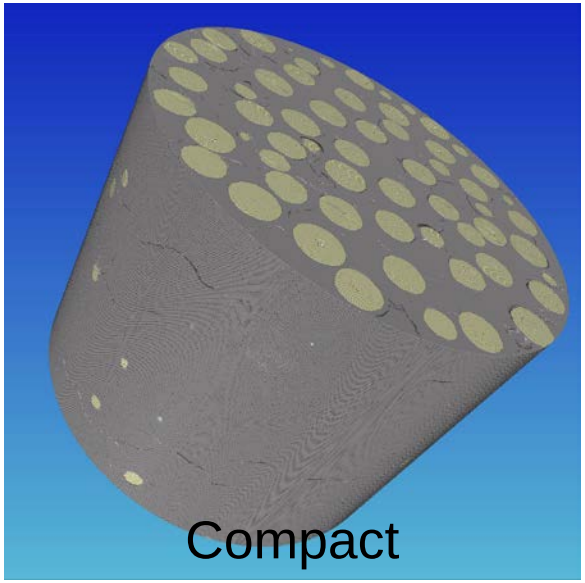
Please pay attention to…

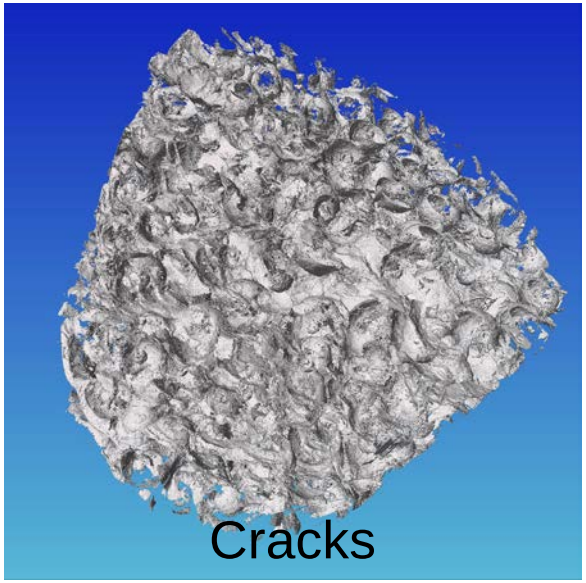
1. Crack shape
2. Particle spatial distribution

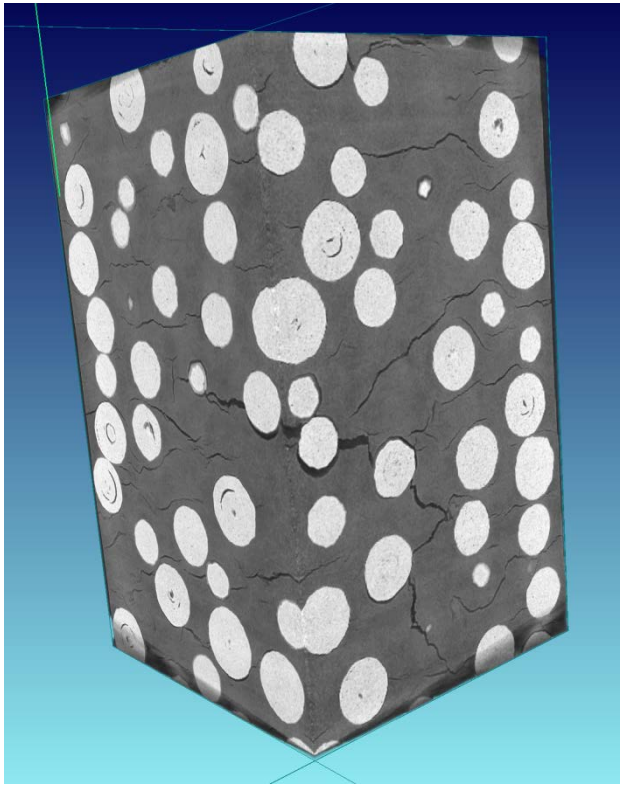


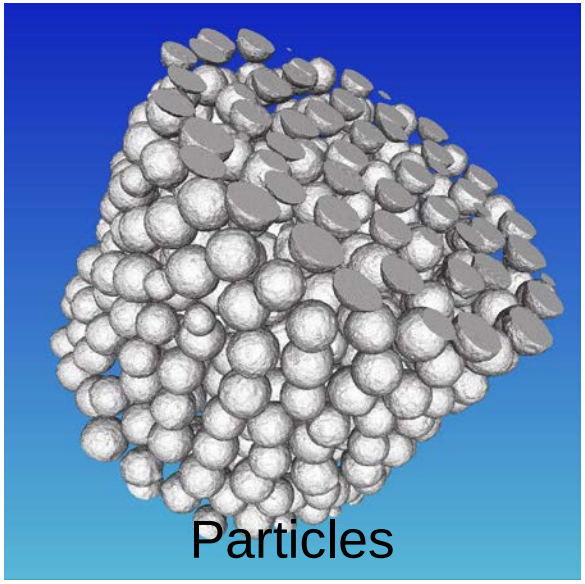


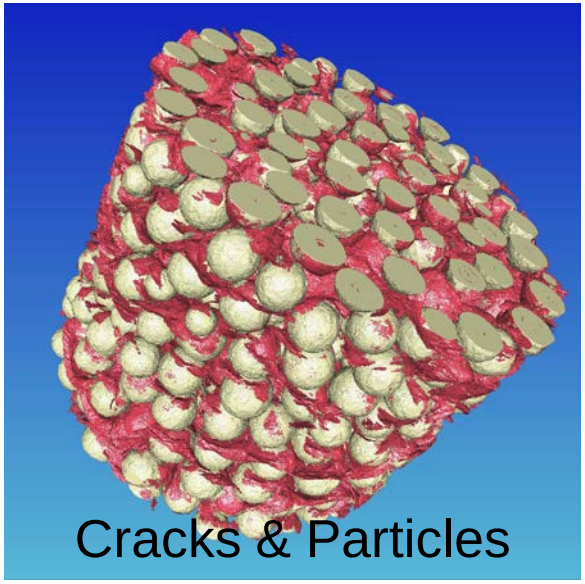
# Surrogate Compact



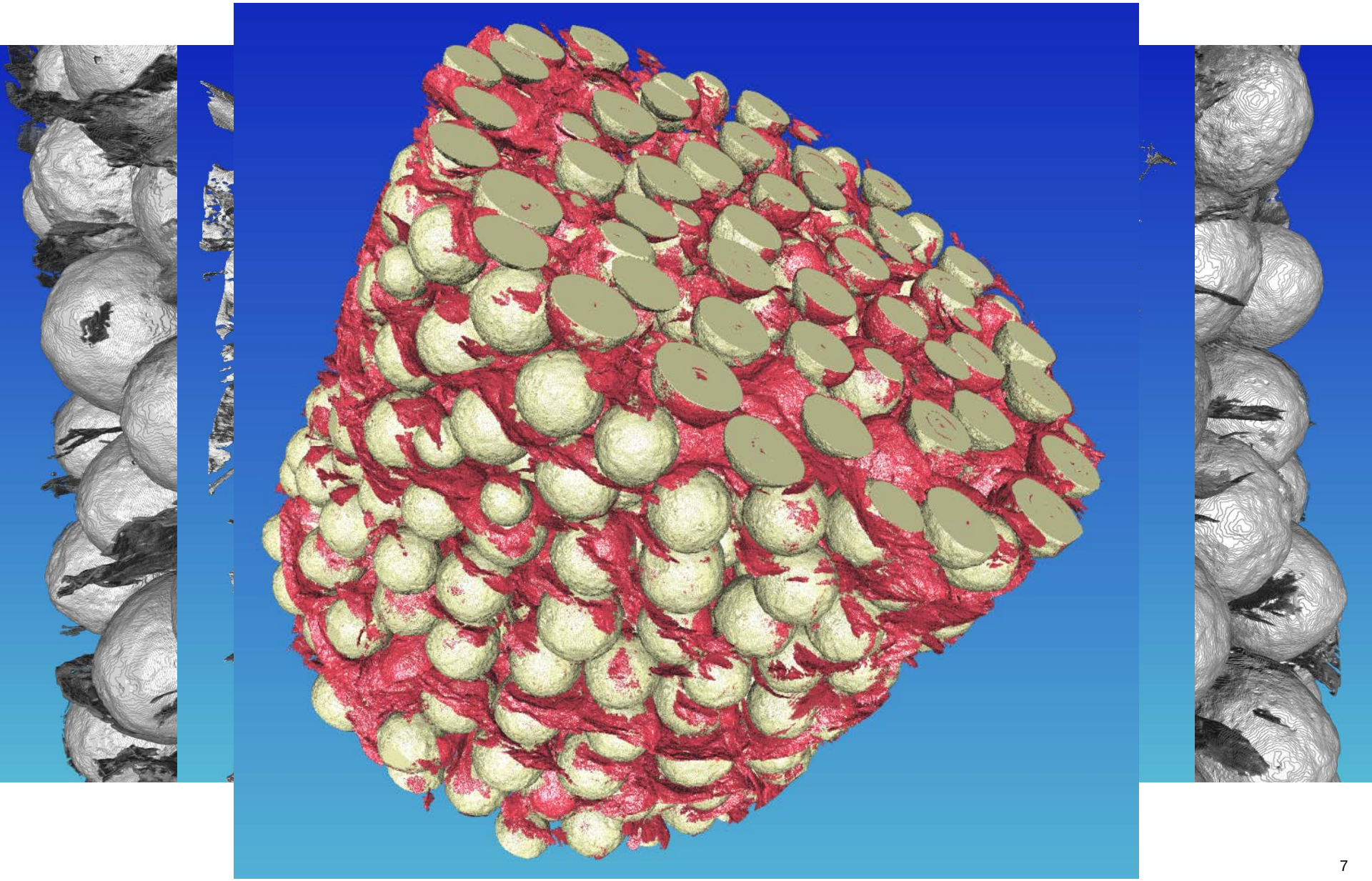





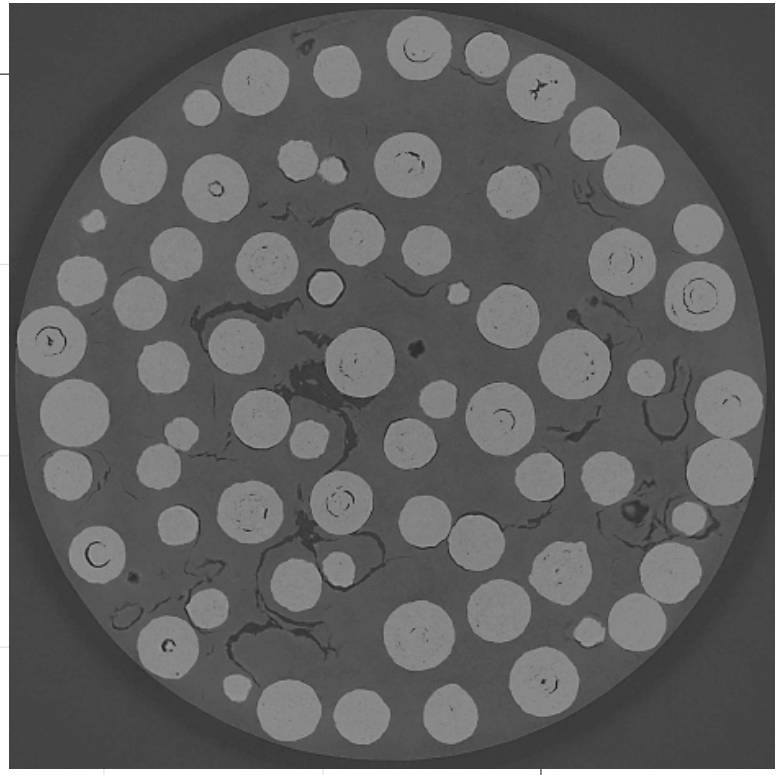

*Particles don't actually intersect surface as seen in video clip labeled compact*

# Surrogate Cracks

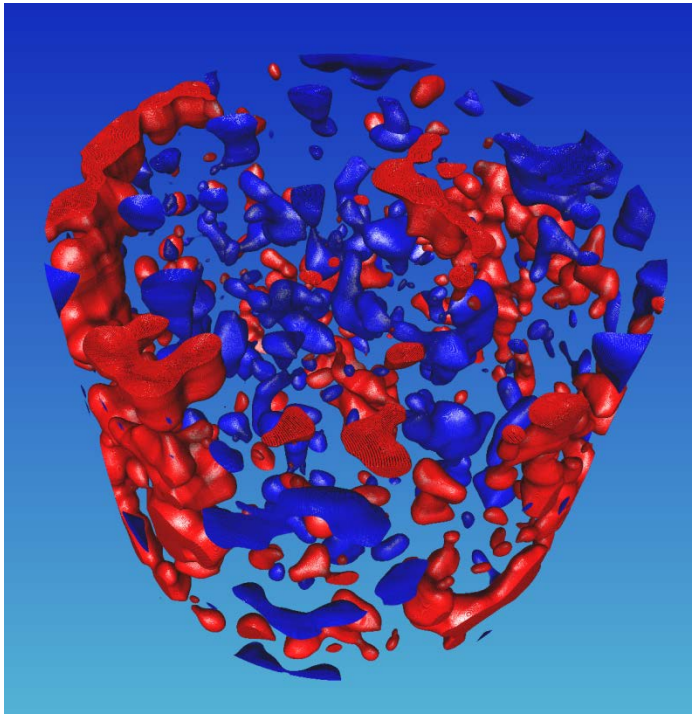


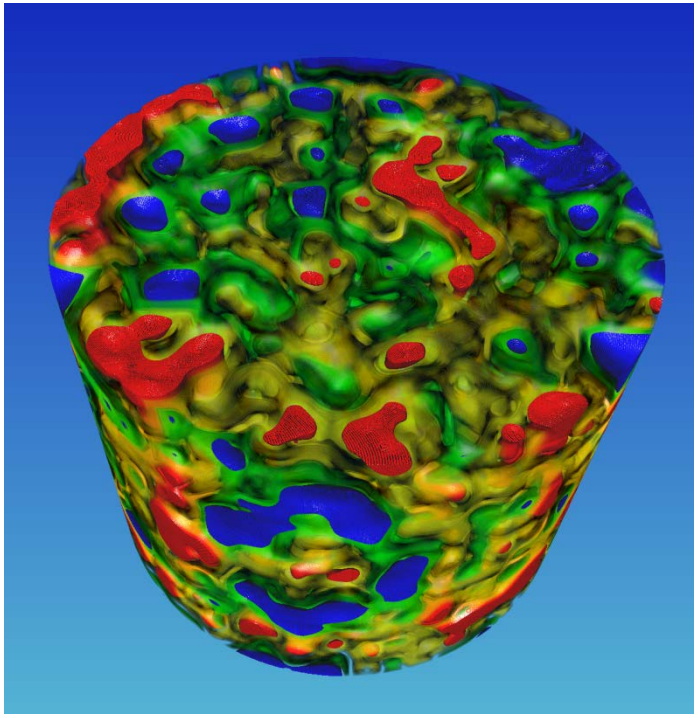
# Surrogate Compact: Quantifying packing fraction

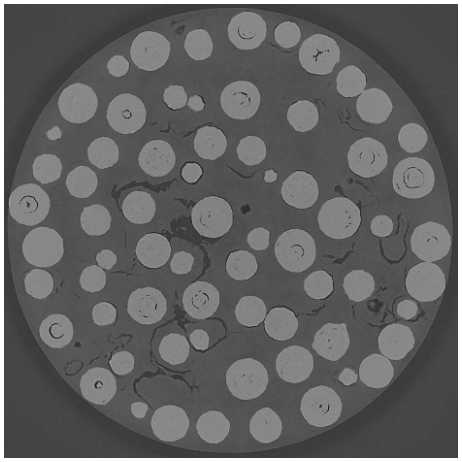
How much variation is allowable?



# *Surrogate Compact: Visualizing packing fraction variation*





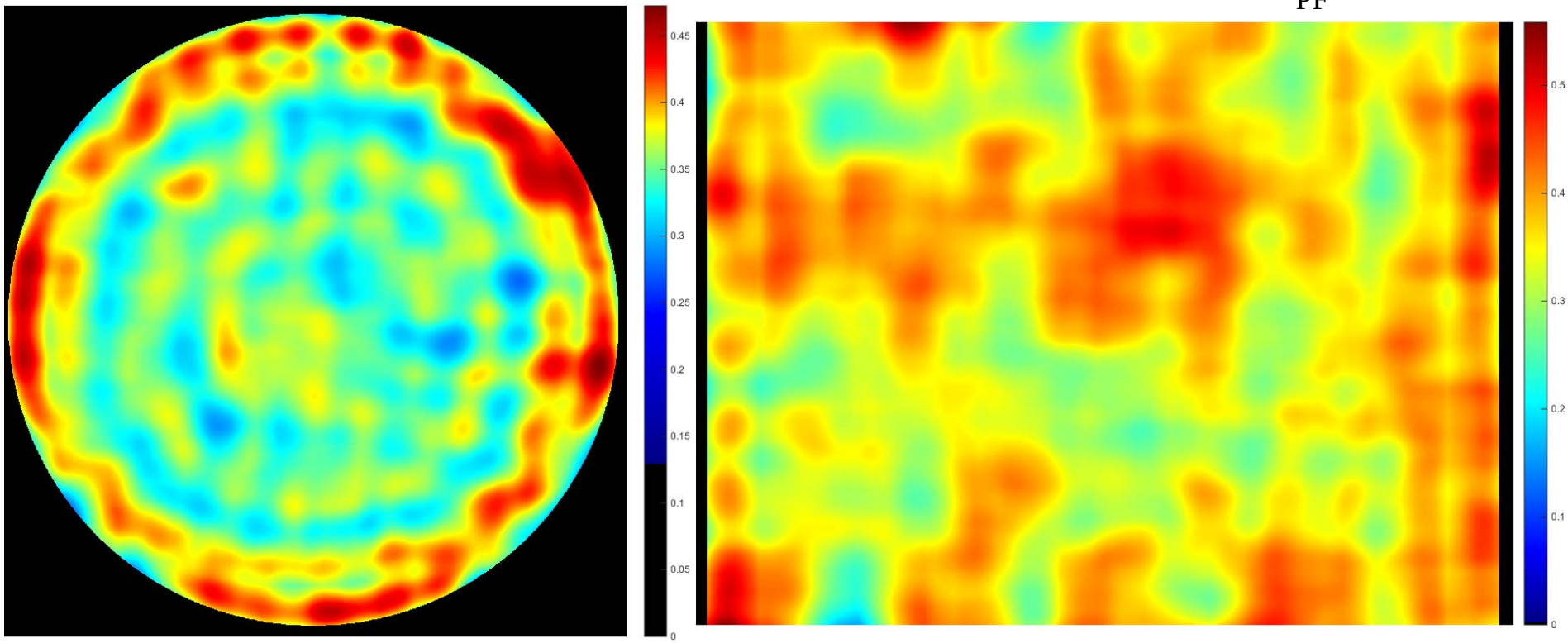


- Lower density interior & Higher density exterior
  - *could accentuate thermal stress within compact*
- How much variation is allowable?

# Surrogate Compact: Quantifying spatial variation in packing fraction

$\mu_{PF} = 0.364$

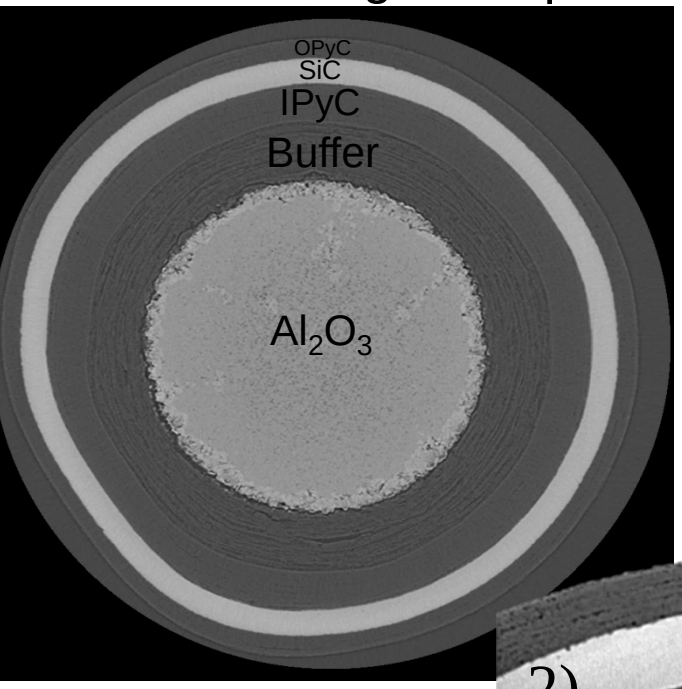
$\sigma_{PF} = 0.053$




- Non-uniformity along axial and radial directions
- Δ as much as 20-30%
- This information can be fed back to manufacturing process

# TRISO Particle

- TRISO particle is an extremely complicated fuel system
- High Temperature Reactors are an extreme materials environment

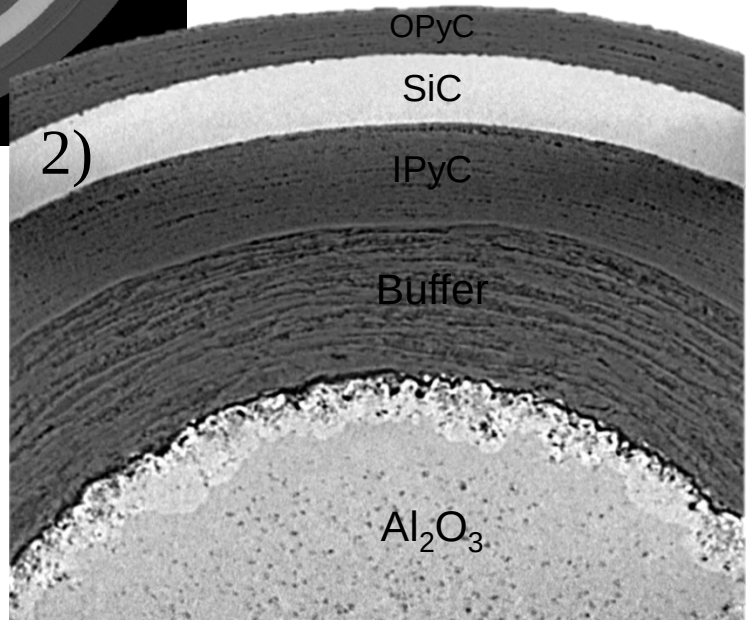


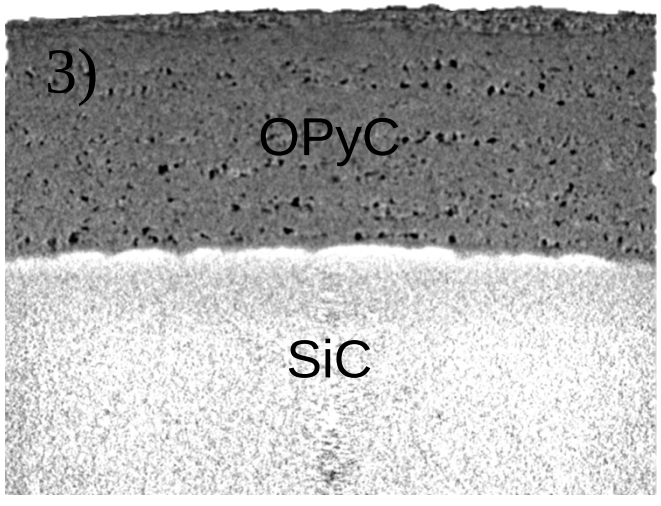

Degradation:

- Irr. induced creep
- Dimensional change
- Soret effect
- SiC thermal creep???

1) 900 nm voxels
2) 380 nm voxels
3) 150 nm voxels

*All 3 X-ray CT scans acquired by Carl Zeiss Microscopy for INL*



# Previous work

*Really good characterization paper with quantitative analysis*

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## Microstructural analysis of TRISO particles using multi-scale X-ray computed tomography

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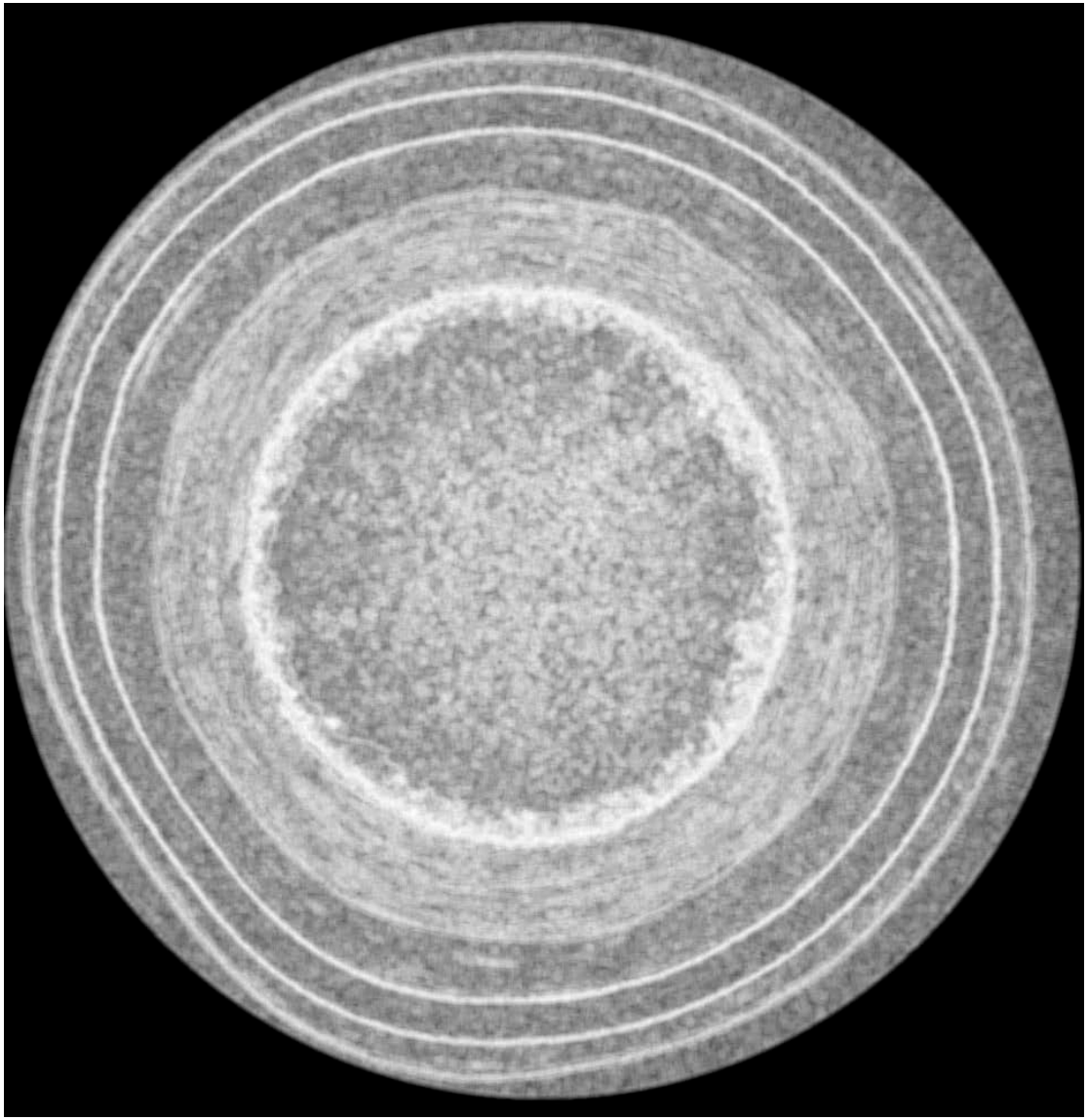
ABSTRACT

TRISO particles, a composite nuclear fuel built up by ceramic and graphitic layers, have outstanding high temperature resistance. TRISO fuel is the key technology for High Temperature Reactors (HTRs) and the Generation IV Very High Temperature Reactor (VHTR) variant. TRISO offers unparalleled containment of fission products and is extremely robust during accident conditions. An understanding of the thermal performance and mechanical properties of TRISO fuel requires a detailed knowledge of pore sizes, their distribution and interconnectivity. Here 50 nm, nano-, and 1 μm resolution, micro-computed tomography (CT), have been used to quantify non-destructively porosity of a surrogate TRISO particle at the 0.3–10 μm and 3–100 μm scales respectively. This indicates that pore distributions can reliably be measured down to a size approximately 3 times the pixel size which is consistent with the segmentation process. Direct comparison with Scanning Electron Microscopy (SEM) sections indicates that destructive sectioning can introduce significant levels of coarse damage, especially in the pyrolytic carbon layers. Further comparative work is required to identify means of minimizing such damage for SEM studies. Finally since it is non-destructive, multi-scale time-lapse X-ray CT opens the possibility of intermittently tracking the degradation of TRISO structure under thermal cycles or radiation conditions in order to validate models of degradation such as kernel movement. X-ray CT in-situ experimentation of TRISO particles under load and temperature could also be used to understand the internal changes that occur in the particles under accident conditions.

# The tricky part…Automated Image Segmentation



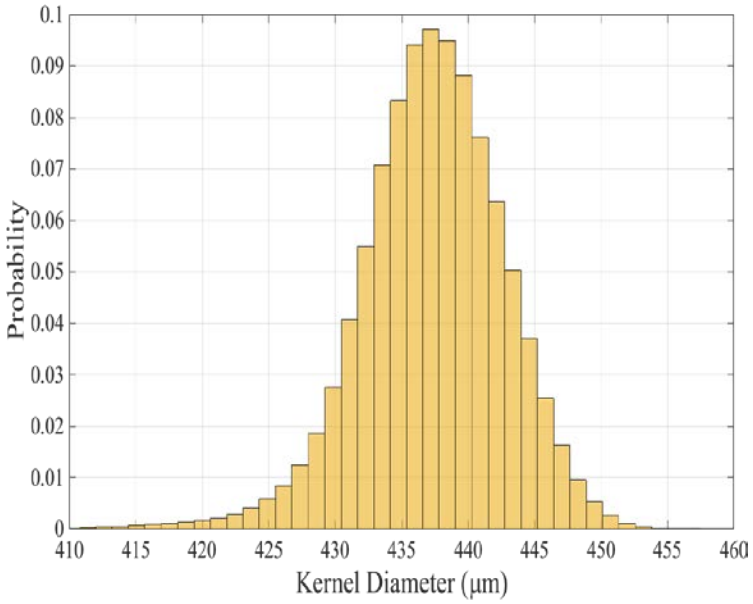
Luckily intensity is not the only criteria for segmentation.

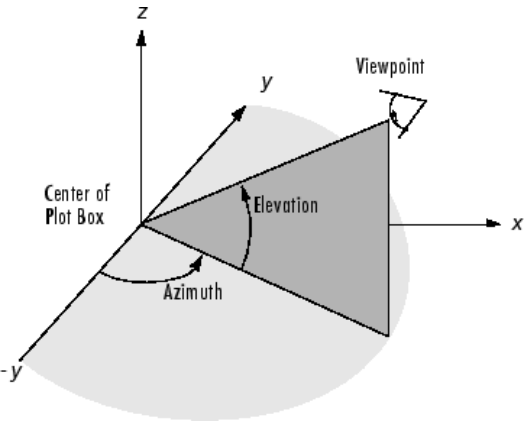
Local Entropy
Texture
Morph. Anisotropy

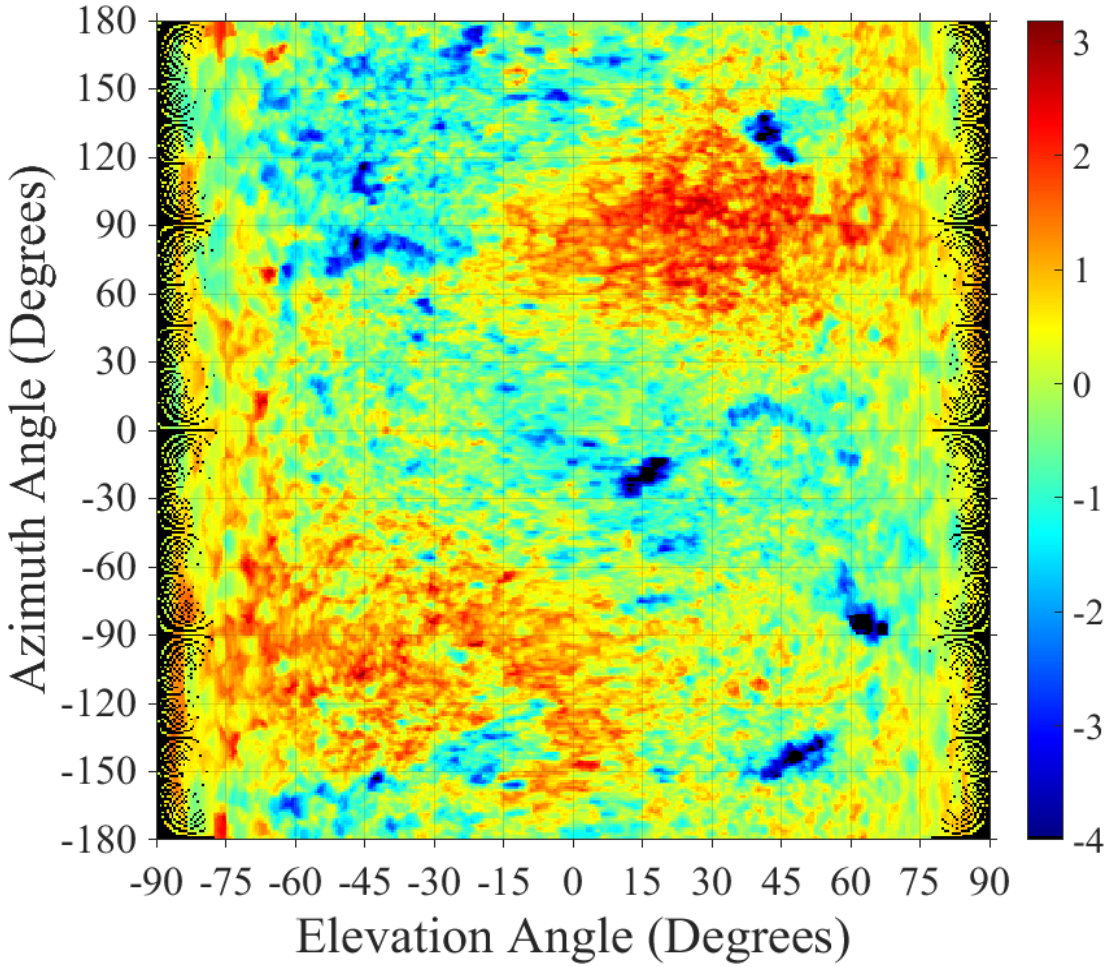
# Kernel Radius

μ= 437 μm

σ= 5 μm

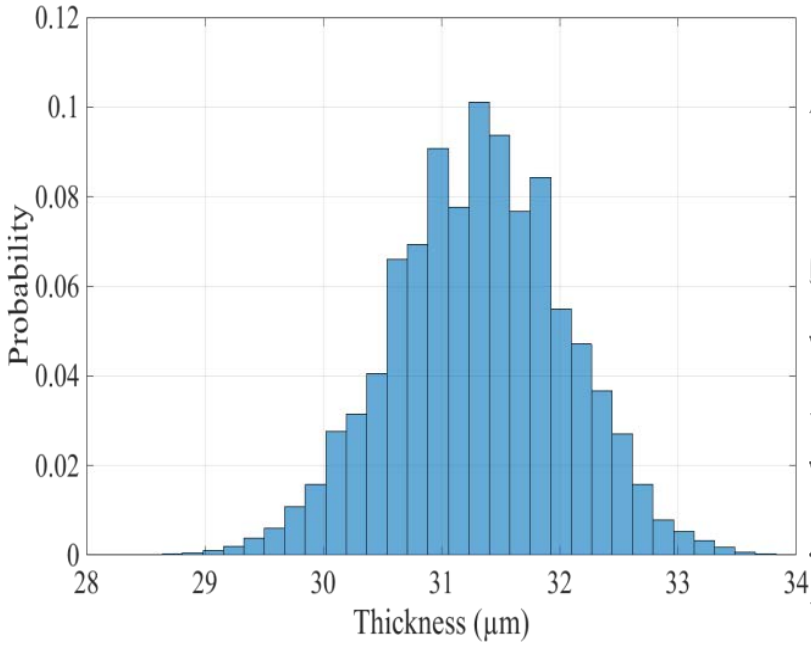


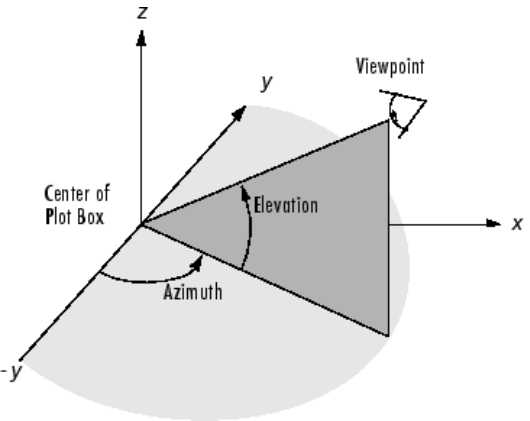



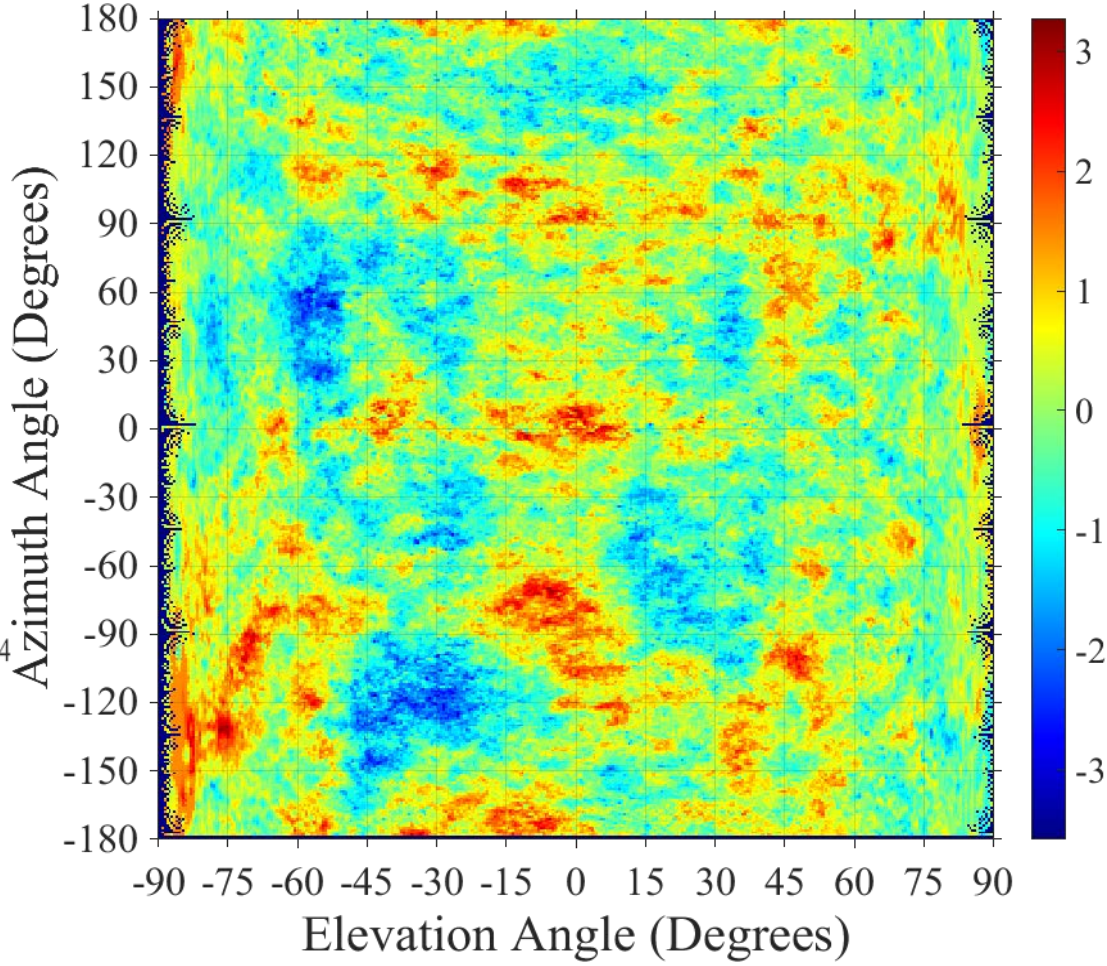



# SiC Layer Thickness

μ= 31.3 μm
σ= 0.7 μm



# Future Work

- Characterize AGR 5/6/7 compacts with natural uranium TRISO
    - 40%, 25%, and 10% PF
    - 40% PF it will be difficult to get enough dynamic range to resolve all features of interest
  - Potentially great feedback to better understand processing

## What's possible?… I could see…

- Characterizing spatial distribution of TRISO in pebble bed fuel
- More 3-D quantification of TRISO particles
  - Pre- and Post-Irradiation
  - Layer thicknesses & changes
  - Pore characterization in IPyC

# *Thank you!*

Contact:

Joshua J. Kane, PhD
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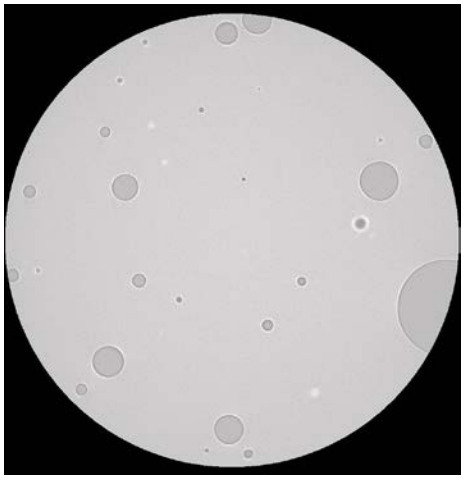
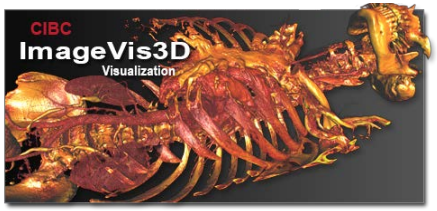
joshua.kane@inl.gov



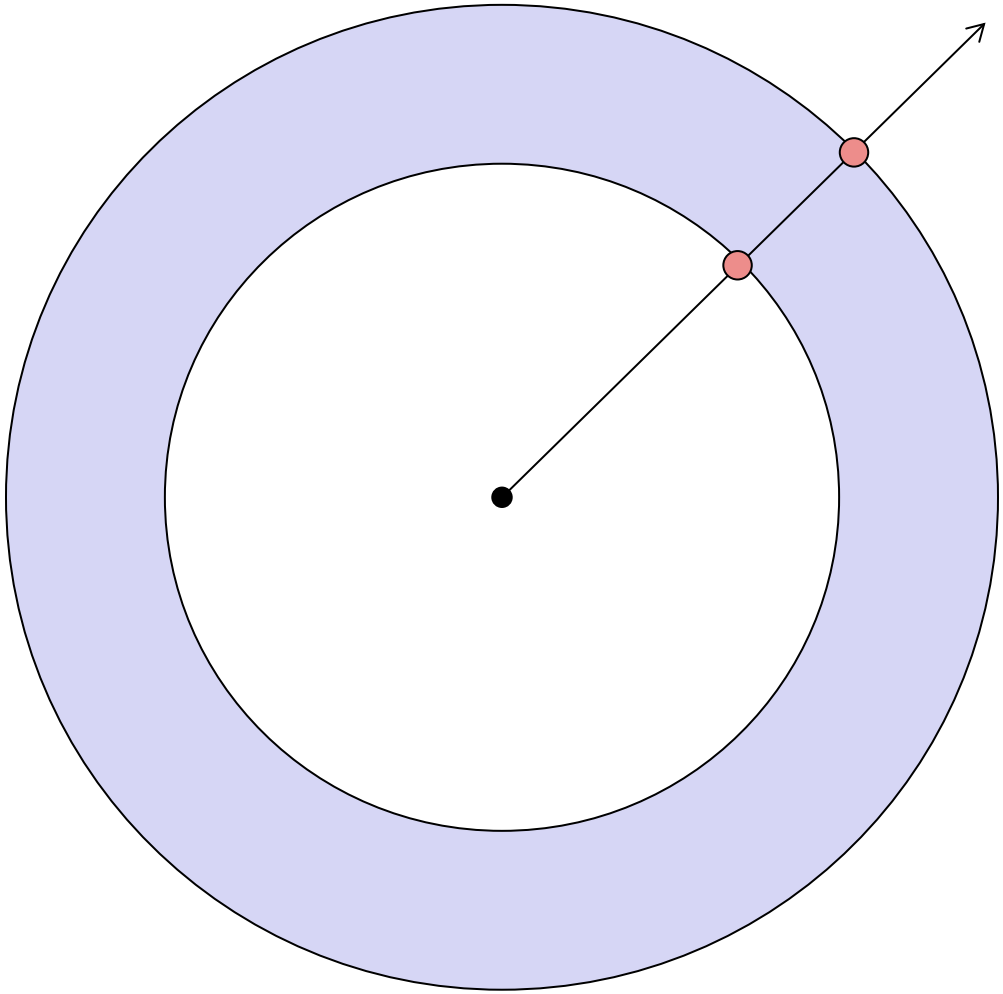
Matlab was used for all image processing and image analysis



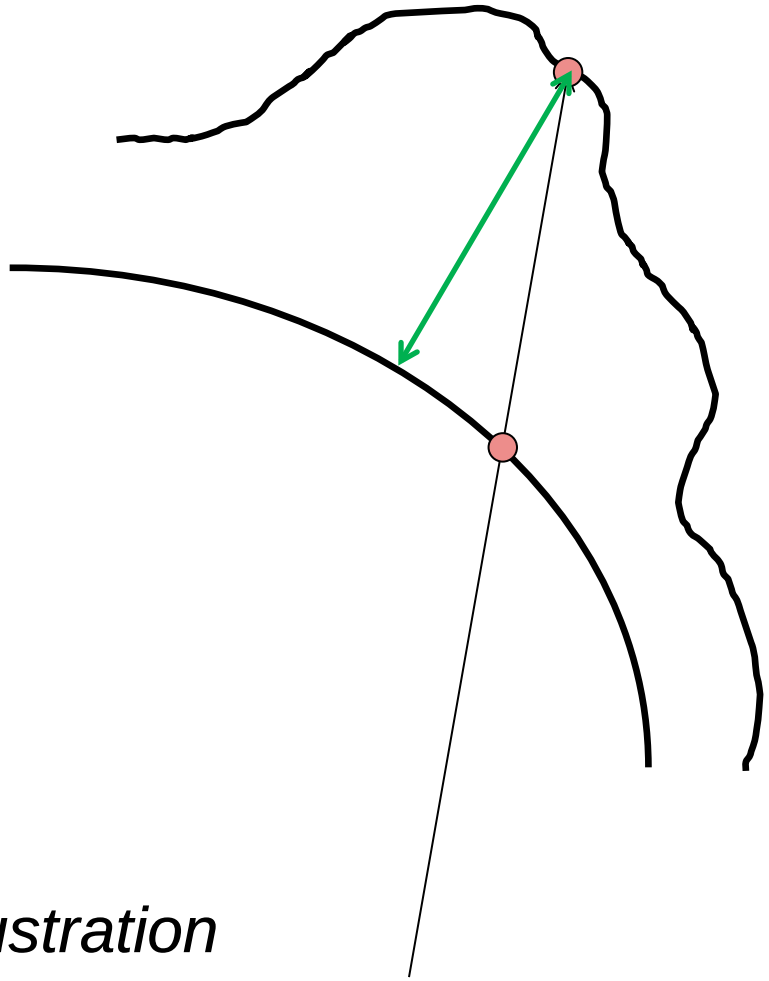

ImageVis3D was used for most volumetric renderings

Thank you to Zeiss XRM team for acquiring TRISO particle scans for INL free of charge.

# Layer thickness found a little differently



# Layer thickness found a little differently



*Exaggerated Illustration*

# Layer thickness found a little differently