



DOE-Sponsored Fuel Development Activities at X-energy

Gas-Cooled Reactor Fuels and Methods Program Review

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Overview and History of X-energy

X-energy is reimagining nuclear's role in solving tomorrow's energy challenges

- X-energy founded in 2009 by Kam Ghaffarian to address the world's most serious energy challenges and make a lasting contribution to clean energy technology
- Dr. Ghaffarian has committed ~\$38.5M since X-energy inception to date
- Secured two Department of Energy (DOE), Office of Nuclear Energy Cooperative Agreements
 - Advanced Reactor Concept (ARC)15: Xe-100 Pebble Bed Small Modular Reactor: Solving Critical Challenges to Enable the Xe-100 Pebble Bed Advanced Reactor Concept (\$53M total project)
 - Industry Funding Opportunity Announcement (iFOA)18: Design and License Application Development for TRISO-X: A Cross-Cutting, High Assay Low Enriched Uranium (HALEU) Fuel Fabrication Facility (\$38M total project)
- XE staff learned TRISO fabrication operating procedures from ORNL staff and became qualified operators according to NQA-1 standards set in place during the AGR campaign

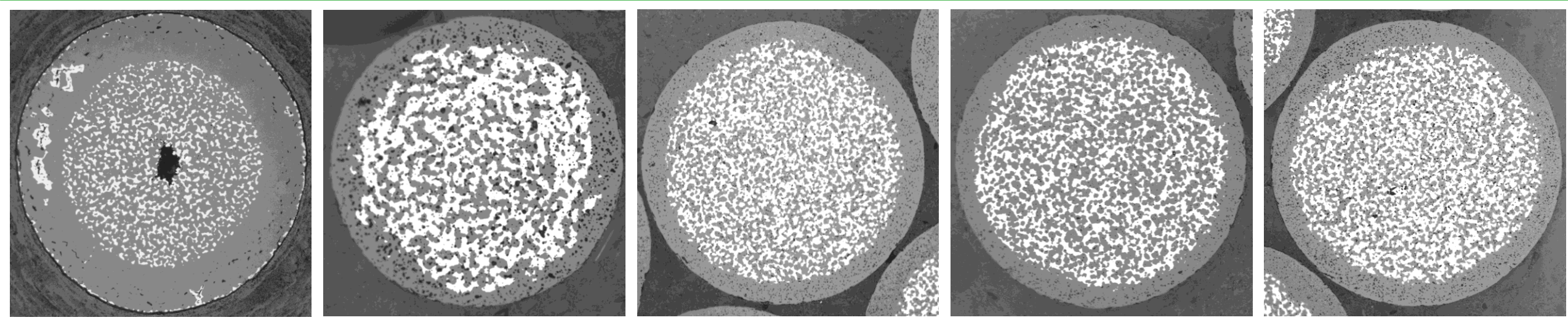


Dr. Kam Ghaffarian
Founder/CEO





Issues Facing UCO Kernel Development



GA HRB-21

AGR-1

AGR-2

AGR-3/4

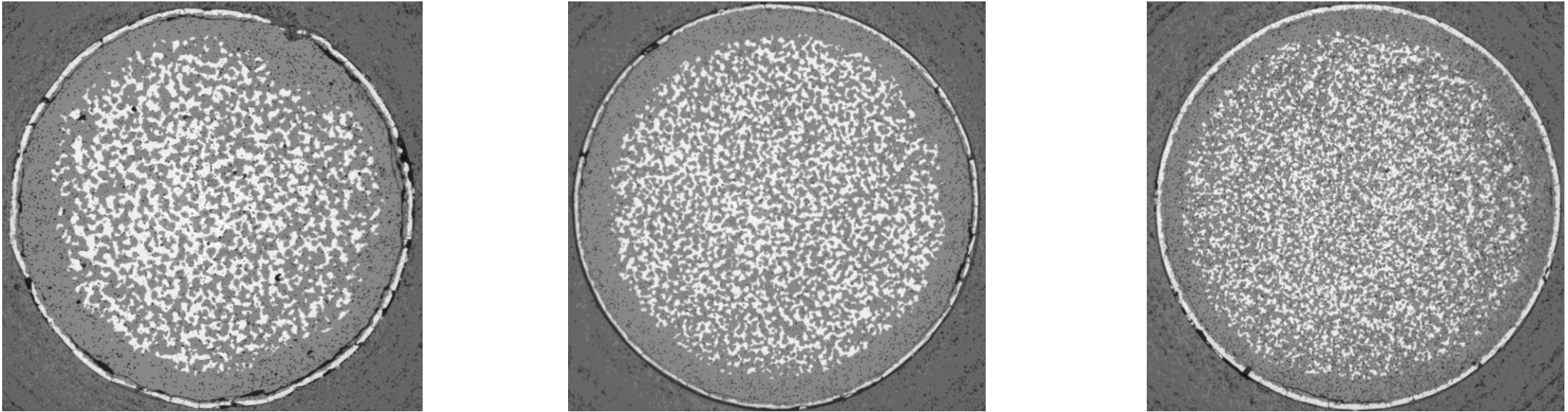
AGR-5/6/7

- The United States has remained the world leader in UCO kernel fabrication throughout time utilizing efforts made by DOE funded projects at ORNL and General Atomics in the 1980's, and the AGR program in the 2000's
- Remaining fabrication issues:
 - Creating an autonomous process to avoid worker related shutdowns
 - Increasing the yield of particles within specification during internal gelation and conversion process
 - Optimizing the carbide phase and overall carbon content





Issues Facing UCO Kernel Development



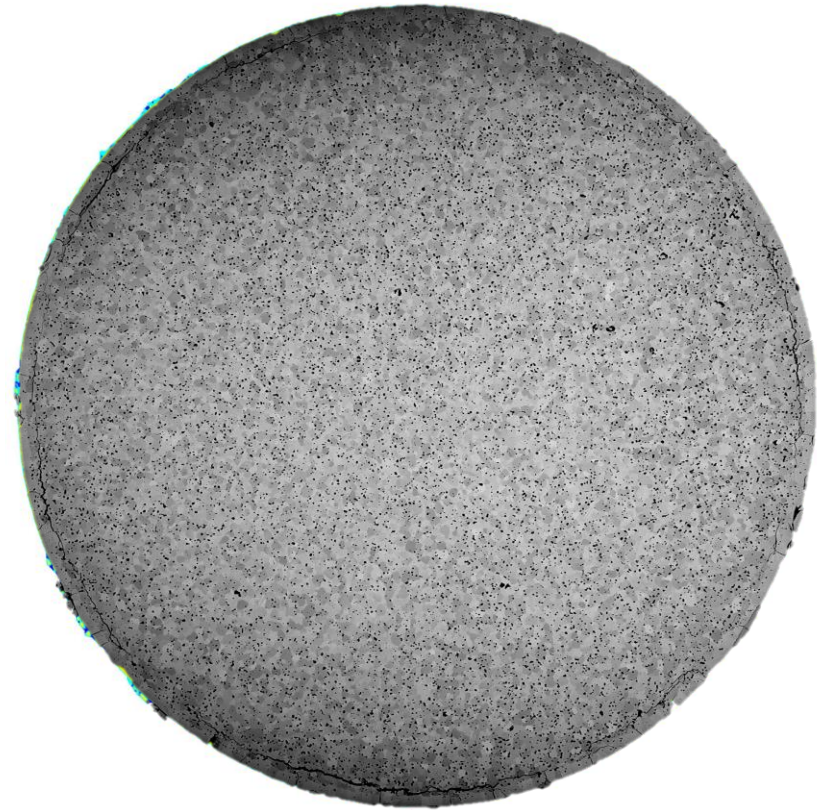
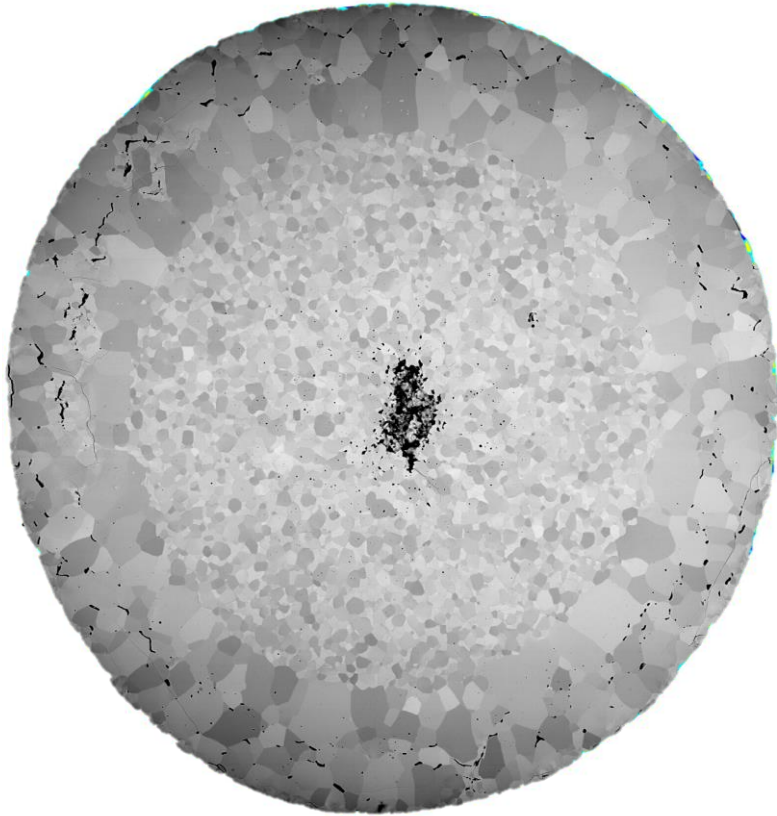
Increasing carbide grain dispersion, constant carbide amount

- The United States has remained the world leader in UCO kernel fabrication throughout time utilizing efforts made DOE funded projects at ORNL and General Atomics in the 1980's, and the AGR program in the 2000's.
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 - Creating an autonomous process to avoid worker related shutdowns
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Connecting Kernel Properties to PIE Results



- Establishing an as-fabricated fuel database:
 - Processing conditions (ramp rates, temperatures, gas fractions)
 - Physical properties (density, oxide rind thickness, carbide skin thickness)
 - Microstructure (oxide and carbide grain size)
 - Chemical properties (UCO phase composition, stoichiometry, impurities)

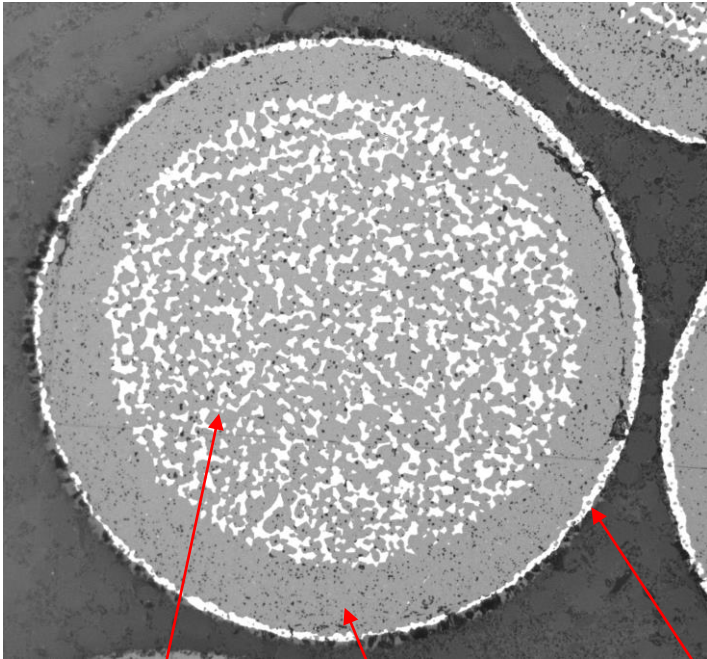
Image analysis: G. Helmreich –OSTI 1490610



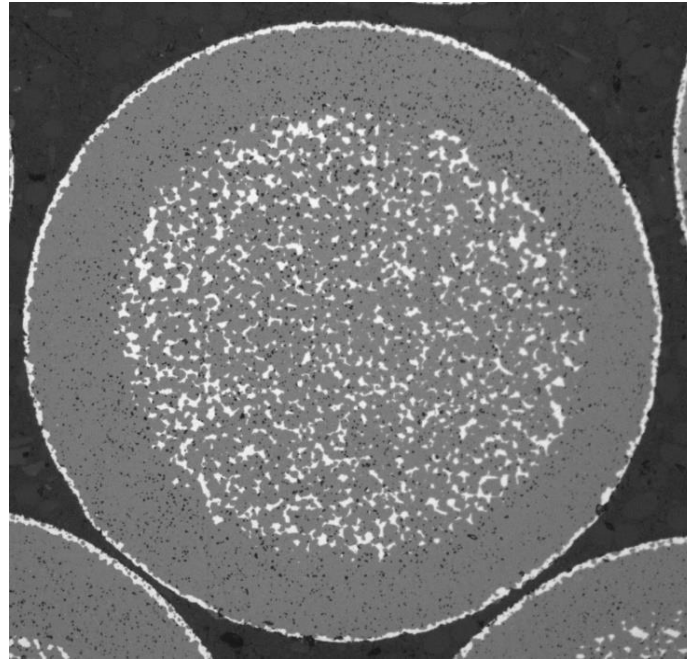


Optimized UCO Kernel Chemistry

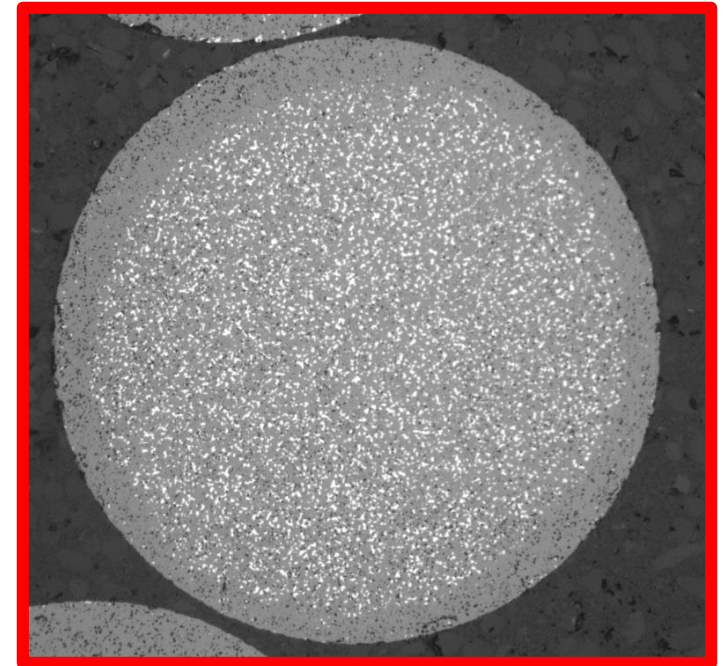
UO₂ / UC₂ Ratio 1



UO₂ / UC₂ Ratio 2



UO₂ / UC₂ Ratio 2 Optimized



-1st of its kind
-highly dispersed UC₂ phase
without carbide skin

Two phase region

Oxide rind

Carbide skin

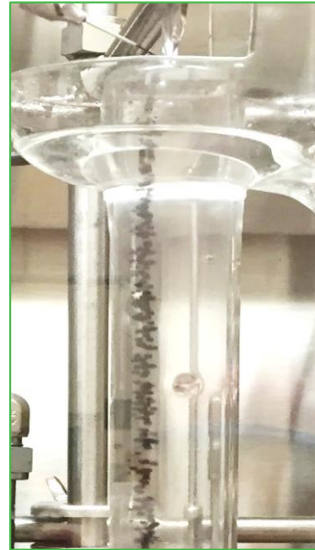
Determination of minimum amount of carbon to maximize benefits of UCO mixture





Droplet Formation Innovation

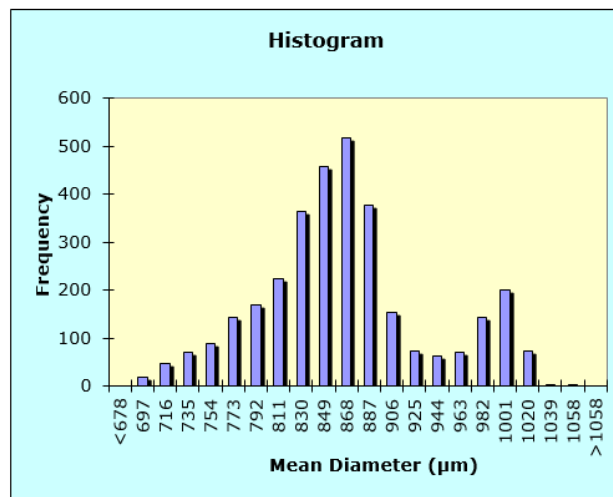
Historical droplet formation method



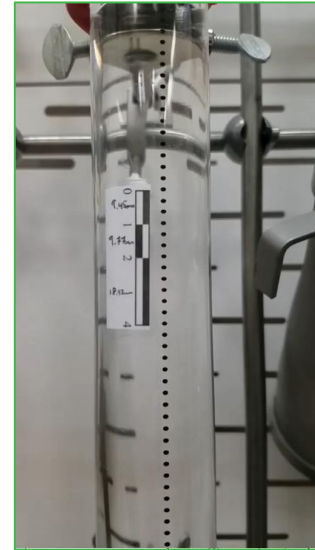
Number of kernels analyzed:	3263
Mean of the average diameter of each kernel (μm):	855.9
Standard deviation in the average diameter of each kernel (μm):	71

Distribution of the average particle diameter (top binned)

Mean Diameter (μm)	Frequency
<678	0
697	18
716	48
735	70
754	89
773	144
792	170
811	225
830	364
849	457
868	518
887	376
906	154
925	74
944	62
963	71
982	144
1001	201
1020	73
1039	4
1058	1
>1058	0



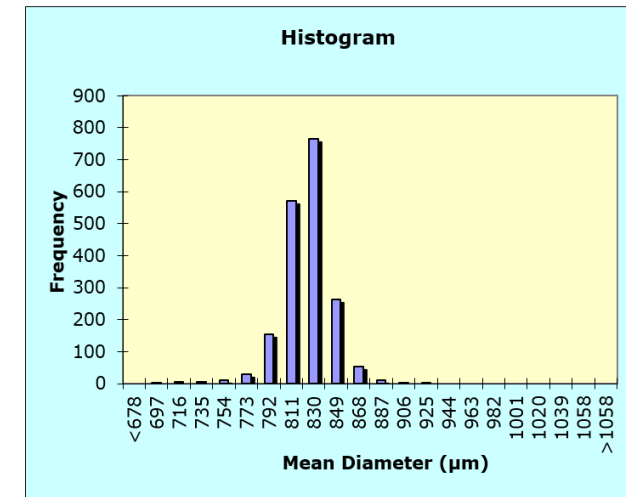
X-energy improved droplet formation method



Number of kernels analyzed:	1879
Mean of the average diameter of each kernel (μm):	814.0
Standard deviation in the average diameter of each kernel (μm):	21

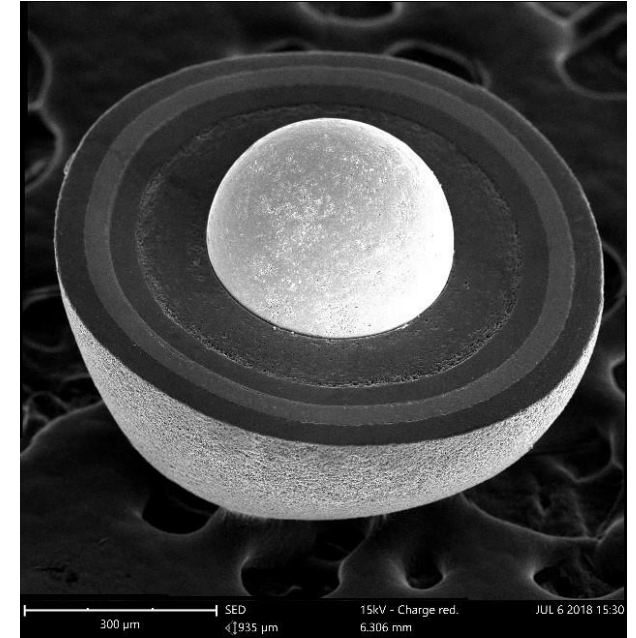
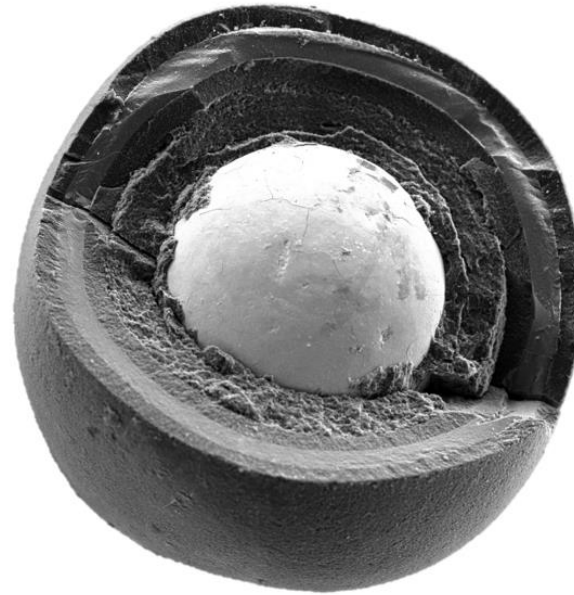
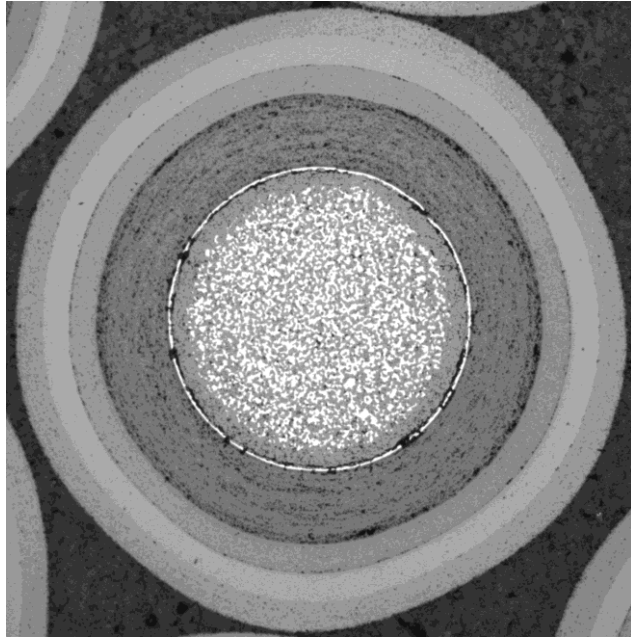
Distribution of the average particle diameter (top binned)

Mean Diameter (μm)	Frequency
<678	0
697	2
716	5
735	5
754	11
773	29
792	154
811	572
830	766
849	264
868	53
887	12
906	3
925	3
944	0
963	0
982	0
1001	0
1020	0
1039	0
1058	0
>1058	0





Issues Facing TRISO Particle Development



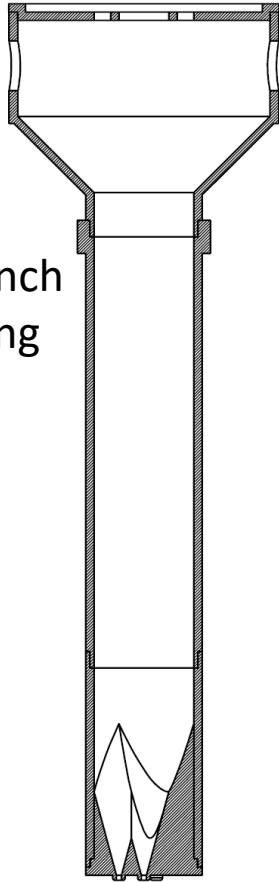
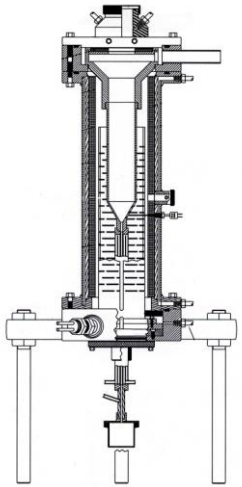
- The understanding of the relationship between layer deposition conditions, layer properties, and fission product retention has expanded during the AGR campaign, leading to production of higher quality particle fuel
- Remaining fabrication issues:
 - Creating an autonomous process to avoid worker related batch variations
 - Improving particle fluidization for homogeneous, spherical layer deposition
 - Optimizing gas distribution of commercial scale coater to replicate laboratory scale coater results
 - Improving the understanding of particle defect origins and process parameters





X-energy 6-inch TRISO Coater

Scale schematics of 2-inch and 6-inch TRISO coating furnaces



Gas distribution system

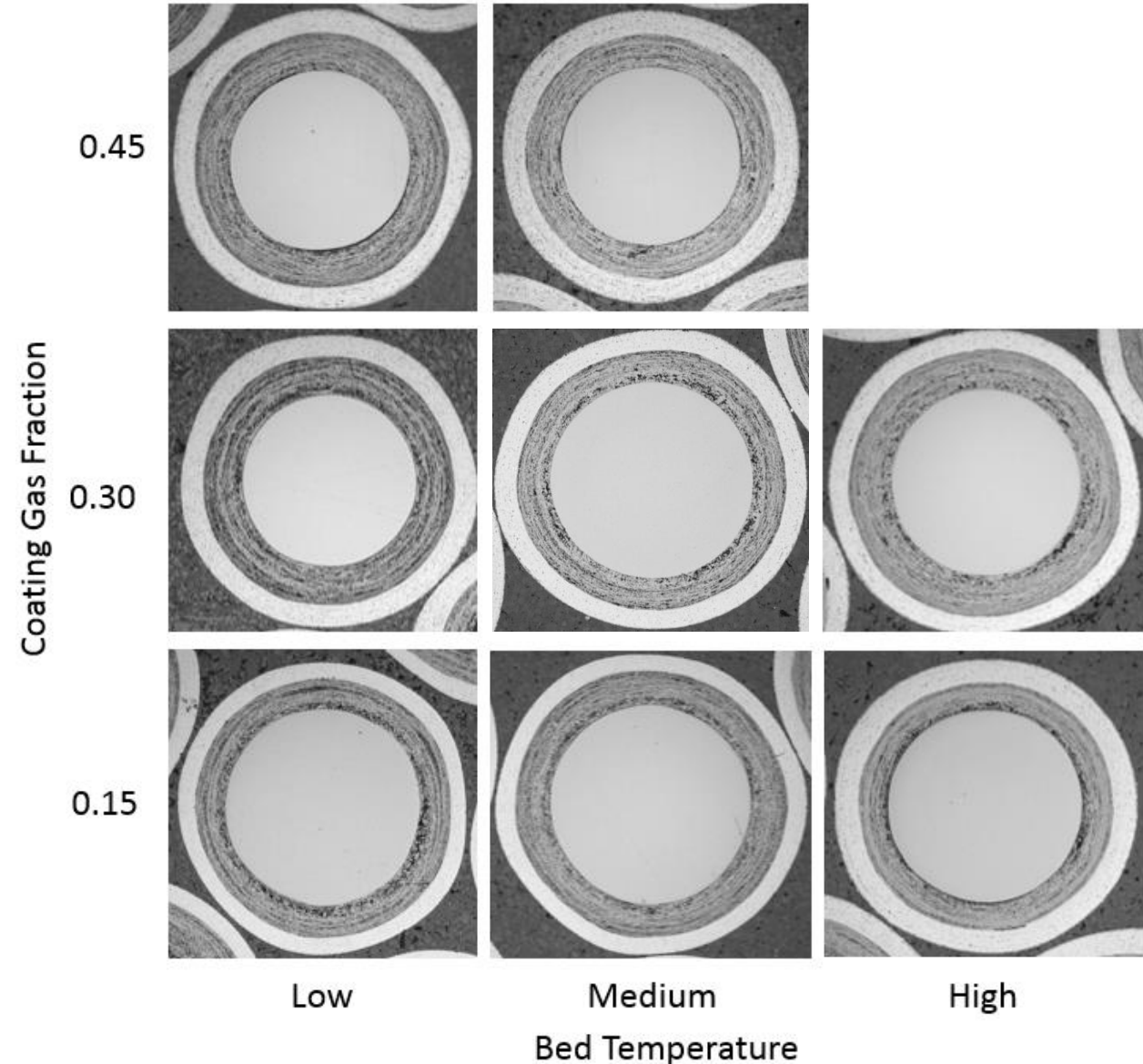
6-inch TRISO-X coating furnace, located in Pilot Facility at ORNL





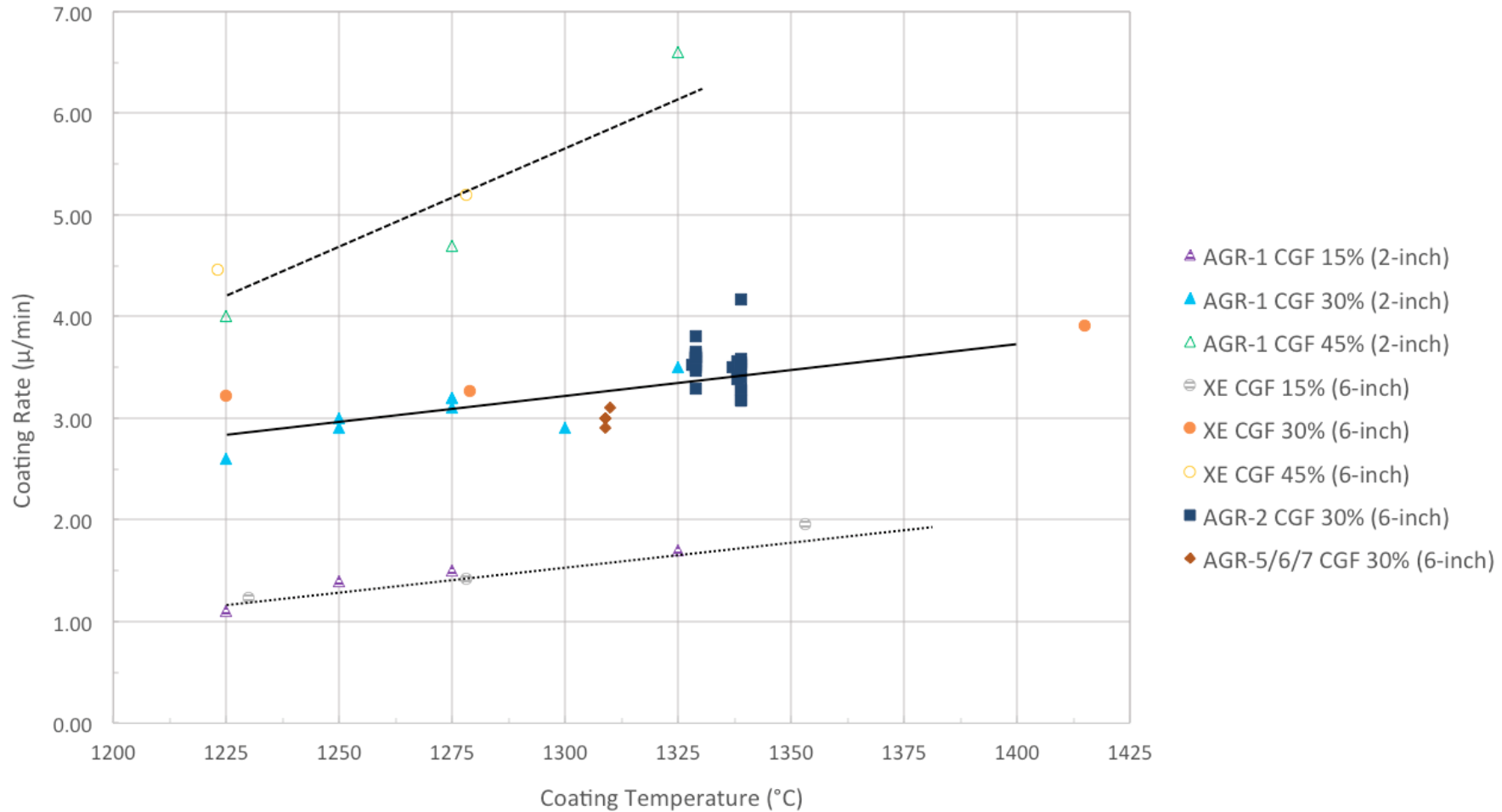
X-energy 6-inch Parametric Study

- Performed parametric study replicating AGR-1, 2-inch and AGR-2, 6-inch TRISO coater studies and compared to AGR data
 - AGR-1 data from: R.A. Lowden - ORNL/TM-2005/533
 - AGR-2 data from: C.M. Barnes – INL/EXT-08-14633
 - AGR-5/6/7 data from: D.W. Marshall – INL/EXT-19-53720
- Study fulfilled a DOE Level 2 Milestone
- Results indicate that X-energy 6-inch TRISO coater has fine control of coating parameters with corresponding trends of the AGR-1, 2-inch TRISO coater
- Work is on going to create response plots to assist in manufacturing of customer specific layer properties





X-energy 6-inch Coater IPyC Parametric Study

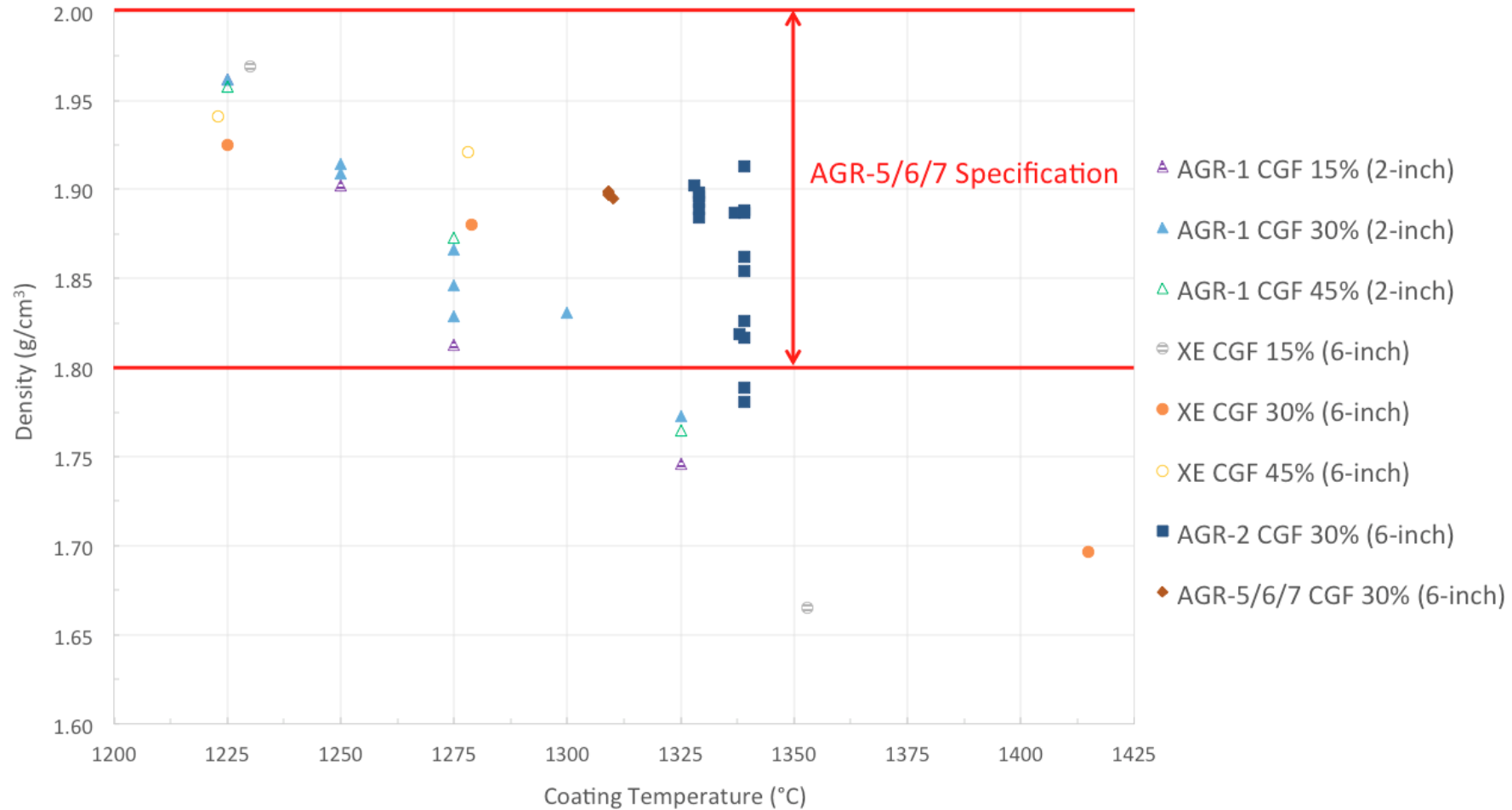


Fine control of the coating rate at a variety of coating gas factions and coating temperatures





X-energy 6-inch Coater IPyC Parametric Study

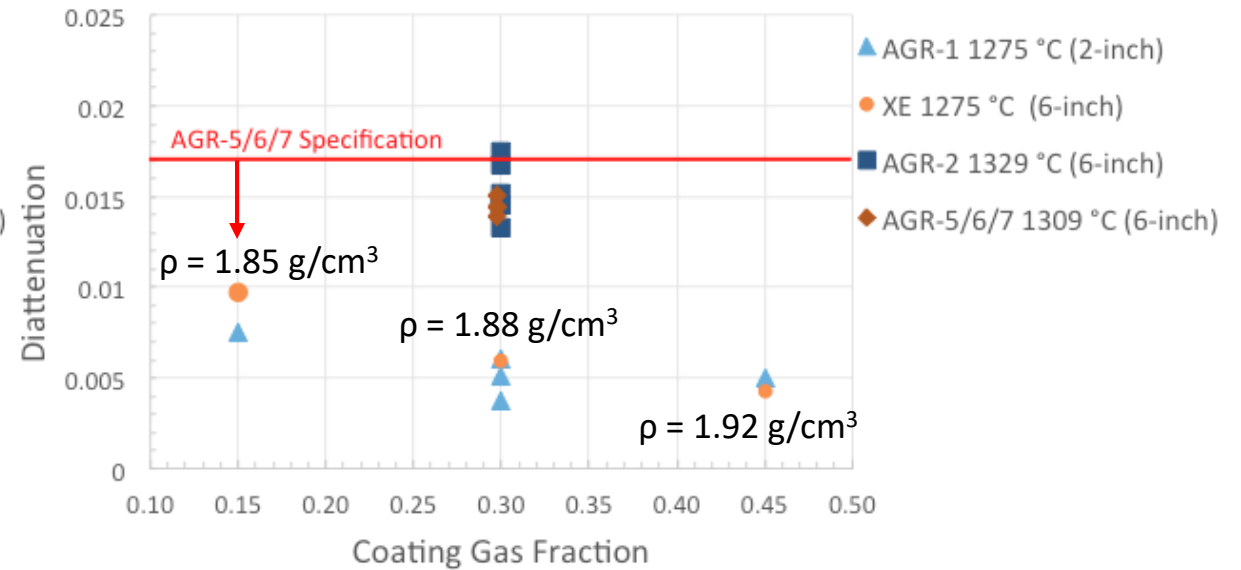
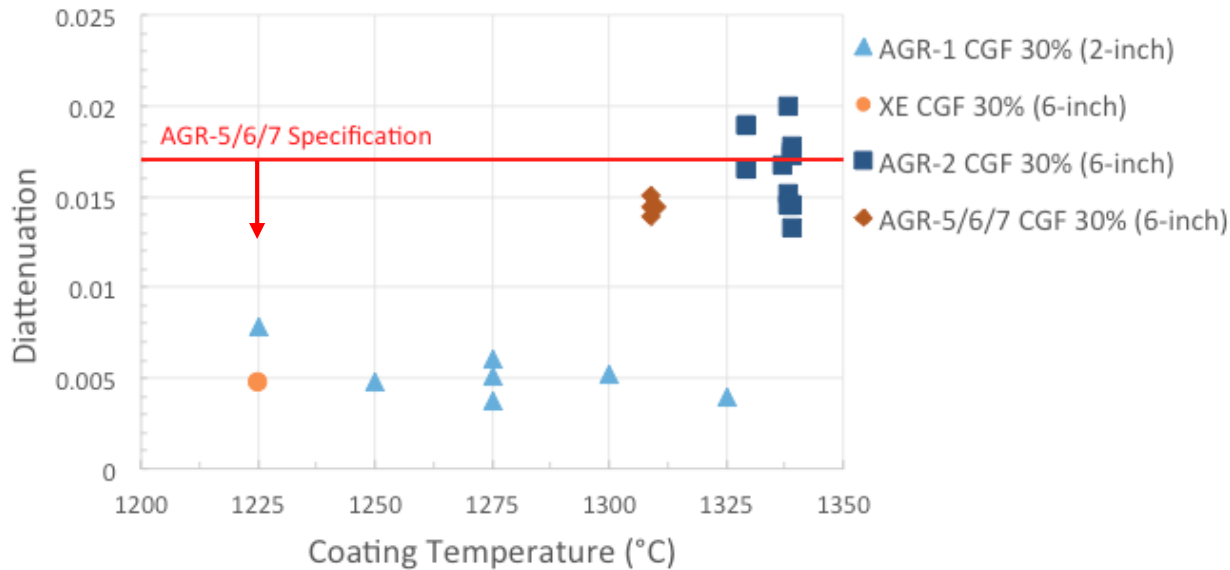


Fine control of the density at a variety of coating gas factions and coating temperatures





X-energy 6-inch Coater IPyC Parametric Study

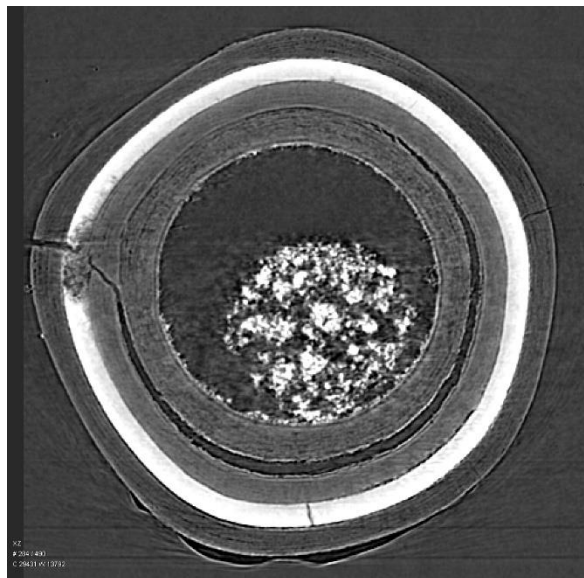
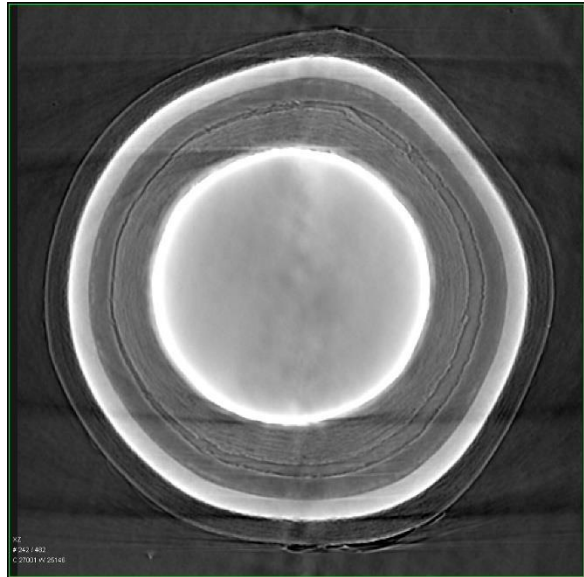


Fine control of the diattenuation at a variety of coating gas fractions and coating temperatures





Development of Buffer Strength Measurement



- Buffer/IPyC bond strength is an important predictor of a potential TRISO failure mechanism
 - Shrinkage of the low-density buffer region in the early stages of irradiation results in separation at the buffer/IPyC interface
 - Strongly-bonded buffer/IPyC can result in incomplete separation, leading to IPyC cracking and SiC failure
- Measurement of buffer/IPyC bonding is challenging due to particle size, system geometry, and the low density and strength of the buffer layer
- Experimental methods for accurately measuring this parameter are in development

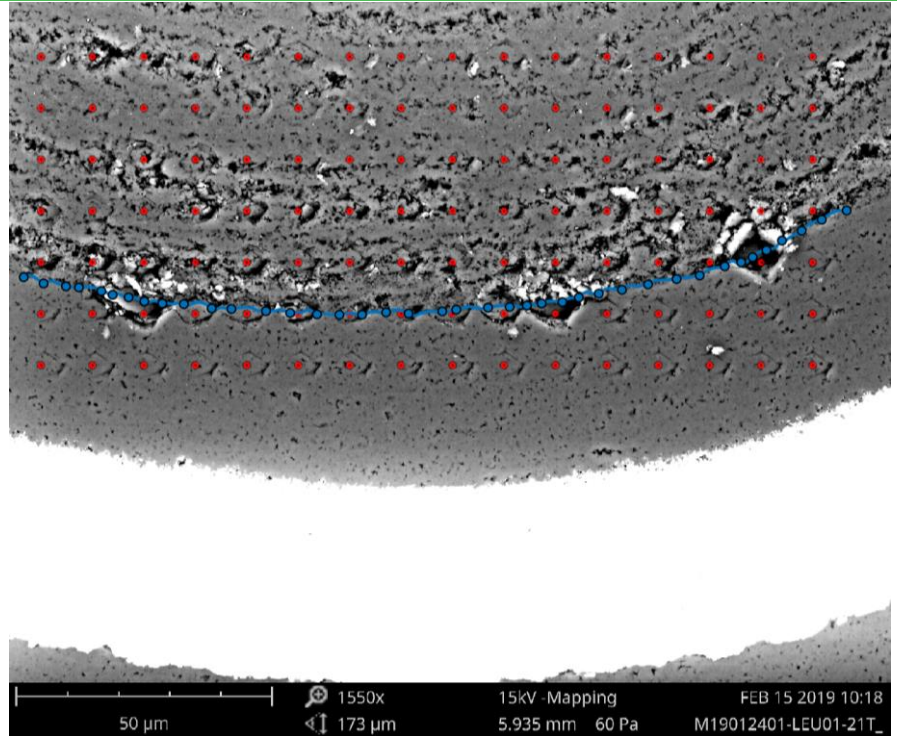
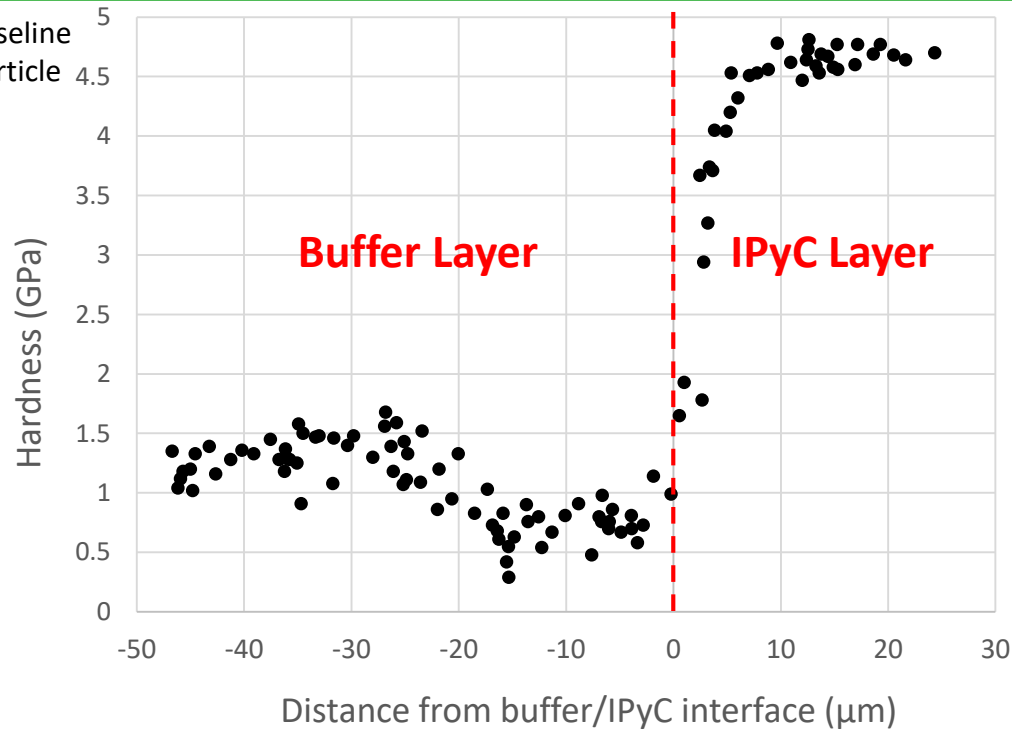
X-ray tomography of irradiated particles with good buffer IPyC interface bond (top) and bad buffer IPyC interface bond (bottom)





Development of Buffer Strength Measurement

Data from AGR-1 baseline conditions TRISO particle

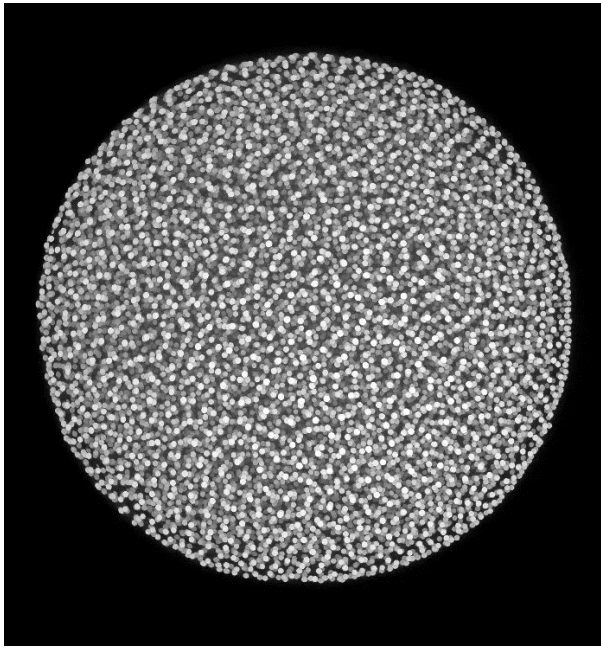


SEM image indicating nanoindentation positions and buffer/IPyC boundary

- Nanoindentation technique is being developed to probe the bond strength
- Initial data indicates a drop in the hardness prior to the buffer and IPyC boundary
- Further work is required to explain physical meaning and relate the data to the bond strength
- Particles from AGR-1 and AGR-2 are being examined
 - A decrease in the bond strength was observed in PIE from AGR-2 resulting in less particle failures



Issues Facing Pebble Development

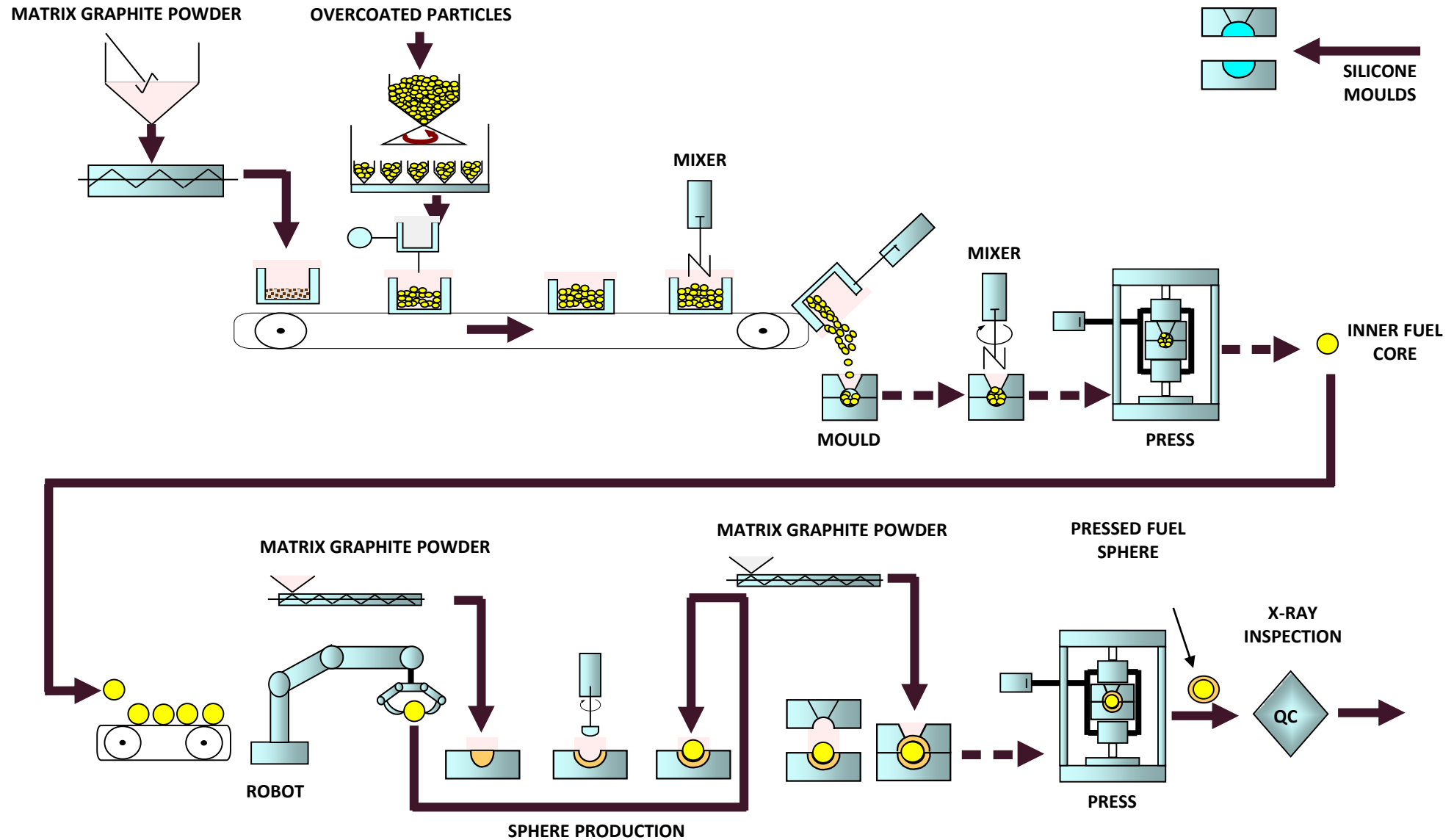


- An advanced method for overcoating particles was discovered and optimized during the AGR program that reduced the processing time and increased the homogeneity of cylindrical fuel elements
- Remaining fabrication issues:
 - Developing a process to produce pebbles
 - Optimizing overcoating process for pebble production
 - Improving particle spacing to increase homogeneity of fuel element
 - Optimizing the fabrication process for commercialization
 - Improving particle handling, upgrading, overcoating, and pressing to minimize broken particles





Pebble Pressing Overview





Development of a Multi-pebble Pressing Operation



- Fulfilled DOE Level 2 Milestone
- Method increases throughput for commercial needs
- Actively refining process parameters to improve consistency

Property	Pebble 1	Pebble 2	Pebble 3
Estimate of the number of loaded TRISO particles	18,000 ± 9	18,000 ± 9	18,000 ± 9
XRCT number of TRISO particles	17993	17991	18005
Fuel core mass [g]	111.45 ± 0.01	110.90 ± 0.01	110.13 ± 0.01
Fuel core diameter [mm]	47.77 ± 0.05	47.66 ± 0.05	47.52 ± 0.05
Pebble Diameter [mm]	59.56 ± 0.05	59.23 ± 0.05	58.99 ± 0.05
Fuel free zone average thickness [mm]	5.93 ± 0.05	6.01 ± 0.05	5.76 ± 0.05
Pebble green mass [g]	212.44 ± 0.01	209.73 ± 0.01	206.42 ± 0.01
Average green matrix density [g/cm ³]	1.90 ± 0.05	1.91 ± 0.05	1.90 ± 0.05
Average nearest neighbor distance [mm]	1.473 ± 0.072	1.467 ± 0.072	1.465 ± 0.072

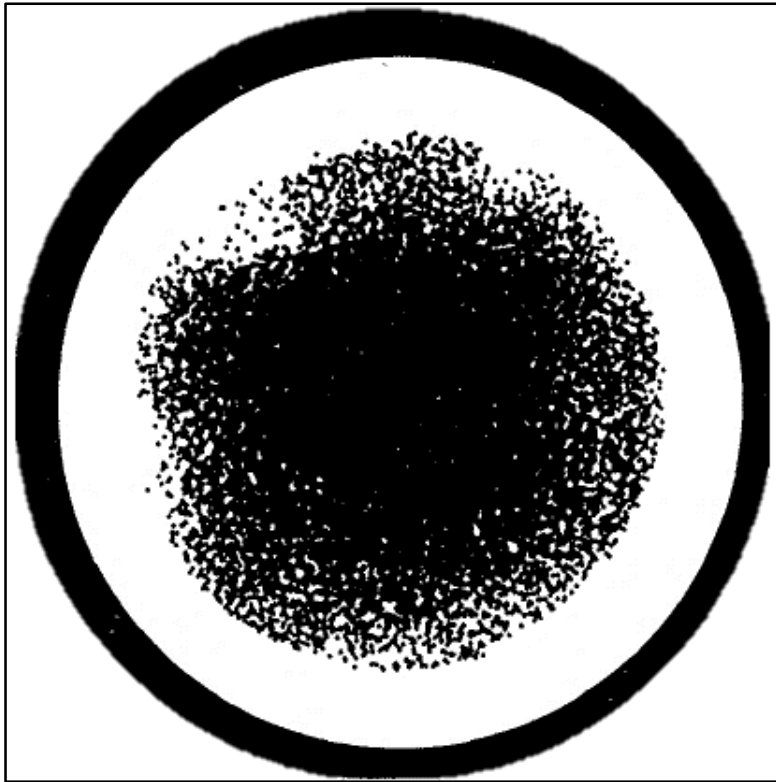
Simultaneously press up to 7 pebbles while maintaining consistent physical properties



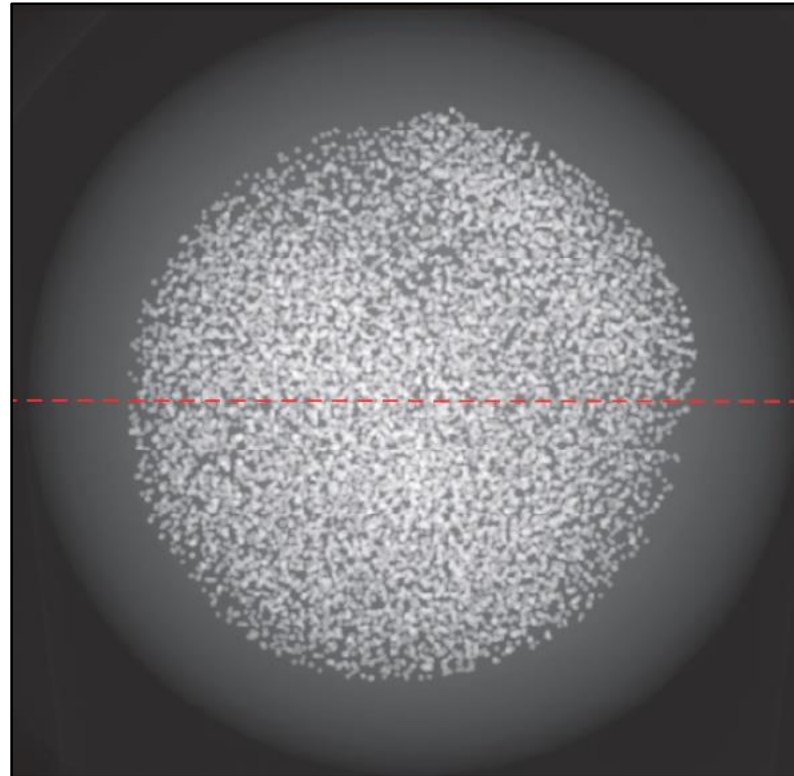


Superior Particle Spacing and Homogeneity

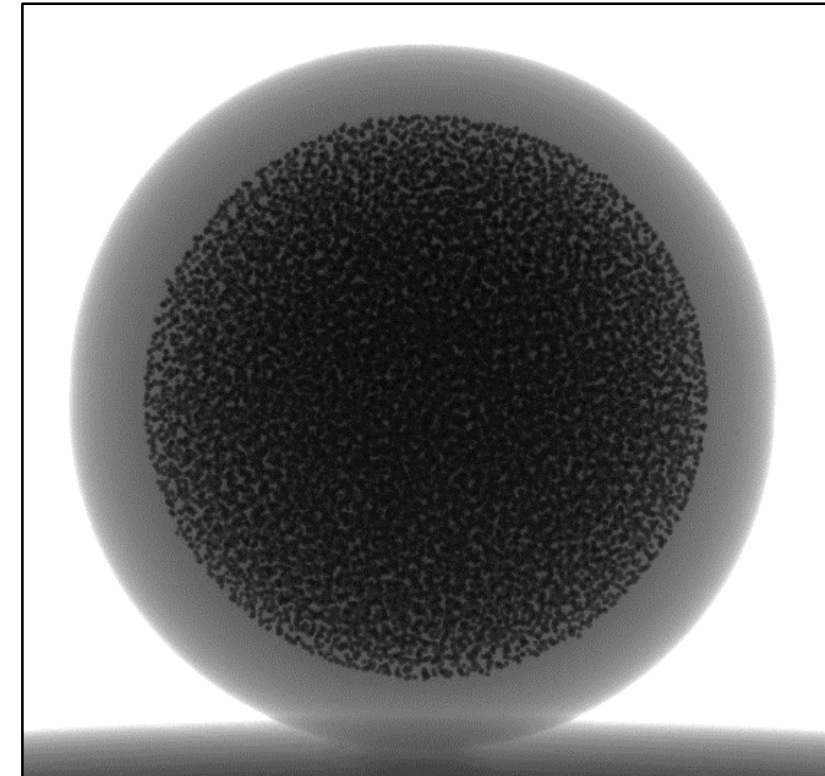
- German 2D radiograph vs Chinese 2D radiograph vs X-energy 2D radiograph
- X-energy fuel features:
 - Increased homogeneity
 - Increased fuel core sphericity



German radiograph



Chinese radiograph



X-energy radiograph





Process Improvements

Process	Improvements over historical methods
Kernel fabrication:	<ul style="list-style-type: none">• Identification of “ideal” carbon content• Novel droplet formation manifold• In-line droplet characterization• Waste reduction with organic de-greasers• Optimized pH for internal gelation
TRISO coating:	<ul style="list-style-type: none">• Improved loading/unloading to minimize particle damage• Novel gas-injector inlet design• Optimized graphite internal geometry for yield and waste minimization• Novel top furnace design to ensure proper fluidization
Fuel element pressing:	<ul style="list-style-type: none">• Optimized overcoating technique for yield and reduced run time• Improved pressing technique to minimize lathing requirements• Improved pressing method leading to uniform distribution of particles• Elimination of loading/mixing steps in pebble pressing process• Combined carbonization/heat treatment step to reduce run time
Characterization & QC:	<ul style="list-style-type: none">• Use of modern materials science techniques for product visualization• Intelligent design through insitu monitoring of fabrication processes• Reduced development time through rapid prototyping• Faster method for determining particle defect fraction

Bottom line: These improvements result in better particle layer integrity and performance compared to previous programs



X-energy Fuel Development Team

John Hunn
ORNL PI



Pete Pappano
VP of Fuel Development

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