HTGR Technology Course for the Nuclear Regulatory Commission

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Module 7b

TRISO Fuel Manufacturing – Fabrication and Quality Control

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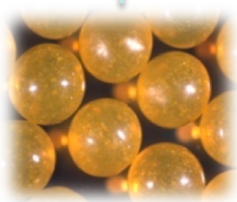
Outline

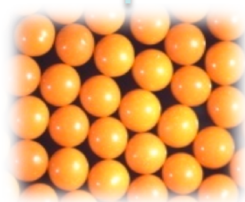
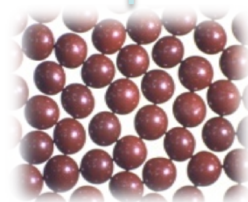
- **TRISO fuel fabrication**
  - Kernel production
  - Coating deposition
  - Compacting
- **TRISO fuel quality control**
- **TRISO fuel characterization**

Kernel Fabrication

- Kernels are fabricated using a sol-gel process to form a spherical bead
- Dried spherical beads are heat treated to form the desired metal oxide and/or carbide phases and sinter the kernel

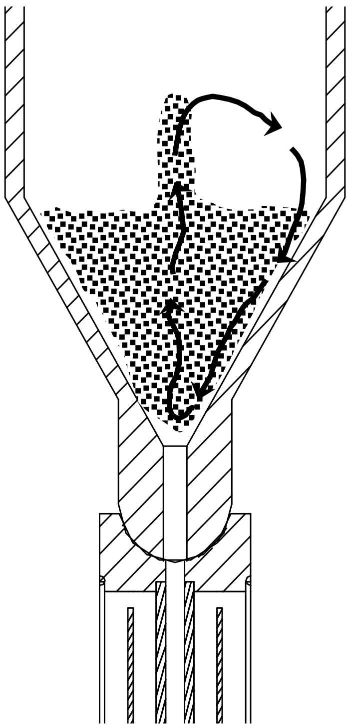
Form Kernels → Age Kernels → Wash&Dry Kernels → Calcine Kernels → Sinter Kernels



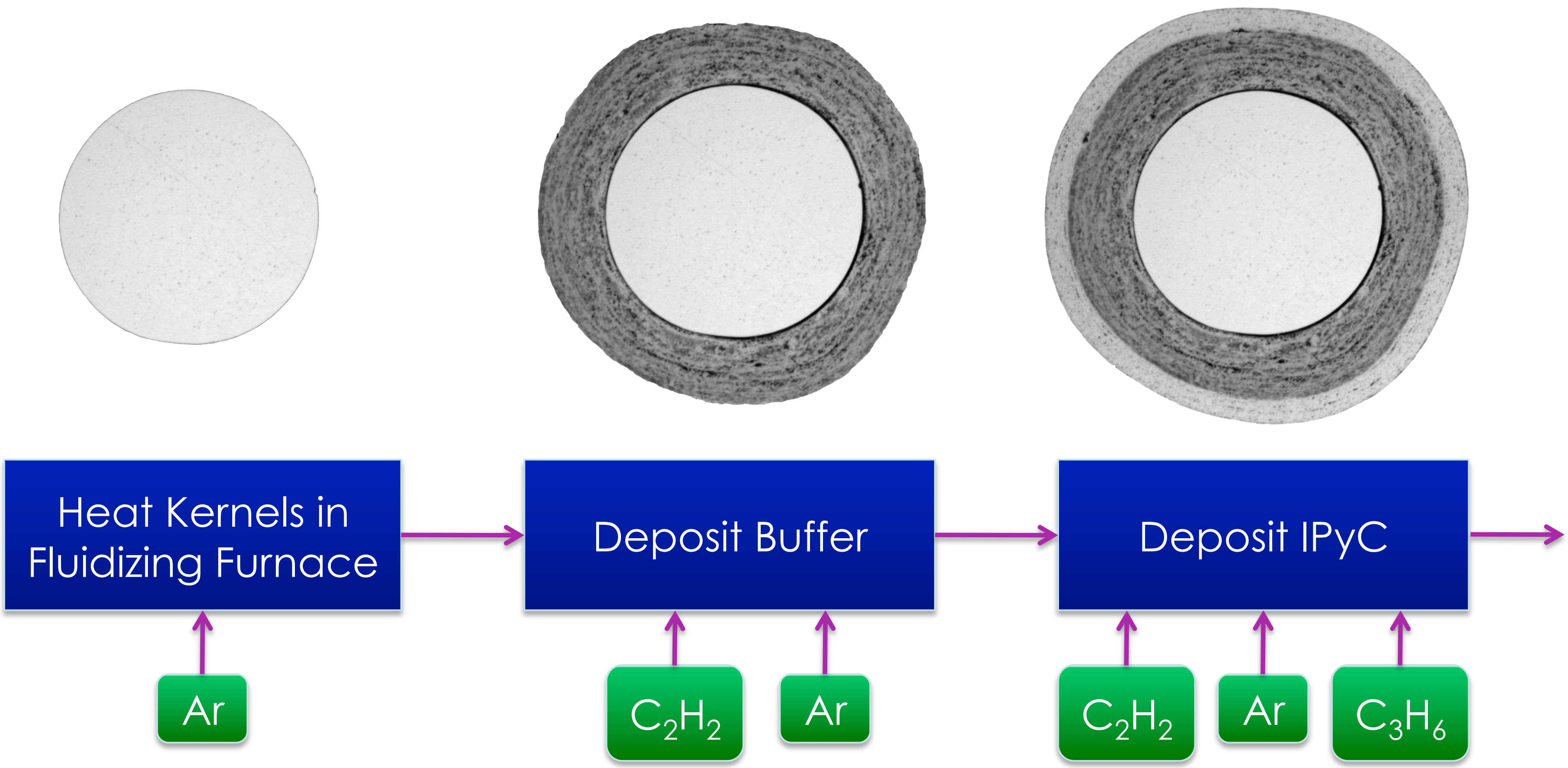




Coating Deposition

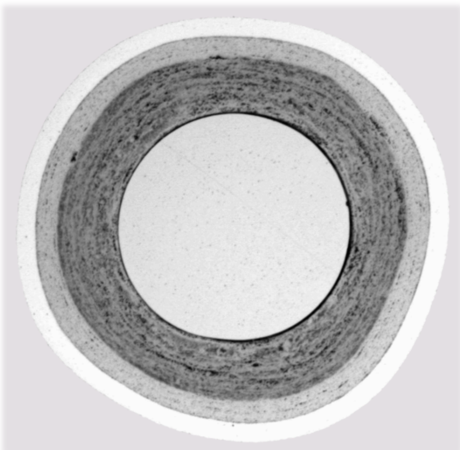
- **Spherical coatings are deposited using a fluidized bed chemical vapor deposition furnace**
- **Reactant gas mixture and temperature are controlled to obtain desired coating properties**
- **Coated particles are sorted by size and shape to upgrade the batch after coating**

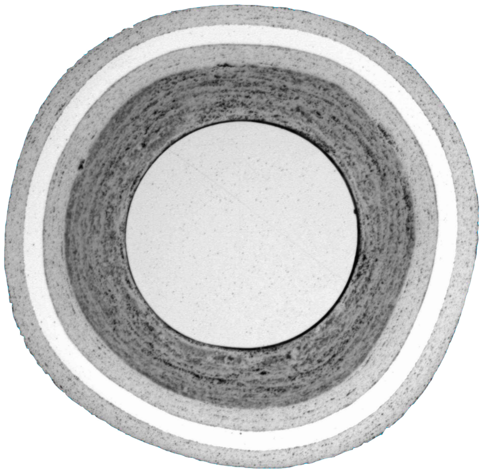


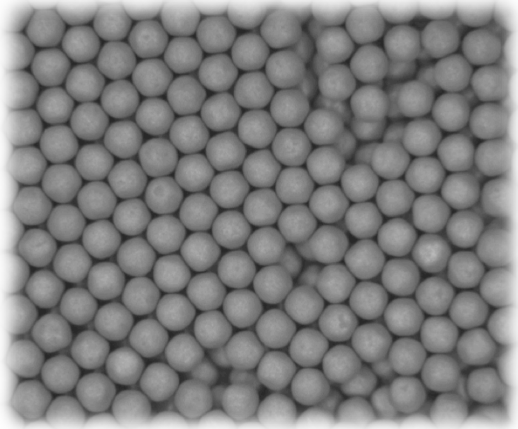
TRISO Coating Process

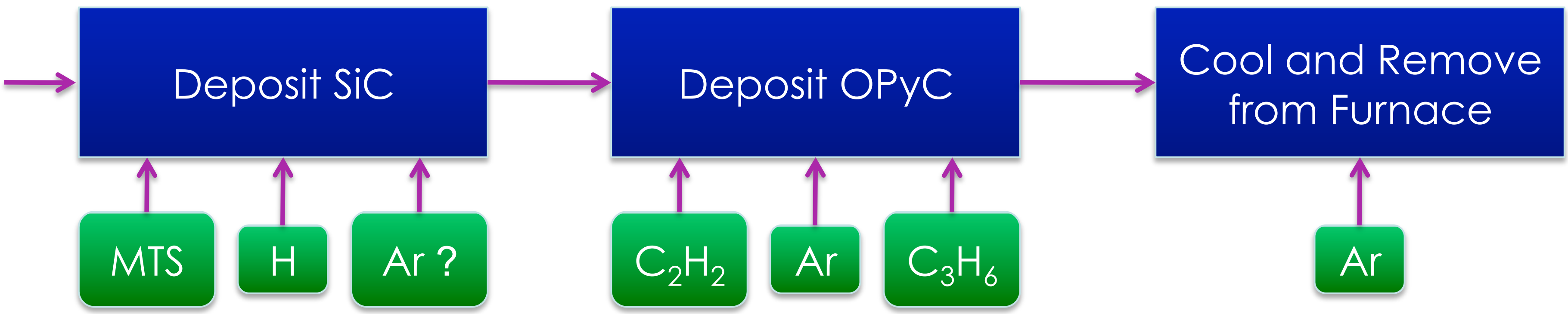


TRISO Coating Process - Continued





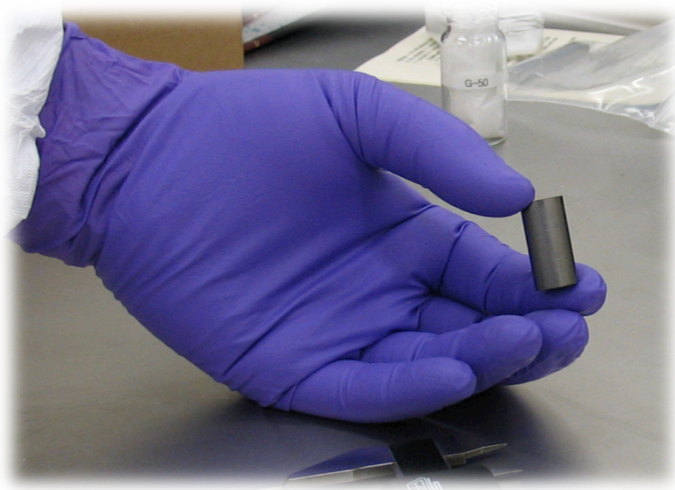




Compacting Fuel Elements

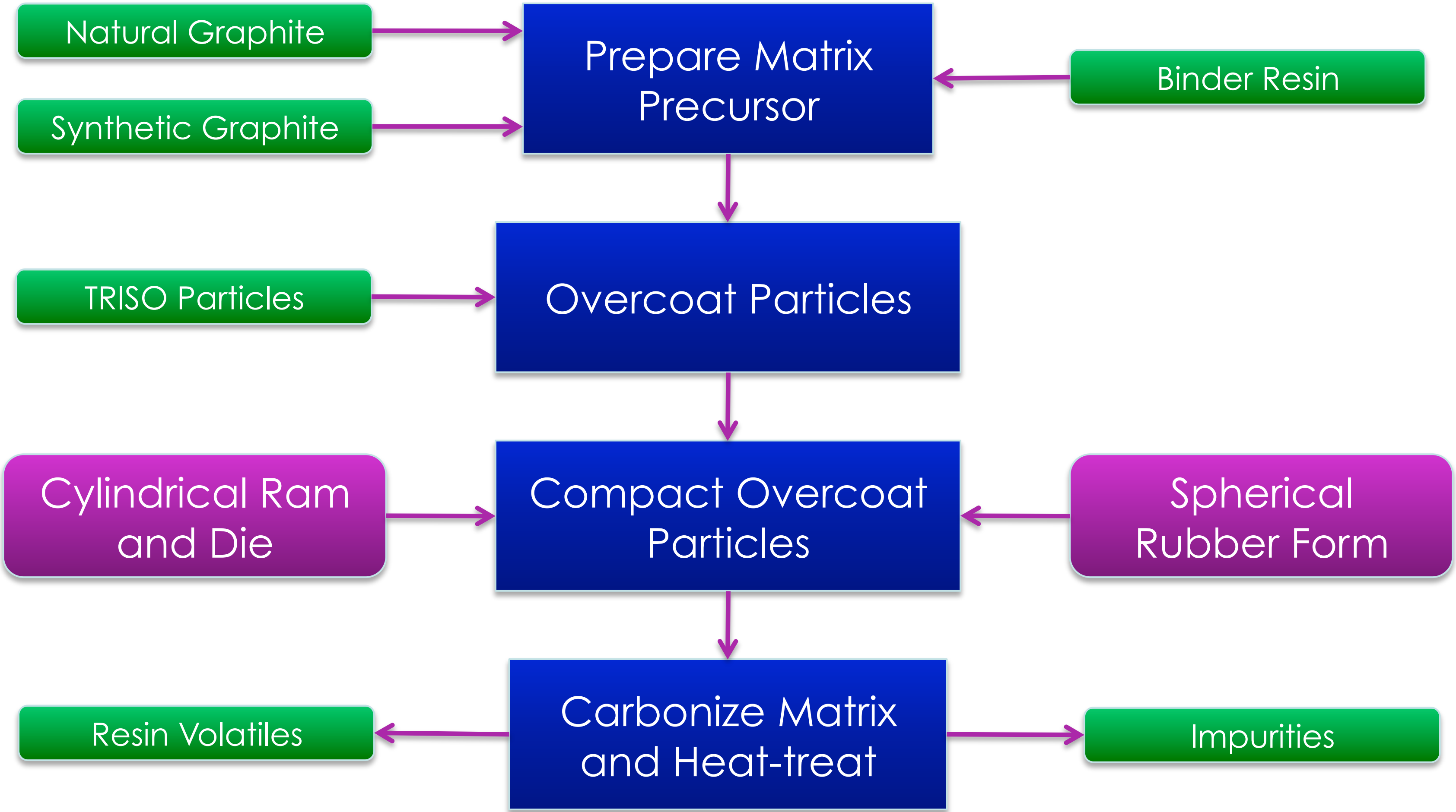
- **TRISO coated particles are compacted into a graphite matrix fuel form**

Cylindrical compacts for a prismatic-core HTGR

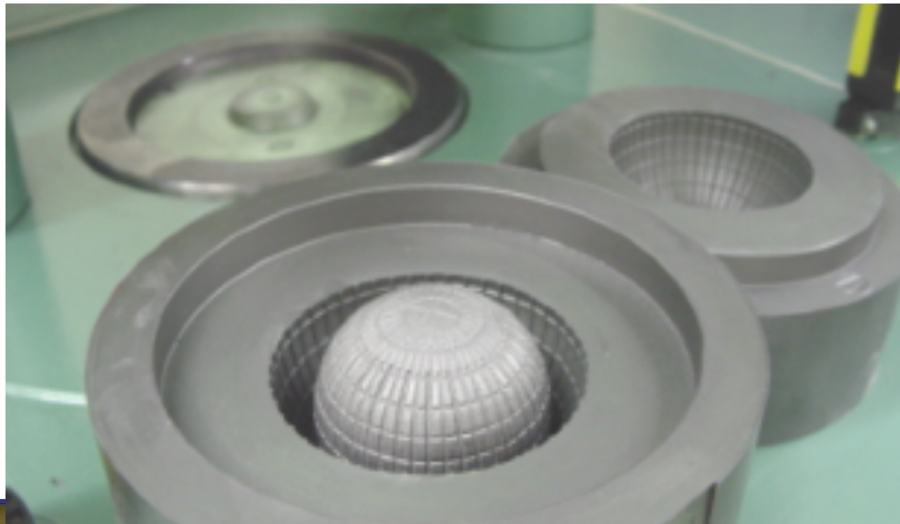


Spherical elements for a pebble-bed HTGR

Overcoated Particle Compacting Process

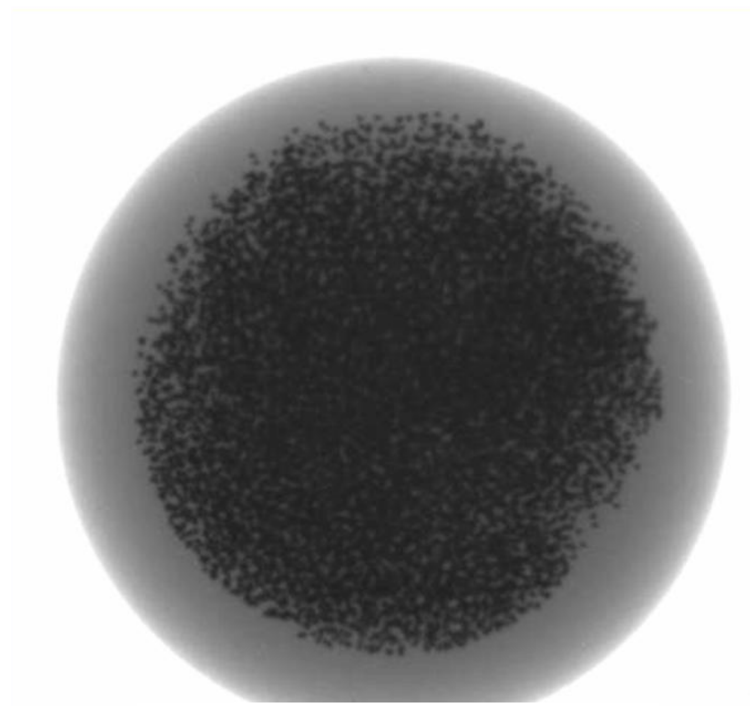


Compacting Spherical Fuel Elements



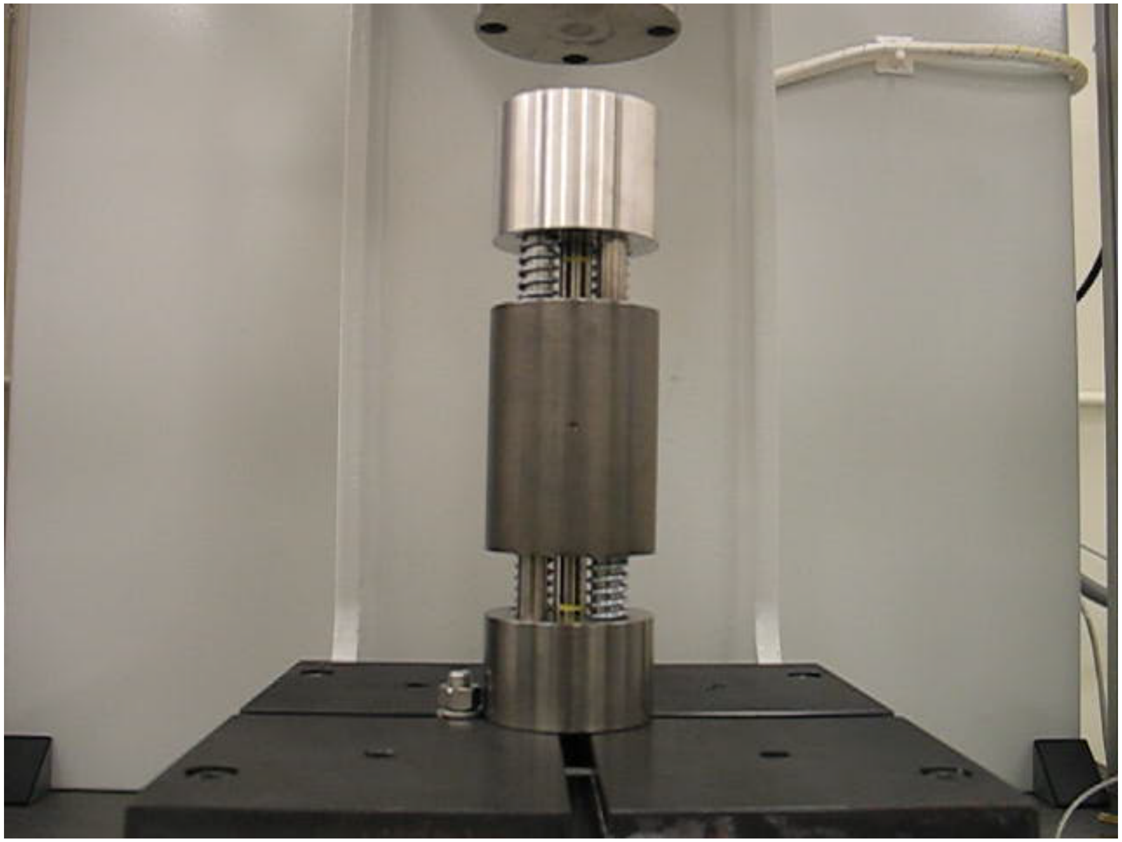
Fuel Sphere Pressing

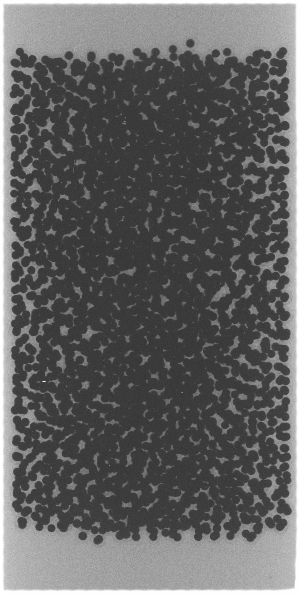
Finished (Machined) Fuel Spheres



Radiograph of Pebble

Compacting Cylindrical Fuel Elements





Substantial Quantities of Coated Particles have been Fabricated Throughout the World

Reactor/ Manufacturer	Country	Fuel Description		U/Th Quantity (kg)
ROVER / GA & LANL	US	BISO	Extrusions	14,000
DRAGON	UK	BISO / TRISO	Compacts	1,000's
Peach Bottom I / GA	US	BISO	Compacts	3,500
UHTREX / GA & LANL	US	TRISO (Early)	Extrusions	200
Fort St. Vrain	US	TRISO	Compacts	33,400
AVR	Germany	BISO / TRISO	Spheres	2,200
THTR / Nukem	Germany	BISO	Spheres	7,700
CNPS / GA	US	TRISO	Compacts	94
HTTR / NFI	Japan	TRISO	Compacts	900
HTR-10	China	TRISO	Spheres	140
Russia, Belgium, France Korea, India, South Africa	various	BISO / TRISO	-----------	Small

Lab-Scale Kernel Fabrication Equipment Used by ORNL for AGR Fuel Development

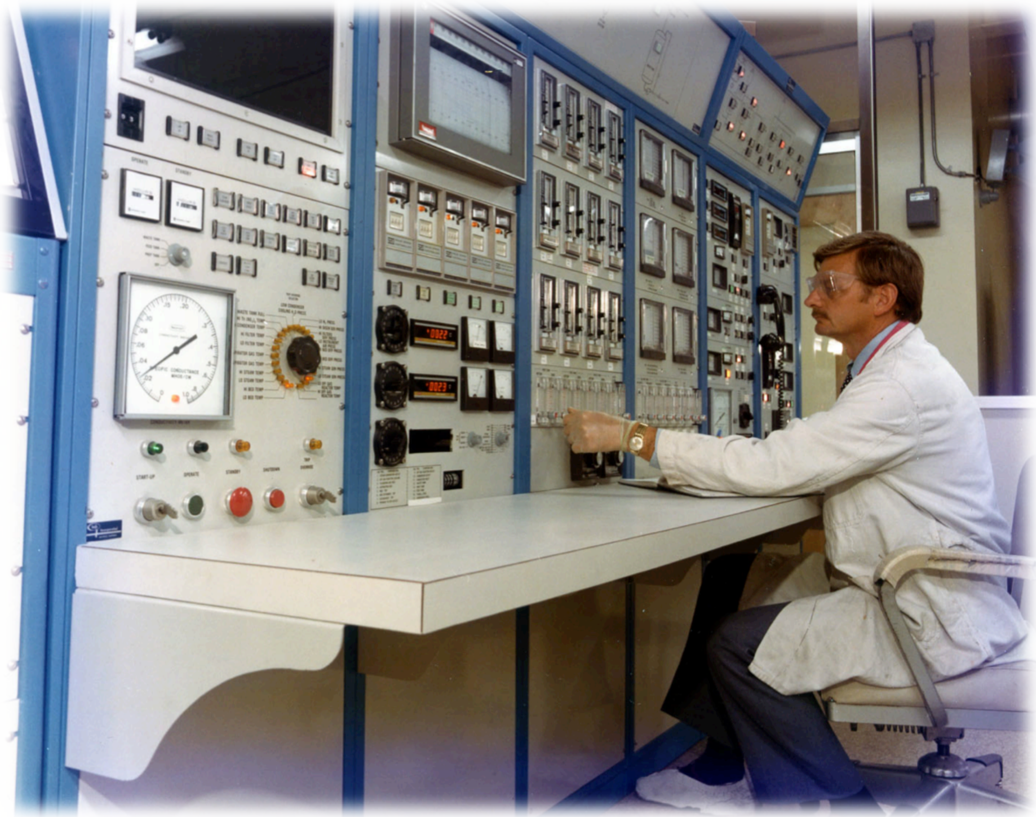
Pilot-Scale Kernel Fabrication Equipment Used by B&W for AGR Fuel Manufacturing

Sol-Gel Equipment

Handling Boxes

Furnaces

Production-Scale Kernel Fabrication Equipment Developed by General Atomics



Lab-Scale ORNL Coater Used for AGR-1

50-mm Coater

Measuring Coating Temperature

Pilot-scale B&W Coater Used for AGR-2

Coater Lid

Coating Chamber

150-mm Coater

Production-Scale Fort St. Vrain Coater

240-mm Coater

Outline

- **TRISO fuel fabrication**
  - Kernel production
  - Coating deposition
  - Compacting
- **TRISO fuel quality control**
- **TRISO fuel characterization**

Quality Control for TRISO Fuels

- **Quality Control (QC) is the process used to verify that a product satisfies the design criteria**
- **QC for coated particle fuel includes:**
  - Specifications on source materials, production processes and process limits
  - Specifications on kernel, coating, and compact properties
  - Specifications on defect populations that may impact performance
- **QC measurements of fuel properties are performed using statistical sampling**

Example of an NQA-1 Fuel Production and Characterization Campaign

- The AGR-1 fuel product was produced for the US Advanced Gas Reactor Fuel Development and Qualification Program
- TRISO-coated 350 μm diameter 19.7% enriched UCO kernels were loaded into 25 mm long, 12.5 mm diameter cylindrical compacts
- A Baseline and three fuel Variants were produced and inserted into the Idaho Advanced Test Reactor in Dec 2006
- After 3 years of irradiation to 19.6% peak burn-up, 4.4E25 n/m^2 peak fast fluence, and 1038-1121°C average temperature, no fission product release due to fuel particle failure was detected

AGR-1 Fuel Specification for QC

- **Specified criteria on both process conditions and fuel properties**
- **Acceptance stages for kernel batches, kernel composites, particle batches, particle composites, and compacts**
- **Specified mean values and critical limits on the dispersion for variable properties, such as:**
  - Kernel diameter
  - Kernel stoichiometry
  - Layer thickness
  - Layer density
  - Pyrocarbon anisotropy
  - Compact dimensions
  - Compact U-loading
  - Compact impurity content
- **Specified maximum defect fractions for attribute properties, such as:**
  - Kernel aspect ratio
  - SiC defects and microstructure
  - OPyC defects
  - Particle aspect ratio
  - Tramp uranium in compacts
  - Uranium dispersion from kernel

Example of QC Acceptance Tests

Inspection Report Form IRF-04A: Coated Particle Composites

Procedure:	AGR-CHAR-PIP-04 Rev. 2
Coated particle composite ID:	LEU01-46T
Coated particle composite description:	Baseline Composite: TRISO on BWXT kernel composite 69302

Property	Measured Data: Mean (x)	Measured Data: Std. Dev. (s)	Measured Data: # measured (n)	Measured Data: k or t value	Specification INL EDF-4380 Rev. 6	Acceptance Criteria	Acceptance Test Value	Pass or fail	Data Records
Average buffer thickness for each particle (μm)	103.5	8.2	213	1.652	mean 100 ± 15	A = x - ts/√n ≥ 85	102.6	pass	DRF-08 DRF-11
						B = x + ts/√n ≤ 115	104.4	pass	
				2.560	dispersion ≤0.01 ≤ 55	C = x - ks > 55	82.5	pass	
Average IPyC thickness for each particle (μm)	39.4	2.3	233	1.651	mean 40 ± 4	A = x - ts/√n ≥ 36	39.2	pass	DRF-08 DRF-11
						B = x + ts/√n ≤ 44	39.6	pass	
				2.549	dispersion ≤0.01 ≤ 30 ≤0.01 ≥ 56	C = x - ks > 30	33.5	pass	
						D = x + ks < 56	45.3	pass	
Average SiC thickness for each particle (μm)	35.3	1.3	233	1.651	mean 35 ± 3	A = x - ts/√n ≥ 32	35.2	pass	DRF-08 DRF-11
						B = x + ts/√n ≤ 38	35.4	pass	
				2.549	dispersion ≤0.01 ≤ 25	C = x - ks > 25	32.0	pass	
Average OPyC thickness for each particle (μm)	41.0	2.1	233	1.651	mean 40 ± 4	A = x - ts/√n ≥ 36	40.8	pass	DRF-08 DRF-11
						B = x + ts/√n ≤ 44	41.2	pass	
				2.549	dispersion ≤0.01 ≤ 20	C = x - ks > 20	35.6	pass	
Buffer envelope density	See IRF-02A							pass	IRF-02A
IPyC sink/float density	See IRF-02B							pass	IRF-02B
SiC sink/float density (Mg/m^3)	3.2075	0.0032	40	1.685	mean ≥ 3.19	A = x - ts/√n ≥ 3.19	3.207	pass	DRF-02
				2.941	dispersion ≤0.01 ≤ 3.17	C = x - ks > 3.17	3.198	pass	
OPyC sink/float density	See IRF-04B								IRF-04B
IPyC anisotropy (BAFo equivalent)	1.022	0.002	10	1.833	mean ≤ 1.035	B = x + ts/√n ≤ 1.035	1.023	pass	DRF-18
				3.981	dispersion ≤0.01 ≥1.06	D = x + ks < 1.06	1.030	pass	
OPyC anisotropy (BAFo equivalent)	1.019	0.003	10	1.833	mean ≤ 1.035	B = x + ts/√n ≤ 1.035	1.021	pass	DRF-18
				3.981	dispersion ≤0.01 ≥1.06	D = x + ks < 1.06	1.031	pass	
Particles with SiC gold spot defects			81507		defect fraction ≤ 1.0×10^{-3}	≤6 in 12,000 or ≤14 in 22,000	66	pass	DRF-20
Particle aspect ratio			1626		dispersion ≤0.01 ≥1.14	≤1 in 500 or ≤7 in 1420	2	pass	DRF-07 DRF-10
Particles with SiC burn-leach defects			120688		defect fraction ≤ 1.0×10^{-4}	≤1 in 50,000 or ≤6 in 120,000	0	pass	DRF-21
Particles with missing OPyC			31227		defect fraction ≤ 3.0×10^{-4}	≤4 in 31,000	0	pass	DRF-19
SiC microstructure			3		comparison to visual standard	all imaged pass visual standard comparison	3	pass	DRF-23

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- **TRISO fuel quality control**
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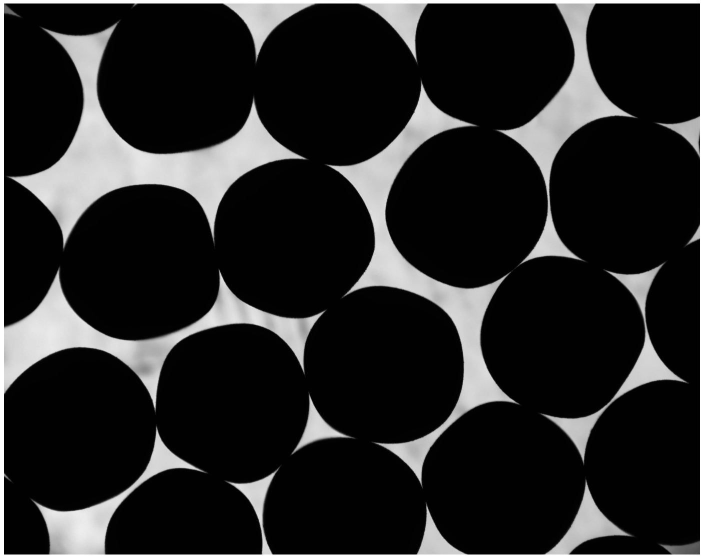
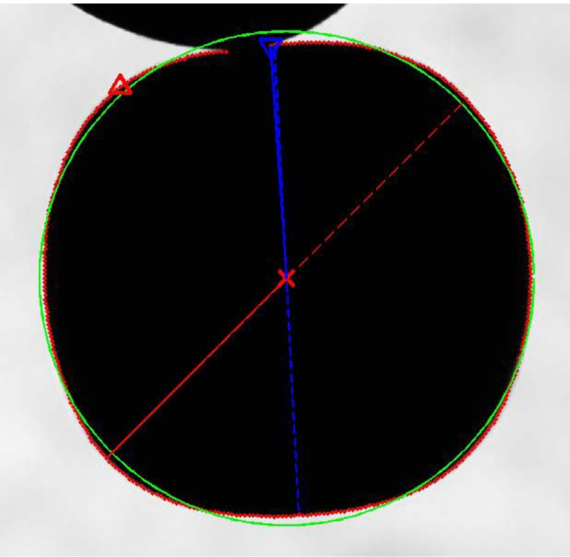
Analysis of Size and Shape

- **Typically image thousands of particles or kernels using transmitted light to detect edges.**



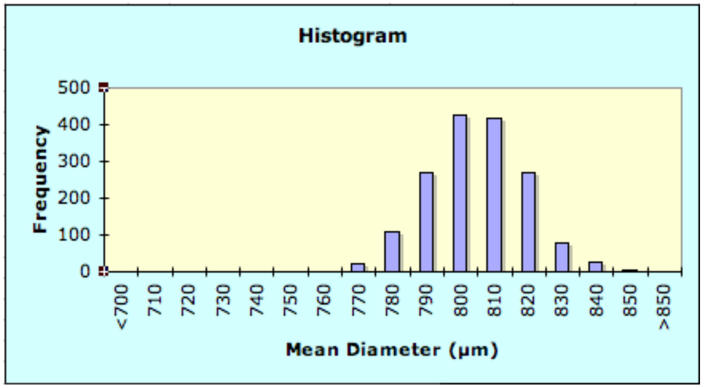
AGR-1 Baseline Coated Particles



- **Image analysis program automatically selects each particle and identifies 360 points around the perimeter. Data is processed for radius, diameter, shape and curvature.**

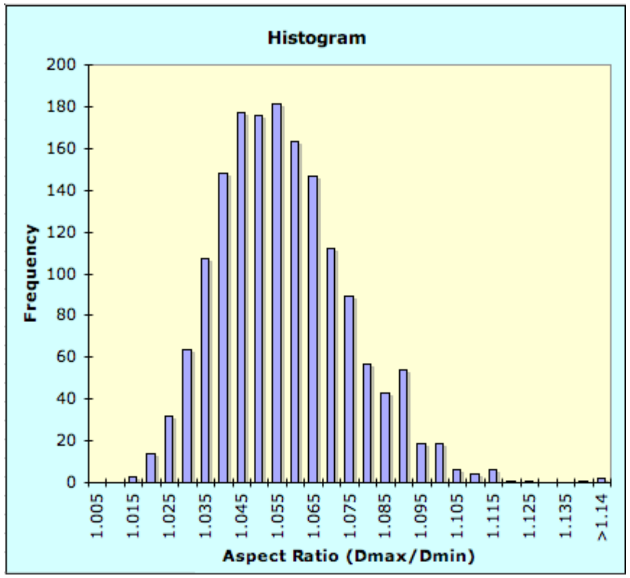
Size and Shape Example: AGR-1 Baseline

800±14 µm diameter



2 particles ≥ 1.14 aspect ratio

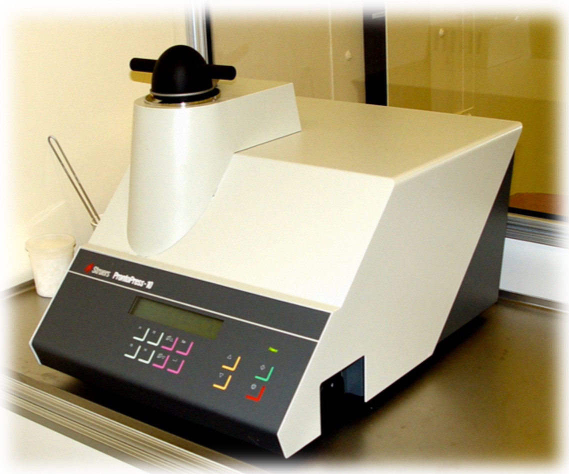
1.054 mean aspect ratio



AGR-1 Baseline fuel

1626 particles measured

Preparation of Coated Particle Cross-sections

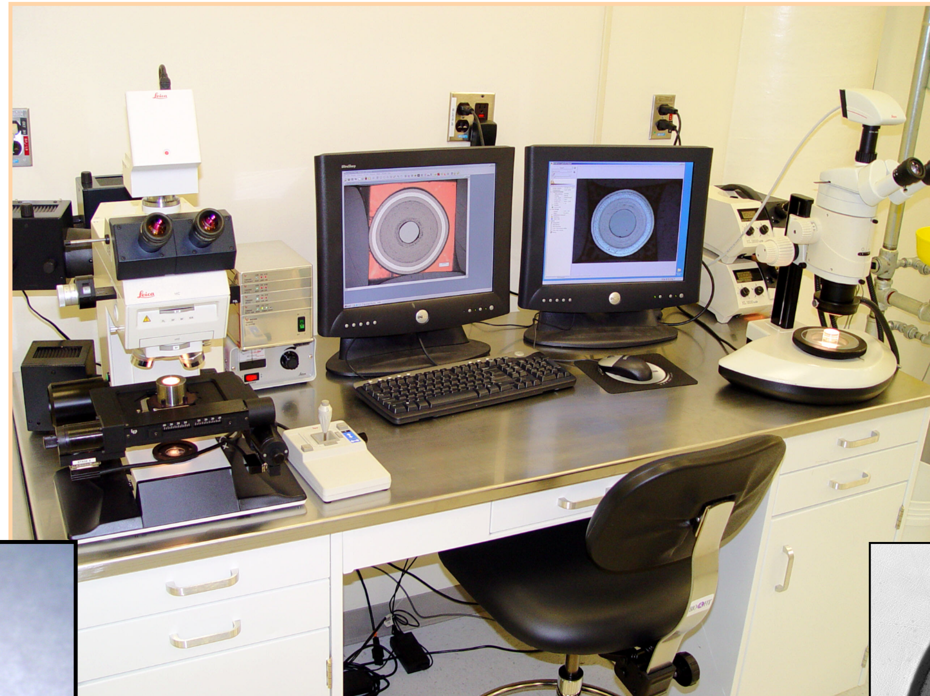


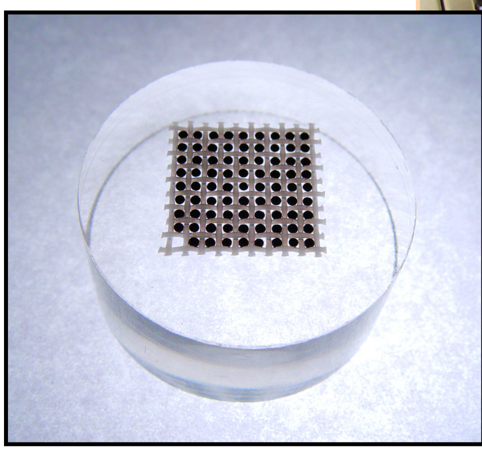
Epoxy Mounting

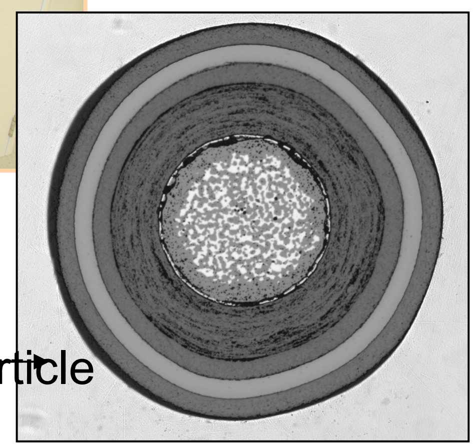
Vacuum Back-potting

Grinding and Polishing

Analysis of Coating Thickness



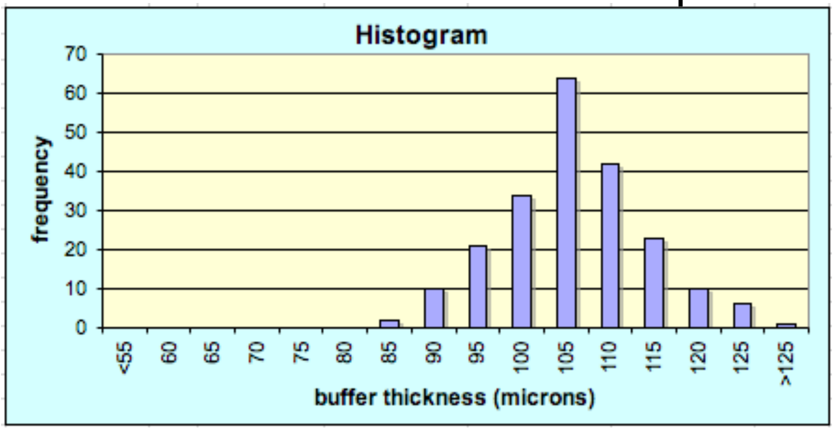




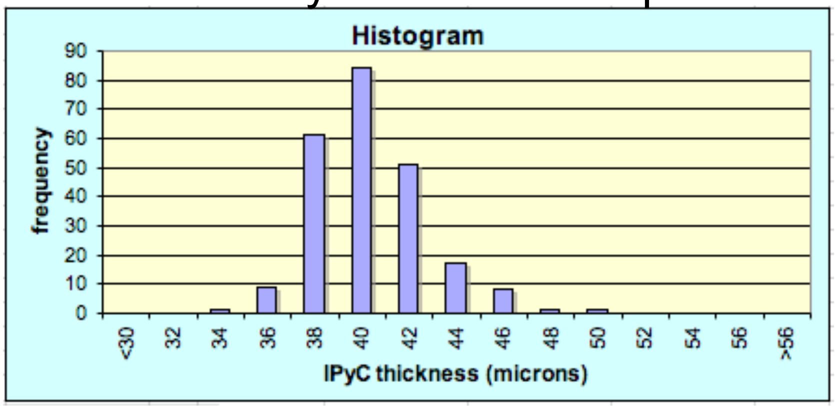
AGR-1 Baseline fuel particle

Coating Thickness Example : AGR-1 Baseline

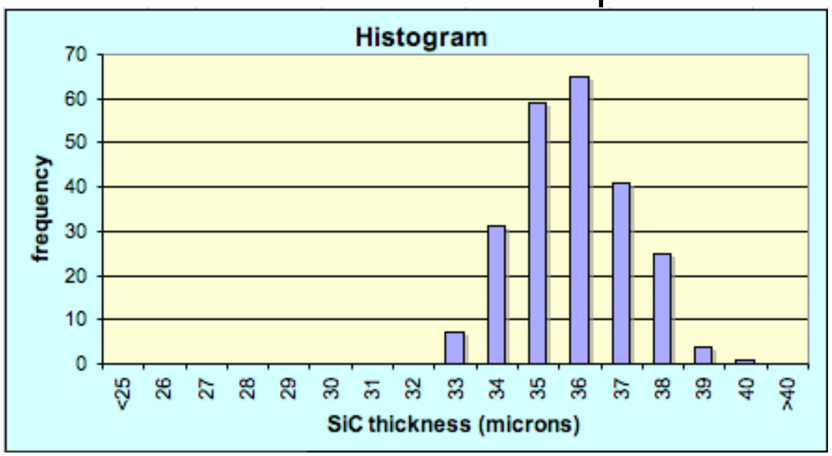
Buffer = 103.5 ± 8.2 μm



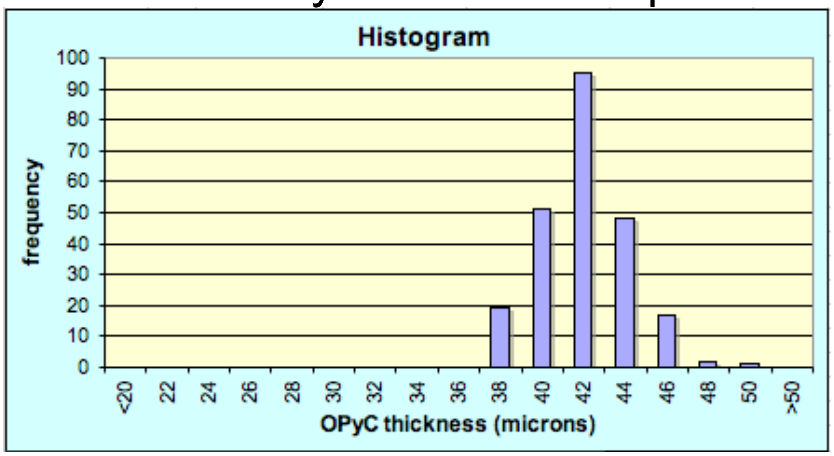
IPyC = 39.4 ± 2.3 μm



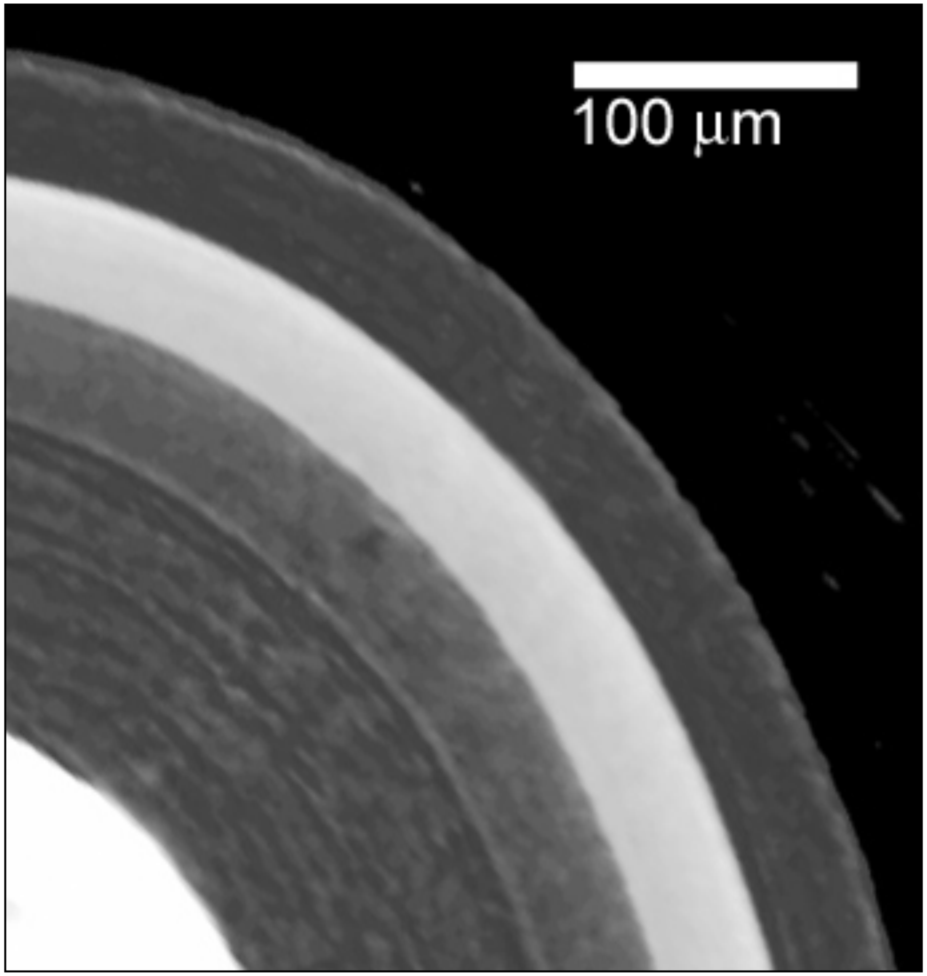
SiC = 35.3 ± 1.3 μm



OPyC = 41.0 ± 2.1 μm

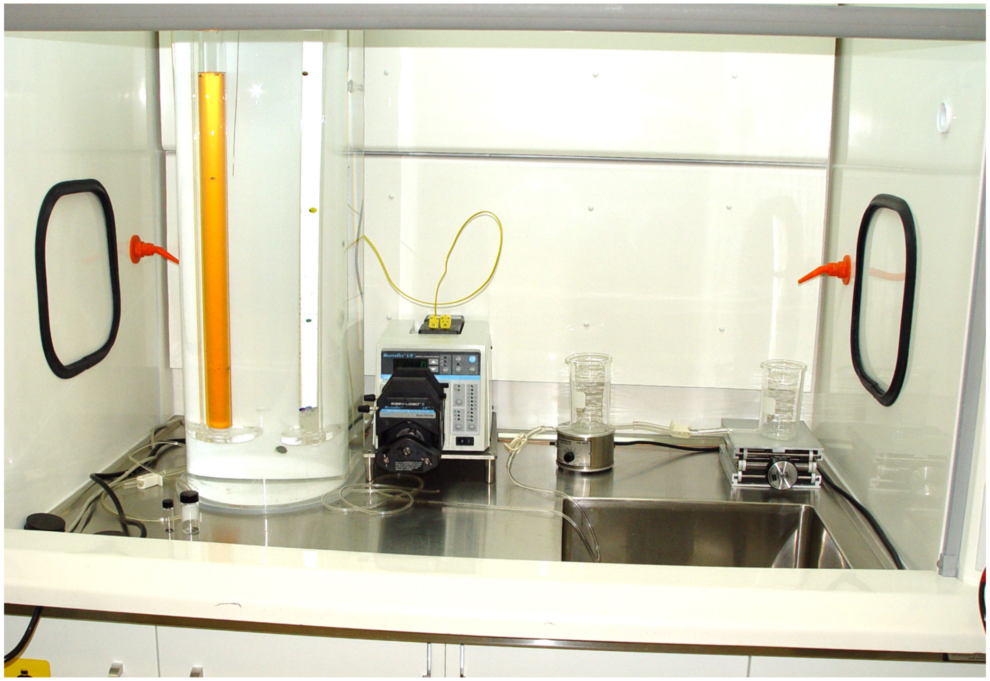


X-ray Imaging is an Alternate Method for Coating Thickness Analysis



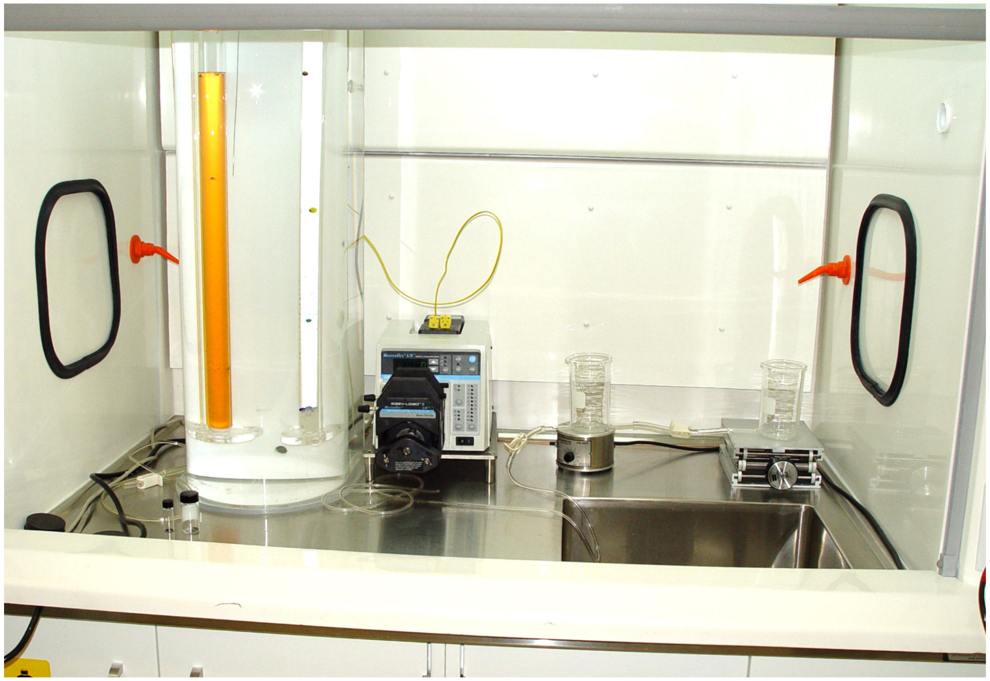
IPyC, SiC, OPyC Sink Float Density

- **AGR-1 SiC mean density = 3.205 - 3.208 g/cc (3.217 g/cc theoretical)**
- **AGR-1 SiC density range = 3.202 - 3.212 g/cc**



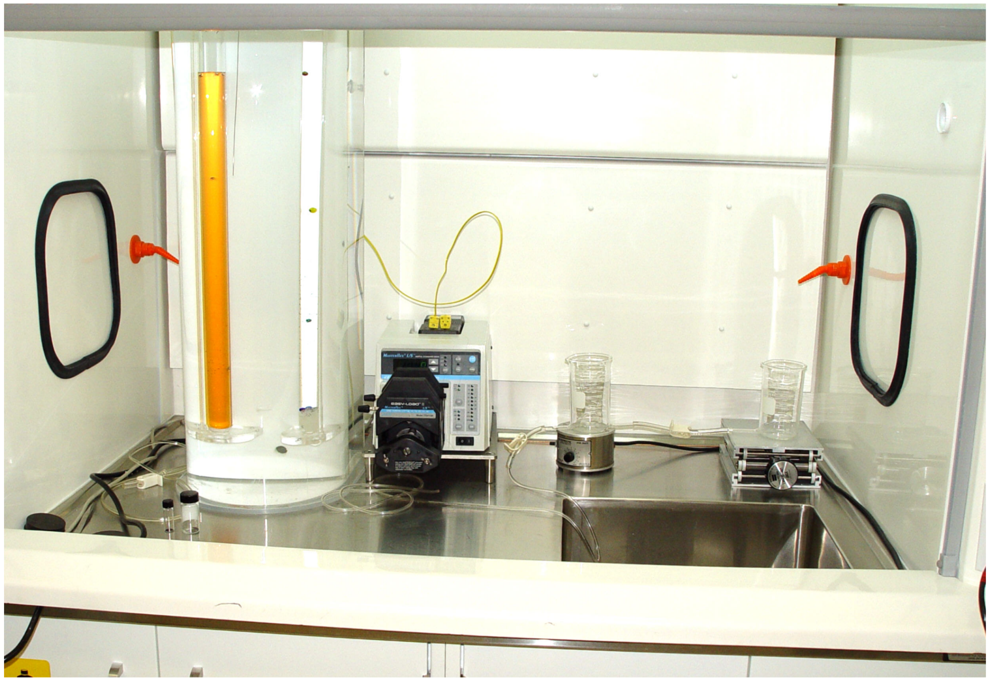
IPyC, SiC, OPyC Sink Float Density

- **AGR-1 IPyC mean density = 1.90 - 1.91 g/cc (1.85 g/cc for variant 1)**
- **AGR-1 IPyC density range = 1.87 - 1.94 g/cc (1.82 - 1.89 g/cc for variant 1)**



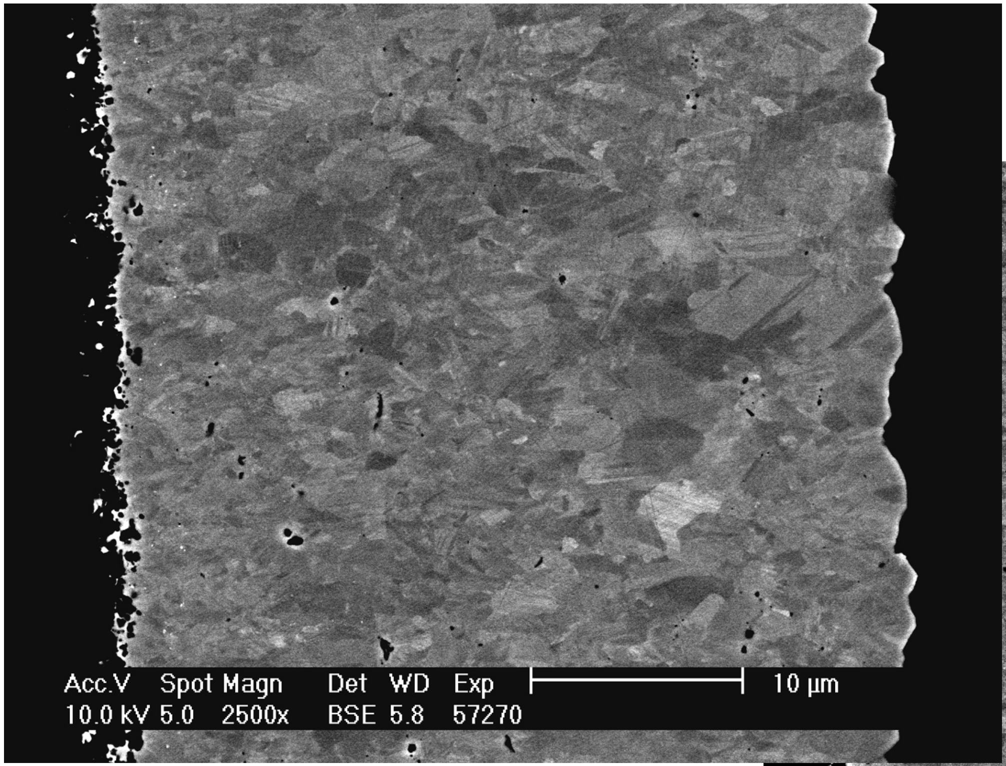
IPyC, SiC, OPyC Sink Float Density

- **AGR-1 OPyC mean density = 1.90 - 1.91 g/cc**
- **AGR-1 OPyC density range = 1.86 - 1.95 g/cc**



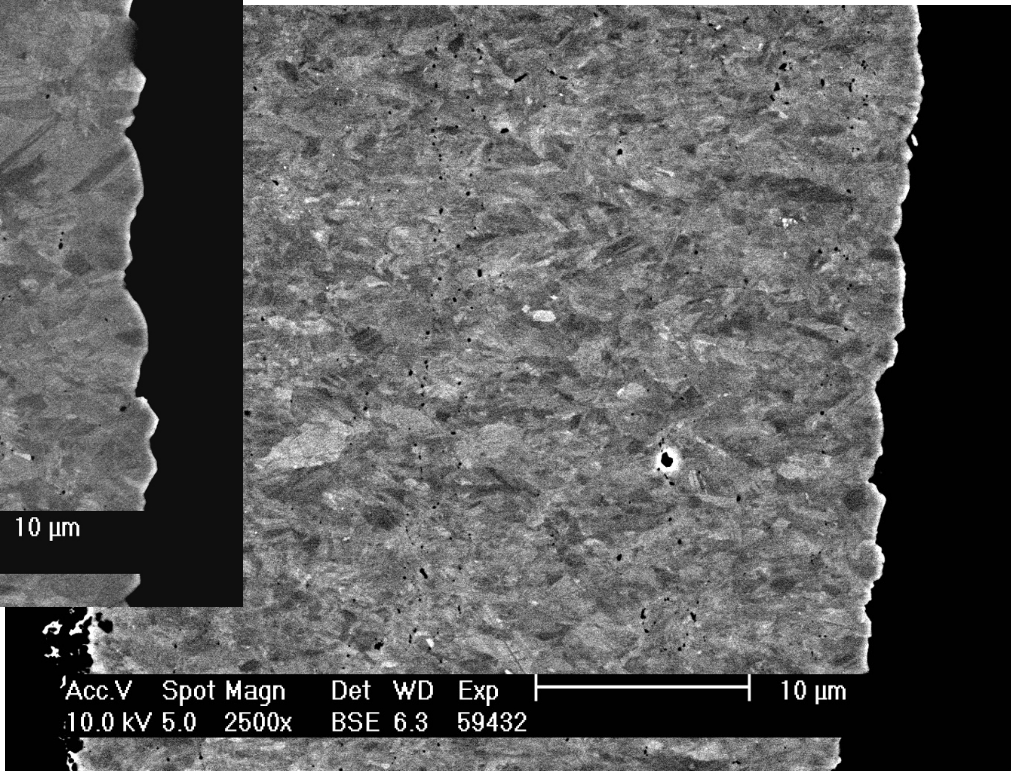
SiC Microstructure

- **Imaged with backscattered electrons in an SEM**



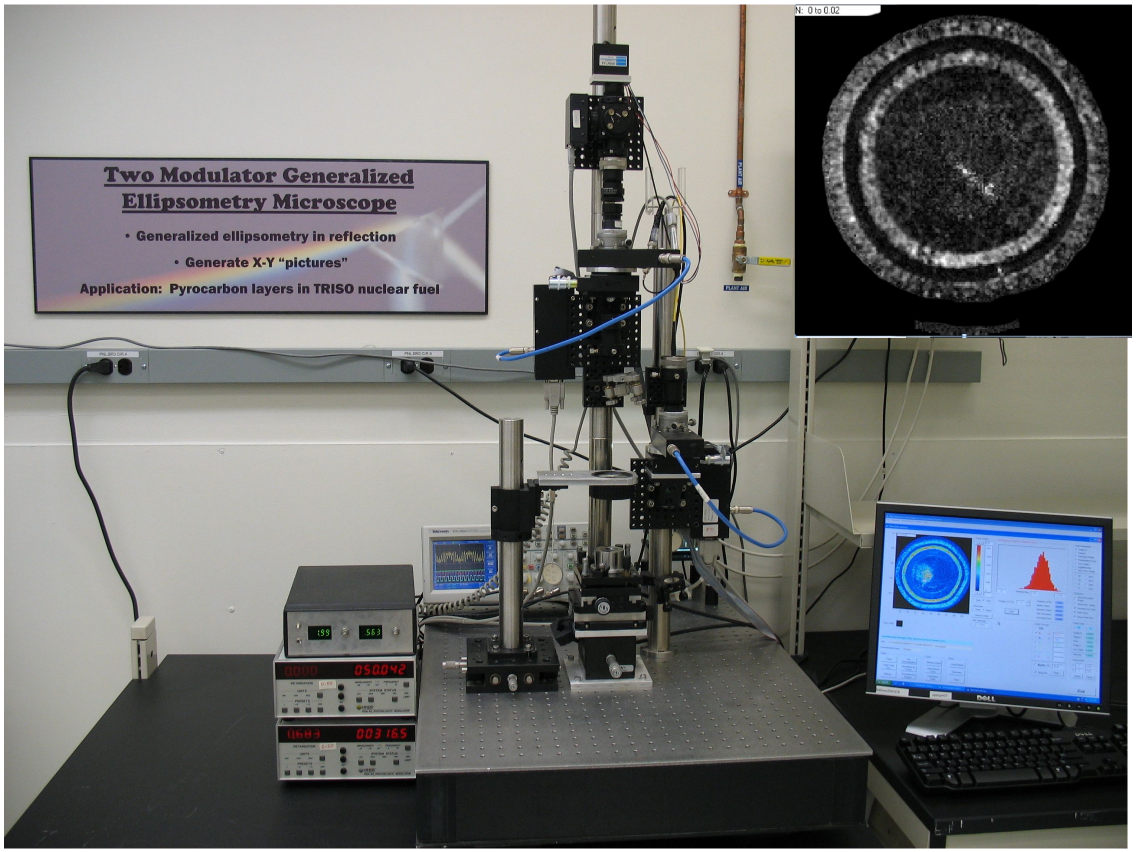
AGR-1 Baseline

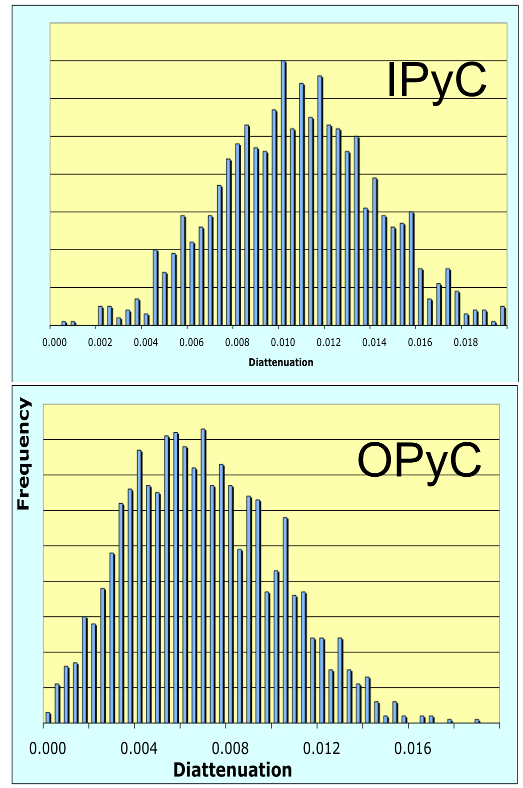
AGR-1 variant 3



Pyrocarbon Anisotropy

- **Imaged with Two-Modulator Generalized Ellipsometry Microscope (2-MGEM)**

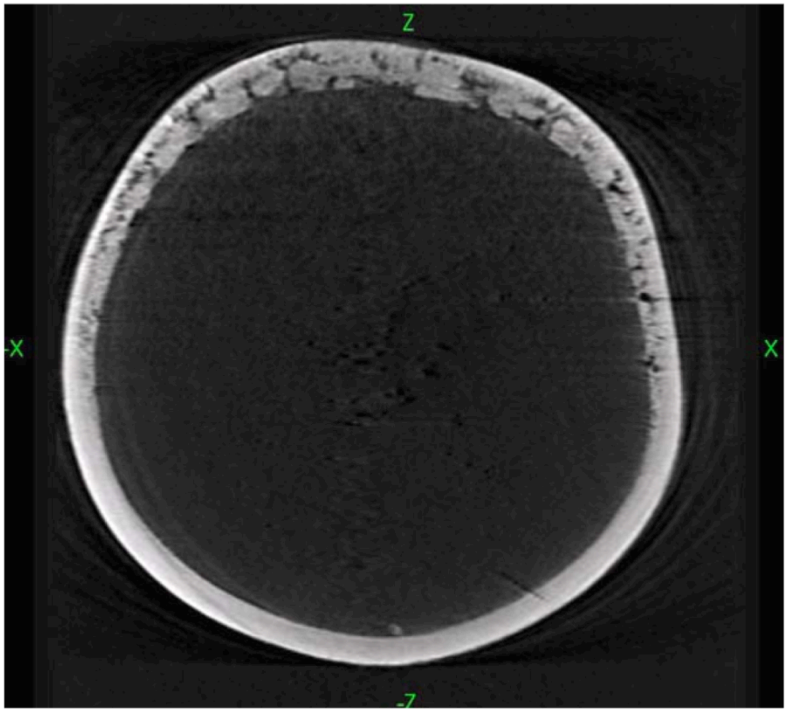




SiC Burn-Leach Defects

- **Particles are heated in air to burn off exposed carbon.**
- **Hot nitric acid dissolves kernels in particles with defective SiC.**
- **Performed before and after compacting.**
- **Low defect fractions require large QC samples**
  - $\leq 1 \times 10^{-4}$ defect fraction specified for AGR-1 particles consumed 120,000.
  - $\leq 1 \times 10^{-4}$ defect fraction specified for AGR-2 compacts consumed 100-180 compacts.

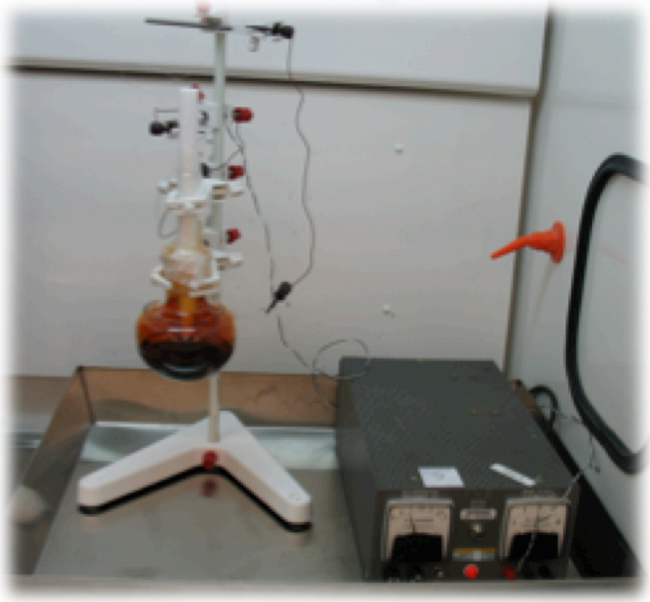
Example of a Burn-Leach SiC Defect



X-ray of Burn-Leach defect showing porous SiC
(the kernel has been completely removed leaving a hollow shell)

Compact Impurities

- **Particles are electrolytically deconsolidated from compacts in concentrated nitric acid and then heated to leach exposed uranium and other impurities**
- **Burn-leach of deconsolidated residue (particles and matrix) is then performed to determine SiC defect fraction and dissolve remaining impurities outside the SiC**



Other Compact Properties Measured

- **Diameter, length and weight measured on every compact**
- **Missing or broken OPyC looked for on particles deconsolidated from final compacts**
- **X-ray imaging used to look for excessive uranium dispersion that may be caused by high permeability in IPyC**
- **Uranium loading measured by dissolving in nitric acid**

Summary

- **TRISO fuel fabrication technology is not new**
  - HTGR fuel manufacturing has progressed over the last five decades and the key manufacturing process conditions and fuel properties have been identified
  - TRISO fuel manufacture has been demonstrated at various scales (Fort St. Vrain and THTR were done at near-production-scale)

Summary

- **The DOE-NE NGNP/AGR Fuel Development and Qualification Program has recently demonstrated excellent irradiation performance for UCO fuel fabricated at laboratory scale**
  - Coating and compacting process scale-up is currently in progress
  - An irradiation test scheduled to start in June will include separate capsules containing UCO and UO_2 fuel particles manufactured using pilot-scale equipment

Summary

- **Statistical sampling is used extensively in QC of TRISO particle fuel**
  - Specifications are met to a 95% minimum confidence level
  - Statistics often force the average fuel quality to significantly exceed specification limits
  - QC makes up a large fraction of the effort for laboratory-scale demonstrations, but this does not necessarily scale with the manufacturing yield

Summary

- **Dramatic advancements in the technology available for HTGR fuel characterization have occurred over the last two decades**
  - This has resulted in greater efficiency and precision in the QC analysis
  - With increased information has come better understanding of the relationships between the processes, properties, and performance

Suggested Reading

- J.D. Hunn, R.N. Morris, J.H. Miller, and R.D. Hunt, "Overview of Key Issues and Guidelines for Regulatory Oversight and Inspection of High Temperature Gas Reactor Fuel Fabrication and Quality Control Activities," ORNL/TM-2009/041, May 2009. NRC POC – Jonathan Barr, ADAMS Database #ML092380347&ML092330678, http://nrcknowledgecenter.nrc.gov/CommunityBrowser.aspx?id=13757