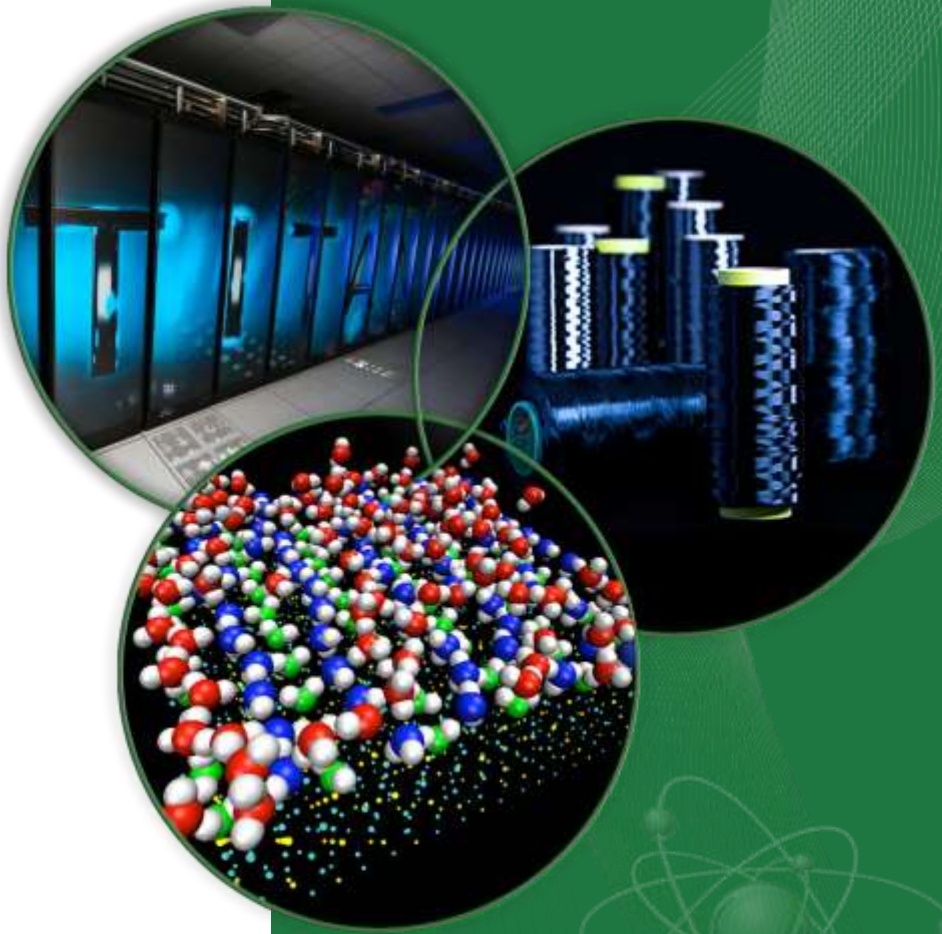
High-Temperature Reactor TRISO Particle Fuel Development in Support of Advanced Reactor Technologies

— ORNL Capabilities and Experience



Presented by John D. Hunn

February 10, 2015

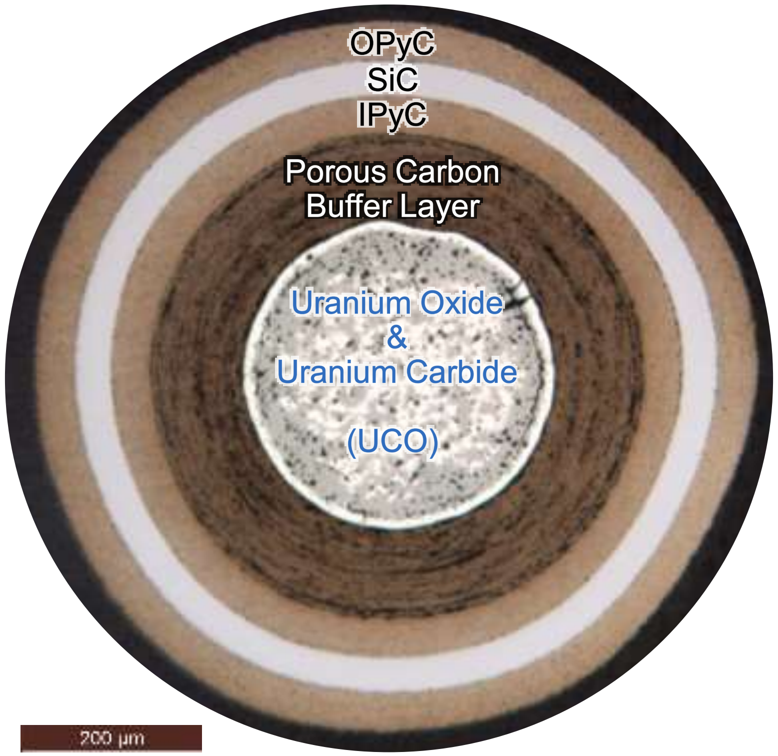
Advanced Reactors Technical Summit III

ORNL is managed by UT-Battelle
for the US Department of Energy

Oak Ridge National Laboratory

The Tristructural-Isotropic (TRISO) Coated Particle

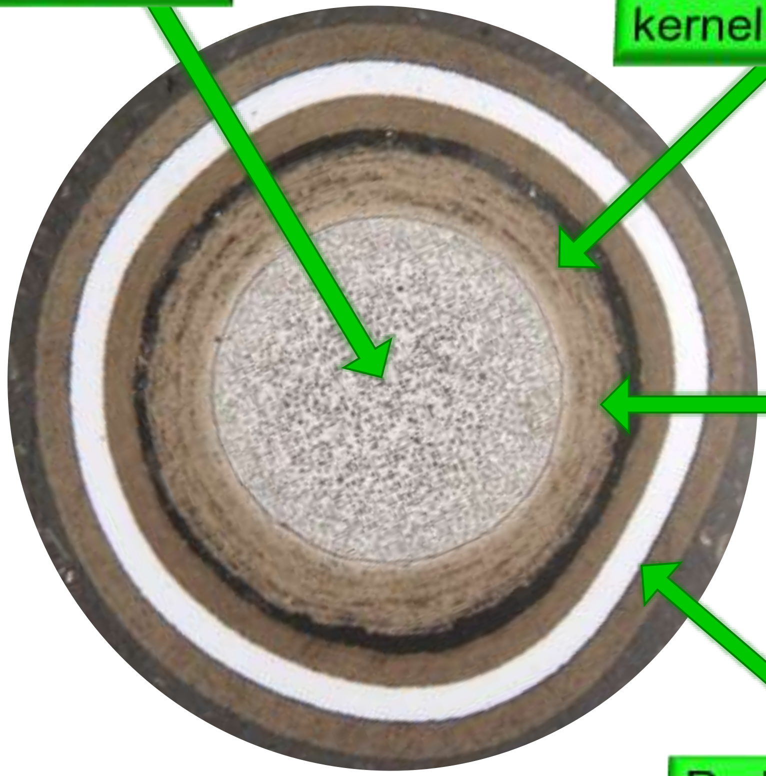
Typical TRISO Before Irradiation



Kernel depends on reactor design
- may contain uranium or other actinides
- may be an oxide, carbide, nitride, or combination for optimized performance (such as UCO)

Kernel retains most of the actinides and fission products

Buffer protects outer layers from fission recoil and accommodates kernel swelling and fission gases



Radiation-induced shrinkage of buffer

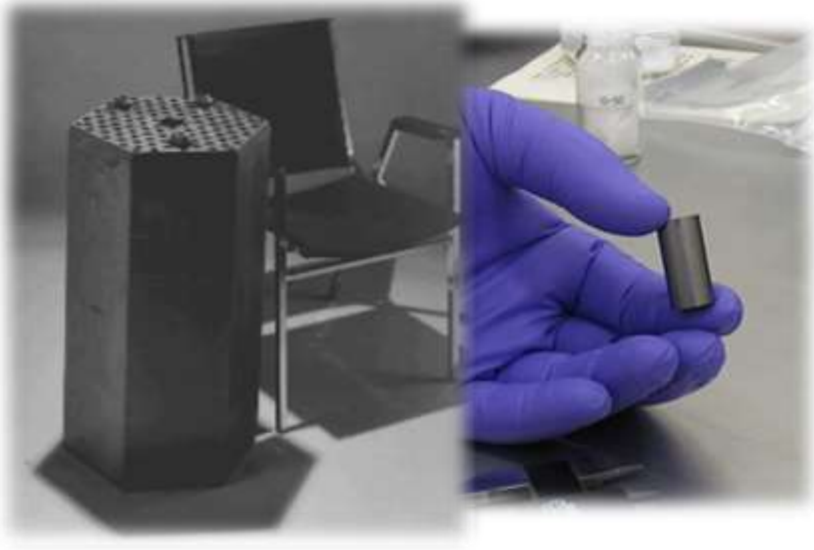
Typical TRISO After Irradiation

Radiation and thermal resistant pyrolytic carbon (PyC) and SiC retain most of the gaseous and metallic fission products that are emitted from the kernel

High-Temperature Gas-cooled Reactor (HTGR) Fuel Forms

- TRISO coated particles are embedded into a graphite matrix fuel form.
- Fuel forms vary with reactor design.
- TRISO particles are also being considered for other reactor types.

Cylindrical compacts for a prismatic block HTGR



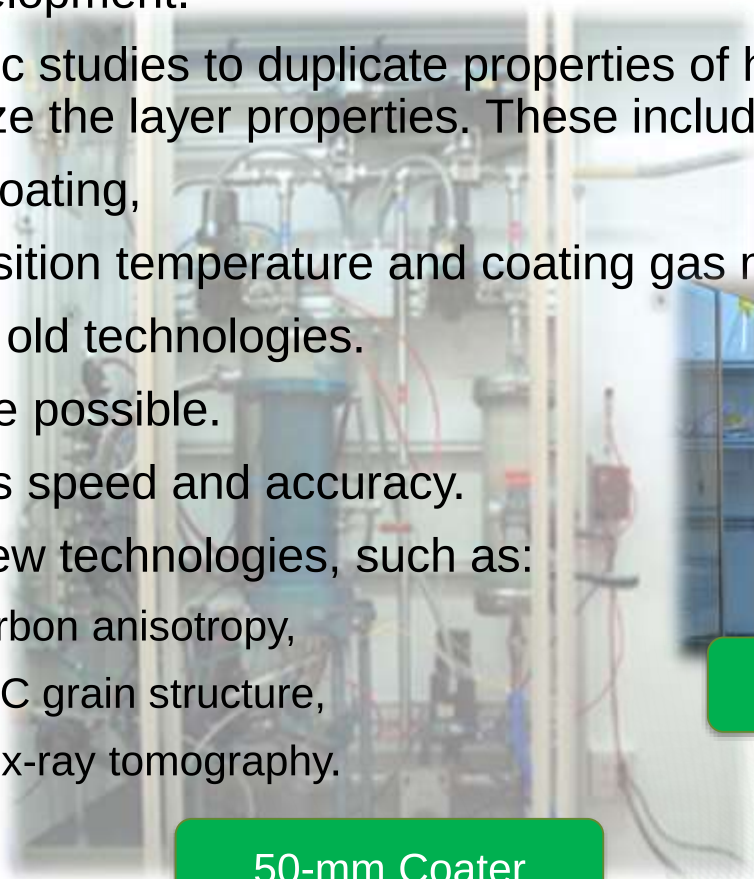
Spherical elements for a pebble bed HTGR

Recent History of ORNL Coated Particle Fuel Development

- ORNL has been involved in coated-particle fuel development since the late 50's and was a key contributor to the selection of the tri-structural isotropic (TRISO) coated-particle as the reference design for gas-cooled reactors.
- After a decade of inactivity, the US Department of Energy began a new concentrated research effort in 2002 under the Advanced Gas Reactor (AGR) Fuel Development and Qualification Program, currently managed by the Idaho National Laboratory (INL) Advanced Reactor Technologies Technology Development Office.
- Since 2002, ORNL has been working closely with INL and BWX-Technologies (BWXT) to optimize TRISO fuel fabrication and quality control processes and to establish a qualification dataset through irradiation and post-irradiation safety testing.
- ORNL installed a new radiological contamination-control laboratory for uranium-related research in 2002-2003, which houses most of the coating, compacting, and characterization capabilities for TRISO fuel, including:
  - a 50-mm-diameter fluidized bed chemical vapor deposition (FB-CVD) coater,
  - various equipment for overcoating and compacting,
  - a suite of characterization equipment.

Recent History of ORNL Coated Particle Fuel Development

- 2003–2004: Kernel fabrication, coating, and characterization procedures were developed using historical methods as a basis.
  - Lab-scale kernel fabrication supported early coating development.
  - Coating process development included various parametric studies to duplicate properties of historical high-performance German TRISO coatings and further optimize the layer properties. These included:
    - exploring the process/property space for pyrocarbon coating,
    - determining the dependence of SiC structure on deposition temperature and coating gas mixtures.
  - Characterization development involved a mix of new and old technologies.
    - Historical methods were surveyed and improved where possible.
    - Computer automation was applied to increase analysis speed and accuracy.
    - New methods were developed to take advantage of new technologies, such as:
      - applying advanced optical ellipsometry to measure pyrocarbon anisotropy,
      - utilizing back-scattered electron imaging to characterize SiC grain structure,
      - analyzing internal TRISO structure with three-dimensional x-ray tomography.



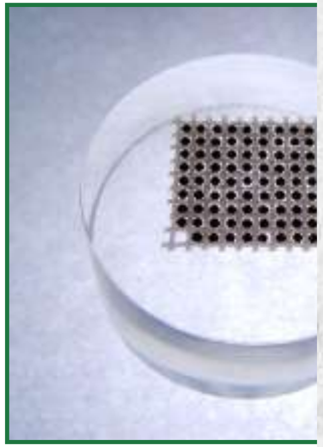
50-mm Coater

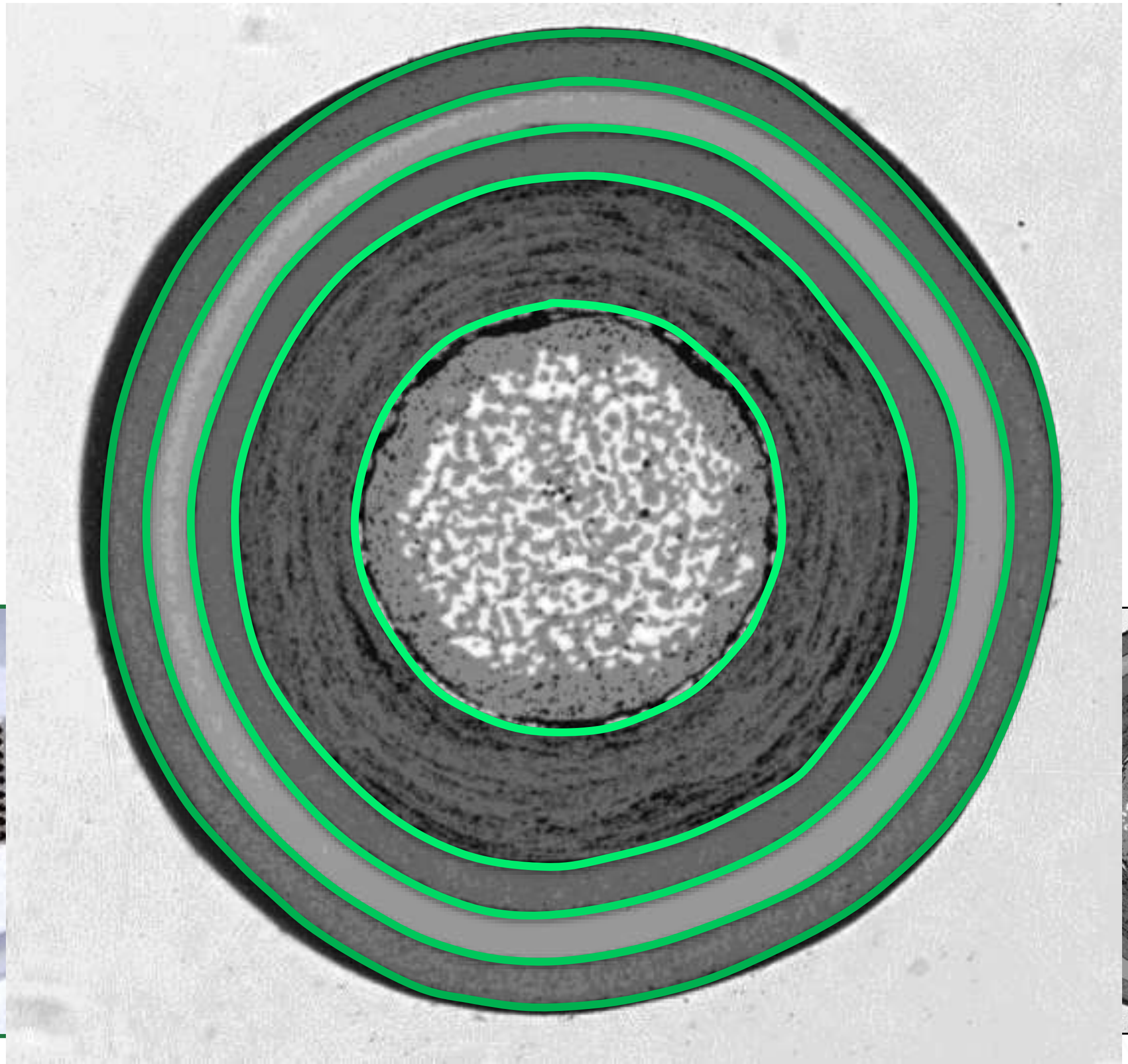
Measuring Coating Temperature

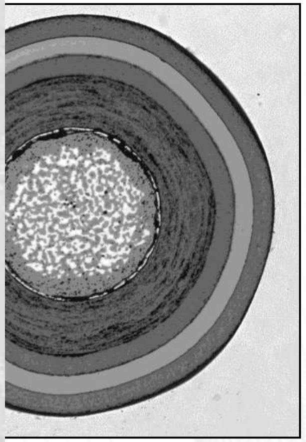
TRISO Fuel Characterization at ORNL — Materialography

Rotary polisher in hood

Electron Microscopy





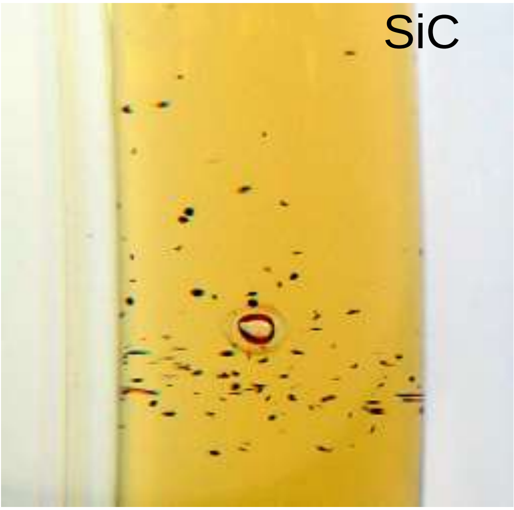


Automated Microscopy and Image Analysis

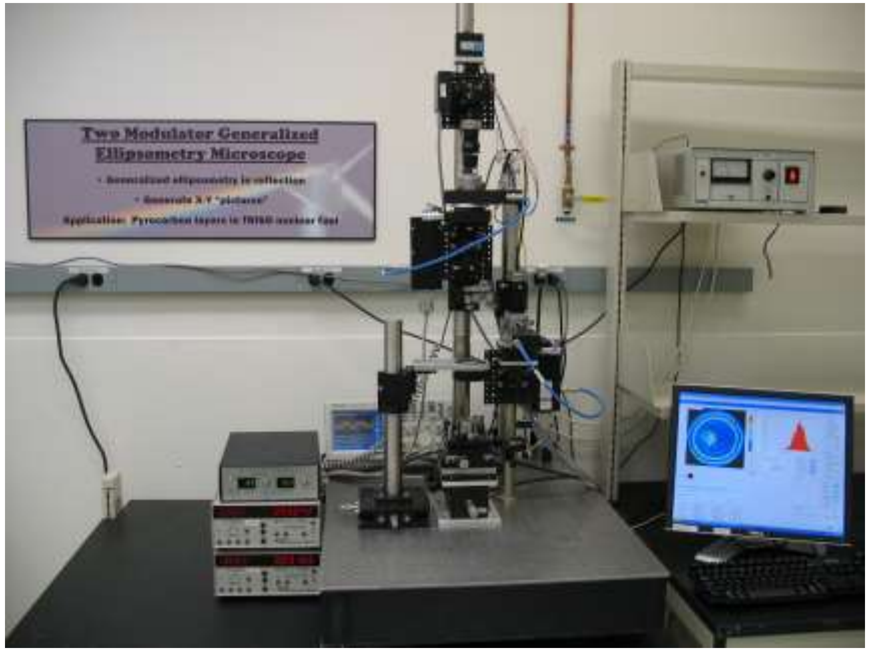
TRISO Fuel Characterization at ORNL — Layer Density and Porosity

Mercury Porosimetry to measure kernel and buffer density and pyrocarbon open porosity

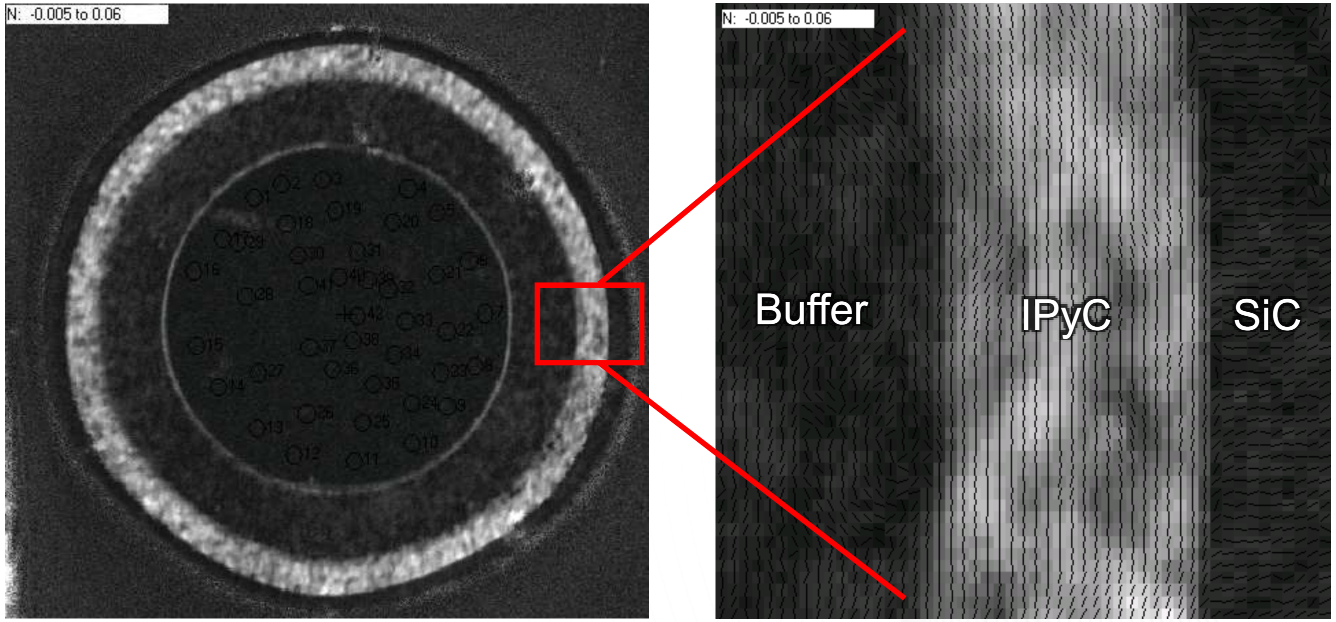
Liquid Gradient-Density Column for IPyC, SiC, OPyC density



TRISO Fuel Characterization at ORNL — Pyrocarbon Anisotropy



Two-Modulator Generalized Ellipsometry Microscope (2-MGEM)



Ellipsometry compared to traditional Polarimetry

More accurate: measures the entire Mueller matrix

More sensitive: 10 times higher resolution of diattenuation

More robust: non-specular reflection doesn't affect accuracy

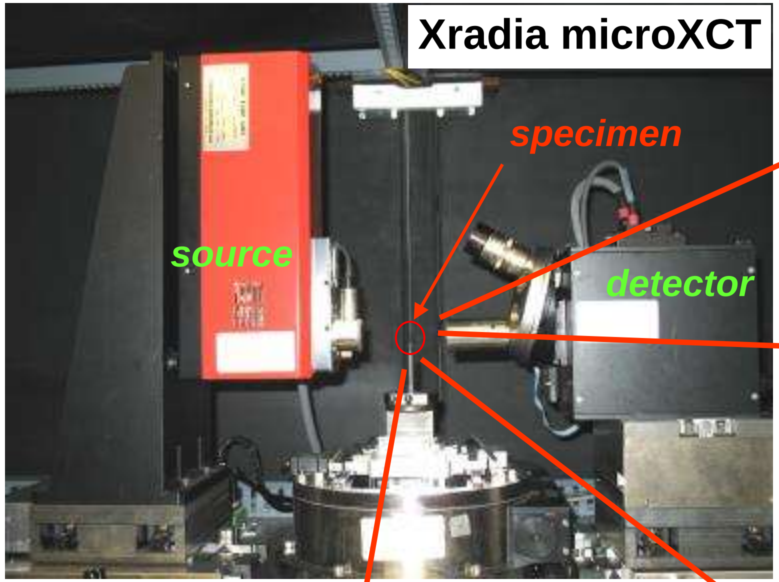
More complete: measures 10,000+ points across the surface

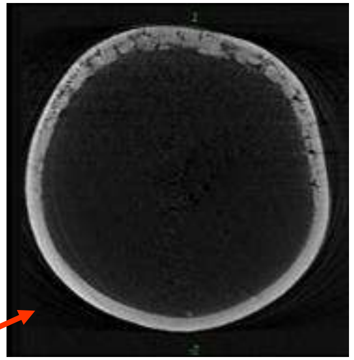
Up to 2 μm spatial resolution imaging of pyrocarbon anisotropy

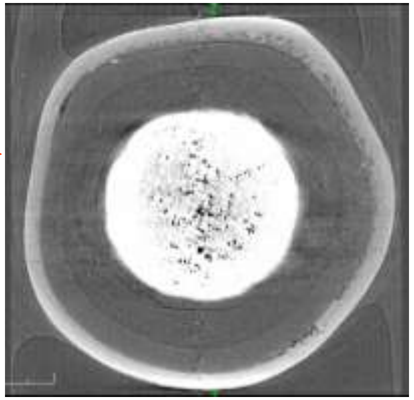
OAK RIDGE National Laboratory

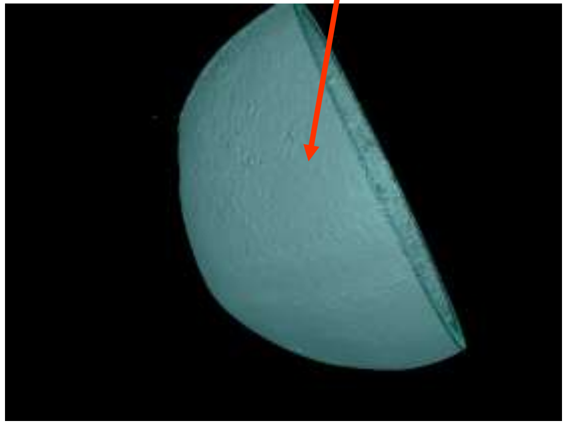
TRISO Fuel Characterization at ORNL — Defect Analysis

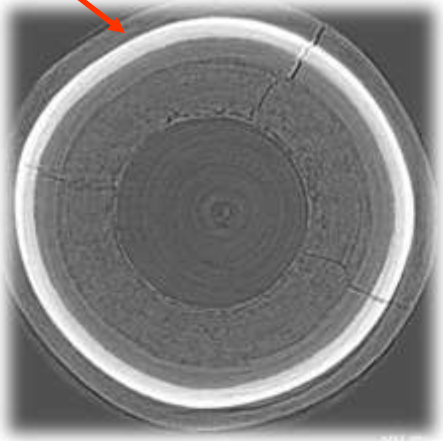
X-ray Tomography for three-dimensional analysis of TRISO particle defects



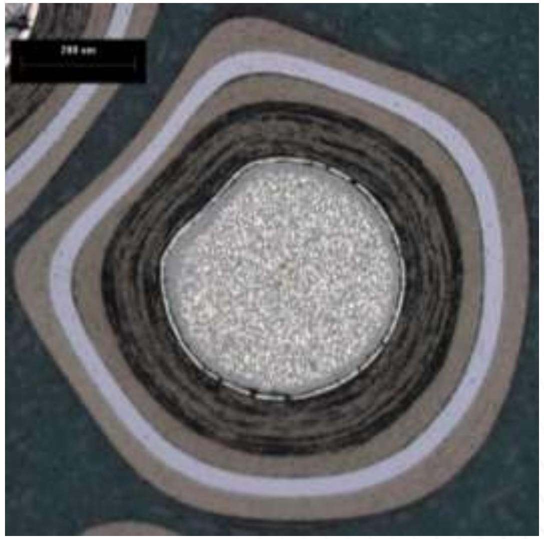








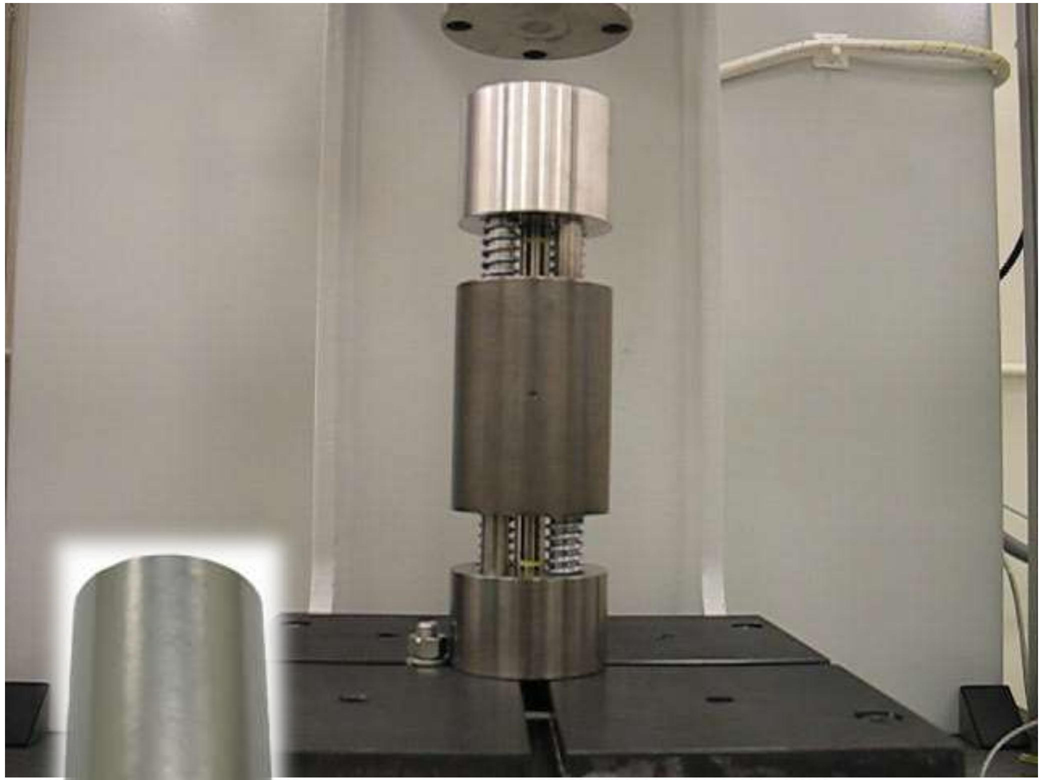
Acid Leaching to detect coating defects



Materialography

Recent History of ORNL Coated Particle Fuel Development

- 2004–2005: Compacting and characterization procedures were developed using historical methods as a basis.
  - Overcoating process development included:
    - survey and selection of resin and graphite candidates,
    - qualification of resin and graphite materials,
    - new method for applying a resinated-graphite overcoat on the TRISO particles (centrifugal overcoating).
  - Compacting process development included:
    - optimiziation of the compacting pressure and schdule,
    - study of carbonization-induced shrinkage and weight loss in the matrix material,
    - interations in the compacting die design (dual-acting die),
    - introducton of an automated servo-mechanical press for improved process control.



OAK RIDGE National Laboratory

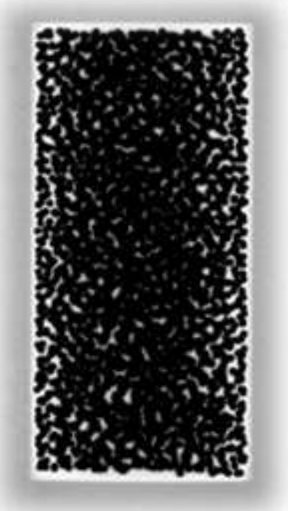
Coated Particle Fuel Fabrication and Testing — AGR-1

- AGR-1 irradiation test — early performance test of fuel design and irradiation capsule shakedown
  - Lab-scale coated particles and compacts fabricated at ORNL (2005-2006)
    - 350 µm diameter UCO kernels, 19.7% enriched provided by BWXT
    - ½” diameter, 1” long compacts
    - four coating variants
  - Compacts irradiated (2006-2009) at INL
    - 620 effective full-power days
    - burn-up: 11.2 - 19.6% FIMA (fissions per initial metal atom)
    - average temperatures: 955 - 1136°C
    - 72 compacts in test, ~300,000 particles
    - no indication of TRISO coating failure during irradiation
  - Post-irradiation examination (PIE) and safety testing at ORNL and INL (2010-2015)
    - fuel compact, matrix, and particle irradiation performance examined
    - emphasis on fission product retention behavior
    - compacts heated at 1600, 1700, and 1800°C to test safety margin

AGR-1 Baseline
UCO Fuel
X-ray Radiograph

Coated Particle Fuel Fabrication and Testing — AGR-2

- AGR-2 irradiation test — initial performance test of fuel from larger BWXT coater
  - Engineering–scale TRISO from BWXT was overcoated and compacted at ORNL (2009-2010)
    - 425 µm diameter UCO, 14% enriched
    - 500 µm diameter UO_2, 9.6% enriched
    - ½” diameter, 1” long compacts
  - Compacts irradiated (2010-2013) at INL
    - 559 effective full-power days
    - burn-up: ~15% peak FIMA
    - 36 UCO compacts, 12 NGNP UO_2 compacts
    - 12 PBMR fuel compacts, 12 CEA fuel compacts
  - PIE and safety testing began in 2014



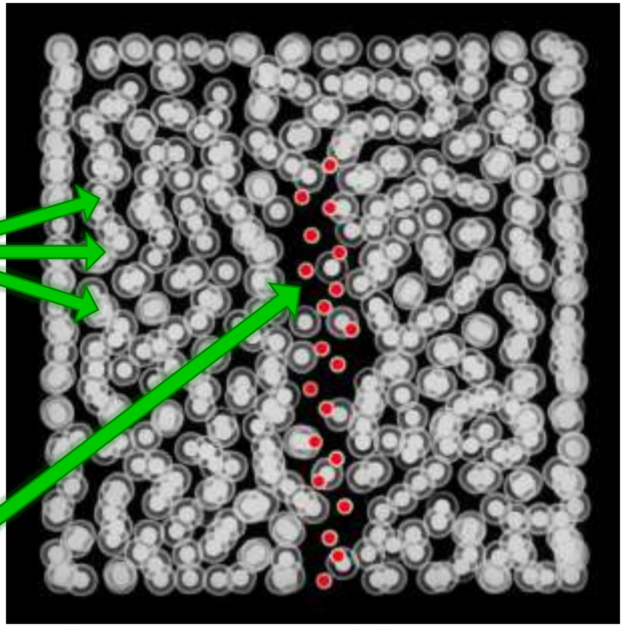
AGR-2 UCO Fuel X-ray Radiograph

AGR-2 UO_2 Fuel X-ray Radiograph

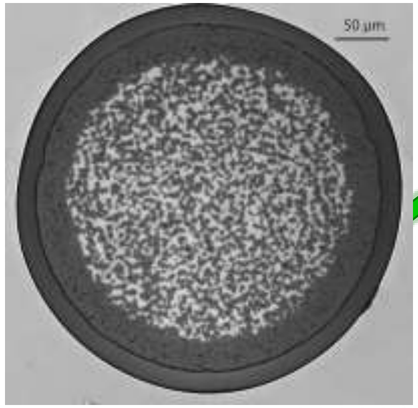
Coated Particle Fuel Fabrication and Testing — AGR-3/4

- AGR-3/4 irradiation test — study fission product transport through matrix and structural graphite
  - Coated particles and compacts fabricated at ORNL (2006, 2010-2011)
    - 350 µm diameter UCO kernels, 19.7% enriched provided by BWXT
    - ½" diameter, ½" long compacts
    - 20 designed-to-fail (DTF) particles in each compact
  - Compacts irradiated (2011-2014) at INL
    - 369 effective full-power days
    - burn-up: ~15.3% peak FIMA
    - 48 DTF compacts in 12 specialized capsules
    - DTF particles failed as designed
  - PIE and safety testing began in 2015

TRISO Driver Fuel



AGR-3/4 UCO Fuel Section X-ray Radiograph



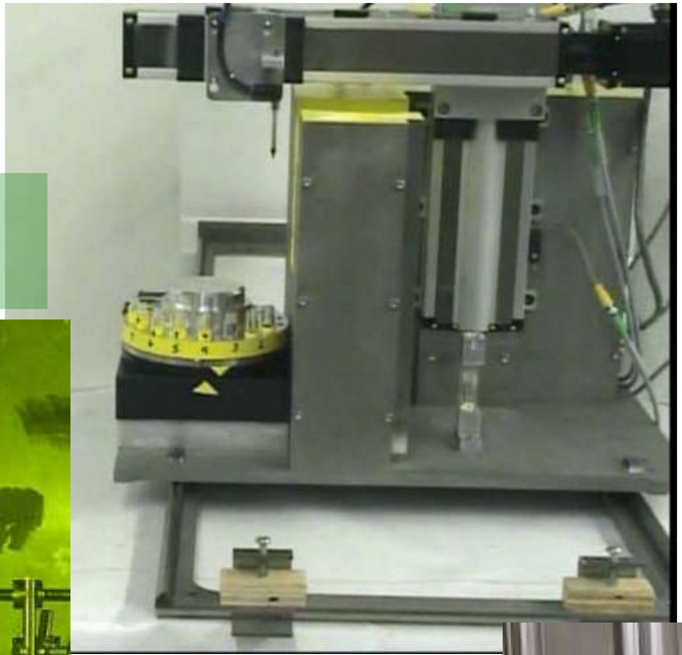
DTF Particle Cross Section Optical Micrograph

Post-irradiation examination at ORNL

- Post-irradiation examination procedures were developed using historical methods as a basis in 2009-2010
  - Upgraded Core Conduction Cooldown Test Facility (CCCTF)
    - airlock for hot swapping deposition cups
    - cold-finger redesigned
    - automated mass flow controllers for sweep gas
  - Redesigned Irradiated Microsphere Gamma Analyzer (IMGA)
  - Installed new grinding and polishing equipment
  - Installed remote digital optical microscope
  - Added energy-dispersive and wavelength-dispersive spectroscopy systems (EDS/WDS) to scanning-electron microscope (SEM)
  - Designed Soxhlet extraction system for leach-burn-leach (LBL)

Post-irradiation examination at ORNL

Deconsolidation and Acid Leaching



IMGA

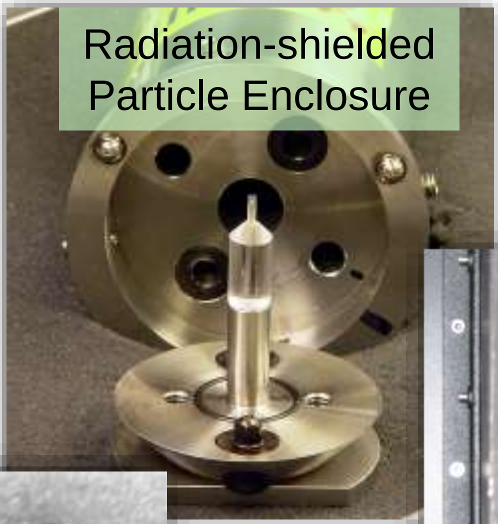
Materialography

SEM with Elemental Analysis

Safety Testing

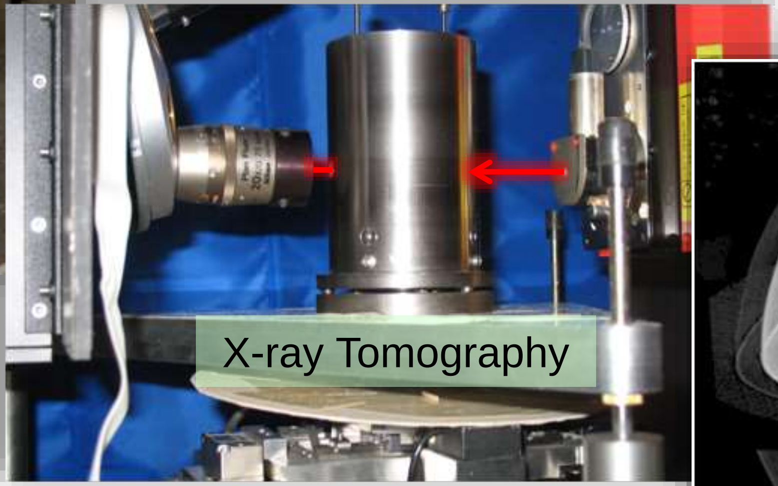
X-ray Tomography of Irradiated Particles

X-ray tomography provides nondestructive three-dimensional (3D) visualization of the coating layers and interfaces

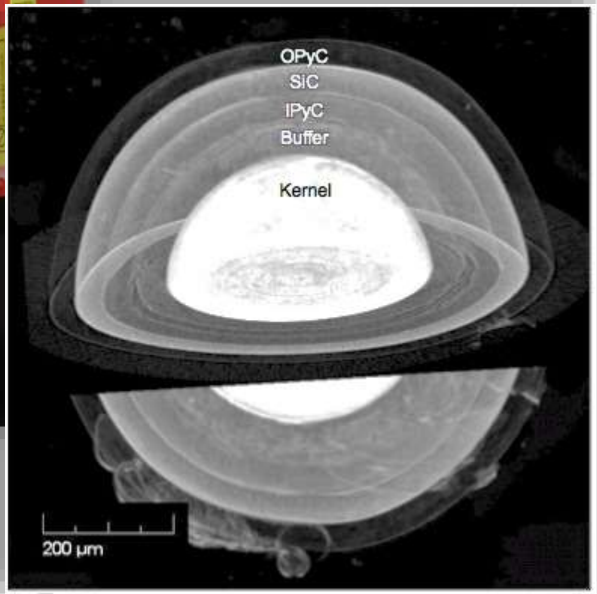


Radiation-shielded Particle Enclosure

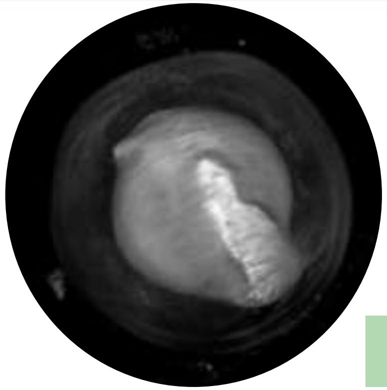
Particle encapsulated in epoxy



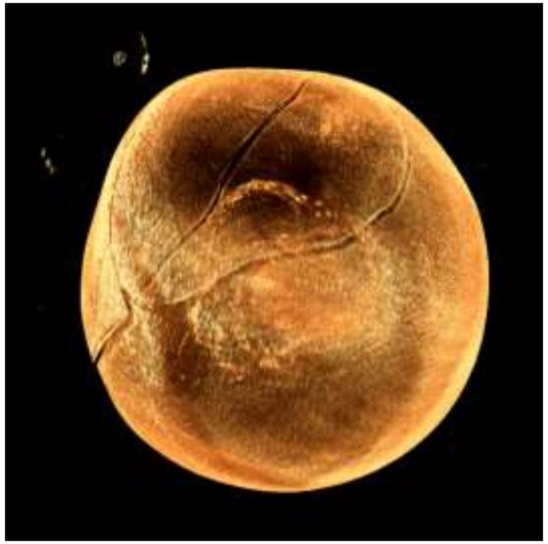
X-ray Tomography



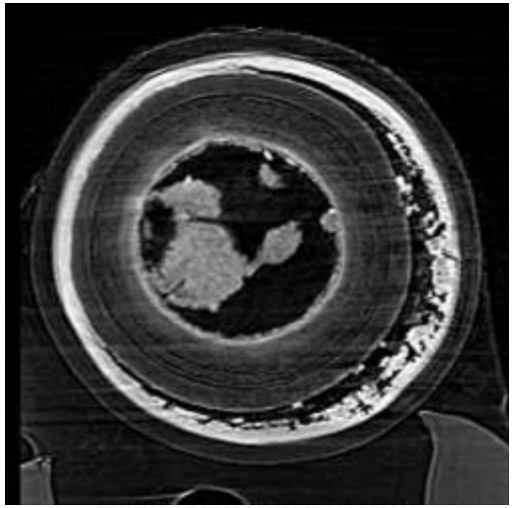
Typical Particle



Kernel Swelling



Failed-TRISO

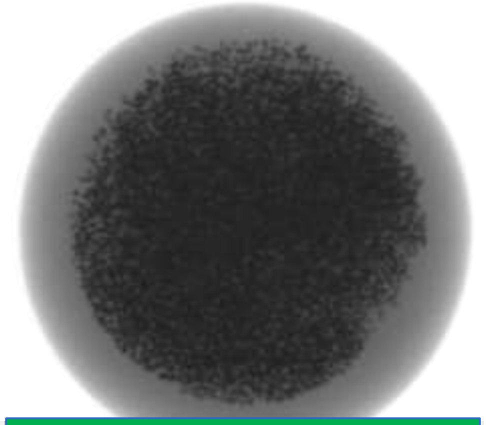


SiC Defect

Current and Upcoming TRISO Fuel Development Activities

- AGR-2 PIE will continue, including safety testing at 1600–1800°C to further study and document TRISO fuel performance and fission product retention under normal operating and accident conditions.
- AGR-3/4 PIE will continue (mostly at INL) to obtain data on fission product transport.
- AGR-5/6/7 irradiation test fuel will be fabricated at BWXT and irradiated in the INL Advanced Test Reactor, followed by PIE at both INL and ORNL, to test the fuel performance under normal operating temperatures (and beyond) and generate data to support plant design and licensing.
- ORNL will partner with X-energy to develop US fabrication and characterization processes and capabilities for the HTGR pebble fuel form.

Rubber Molds for Pebble Pressing



Radiograph of TRISO Particle Distribution

Machined Fuel Spheres

Thank you for your attention

John Hunn

hunnjd@ornl.gov

Work sponsored by
US Department of Energy
Office of Nuclear Energy

Advanced Reactor Technologies