Advanced Gas Reactor TRISO Fuel Development and Qualification Program Overview

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DOE-NE Crosscut Coordination Meeting

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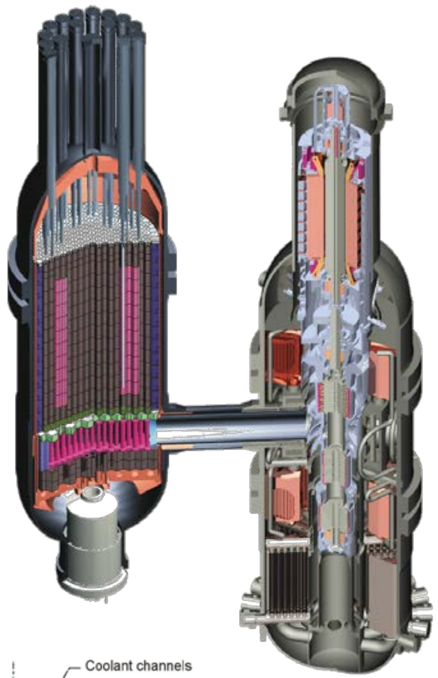
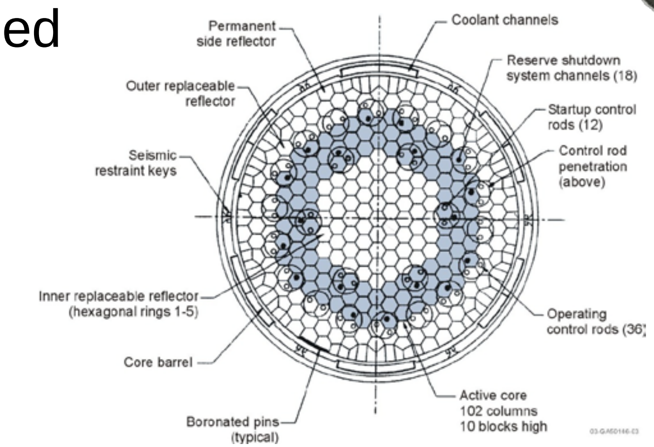
High Temperature Gas Cooled Reactor (HTGR)

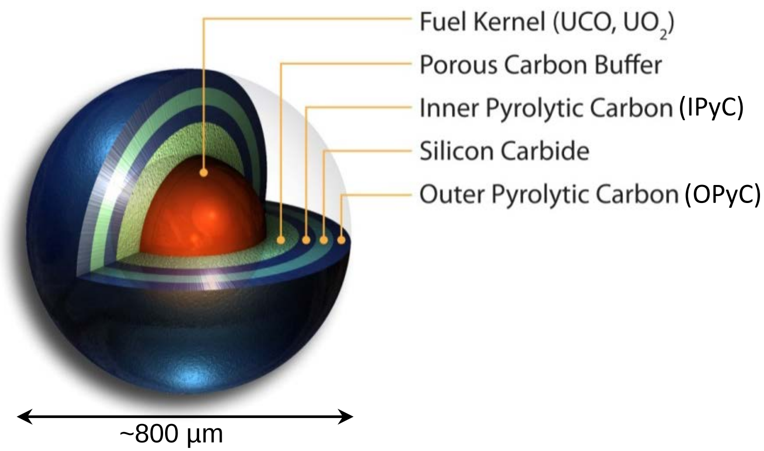
- Helium coolant
- Coated particle fuel
- Outlet temperature 750-950°C
- Production of electricity and high temperature process heat for industrial applications
- Passive safety characteristics
- High thermal efficiency
- HTGRs have numerous advantages, but a commercial scale demonstration is needed

- Fuels program: Develop and qualify coated particle fuel to support licensing of a HTGR





Tristructural isotropic (TRISO) Fuel



Tristructural isotropic (TRISO) particle

AGR fuel compact

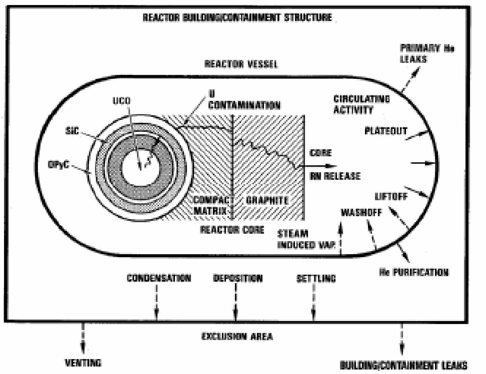
- TRISO fuel is at the heart of the safety case for modular high temperature gas-cooled reactors
- Key component of the "functional containment" licensing strategy
  - Radionuclides are retained within multiple barriers, with emphasis on retention at their source in the fuel

High-quality, low-defect fuel fabrication

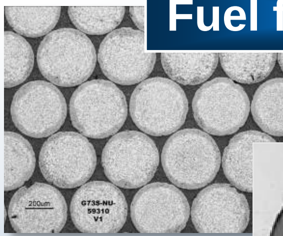
Robust performance during irradiation and during high-temperature reactor transients

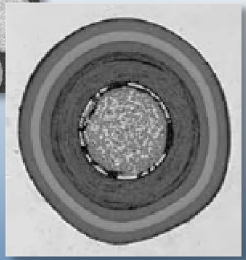
Low fission product release

Advanced Gas Reactor Fuel Development and Qualification Program Elements

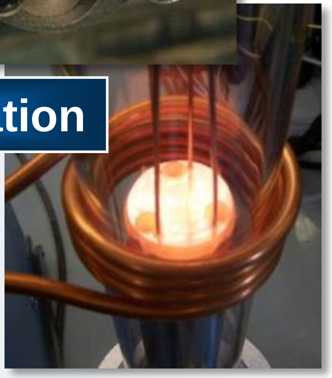


Fission product transport & source term



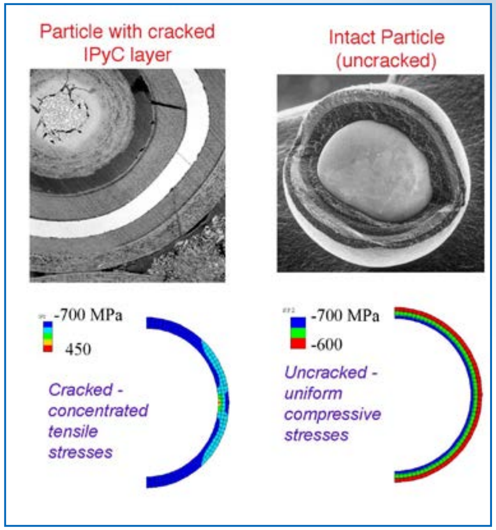


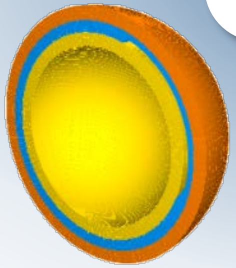
Fuel fabrication



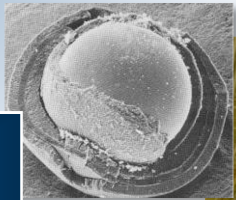
Fuel irradiation

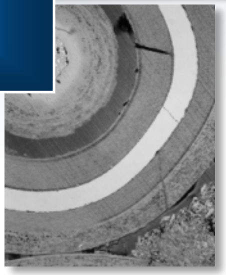
Program participants:
INL, ORNL, BWXT, GA

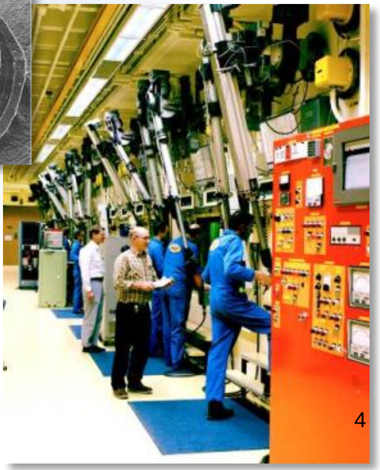




Fuel performance modeling

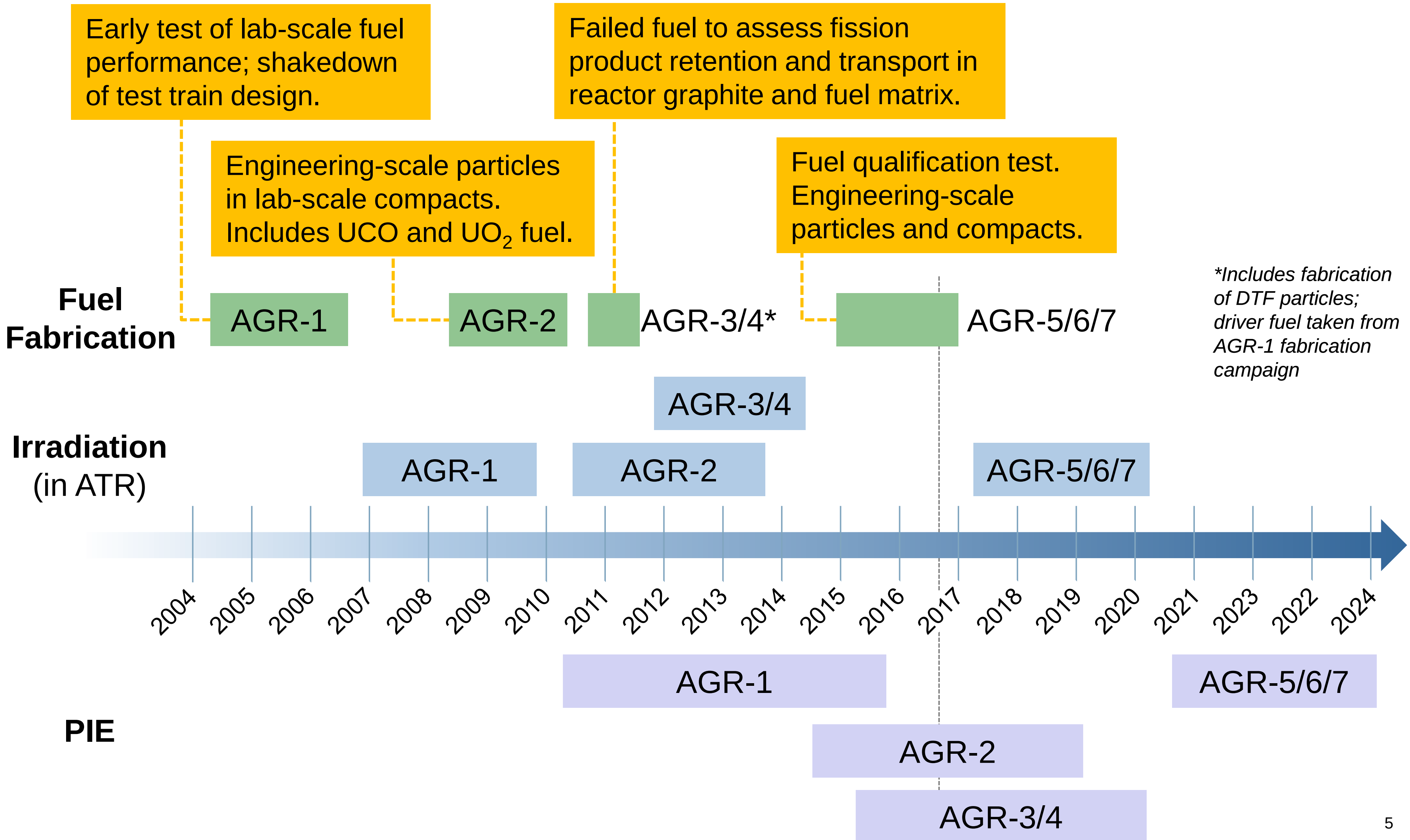






PIE and safety testing

AGR Program Timeline



Key Fuel Fabrication Accomplishments

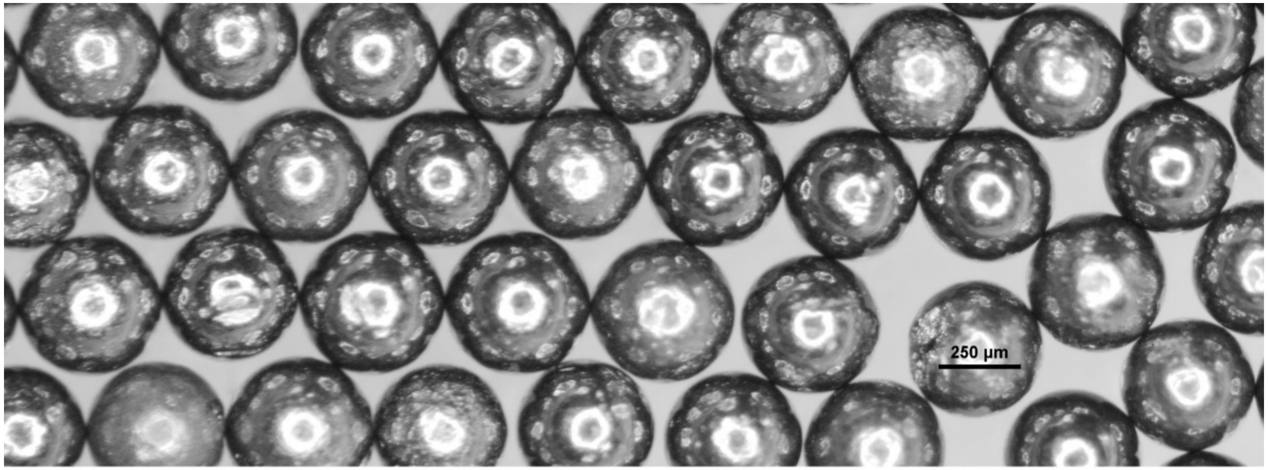
	Kernels	Coatings	Compacts
AGR-1	Engineering scale	Lab Scale	Lab Scale
AGR-2	Engineering Scale	Engineering scale	Lab Scale
AGR-5/6/7	Engineering Scale	Engineering Scale	Engineering Scale

Completed

- Re-established TRISO fabrication and characterization capabilities in the US after ~15 year hiatus
- Significantly improved fuel quality, reproducibility, process control, and characterization capabilities for TRISO fuel
- Established TRISO fuel fabrication capability at domestic industrial vendor (BWXT, Lynchburg, VA)
- Fabricating high-quality, low-defect ($<10^{-5}$) TRISO fuel at industrial scale, meeting all physical specifications
- AGR-5/6/7 fuel fabrication is currently in progress

FY16 Progress: Fuel Fabrication

- Completed fabrication and certification of LEUCO kernels for AGR-5/6/7 with a low fissure fraction
  - Certified “Phase I” kernel lot (19 kg, J52R-16-69317)
  - Certification of “Phase II” kernel lot (5 kg, J52R-16-69318) is in progress



J52R-16-69317 Analysis Sample #6

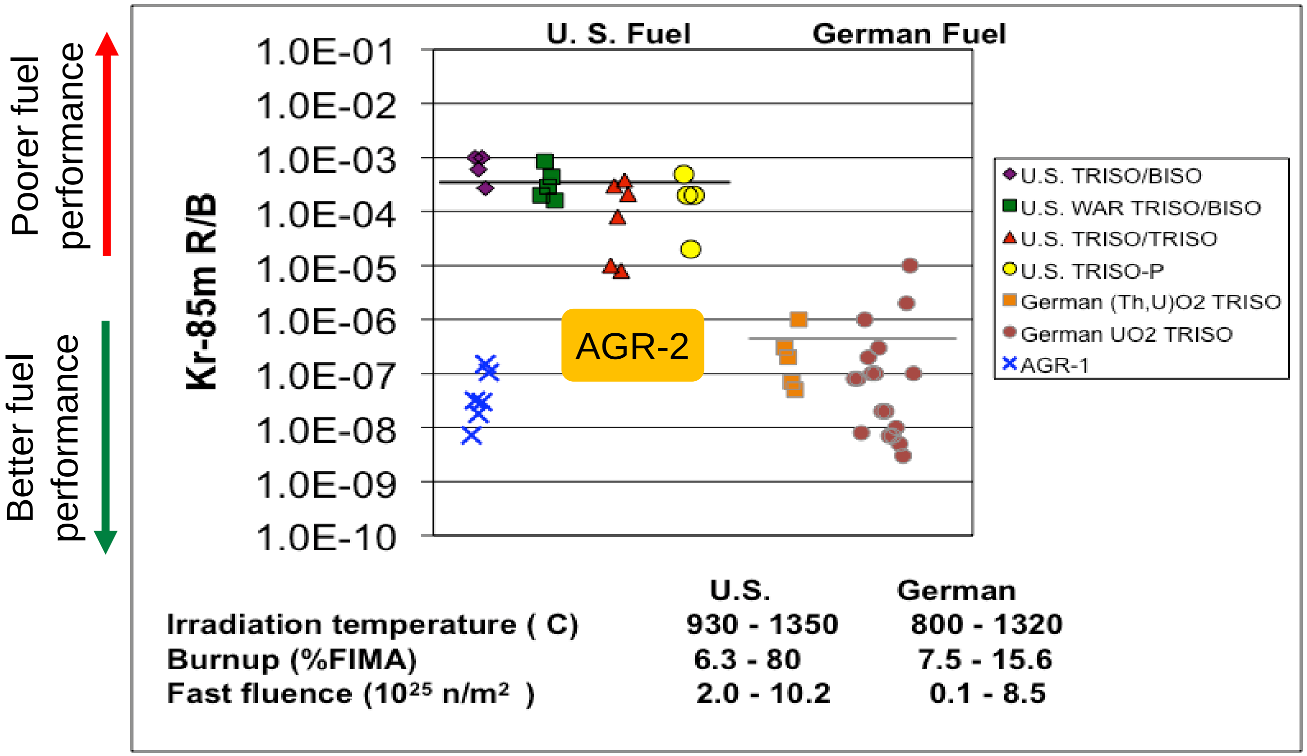
- Restored functionality of the TRISO coating furnace and operator expertise
- Completed four development coating runs and adjusting parameters to meet fuel specifications

FY16 Progress: Fuel Fabrication (cont'd)

- Developed flow sheets parameters and demonstrated overcoating TRISO particles for compacts with nominal 25% and 10% packing fraction
- Refined compacting and thermal treatment parameters
- Pressed nearly 600 compacts at 40% PF using the refined parameters

AGR Fuel Irradiation Performance

German fuel has historically demonstrated ~1,000 times better performance than U.S. fuel.



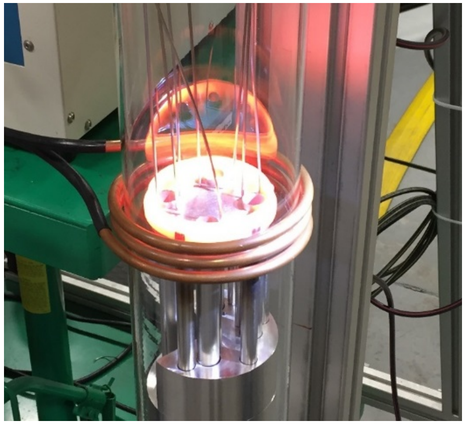
Plot of Kr-85m release-to-birth ratio for various fuel types

AGR-1:
- Zero TRISO failures out of ~300,000 particles in the experiment
- Peak burnup ~20% FIMA

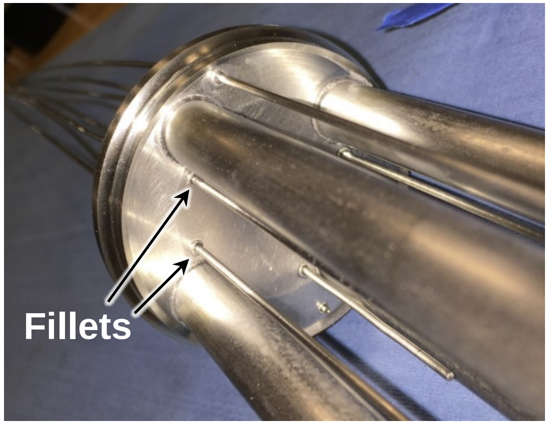
Today, in-reactor AGR TRISO fuel performance is as good as German fuel at twice the burnup

FY-16 Irradiation Accomplishments

- Completed AGR-5/6/7 Final Design Review
- Completed 95% of AGR-5/6/7 machine shop fabrication
- AGR-5/6/7 Capsule Heads
  - Practiced brazing methodology on dummy capsule heads
  - Completed actual brazing on 2 of 5 capsule heads
- AGR-5/6/7 Supplemental Instrumentation
  - Procured instruments/fabricated cabinet



Brazing Process

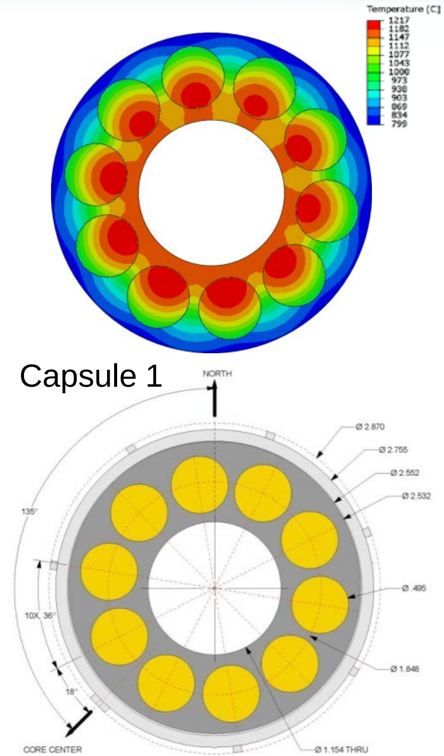


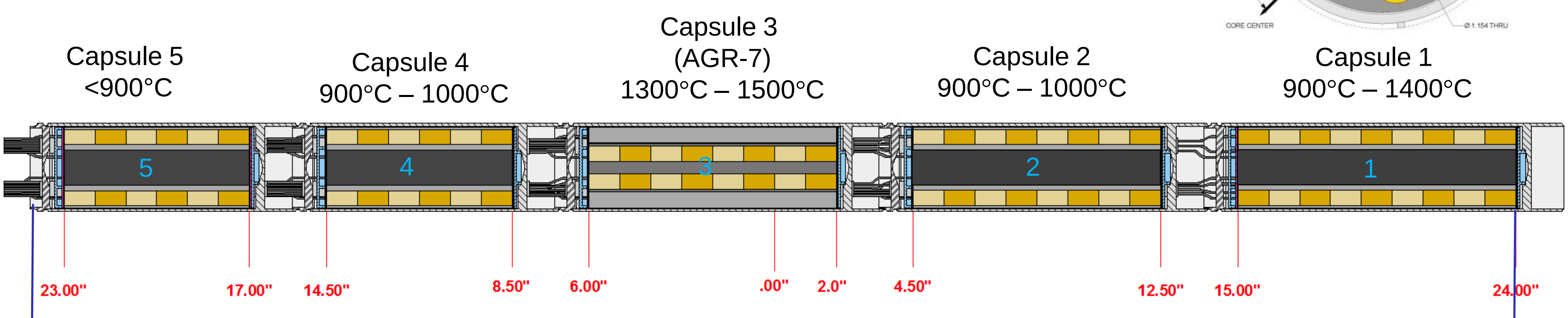
Brazing Completed

Supplemental Instrumentation Cabinet

AGR-5/6/7 Irradiation

- AGR-5/6/7 irradiation capsule design
  - 194 UCO fuel compacts (~575,000 particles)
  - Fuel temperatures ~600 to 1500°C
  - Burnup 8.0 to 18.6% FIMA
  - Irradiation to begin August 2017

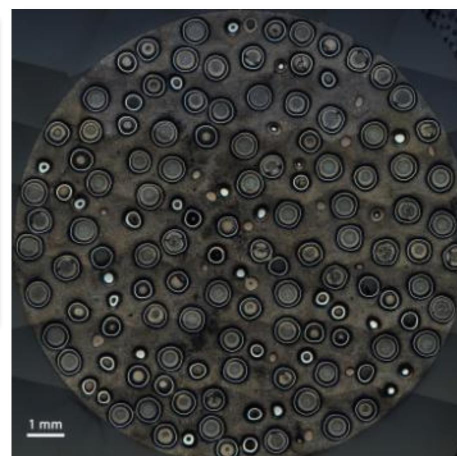




AGR-5/6/7 test train axial cross section

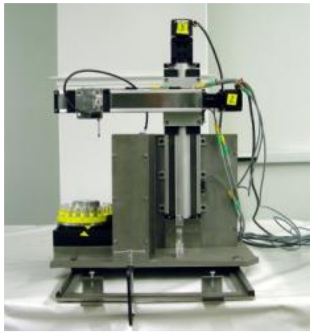
Post-Irradiation Examination (PIE) and Safety Testing of TRISO Fuel

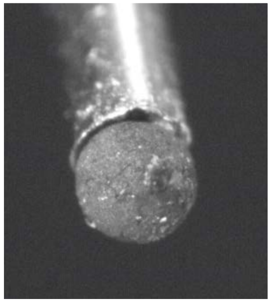
- **Examine fuel performance:**
  - Fission product retention:
    - during irradiation
    - during high temperature accident scenarios (safety testing)
  - Fuel kernel and coating microstructure evolution and causes of coating failures

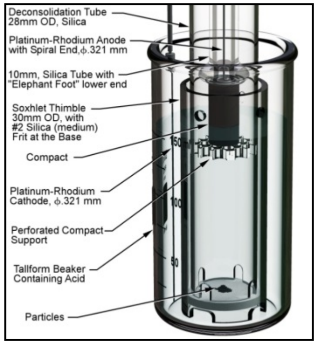


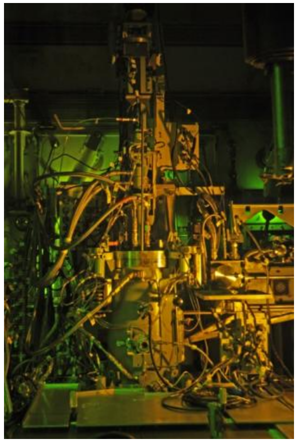
Key AGR PIE Accomplishments and Results

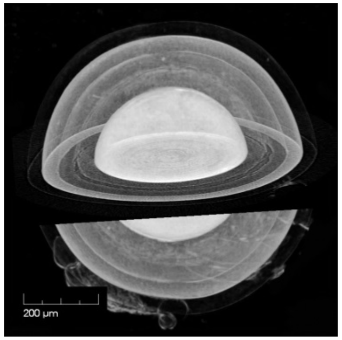
- Re-established coated particle fuel PIE and safety testing capabilities at both INL and Oak Ridge National Laboratory
- Developed numerous new tools and approaches for analyzing irradiated particle fuel
- AGR-1 PIE is complete and demonstrated excellent fuel performance
  - Low fission product release (particularly Cs-137, Sr-90) in-reactor and at temperatures up to 1800°C
  - In-reactor coating failures are very limited (0 failed TRISO, 4 failed SiC out of 300,000 particles)
- Advanced PIE methods are enabling an unprecedented level of understanding of coated particle fuel behavior



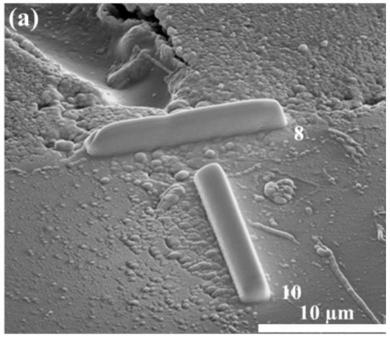




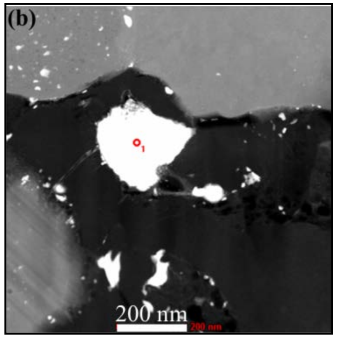




Three dimensional reconstruction of intact irradiated particle



Preparation for extract FIB lamella from irradiated SiC layer on TRISO particle



TEM micrograph showing fission product inclusion in the SiC layer of an irradiated TRISO particle

Studying failed particles greatly improves ability to characterize and understand fuel performance

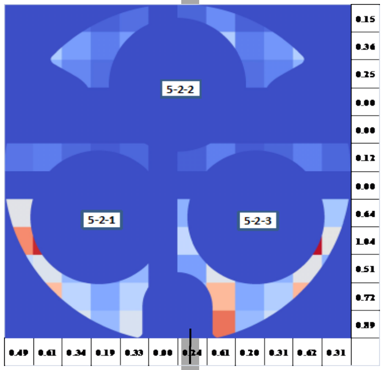
72 fuel compacts containing 300,000 particles in AGR-1 irradiation

Fuel Compacts

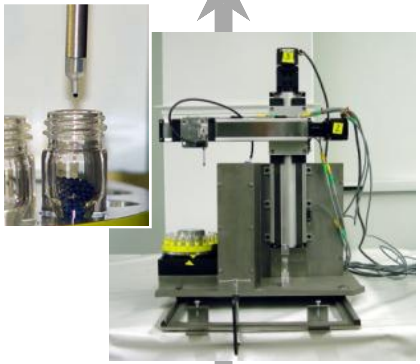
Plenum between Capsules

AGR-1 Test Train Vertical Section

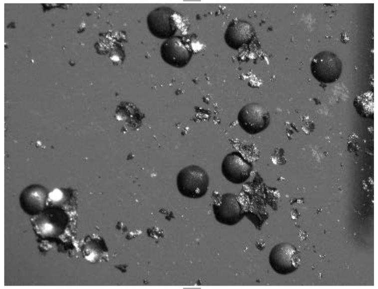
Capsule disassembly



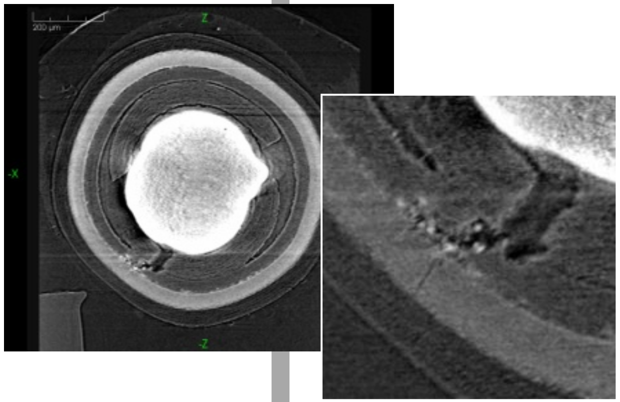
Gamma scan to identify cesium hot spots and compact location



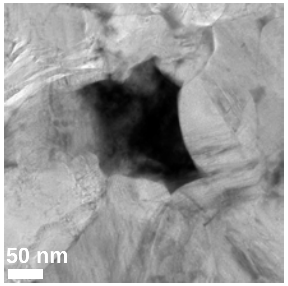
IMGA to find particles with low cesium retention



Deconsolidation to obtain ~4,000 particles from compact

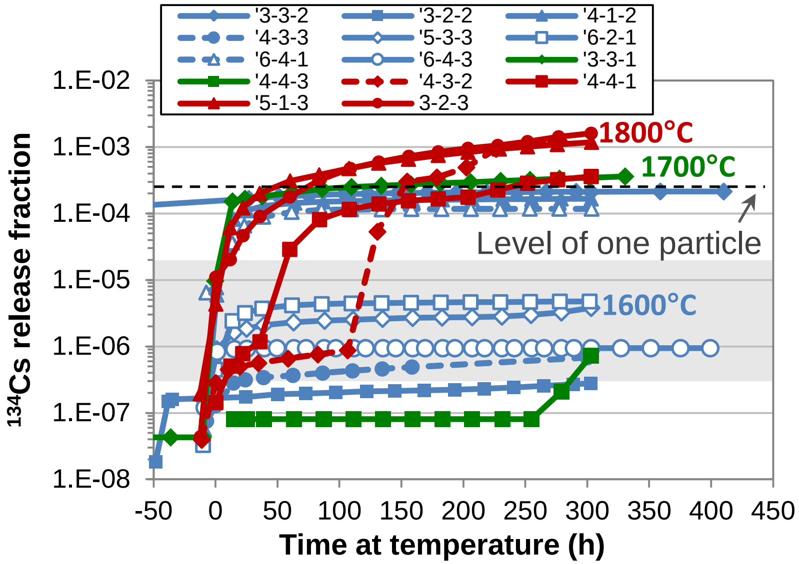


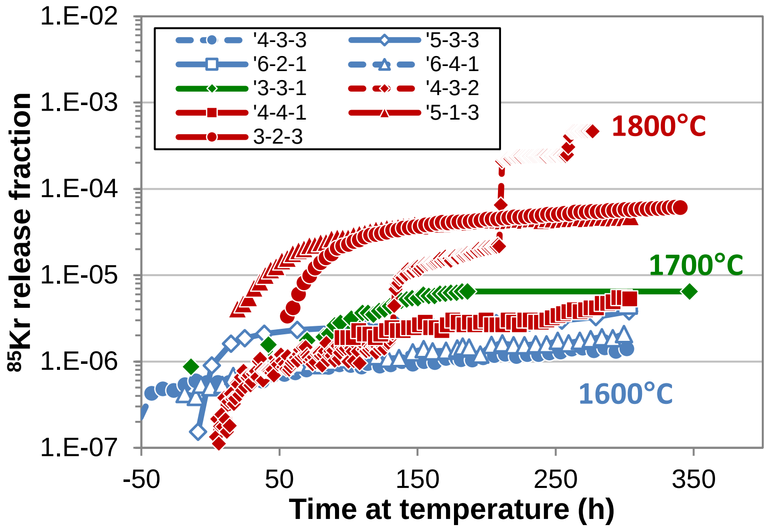
X-ray tomography to nondestructively locate defects/fractures



Advanced microscopy to study microstructure in detail

AGR-1 Safety Testing Results Highlights

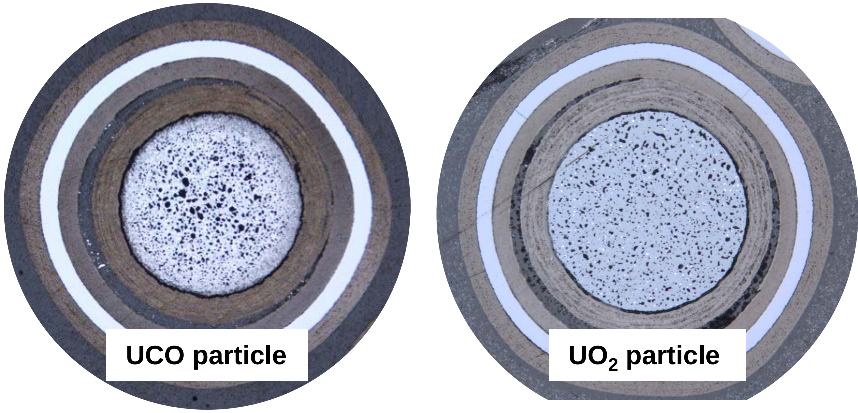




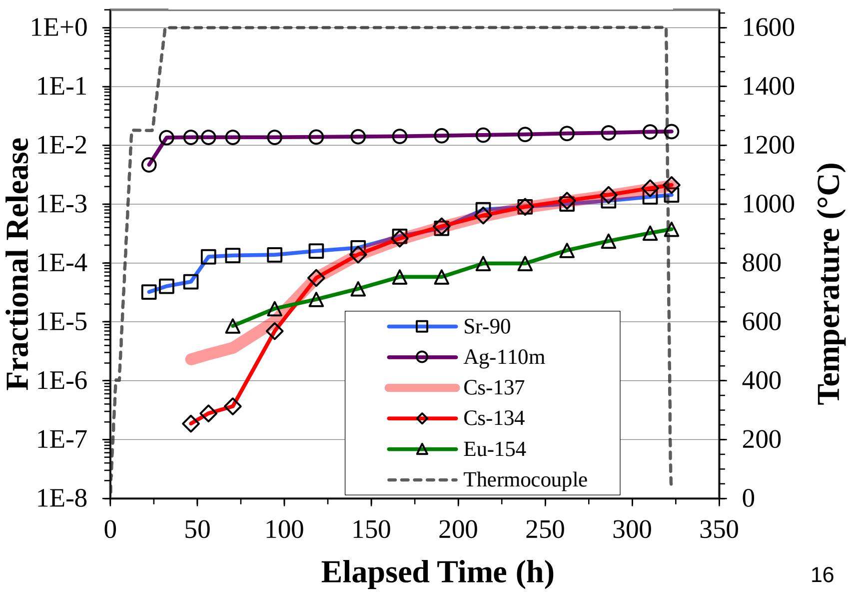
- Fuel compacts were heated to 1600 – 1800°C for 300 h while measuring release of fission products
- No TRISO failures at 1600 and 1700°C; only two failures in a single compact at 1800°C
- Cs release used as indication of SiC layer failure; fuel compacts with SiC failures processed to identify failed particles and characterize the coatings
- Specific mechanism of SiC failure was identified (IPyC failure followed by Pd attack of SiC)
- High temperature fuel performance generally considered very good

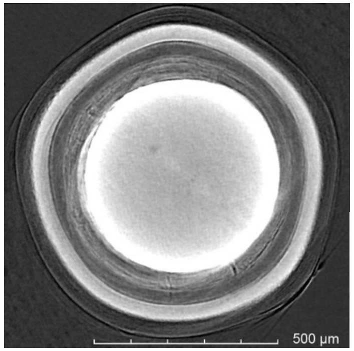
FY16 Progress: AGR-2 PIE and Safety Testing

- Destructive PIE and safety testing of AGR-2 fuel compacts is in progress
- Includes both UCO and UO2 fuel forms for comparison
- UCO fuel performance to date is similar to AGR-1
- Some notable differences in UO_2 performance vs. UCO
  - Less buffer fracture during irradiation
  - Higher cesium release during safety testing (higher SiC failure fractions)



Compact 3-3-2 safety test data



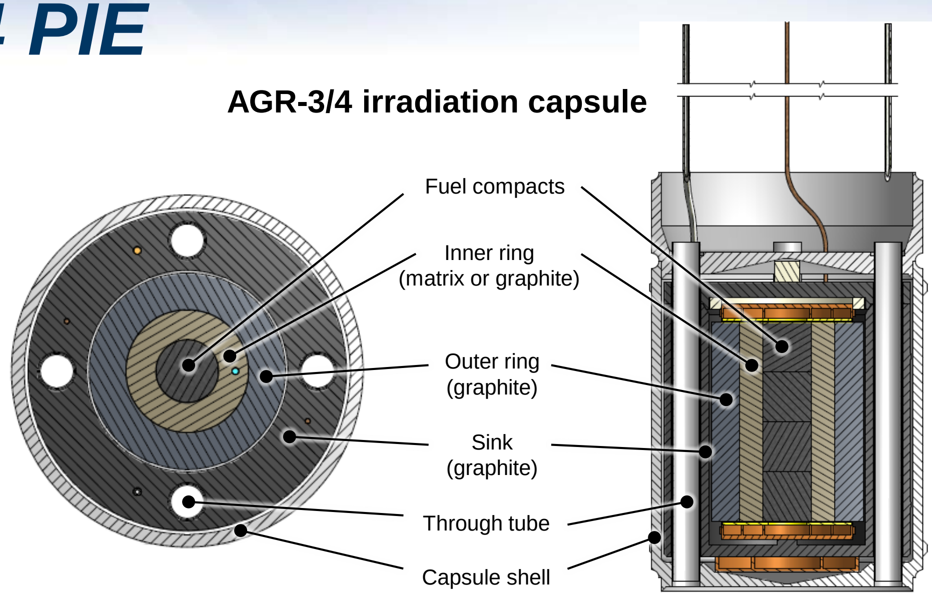


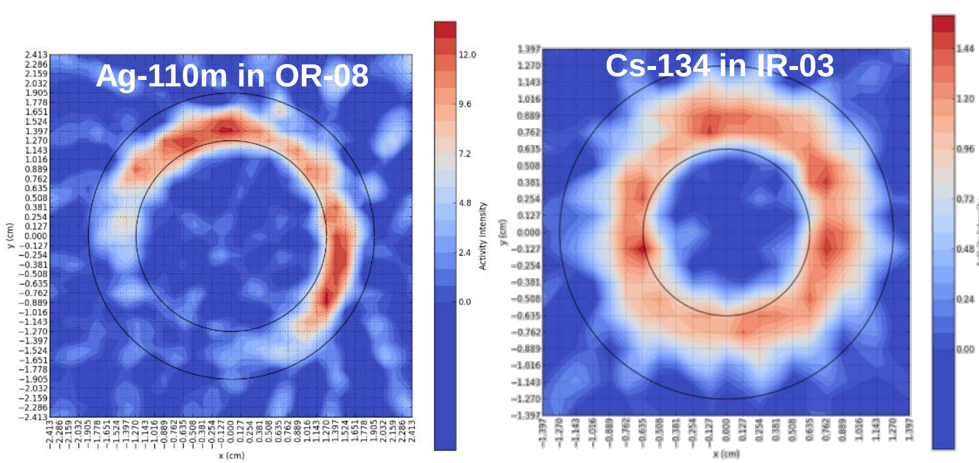
X-ray tomography of Compact 3-3-2 particle with failed SiC layer

FY16 Progress: AGR-3/4 PIE

- Experiment designed to study fission product transport in graphitic core materials
- “Designed-to-fail” (DTF) particles in fuel compacts provide known source of fission products that diffuse into surrounding graphite rings during irradiation
- Completed dimensional measurements of capsule components to determine radiation-induced changes
- Nondestructive gamma analysis of rings is in progress to determine inventory and distribution of fission products in the rings
- Preparations for destructive sampling of the rings and destructive PIE on fuel compacts are in progress

AGR-3/4 irradiation capsule





Looking Ahead

- Fuel Fabrication
  - Complete AGR-5/6/7 fuel fabrication
- Irradiation
  - Complete AGR-5/6/7 irradiation test train fabrication
  - Perform AGR-5/6/7 irradiation
- PIE
  - AGR-2 PIE: evaluating performance of engineering-scale UCO and UO_2 particles
  - AGR-3/4 PIE: assess fission product transport in reactor graphite and compact matrix materials
  - AGR-5/6/7 PIE: evaluate performance of qualification fuel, including data on performance margin (outside normal operating envelope)

Summary

- Program has established the capability to fabricate high-quality, low-defect fuel at the industrial scale
- TRISO and SiC failure fractions during irradiation and during safety testing are well below applicable reactor design specifications
- Our understanding of fission product behavior in TRISO fuel and coating evolution during irradiation has been greatly advanced by the AGR-1 PIE
- Release of key fission products is low
- PIE of AGR-2 and AGR-3/4 experiments is in progress
- AGR-5/6/7 fuel (qualification fuel) fabrication is currently in progress, with irradiation and PIE planned from ~2017 – 2024
- AGR Program publications:
  - 50+ Journal articles
  - 70+ Conference proceedings
- **Many areas of the program will be presented and discussed at the HTR2016 conference in Las Vegas Nov. 6-10, 2016**

Idaho National Laboratory

The National Nuclear Laboratory