Advanced Gas Reactor TRISO Fuel Development and Qualification Program Overview

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DOE-NE Materials Crosscut Coordination Meeting

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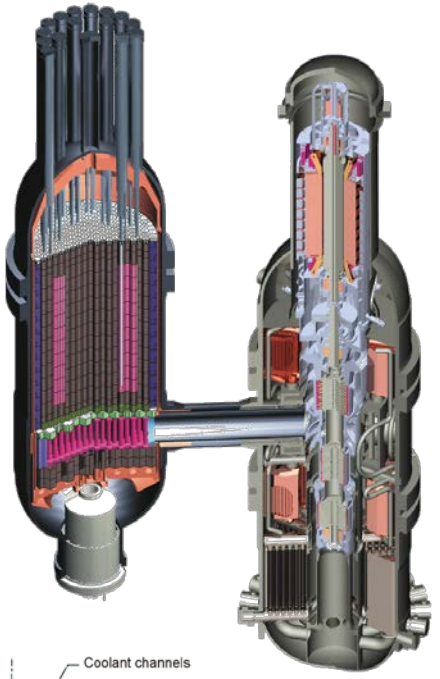
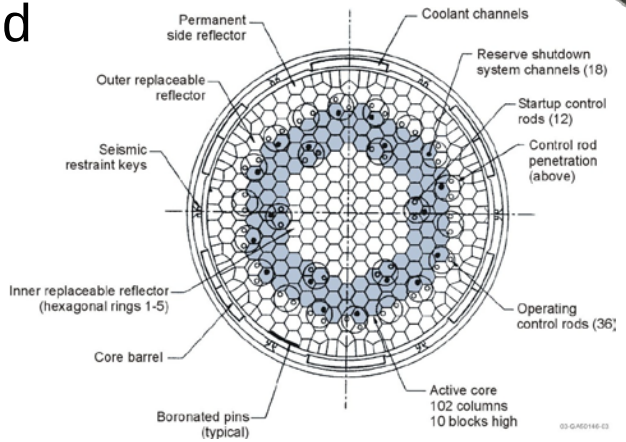
Idaho National Laboratory

High Temperature Gas Cooled Reactor (HTGR)

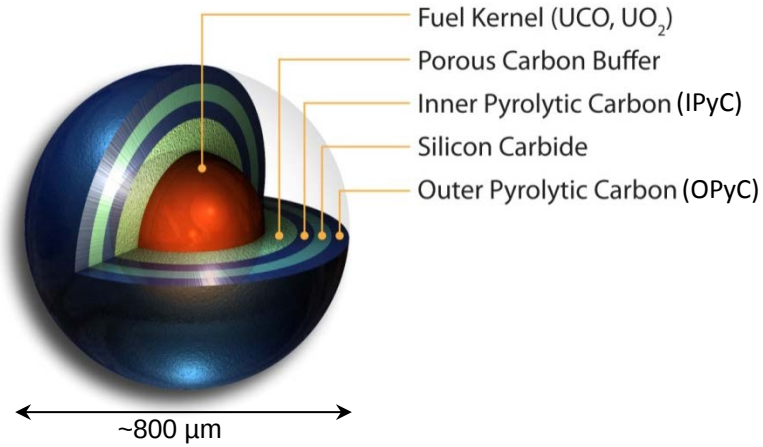
- Helium coolant
- Coated particle fuel
- Outlet temperature 750-950°C
- Production of electricity and high temperature process heat for industrial applications
- Passive safety characteristics
- High thermal efficiency
- HTGRs have numerous advantages, but a commercial scale demonstration is needed

- 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

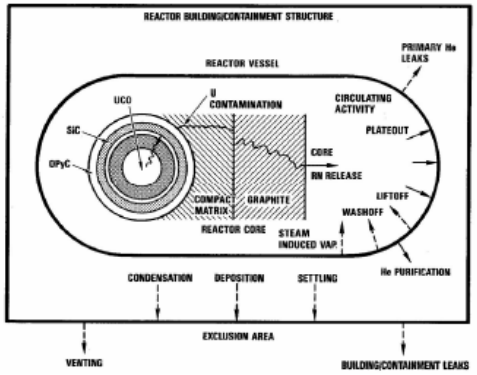
- TRISO fuel is at the heart of the safety case for modular high temperature gas-cooled reactors
- Key component of the "functional containment" licensing strategy
  - Radionuclides are retained within multiple barriers, with emphasis on retention at their source in the fuel

High-quality, low-defect fuel fabrication

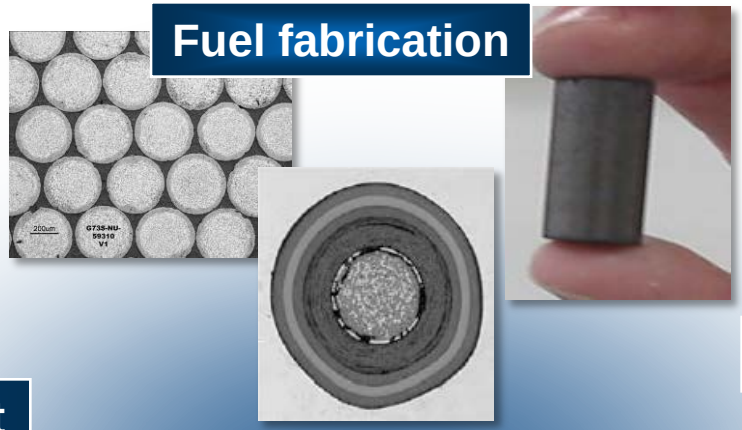
Robust performance during irradiation and during high-temperature reactor transients

Low fission product release

Advanced Gas Reactor Fuel Development and Qualification Program Elements

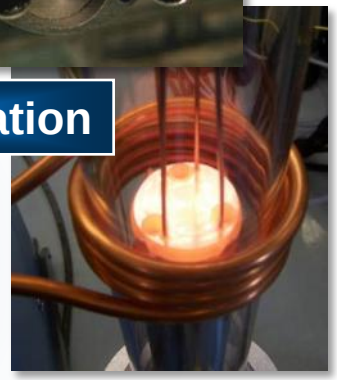


Fission product transport & source term

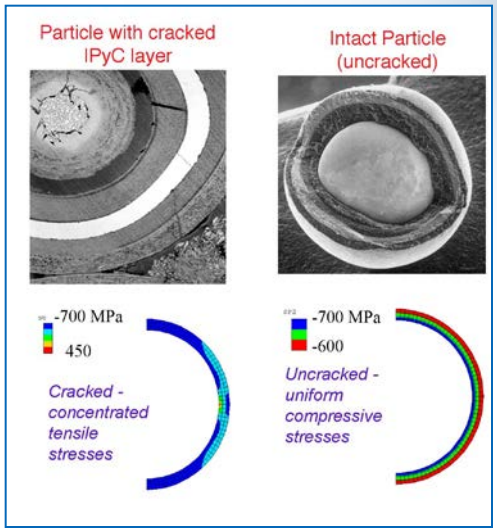


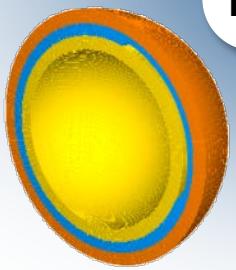
Fuel fabrication

Fuel irradiation



Program participants:
INL, ORNL, BWXT, GA

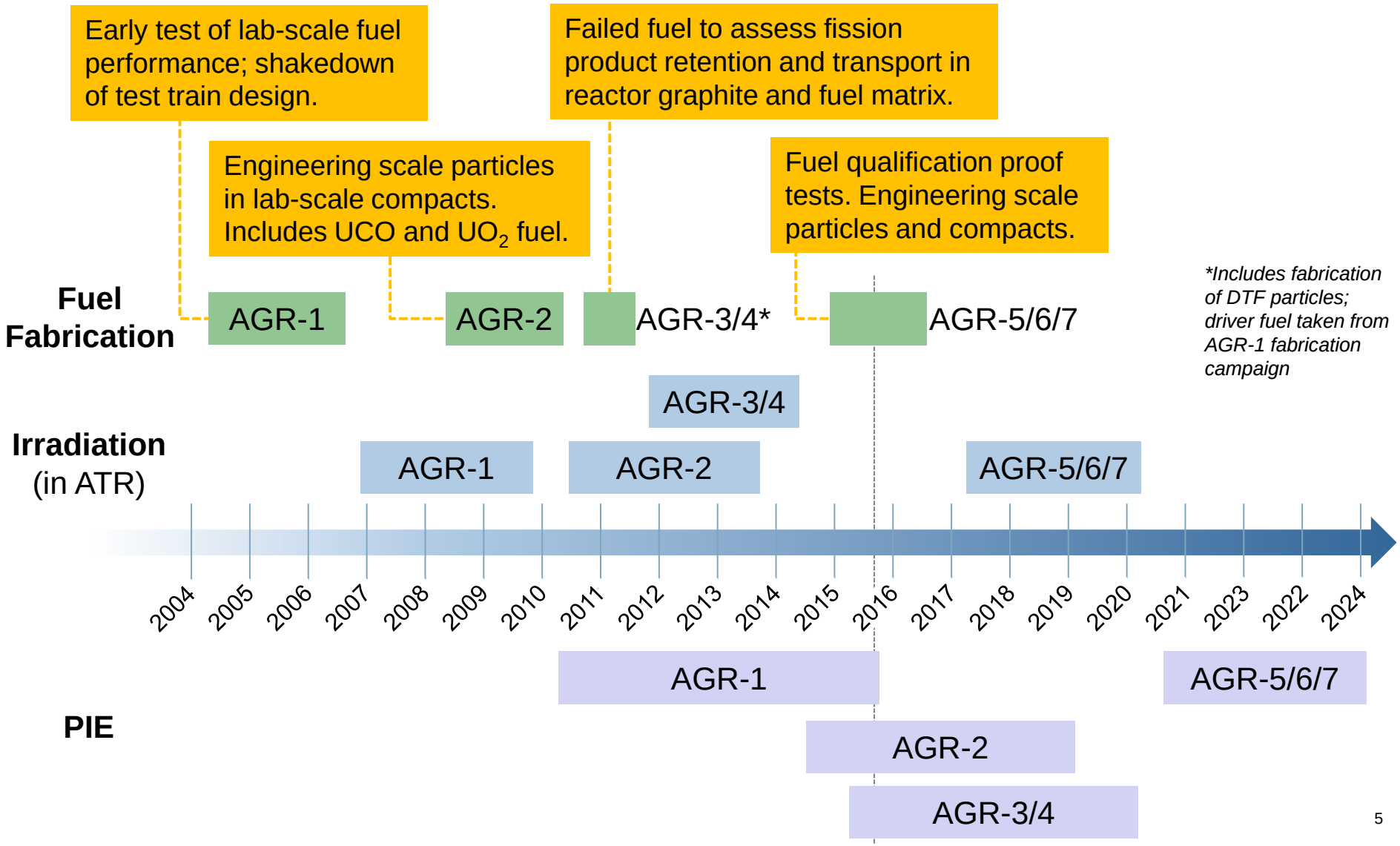




Fuel performance modeling

PIE and safety testing

AGR Program Timeline



Key Fuel Fabrication Accomplishments

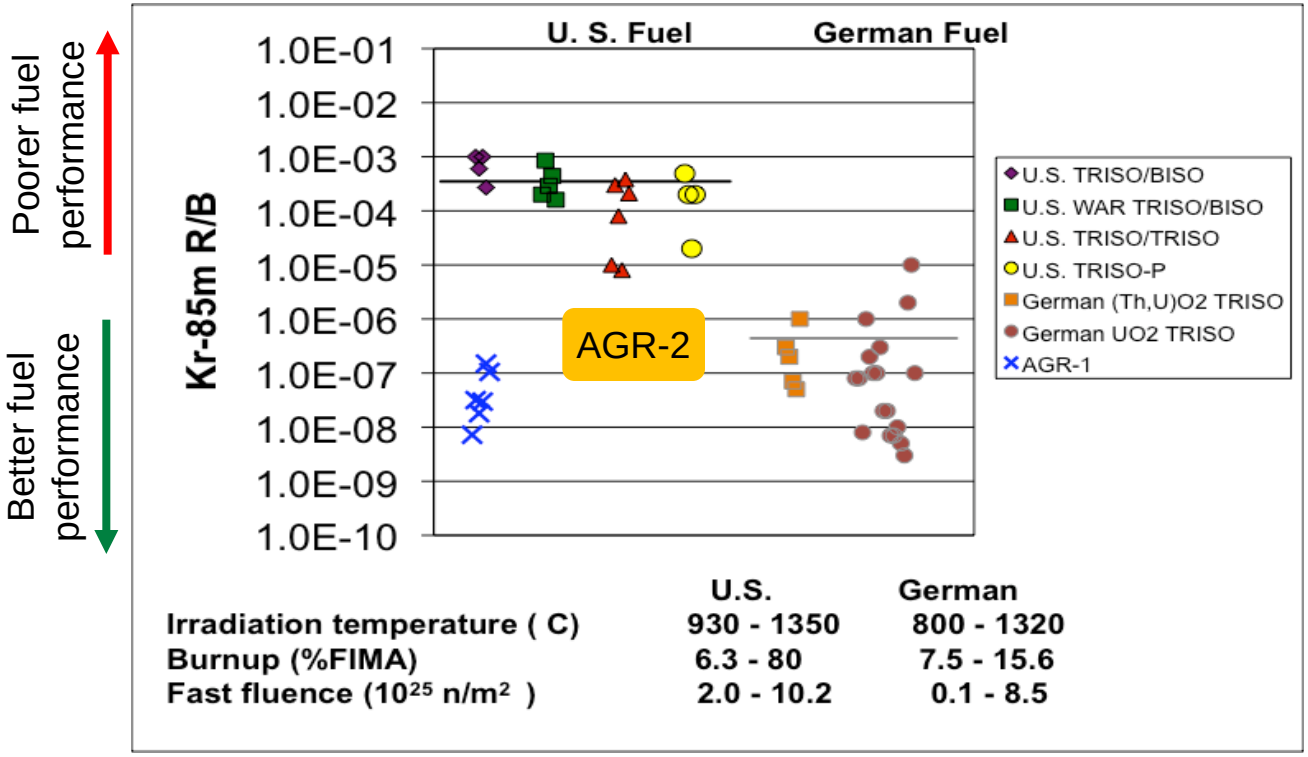
	Kernels	Coatings	Compacts
AGR-1	Engineering scale	Lab Scale	Lab Scale
AGR-2	Engineering Scale	Engineering scale	Lab Scale
AGR-5/6/7	Engineering Scale	Engineering Scale	Engineering Scale

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

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

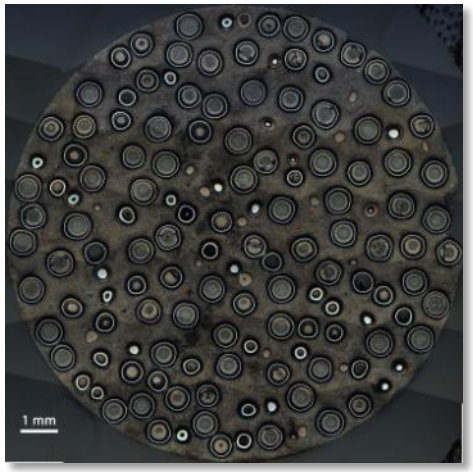
AGR-1:

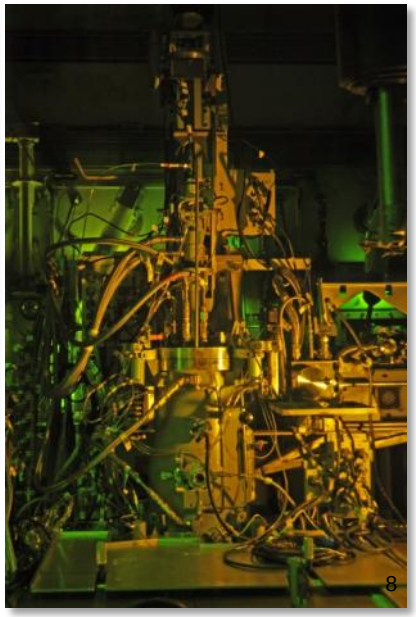
- Zero TRISO failures out of ~300,000 particles in the experiment
- Peak burnup ~20% FIMA

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

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

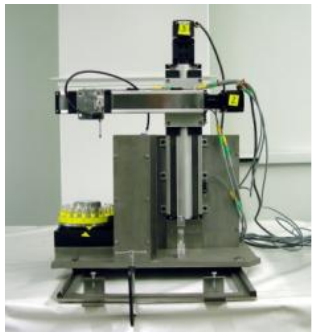
- **Examine fuel performance:**
  - Fission product retention:
    - during irradiation
    - during high temperature accident scenarios (safety testing)
  - Fuel kernel and coating microstructure evolution and causes of coating failures

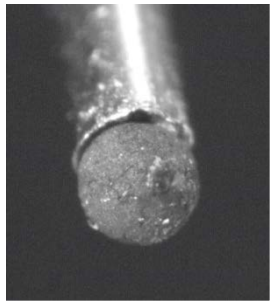


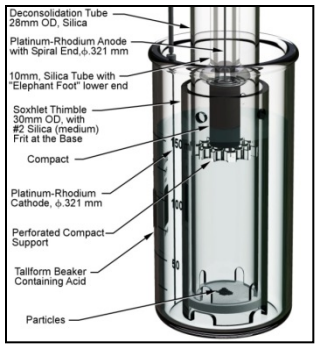


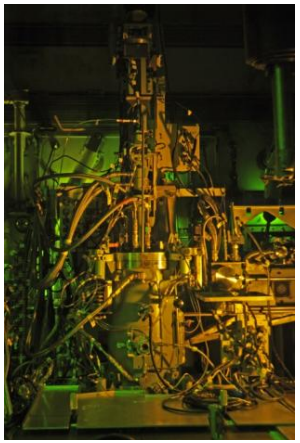
Key AGR PIE Accomplishments and Results

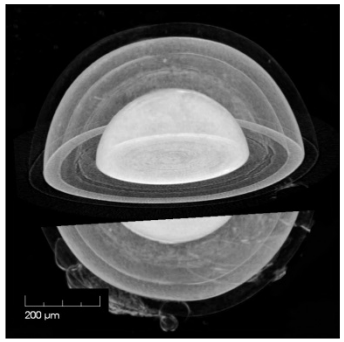
- Re-established coated particle fuel PIE and safety testing capabilities at both INL and Oak Ridge National Laboratory
- Developed numerous new tools and approaches for analyzing irradiated particle fuel
- AGR-1 fuel has performed extremely well
  - Low fission product release (particularly Cs-137, 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

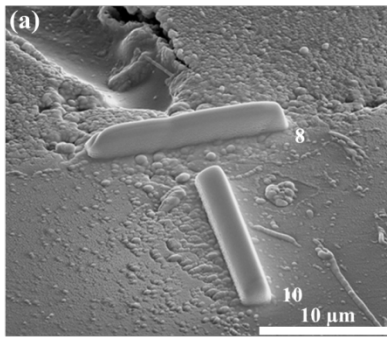


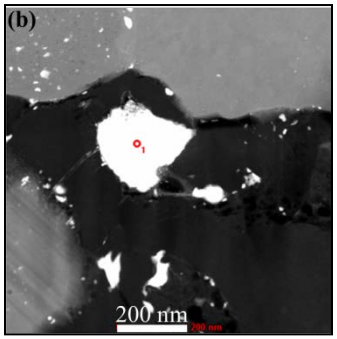










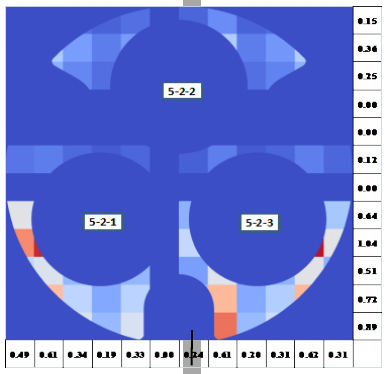


Studying failed particles greatly improves ability to characterize and understand fuel performance

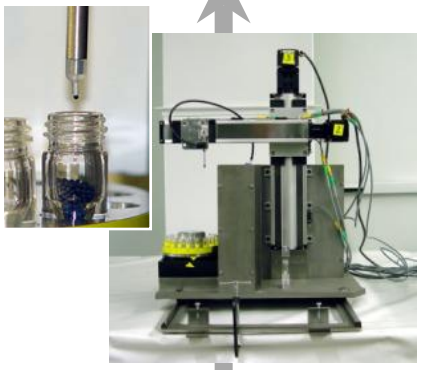
72 fuel compacts containing 300,000 particles in AGR-1 irradiation

AGR-1 Test Train Vertical Section

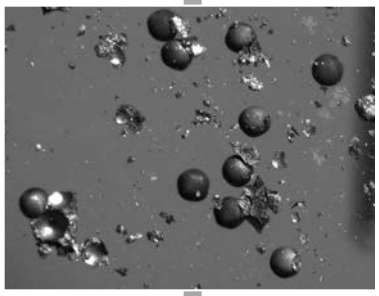
Capsule disassembly



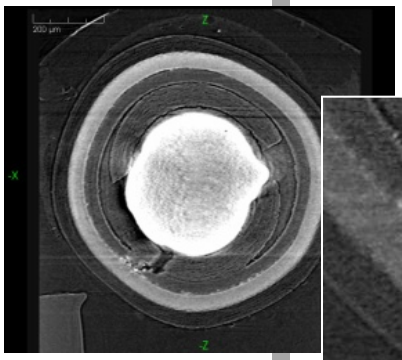
Gamma scan to identify cesium hot spots and compact location

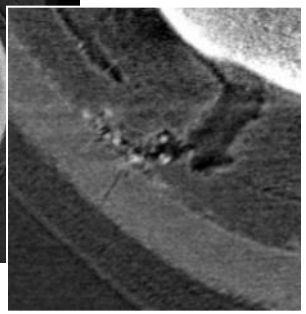


IMGA to find particles with low cesium retention

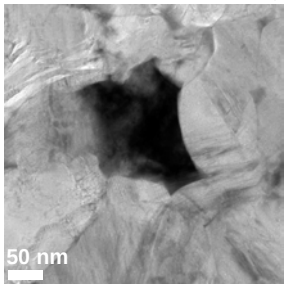


Deconsolidation to obtain ~4,000 particles from compact





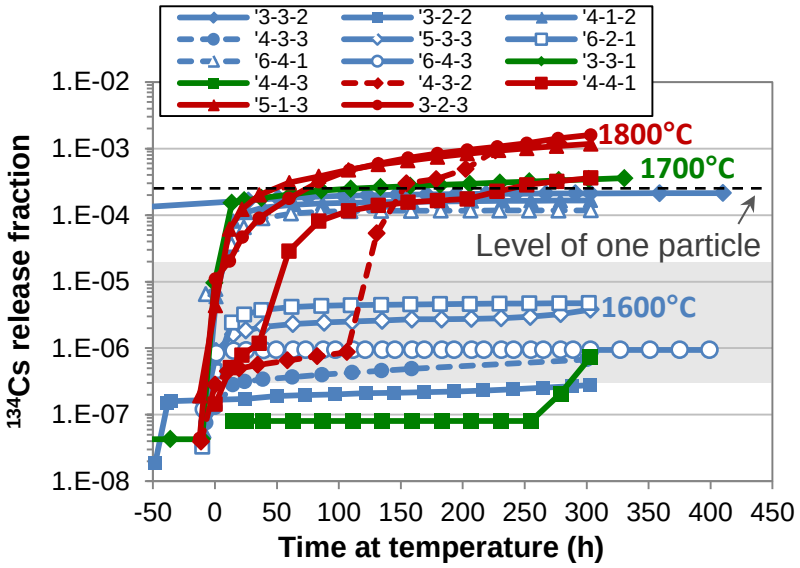
X-ray tomography to nondestructively locate defects/fractures

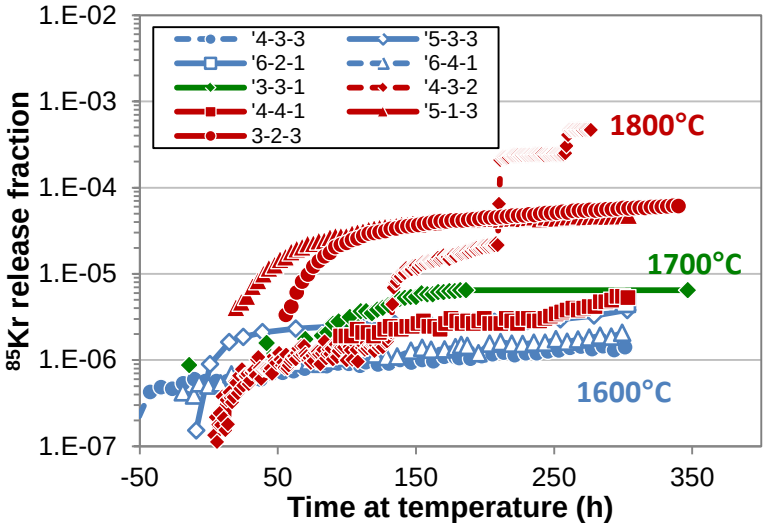


Advanced microscopy to study microstructure in detail

OAK RIDGE National Laboratory

AGR-1 Safety Testing Results Highlights

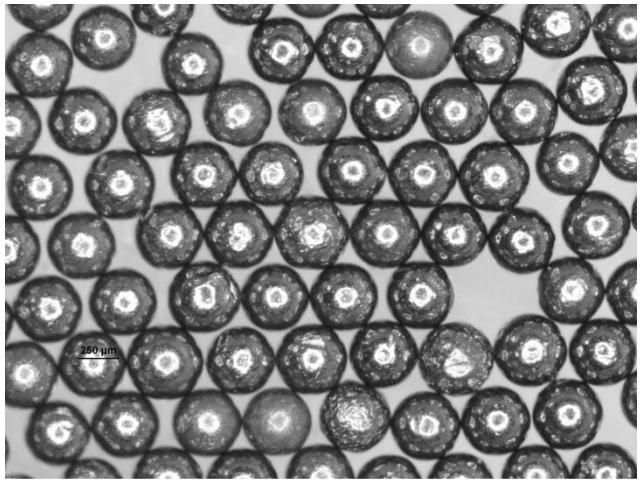




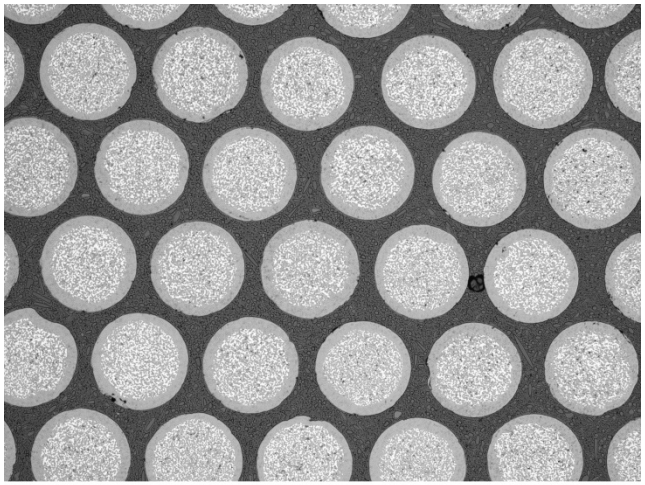
- Fuel compacts were heated to 1600 – 1800°C for 300 h while measuring release of fission products
- No TRISO failures at 1600 and 1700°C; only two failures in a single compact at 1800°C
- Cs release used as indication of SiC layer failure; fuel compacts with SiC failures processed to identify failed 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

FY15 Progress: Fuel Fabrication

- Completed four TRISO coating qualification runs with excellent reproducibility
- Prepared low-enriched acid-deficient uranyl nitrate solutions (30 kg U) for fuel kernel fabrication
- Completed fabrication of a low-enriched uranium carbide/oxide (LEUCO) kernel lot for the AGR-5/6/7 irradiation experiments (certification is pending).



J52R-16-59526
Loose AGR Sintered Kernels



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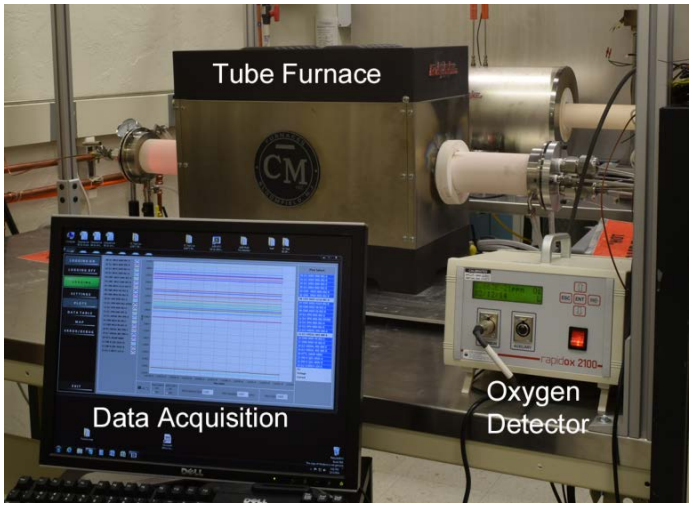
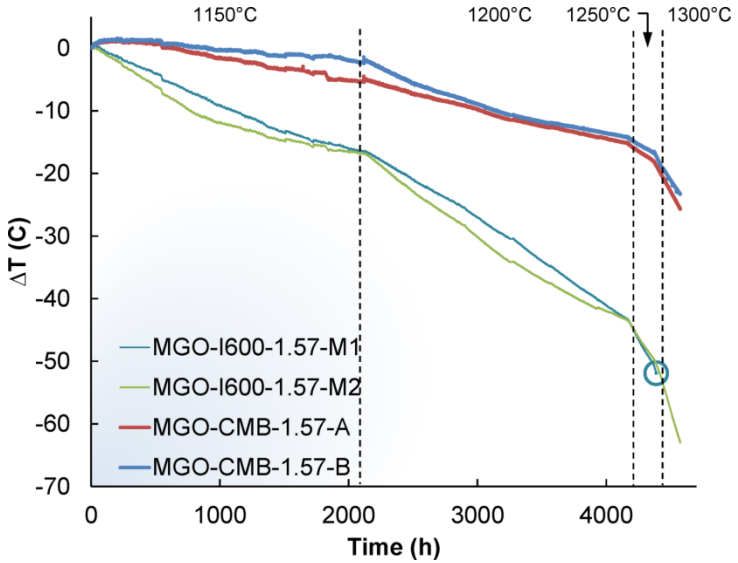
FY15 Progress: Fuel Fabrication (cont'd)

- Analyzed compacts from the first phase of compacting process refinement studies and established target parameters for compacts with low fuel packing fractions.
- Fabrication of AGR-5/6/7 coated particles has begun

FY15 Progress: Irradiation

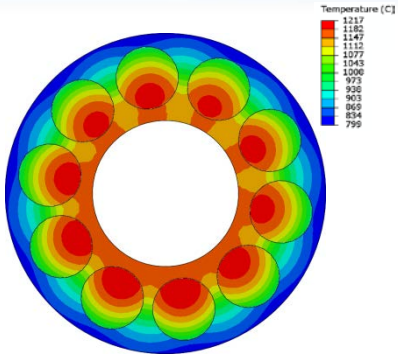
- Completed AGR-5/6/7 pre-test physics and thermal predictions
- Performance testing of experimental thermocouples for the AGR-5/6/7 irradiation test train (Type N junctions with variations in sheath and insulation materials, and Mo/Nb)



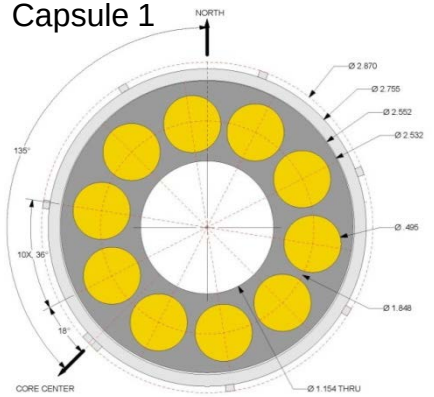


FY15 Progress: Irradiation (cont'd)

- AGR-5/6/7 irradiation capsule design
  - Final design review held September 2015
  - 194 UCO fuel compacts (~575,000 particles)
  - Fuel temperatures ~600 to 1500°C
  - Burnup 8.0 to 18.6% FIMA
  - Irradiation to begin April 2017



Capsule 1



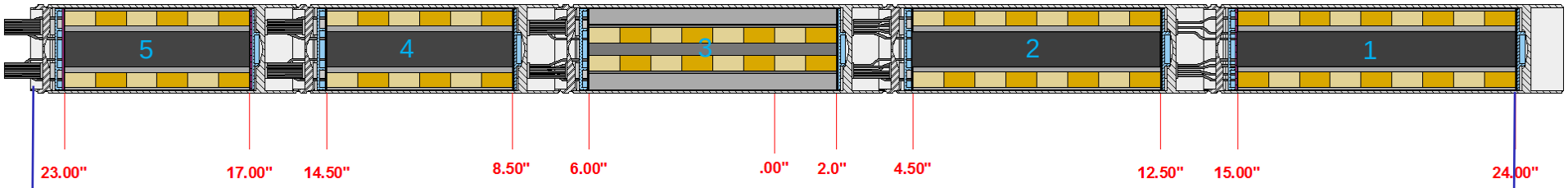
Capsule 5 <900°C

Capsule 4 900°C – 1000°C

Capsule 3 (AGR-7) 1300°C – 1500°C

Capsule 2 900°C – 1000°C

Capsule 1 900°C – 1400°C



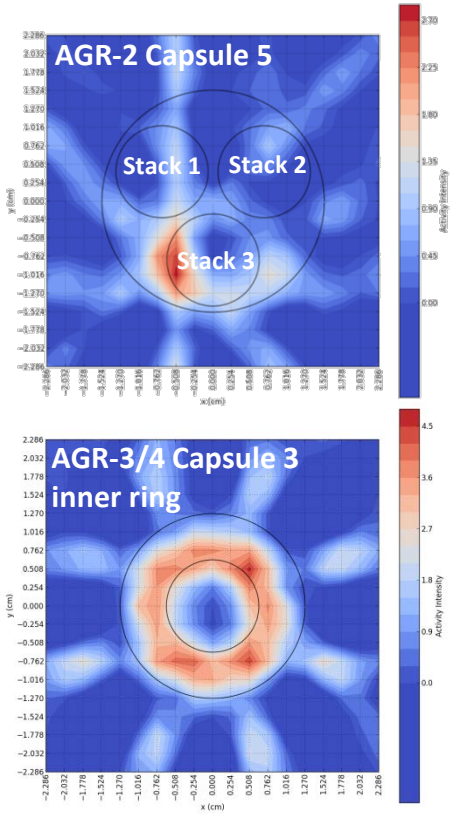
Top of ATR fuel

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

Bottom of ATR fuel

FY15 Progress: Post-Irradiation Examination

- Completed AGR-1 PIE:
  - Final summary report issued (INL/EXT-15-36407)
  - ~65 interim and topical reports, proceedings, and journal publications
- Continued AGR-2 PIE (initiated in FY14)
  - Finished metrology of components
  - Gamma scanning of compacts and capsule components
  - Initiated analysis of fission products released to the capsule components
  - Initiated safety testing and compact destructive exams
- Initiated AGR-3/4 PIE
  - Disassembly and metrology
  - Gamma scanning of graphite rings



Looking Ahead

- Fuel Fabrication
  - Complete AGR-5/6/7 fuel fabrication
- Irradiation
  - Fabricate AGR-5/6/7 irradiation test train
  - 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:
  - 40+ Journal articles
  - 60+ Conference proceedings

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