INL/MIS-25-84812-Revision-0

Two Decades of AGR Program Accomplishments and Results

May 2025

Changing the World's Energy Future

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Idaho National Laboratory

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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Coated Particle Fuel Workshop | May 13-15, 2025
Idaho Falls, Idaho

Advanced Fuels Campaign

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Fuel Fabrication

- Defined acceptable properties and established detailed fuel specifications
  - AGR-5/6/7:
    - 49 different property specs for mean values (kernels, particles, compacts)
    - 25 critical limits
- Re-established US fuel fabrication capability
- Developed/improved fuel quality control (QC) methods to demonstrate compliance with specifications
- Kernel fabrication method improvements
- Coating process development to narrow property distributions and improve consistency
- Overcoating development: Successfully adopted German-like fabrication process

Table 4. UCO heat-treated compact specifications.

Property	Mean[a]	Critical Limits	Critical Fraction	Notes
Variable Properties				
Mean uranium loading (gU/compact) Nominally 40% packing fraction Nominally 25% packing fraction	 1.36 ± 0.10 0.90 ± 0.08	Not specified	Not specified	b
Diameter (mm)	Not specified	≤ 12.20 ≥ 12.44	0 0	c, d
Length (mm)				
Matrix density (g/cm^3				
Iron (µg Fe outside of SiC				
Transition metals (µg Cr, Mn, Co, and Ni ou				
Calcium (µg) Ca outside SiC per co				
Aluminum (µg Al outside SiC pe				
Titanium + Vanadium (µg (Ti + V) outside S				
Dispersed uranium fra ($g{\cdot}U_{leached}/g{\cdot}U_{sample}$)				
Attribute Properties				
Exposed kernel fracti (kernel equiv./particle				
Defective SiC coating (kernel equiv./particle				
Defective OPyC coati				

(a) The ± values represe
(b) The actual packing f packing fractions are
(c) VHTR compact dim (full-height) and a n 12.62 mm). The AG
(d) The compact diamet

Table 3. LEU TRISO particle specifications.

TRISO Particle Property	Mean[a]	Critical Region	Critical Fraction	Notes
Lot Variable Properties				
Buffer density (g/cm^3)	1.05 ± 0.10	Not specified	Not specified	Point estimate, b
IPyC density (g/cm^3)	1.90 ± 0.05	≤ 1.80 ≥ 2.00	≤ 0.01 ≤ 0.01	b, c
Buffer thickness (µm)	100 ± 15	≤ 58	≤ 0.01	d
IPyC thickness (µm)	40 ± 4	≤ 30 ≥ 52	≤ 0.01 ≤ 0.01	d
SiC thickness (µm)	35 ± 3	≤ 28	≤ 0.01	d
OPyC thickness (µm)	40 ± 4	≤ 20	≤ 0.01	d
SiC density (g/cm^3)	≥ 3.19	≤ 3.17	≤ 0.01	c
OPyC density (g/cm^3)	1.90 ± 0.05	≤ 1.80 ≥ 2.00	≤ 0.01 ≤ 0.01	c
IPyC diattenuation	≤ 0.0170	≥ 0.0242	≤ 0.01	e
OPyC diattenuation	≤ 0.0122	≥ 0.0242	≤ 0.01	e
SiC aspect ratio (faceting)	Not specified	≥ 1.14	≤ 0.01	f
Lot Attribute Properties				
Defective IPyC coating fraction	≤ 1.0×10^{-4}	Not specified	Not specified	g
Defective OPyC defect fraction	≤ 3.0×10^{-4}	Not specified	Not specified	h
Lot Measurement Only				
Pre-burn exposed uranium fraction (kernel equiv./particle count)	— Not specified —			i
Post-burn exposed uranium fraction (kernel equiv./particle count)	— Not specified —			j
SiC microstructure	Grains size < visual standard			k

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Fuel Fabrication

- Fabrication of AGR-1 fuel variations to explore specification range on key properties for IPyC and SiC layers
- Fabricated of AGR-3/4 DTF particles and compacts with successful in-pile performance
- Coating scale-up: 2” coater (~60 g batch) to 6” coater (~1 – 2 kg batch) – AGR-2 and AGR-5/6/7 coated particles
- Overcoating and compacting process scale up – AGR-5/6/7 compacts
- Met most fuel specifications with a few exceptions
  - Mainly particle defect fractions in particles/compacts made at pilot scale

- ORNL:
  - Completed 286 coating runs for the AGR fabrication campaigns
- BWXT:
  - Completed 18 kernel sintering runs to support AGR-5/6/7 experiment (47 kgU)
  - Completed 193 coating runs for AGR fabrication campaigns (AGR-2, AGR-5/6/7)

Irradiation Testing

- Development of multi-capsule instrumented lead experiment designs
  - Temperature measurement seen as highly advantageous
  - Inert gas flow helps with temperature control and provides critical fission gas measurement capability
- Incorporate burnable absorber in capsule graphite to provide more consistent fuel power in Large B positions (AGR-1 and AGR-2)
- Thermometry development: Use of standard and optimized TC design and development of new High-Temperature Irradiation Resistant (HTIR) TCs
- Physics and thermal model development
  - AGR-5/6/7 thermal model contained ~1,200,000 finite elements
- R/B measurement capability
  - Up to 12 capsules per experiment; 21 active monitors when AGR-2 and AGR-3/4 in ATR simultaneously
  - Gross gamma and HPGe gamma energy spectrum measurements for isotopic data

Irradiation Testing

Fuel performance testing

Fission product transport experiment

Fuel fabrication scale-up

Irradiation experiments:

AGR-1 → **AGR-2** → **AGR-5/6/7** | **AGR-3/4**

- **AGR-1**: *Early test of lab-scale UCO fuel performance; shakedown of test train design.*
- **AGR-2**: *Engineering-scale particles in lab-scale compacts. Includes UCO and UO_2 fuel.*
- **AGR-5/6/7**: *Fuel qualification test. Engineering-scale UCO particles and compacts.*
- **AGR-3/4**: *"Designed-to-fail" (DTF) fuel to assess fission product retention and transport in reactor graphite and fuel matrix.*

- Completed four irradiation experiments in ATR
- From Dec 24, 2006 to July 22, 2020
  - Experiments in reactor for cumulative ~4000 calendar days (~11 years)
  - Accumulated ~1900 effective full power days (EFPD)
- Tracking of continuous data streams: TC readings, gas inlet/outlet, flows, gas mixtures, pressure, detector counts, reactor power

Post-Irradiation Examination

- Capsule disassembly, inspection and dimensional measurements
- Special tools and capabilities developed
  - Deconsolidation-leach-burn-leach – Fuel QC method implemented in INL and ORNL hot cells for irradiated fuel
  - Particle handling, inspection and gamma counting at INL and ORNL
    - New Irradiated Microsphere Gamma Analyzer (IMGA) at ORNL
  - Graphite holder gamma scanning – Tomographic scans to locate fission product hot spots
  - Irradiated particle and compact x-ray computed tomography
- Demonstrated ability to locate individual particles with failed SiC layers and examine in detail
- Deployed numerous microanalytical methods to examine particle and fission product behavior in detail (SEM, FIB, STEM, EPMA, APT, etc)

PIE By the Numbers

- This has been the most extensive TRISO fuel PIE effort in history
- Complete fission product mass balance on 29 irradiation capsules
- 350 irradiated compacts dimensional measurements and gamma scanning
- ~50 as-irradiated compact deconsolidation-leach-burn-leach analyses (includes 12 AGR-3/4 radial DLBL)
- Thousands of particles examined in cross section with optical microscopy
- Hundreds of particles examined with electron microanalysis methods

Inert Safety Testing

- Refurbishment of Core Conduction Cooldown Test Facility (CCCTF) at ORNL
- Development of Fuel Accident Condition Simulator (FACS) system at INL
- Total *fuel performance* safety tests (1500 – 1800 °C) to date (AGR-1, AGR-2, AGR-5/6/7):
  - 51 compact safety tests involving 57 compacts

  (Does not include numerous AGR-3/4 heating tests and AGR-1 and AGR-2 loose particle heating tests)
- Extensive post-test analysis of many compacts to identify causes of particle failure
  - ~40 compacts deconsolidated following AGR-1, AGR-2, and AGR-5/6/7 safety tests
- Individual gamma counting of an estimated >100,000 particles (as-irradiated and post safety test)

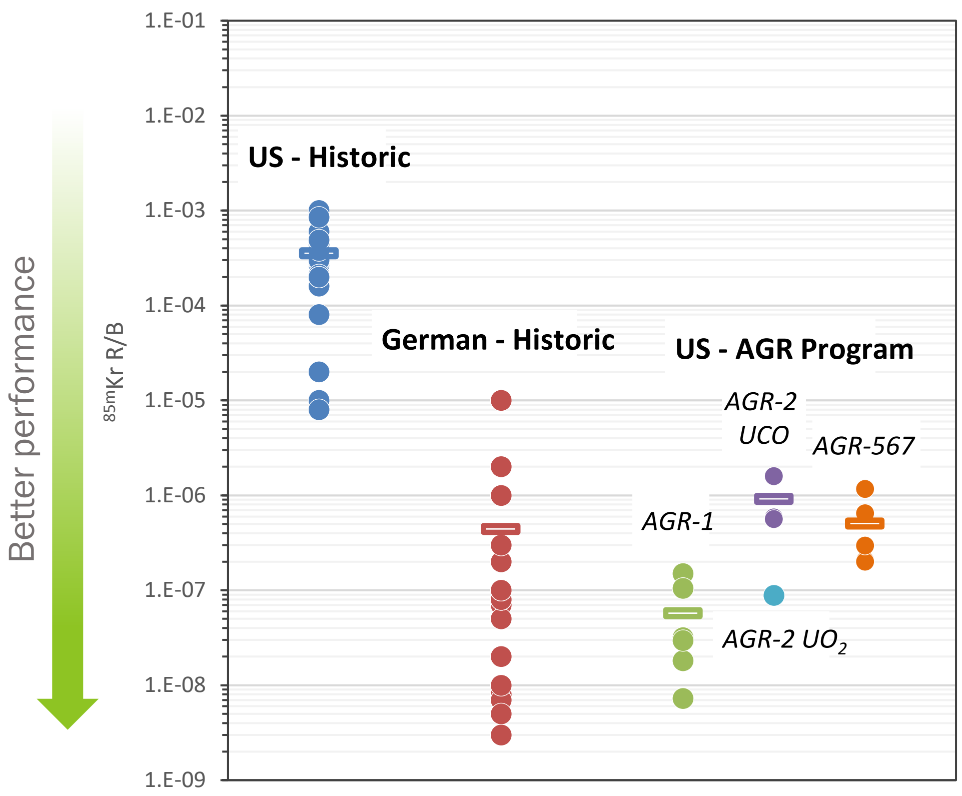
Irradiation Testing Results

- ~1,000,000 UCO particles in ~300 fuel compacts irradiated under a broad range of HTGR conditions

Experiment	EFPD[a]	Burnup (%FIMA)	Fast fluence (×10^{25} nm^{-2})[b]	TA Peak Temp. (deg C)[c]
AGR-1	620	11.3 – 19.6	2.2 – 4.3	1069 – 1197
AGR-2[d]	559	7.3 – 13.2	1.9 – 3.5	1080 – 1360
AGR-5/6	361	5.7 – 15.3	1.6 – 5.4	741 – 1231
AGR-7	361	13.6 – 15.0	5.2 – 5.6	1328 – 1432

- Explored severe temperature fuel performance
- ^{85m}Kr R/B of ~10^{-8} – 10^{-6} at peak burnup of 19.6% FIMA
- Operational issues with AGR-2 and AGR-5/6/7 impaired R/B measurement during later cycles

Comparison of US and German ^{85m}Kr R/B data



AGR-2 R/B values are through the first ~1/4 of the irradiation (149 EFPD)
AGR-567 R/B values are through the first ~1/2 of the irradiation (174 EFPD)

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[a] Effective full power days
[b] E > 0.18 MeV
[c] Time-average peak temperature
[d] Includes only UCO TRISO fuel

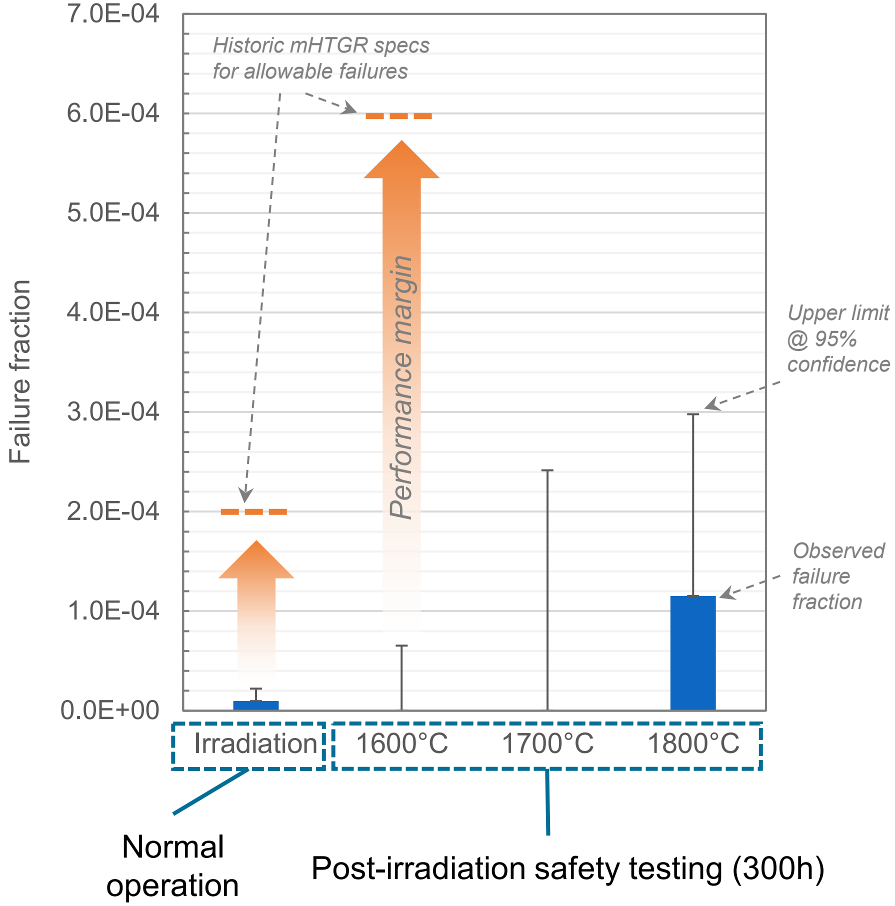
Fuel Performance Evaluation Results So Far

- Demonstrated low in-pile particle failure fractions (≤ 1/50,000 particles[1])
- Fuel can withstand hundreds of hours at 1600 °C without significant particle failures (≤ 1/15,000 particles[1])
- Fuel effectively retains most fission products within the coated particles

Temperature (°C)	Avg ^{134}Cs release (~300 h)
1600	4×10^{-5}
1800	6×10^{-4}

- There is significant performance margin in terms of time at temperature

Experimental TRISO failure fractions for AGR-1 + AGR-2



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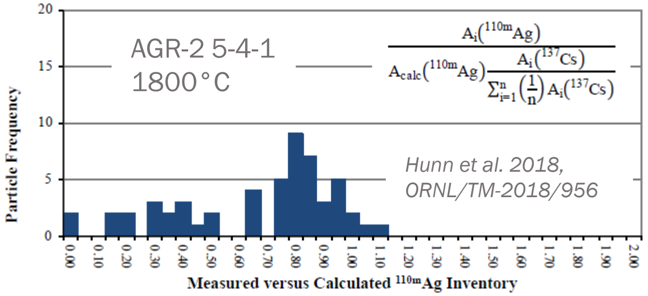
[1] *AGR-1 and AGR-2 data; values are upper bound at 95% confidence*

Extensive Fission Product Release Data

- In-pile release of condensable FPs from fuel compacts
- Fuel compact retained ^{110m}Ag inventory
- Release from fuel compacts during safety tests
- FP retention in fuel compact matrix
- Particle FP retention distributions

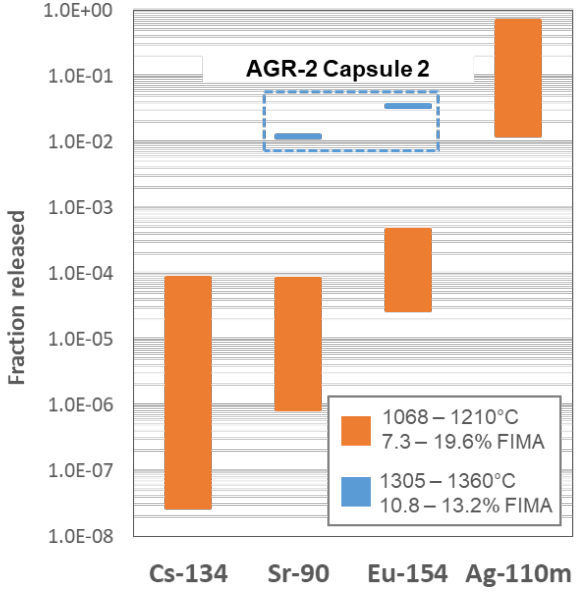
- Robust experimental database of FP behavior under a wide range of conditions to support core release models

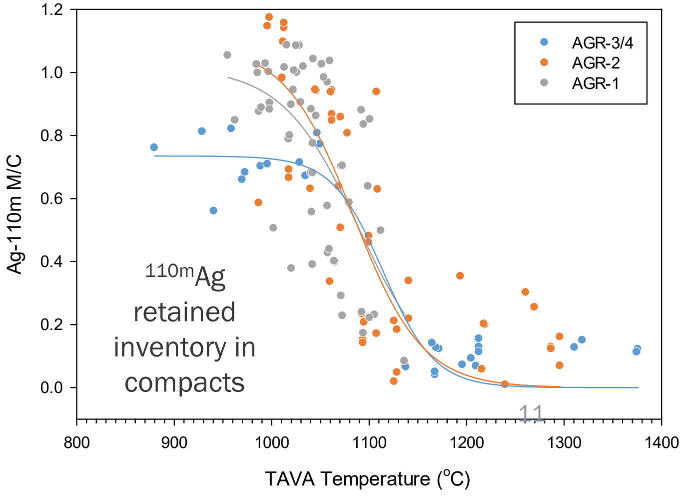
Particle FP inventory distributions



Report summarizing fission product release behavior from AGR-1, AGR-2, and AGR-3/4 fuel (Stempien et al., INL/RPT-23-74651, 2023)

Fission product release from AGR-1 and AGR-2 UCO fuel compacts





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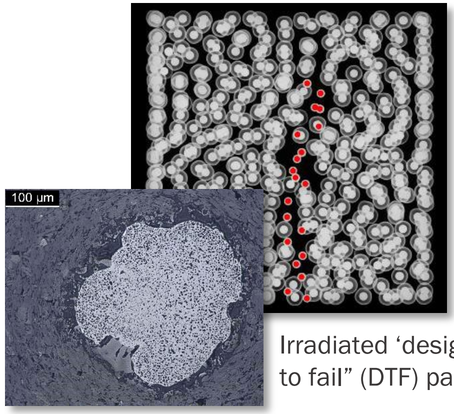
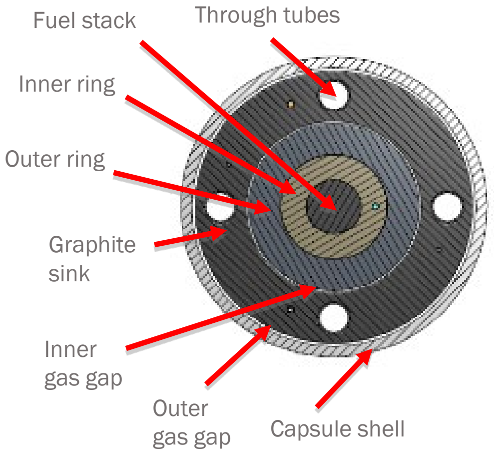
AGR-3/4 Irradiation Experiment

- Experiment dedicated to assessing fission product transport behavior
  - Supports reactor source term analysis
- Extensive in-pile data of isotopic fission gas release from exposed fuel kernels in 12 capsules
- Detailed non-destructive and destructive examination of fission products in graphite/matrix rings in 8 capsules
- Heating test and/or destructive examination of 24 compacts to assess FP release and transport
- Data analysis in progress to refine FP transport parameters

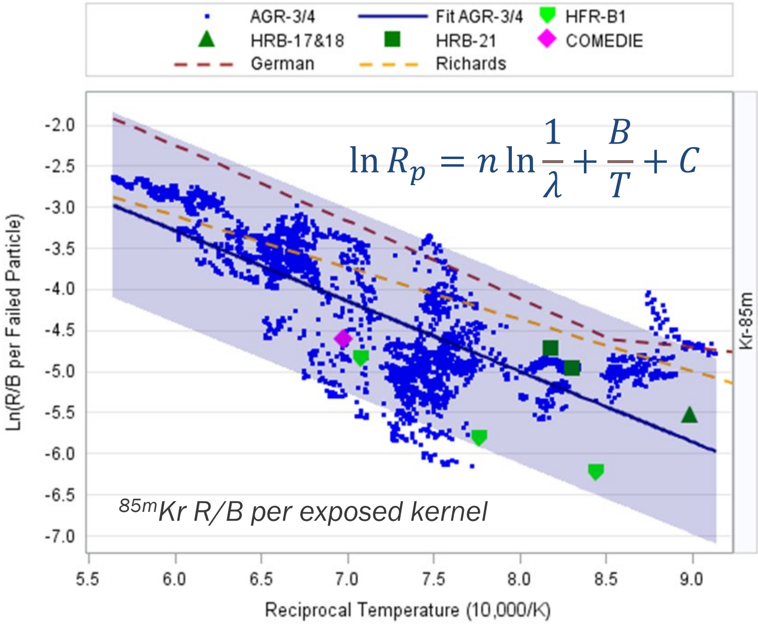
X-radiograph of unirradiated AGR-3/4 compact; DTF highlighted by red dots



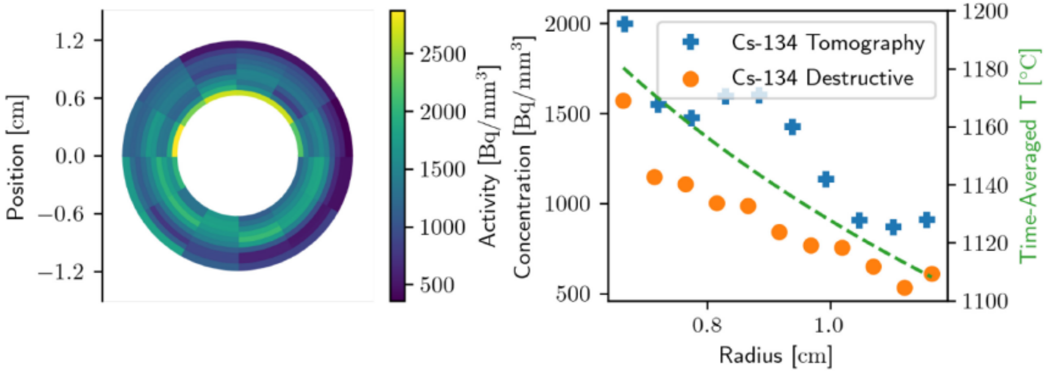
Irradiated 'designed to fail" (DTF) particle



AGR-3/4 Capsule Cross Section



Non-destructive and destructive analysis of fission product distribution in graphite/matrix rings



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Fuel Performance Modeling

- Developed PARFUME (PARticle FUel ModEl), an integrated mechanistic code that evaluates the thermal, mechanical, and physico-chemical behavior of TRISO fuel particles
- Compiled data and correlations from various sources
- Improved upon previous codes, incorporating more failure modes beyond pressure vessel failure
- Model used to inform AGR fuel specs; e.g., with sensitivity studies
- Compare model predictions with experimental data (benchmarking); particle failure probabilities, fission product release
- Participated in international modeling benchmarks (IAEA, GIF)
- Collaborated with NEAMS program to implement PARFUME models in Bison, where code refinements continue

Summary

- Substantial experience base developed on TRISO fuel fabrication and QC
- Well-established UCO TRISO fuel performance data set
  - AGR-5/6/7 fuel performance data is still being collected and analyzed
- Extensive amount of detailed post-irradiation examination work to understand fuel behavior mechanisms and fission product transport
- World-leading TRISO fuel performance codes under continual refinement

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Locating and Studying Failed Particles Greatly Improves Understanding of Fuel Performance

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

Fuel Compacts

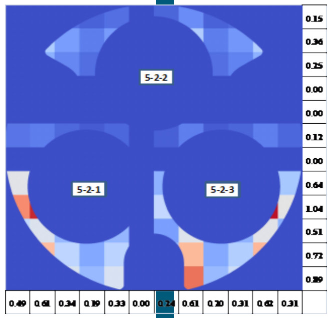
Plenum between Capsules

AGR-1 Test Train Vertical Section

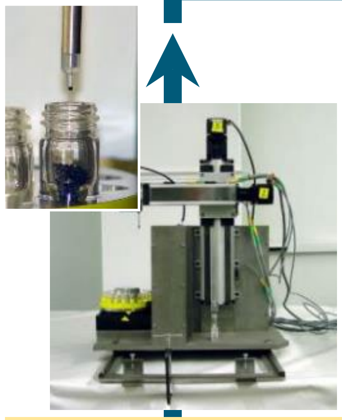
Identify compacts with leakers

Capsule disassembly

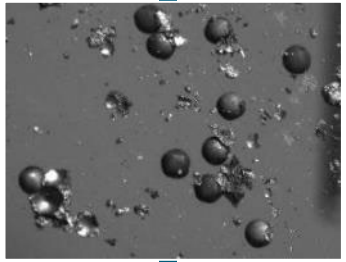
Gamma scan to identify cesium hot spots and compact location



Identify particles with failed coatings



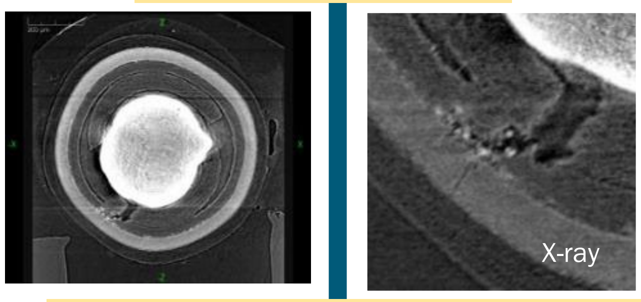
Gamma count to find particles with low cesium retention



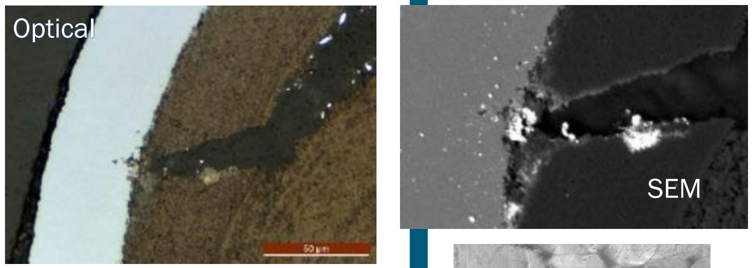
Deconsolidation to obtain ~4,000 particles from compact

Detailed examination of particles with failed coatings

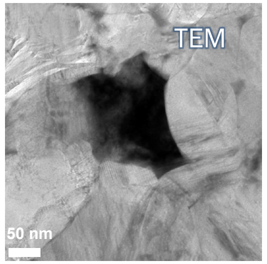
X-ray tomography to locate failures



Materialography to expose defective region for analysis



Advanced microscopy to study coating layers in detail



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