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TRISO Fuel Development and Qualification in the US

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IAEA Consultancy Meeting

19 July 2023

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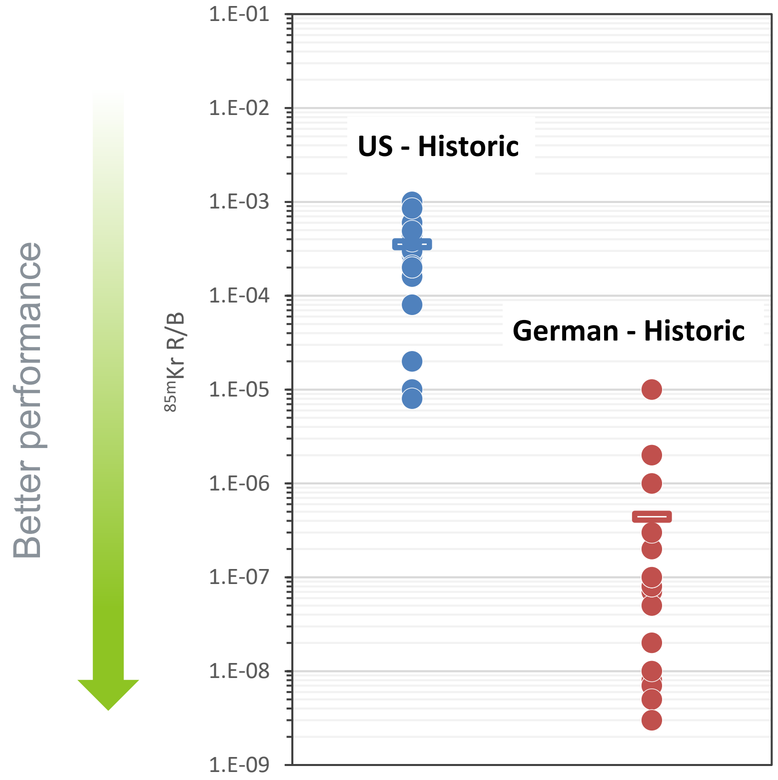
Background: Status of HTGR and TRISO Technology Circa 2000

- Four decades of experience with coated particle fuel in numerous countries and operation of several demonstration reactors
- Successful demonstration of TRISO fuel performance (German program in 1980s and 1990s)
- Major issues with US TRISO fuel performance in the NPR/MHTGR program irradiations in the early 1990s
- Generation IV International Forum included VHTR, but in the US and elsewhere more modest goals of an HTGR (outlet ≤ 850°C were established based primarily on lack of suitable high-temperature metals, not fuel performance shortcomings

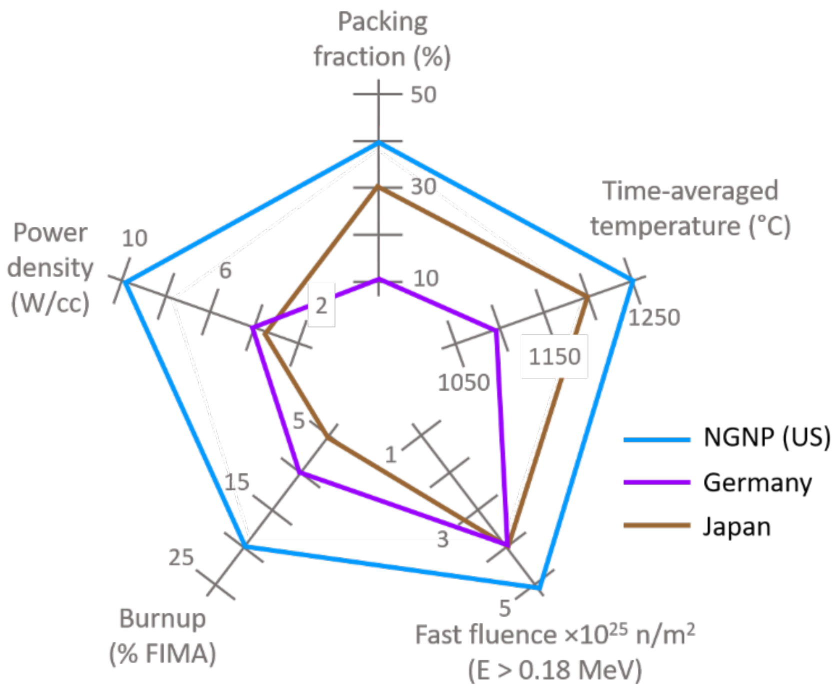
Comparison of US and German ^{85m}Kr R/B data



US DOE Advanced Gas Reactor (AGR) Fuel Development and Qualification Program

- Focus on LEU UCO TRISO fuel in cylindrical compacts, consistent with prismatic reactor designs that had been pursued in the US
- Pursued a more aggressive performance envelope compared to German and Japanese programs
- Objectives and Motivation:
  - Provide data for fuel qualification in support of reactor licensing
  - Establish a domestic commercial TRISO fuel fabrication capability

Reduce market entry risk



Fuel Qualification Approach

- Develop fuel performance models to describe particle behavior, explain past particle failures (NPR/MHTGR), and guide particle development
- Emulate successful German UO_2 particle coating design and properties
  - Petti et al., Nucl. Eng. Des. 222 (2003) 281
- Retain UCO kernel from past US development work to accommodate burnup to 20% FIMA in prismatic reactor designs
  - Reduce/eliminate kernel migration (“amoeba effect”) and CO(g) corrosion of SiC
- Phased approach for fuel fabrication: demonstrate lab scale production of high-quality fuel with acceptable performance before committing to pilot scale fabrication

Fuel performance testing

Fuel fabrication scale-up

Fission product transport experiment

Irradiation experiments:

AGR-1 → **AGR-2** → **AGR-5/6/7**

AGR-3/4

Early test of lab-scale UCO fuel performance; shakedown of test train design.

Engineering-scale particles in lab-scale compacts. Includes UCO and UO_2 fuel.

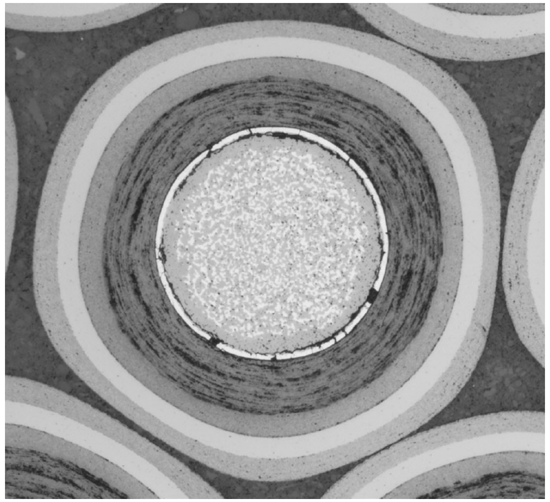
Fuel qualification test. Engineering-scale UCO particles and compacts.

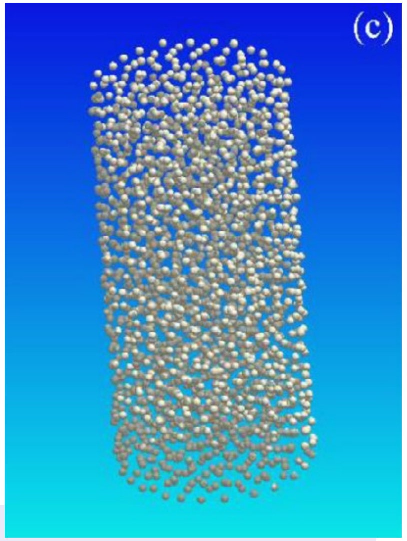
“Designed-to-fail” (DTF) fuel to assess fission product retention and transport in reactor graphite and fuel matrix.

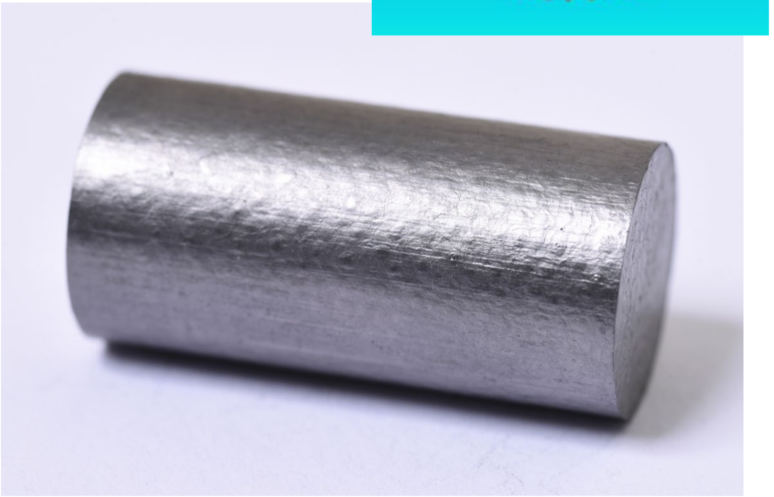
US TRISO Fuel

Experiment	Kernel (dia., μm)	Enrichment (% ^{235}U)	Particles/ compact (packing fraction, %)	gU per compact
AGR-1	UCO (350)	19.7	4140 (37)	0.91
AGR-2	UCO (427) UO_2 (508)	14.0 9.6	3180 (37) 1540 (23)	1.26 0.99
AGR-5/6/7	UCO (426)	15.5	2240 (25) 3430 (38)	0.89 1.36

AGR-5/6/7 fuel images







Fabrication scale up

	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

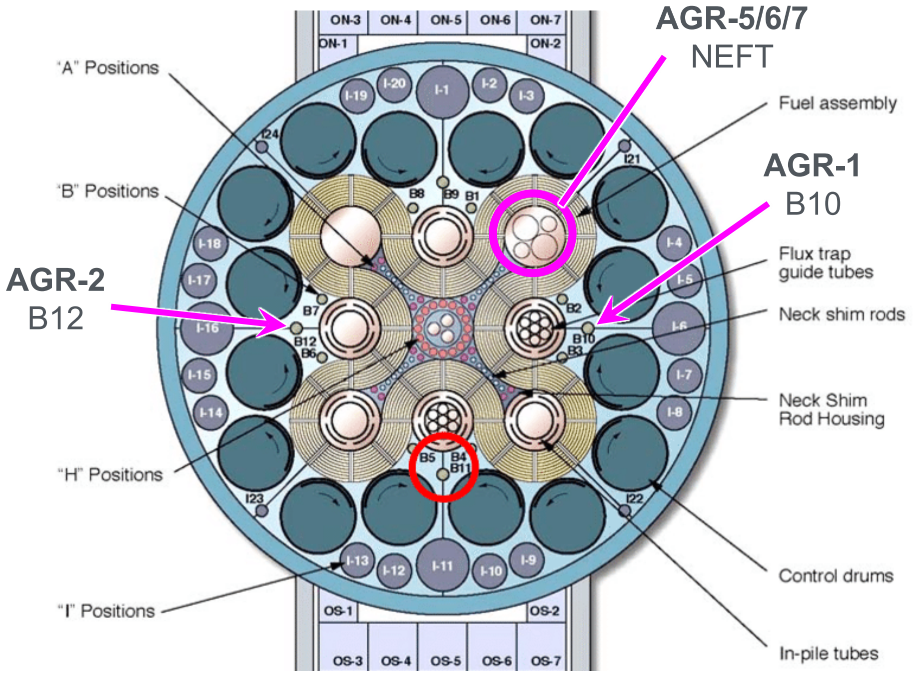
Lab Scale – ORNL
Engineering Scale – BWXT

Irradiation Testing

- Irradiation tests performed in the Advanced Test Reactor at Idaho National Laboratory
- Multi-capsule, instrumented lead experiments with independent temperature control and fission gas measurement in each capsule

Experiment	Kernel type	Compacts/ particles	Temperature (°C)[a]	Burnup (%FIMA)	Fast fluence ($\times 10^{25}$ n/m^2)[b]
AGR-1	UCO	72 / 298,000	1069 – 1197	11.3 – 19.6	2.2 – 4.3
AGR-2	UCO UO2	36 / 114,000 12 / 18,500	1080 – 1360 1072 – 1105	7.3 – 13.2 9.0 – 10.7	1.9 – 3.5 3.1 – 3.5
AGR-5/6	UCO	170 / 516,000	741 – 1231	5.7 – 15.3	1.6 – 5.4
AGR-7	UCO	24 / 54,000	1328 – 1432	13.6 – 15.0	5.2 – 5.5

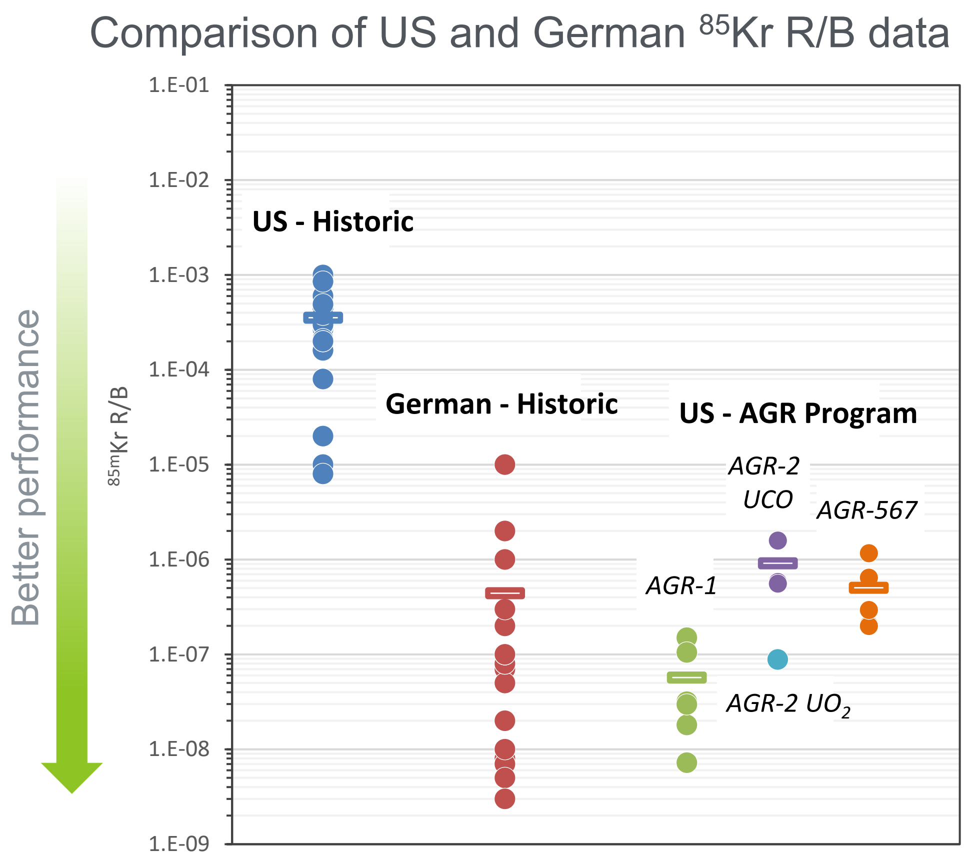
[a] Time-average peak temperature
[b] E ≥ 0.18 MeV



ATR core cross section

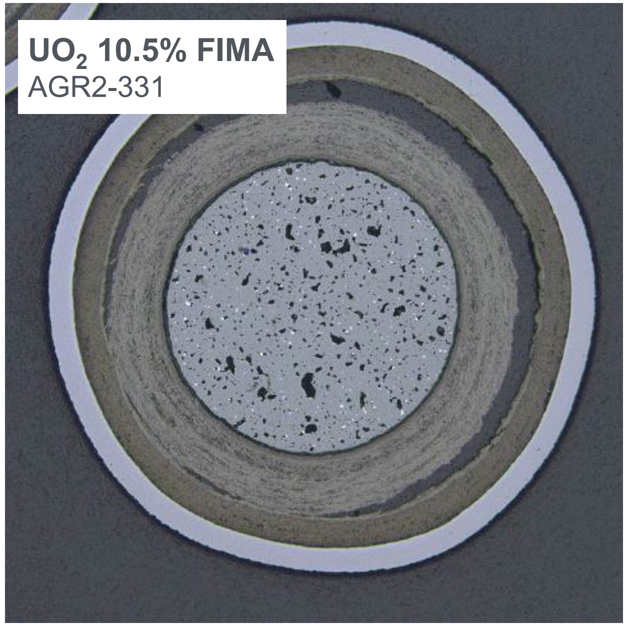
Irradiation Testing Results

- ~10^6 UCO particles in ~300 fuel compacts irradiated under a broad range of HTGR conditions
- ^{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

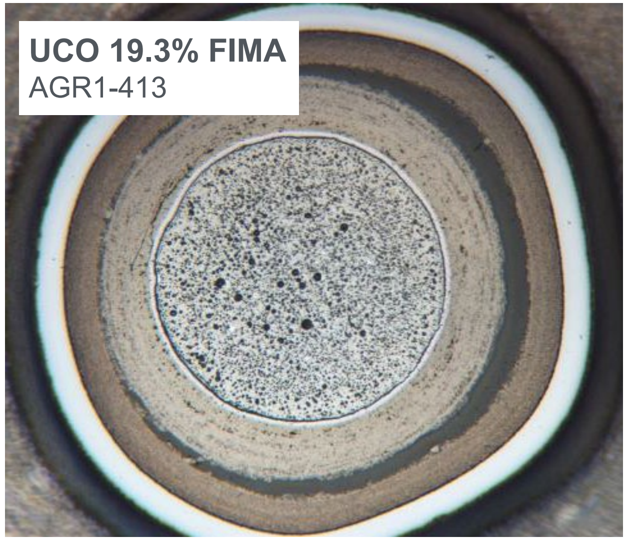


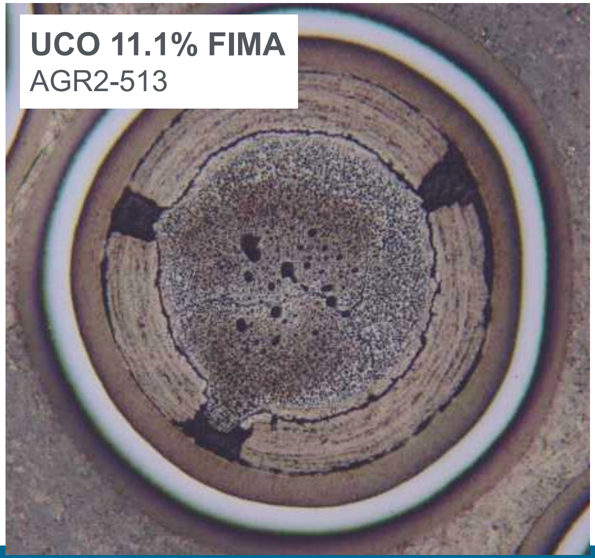
AGR-2 R/B values are through the first ~1/4 of the irradiation (149 EFPD)
AGR-567 R/B values are through the first ~1/2 of the irradiation (174 EFPD)

Kernel and Coating Behavior During Irradiation



- Kernel swelling and pore formation
- Buffer densification and volume reduction
- Separation of buffer and IPyC layers

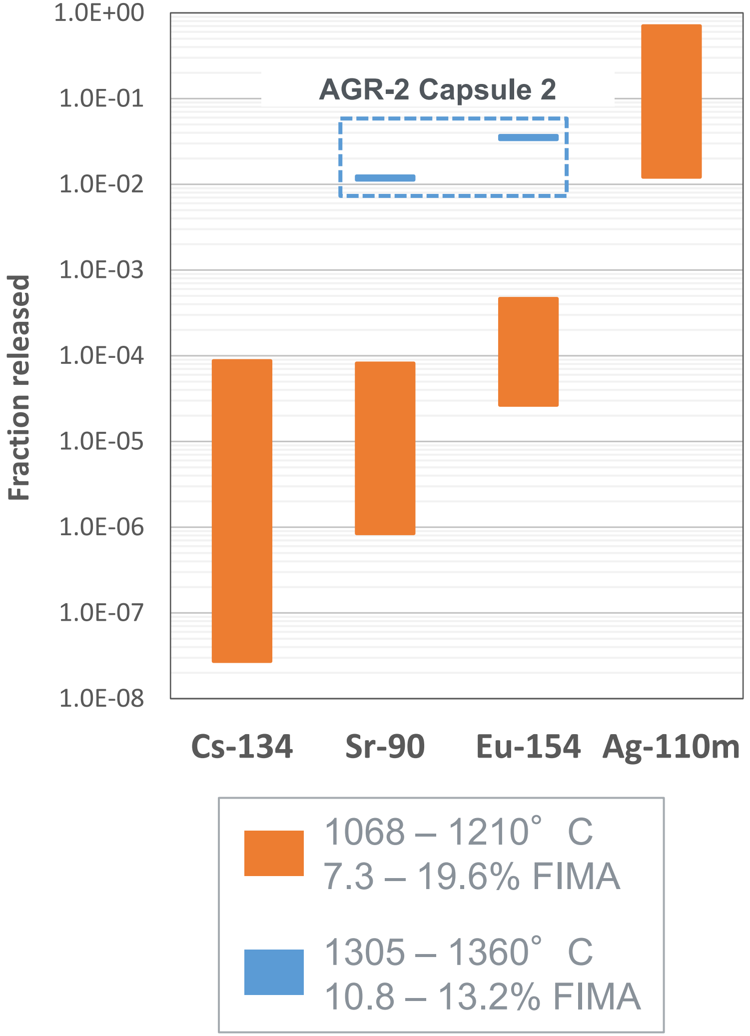




- Buffer fracture relatively common in UCO fuel particles
- Kernel can swell into gap
- Dependent on irradiation temperature and fast neutron fluence
- When buffer separates from IPyC, buffer fracture appears to have no detrimental effect on dense coating layers

Fission Product Release from UCO Fuel Compacts: AGR-1 and AGR-2 Examples

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



Time-average peak temperatures

- Cs release is very low with intact SiC; higher releases are associated with a limited number of particles with failed SiC
- Sr and Eu can exhibit modest release; release is appreciably higher with high in-pile temperatures
- High Ag release
- Note these releases do not account for retention in core graphite

Locating and Studying Failed Particles Greatly Improves Understanding of Fuel Performance

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

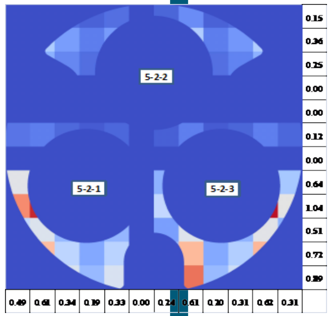
Fuel Compacts

Plenum between Capsules

AGR-1 Test Train Vertical Section

Identify compacts with leakers

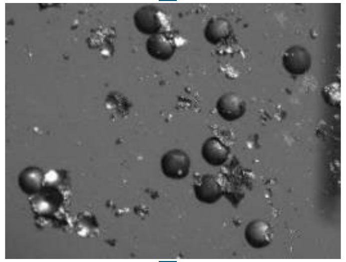
Capsule disassembly



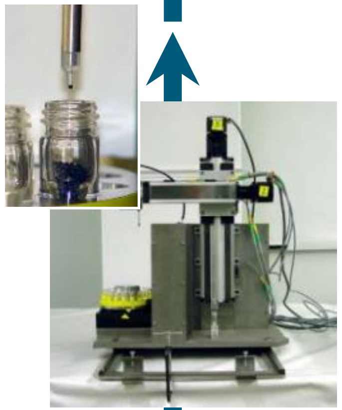
Gamma scan to identify cesium hot spots and compact location

Identify particles with failed coatings

Deconsolidation to obtain ~4,000 particles from compact

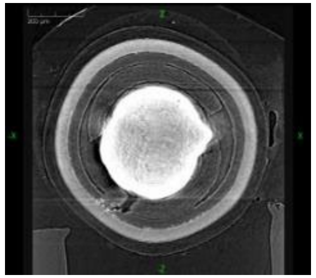


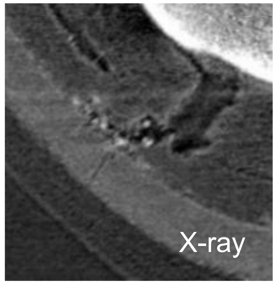
Gamma count to find particles with low cesium retention



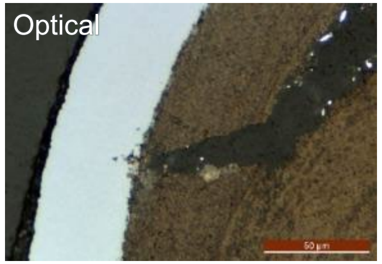
Study particles with failed coatings

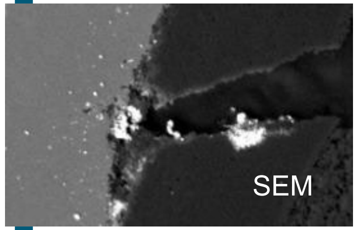
X-ray tomography to locate failures

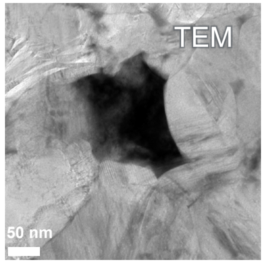




Materialography to expose defective region for analysis





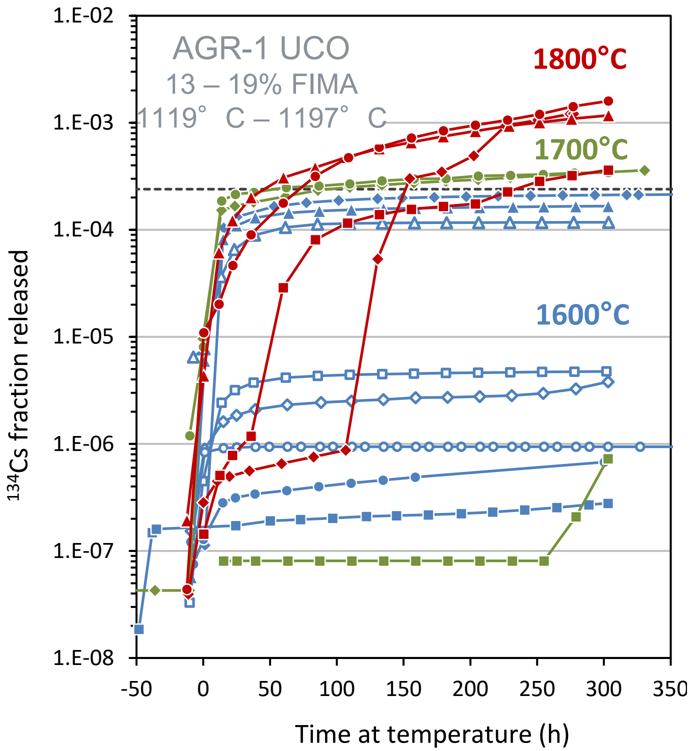


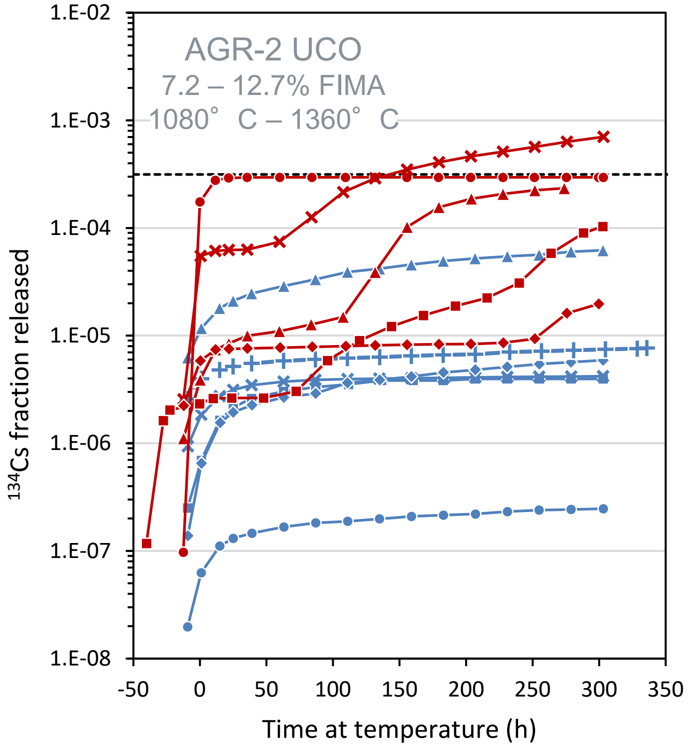
Advanced microscopy to study coating layers in detail

Safety Test Results for US UCO Fuel

- Zero TRISO layer failures at 1600 – 1700° C (very low Kr release)
- Cs release through intact SiC is very low (<10^{-5})
- Higher releases are dominated by a small number of particles with failure of the SiC layer
- Increasing test temperature increases the incidence of SiC failure

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





Temperatures are time-average peak irradiation temperature

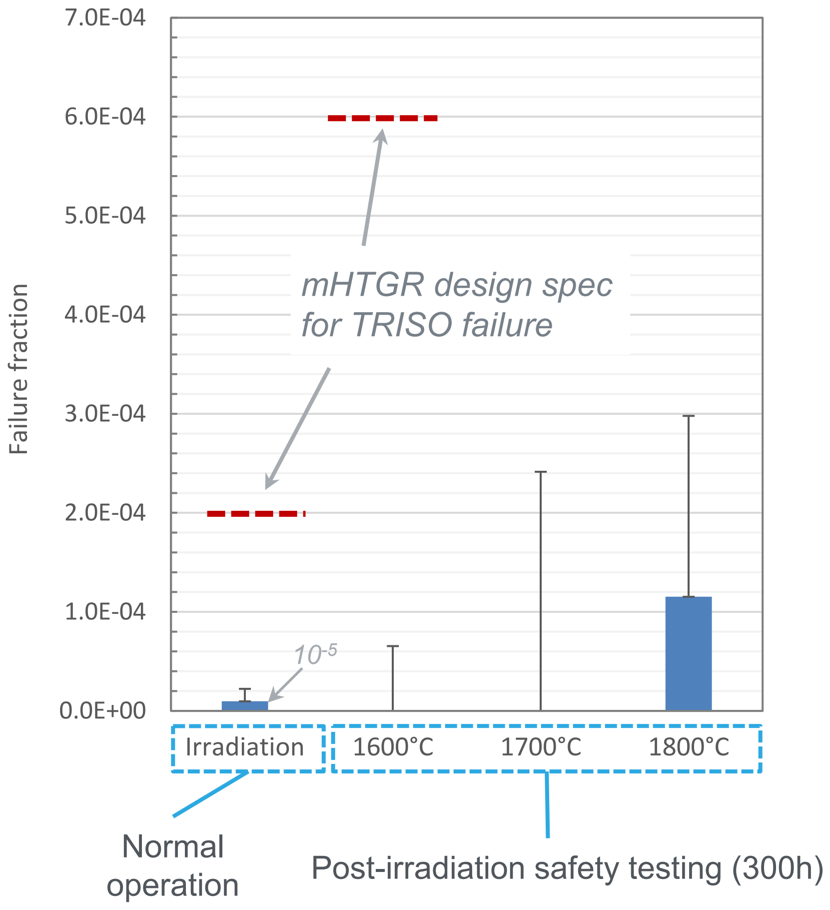
Accident Performance Summary

- Fuel withstands temperatures of 1600° C and beyond for 100s of hours without significant TRISO failure
- Release of condensable fission products is dominated by stored inventory in the matrix and gradual degradation of the SiC layer
- There is significant performance margin in terms of time at temperature

Key Outstanding Data Needs:

- Behavior of fuel and fission products under **core oxidizing conditions** (steam, air)
- Behavior of **short-lived fission products** during high-temperature accidents (e.g., ^{131}I)

Experimental TRISO failure fractions for AGR-1 + AGR-2 (upper limit at 95% confidence)



Fuel Performance and Fission Product Transport Modeling with PARFUME

PARFUME – PARticle Fuel ModEl

- Fuel Performance Code PARFUME
  - An integrated mechanistic code that evaluates the thermal, mechanical, and physico-chemical behavior of TRISO fuel particles
  - Capable of evaluating fuel particle failure under both irradiation and accident conditions
  - Tracks the probability of fuel particle failure given the particle-to-particle statistical variations in physical dimensions and material properties.

Early particle fuel performance codes were 1-D and considered only pressure vessel failure

- Various irradiation experiments had greater levels of failure than could be predicted by pressure vessel failure alone
- PIE results from NP-MHTGR and other experiments have revealed that other multi-dimensional effects may have contributed to the observed fuel failures
- To investigate these failure mechanisms, INL started development of an integrated mechanistic fuel performance modeling code called PARFUME

By 2000, the main components of PARFUME consisted of

- Closed form stress solution for a three-layer particle
- Monte Carlo sampling of particle attributes
- Failure probabilities calculated with Weibull distributions in coating layer strengths

By 2005, major code enhancements were in place which included

- Particle sampling performed by a multiple integration technique allowing for very small failure probabilities to be calculated
- Kernel migration and Pd penetration failure mechanisms considered
- Consistent set of material properties

By 2007, safety test conditions could be modeled within PARFUME where

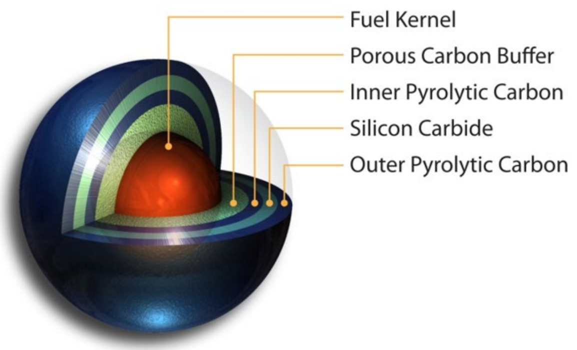
- Particle layer failures are synchronized with fission product diffusion
- Correlations from TMAP (Tritium Migration Analysis Program) are used to calculate fission product diffusion

PARFUME Capabilities

- Uses spherical symmetry to reduce the particle response to a 1D model and uses closed-form analytical solution for the stress-strain-displacement relationship.
- Correlates a 1D solution using strength and stress values obtained using a 2D finite element analysis to estimate multidimensional mechanisms of particle failures.
- Solution schemes include either Monte Carlo or direct numerical integration (both fast and full).
- Ability to model four types of reactor geometries:

Pebble Bed	Prismatic
Slab	Cylindrical

- Models intact UCO or UO_2 fuel particles and calculates failure probability due to tradition pressure vessel failure, cracking of the IPyC layer, partial debonding of IPyC/SiC, and pressure vessel failure of an aspherical particle.

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Revision 2

PARFUME Theory and Model Basis Report

February 2023

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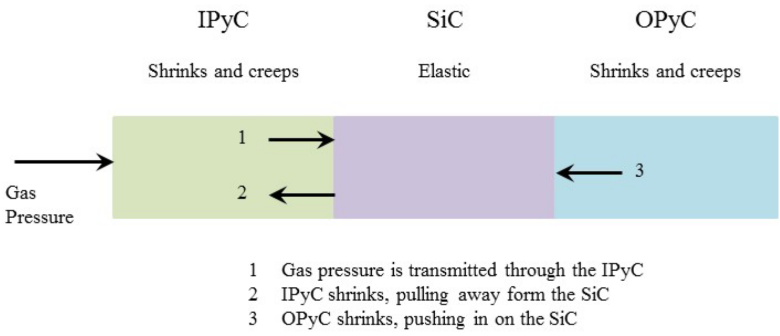
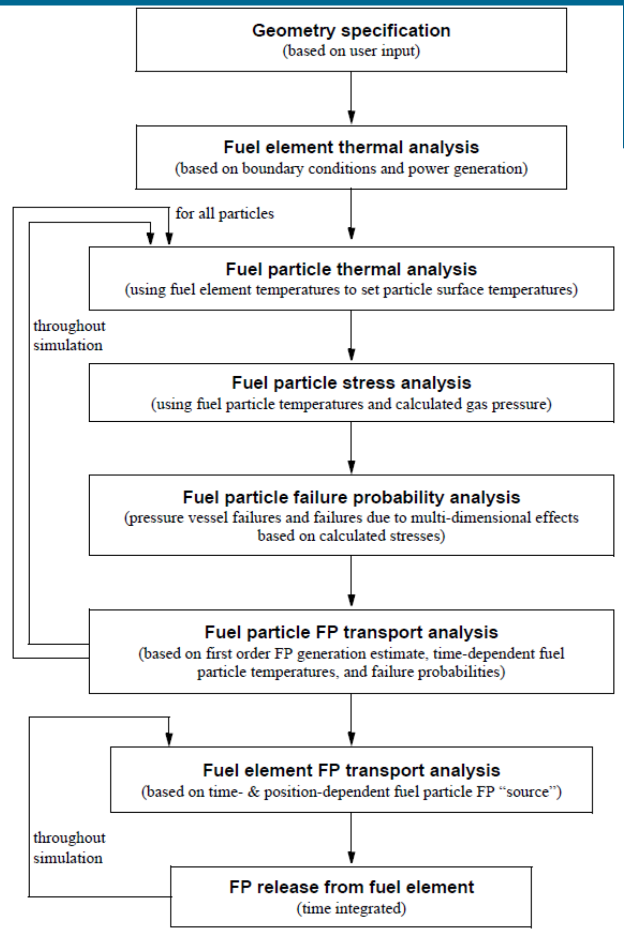
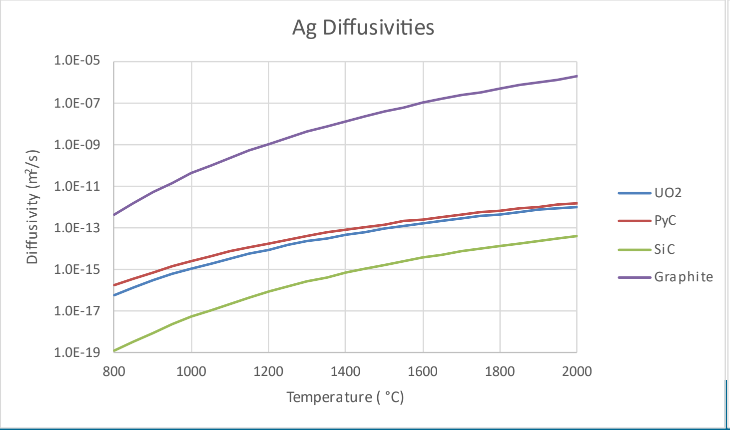


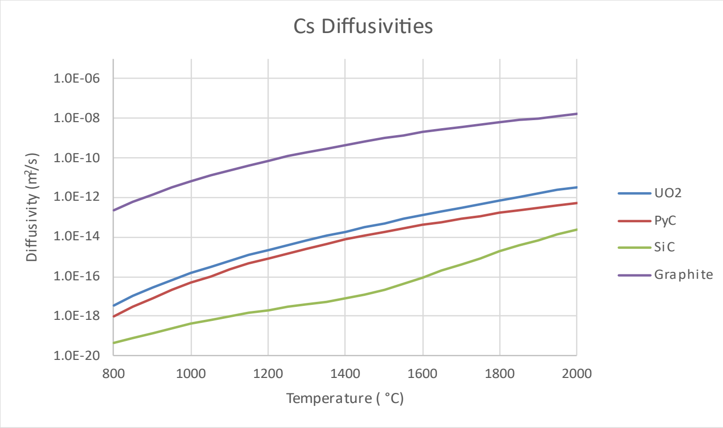
PARFUME Capabilities (cont.)

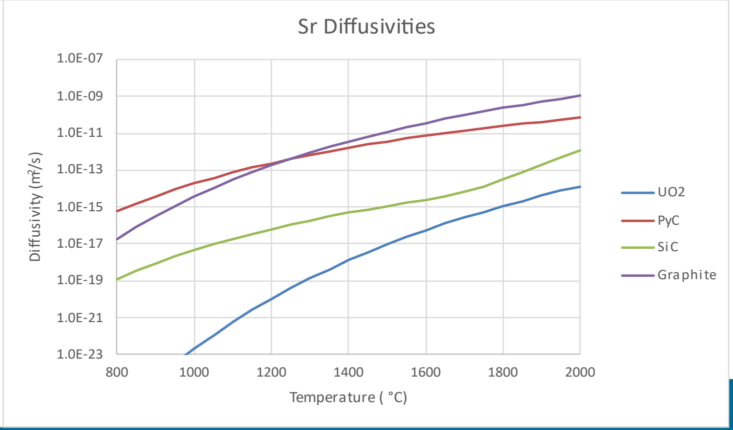


- Physico-chemical models include:
  - Booth equivalent sphere fission gas release using Turnbull diffusivities
  - Redlich-Kwon equation of state
  - HSC thermodynamic based analysis for CO production
  - Fission product SiC interactions (e.g. Pd)
  - Amoeba effect
- Fission product transport in PARFUME is based on coding extracted from the Tritium Migration Analysis Program Version 4 (TMAP4).
  - PARFUME calculates fission products (silver, cesium, and strontium) transport through individual TRISO-coated particles to the surrounding graphite matrix and subsequent release from the fuel element.
  - Diffusion coefficients used in PARFUME for each of these species in the successive coating layers and matrix are obtained from IAEA TECDOC-978.

$$D(T) = \sum_i D_{0,i} e^{\left(-\frac{Q_i}{RT}\right)}$$

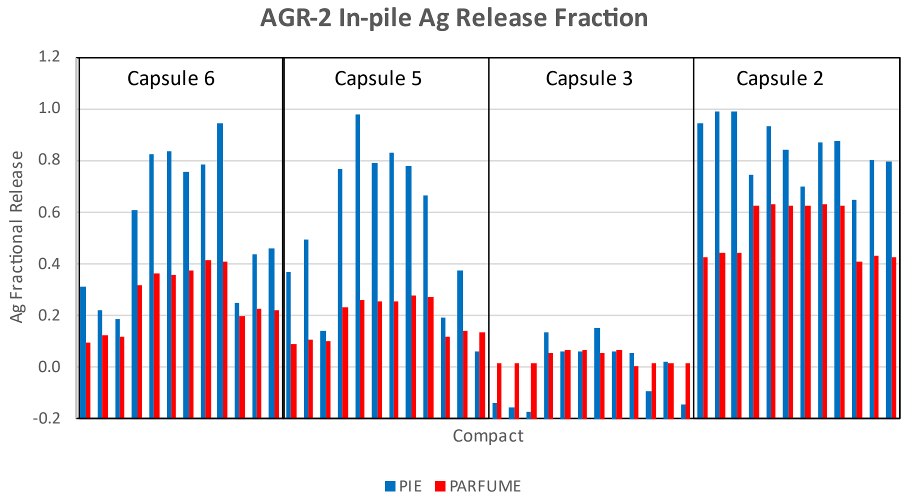






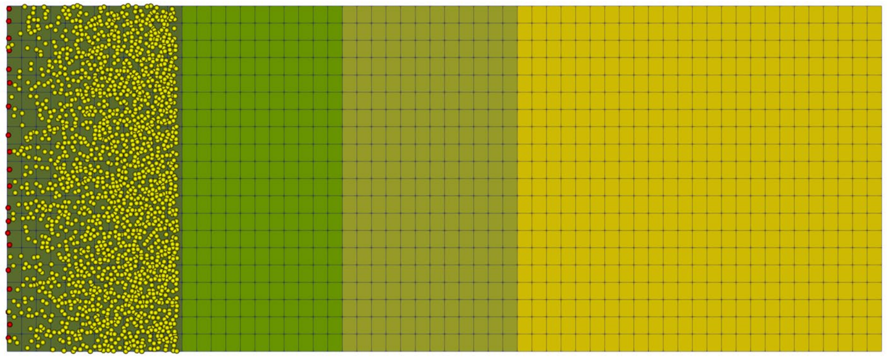
Fuel Performance Modeling to Support the AGR Irradiation Experiments

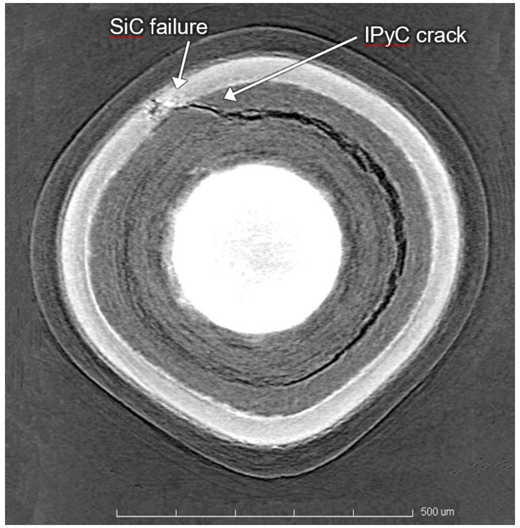
- Pre- and post-irradiation fuel performance predictions
- Comparison of in-pile fission product release predictions with measured values
- Comparison of post-irradiation safety test fission product release predictions with measured values
- Support fuel specification development



Additional Fuel Performance Modeling Activities

- Additional activities
  - IAEA CRP-6
  - Material properties sensitivity study for TRISO fuel particles GIF accident benchmark code comparison
  - Kernel/buffer volume fraction impact on performance
- Future model improvements
  - Fission product transport model
  - Thermomechanical buffer layer modeling
  - Pyrocarbon creep rate

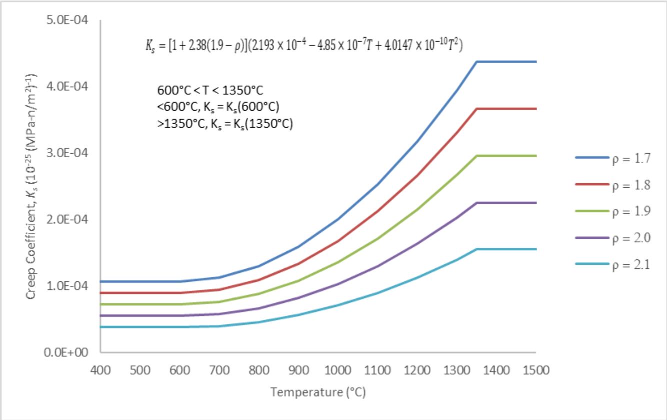




AGR-5/6/7 predicted fuel particle failure using PARFUME.

Capsule	5	4
Average compact temperature (°C)	741	839
Average compact predicted failure fraction	2.60E-04	1.14E-04
Total number of TRISO particles	81432	52728
Predicted number of TRISO particle failures	21	6
Observed number of TRISO particle failures[1]	0	0

1. Per AGR-5/67 irradiation as-run report based on the data currently available.



Questions?

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