INL/MIS-23-75732-Revision-0

# DOE Advanced Gas Reactor Fuel Development and Qualification Program

November 2023

Changing the World's Energy Future

Paul A Demkowicz

Idaho National Laboratory

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**November 2023**

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AGR Program Technical Director

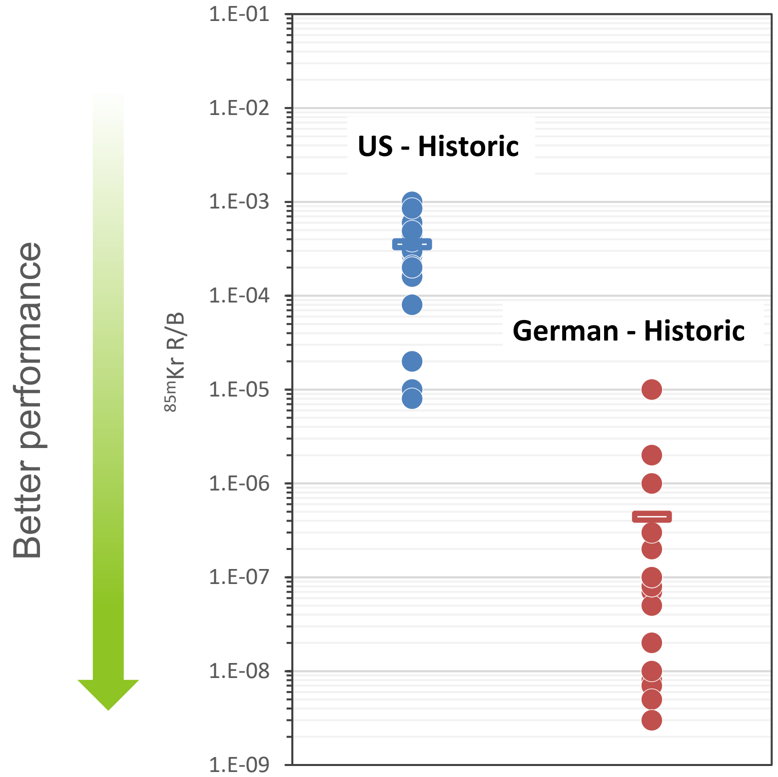
# DOE Advanced Gas Reactor Fuel Development and Qualification Program

ART Advanced Reactor Technologies
GAS-COOLED REACTORS

# Background: Status of TRISO Technology Circa 2000

- Four decades of experience with coated particle fuel in numerous countries and operation of several demonstration reactors
- Successful demonstrations of TRISO fuel performance (German program in 1980s and 1990s)
- Major issues with US TRISO fuel performance including 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

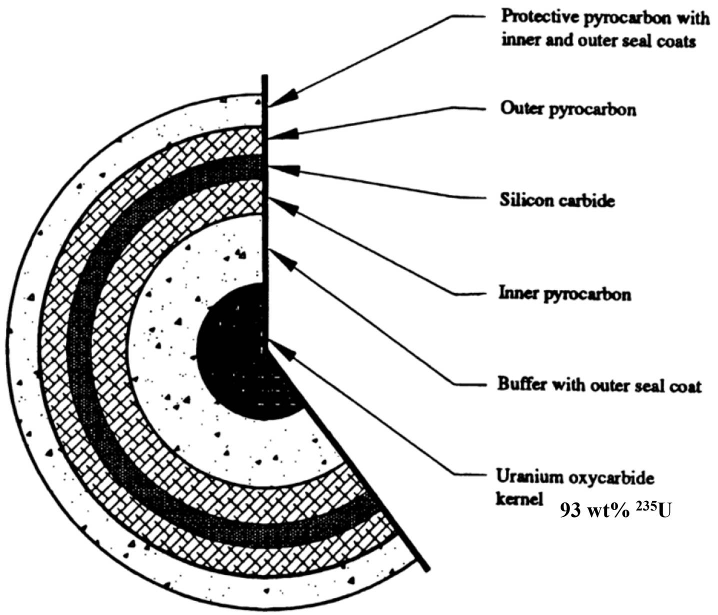
Comparison of US and German $^{85m}$Kr R/B data



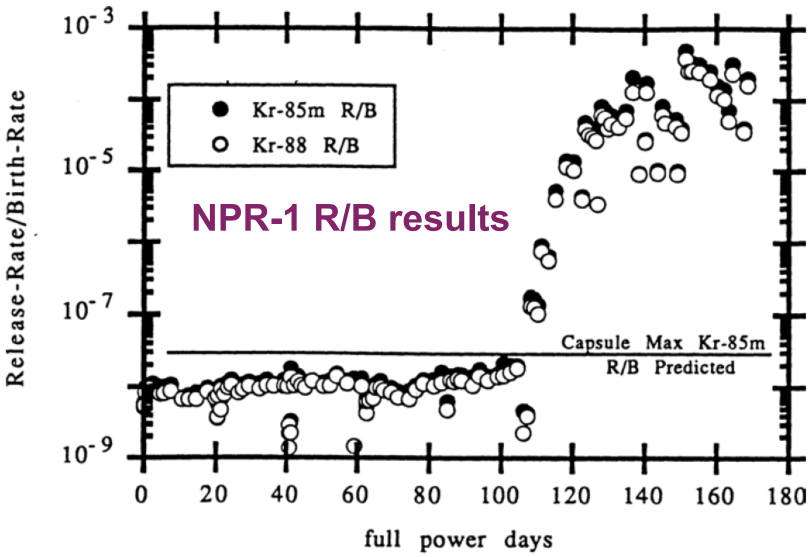
# New Production Reactor (NPR) Fuel Experience

- NPR program started 1988 to produce tritium in an MHTGR
- General Atomics implemented several changes to particle design including: PPyC, thicker IPyC, and thin PyC "seal coats"
  - Best as-manufactured fuel quality ever in the US
- Fuel performance models predicted no failures
- Three irradiations: NPR-1, NPR-2, NPR-1A
  - Failures occurred during all three irradiation tests at similar fast neutron fluence; total failed was ~700/230,000 or $3 \times 10^{-3}$
  - Pyrocarbon layers were implicated in high failure rates
- Sep 1992 – DOE announces termination of program
- Sep 1993 – Project closeout completed
- "*These results indicate that future particle fuel designs would benefit by considering the performance of the entire system of coating layers with respect to particle integrity under irradiation.*" (Maki et al., INEEL/EXT-02-01268, 2002)

NPR fissile particle design




Maki et al., INEEL/EXT-02-01268, 2002



# Fuel Qualification

- *"Demonstration that a fuel product fabricated in accordance with a specification behaves as assumed or described in the applicable licensing safety case, and with the reliability necessary for economic operation of the reactor plant."* (Crawford et al., J Nuc Mater 371 (2007) 232)

- Requires:
  - Specification for the fuel design, including relevant material properties and geometry
  - "A database of fuel properties and irradiation behavior to sufficiently reduce the safety and reliability uncertainty for use of the fuel design."

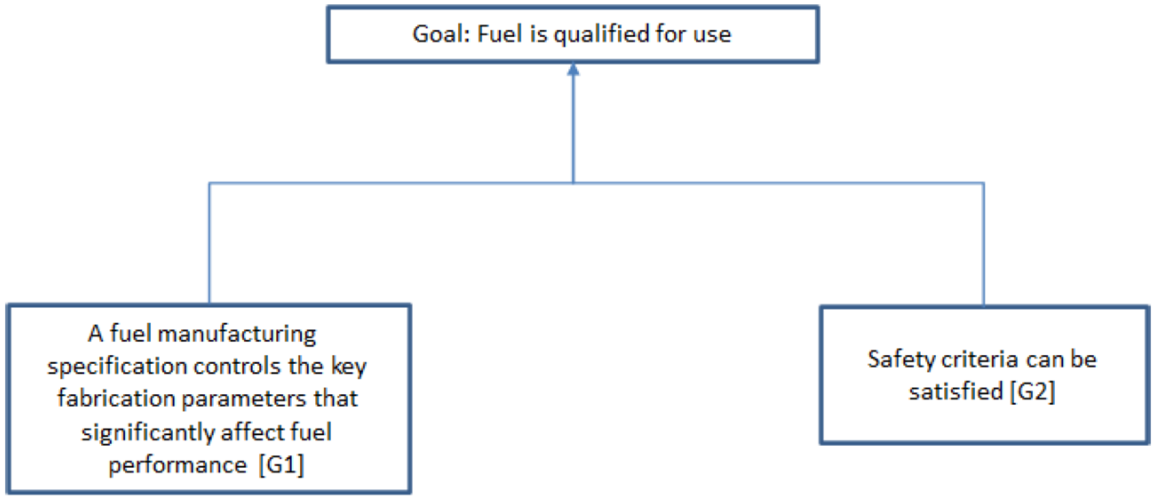


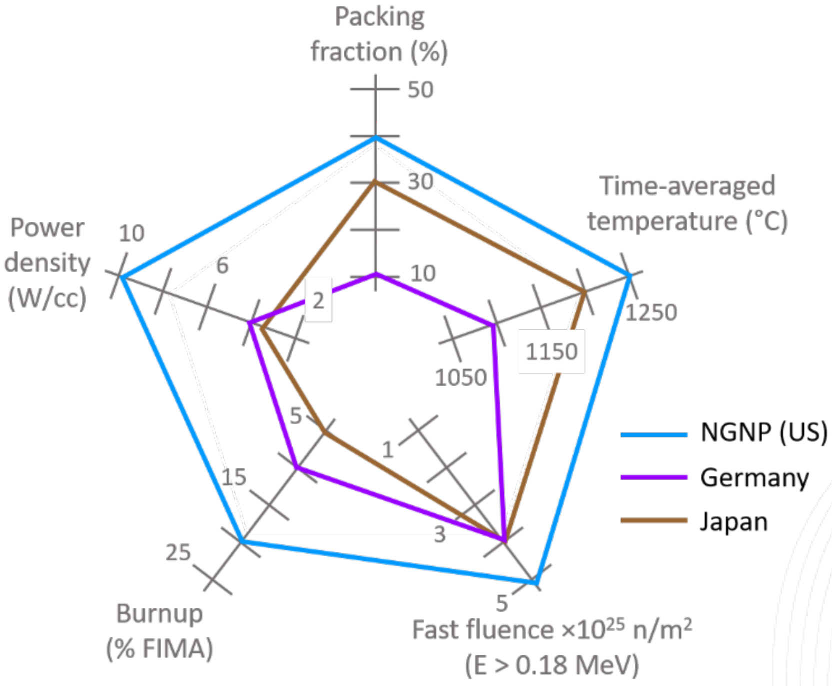

**Figure 3-1 Decomposition of the Main Goal**

NUREG-2246, "Fuel Qualification for Advanced Reactors"
https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2246/index.html

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

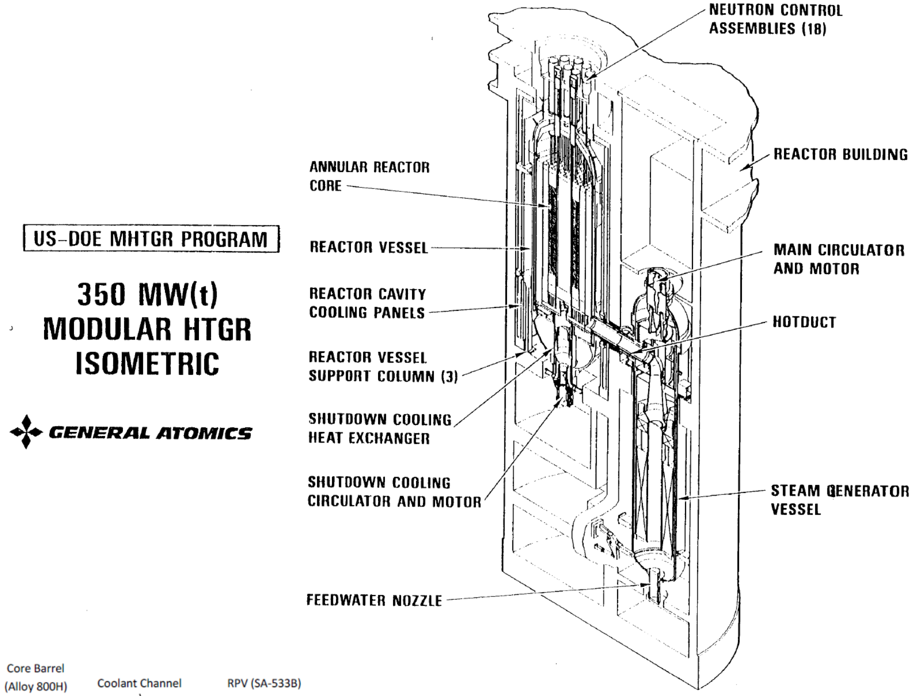
- Focus on LEU UCO TRISO fuel in cylindrical compacts, consistent with prismatic reactor designs that had been pursued in the US
- Pursued a more aggressive performance envelope compared to German and Japanese programs
- Objectives and Motivation:
  - Provide data for fuel qualification in support of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

**Reduce market entry risk**



# Initial AGR Program Reference HTGR Design

- General Atomics *Modular High Temperature Gas Cooled Reactor* (MHTGR)
  - 350 MWt prismatic design
  - He-cooled, graphite moderated
  - 687 °C core outlet temperature
  - UCO TRISO fuel (15.5 wt% $^{235}$U) in cylindrical compacts




R.F. Turner and A.J. Neylan, GA-A19391, 1988

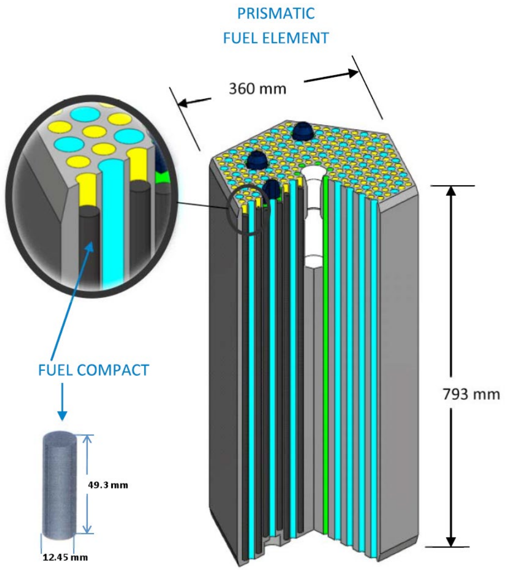



Fig. 5. Isometric view of fuel element containing fuel compacts.

*Diagram reflects later GA SC-MHR design (M. Richards et al., GA-A27283, 2012)*

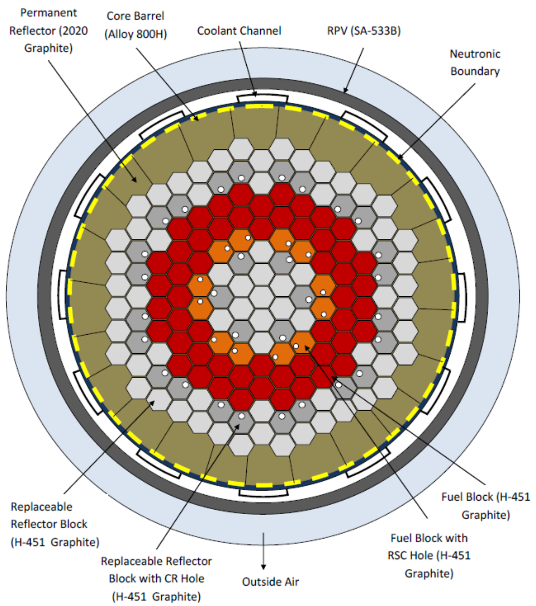



**Figure I-3: MHTGR Reactor Unit Layout – Plane**

# Fuel Qualification Approach

- Develop fuel performance models to describe particle behavior, explain past particle failures (NPR), 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

**Irradiation experiments:**

Fuel performance testing

*Fuel fabrication scale-up*

**AGR-1** → **AGR-2** → **AGR-5/6/7**

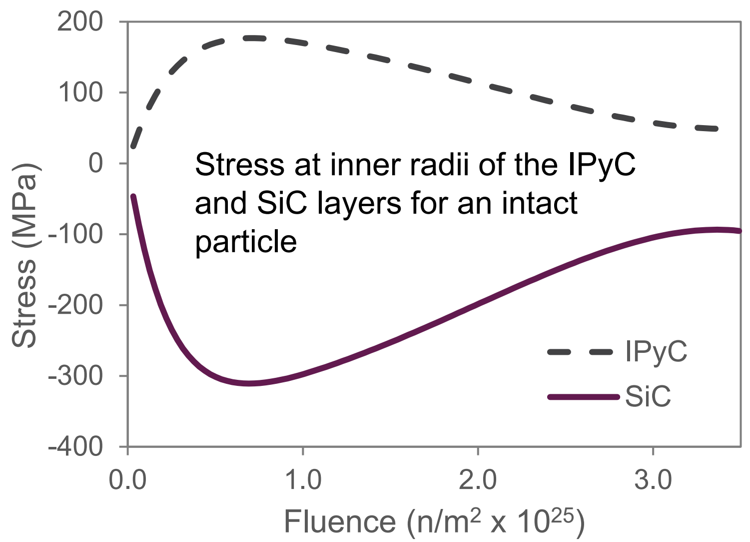
- **AGR-1**: *Early test of lab-scale UCO fuel performance; shakedown of test train design.*
- **AGR-2**: *Engineering-scale particles in lab-scale compacts. Includes UCO and $UO_2$ fuel.*
- **AGR-5/6/7**: *Fuel qualification test. Engineering-scale UCO particles and compacts.*

Fission product transport experiment

**AGR-3/4**: *“Designed-to-fail” (DTF) fuel to assess fission product retention and transport in reactor graphite and fuel matrix.*

# Fuel Performance Modeling


1. Gas pressure is transmitted through IPyC
2. IPyC shrinks, pulling away from the SiC
3. OPyC shrinks, pushing on the SiC




- Model thermomechanical behavior of coatings as a function of particle properties and irradiation conditions
- **Predict coating failure fractions**
- Predict fission product release
- Optimize particle design
- Help establish fuel product specifications
- Numerous codes developed in various countries dating to the 1960s
  - 2000s: Particle Fuel Performance Model (PARFUME)
  - 2010s: BISON Nuclear Fuel Performance Code

W. Jiang et al, *TRISO particle fuel performance and failure analysis with BISON*, JNM 548 (2021) 152795

# Fuel Fabrication

## Major effort to improve fuel fabrication capabilities

- Better understand coating layer properties that result in desirable fuel behavior
- Many improvements to fabrication methods
  - Minimize as-fabricated coating layer defects
  - Optimize kernel and coating properties
  - Narrow property distributions
- Improve measurement science for reliable fuel property characterization


INEEL/EXT-02-00300

INEEL

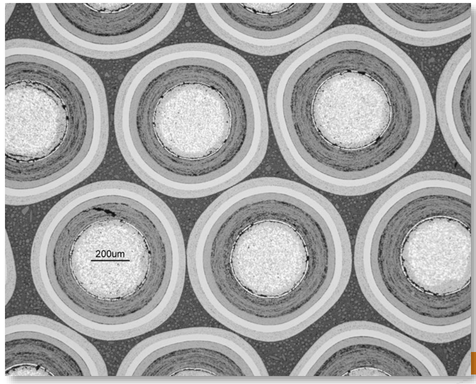
Key Differences in the Fabrication, Irradiation and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance

David A. Petti
John T. Maki
Jacopo Buongiorno
Richard R. Hobbins
Gregory K. Miller

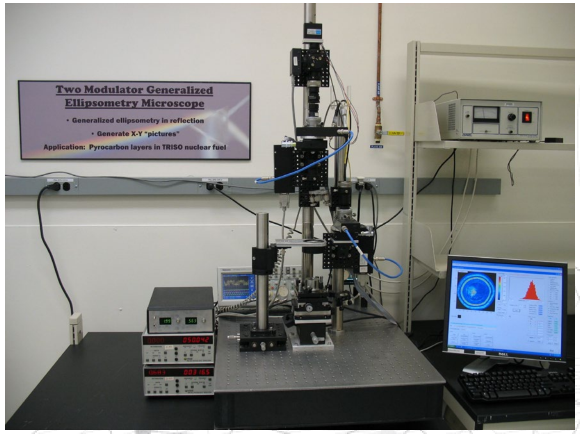
June 2002

*Coater chalice*

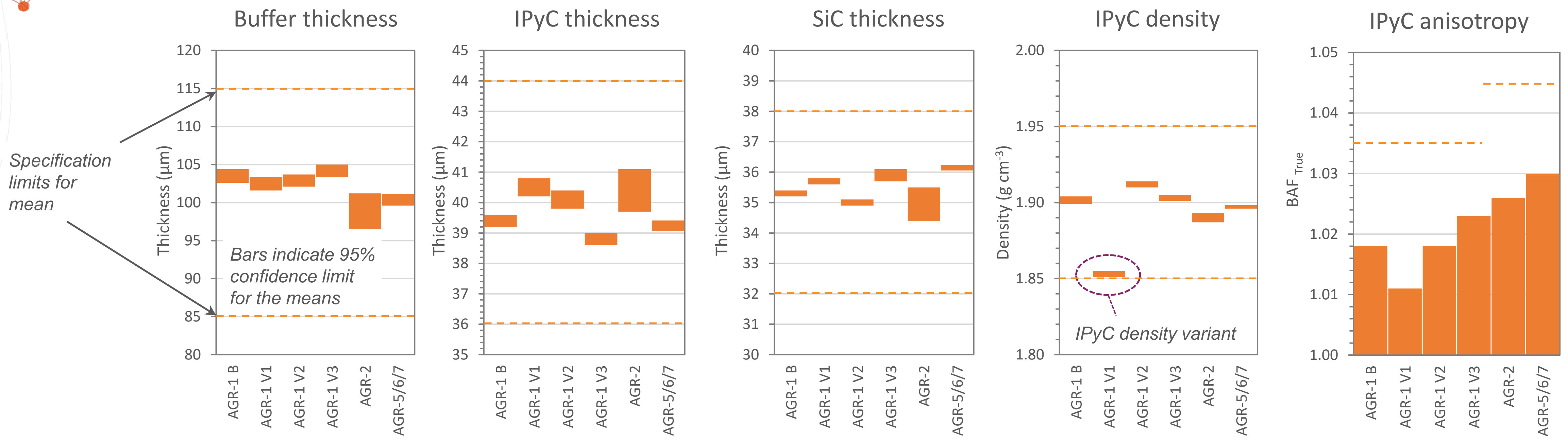
*Kernel formation*




*PyC anisotropy measurements*



# Selected AGR-1, AGR-2, and AGR-5/6/7 Fuel Property Means

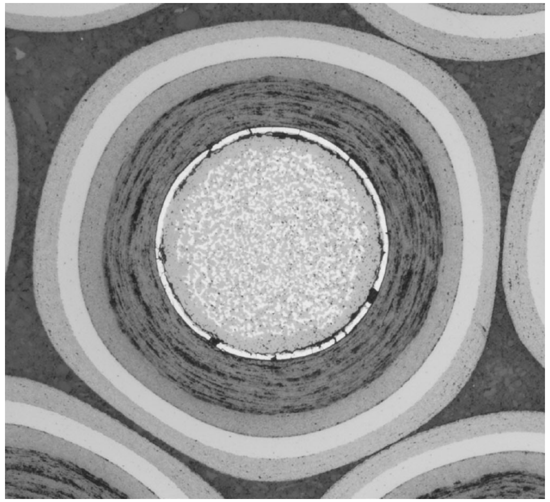


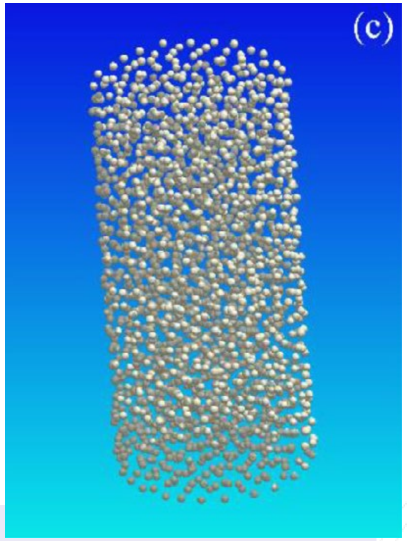

- Mean must be within the specification limits at 95% confidence
- Measured values typically lie well within the specification range
- Note that some specifications were changed following AGR-1, based on computational modeling results on fuel behavior

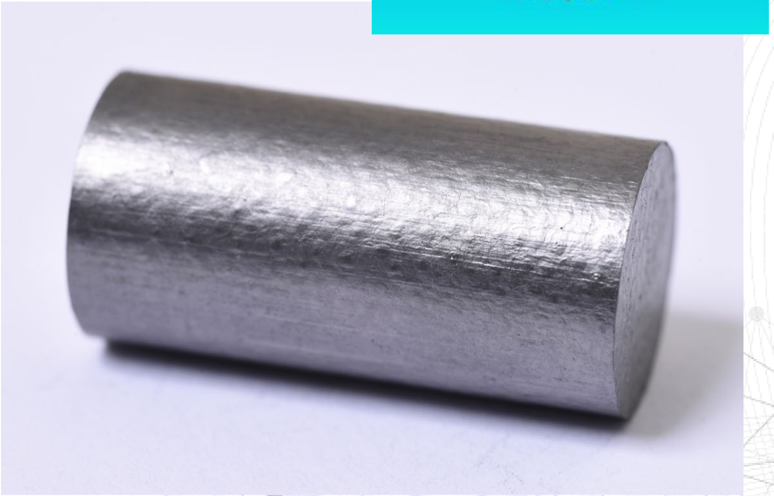
# AGR Program TRISO Fuel

| 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)<br>$UO_2$ (508) | 14.0<br>9.6 | 3180 (37)<br>1540 (23) | 1.26<br>0.99 |
| AGR-5/6/7 | UCO (426) | 15.5 | 2240 (25)<br>3430 (38) | 0.89<br>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*

# Key TRISO Fuel Performance Data

## During irradiation

- Fission gas release during irradiation: release-rate-to-birth-rate ratio (R/B)
- Coating layer failure statistics

## Post-irradiation examination

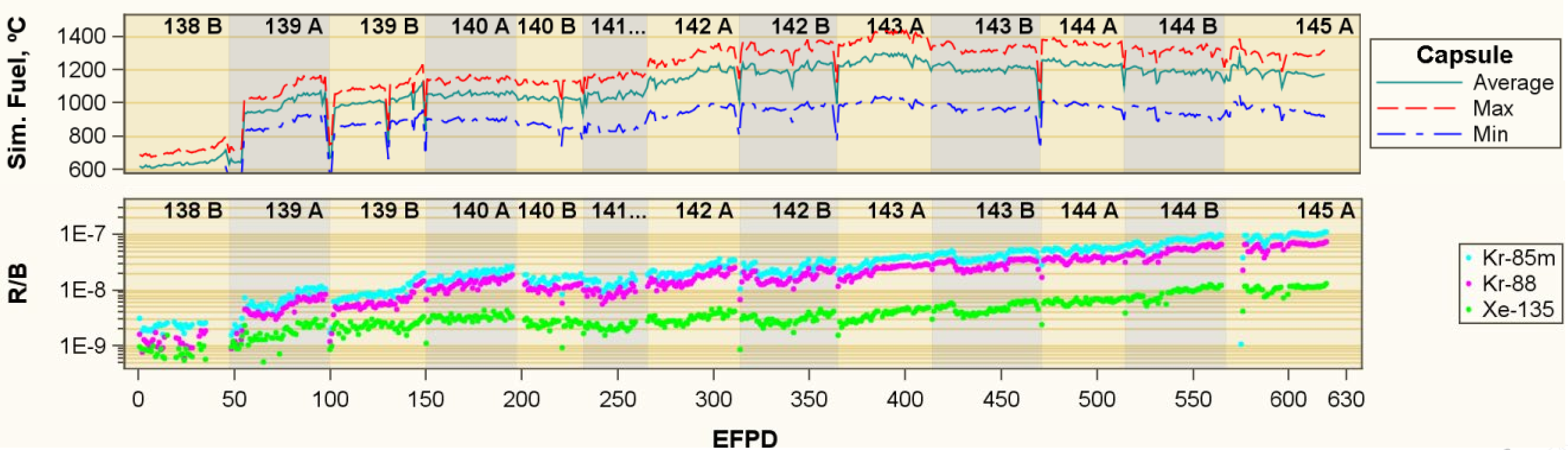
- Kernel and coating morphology evolution
- Condensable fission product release during irradiation (e.g., Cs, Ag, Sr)
- Fission product release during high-temperature accidents
- Coating layer failure statistics
- Oxidation behavior of fuel and fission products

# Irradiation Performance: Fission Gas R/B

- Sources of fission gas release:
  - Uranium contamination outside of intact SiC layers
  - Exposed kernel defects (as-fabricated)
  - Exposed kernels from in-service coating layer failure

*Allowable levels dictated by specifications*

- Fission gas release-rate-to-birth-rate ratio (R/B) provides information on the extent of coating failures during irradiation



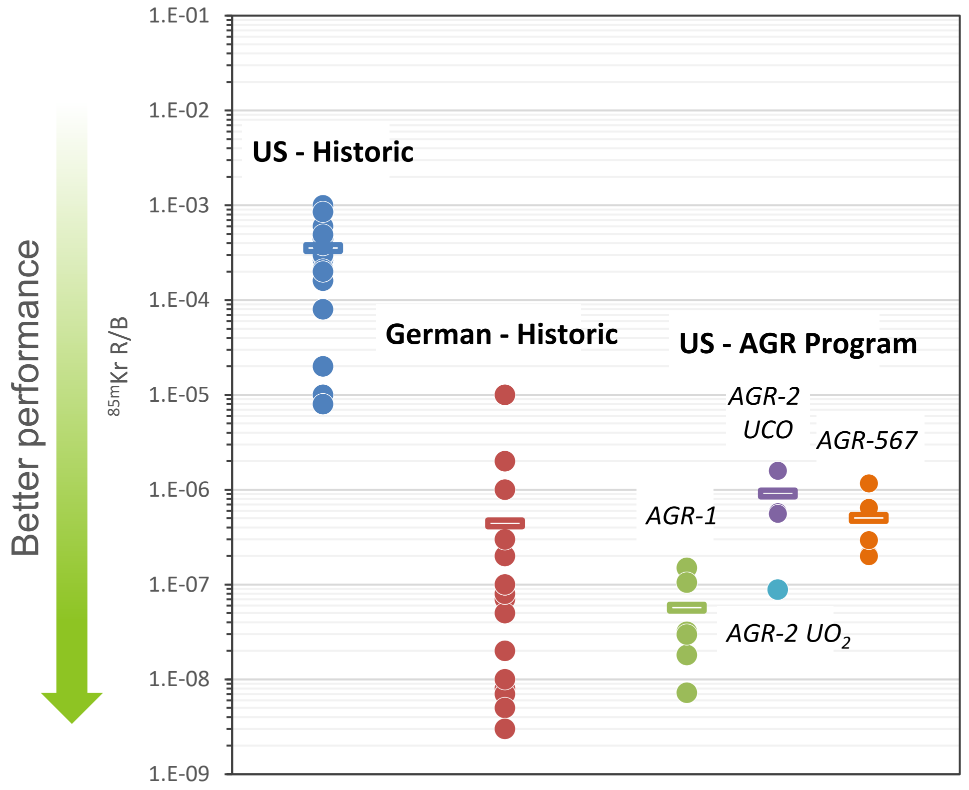

***AGR-1 Capsule 6 Data***

***→ Data indicate zero as-fabricated exposed kernels or in-pile TRISO failures in this capsule***

# Irradiation Testing Results

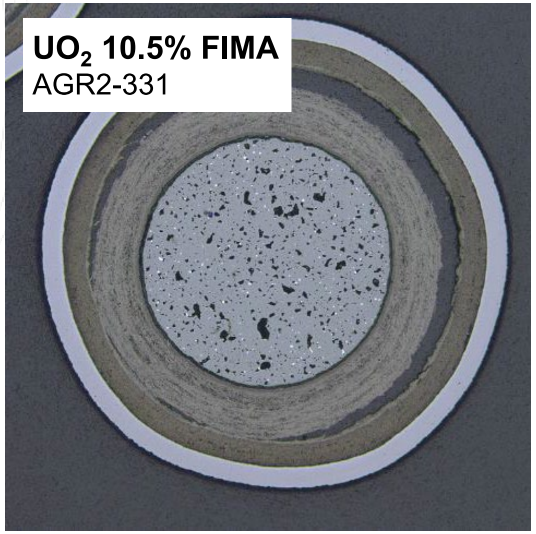
- ~$10^6$ UCO particles in ~300 fuel compacts irradiated under a broad range of HTGR conditions
- $^{85m}$Kr R/B of ~$10^{-8}$ – $10^{-6}$ at peak burnup of 19.6% FIMA
- Operational issues with AGR-2 and AGR-5/6/7 impaired R/B measurement during later cycles

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

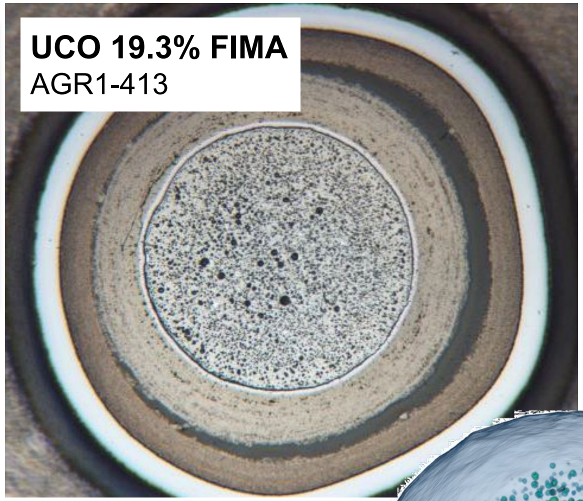


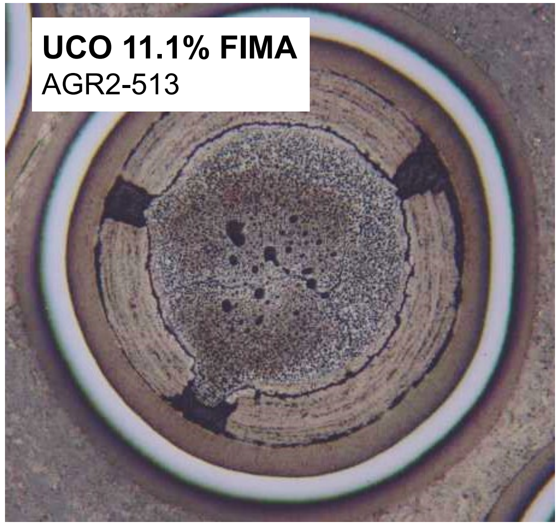

*AGR-2 R/B values are through the first ~1/4 of the irradiation (149 EFPD)*
*AGR-567 R/B values are through the first ~1/2 of the irradiation (174 EFPD)*

# Kernel and Coating Behavior During Irradiation

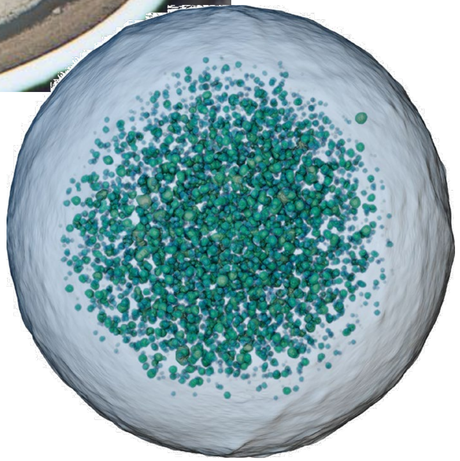



- Kernel swelling and pore formation
- Buffer densification and volume reduction
- Separation of buffer and IPyC layers




- 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



*3D rendering of irradiated AGR-2 UCO kernel pore structure from x-ray computed tomography*

# Locating and Studying Failed Particles Greatly Improves Understanding of Fuel Performance

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

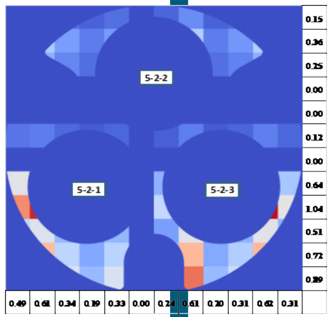
**Fuel Compacts**

**Plenum between Capsules**

AGR-1 Test Train Vertical Section

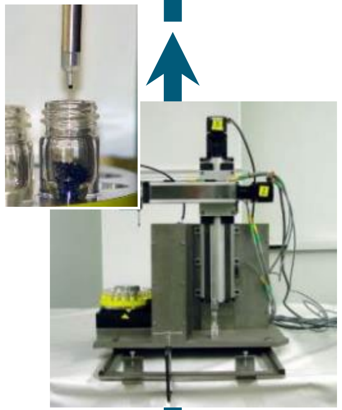
*Identify compacts with leakers*

Capsule disassembly

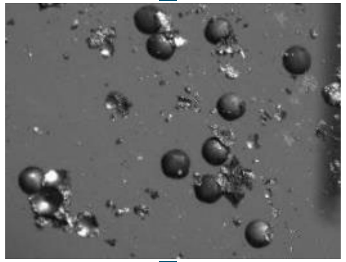



Gamma scan to identify cesium hot spots and compact location

*Identify particles with failed coatings*



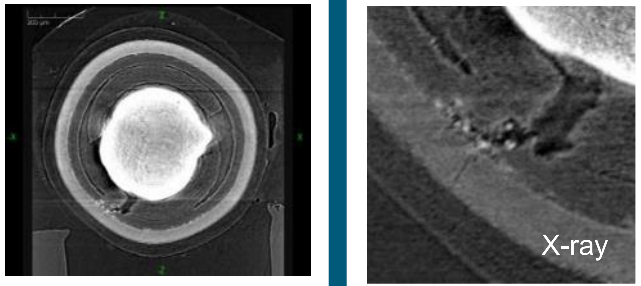
Gamma count to find particles with low cesium retention



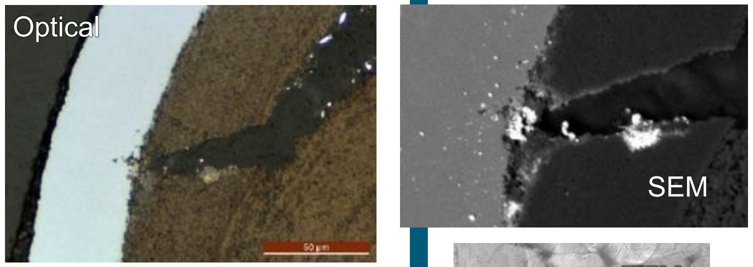
Deconsolidation to obtain ~4,000 particles from compact

*Study particles with failed coatings*

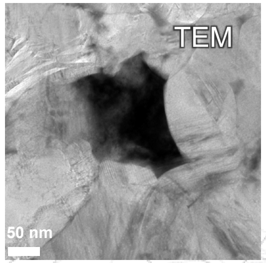
X-ray tomography to locate failures




Materialography to expose defective region for analysis

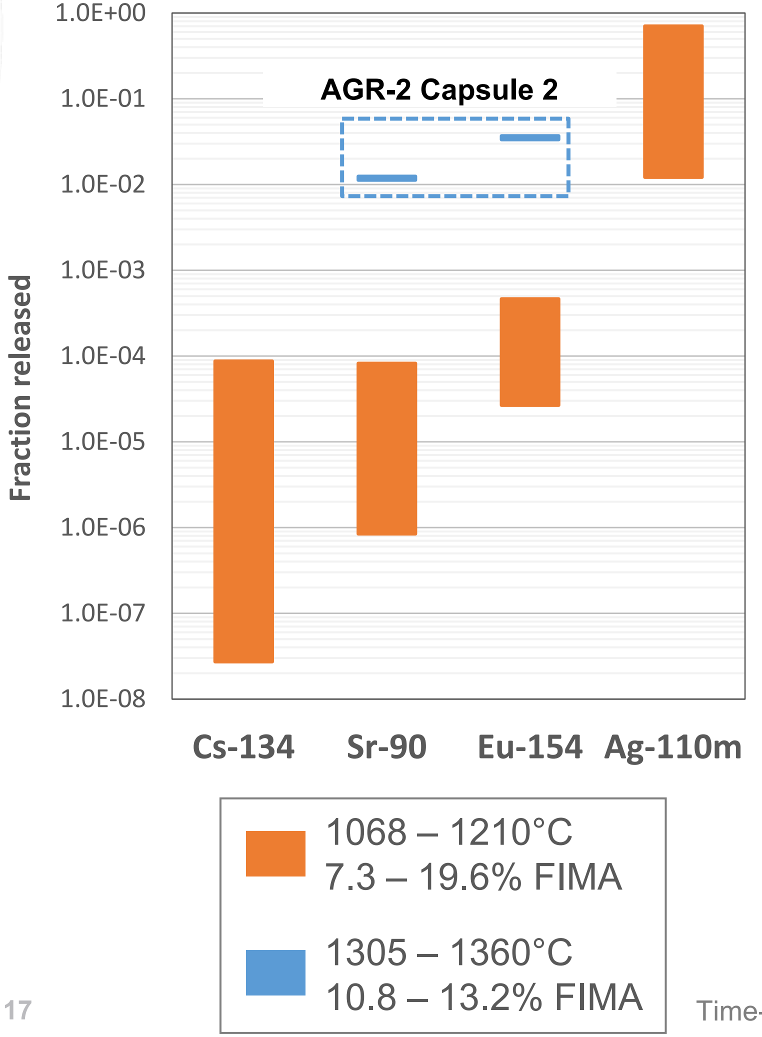



Advanced microscopy to study coating layers in detail



# 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

# HTGR Accident Safety Testing of TRISO Fuel

- Temperature transients are relatively slow (days)
- Peak fuel temperatures are limited to ~1600°C in modular HTGR designs
- Fuel particles are designed to withstand accident conditions while still retaining key safety-significant fission products
- Total duration at peak temperatures is tens of hours, with a small fraction of the fuel in the core experiencing temperatures near the peak
- Extremely rapid reactivity insertion accidents (RIAs) are precluded by HTGR core design
- Assess fuel performance by post-irradiation heating tests while measuring fission product release at 1600 – 1800°C

*Core temperature during depressurized loss of forced cooling accident – HTR Module*

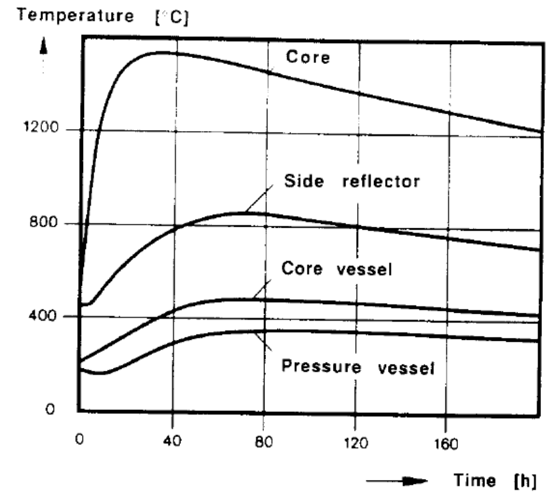



Fig. 11. Time-dependent component temperatures after depressurization accident.

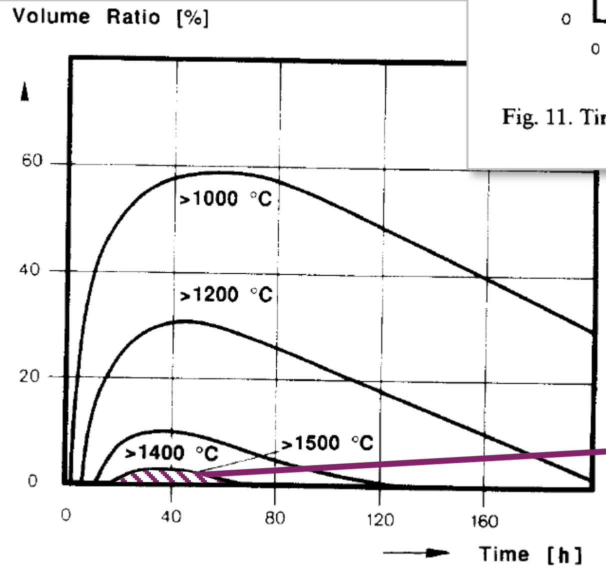
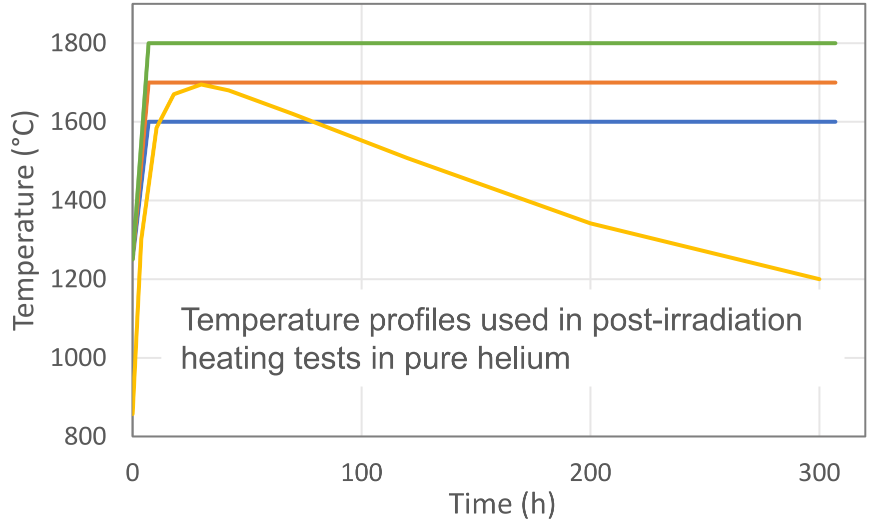


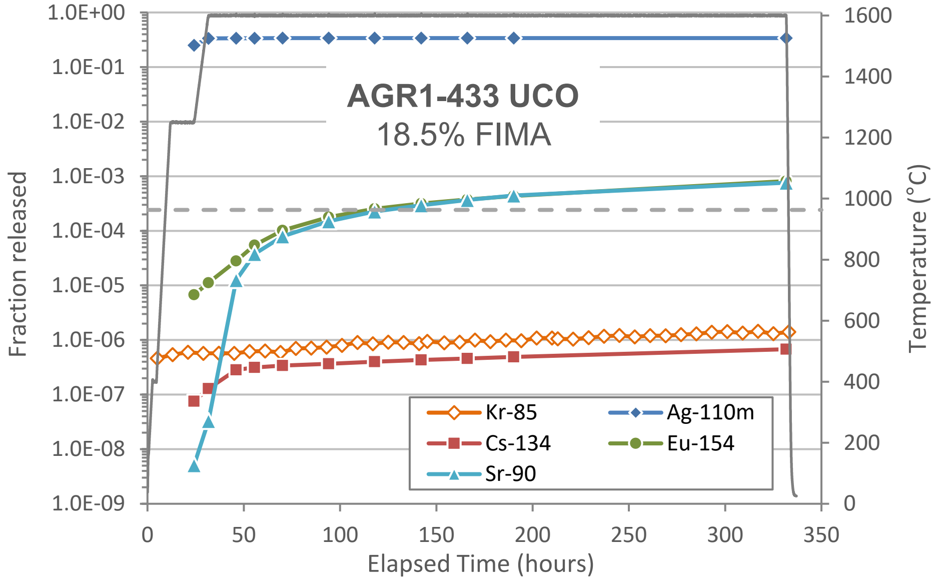

Fig 12. Time-dependent volume ratio of fuel element temperatures.

~3% of fuel >1500°C

*G. Lohnert, et al. Nuc. Eng. Des. 121 (1990) 259-275*

# Evaluating Behavior During D-LOFC Accidents



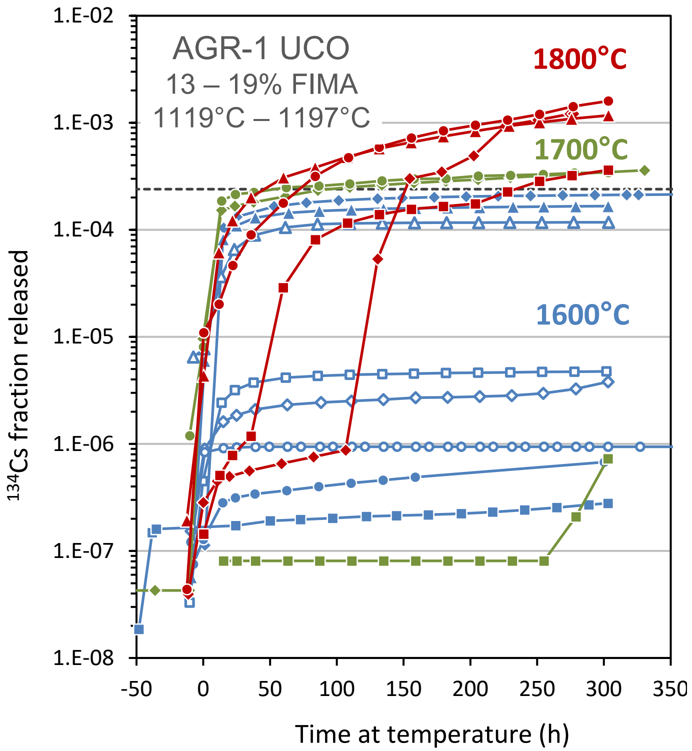



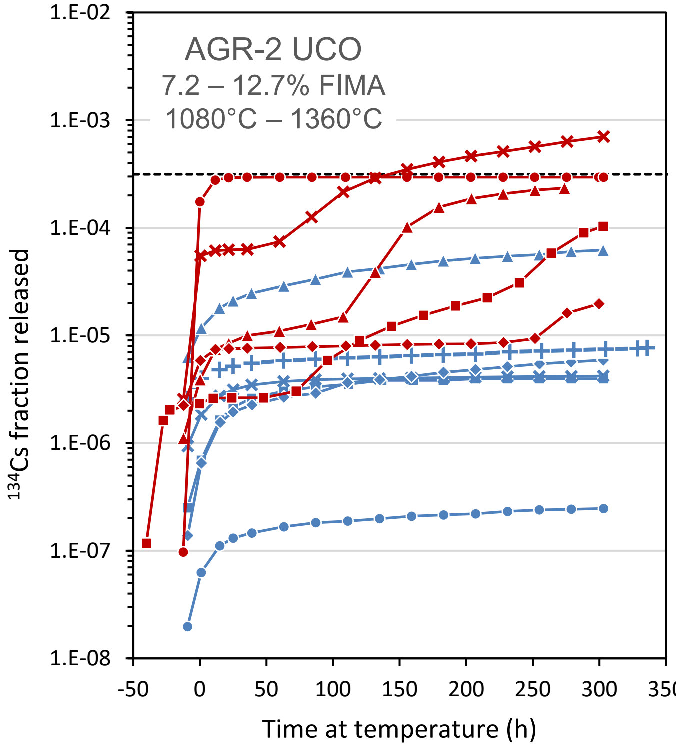

- Two types of heating profiles used:
  - Isothermal
  - Variable temperature mimicking peak fuel temperature during D-LOFC
- Hundreds of hours in pure helium
- Two test systems used:
  - Core Conduction Cooldown Test Facility (CCCTG) – ORNL
  - Fuel Accident Condition Simulator (FACS) – INL
- Kr release: indication of failed TRISO
- Cs release: indication of failed SiC (if PyC intact)

# 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 | $4 \times 10^{-5}$ |
| 1800 | $6 \times 10^{-4}$ |

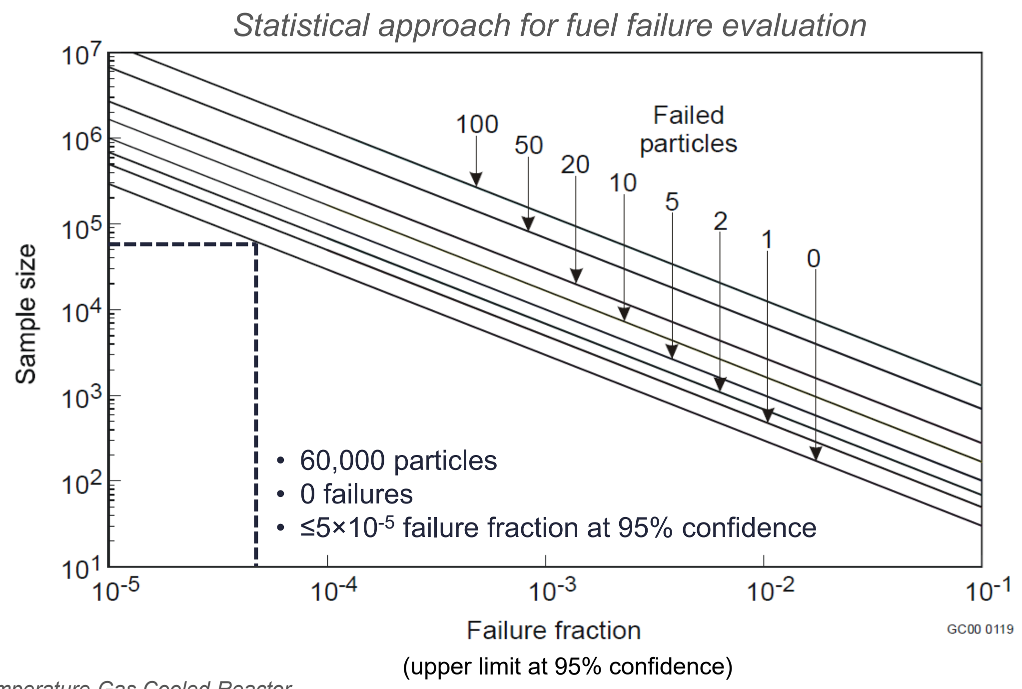


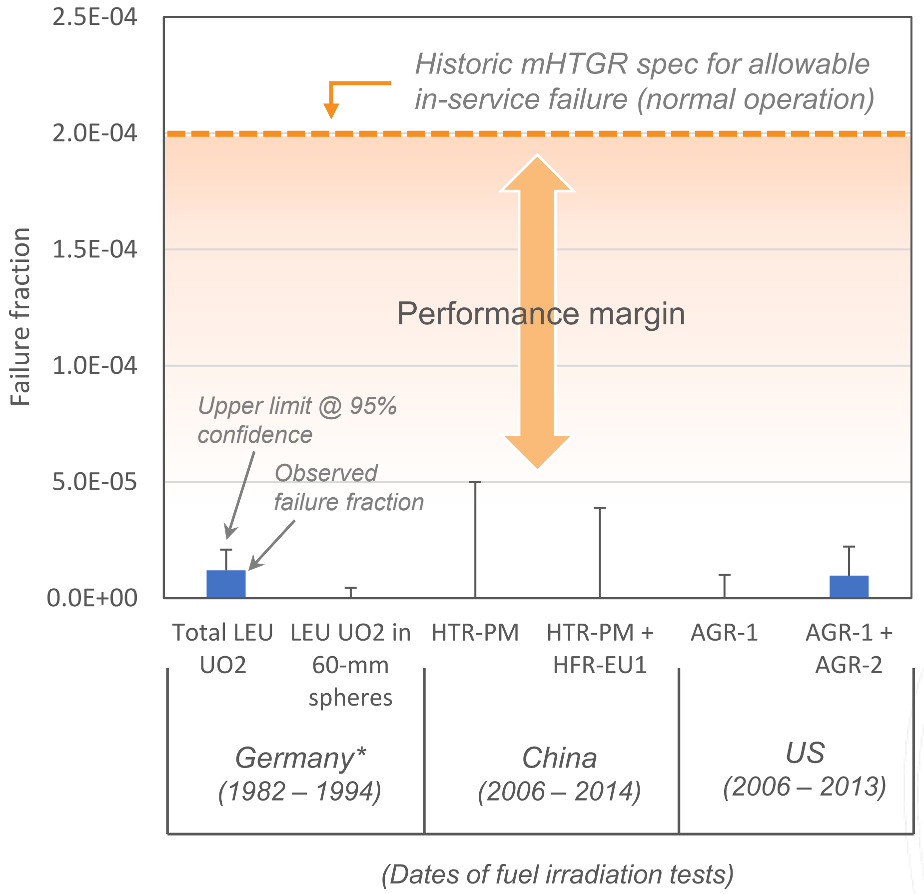




Temperatures are time-average peak irradiation temperature

# Particle Failure Evaluation

- High-quality TRISO fuel demonstrates in-pile particle failure rates substantially below historic reactor design specifications
- Requires adequate particle population to demonstrate low failure fraction at the 95% confidence level



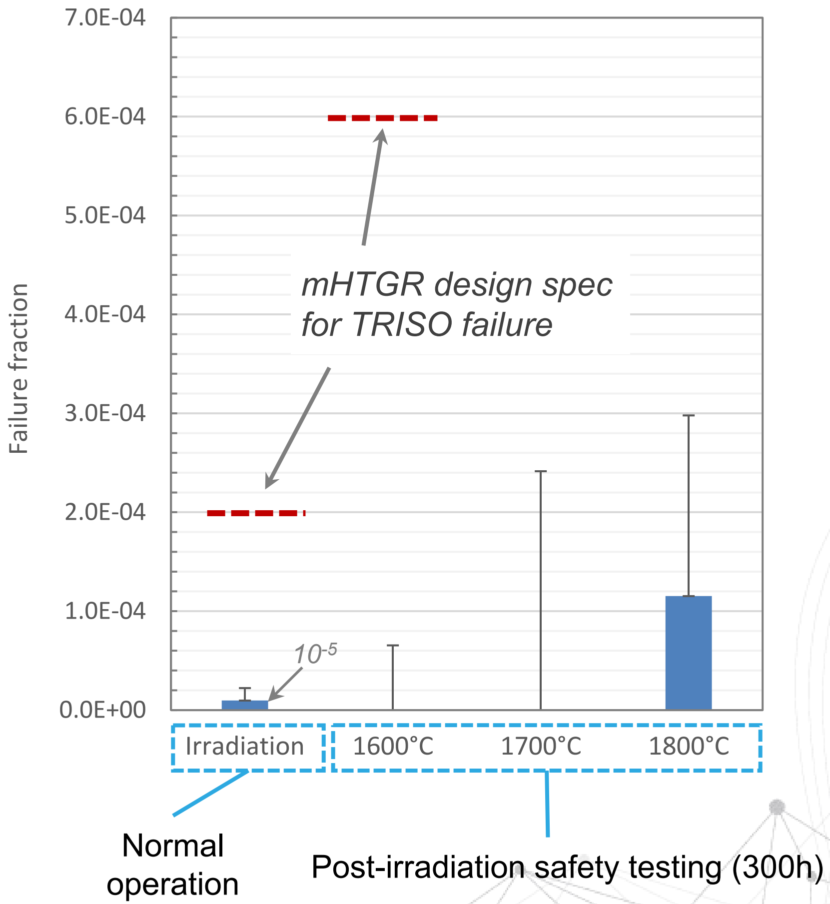

* Kania et al., J. Nucl. Mater. 441 (2013) 545-562

*IAEA TECDOC-1645, High Temperature Gas Cooled Reactor Fuels and Materials, International Atomic Energy Agency, 2010*

# Fuel Performance Summary

- Very low in-pile particle failure rates
- 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

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



# Ongoing Work and Outstanding Data Needs

- AGR-3/4 data analysis and reporting
- AGR-5/6/7 PIE and safety testing
  - Destructive fuel compact analysis
  - High temperature safety testing
- Fuel and fission product behavior in oxidizing environments
- Fuel performance and fission product transport modeling
  - Comparison of codes to empirical data; code refinement

# Core Oxidation

- Accident scenarios in steam-cycle gas-cooled reactors can include air or steam ingress into the core (design basis events or beyond design basis events)
- Core behavior under these conditions should be evaluated
  - Graphite and matrix oxidation
  - Fission product volatilization from matrix/graphite and exposed kernels
  - Oxidation of coated particles could impact particle integrity
- Previous work has included characterization of oxidation behavior of core materials:
  - Graphite oxidation data is available in literature
  - Limited data on matrix oxidation
  - Limited data on kernel and coated particle response to core oxidants

Fission gas release from irradiated UCO fuel kernel in response to water vapor injection (HRB-17 experiment)

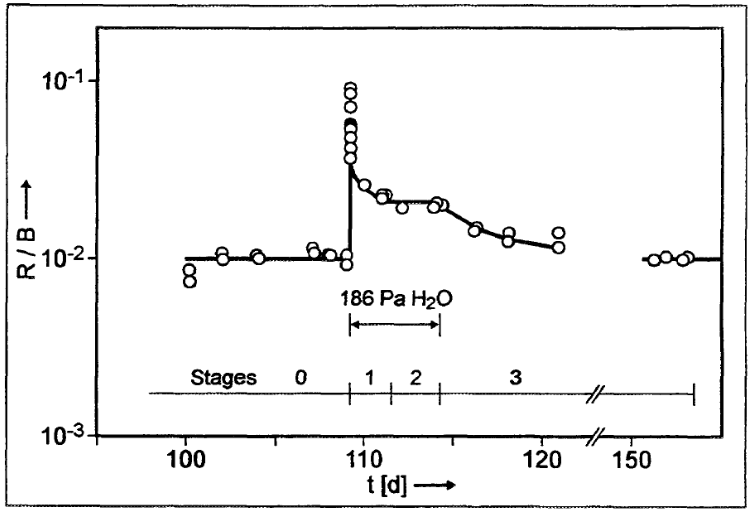


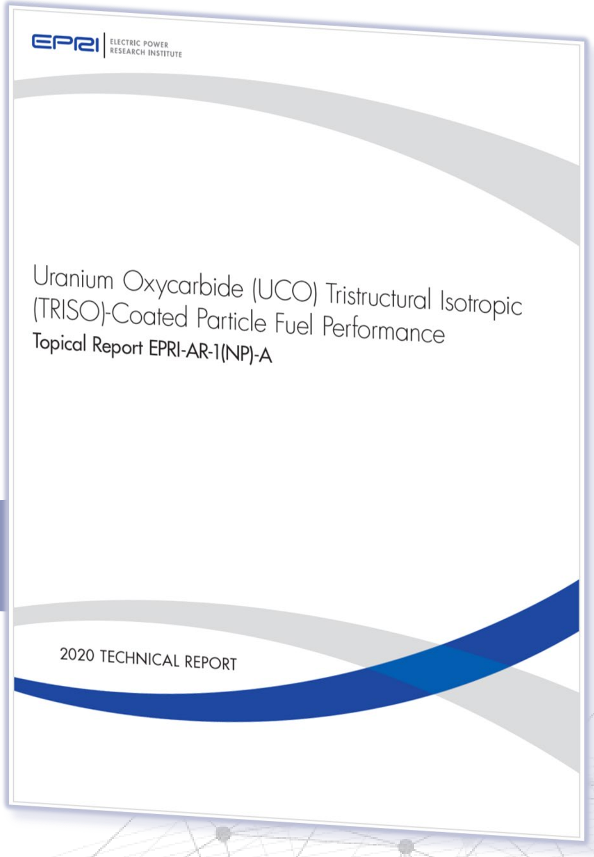

Fig. 5-1: R/B-time profile for Kr-85m before, during, and after a water vapor injection test with 186 Pa of water vapor at 755 °C

IAEA-TECDOC-978 (1997) is a good reference for earlier studies of fuel response to oxidants

# Industry Engagement

- General Atomics supported early AGR program development
- BWXT fabricated AGR fuel
- NGNP Alliance
  - Active during NGNP program and subsequent years
- NEI High-Temperature Reactor Technology Working Group (HTR-TWG)
  - HTR developer's forum that addresses cross cutting issues
- EPRI TRISO topical report
- Ongoing industry engagement regarding AGR data interpretation, remaining program activities, and future licensing topical reports

The NGNP Industry Alliance
Promoting the development and commercialization of High Temperature Gas-cooled Reactor (HTGR) technology


EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO)-Coated Particle Fuel Performance
Topical Report EPRI-AR-1(NP)-A

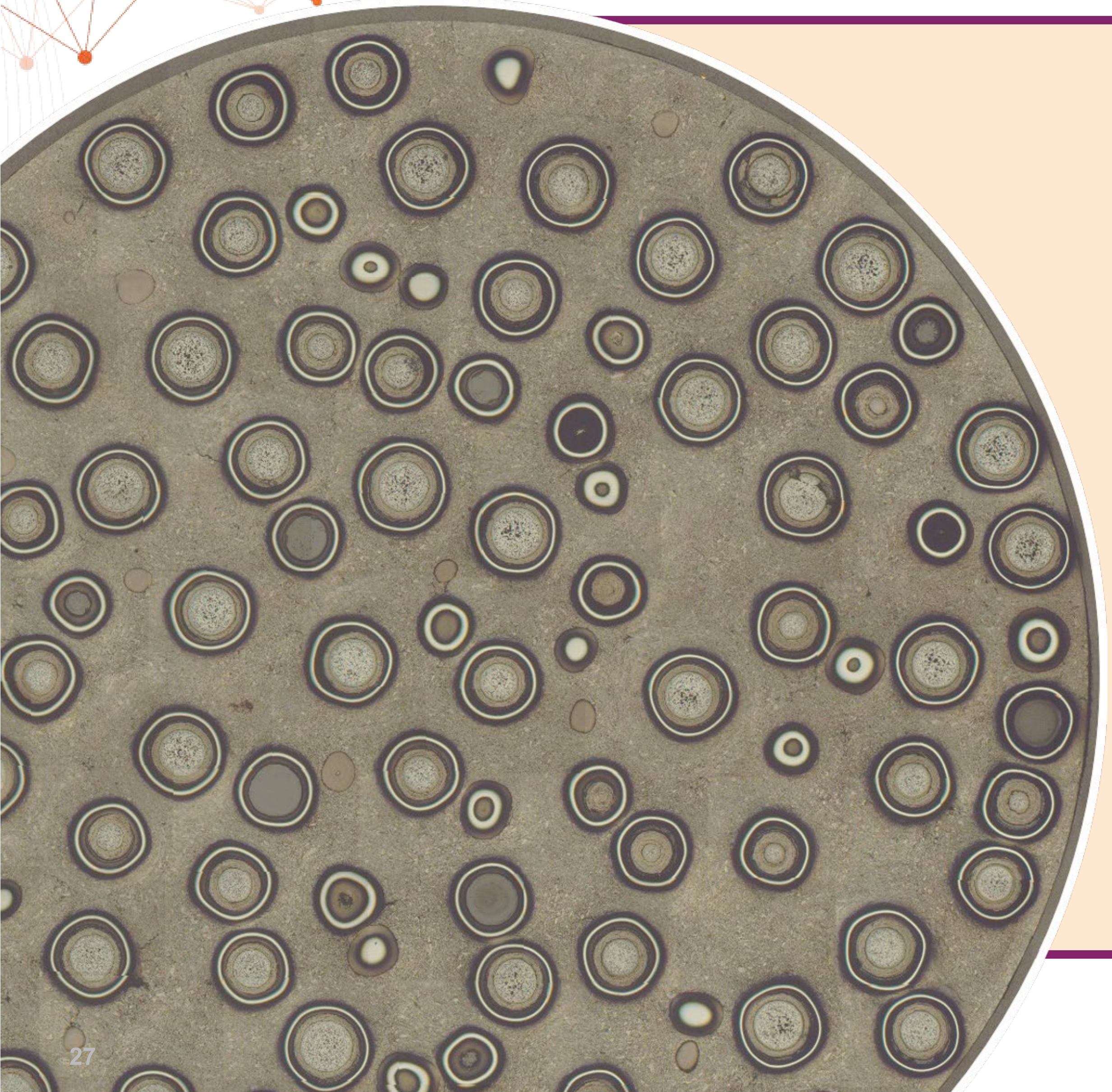
2020 TECHNICAL REPORT

# Coated-Particle-Fueled Reactor Concepts and Fuel Designs

| Developer | Description | Fuel design |
|---|---|---|
| X-energy | Xe-100 200 MWt PB HTGR<br>Xe-Mobile 1 – 5 MWe microreactor | UCO TRISO pebbles, graphitic matrix<br>UCO TRISO |
| Kairos Power | KP-FHR 140 MWe salt-cooled SMR<br>Hermes 35 MWt test reactor | UCO TRISO pebbles, graphitic matrix<br>UCO TRISO pebbles, graphitic matrix |
| BWXT | BANR 50 MWt microreactor<br>Pele/MNPP 1 – 5 MWe transportable microreactor | UN TRISO in SiC matrix<br>TRISO |
| Ultrasafe Nuclear | MMR 15 MWt microreactor | UCO TRISO in SiC matrix (“FCM”) |
| Westinghouse | eVinci 7-12 MWt microreactor | UCO TRISO compacts, graphitic matrix |
| Radiant Nuclear | Kaleidos >1 MWe transportable microreactor | UCO TRISO compacts, graphitic matrix |
| Framatome | SC-HTGR 625 MWt | UCO TRISO compacts, graphitic matrix |
| StarCore Power | 10 MWe HTGR | TRISO |
| HolosGen | 22 MWt scalable microreactor | TRISO fuel compacts |
| ORNL | Transformational Challenge Reactor | UN TRISO in SiC matrix |
| NASA | Nuclear thermal propulsion (NTP), nuclear electric propulsion (NEP) | Various |


**Useful references:**

- Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, IAEA (https://aris.iaea.org/Publications/SMR_Book_2020.pdf)
- https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx (updated Jan 2023)



*Thank you for your attention*

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