May 20, 2024

Paul Demkowicz, Ph.D.

DOE TRISO Fuel Qualification

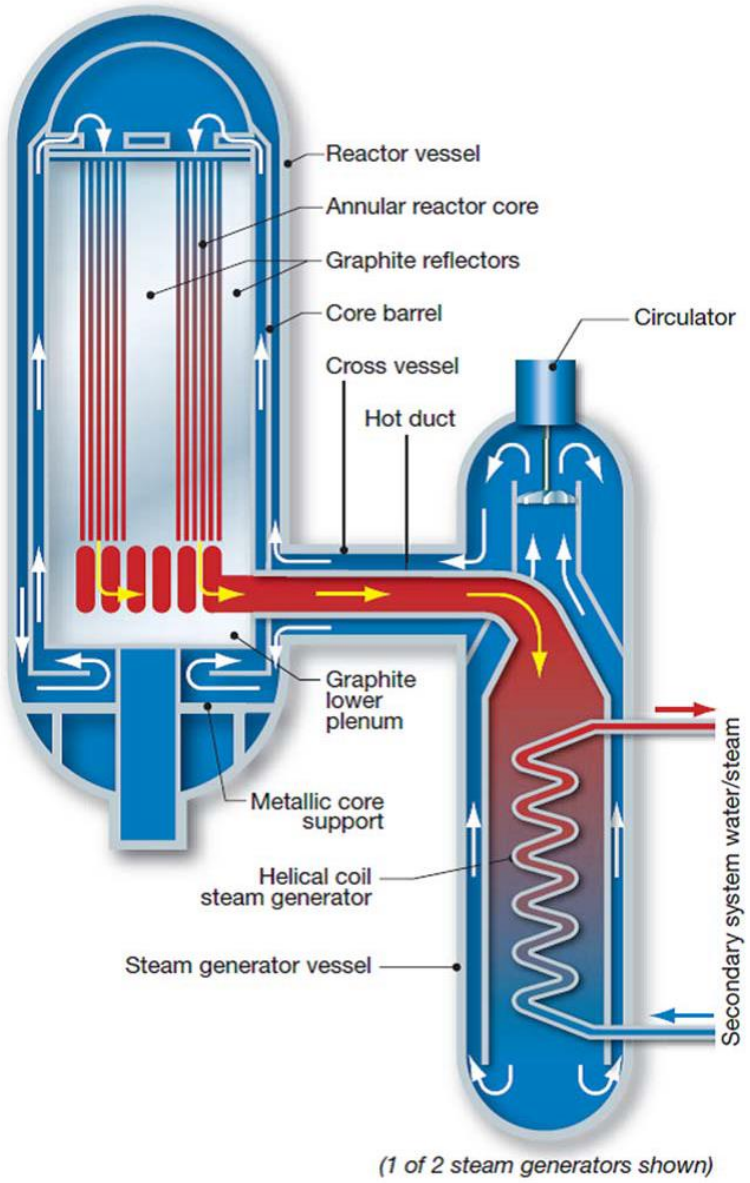
Establishing a Foundation for Advanced Reactor Deployment

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

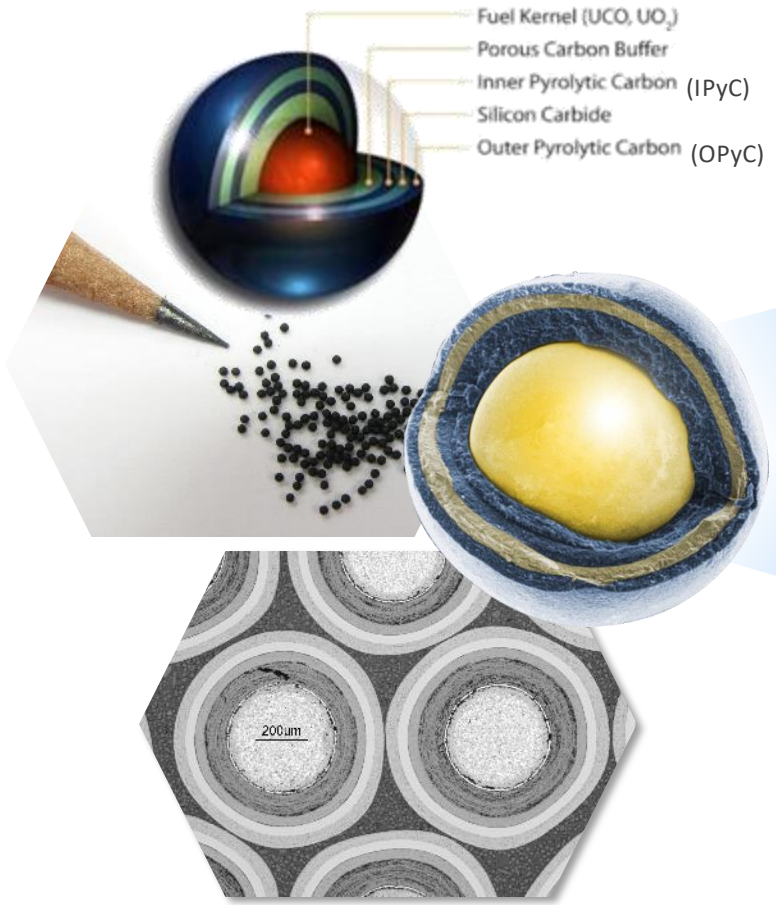
Idaho National Laboratory

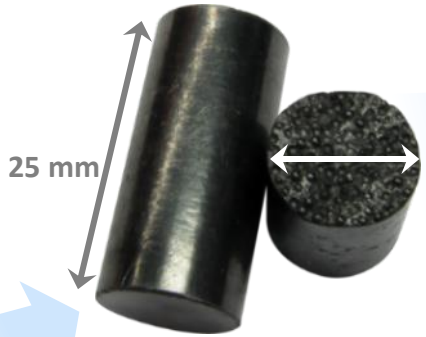
High-Temperature Gas-Cooled Reactors

- **Helium coolant at 750 °C – 900 °C**
- **Graphite moderated core**
- **Coated particle fuel developed for use in HTGRs**
- **HTGR advantages:**
  - High thermal efficiency for electricity production
  - High-temperature heat source for industrial processes
  - Passive safety characteristics
    - Inert coolant
    - Slow temperature response during accidents
    - Refractory core and fuel that can withstand accident temperatures
    - Maintain adequate core cooling during loss of coolant flow



Tristructual Isotropic (TRISO) Coated Particle Fuel

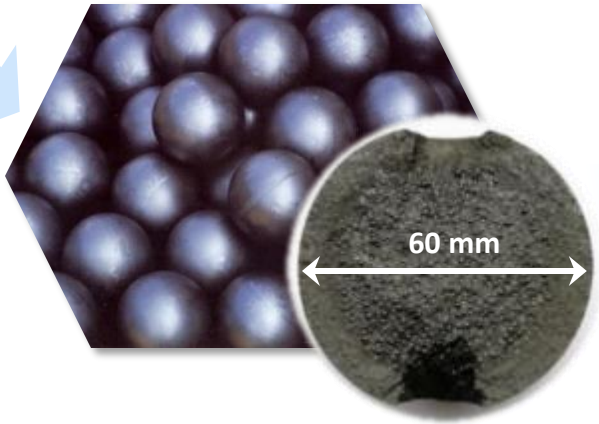




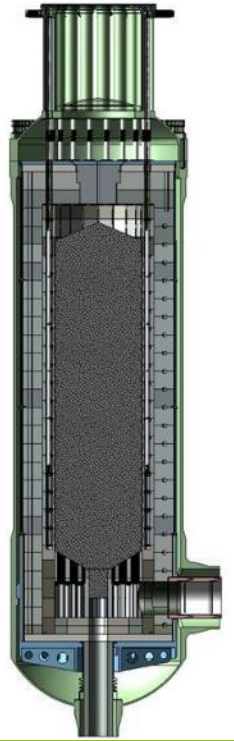


Prismatic reactor





Pebble-bed reactor



Micro-scale confinement of radioactive fission products within the fuel particle

HTGRs Utilizing Coated Particle Fuel

Demonstration Plants



Dragon – 20 MWt
(UK) 1964 – 1975



AVR – 46 MWt
(FRG) 1967 – 1988



Peach Bottom 1 – 115 MWt
(USA) 1967 – 1974



HTTR – 30 MWt
(Japan) 1999 – Present



HTR-10 – 10 MWt
(China) 2000 – Present

Prototype Plants

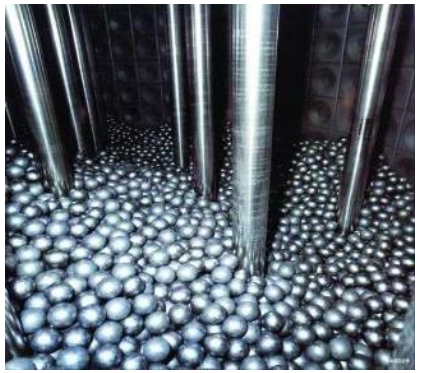


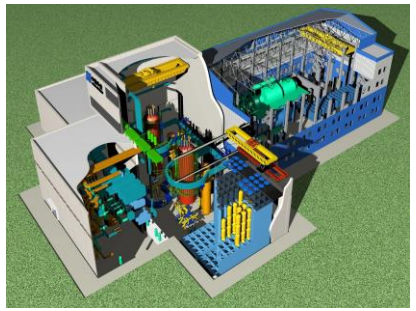
Fort St. Vrain – 842 MWt
(USA) 1976 – 1989





THTR – 750 MWt
(FRG) 1986 – 1989





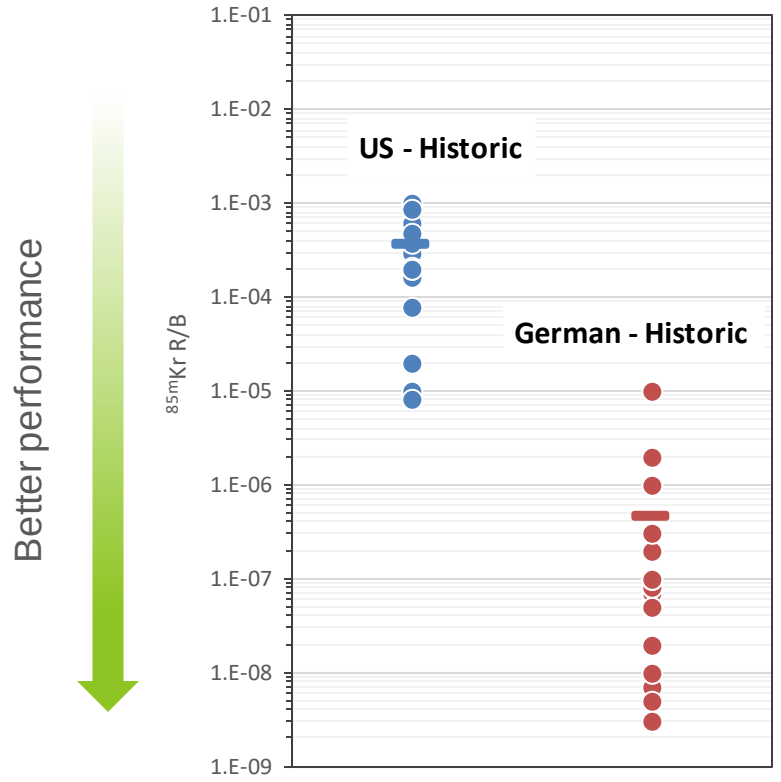
HTR-PM – 250 x 2 MWt
(China) 2021 – Present

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

- Started in 2002 to address historically poor US TRISO fuel performance relative to German fuel
- Focus on **LEU UCO TRISO** fuel to enable higher in-pile temperatures and higher burnup compared to UO_2 TRISO
- Four irradiation campaigns
  - Demonstrate fuel performance under normal and accident conditions
  - Demonstrate scale-up of fuel fabrication processes while maintaining acceptable fuel quality
  - Evaluate fission product transport behavior to support reactor safety analyses

Major components of fuel qualification

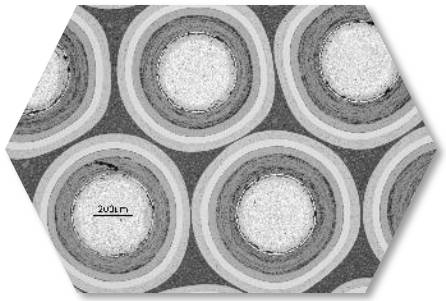
Comparison of US and German ^{85m}Kr R/B data



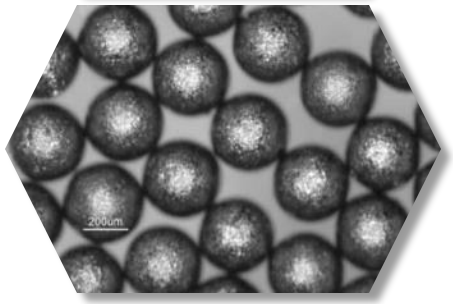
** R/B is the fission gas release-rate-to-birth-rate ratio*

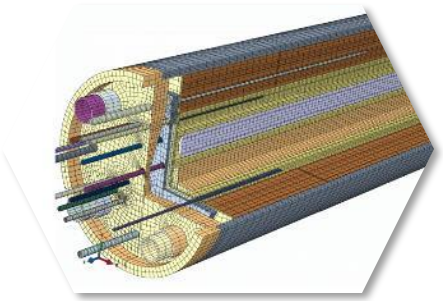
TRISO Fuel Qualification Program Elements

Program participants:
- *INL*
- *ORNL*
- *BWXT*
- *General Atomics*



Fabrication

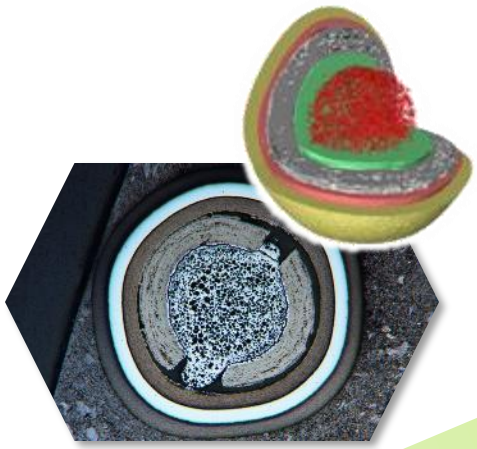




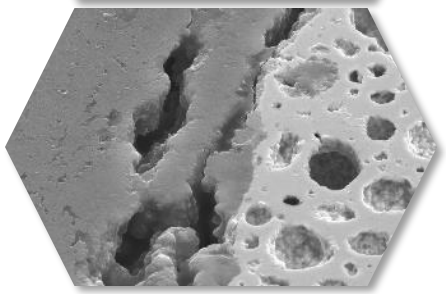


Irradiation



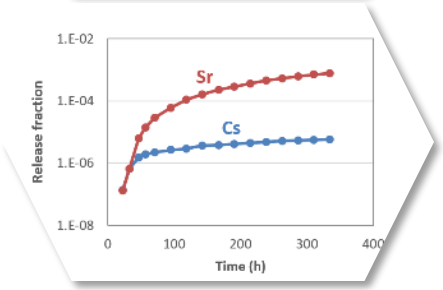


Post-Irradiation Examination

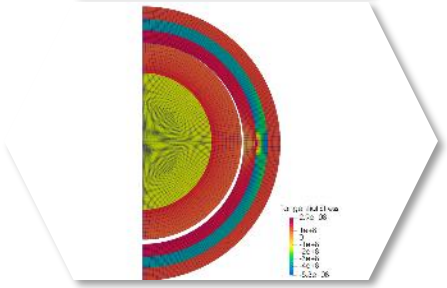


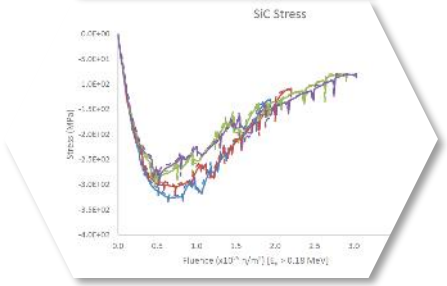


Safety Testing



Modeling and Simulation

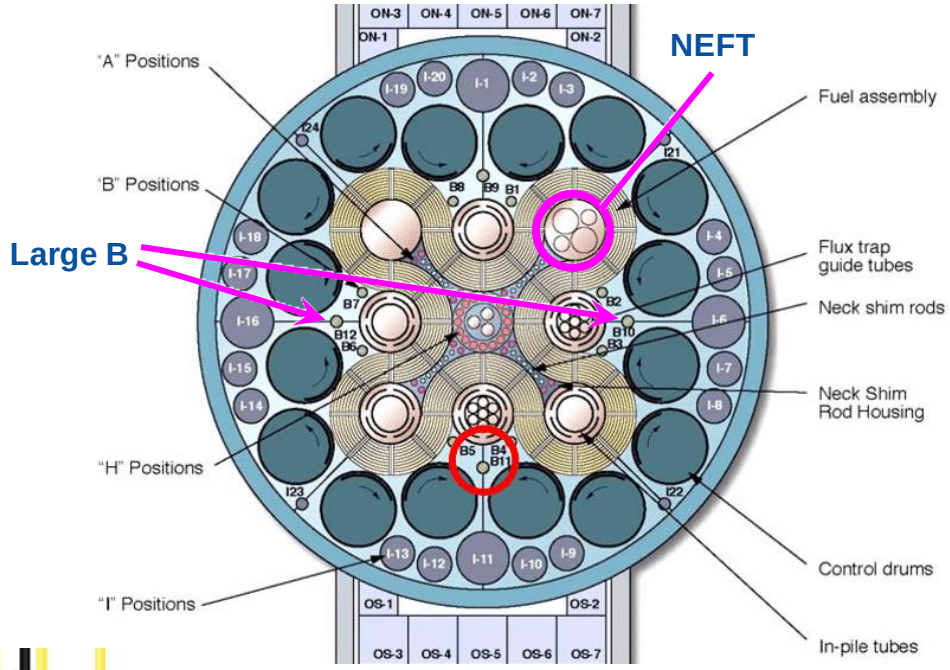


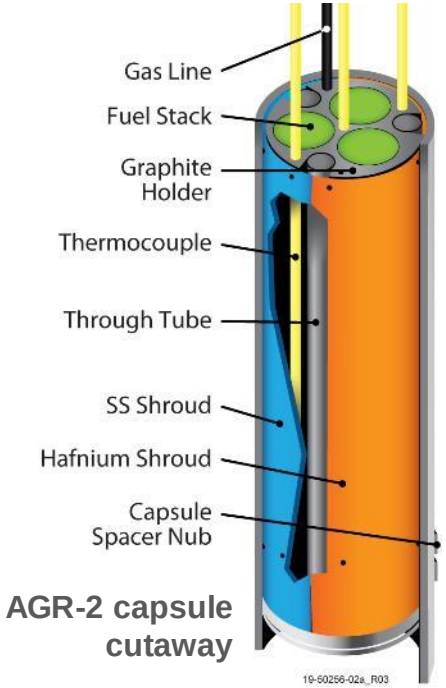


AGR Program Irradiation Experiments

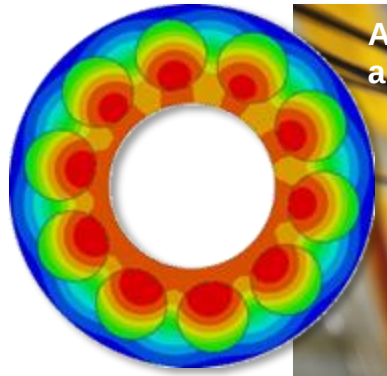
- AGR Program irradiations performed in ATR
  - Large “B” positions – **AGR-1, AGR-2**
  - Northeast Flux Trap (NEFT) – **AGR-3/4, AGR-5/6/7**
- Multi-capsule, instrumented lead experiments
- Continuous monitoring of fission gas effluent from capsules (5 – 12 capsules per experiment)
- Thermocouples used to measure temperature and compare with thermal model
- Complex neutronic and thermal models of the test trains to calculate irradiation conditions

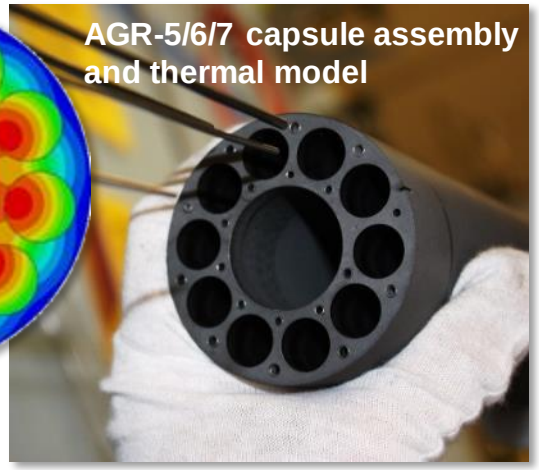
ATR core cross section





AGR-2 capsule cutaway



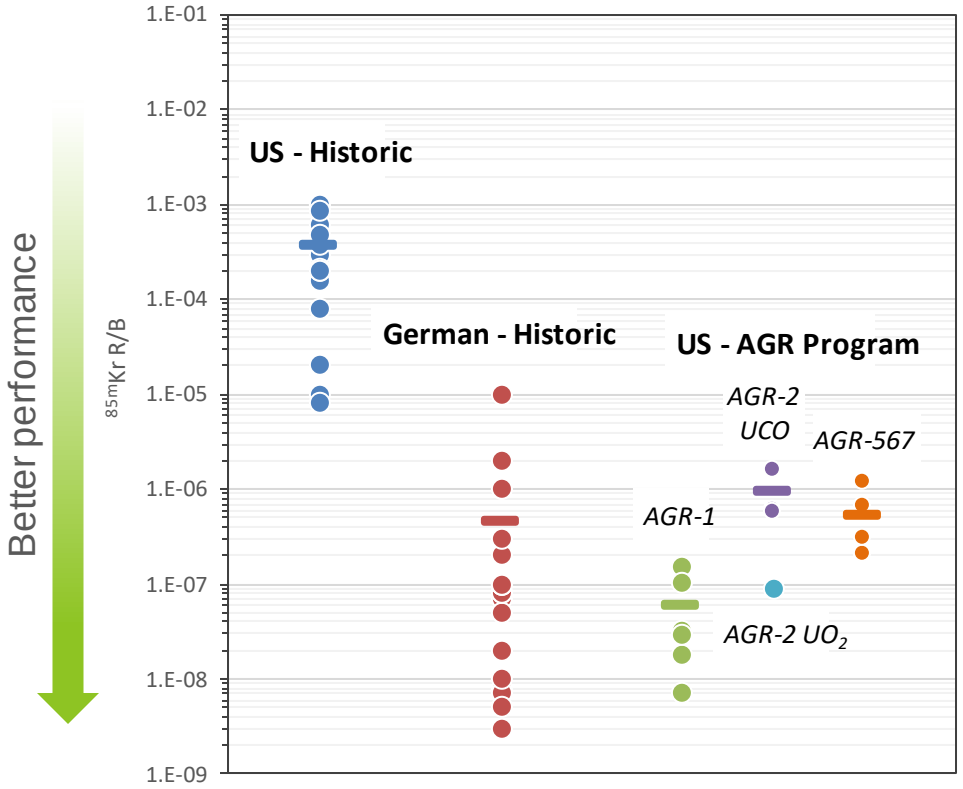


AGR-5/6/7 capsule assembly and thermal model

Fuel Irradiation Results

- Three fuel performance irradiation tests completed
- Fission gas (^{85m}Kr) R/B values are $<10^{-6}$
  - Fuel burnup of ~20% FIMA
  - Time-average temperatures as high as ~1350°C
- Results demonstrate in-pile behavior similar to historic German results at higher fuel temperature and approximately twice the fuel burnup

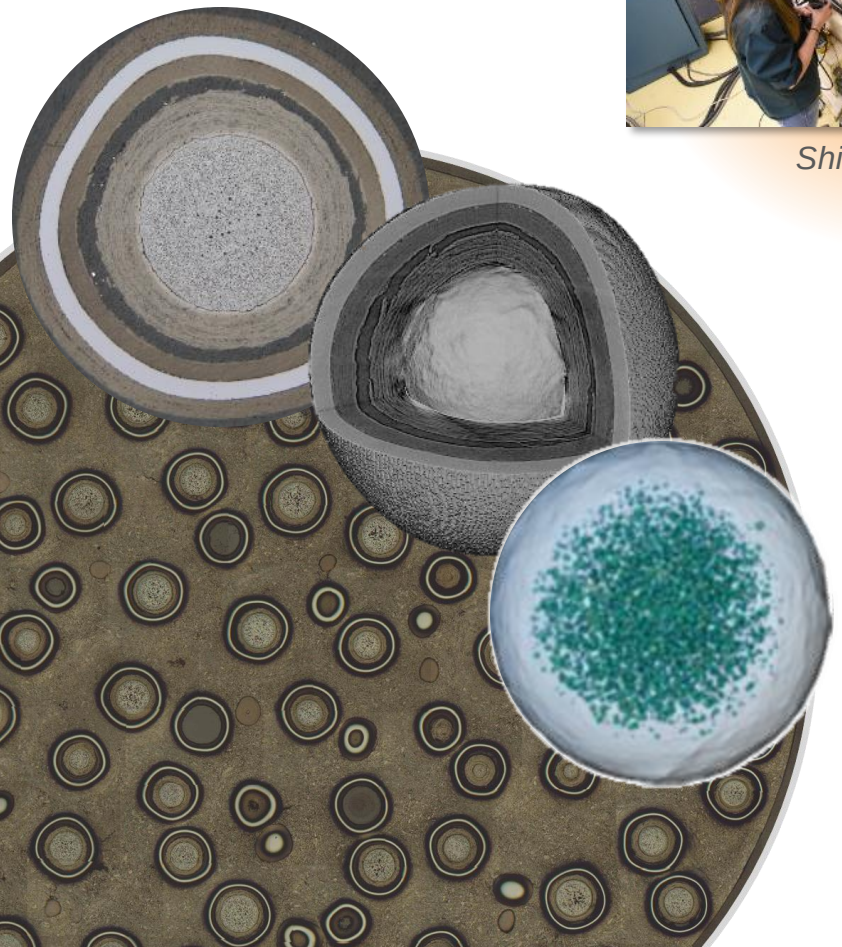
Comparison of US and German ^{85}Kr R/B data



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)

TRISO Fuel Microanalysis to Understand Kernel and Coating Behavior

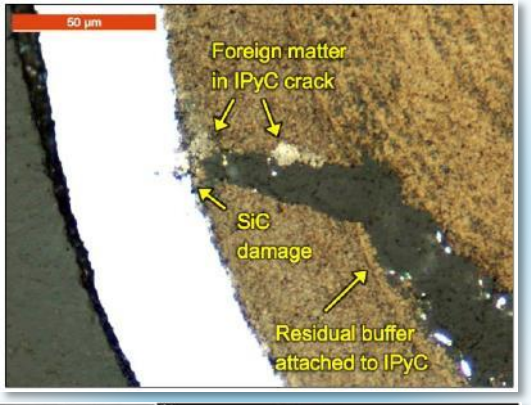
Kernel and coating layer morphologies

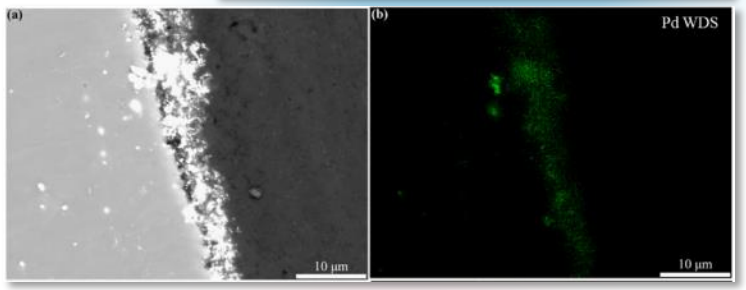


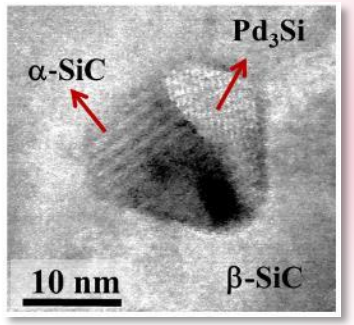


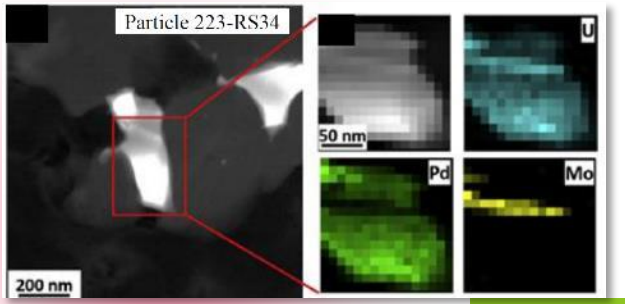
Shielded hot cells

Fission product corrosion of the SiC layer



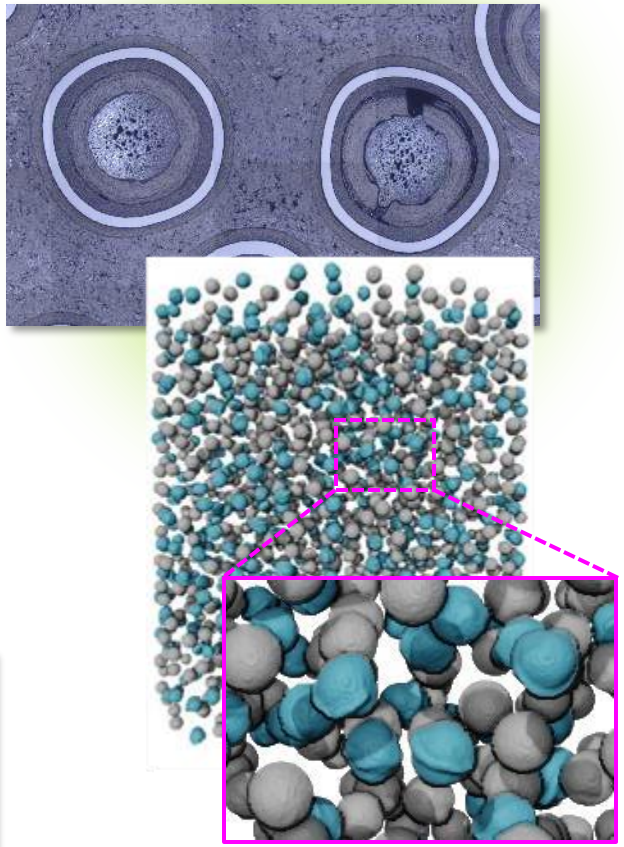






Very-fine-length-scale analysis of fission products

X-ray analysis of particles within irradiated compact



Accident Safety Testing of TRISO Fuel

- Temperature transients are relatively slow (days) during a depressurized loss of forced cooling(D-LOFC) accident
- 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

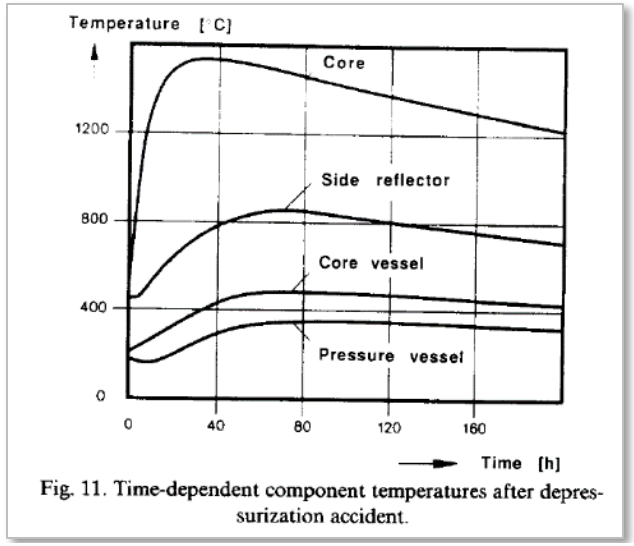
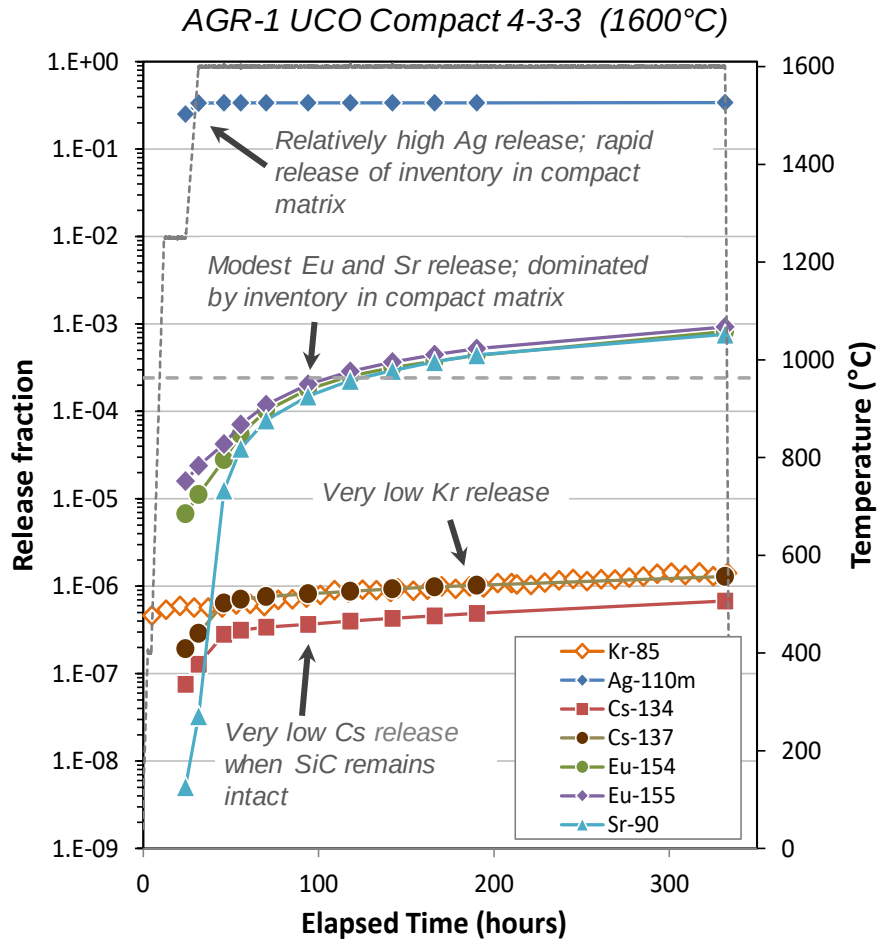


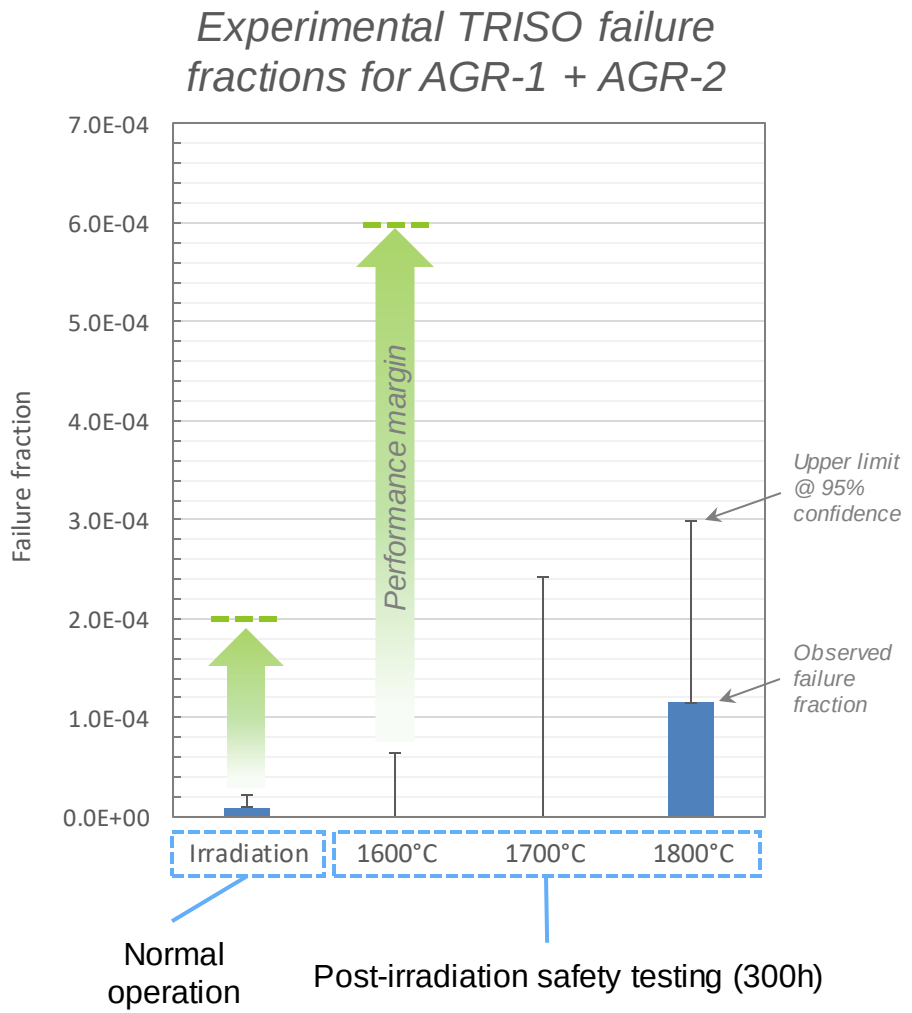
Fig. 11. Time-dependent component temperatures after depressurization accident.

Core temperature during depressurized loss of forced cooling accident – HTR Module
G. Lonhert, Nuc. Eng. Des. 121 (1990) 259-275



Fuel Performance Evaluation Results

- AGR Program has irradiated ~**1,000,000** particles in Advanced Test Reactor
- Demonstrated low in-pile particle failure fractions (≤ 1/50,000 particles)
- Fuel can withstand hundreds of hours at 1600 °C without significant particle failures (≤ 1/15,000 particles)
- Fuel effectively retains fission products within the coated particles



Coated-Particle-Fueled Reactor Concepts and Fuel Designs

Significant industry interest in coated particle fuel for HTGRs and beyond

Developer	Description	Fuel design
X-energy	Xe-100 200 MWt PB HTGR Xe-Mobile 1 – 5 MWe microreactor	UCO TRISO pebbles, graphitic matrix UCO TRISO
Kairos Power	KP-FHR 140 MWe salt-cooled SMR Hermes 35 MWt test reactor	UCO TRISO pebbles, graphitic matrix UCO TRISO pebbles, graphitic matrix
BWXT	BANR 50 MWt microreactor Pele/MNPP 1 – 5 MWe transportable microreactor	UN TRISO in SiC matrix 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
NASA	Nuclear thermal propulsion (NTP), nuclear electric propulsion (NEP)	Various
Framatome	SC-HTGR 625 MWt	UCO TRISO compacts, graphitic matrix
StarCore Power	10 MWe HTGR	TRISO
HolosGen	22 MWt scalable microreactor	TRISO fuel compacts

- Microreactor designs
- Space propulsion
- Alternative coolants (e.g., molten salt)
- Unique coated particle fuel designs

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)



Idaho National Laboratory

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