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Current TRISO Fuel Performance Capabilities and Considerations for Expanded Operational Envelopes

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Changing the World's Energy Future

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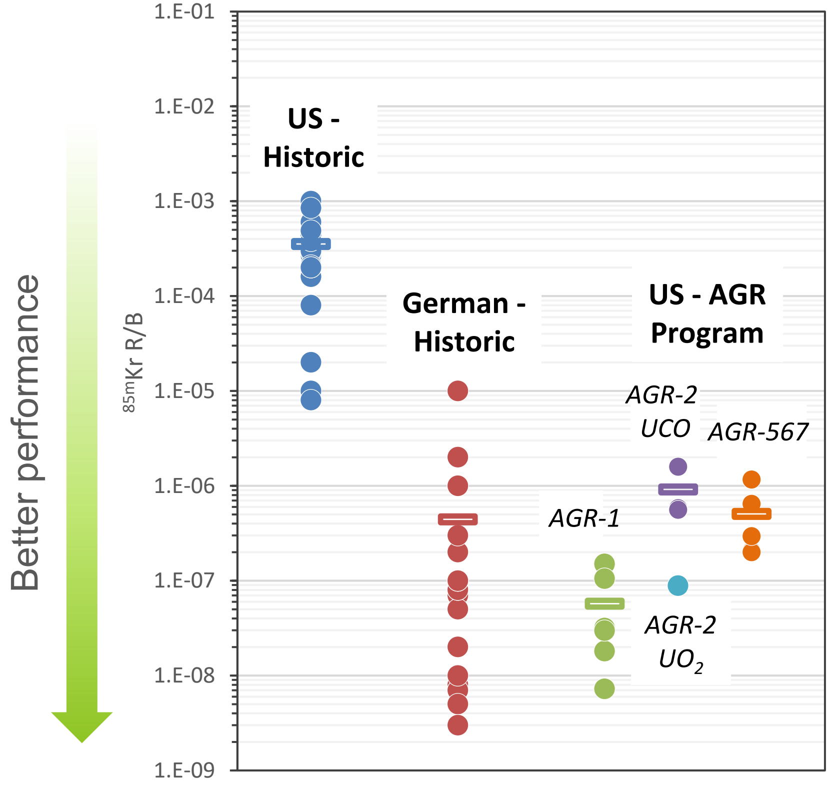
7th Workshop on Material Properties of TRISO Fuels, Manchester, UK

US-DOE TRISO Fuel Development

- *Advanced Gas Reactor (AGR) Fuel Development and Qualification Program* 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

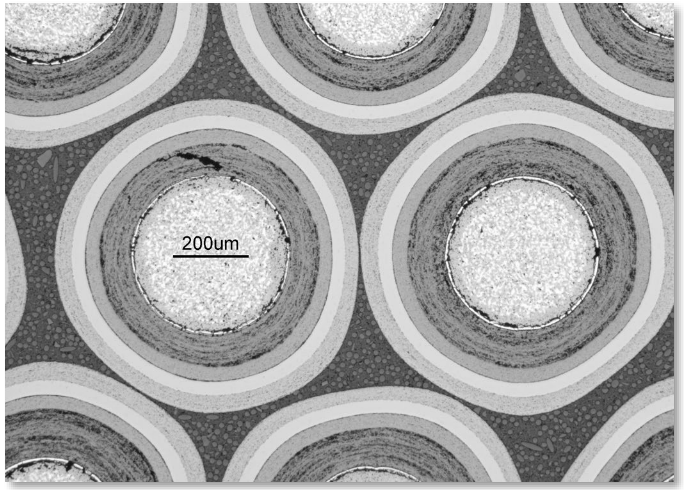
Comparison of US and German ^{85m}Kr R/B data

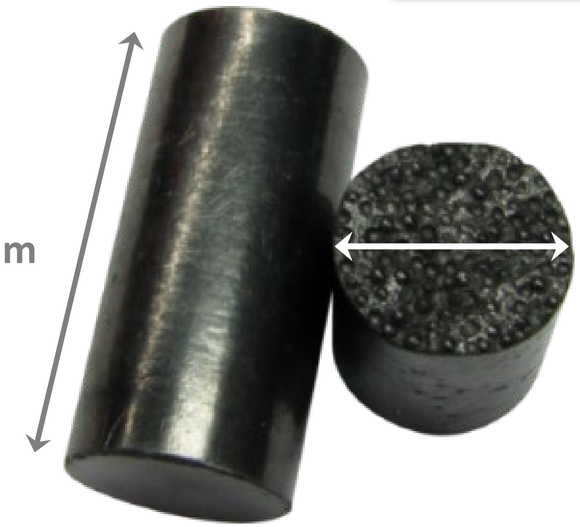


R/B is the fission gas release-rate-to-birth-rate ratio
AGR-2 R/B values are through the first ~1/4 of the irradiation (149 EFPD)
AGR-567 R/B values are through the first ~1/2 of the irradiation (174 EFPD)

AGR Fuel Design and Performance Requirements

- 425 µm UCO kernels
- German-like TRISO coatings
- Cylindrical compacts
- Graphite and binder resin





- NGNP Program preliminary reference reactor design[1]:
  - 600 MW_{th} prismatic core
  - 750 °C outlet
  - 1250 °C peak time-average fuel temperature
  - Burnup up to 20% FIMA
- Preliminary fuel quality and performance requirements

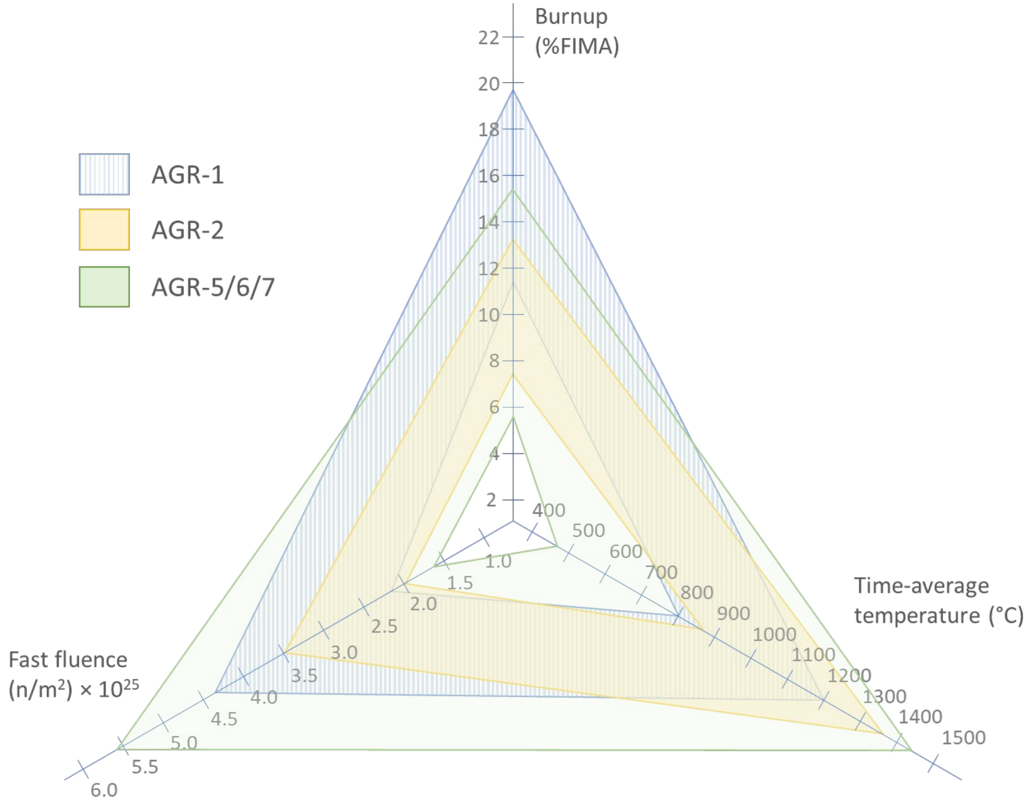
Heavy metal contamination	$\leq 2\times10^{-5}$
In-service failures (normal operation)	$\leq 2\times10^{-4}$
In-service failures (accidents)	$\leq 6\times10^{-4}$

[1] *Fuel performance requirements basis provided in: D. Hansen, Technical Basis for NGNP Fuel Performance and Quality Requirements, GA-911168 (2009)*

AGR Program Fuel Irradiations

	AGR-1	AGR-2	AGR-5/6/7
# Compacts	72	48	194
# Particles	298,000	132,500	570,000
Start	24 Dec 2006	22 Jun 2010	16 Feb 2018
End	6 Nov 2009	16 Oct 2013	22 Jul 2020
EFPD[1]	620	559	361
Duration (d)	1048	1212	887
Burnup (% FIMA)	11.3 – 19.6	7.3 – 13.2	5.7 – 15.3
Fast Fluence ($n/m^2 \times 10^{25}$)[2]	2.2 – 4.3	1.9 – 3.5	1.6 – 5.6
TA temperature (°C)[3]	800 – 1197	868 – 1360	467 – 1432
Fabrication			
Kernels	BWXT	BWXT	BWXT
Coatings	ORNL	BWXT	BWXT
Compacts	ORNL	ORNL	BWXT

[1] Effective full power days
[2] E > 0.18 MeV
[3] Time-average temperature

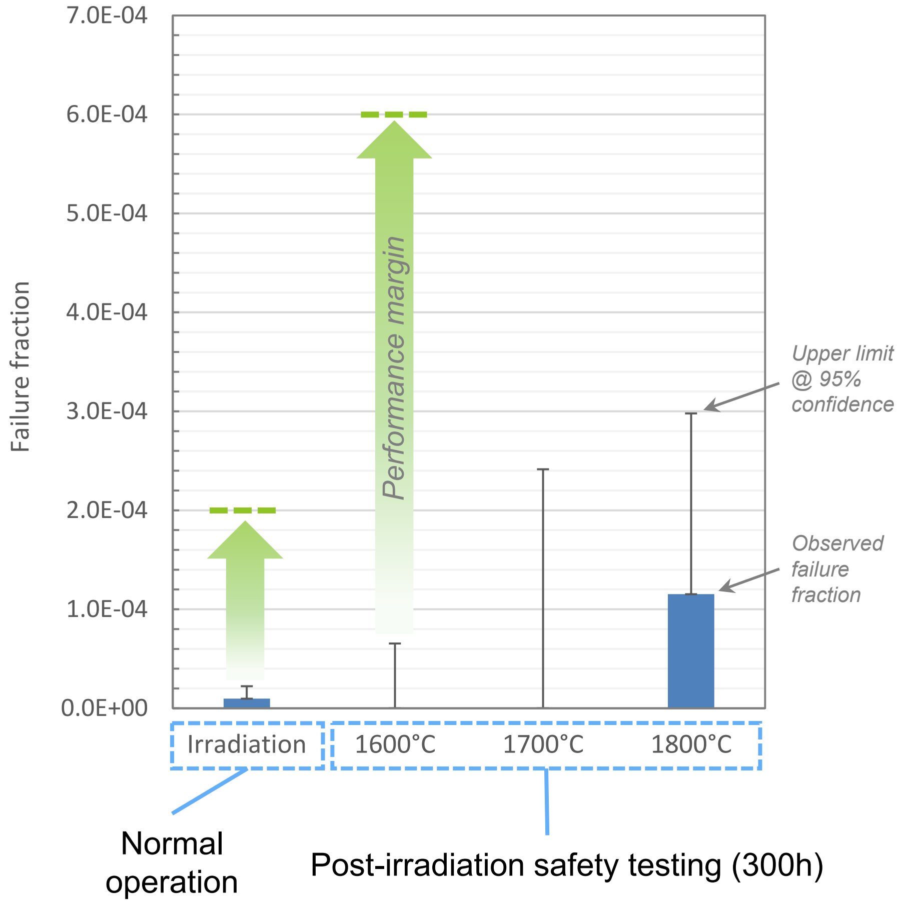


➲ All irradiations performed in the Advanced Test Reactor

UCO 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[1])
- Fuel can withstand hundreds of hours at 1600 °C without significant particle failures (≤ 1/15,000 particles[1])
- Fuel effectively retains fission products within the coated particles

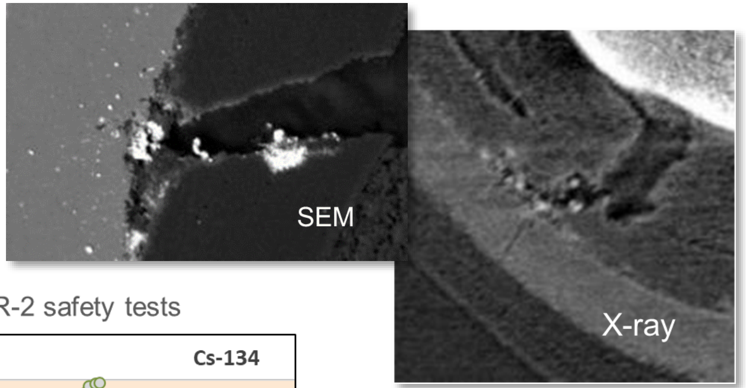
Experimental TRISO failure fractions for AGR-1 + AGR-2

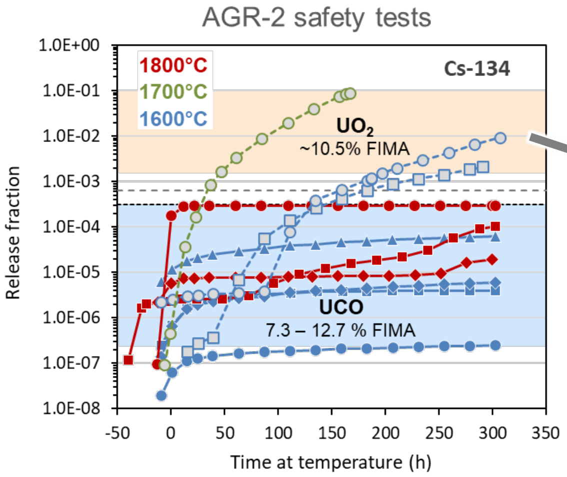


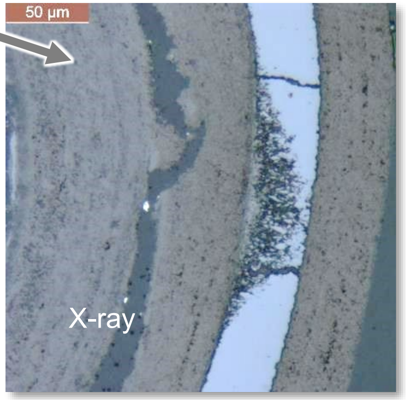
[1] *Values are upper bound at 95% confidence*

Performance Limiting Phenomena

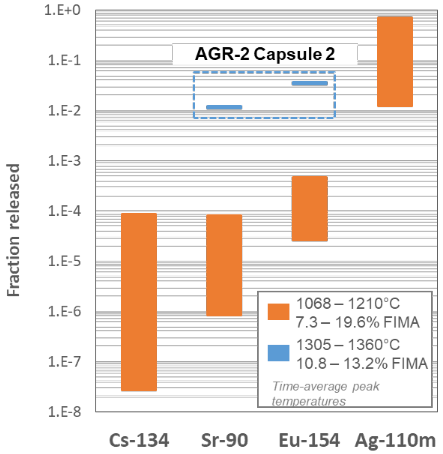
- Pd corrosion is source of infrequent SiC failure observed in UCO fuel
  - Exacerbated by IPyC failure?
- CO(g) corrosion is source of SiC degradation and Cs release in UO_2 fuel
- FP release through intact coatings at higher temperatures
- Silver release (maintenance hazard?)
- Kernel migration possibly observed even in UCO at very high temperature
- Particle defects (increasing failure probability with increasing severity of operating conditions)
  - Asphericity/faceting
  - Coating inclusions
- Layer failures often observed only on post-irradiation heating to 1600 – 1800 °C

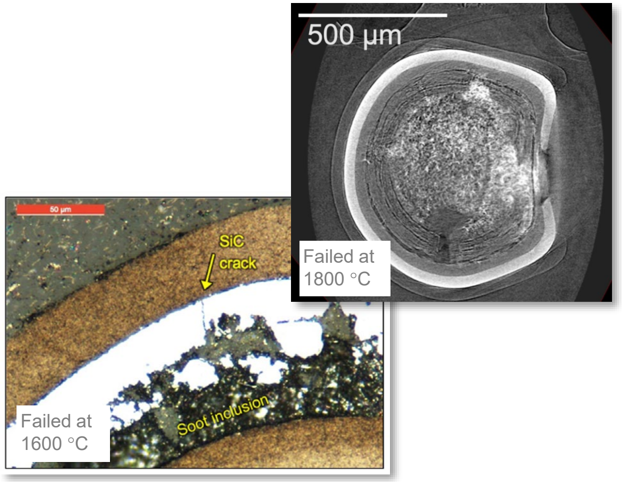






In-pile fission product release from AGR-1 and AGR-2 UCO fuel compacts





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 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
- Alternative coolants (e.g., molten salt)
- Space propulsion
- 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)

Expanded Fuel Performance Envelope

- Extended irradiation durations
  - mHTGR core life ~3 years
  - Fuel qualification test irradiations ~1 to 2 years
- Higher fuel temperatures
  - Higher operating temperatures
  - Higher peak core temperatures in accidents (≥1600°C)
- Higher burnup (UO_2)
- Varying accident conditions
  - Oxidant ingress
  - More severe transients relative to mHTGRs
- Designs driving expanded operational envelope could also have different fuel performance requirements

Accelerated Fuel Qualification

- Challenges with accelerated irradiation testing
  - Increased particle power and thermal gradients in particle
  - How to account for time-at-temperature effects?
  - Prototypical balance of thermomechanical phenomena (e.g., PyC irradiation strain and thermal creep)
- Use of M&S
  - Evaluate/screen fuel concepts
  - Suggest performance-limiting phenomena under specific operating conditions
- Separate effects testing
  - Improve material properties database → improve fuel performance models
- Small-scale, rapid irradiation experiments to evaluate/screen fuel concepts
  - Assess separate effects (e.g., FP chemistry in new kernel compositions)
  - Assess gross fuel performance concerns
  - Statistics limit ability to assess failure fractions of promising designs

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