INL/MIS-21-64889-Revision-0

# TristructuralIsotropic (TRISO) Fuel Qualification in the US

October 2021

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**http://www.inl.gov**

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# Tristructural Isotropic (TRISO) Fuel Qualification in the US

Nuclear Fuels and Materials Division Lunch and Learn Seminar

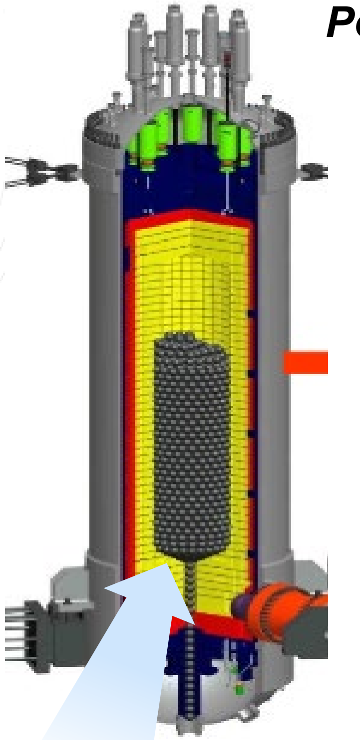
ART
Advanced Reactor Technologies

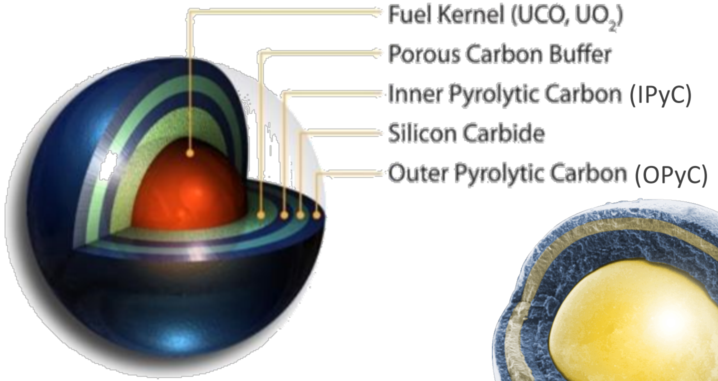
# Presentation Outline

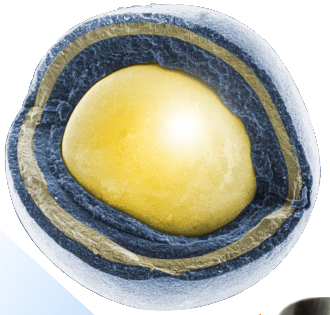
- TRISO development background and particle design
- US DOE AGR Program
- Fuel fabrication and quality control
- Irradiation testing
- Post-irradiation examination and high-temperature safety testing

# Conventional TRISO Coated Particle Fuel Forms for High-Temperature Gas-Cooled Reactors (HTGRs)

***Pebble bed reactor***



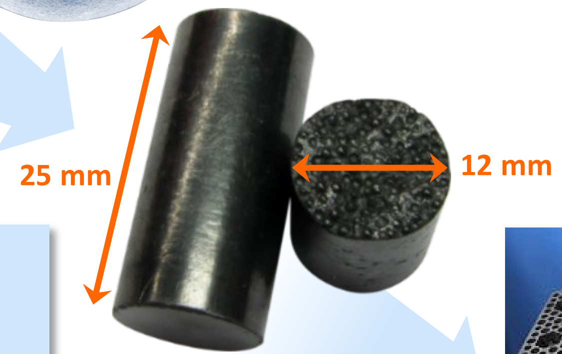


***TRISO particle***

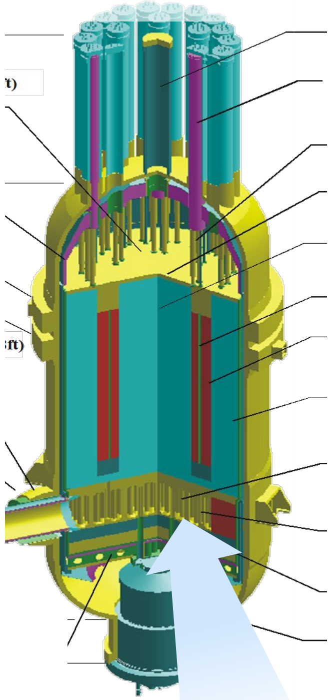

*Spherical fuel pebbles*

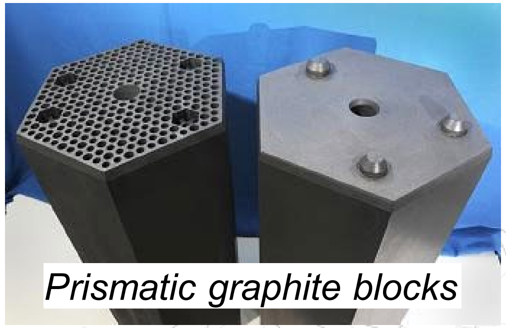
Particle design provides excellent fission product retention in the fuel and is at the heart of the safety basis for high temperature gas reactors




*Cylindrical fuel compacts*

***Prismatic reactor***

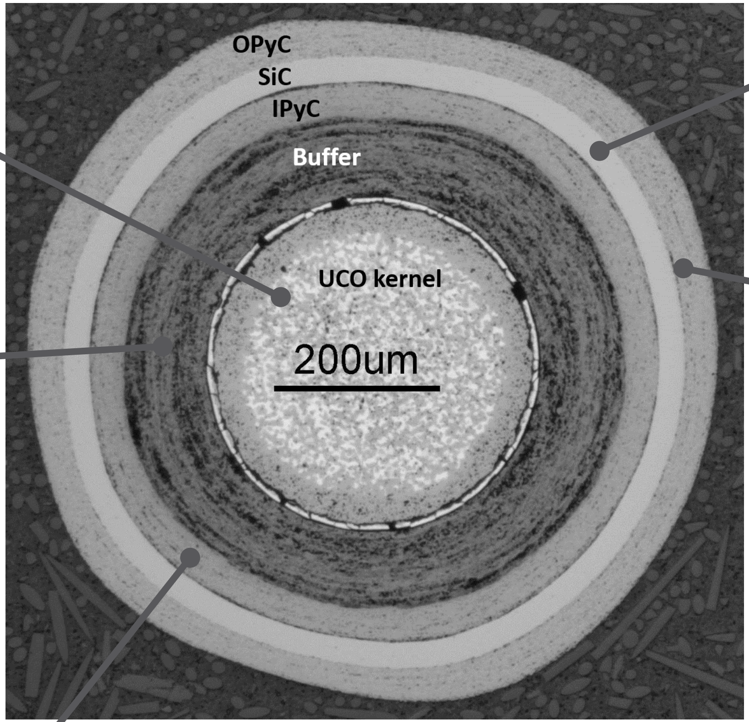




*Prismatic graphite blocks*

# Modern TRISO Particle Design

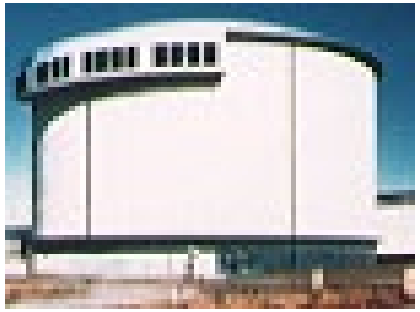
- **Kernel (350-500 µm)**
  - $UO_2$ or UCO
  - Retention of fission products
- **Buffer (~100 µm)**
  - ~50% dense pyrolytic carbon
  - Provides space for fission gas and CO(g) accumulation
  - Accommodates fission recoils




- **SiC (~35 µm)**
  - Main structural layer
  - Primary coating layer for retaining non-gaseous fission products
- **OPyC (~40 µm)**
  - Contributes to fission gas retention
  - Surface for bonding to matrix
  - Protects SiC layer during handling
- **IPyC (~40 µm)**
  - Protects kernel from chlorine during SiC deposition
  - Surface for SiC deposition
  - Contributes to fission gas retention
  - Irradiation shrinkage contributes to compression in SiC layer

# HTGRs Utilizing Coated Particle Fuel

## Demonstration Plants



**Dragon – 20 MWt**
(UK) 1964 – 1975

**AVR – 46 MWt**
(FRG) 1967 – 1988

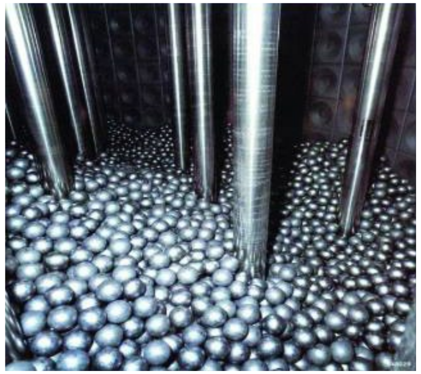
**Peach Bottom 1 – 115 MWt**
(USA) 1967 – 1974

**HTTR – 30 MWt**
(Japan) 1999 – Present

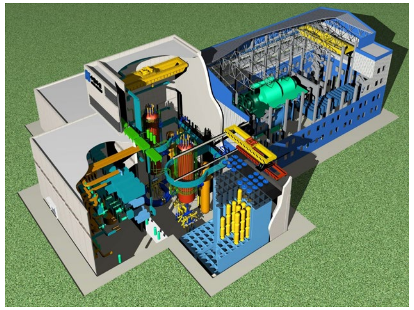
**HTR-10 – 10 MWt**
(China) 2000 – Present

## Prototype Plants

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



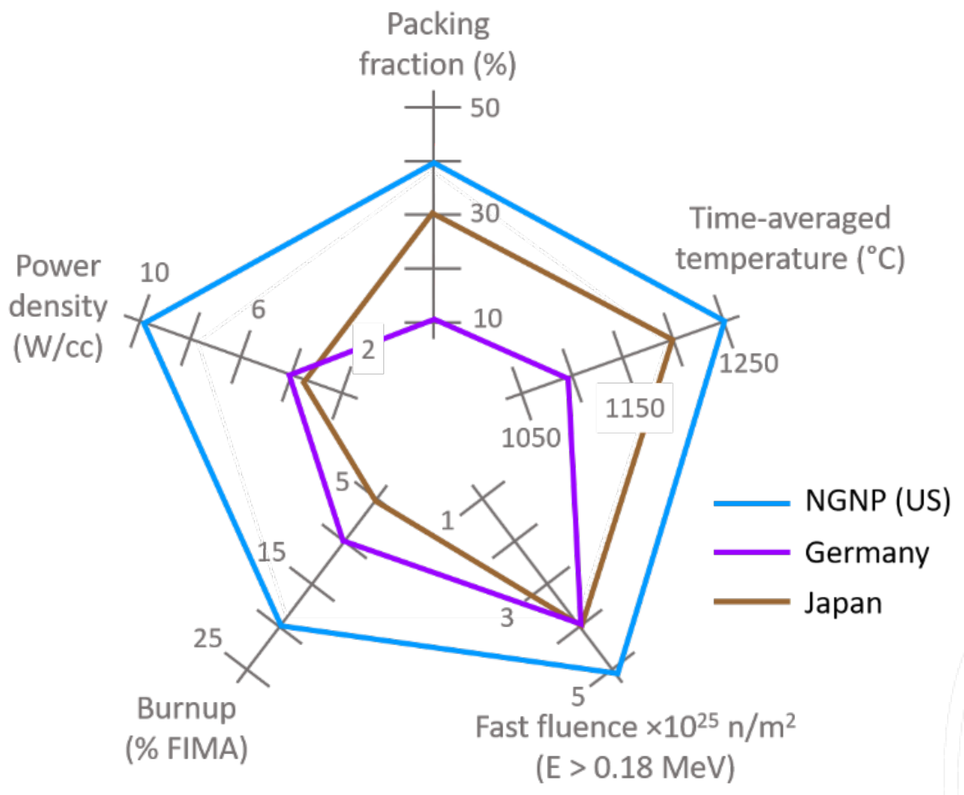
**THTR – 750 MWt**
(FRG) 1986 – 1989



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

# Modular HTGRs and TRISO Fuel Performance Envelope

- Typically <300 MWe
- He cooled, graphite moderated
- Low power density core relative to LWR
- Coolant outlet temperature ~750-950°C
- Design enables passive heat removal during accidents
- Applications include electricity generation and industrial process heat supply
- TRISO coated particle fuel: Developed over last ~5 decades
  - Fuel operational envelope is well established with a large volume of performance data

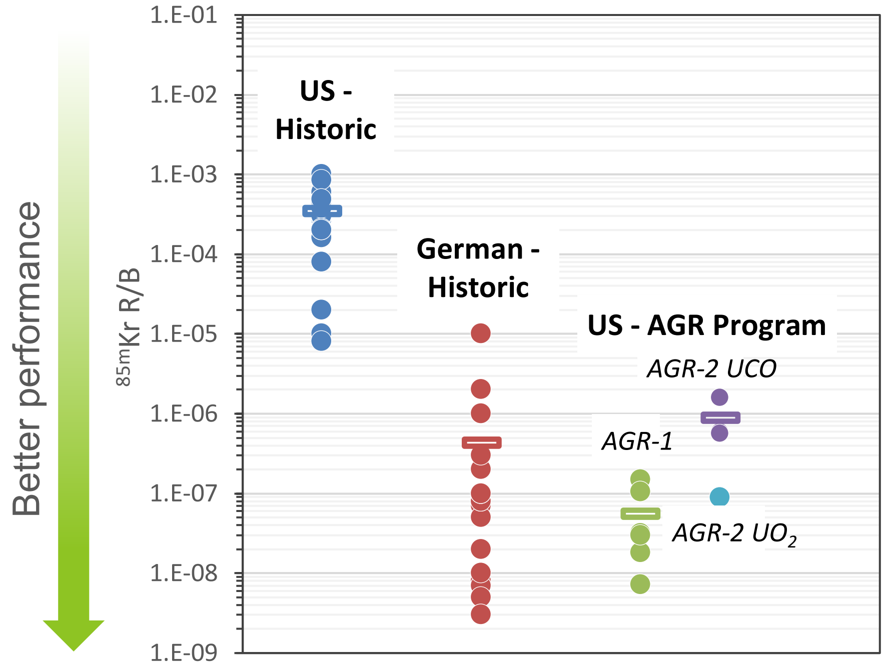



*Conventional TRISO fuel performance envelopes*

# 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
  - Evaluate fission product transport behavior to support reactor safety analyses

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



# Advanced Gas Reactor Fuel Development and Qualification Program

## Objectives and Motivation

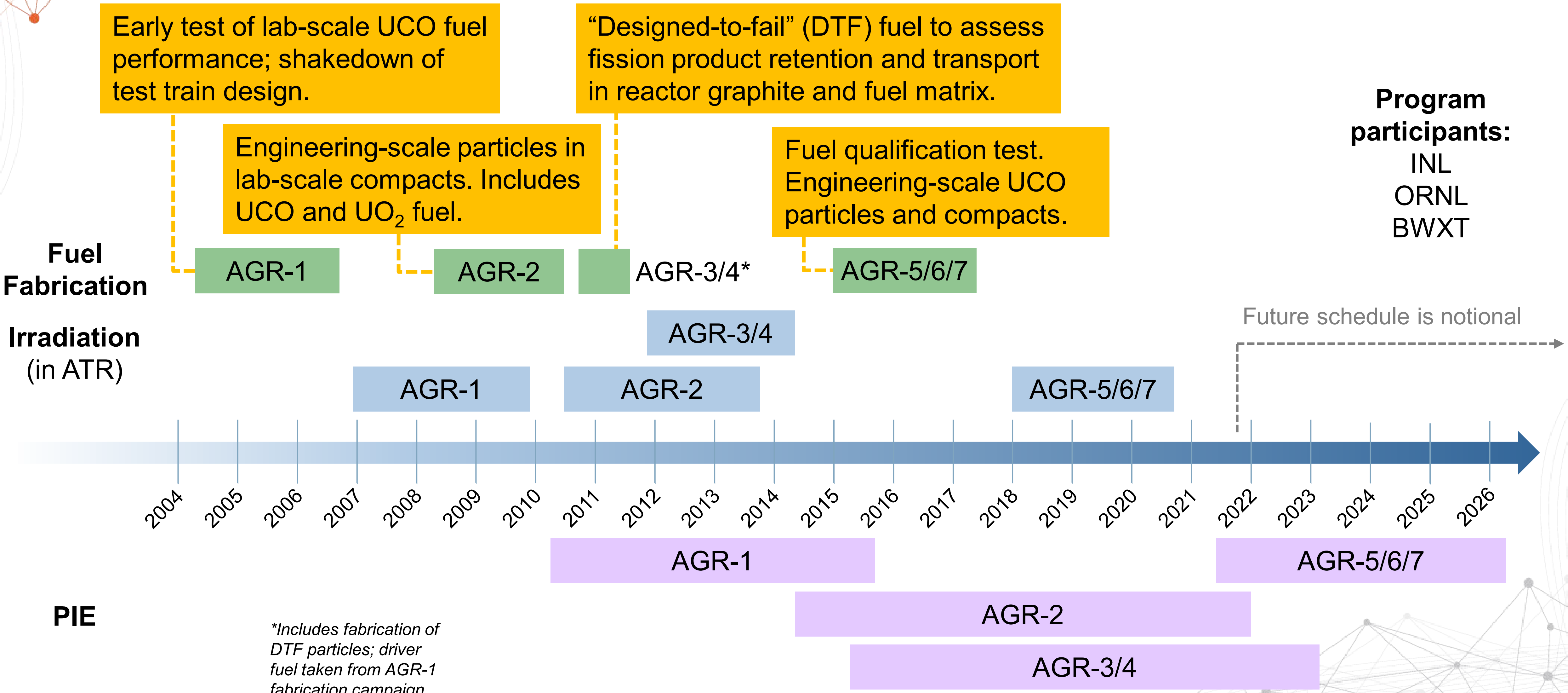
- Provide data for fuel qualification in support of reactor licensing
- Establish a domestic commercial TRISO fuel fabrication capability

**Reduce market entry risk**

## Approach

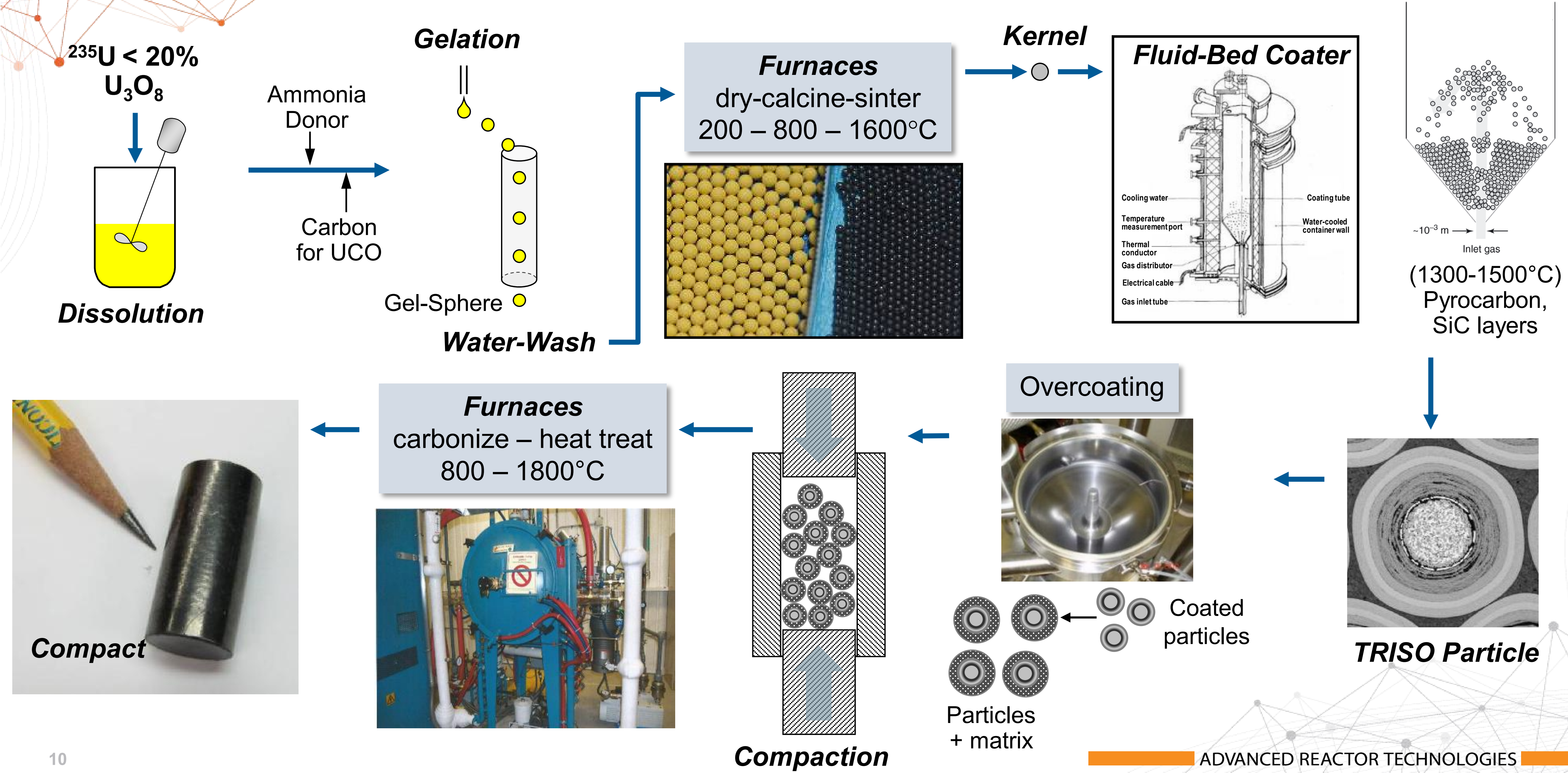
- Focus is on developing and testing **UCO** TRISO fuel
  - **Develop fuel fabrication and quality control measurement methods**, first at lab scale and then at industrial scale
  - **Perform irradiation testing** over a range of conditions (burnup, temperature, fast neutron fluence)
  - **Perform post-irradiation examination and safety testing** to demonstrate and understand performance during irradiation and during accident conditions
  - **Develop fuel performance models** to better predict fuel behavior
  - **Perform fission product transport experiments** to improve understanding and refine models

# AGR Program Timeline




**Includes fabrication of DTF particles; driver fuel taken from AGR-1 fabrication campaign*

# TRISO Fuel Fabrication: Process Overview



# AGR Fuel Development Approach

- LEU UCO kernel
  - Improved performance at high burnup and high temperatures compared to $UO_2$
  - Significant development in US since ~1980
- Use standard German $UO_2$ TRISO coating design based on proven performance
- Higher particle packing fractions (~35 – 40%) compared to German spheres (<10%), consistent with the use of cylindrical compacts in prismatic block reactor designs
- Target peak burnup of 20% FIMA and average fuel temperatures of ≤1250°C
- Demonstrate fuel fabrication at the lab scale first (ORNL), then demonstrate fabrication process scale up (BWXT)

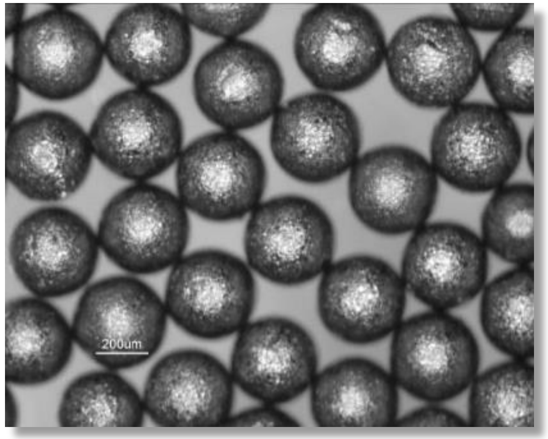
***Fabrication scale up*** ↓

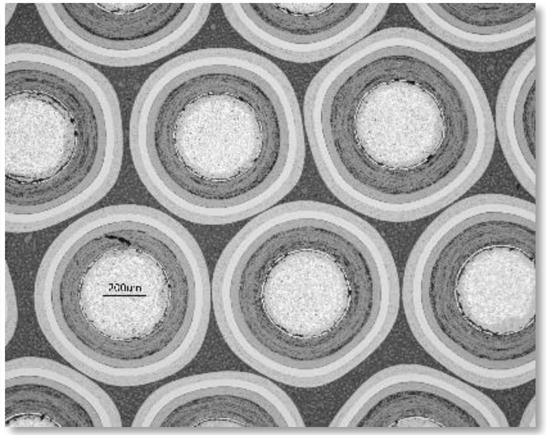
| | Kernels | Coatings | Compacts |
|---|---|---|---|
| AGR-1 | Engineering scale | Lab Scale | Lab Scale |
| AGR-2 | Engineering Scale | Engineering scale | Lab Scale |
| AGR-5/6/7 | Engineering Scale | Engineering Scale | Engineering Scale |

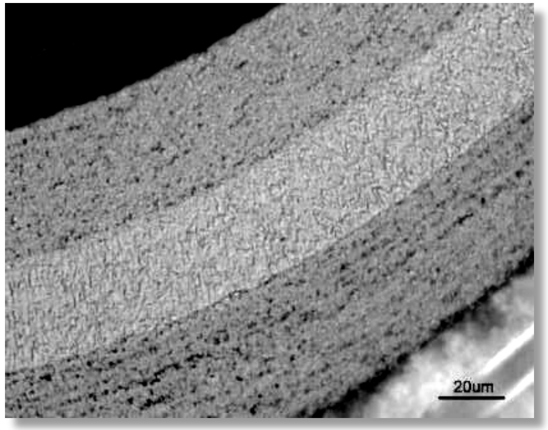
*Lab Scale – ORNL*
*Engineering Scale – BWXT*

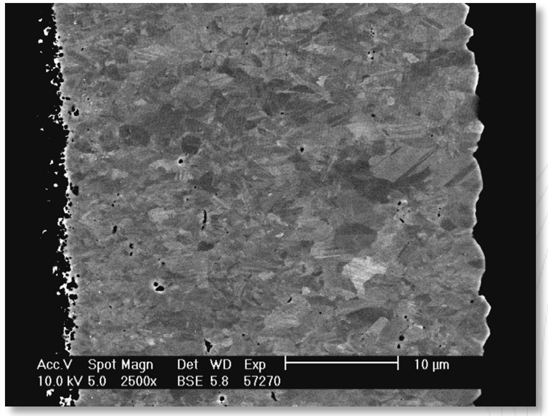
# AGR Program Fuel Specifications for QC

- Specified criteria on both process conditions and fuel properties
- Acceptance stages for kernel batches, kernel composites, particle batches, particle composites, and compacts
- Specified mean values and/or critical limits on the dispersion for variable properties, such as:
  - Kernel diameter
  - Kernel stoichiometry
  - Layer thickness
  - Layer density
  - Pyrocarbon anisotropy
  - Kernel and particle aspect ratio
  - Compact dimensions
  - Compact U loading
  - Dispersed U fraction
  - Compact impurity content
- Specified maximum defect fractions for attribute properties, such as:
  - SiC defects
  - IPyC/OPyC defects
  - Exposed kernel defects



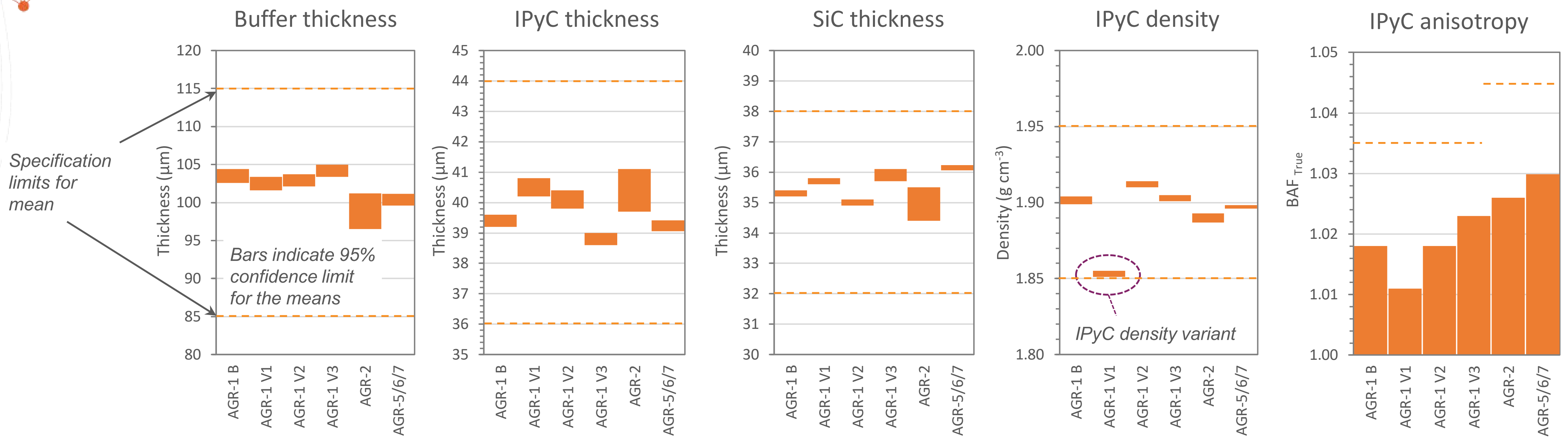






*Particle defect specifications apply to the **compact***

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

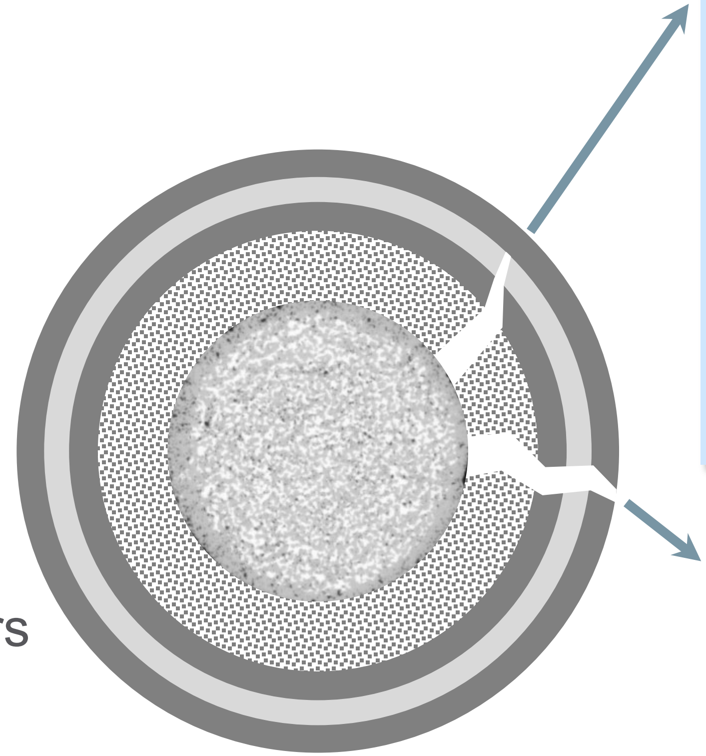



- Mean must be within the specification limits at 95% confidence
- Measured values typically lie well within the specification range
- Note that some specifications were changed following AGR-1, based on computational modeling results on fuel behavior

# TRISO Fuel Performance

***Key metrics of fuel performance:***

1. Coating integrity
   - Layers remain intact to retain fission products
2. Fission product retention – key factors:
   - Retention in kernel
   - Coating integrity
   - Diffusive transport through layers
   - Fuel matrix retention

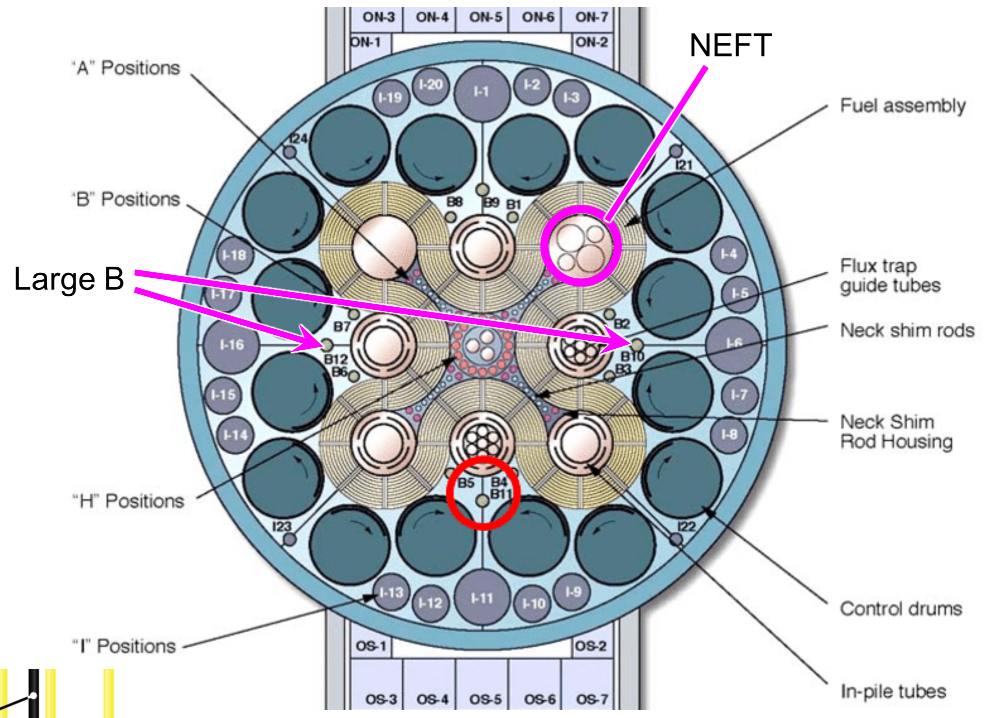


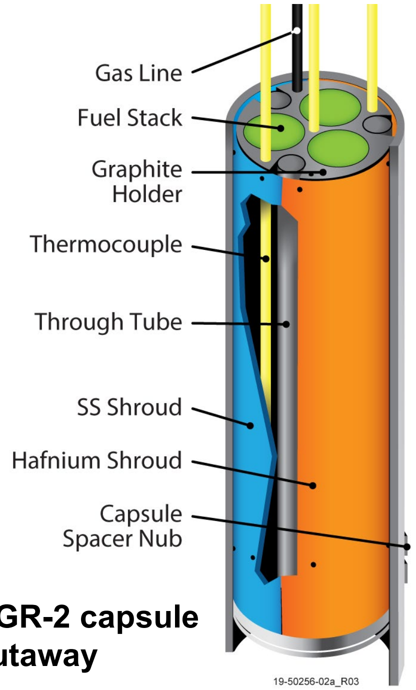
- SiC layer failure:
  – Breach in the SiC layer with at least one pyrocarbon layer intact
  – Release most condensable fission products (e.g. **Cs**) but retain fission gas

- TRISO layer failure (exposed kernel):
  – All three dense coating layers breached
  – Release of fission gas and condensable fission products

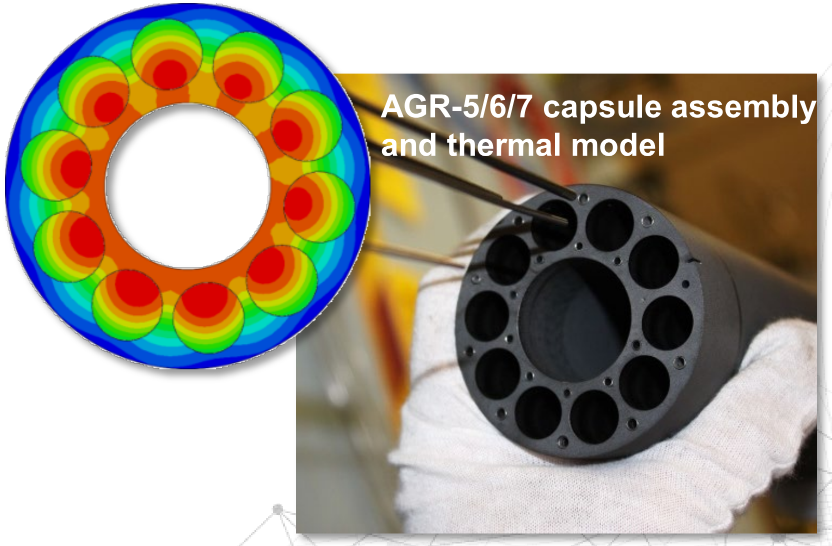
# AGR Program Irradiation Experiments

- 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
- Thermocouples used to measure temperature and compare with thermal model
- Complex neutronic and thermal models of the test trains calculate irradiation conditions



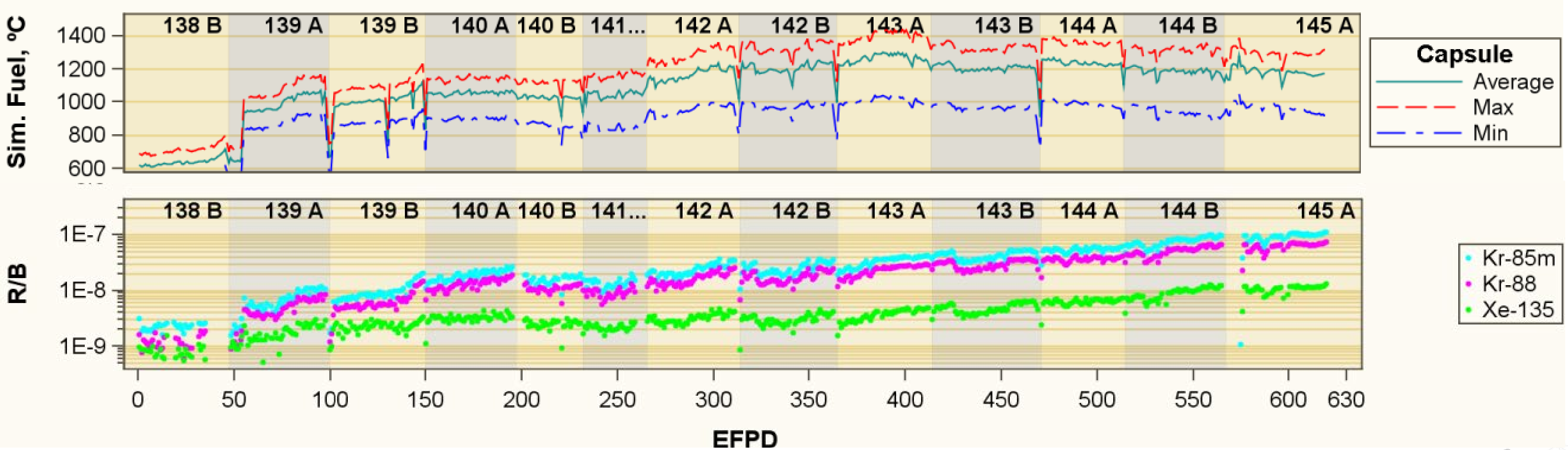

**AGR-2 capsule cutaway**



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

# Irradiation Performance: Fission Gas Release

- Fission gas **release rate to birth rate ratio (R/B)** is the main metric of fuel performance during irradiation
- Sources of fission gas release are (1) U contamination, (2) coating defects, and (3) coating failures
- 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***

# AGR Program Fuel Performance Irradiation Tests

| Irradiation test | Fuel type | Kernel ø (µm) | $^{235}U$ (wt %) | Compacts (particles) | Completed | EFPD | Burnup (%FIMA) | Temperature (°C)[a] | EOL $^{85m}Kr$ R/B |
|---|---|---|---|---|---|---|---|---|---|
| **AGR-1** | UCO | 350 | 19.7 | 72 (298,000) | Nov 2009 | 620 | 11.3 – 19.6 | 1069 – 1197 | $0.1 – 1\times10^{-7}$ |
| **AGR-2** | UCO<br>$UO_2$ | 427<br>508 | 14.0<br>9.6 | 36 (114,000)<br>12 (18,500) | Oct 2013 | 559 | 7.3 – 13.2<br>9.0 – 10.7 | 1080 – 1360<br>1072 – 1105 | $\sim10^{-6}$ [b]<br>$10^{-7}$ [b] |
| **AGR-5/6** | UCO | 426 | 15.5 | 170 (515,000) | Jul 2020 | 361 | 5.7 – 15.3 | 741 – 1231 | $0.1 – 1\times10^{-6}$ [c] |
| **AGR-7** | UCO | 426 | 15.5 | 24 (54,000) | Jul 2020 | 361 | 13.6 – 15.0 | 1328 – 1432 | $0.1 – 1\times10^{-6}$ [c] |

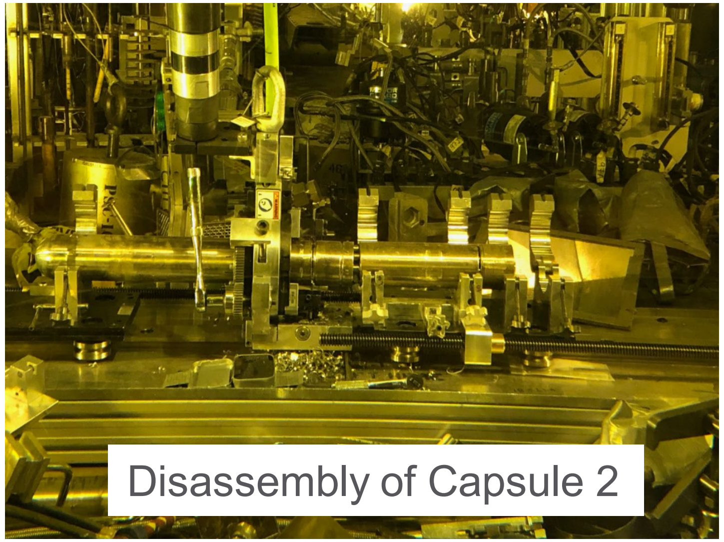
[a] Time-average peak temperatures

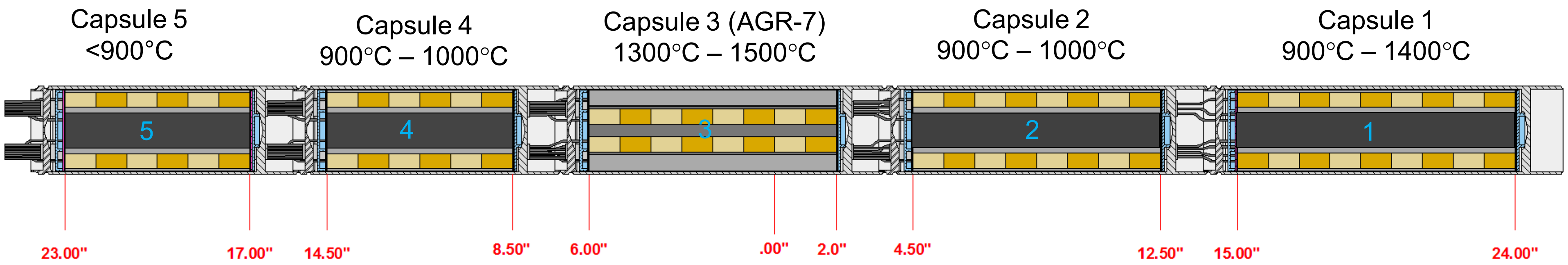
[b] R/B values through the first 3 irradiation cycles

[c] R/B values through the first 5 irradiation cycles

# AGR-5/6/7 Special Issues

- Final fuel qualification irradiation and performance margin test (peak fuel temperatures ~1550°C)
- Large increases in fission gas release from Capsule 1 in Oct 2019 indicate significant number of particle failures
- Cause remains unknown, but nature of the release suggests it was induced by the experiment (i.e., this is most likely not intrinsic fuel failure); PIE needed to fully understand this behavior
  - *Capsule 1 PIE is considered highest priority activity*
- PIE began in May 2021


Disassembly of Capsule 2

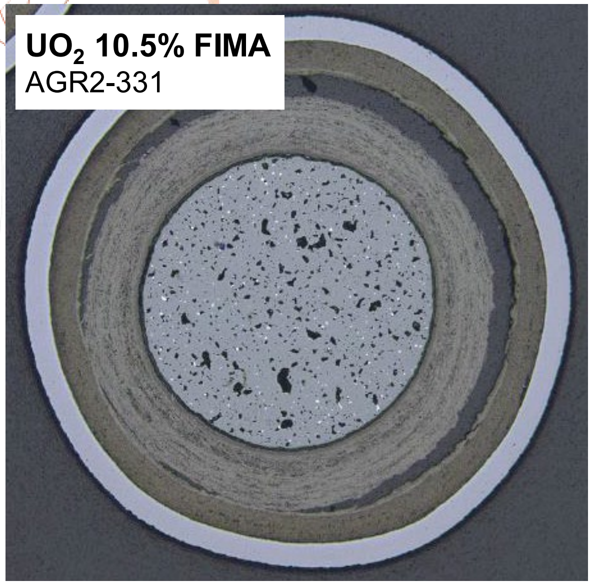


AGR-5/6/7 test train axial cross section

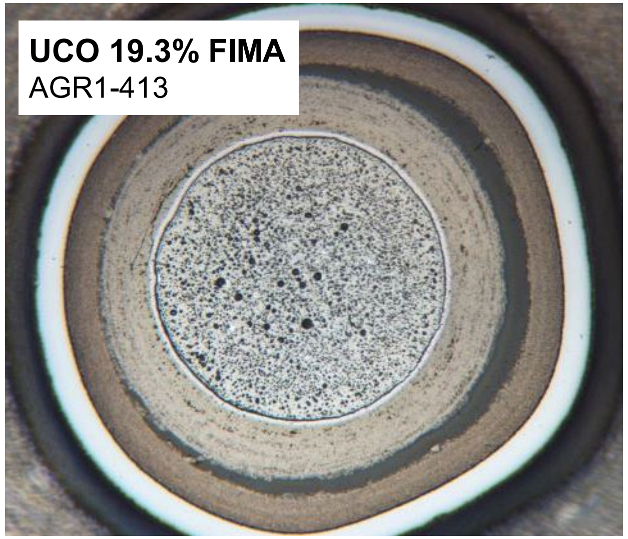
# TRISO Fuel Post-Irradiation Examination and High-Temperature Accident Safety Testing

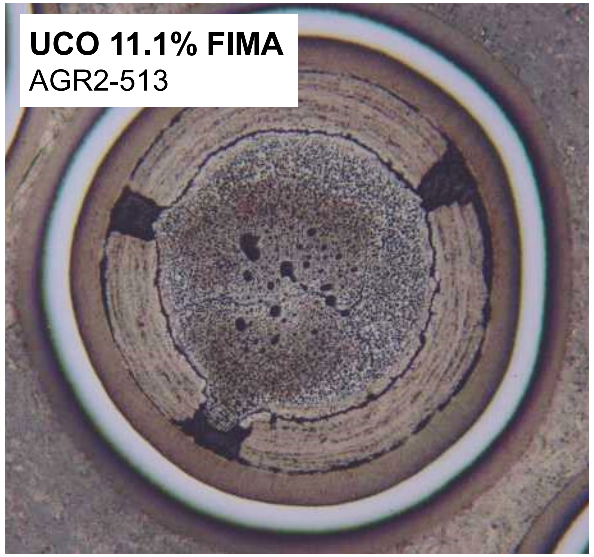
- Main objectives:
  - Measure fission product retention during irradiation
  - Measure fission product retention during high temperature post-irradiation heating
  - Examine kernel and coating microstructures to understand irradiation-induced changes and the impact on fuel performance
- Both conventional and specialized equipment used for TRISO fuel examinations


# Kernel and Coating Behavior During Irradiation: AGR Particles




- 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

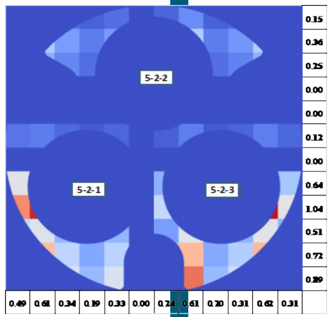
# Locating and Studying Failed Particles Greatly Improves Understanding of Fuel Performance

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


AGR-1 Test Train Vertical Section

*Identify compacts with leakers*

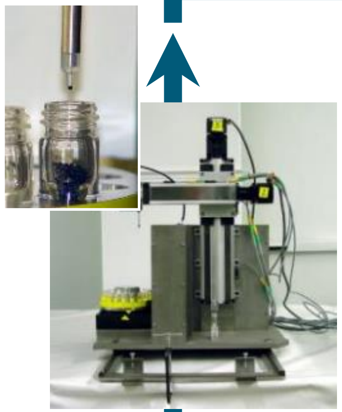
Capsule disassembly



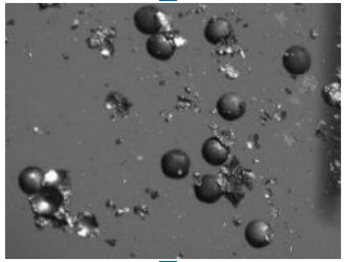

Gamma scan to identify cesium hot spots and compact location

*Identify particles with failed coatings*

Deconsolidation to obtain ~4,000 particles from compact

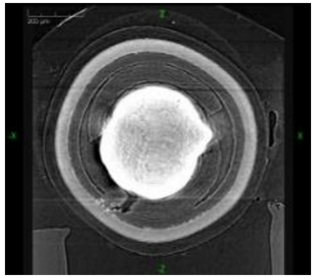


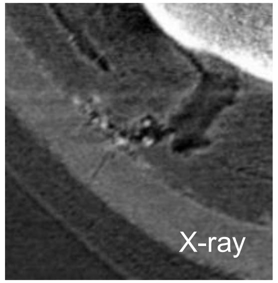
Gamma count to find particles with low cesium retention



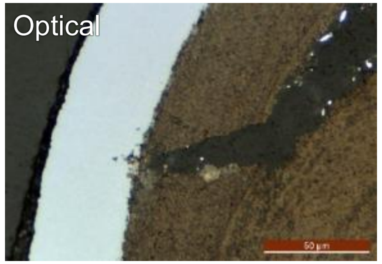
*Study particles with failed coatings*

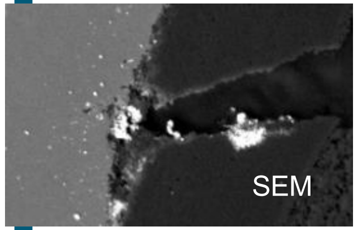
X-ray tomography to locate failures



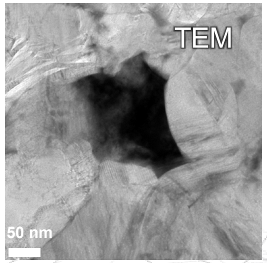



Materialography to expose defective region for analysis



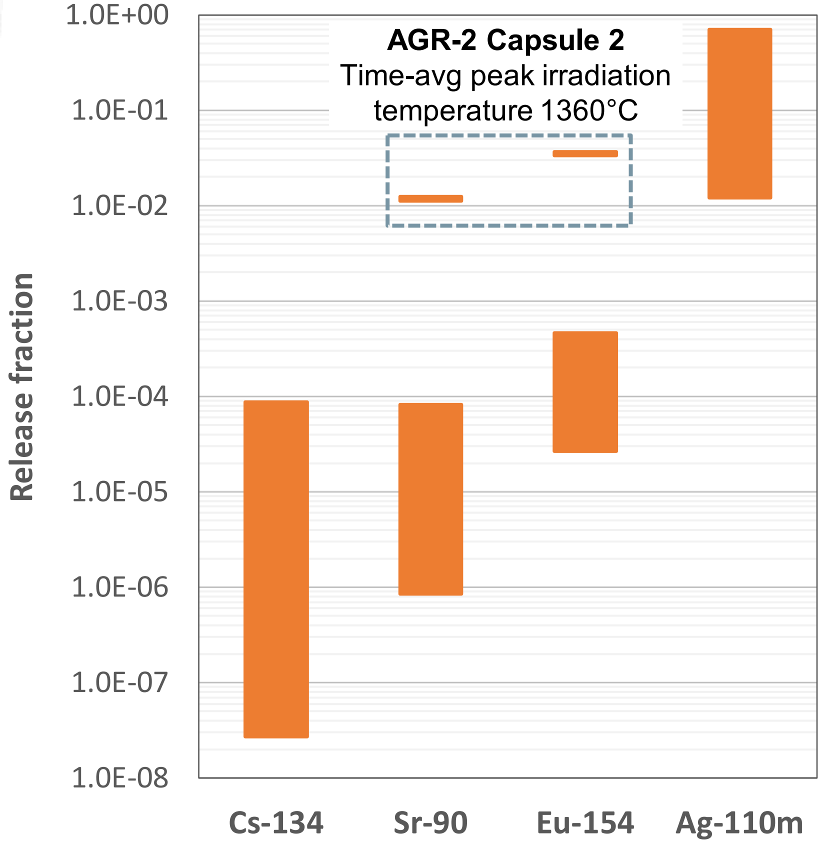




Advanced microscopy to study coating layers in detail



# 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*

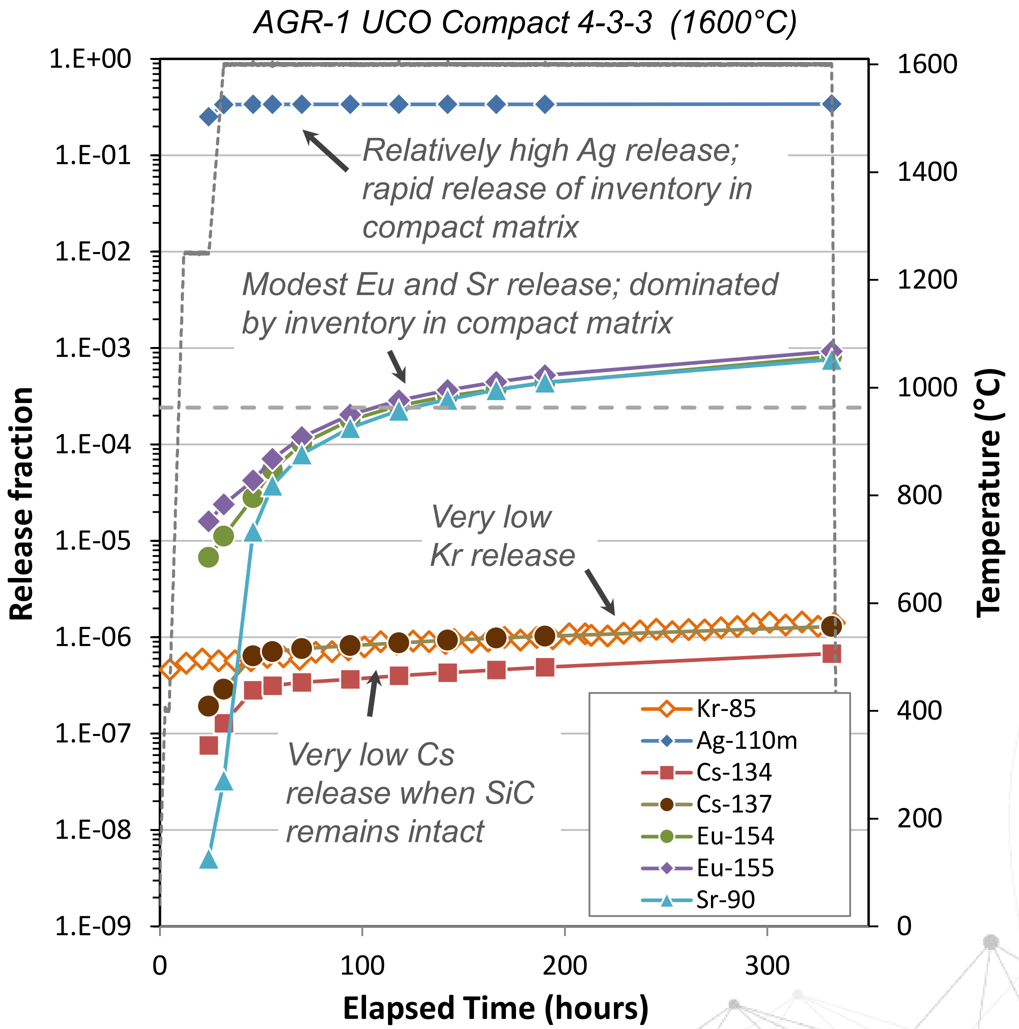



- Cs release is very low with intact SiC; higher releases are associated with a limited number of particles with failed SiC
- Sr and Eu can exhibit modest release; release is much higher with high in-pile temperatures (AGR-2 Capsule 2 time-average peak temperatures 1360°C)
- High Ag release
- Note these releases do not account for retention in core graphite

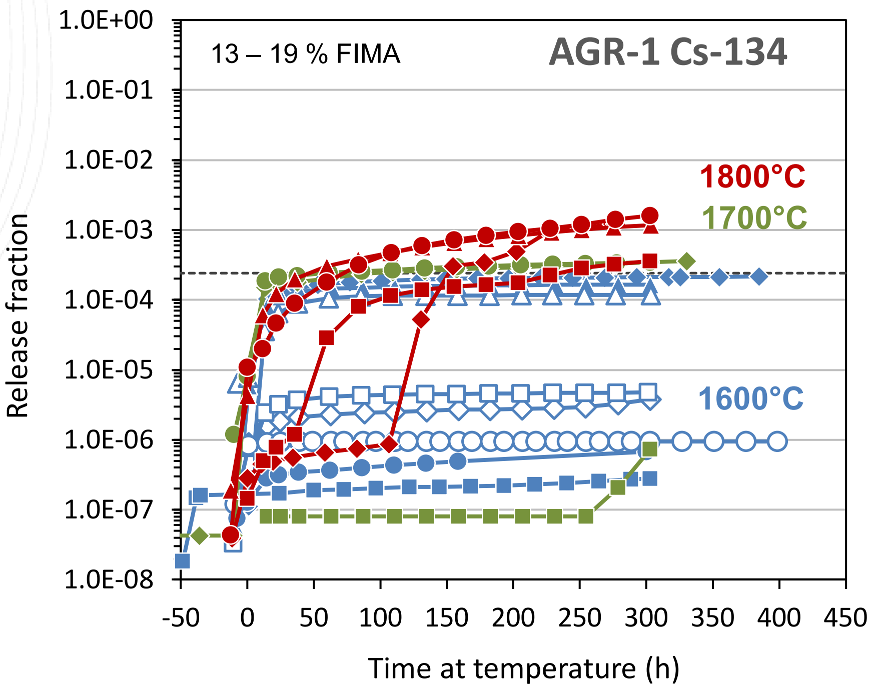
~150 – 300°C higher than peak temperatures in other AGR-1 and AGR-2 fuel compacts

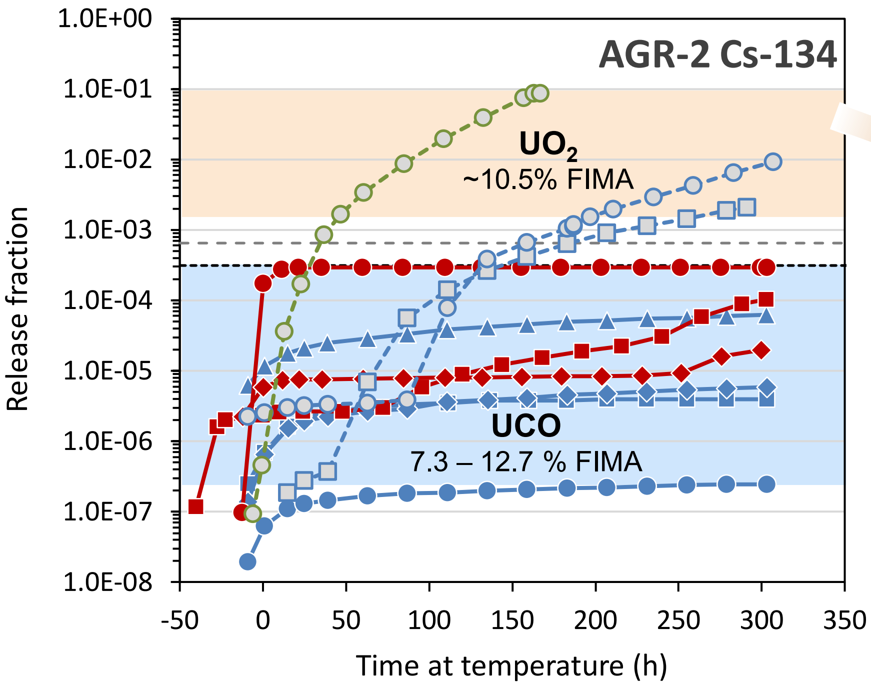
# AGR-1 Safety Test Performance

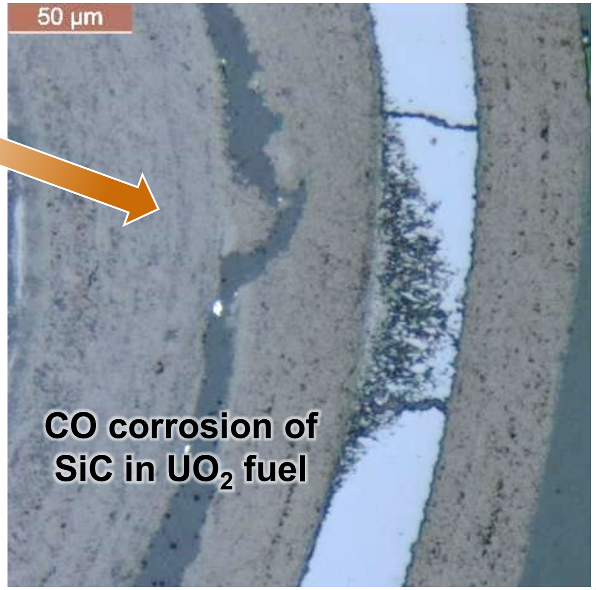
- **Low Cs release** (dependent on intact SiC)
- **Low Kr release**
- **Modest Sr and Eu release** (influenced by irradiation temperature)
- **High Ag release** (dominated by in-pile release from particles)
- **Excellent UCO performance up to 1800°C**
- **Low coating failure fractions** (UCO)
- **$UO_2$ demonstrates much higher incidence of SiC failure due to CO attack**



# Cesium Release Results: AGR Program Safety Testing




- **UCO fuel**: relatively low Cs release; release >$10^{-4}$ results from discrete SiC layer failure in 1 or more particles
- **$UO_2$ fuel**: higher Cs release compared to UCO; driven by CO attack on the SiC layer causing more widespread SiC failure; fission gas release generally remains low

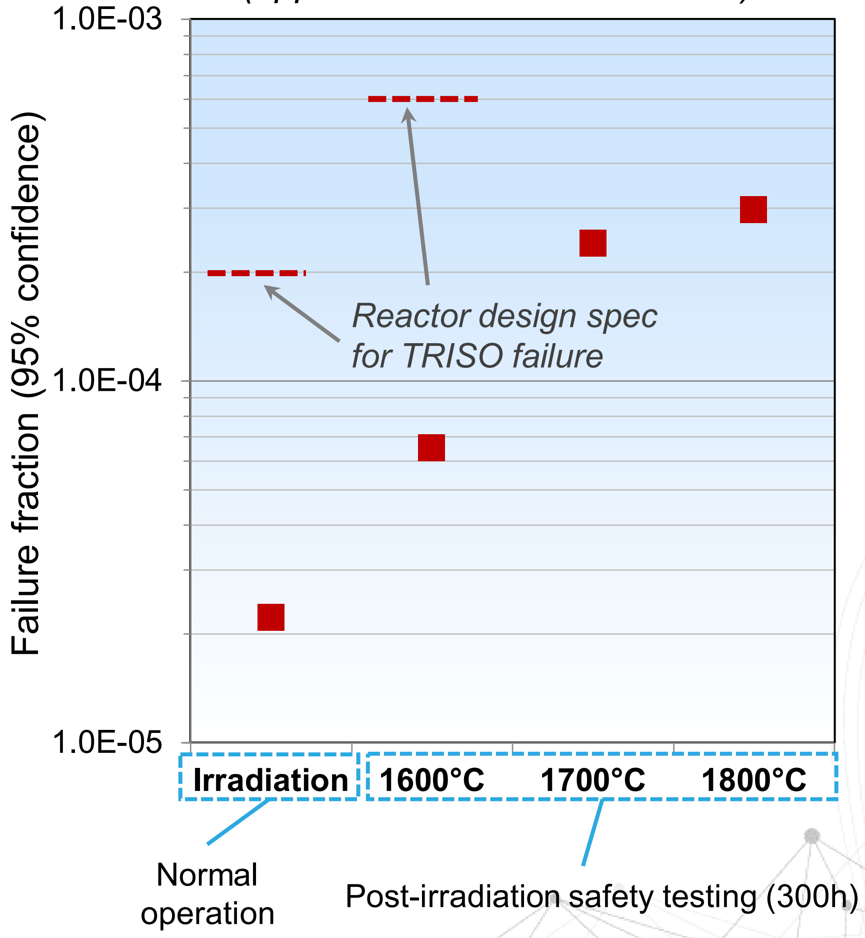
# Accident Performance Summary

- 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

Outstanding Data Needs:

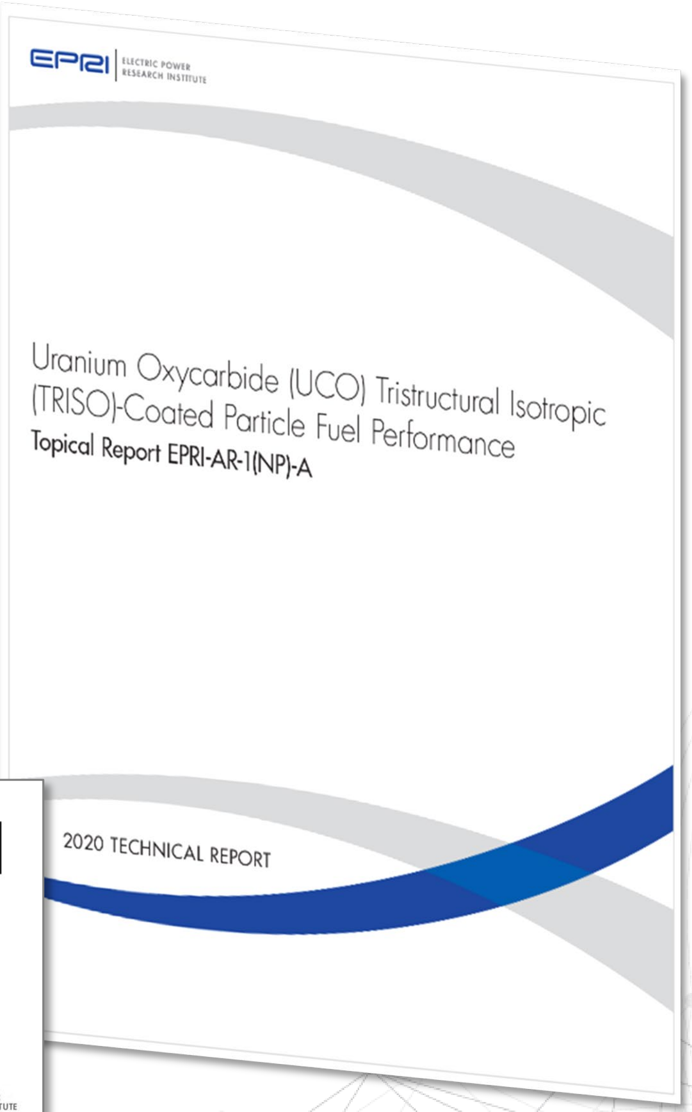
- Behavior of fuel and fission products under **core oxidizing conditions** (steam, air)
- Behavior of **short-lived fission products** during high-temperature accidents (e.g., $^{131}I$)

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



# UCO TRISO Fuel Performance Topical Report to US NRC

- AGR fuel program staff—in conjunction with U.S. HTGR reactor and fuel vendors and the Electric Power Research Institute (EPRI)—developed a Topical Report for review by the Nuclear Regulatory Commission to support reactor licensing
  - https://www.epri.com/research/products/000000003002019978
- Scope focused on UCO TRISO fuel particle irradiation and accident performance as demonstrated by the AGR-1 and AGR-2 irradiation, PIE, and safety test data collected to date
- Report asserts that UCO fuel particles with properties similar to the AGR-1 and AGR-2 particles will exhibit similar performance under similar condition
- NRC Safety Evaluation Issued in August 2021
- The Topical Report and associated SE can be referenced by applicants during reactor licensing


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

# Additional Components of UCO TRISO Fuel Qualification

- Fission product transport experiments (AGR-3/4)

- Fuel performance modeling

# Coated-Particle-Fueled Reactor Concepts and Fuel Designs

| Developer | Description | Fuel design |
|---|---|---|
| X-energy | Xe-100 (200 MWt PB HTGR) | UCO TRISO fuel pebbles |
| | Xe-Mobile (1 – 5 MWe microreactor) | UCO TRISO |
| Framatome | SC-HTGR (625 MWt) | UCO TRISO fuel compacts |
| UltraSafe Nuclear | MMR (15 MWt microreactor) | TRISO particles in SiC matrix ("FCM") |
| BWXT | Microreactor (50 MWth) | UCO TRISO compacts |
| | BANR[6] | UN TRISO in SiC matrix |
| Kairos Power | KP-FHR (140 MWe salt-cooled SMR) | UCO TRISO fuel pebbles |
| | HERMES (50 MWt test reactor) | UCO TRISO fuel pebbles |
| Urenco | U-Battery 10 MWt microreactor | $UO_2$ TRISO fuel compacts |
| Westinghouse | eVinci 7-12 MWt microreactor | TRISO or other |
| StarCore Power | 20 MWe HTGR | TRISO |
| HolosGen | 22 MWt scalable microreactor | TRISO in fuel compacts |
| Radiant Nuclear | >1 MWe microreactor | TRISO |
| ORNL | Transformational Challenge Reactor | UN TRISO in SiC matrix |
| NASA | NTP, NEP | Various |

**Useful references:**

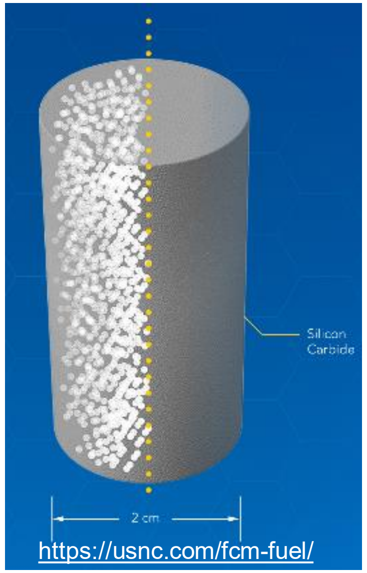

- Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, IAEA (https://aris.iaea.org/Publications/SMR_Book_2020.pdf)
- https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

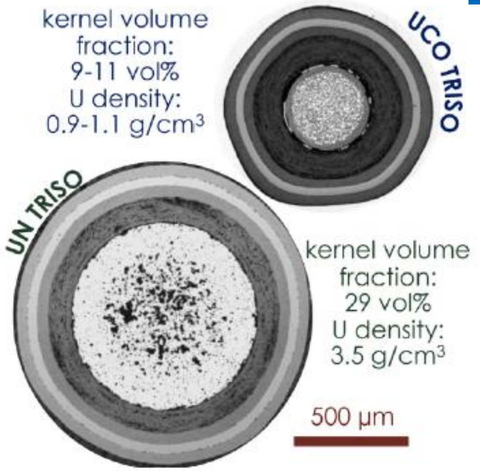
# Unconventional Coated Particle Fuel Designs

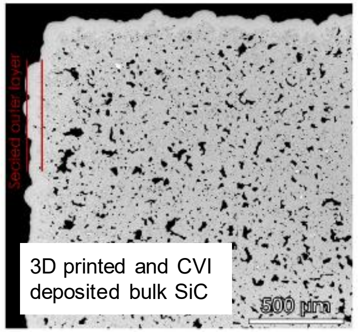
New reactor designs (e.g., microreactors, molten salt-cooled reactors) and new proposed applications of TRISO fuel (e.g., nuclear thermal propulsion) are prompting experimentation with unconventional coated particle fuel designs

- $UCO/UO_2$ TRISO in graphite
  - Kernel size variations
  - Coating geometry changes
  - Packing fraction changes
  - Different fuel element designs (differing cylindrical compact dimensions, annular spherical pebbles, etc.)
- TRISO in SiC matrix
- UN TRISO – Kernel composition, kernel size changes

Many of these fuel forms have limited or no irradiation data

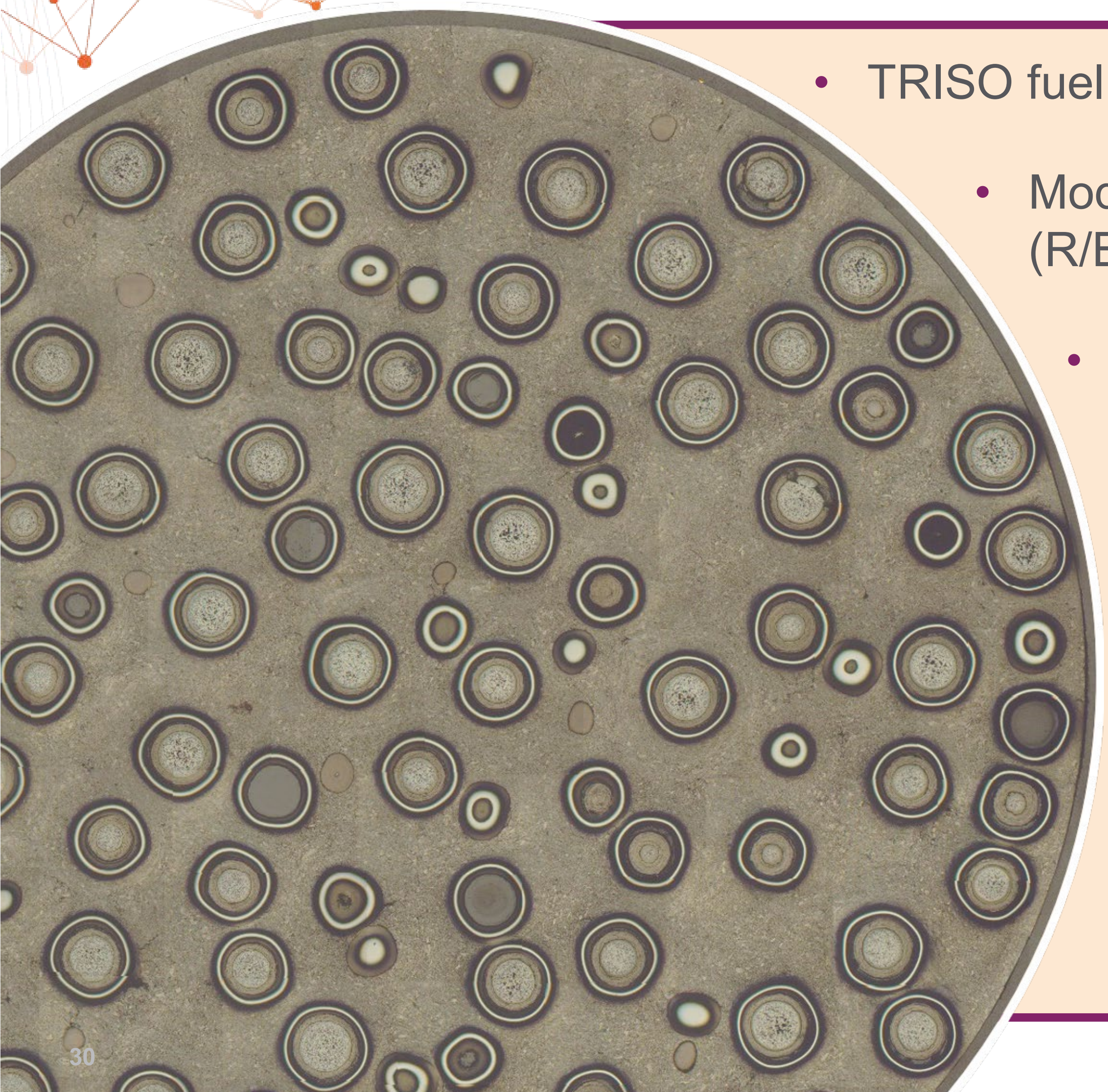



Terrani et al. JNM 547 (2021) 152781

# Summary



- TRISO fuel development spans over 5 decades
- Modern TRISO fuel exhibits very low fission gas release (R/B) values during irradiation
- Coating failure remains low during normal operation and high-temperature accidents in UCO fuel
- Kernel and coating morphological changes during irradiation are well documented
- TRISO fuel FP release behavior is well characterized
- Unconventional coated particle fuel forms will likely require additional testing to demonstrate performance

Idaho National Laboratory