INL/MIS-21-62429-Revision-0

TRISO Fuel Part I: Background, Fabrication, and Irradiation Performance

April 2021

Changing the World's Energy Future

Paul A Demkowicz

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-21-62429-Revision-0

TRISO Fuel Part I: Background, Fabrication, and Irradiation Performance

Paul A Demkowicz

April 2021

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

TRISO Fuel I:

Background, Fabrication, and Irradiation Performance

CNSC Seminar

Course Module Objective

- Review TRISO fuel design, fabrication, and performance, with a focus on recent results and developments in the last ~15 years

The Training Course delivered to the NRC in 2010 included several modules discussing TRISO fuel (Modules 7a, 7b, and 8). You are encouraged to review that course material for additional details on fuel fabrication and performance history.

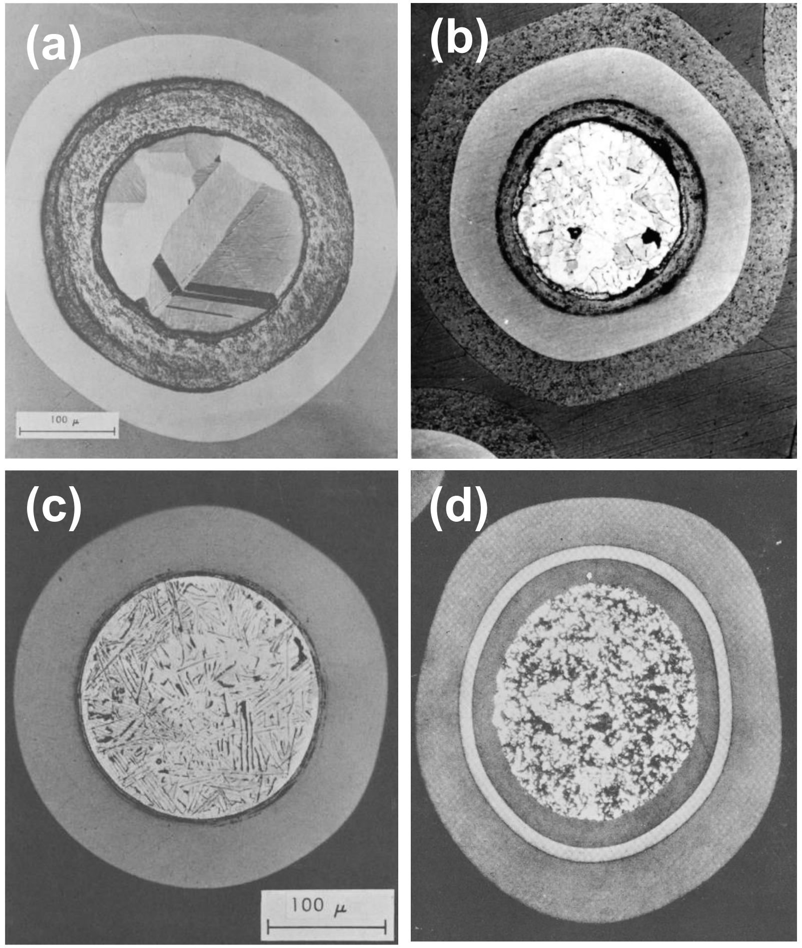
Outline

Part I

- TRISO Fuel Background and Design
- US DOE Advanced Gas Reactor (AGR) Program
- Fuel Fabrication and Quality Control
- Fuel Irradiation Performance

Coated Particle Fuel: Early History

- First developed in late 1950s to support Dragon reactor in UK
- Originated as single pyrocarbon layer to protect carbide kernels during fabrication
- Quickly evolved in 1960s into more sophisticated coating designs to provide fission product retention
- First demonstration reactors:
  - Dragon - **UK**
  - Peach Bottom Unit 1 - **USA**
  - Arbeitsgemeinschaft Versuchsreaktor (AVR) - **Germany**

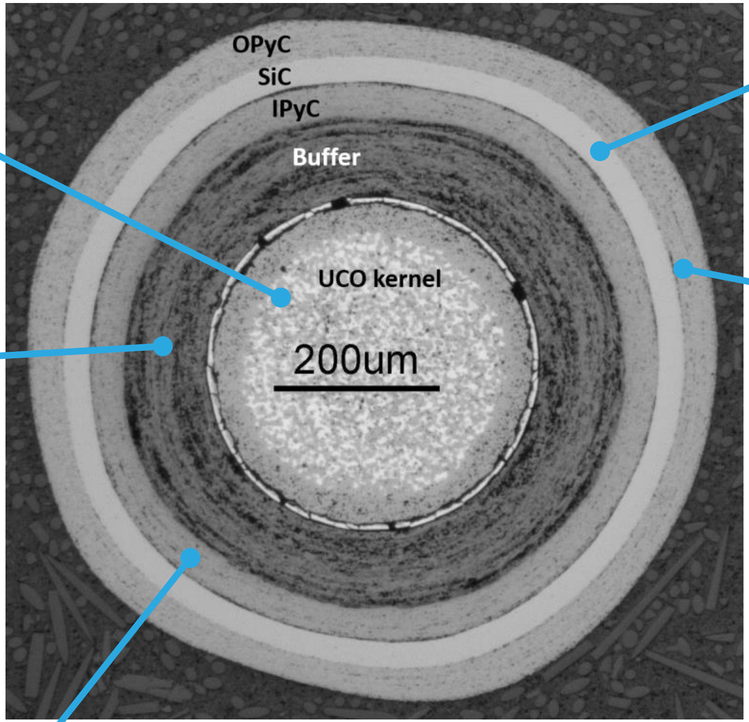


(a) Early example of a BISO (bistructural isotropic) particle. (b) Particle with "Triplex" structure (porous buffer layer followed by laminar and columnar pyrocarbon layers). (c) Carbide particle with single PyC coating layer used in Peach Bottom first core. (d) Fertile (Th,U)C_2 particle used in Dragon first charge, consisting of PyC-SiC-PyC structure.

P.A. Demkowicz et al., Coated particle fuel: Historical perspectives and current progress, J. Nucl. Mater. 515 (2019) 434-450

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

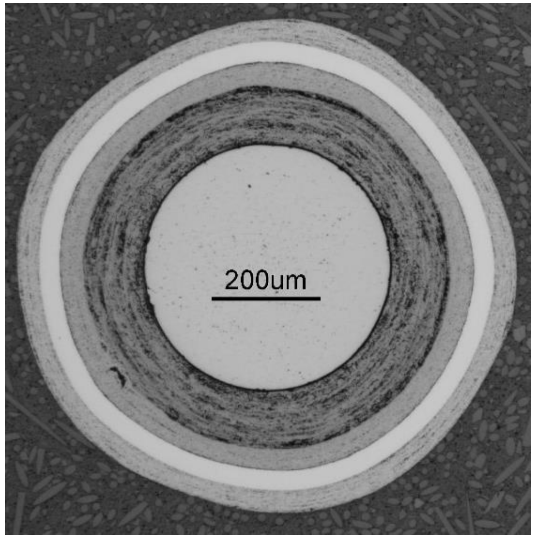


- **SiC (~35 µm)**
  - Main structural layer
  - Primary coating layer for retaining non-gaseous fission products
- **OPyC (~40 µm)**
  - Contributes to fission gas retention
  - Surface for bonding to matrix
  - Protects SiC layer during handling
- **IPyC (~40 µm)**
  - Protects kernel from chlorine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

TRISO Fuel Kernel Types

- Kernels are mechanically decoupled from the outer coating layers, giving great flexibility in kernel types
- HTGRs can use many fuel types
  - Fissile: UC_2, PuO_2, $(Th,U)C_2$, $(Th,U)O_2$, UO_2, UCO
    - Prior to the late 1970s, mostly HEU fuel
  - Fertile: ThC_2, ThO_2, UO_2, UCO
- LEU UO_2 is most widely used fuel type today
  - Used in AVR (Germany), HTTR (Japan), HTR-10 and **HTR-PM** (China)
  - Extensive irradiation and heating test database from German/EU HTGR Program; emerging results from HTR-PM fuel testing
- UCO offers improved fuel performance at higher fuel burnup
  - Selected as reference fuel in the US HTGR program in early 1980s
  - Focus of the US Advanced Gas Reactor (AGR) Fuel Development and Qualification Program
  - UCO selected as reference fuel design by X-energy, Kairos Power, Framatome, and others

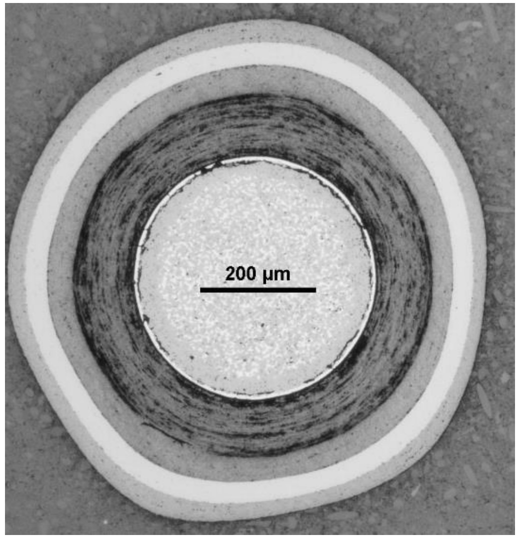
UO_2 and UCO TRISO Fuel

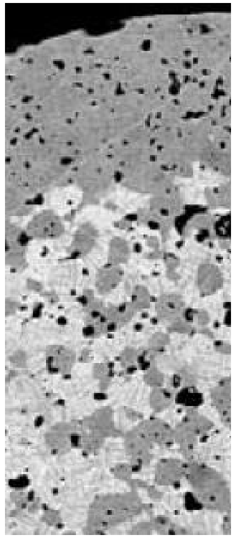


UO_2

UCO

(mixture of UO_2 and UC_x)





- *Different kernel*
- *Same coatings*

UO_2

- Utilized in modern pebble bed reactor designs (burnup limited to ~11% FIMA)
- Extensive development and testing since the 1970s in many countries
- Good fission product retention in the kernel, but results in formation of CO(g) during irradiation
  - Contributes to internal gas pressure
  - Kernel migration, CO corrosion of SiC

UCO

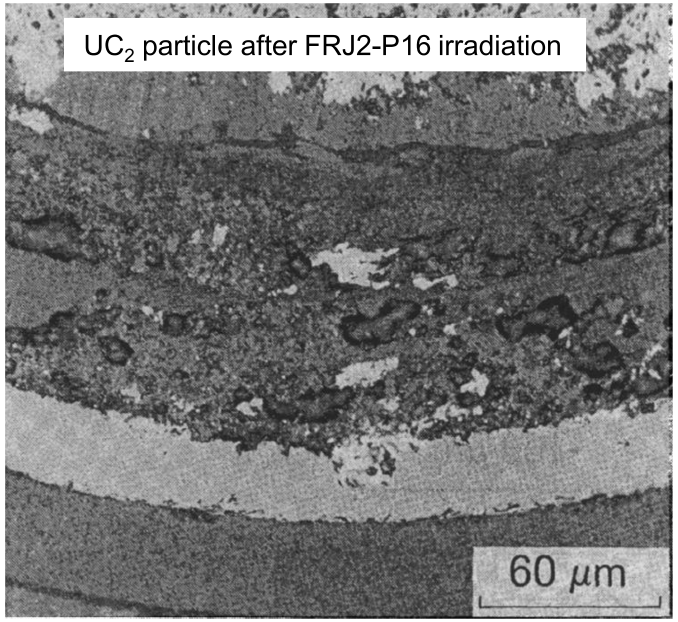
- Mitigates CO(g) formation
- Suited for higher burnup (up to ~20% FIMA and beyond) and larger temperature gradients in prismatic reactors
- Good retention of most rare earth fission products similar to UO_2; Sr and Eu are exceptions
- Developed primarily in the US since the 1970s
- No large-scale, successful performance demonstration through the early 2000s

Introduction of Oxide and Oxycarbide Kernels

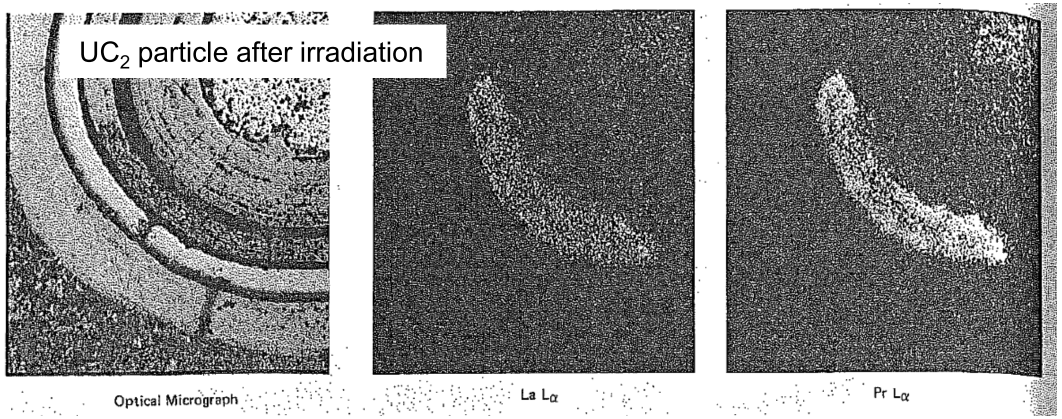
- Many programs converted to oxide fuels in 1970s
  - Good retention of U during high temperature fuel pebble fabrication (1900°C)
  - Good metallic fission product retention (beneficial for BISO fuel in AVR)
  - Suitable for lower temperature reactors
- The US retained carbide fuel because of issues with UO_2 at high temperature and larger temperature gradients common in large HTGR designs
  - Amoeba effect
  - CO(g) corrosion of SiC

Fission Product Interactions with SiC

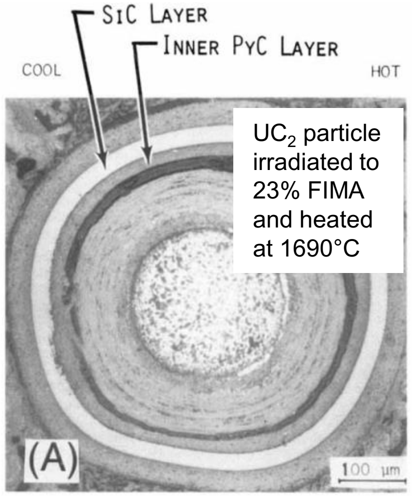
- By the 1970s, extensive irradiation experience with carbide kernels was available and indicated the potential for fission product interaction with the SiC layer
- In addition to some platinum-group metals (e.g., Pd), this include rare-earth fission products, which are not strongly retained in the carbide kernel

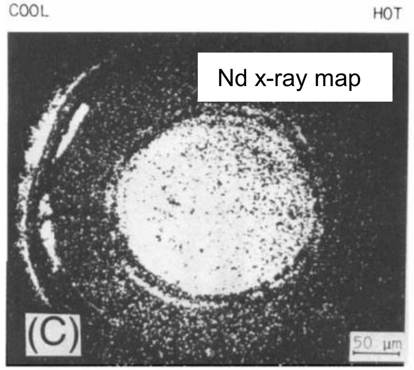


H. Grübmeier, A. Naoumidis, B. A. Thiele, Silicon-carbide corrosion in high-temperature gas-cooled reactor fuel particles, Nucl. Tech. 35 (1977) 413-427



F.J. Homan, T.B. Lindemer, E.L. Long, Jr., T.N. Tiegs, R.L. Beatty, Stoichiometric effects on performance of high-temperature gas-cooled reactor fuels from the U-C-O system, Nucl. Tech 35 (1977) 428-441

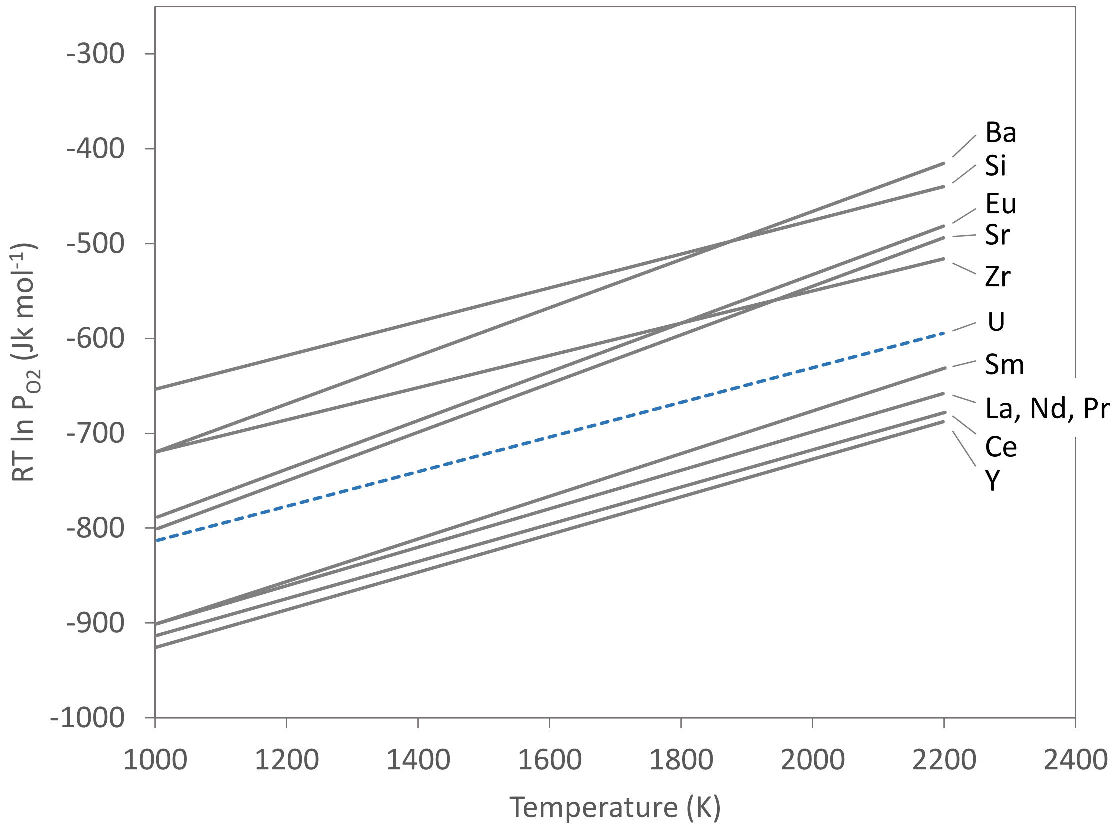




C.L. Smith, SiC-fission product reactions in HTGR TRISO UC_2 and UC_xO_y fission fuel: I, kinetics of reactions in a thermal gradient, J. Am. Ceram. Soc. 62 (1979) 600-606

Fission Product Thermochemistry in UC_xO_y Fuels

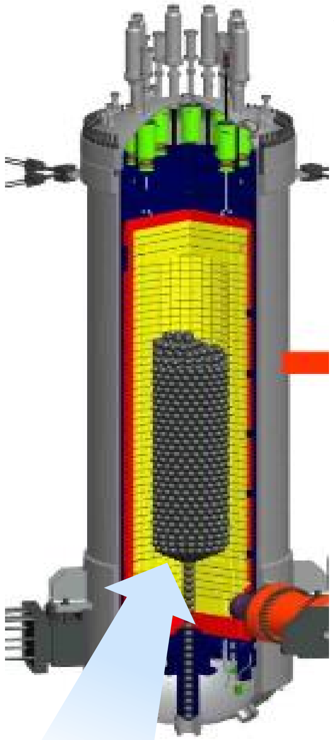
- Homan et al. (1977) published thermochemical analysis of oxide and carbide phases of various fission products
- Demonstrates strong tendency of rare-earth elements to form oxides
- UC_xO_y fuel is developed to provide improved fission product retention compared to UC_x, while also mitigating excess CO(g) formation of UO_2 fuel
- US chose UCO as reference fuel in early 1980s

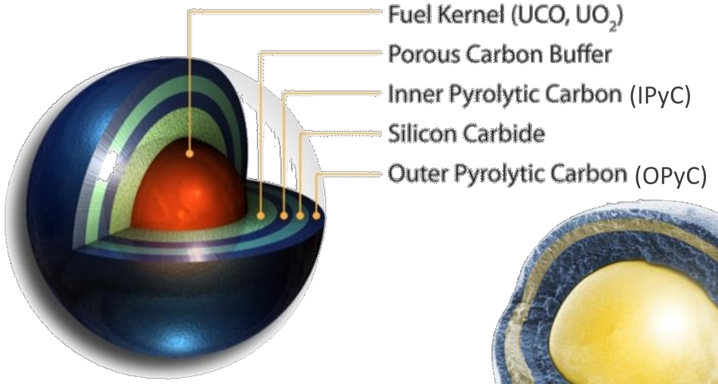


Oxygen potential of oxide—carbide equilibria
(reproduced from *Homan et al. 1977*)

TRISO Coated Particle Fuel Forms

Pebble bed reactor

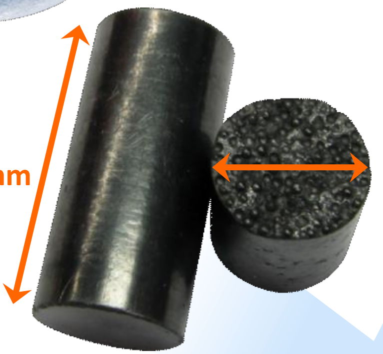




TRISO particle

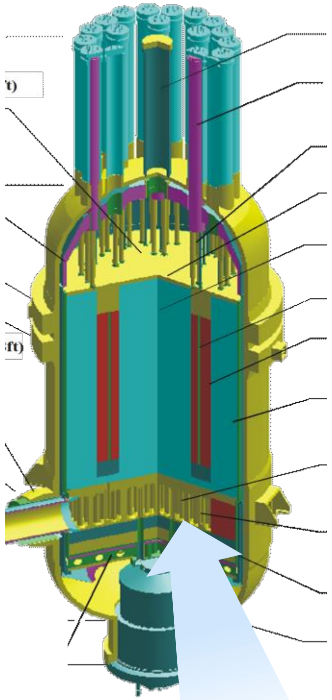
Spherical fuel pebbles

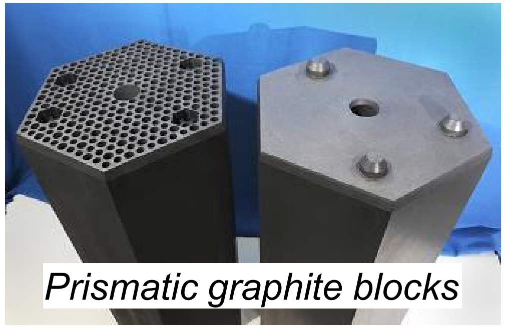
Particle design provides excellent fission product retention in the fuel and is at the heart of the safety basis for high temperature gas reactors



Cylindrical fuel compacts

Prismatic reactor

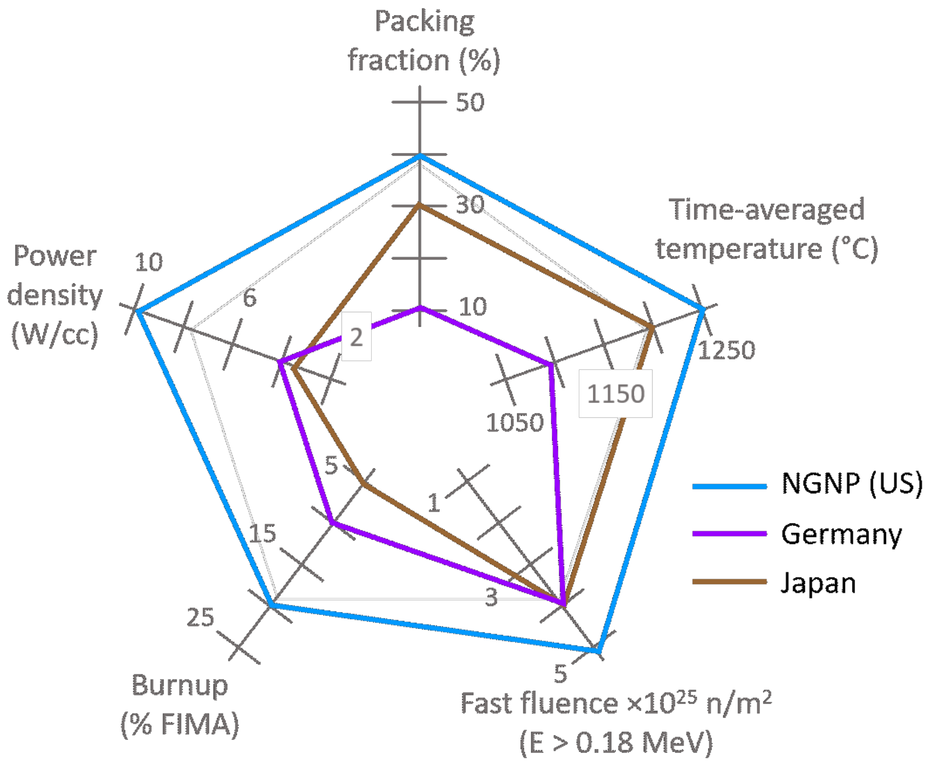




Prismatic graphite blocks

Emerging Reactor Designs Requiring TRISO Fuel

- Molten-salt-cooled reactors (FHR)
  - Most irradiation conditions are within the fuel performance envelope explored in the US AGR program, with some exceptions, e.g.:
    - Power density may be higher
    - Irradiation temperature may be lower
  - No data on TRISO performance in salt coolant
- Microreactors
  - Significantly different core design and fuel requirements are prompting proposed changes to TRISO particle designs
  - Limited analyses on conceptual designs suggest that irradiation and accident conditions are less severe than larger gas reactor designs
- Fully Ceramic Microencapsulated (FCM) fuels as Accident Tolerant Fuel for LWRs
  - TRISO particles in alternate matrix materials (e.g., SiC)



Conventional TRISO fuel performance envelopes

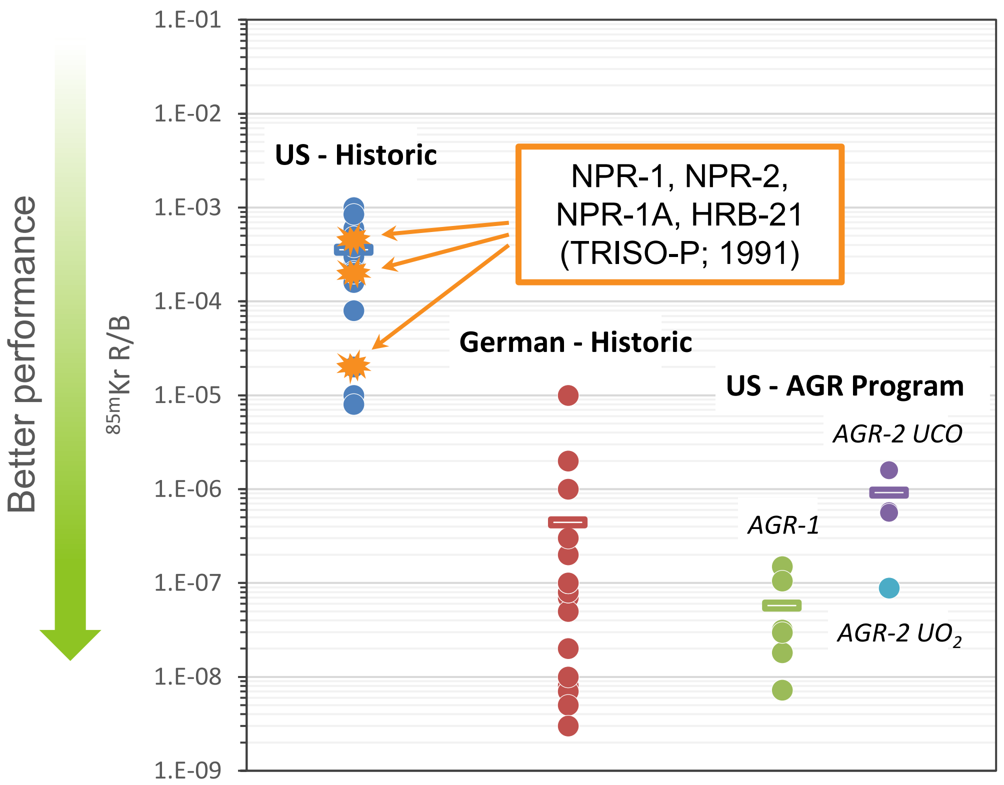
Outline

Part I

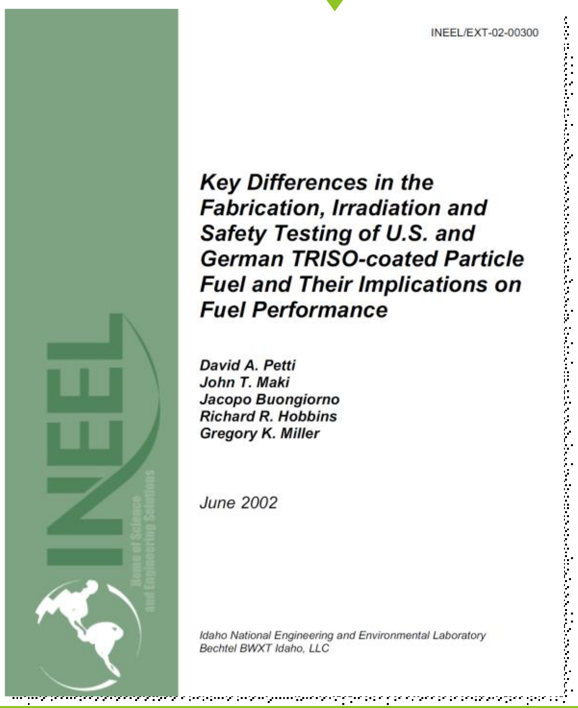
- TRISO Fuel Background and Design
- US DOE Advanced Gas Reactor (AGR) Program
- Fuel Fabrication and Quality Control
- Fuel Irradiation Performance

US DOE Advanced Gas Reactor (AGR) Program Motivation

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



- US TRISO fuel historically demonstrated much lower performance compared to German UO_2
- US-DOE objectives in early 2000s were to understand the causes of these differences
- Significant effort expended on understanding and modeling fuel performance, and improving fuel fabrication and characterization capabilities
- AGR-1 LEU UCO TRISO fuel demonstrated exceptionally low fission gas release at burnup as high as ~20% FIMA



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 Fuel Development Approach

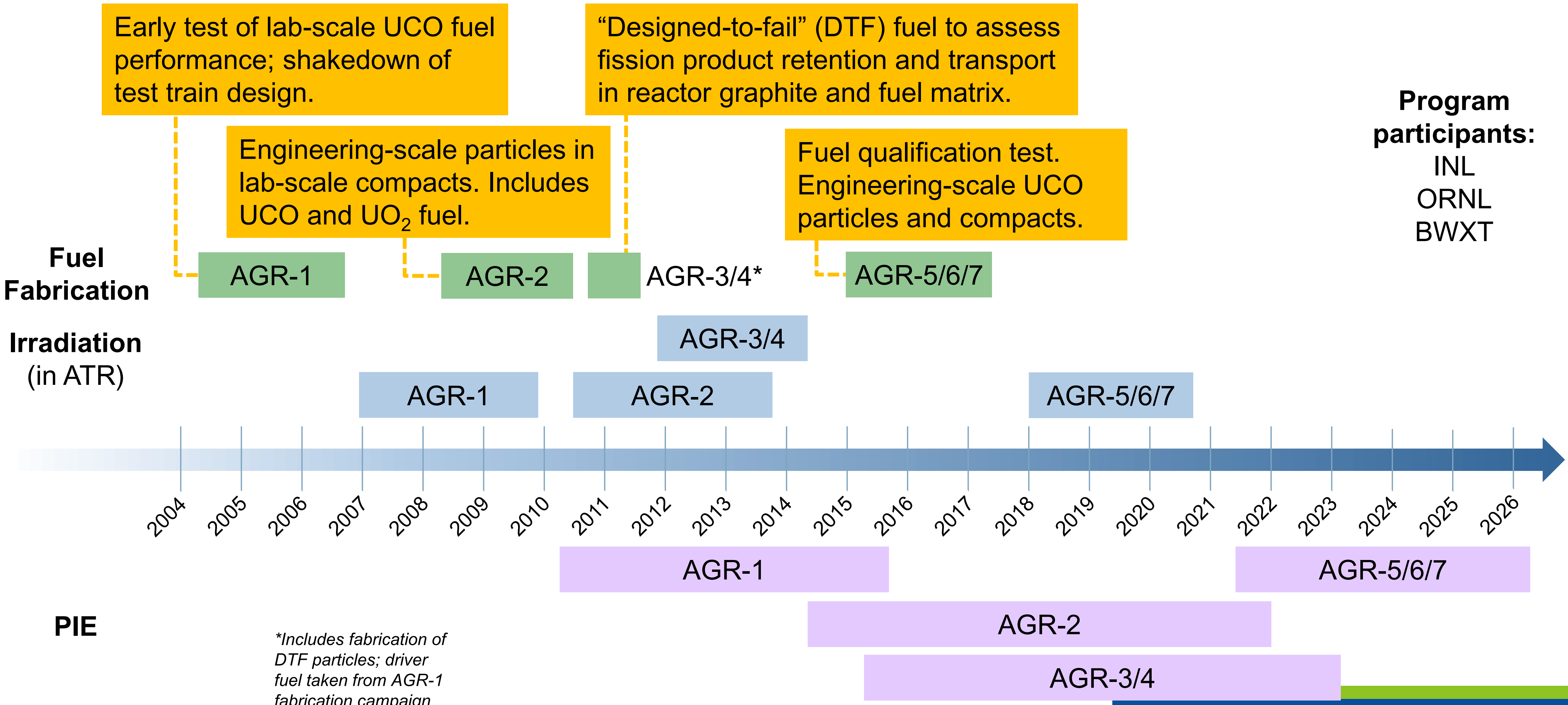
- LEU UCO kernel
  - Improved performance at high burnup and high temperatures compared to UO_2
- Use standard German UO_2 TRISO coating design based on proven performance
- Higher particle packing fractions (~35 – 40%) compared to German spheres (<10%), consistent with the use of cylindrical compacts 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 Timeline



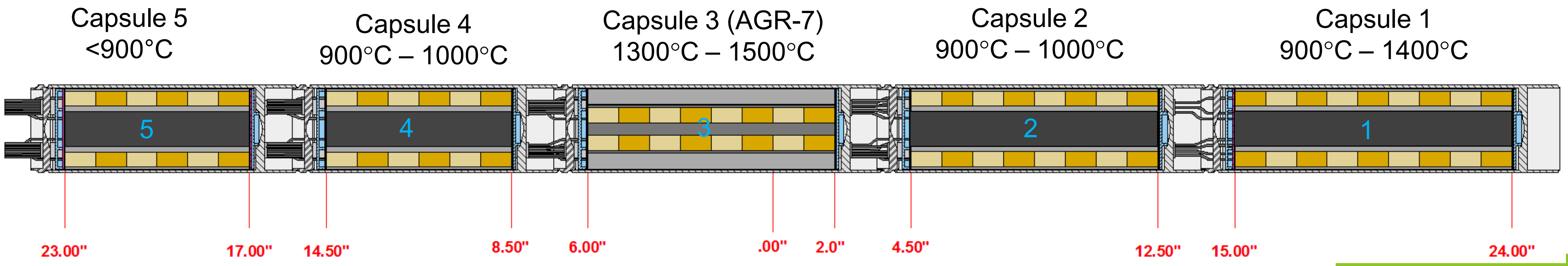
**Includes fabrication of DTF particles; driver fuel taken from AGR-1 fabrication campaign*

AGR Program Status

- AGR-1: Demonstration of lab-scale 350-μm UCO fuel performance to 20% FIMA
  - Irradiation and PIE complete
- AGR-2: Demonstration of pilot-scale 425-μm UCO and 500-μm UO_2 fuel particle performance
  - Final PIE report September 2021
- AGR-3/4: Fission product transport in fuel matrix and core graphite
  - PIE in progress; completion in ~2023
- AGR-5/6/7: Full pilot scale 425-μm UCO fuel qualification and high-temperature performance margin test
  - Irradiation complete July 2020
  - PIE begins April 2021

AGR-5/6/7 Status

- Final fuel qualification irradiation and performance margin test (peak fuel temperatures ~1500°C)
- 194 UCO fuel compacts (~570,000 particles)
- 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*
- Experiment terminated early in July 2020 after approximately 360 EFPD and peak burnup ~15.3% FIMA
- PIE will begin in May 2021



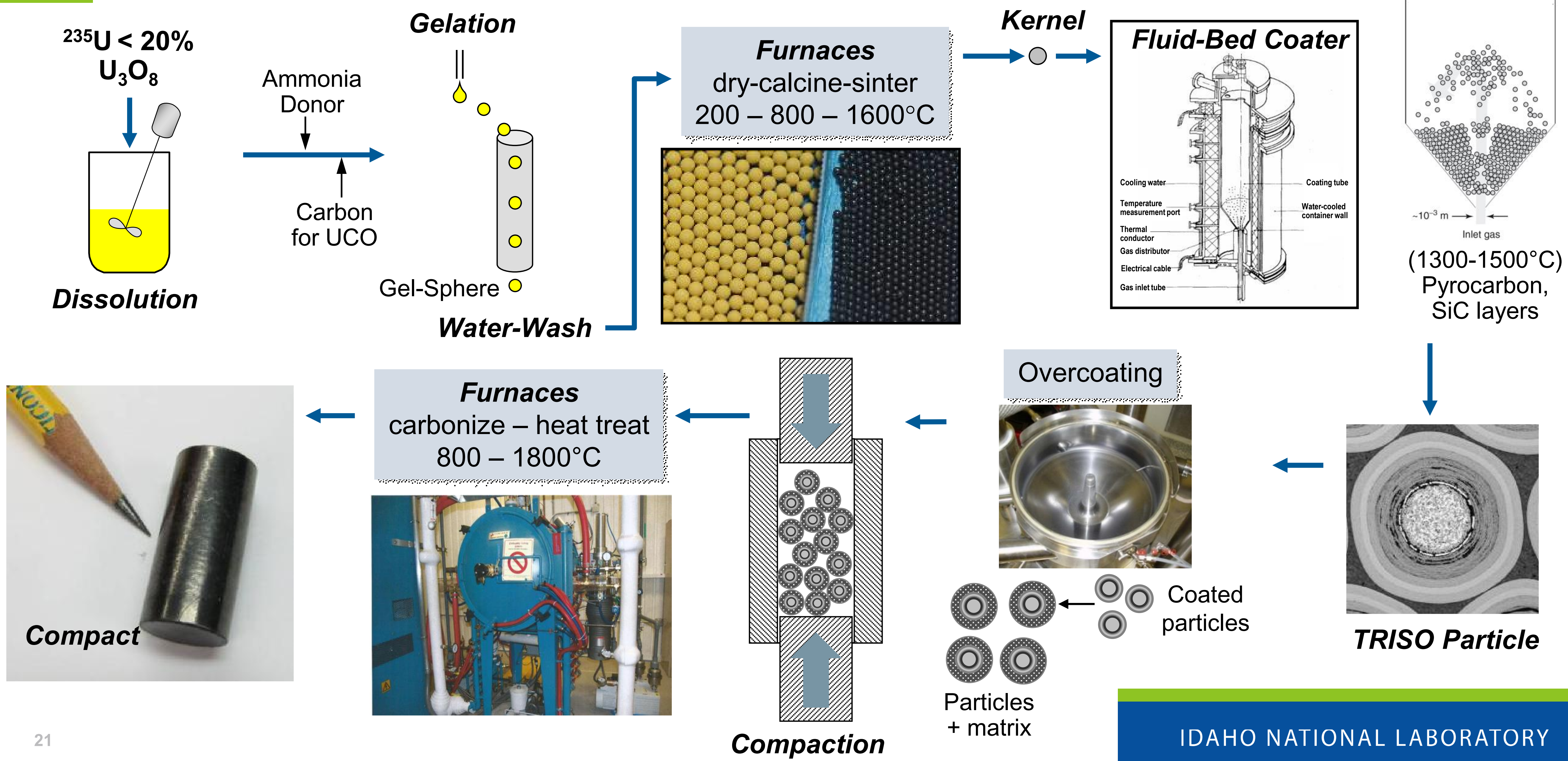
AGR-5/6/7 test train axial cross section

Outline

Part I

- TRISO Fuel Background and Design
- US DOE Advanced Gas Reactor (AGR) Program
- Fuel Fabrication and Quality Control
- Fuel Irradiation Performance

TRISO Fuel Fabrication: Process Overview



Kernel Fabrication

- Kernels are fabricated using a sol-gel process to form a spherical bead
- Dried spherical beads are heat treated to form the desired metal oxide and/or carbide phases and sinter the kernel

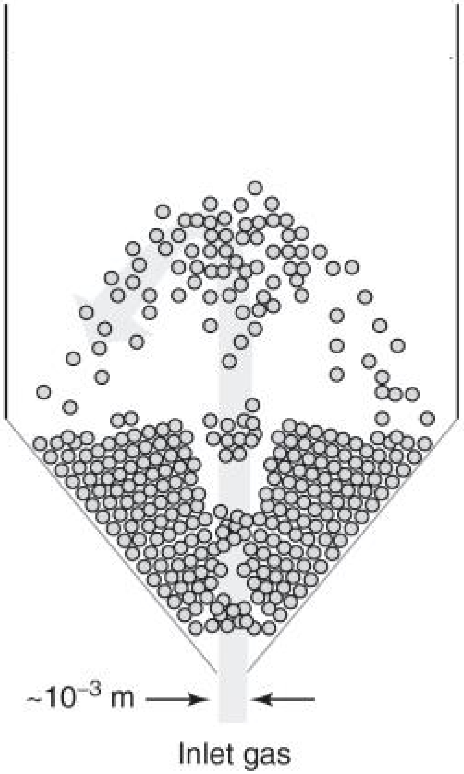
Form Kernels → Age Kernels → Wash & Dry Kernels → Calcine Kernels → Sinter Kernels

Coating Deposition

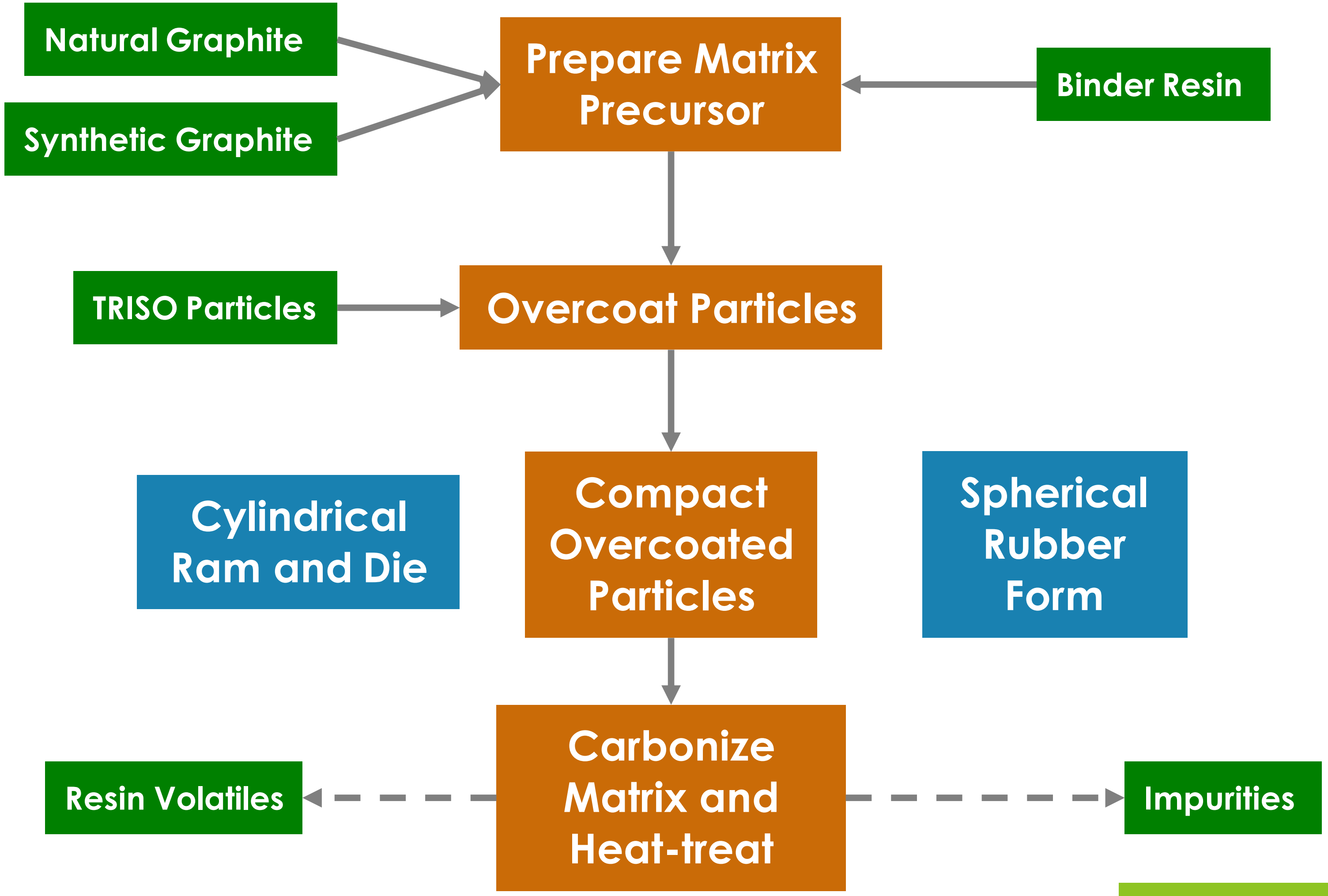
- Coatings are deposited onto kernels using a fluidized bed chemical vapor deposition furnace
- Coatings are applied using a continuous process
- Reactant gas mixture and temperature are controlled to obtain desired coating properties
- Coated particles are sorted by size and shape to remove under- and over-sized particles

Coater converging section and gas nozzle

Industrial Scale 150-mm Coater (BWXT)



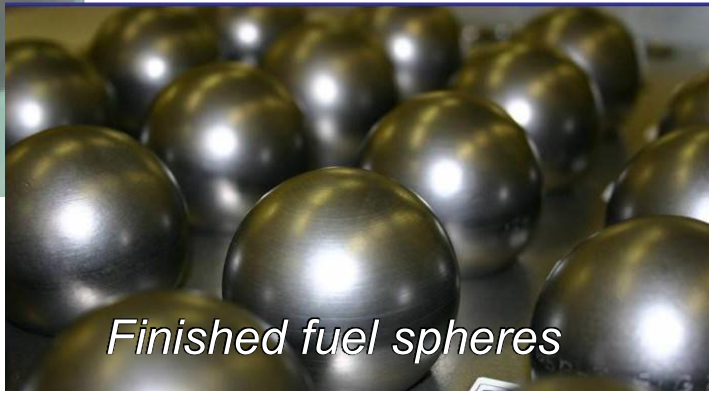
Fuel Compact/Sphere Fabrication

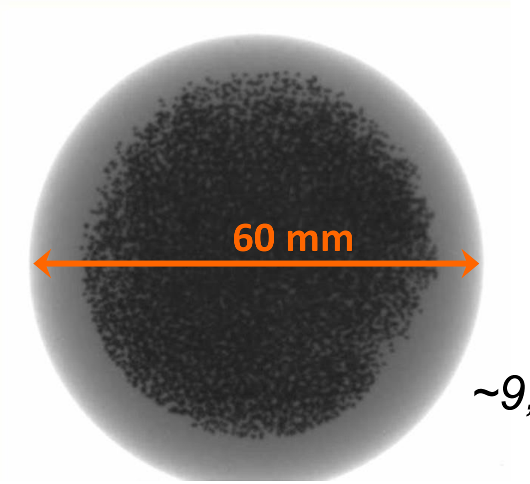


Fuel Elements

Spherical fuel elements


Fuel sphere press

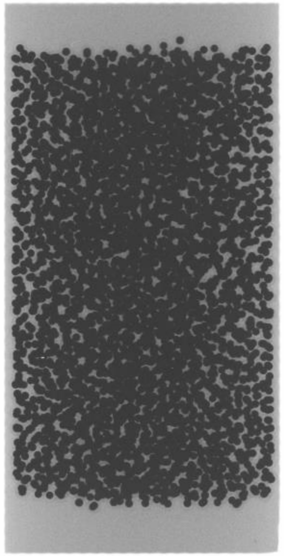

Finished fuel spheres



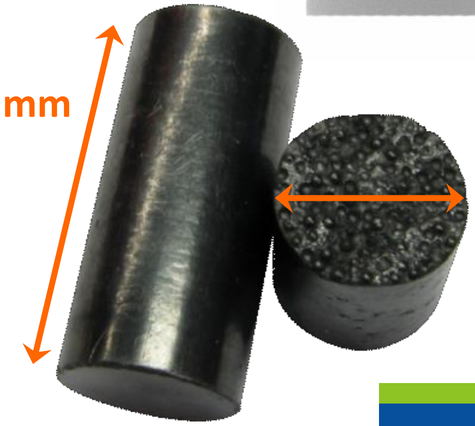
Machining of pressed sphere is used to obtain final dimensions

~9,000 – 18,000 particles

Cylindrical fuel elements



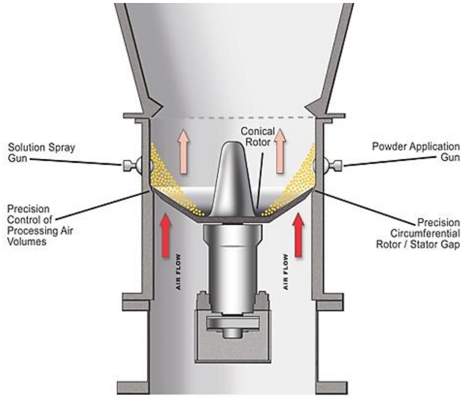

Floating-body die compact press

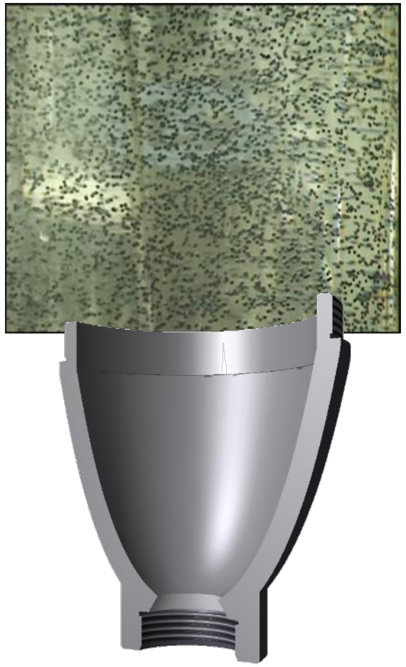


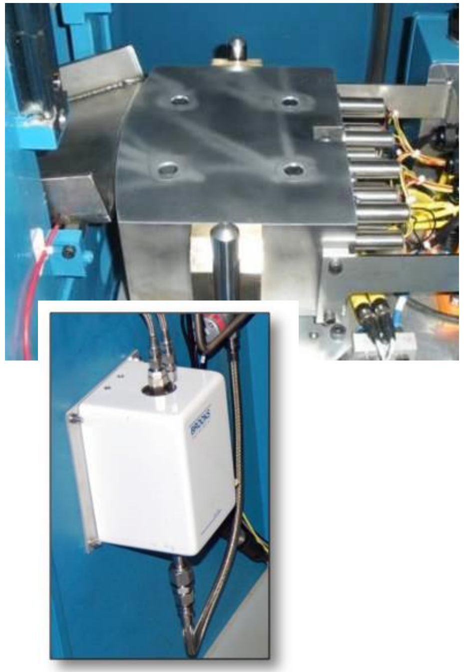
~1,500 – 4,100 particles

US AGR Program Fuel Fabrication Process Improvements

- Reduced human interactions in the process
  - Eliminated tabling with 3D sieving of coated particles
  - Improved matrix production (dry mixing and jet milling)
  - Improved overcoating with automated fluidized bed overcoater
  - Multicavity compacting press with automatic fill
- Kernel fabrication
  - Internal gelation to improve sphericity
  - Method of carbon addition modified to improve distribution of oxide and carbide phases
- Improved chemical vapor deposition process control
  - Argon dilution during SiC coating
  - Coater “chalice” and multiport nozzle to improve process yields (>95%)
  - Mass flow controllers to control gas flows during deposition of each coating layer
  - Improved MTS vaporizer (SiC layer deposition)





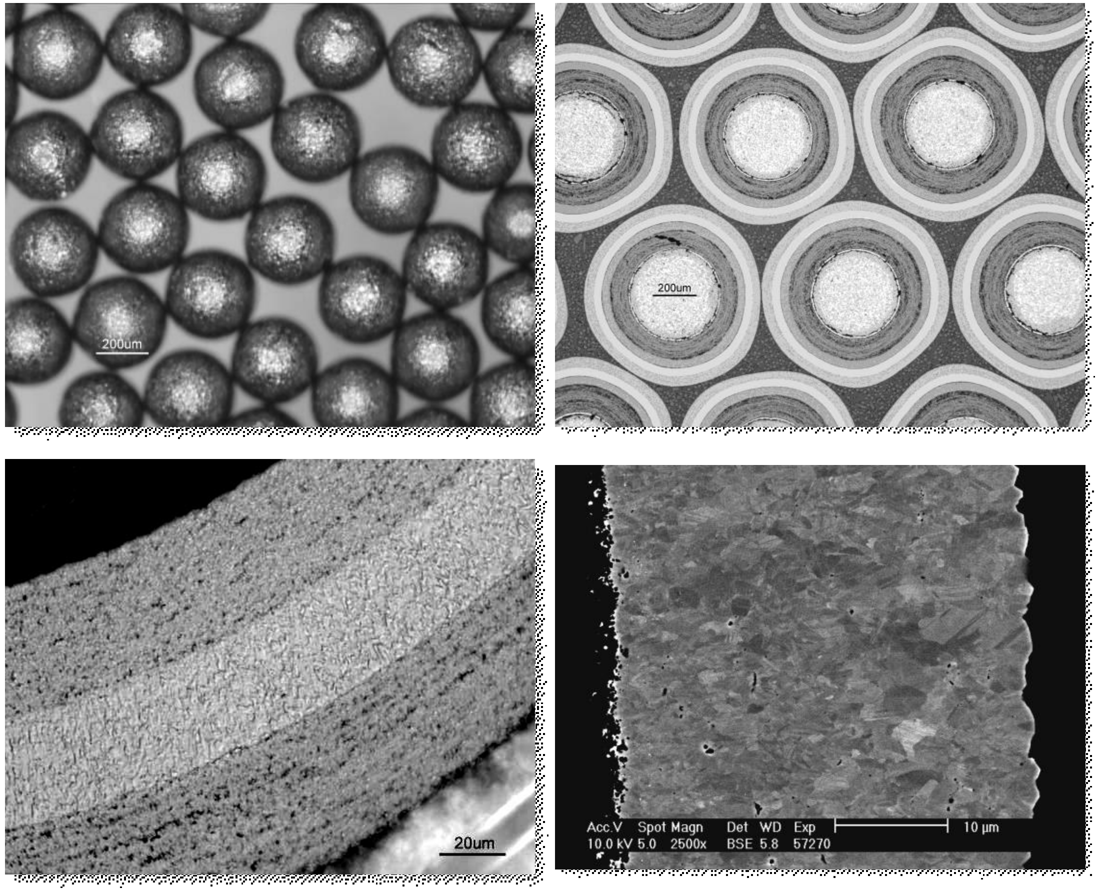


TRISO Fuel Quality Control

- Quality Control (QC) is the process used to verify that a product satisfies the design criteria
- QC for coated particle fuel includes:
  - Specifications on source materials, production processes, and process limits
  - Specifications on kernel, coating, and compact properties
  - Specifications on defect populations that may impact performance
- QC measurements of fuel properties are performed using statistical sampling
  - Specifications are met to a 95% minimum confidence level
  - Statistics often force the average fuel quality to be significantly better than the specifications
- IAEA Coordinated Research Program CRP-6
  - Fuel QA/QC round robin experimental study (also included HTGR fuel predictive code benchmarking exercises); *see IAEA TECDOC-1674 (2012)*

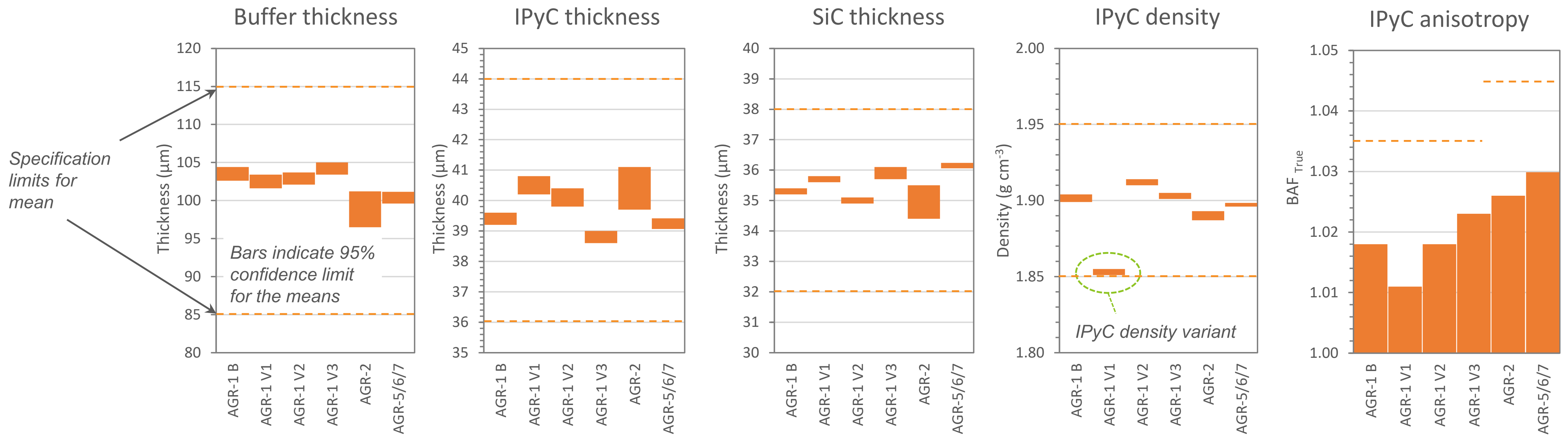
AGR Program Fuel Specifications for QC

- 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



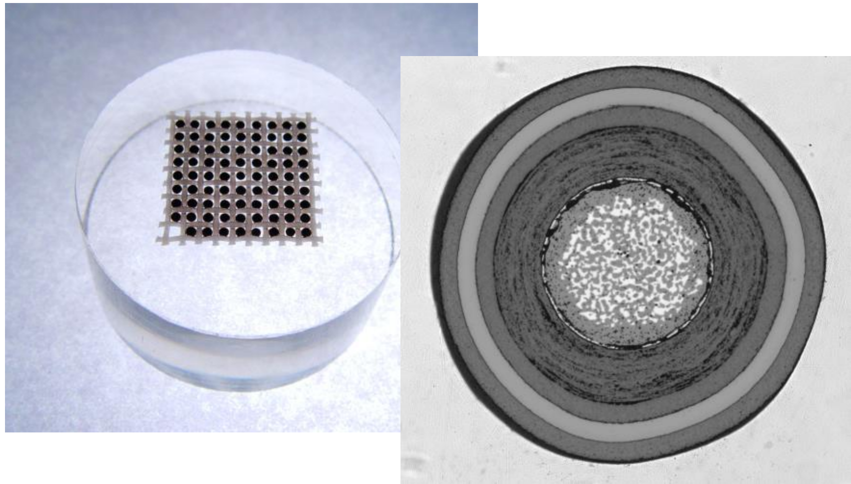
Particle defect specifications apply to the ***compact/sphere***

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



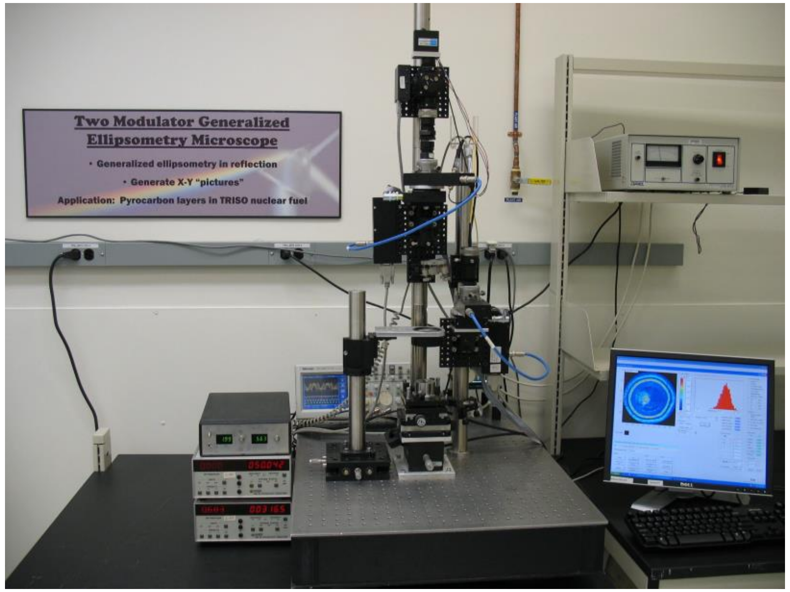
- Mean must be within the specification limits at 95% confidence
- Measured values typically lie well within the specification range
- Note that some specifications were changed following AGR-1, based on computational modeling results on fuel behavior

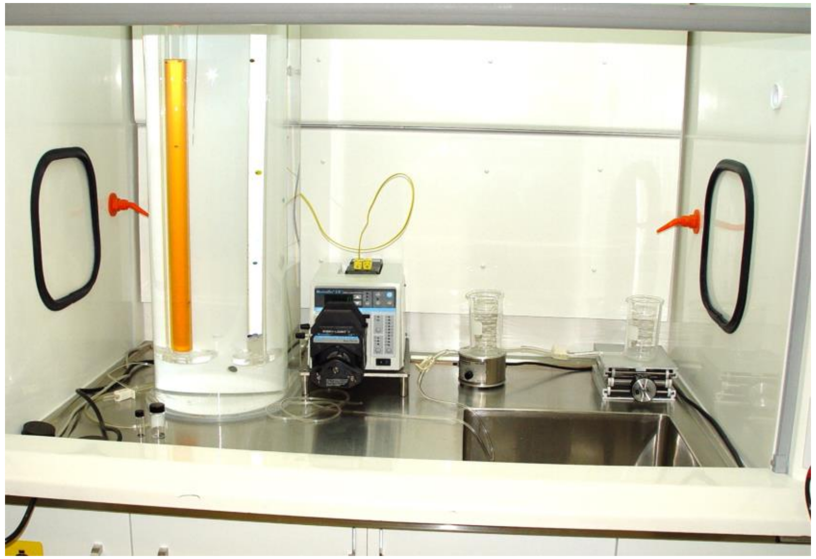
Improved Measurement Science



Computer measurements of thicknesses

Greatly improved PyC anisotropy measurements



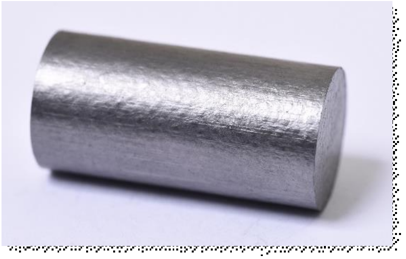


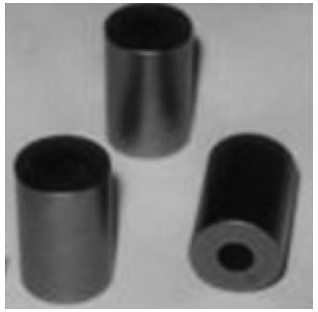
Improved density measurements using better density column fluids

Common Fuel Particle and Sphere/Compact Properties

Property	German proof-test	HTR-PM[a]	US AGR-5/6/7	HTTR[a]
Kernel type	UO_2	UO_2	UCO	UO_2
Kernel diameter (µm)	508	500	426	600
Enrichment (wt% ^{235}U)	10.6	17	15.5	3 – 10
Buffer thickness (µm)	102	95	100	60
IPyC thickness (µm)	39	40	39.2	30
SiC thickness (µm)	36	35	36.2	25
OPyC thickness (µm)	38	40	35	45
Particles per sphere/compact	14,600	12,000	3,400	13,000
Sphere/compact dimensions	60 mm diameter	60 mm diameter	25 mm x 12.3 mm OD	39 mm x 29 mm OD x 10 mm ID

[a] Properties are nominal values from specifications, not measured values





Fuel Fabrication Summary

- TRISO fuel fabrication is a process that has matured over the last 50 years
- Statistical sampling is used to verify fuel quality
- Specifications are met to at least a 95% confidence level
- US AGR program has implemented numerous fuel fabrication process and characterization method improvements
- TRISO fuel fabricators continue to innovate and improve fabrication processes

Outline

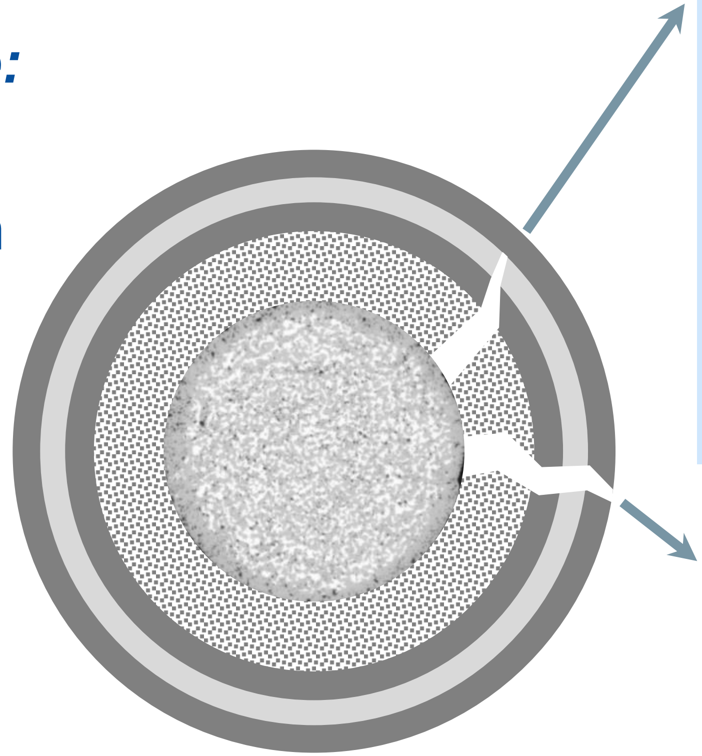
Part I

- TRISO Fuel Background and Design
- US DOE Advanced Gas Reactor (AGR) Program
- Fuel Fabrication and Quality Control
- Fuel Irradiation Performance

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



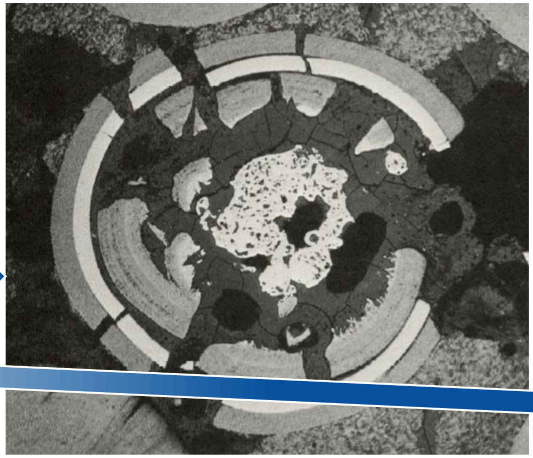
- SiC layer failure:
  - Breach in the SiC layer with at least one pyrocarbon layer intact
  - Release most condensable fission products but retain fission gas

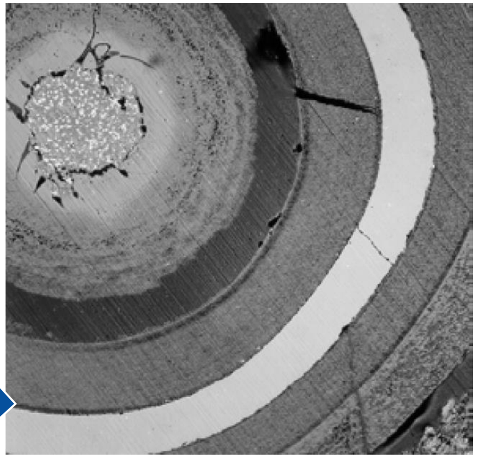
- TRISO layer failure (exposed kernel):
  - All three dense coating layers breached
  - Release of fission gas and condensable fission products

Fuel Failure Mechanisms

Mechanical

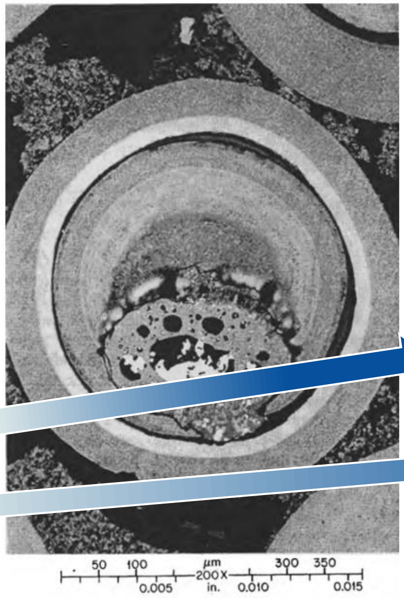
- Pressure vessel failure
- Irradiation-induced PyC failure leading to SiC cracking
- IPyC-SiC partial debonding

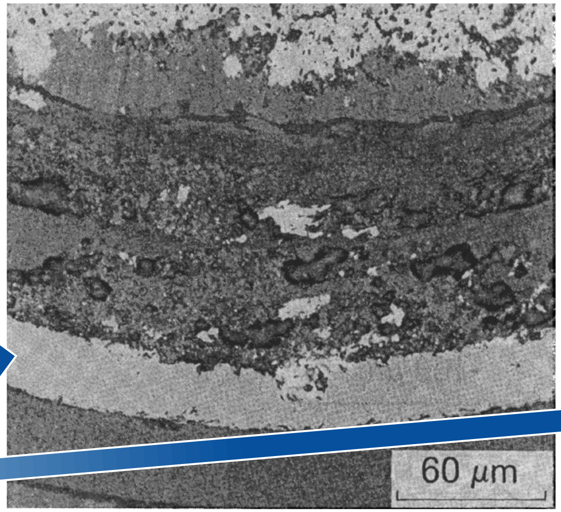




Thermochemical

- Kernel migration
- SiC thermal decomposition (T > 2000°C)
- Fission product attack of SiC
- Corrosion of SiC by CO



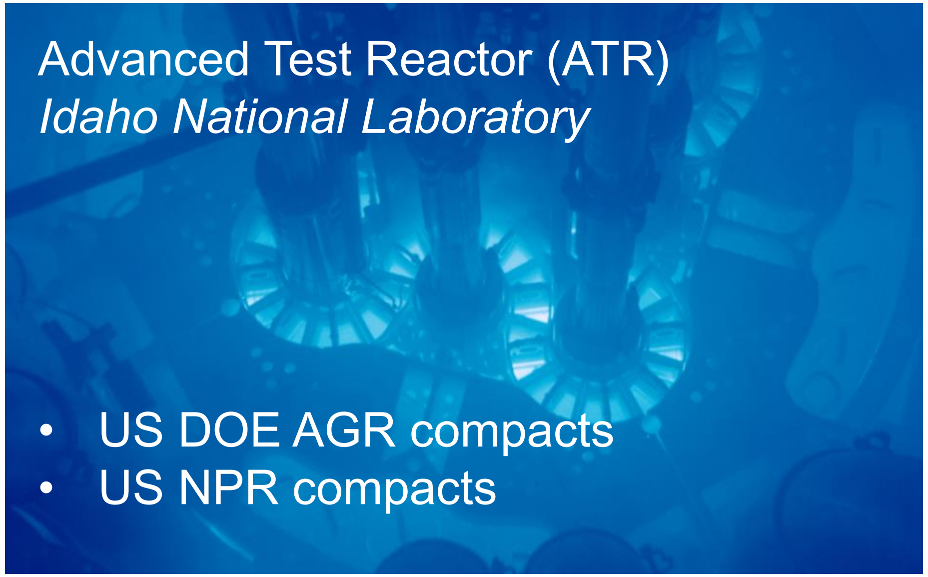


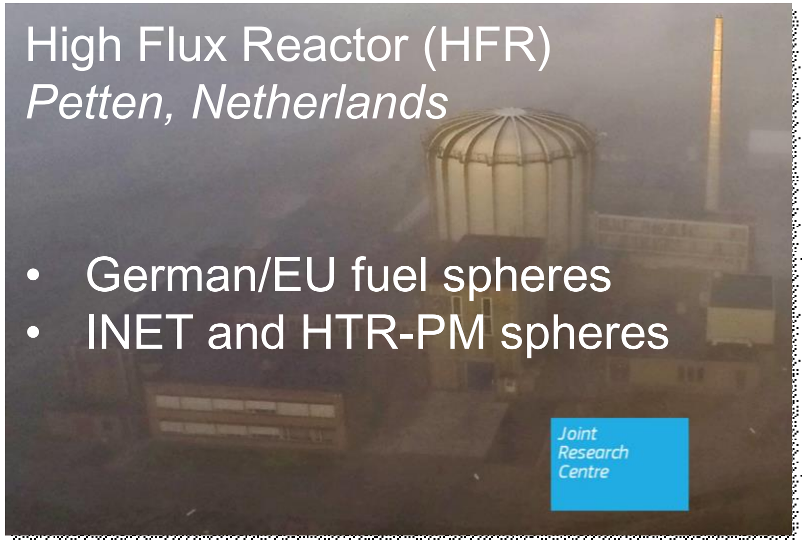
- Many of these mechanisms are precluded by improved particle design, improved manufactured fuel quality, and by operation of the fuel within its intended performance envelope

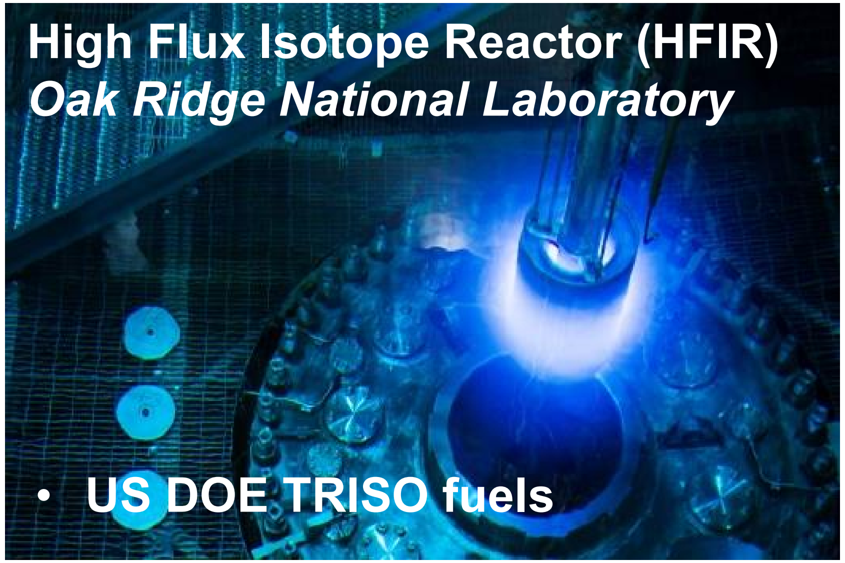
Irradiation Testing

	Pros	Cons
Prototype Reactors	• Prototypical conditions (neutron spectrum and flux, burnup accumulation rate)	• Long duration • Difficult online measurement of fuel performance • Less certainty on fuel temperature
Materials Test Reactors (MTRs)	• Accelerated irradiation times • Measurement and control of fuel temperature • Real-time measurement of fission product release	• Conditions may differ somewhat from HTGRs (neutron spectrum and flux, burnup accumulation rate)

Irradiation Testing of TRISO Fuel in MTRs





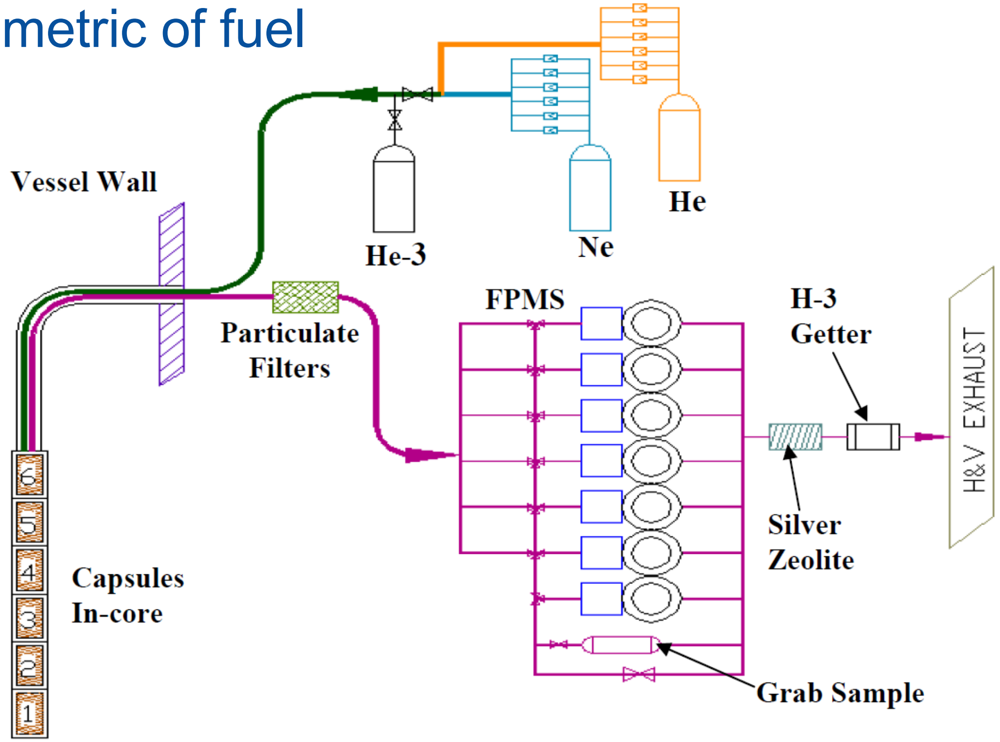


Many other MTRs have been used to test TRISO fuel

Irradiation Performance: R/B

- It is critical to have reliable measurement of fission gas release during irradiation (real-time or intermittent through gas capture and analysis)
- Fission gas *release rate to birth rate ratio* (***R/B***) is the main metric of fuel performance during irradiation
- Sweep gas (He + Ne) injected into the capsules controls capsule temperature and carries fission gas to the FGMS
- Gamma spectrometers quantify short-lived ($t_{1/2}$ ~30 s to 12 d) Kr and Xe isotopes

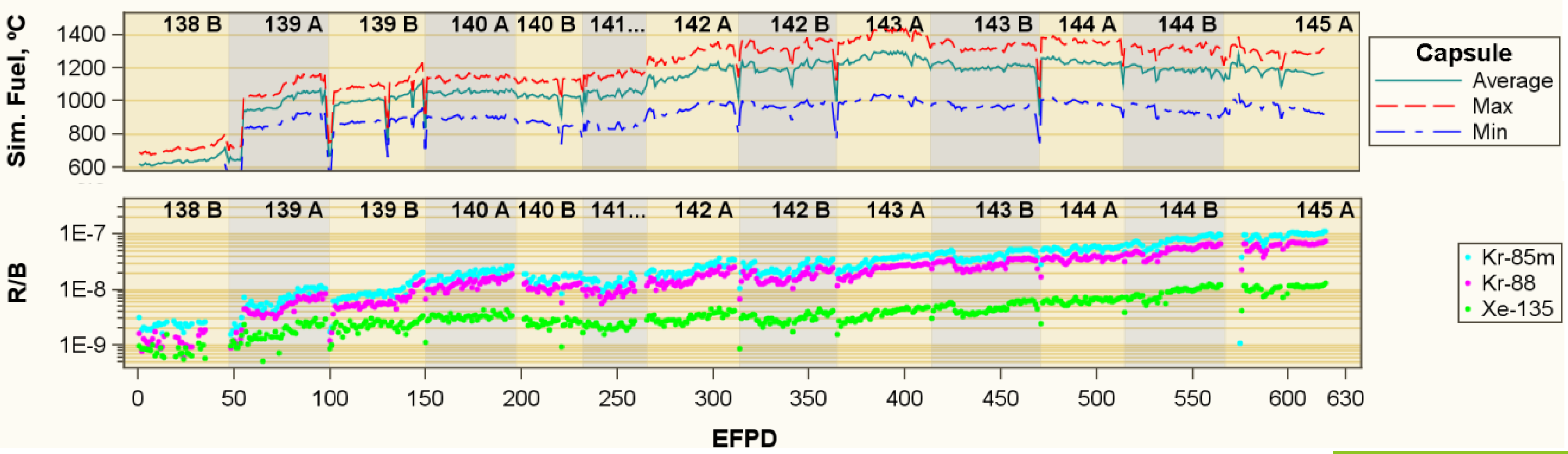
Kr-85m	**Xe-131m**
Kr-87	**Xe-133**
Kr-88	**Xe-135**
Kr-89	**Xe-135m**
Kr-90	**Xe-137**
	Xe-138
	Xe-139



AGR-1 Fission Gas Monitoring System (FGMS)

Irradiation Performance: R/B (cont'd)

- 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
- R/B provides information on the extent of coating failures during irradiation
- Release rate is a function of temperature and isotope half-life



AGR-1 Capsule 6 Data

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

Recent TRISO Fuel Irradiation Tests (2000 – Present)

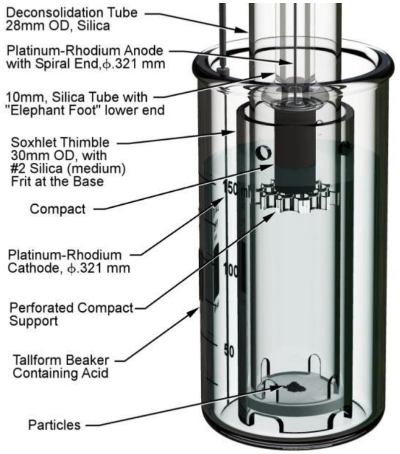
Irradiation test	Location	Fuel type	Spheres or compacts (particles)	Completed	Burnup (%FIMA)	Temperature (°C)[a]	EOL ^{85m}Kr R/B
US DOE-AGR							
AGR-1	ATR	UCO	72 (298,000)	Nov 2009	11.3 – 19.6	1069 – 1197	$0.1 - 1\times10^{-7}$
AGR-2	ATR	UCO UO_2	36 (114,000) 12 (18,500)	Oct 2013	7.3 – 13.2 9.0 – 10.7	1080 – 1360 1072 – 1105	$\sim10^{-6}$ [b] 10^{-7} [b]
AGR-5/6	ATR	UCO	170 (515,000)	Jul 2020	5.7 – 15.3	~600 – 1350	$0.1 - 1\times10^{-6}$ [c]
Germany/EU							
HFR-EU1	HFR	UO_2	3 (28,700)	Feb 2010	13.5 – 14.3	~950[c]	2.5×10^{-7}
HFR-EU1bis	HFR	UO_2	5 (47,800)	Oct 2005	~11	~1250	4×10^{-6}
China							
HTR-10/IVV-2M	IVV-2M	UO_2	4 (33,200)	Feb 2003	11.6 – 13.1	1000 ±50	$0.1 - 8\times10^{-5}$
HFR-EU1	HFR	UO_2	2 (16,600)	Feb 2010	9.3, 11.6	900 – 940[d]	7×10^{-8}
HFR-PM	HFR	UO_2	5 (60,000)	Dec 2014	10.1 – 12.7	1050 ±50	$\sim3\times10^{-9}$

[a] Time-average peak temperatures (except where noted)
[b] R/B values through the first 3 irradiation cycles
[c] R/B values through the first 5 irradiation cycles
[d] Sphere surface temperatures

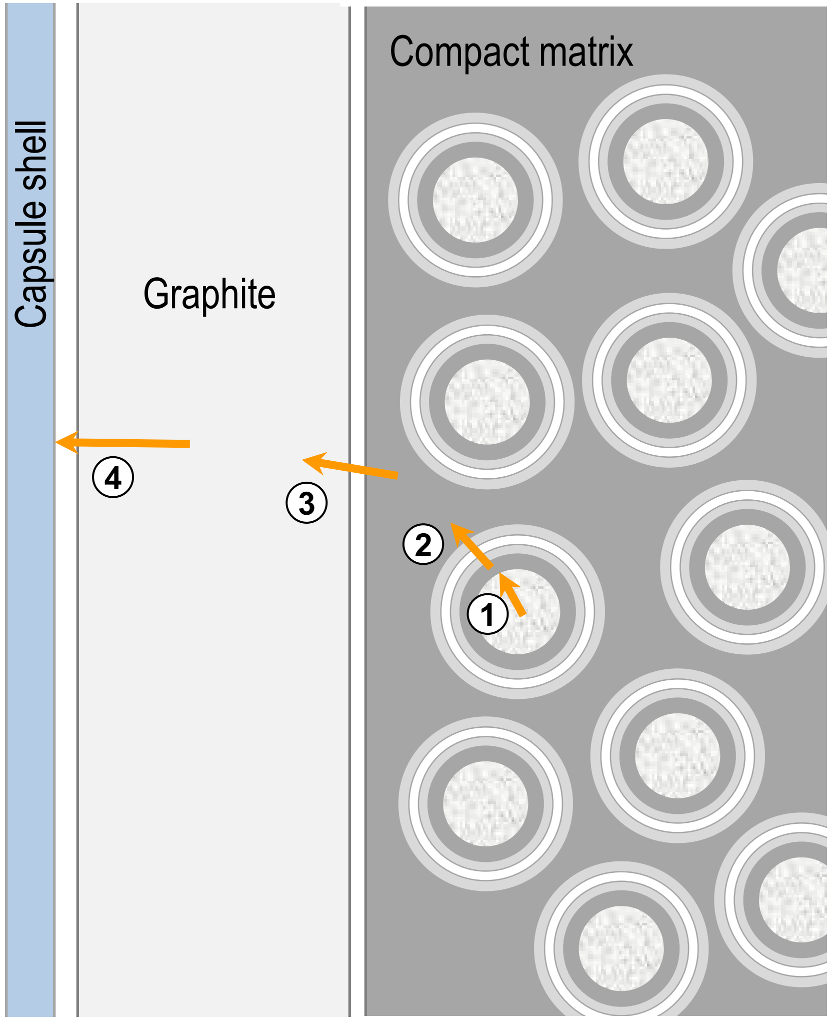
Excellent performance within intended fuel performance envelope

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



In-Pile Fission Product Release Evaluation



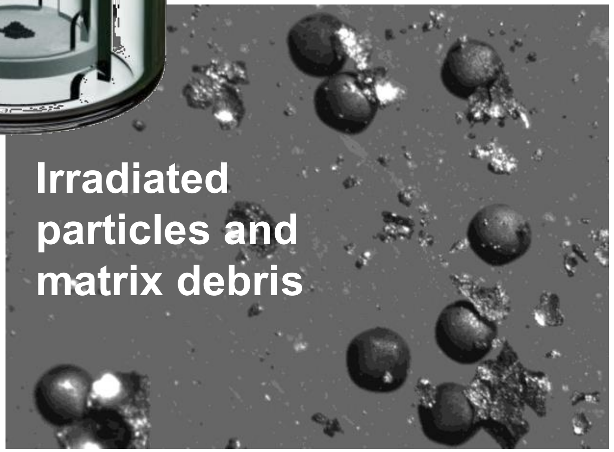
1. Release from kernel to coating layers
2. Release from coating layers to compact matrix
3. Release from compact matrix to structural graphite
4. Release from structural graphite to capsule shell (or reactor vessel)

Look for fission products:

- In fuel compacts
- On capsule components
- In compact matrix
- In individual particles

Compact Deconsolidation-Leach-Burn-Leach Analysis

Deconsolidation hardware



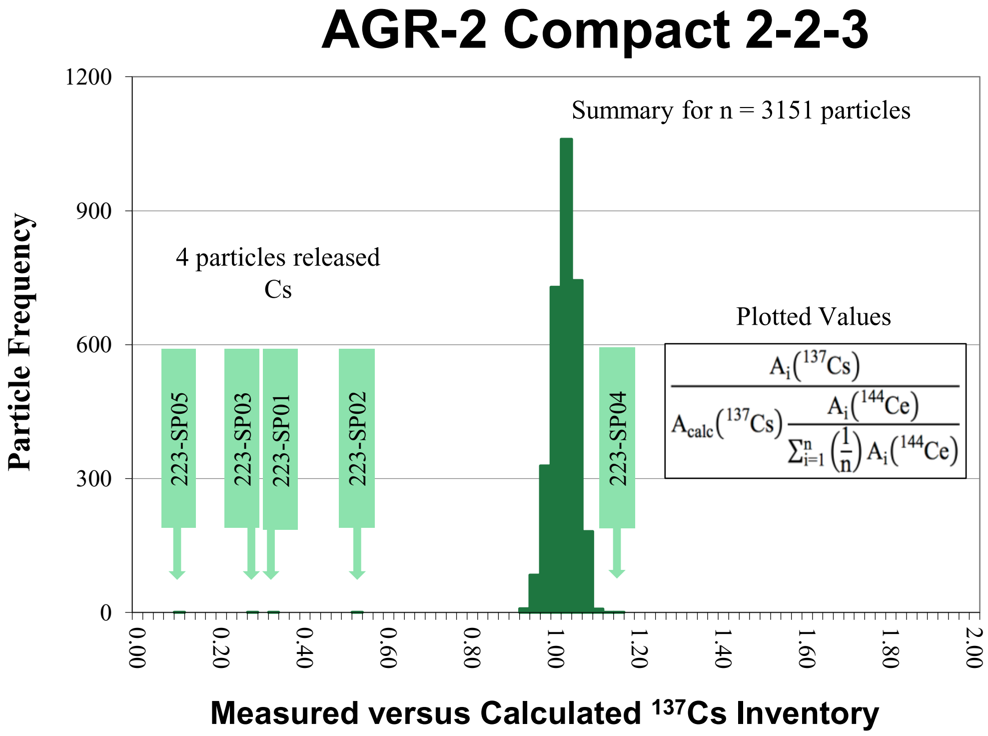
Disintegrate matrix and liberate loose particles	Electrolytic deconsolidation	
Quantify isotope inventories	Nitric acid leach of particles and matrix debris (X2)	→ Analyze leachate for FPs and actinides
Oxidize carbon (matrix and OPyC layers)	Air oxidation ("burn") of particles and debris	
Quantify isotope inventories	Nitric acid leach of remaining material (X2)	→ Analyze leachate for FPs and actinides

- **Process provides inventory of FPs and actinides in matrix outside of intact SiC**

Irradiated Particle Gamma Counting

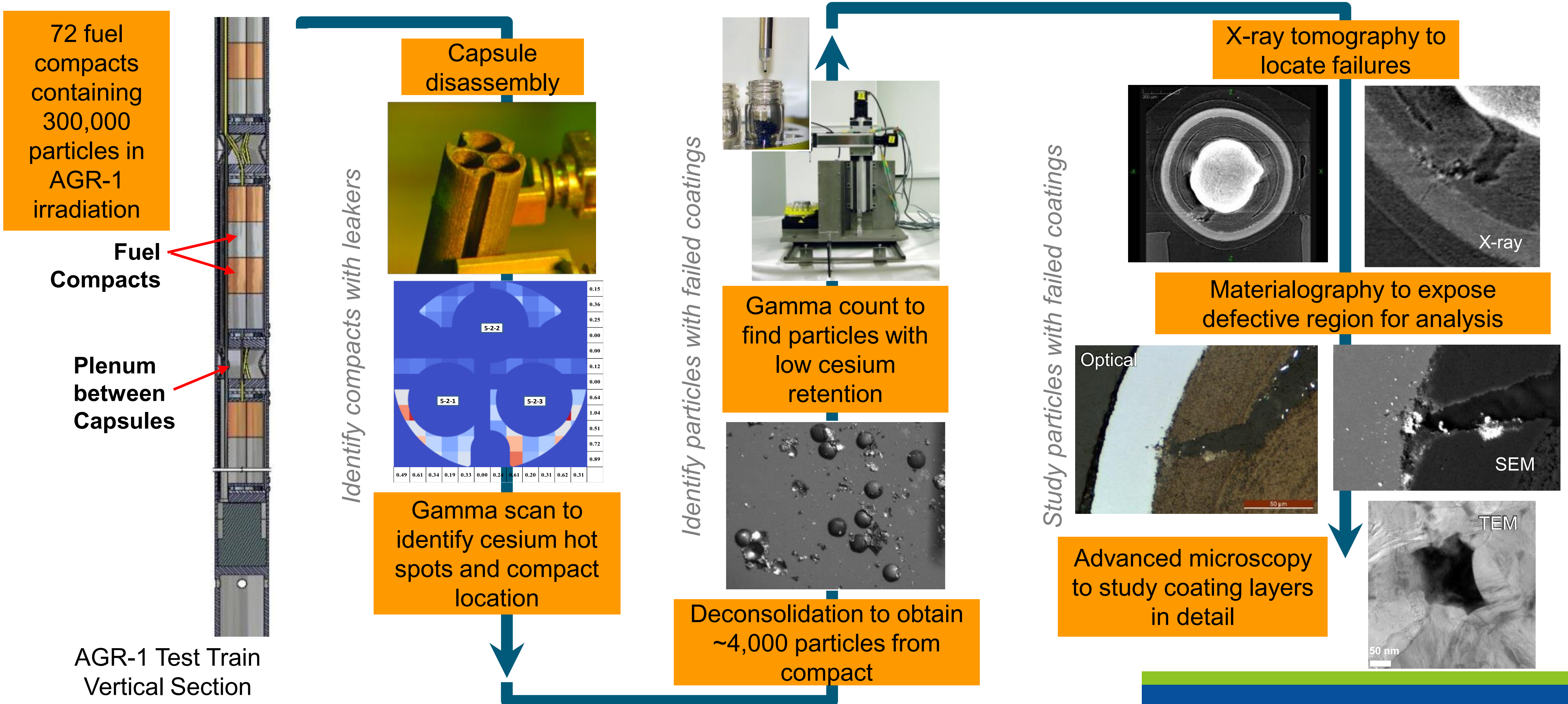
- Gamma count individual particles to quantify FP inventory (Ag-110m, Cs-134, Cs-137, Eu-154, Ce-144)
- Identify particles with abnormal inventory

ORNL Irradiated Microsphere Gamma Analyzer (IMGA)

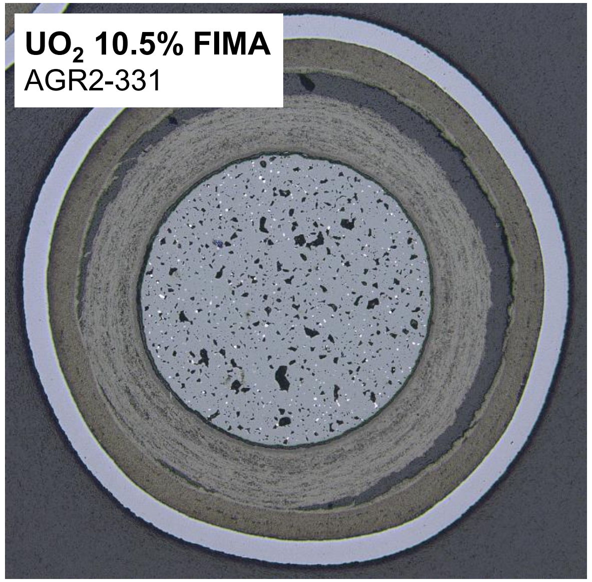


➲ *Low Cs inventory indicates SiC failure and Cs release*

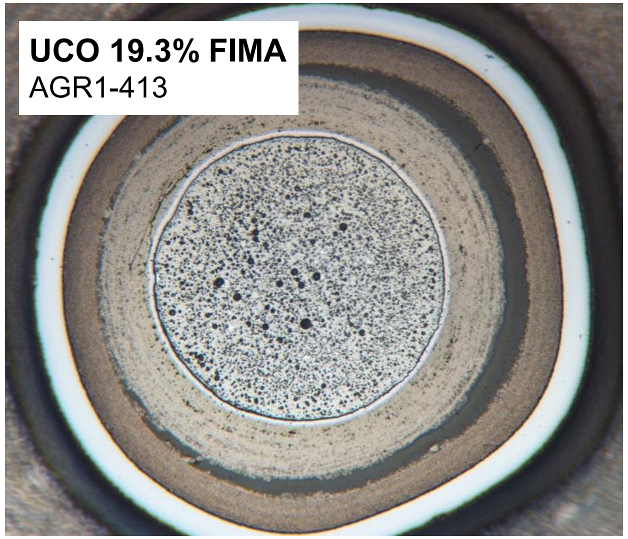
Studying Failed Particles Greatly Improves Understanding of Fuel Performance

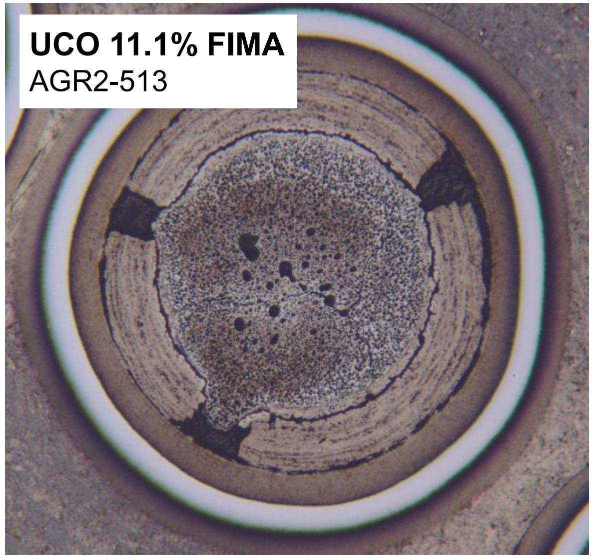


Kernel and Coating Behavior During Irradiation: AGR Particles



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

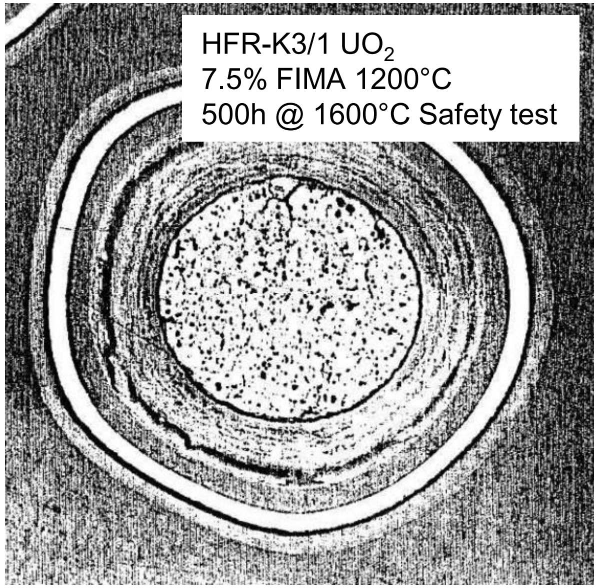


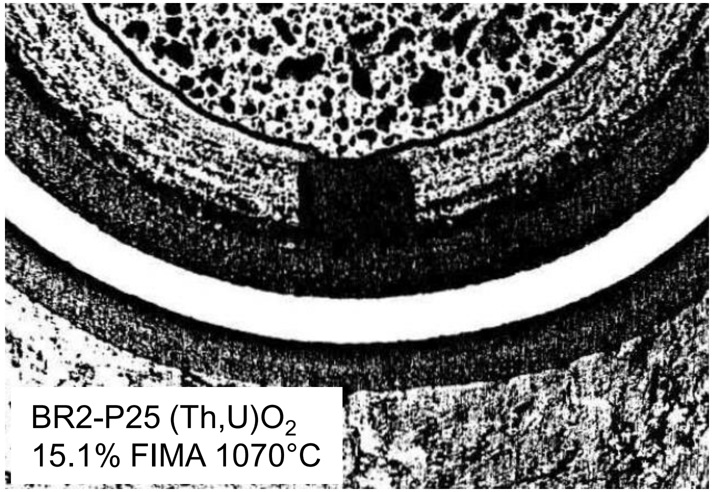


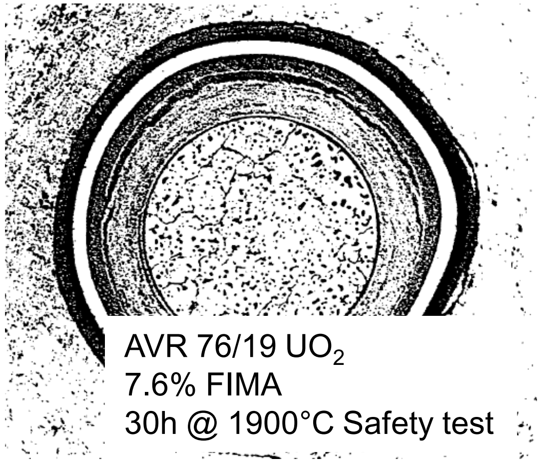
- Buffer fracture relatively common in UCO fuel particles
- Kernel can swell into gap
- Dependent on irradiation temperature and fast neutron fluence
- When buffer separates from IPyC, buffer fracture appears to have no detrimental effect on dense coating layers

Historic Observations of Irradiated Kernel and Coating Morphologies

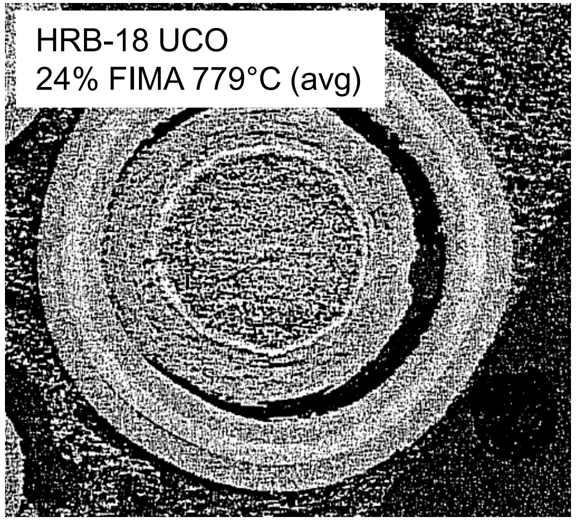
Oxide Fuel

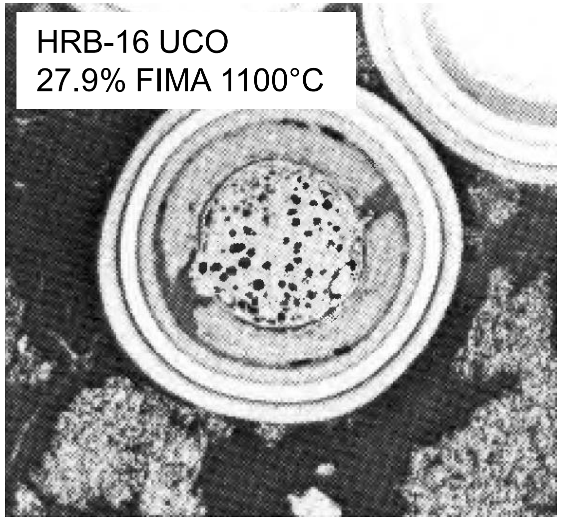

HFR-K3/1 UO_2
7.5% FIMA 1200°C
500h @ 1600°C Safety test


BR2-P25 $(Th,U)O_2$
15.1% FIMA 1070°C


AVR 76/19 UO_2
7.6% FIMA
30h @ 1900°C Safety test

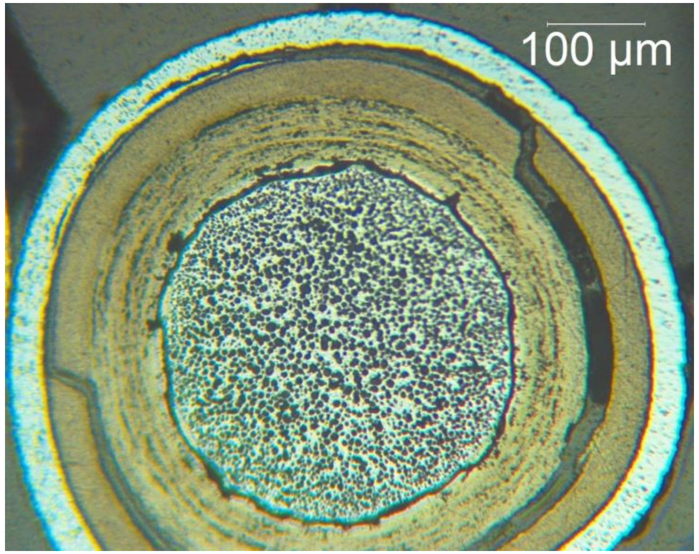
Oxycarbide Fuel


HRB-18 UCO
24% FIMA 779°C (avg)

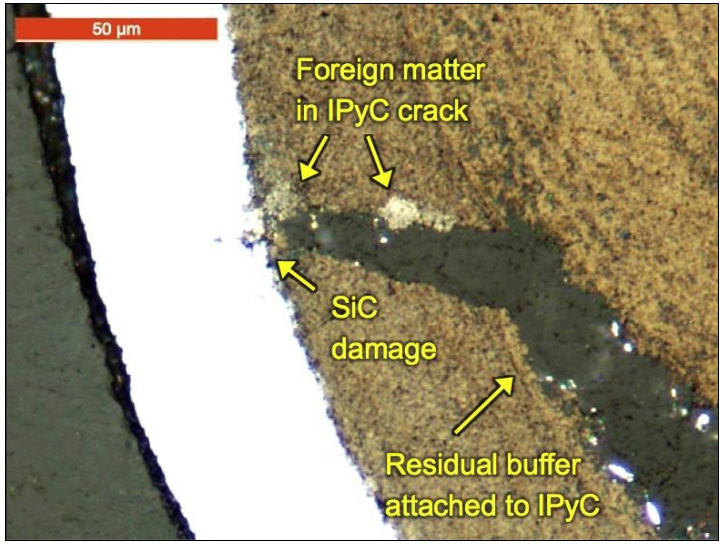

HRB-16 UCO
27.9% FIMA 1100°C

- Buffer-IPyC separation and buffer fracture observed in previous UO_2 and UCO irradiations

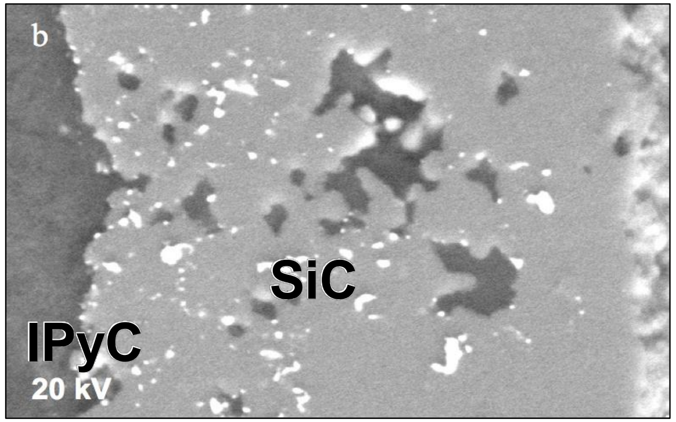
AGR UCO Particle SiC Failure



IPyC cracking and SiC separation during irradiation (no SiC failure)



SiC failure during irradiation

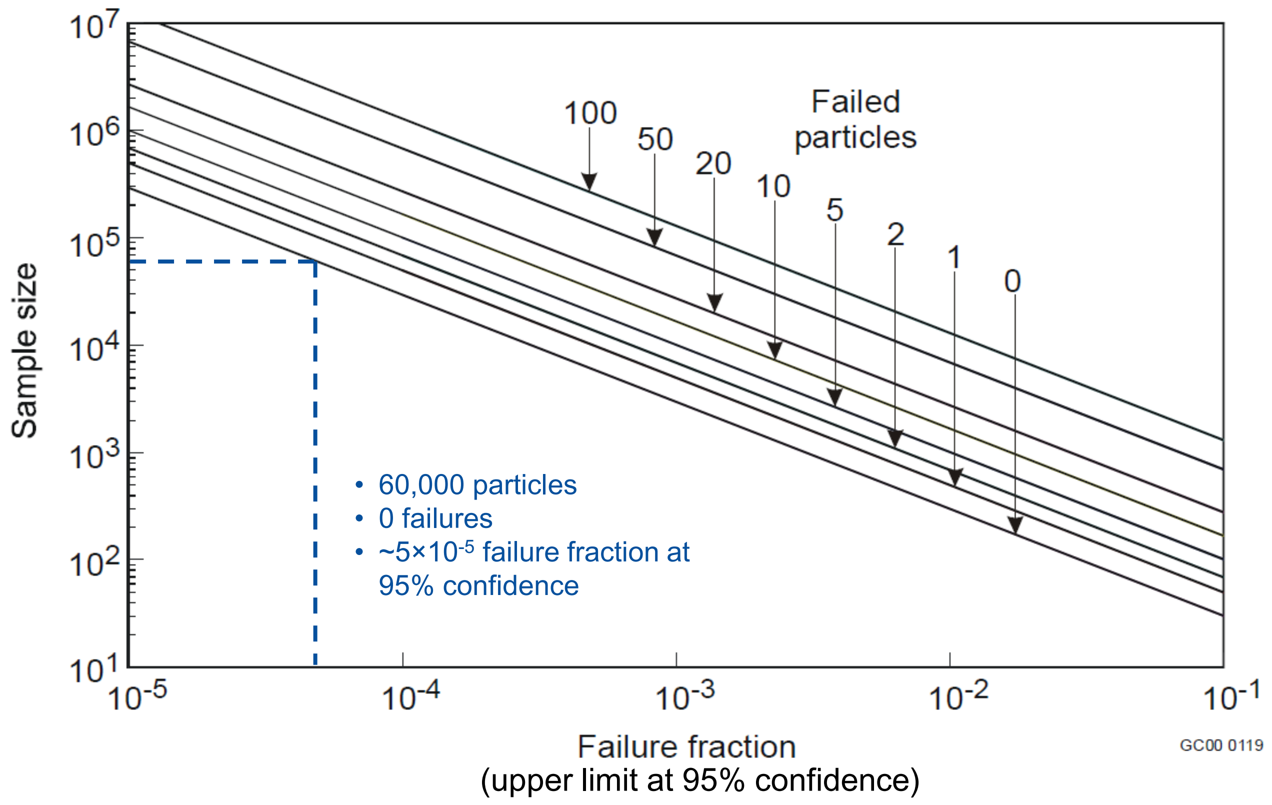


SiC degradation and failure after 300 h at 1700°C

- Buffer densification in conjunction with strong buffer-IPyC bonding can lead to IPyC cracking and separation from SiC layer
- Allows localized attack of SiC layer by fission products (especially Pd)
- Pd attack can eventually result in loss of FP retention by SiC layer
- Degradation is worse at higher safety test temperatures

Particle Failure Statistical Analysis

- Specifications for allowable in-service failures are relatively low
  - e.g., 2×10^{-4} for normal operation
- Use binomial statistics to calculate the failure fraction with 95% confidence based on the observed number of failures
- Example:
  - 60,000 particles irradiated
  - 0 observe failures
  - $\leq 5\times10^{-5}$ ($^1/_{20,000}$) failure fraction at 95% confidence



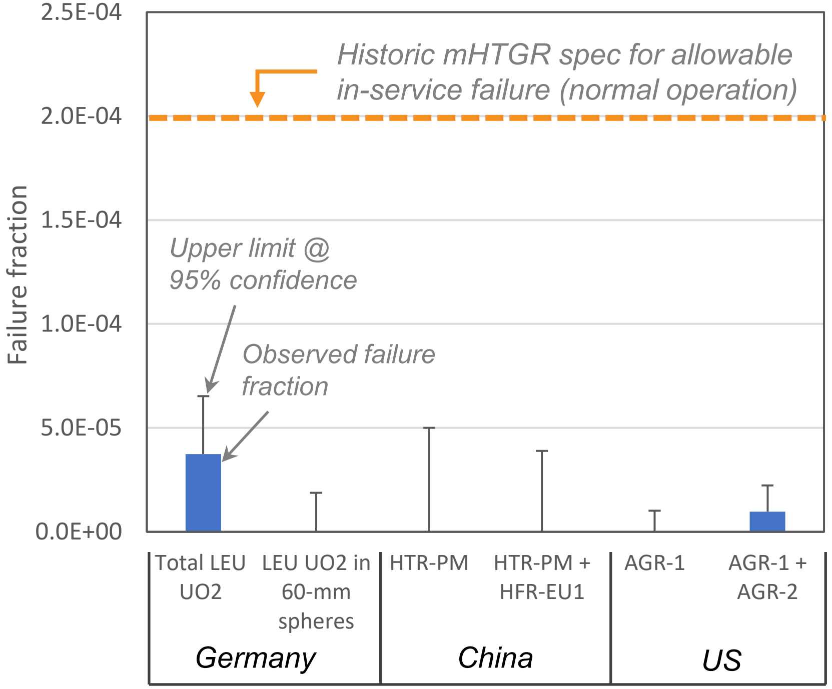
IAEA TECDOC-1645, High Temperature Gas Cooled Reactor Fuels and Materials, International Atomic Energy Agency, 2010

Analysis of Particle Failure Rates During Irradiation

Particle failure rate data (TRISO failures) for MTR irradiations of UO_2 (Germany, China) and UCO (US)

Country	Particle sample	# particles	# TRISO failures	Failure fraction	Upper limit @ 95% confidence
Germany[a]	Total LEU UO_2	240,452	9	3.7×10^{-5}	$\leq6.6\times10^{-5}$
	LEU UO_2 in 60-mm spheres	159,880	0	0	$\leq1.9\times10^{-5}$
China	HTR-PM	60,000	0	0	$\leq5.0\times10^{-5}$
	HTR-PM + HFR-EU1	77,000	0	0	$\leq3.9\times10^{-5}$
US	AGR-1	298,000	0	0	$\leq1.1\times10^{-5}$
	AGR-1 + AGR-2	412,000	≤4[b]	9.7×10^{-6}	$\leq2.3\times10^{-5}$

[a] German data from Kania et al., J. Nucl. Mater. 441 (2013) 545-562
[b] Reflects the preliminary estimate on the number of particle failures in the AGR-2 experiment based on post-irradiation analysis

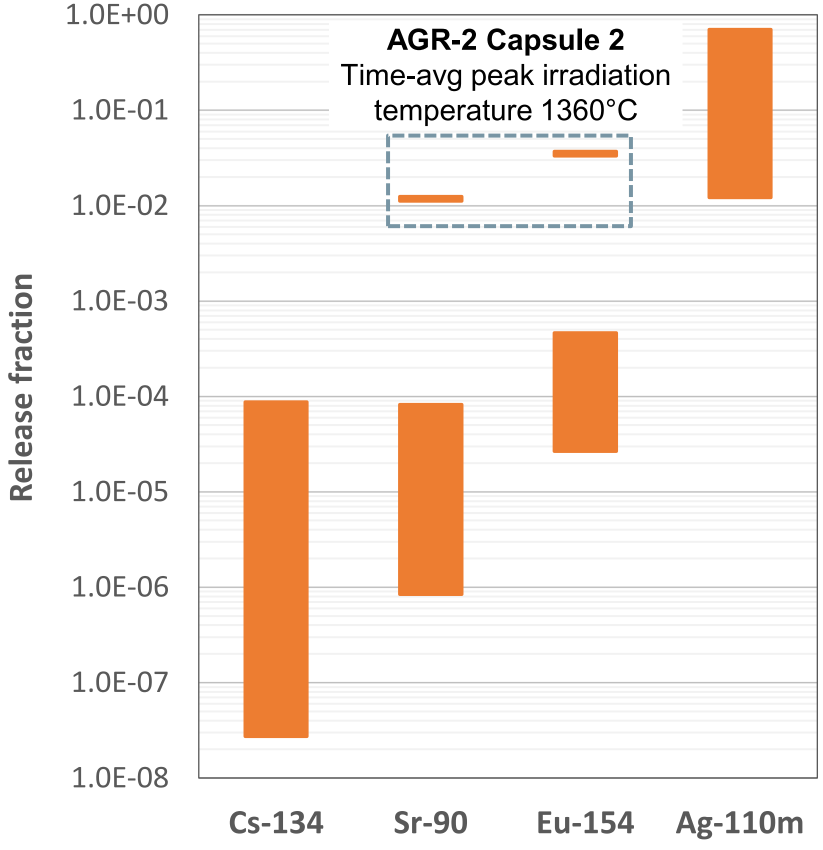


Fission Product Behavior

Element	Behavior in TRISO Fuel
Kr, Xe, I	• Retained by intact PyC or SiC layers • Release is from uranium contamination and exposed kernels • Kr and Xe are key indicator of failed TRISO layers
Cs	• Retained by SiC but released through intact PyC • Key indicator of failed SiC
Sr	• Moderate retention in the fuel kernel • Modest release through intact coatings (T > 1100°C); significantly higher release for very high irradiation temperatures • Some retention in the compact matrix
Eu	• Similar to Sr, although evidence indicates slightly higher releases
Ag	• Significant release through intact SiC (T > 1100°C) • Relatively low retention in compact matrix

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

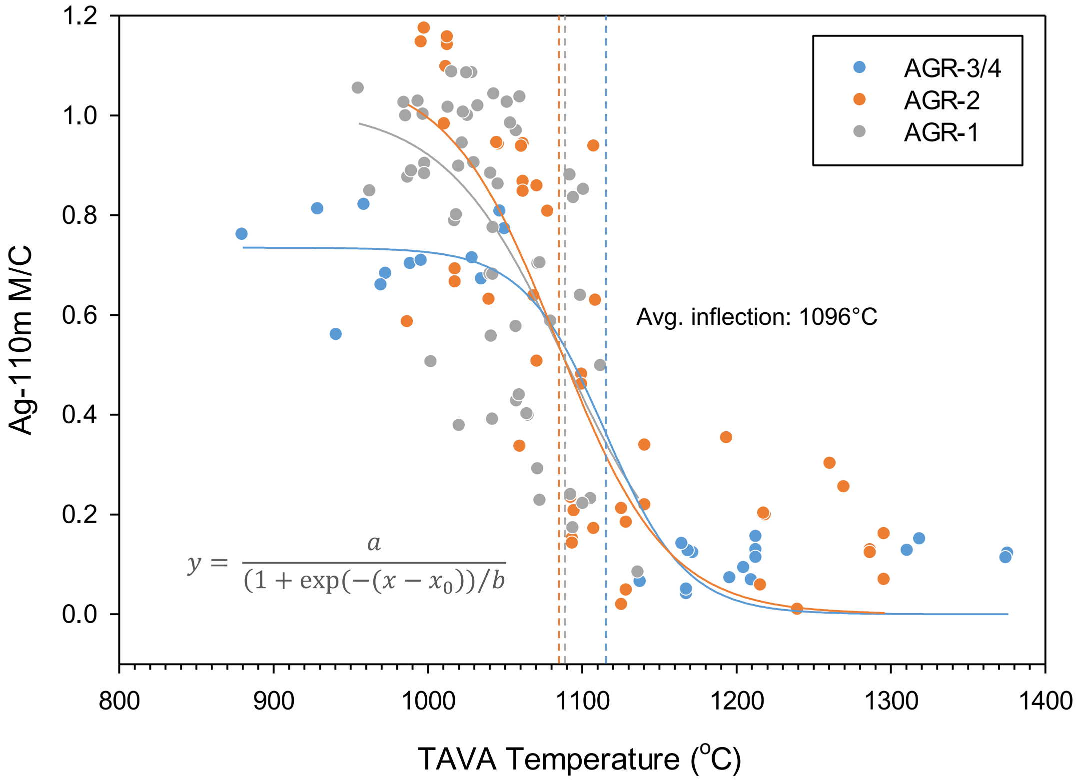
Fission product release from AGR-1 and AGR-2 UCO fuel compacts



- 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

Ag Release from AGR Compacts



Time-average, volume-average temperature

- Measure Ag-110m inventory remaining in compacts after irradiation using gamma spectrometry
- Compare with predicted inventory ("Ag-110 M/C")
- Inflection points for all three experiments (AGR-1, AGR-2, and AGR-3/4) agree within ~30°C with an average of ~1100°C
- Ag release becomes more pronounced above 1100°C

Fuel Irradiation Performance Summary

- There is an extensive database of TRISO irradiation testing in MTRs
  - Historic testing in the US, German program testing, and others
  - Recent demonstrations include EU tests (archived German fuel), HTR-PM fuel, and US AGR program
- Modern TRISO fuel exhibits very low fission gas release (R/B) values during irradiation (low level of coating failures)
- Kernel and coating morphological changes during irradiation are well documented and rarely result in SiC layer failure or TRISO particle failure
- TRISO fuel FP release behavior is well-characterized

Idaho National Laboratory