TRISO Fuel: Design, Manufacturing, and Performance

Advanced Reactor Technologies

Idaho National Laboratory

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Idaho National Laboratory

ADVANCED REACTOR TECHNOLOGIES

Course Module Objective

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

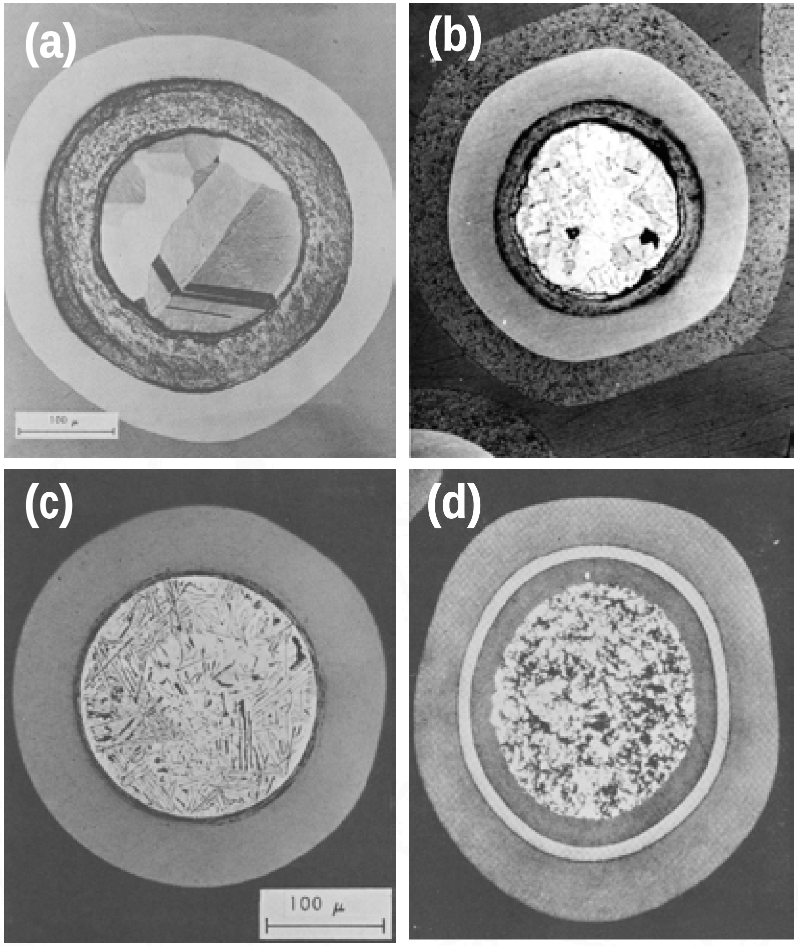
The Training Course delivered to the NRC in 2010 included several modules discussing TRISO fuel (Modules 7a, 7b, and 8). You are encouraged to review that course material for additional details on fuel fabrication and performance history.

Outline

- TRISO fuel background and history
- Fuel fabrication and quality control
- Fuel irradiation performance
- Fuel accident performance
- Fuel performance and fission product transport modeling

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
  - Peach Bottom Unit 1
  - Arbeitsgemeinschaft Versuchsreaktor (AVR)

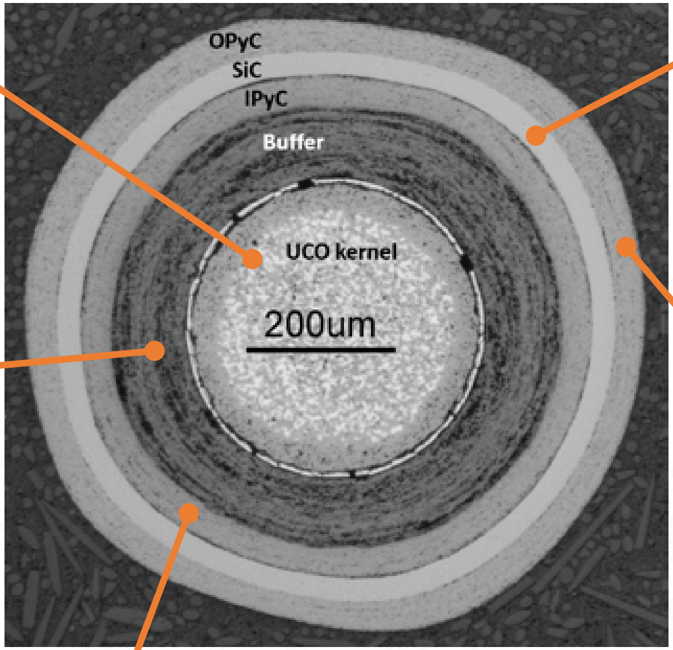


(a) Early example of a BISO (bistructural isotropic) particle. (b) Particle with "Triplex" structure (porous buffer layer followed by laminar and columnar pyrocarbon layers). (c) Carbide particle with single PyC coating layer used in Peach Bottom first core. (d) Fertile (Th,U)C_2 particle used in Dragon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

- **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

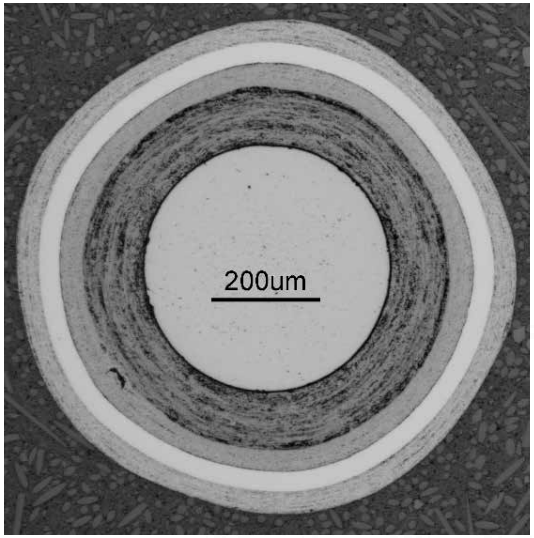


- **IPyC (~40 μm)**
  - Protects kernel from chloride during SiC deposition
  - Surface for SiC deposition
  - Contributes to fission gas retention
- **SiC (~35 μm)**
  - Main structural layer
  - Primary coating layer for retaining non-gaseous fission products
- **OPyC (~40 μm)**
  - Contributes to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

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
  - Fertile: ThC_2, ThO_2, UO_2, UCO
- LEU UO_2 is most widely used fuel type
  - Used in AVR (Germany), HTTR (Japan), HTR-10 and **HTR-PM** (China)
  - Extensive irradiation and heating test database from German HTGR Program
  - Reference fuel type for PBMR
- UCO offers improved fuel performance at higher fuel burnup
  - UCO selected as reference fuel design by X-energy
  - Several countries involved in the Generation IV International Forum (GIF) Very High Temperature Reactor (VHTR) Fuel and Fuel Cycle (FFC) Project Management Board are pursuing R&D on UCO fuel fabrication based on the favorable US program results

UO_2 and UCO TRISO Fuel

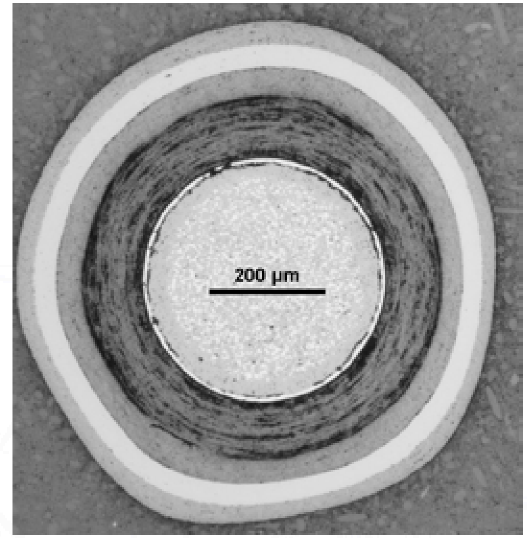


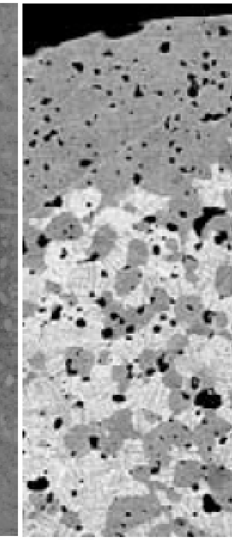
UO_2

UCO

(mixture of UO_2 and UC_x)

- Different kernel
- Same coatings



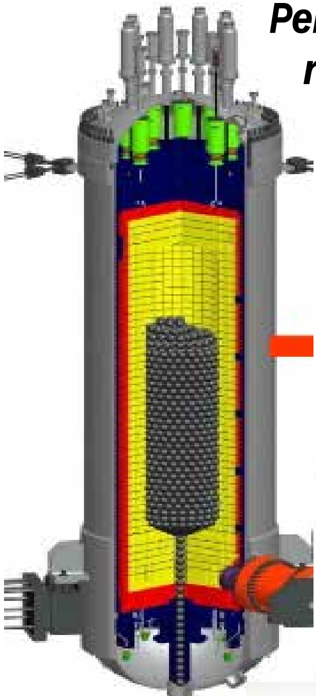


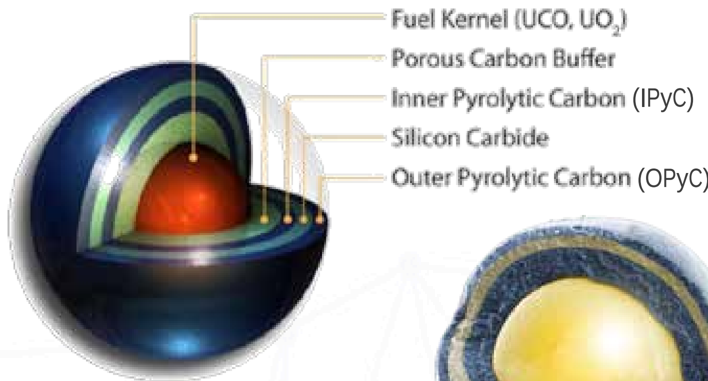
- Utilized in modern pebble bed reactor designs (burnup limited to ~11% FIMA)
- Extensive development and testing since the 1970s in many countries
- Good fission product retention in the kernel, but results in formation of CO(g) during irradiation
  - Contributes to internal gas pressure
  - Kernel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

- Mitigates CO(g) formation
- Suited for higher burnup (up to ~20% FIMA and beyond) and larger temperature gradients in prismatic reactors
- Comes at the cost of lower retention of some fission products in the kernel
- Development primarily in the US since the 1970s
- No large-scale, successful performance demonstration through the early 2000s

Tristructural Isotropic (TRISO) Coated Particle Fuel

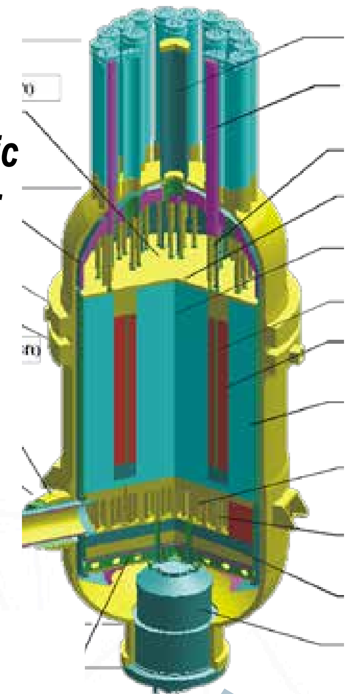
Pebble bed reactor

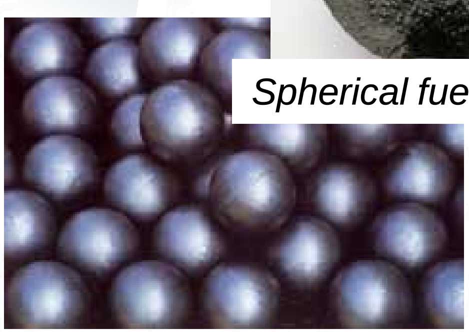




TRISO particle

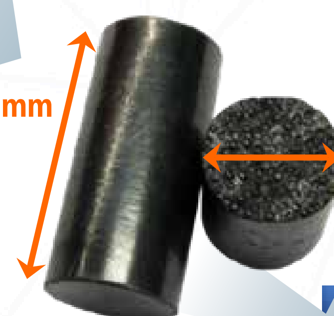
Prismatic reactor



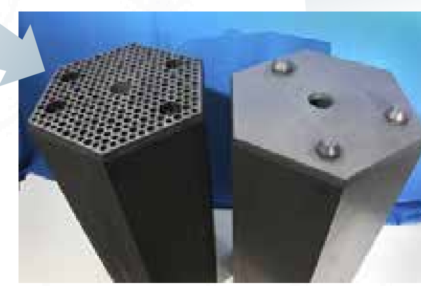


Spherical fuel pebbles

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



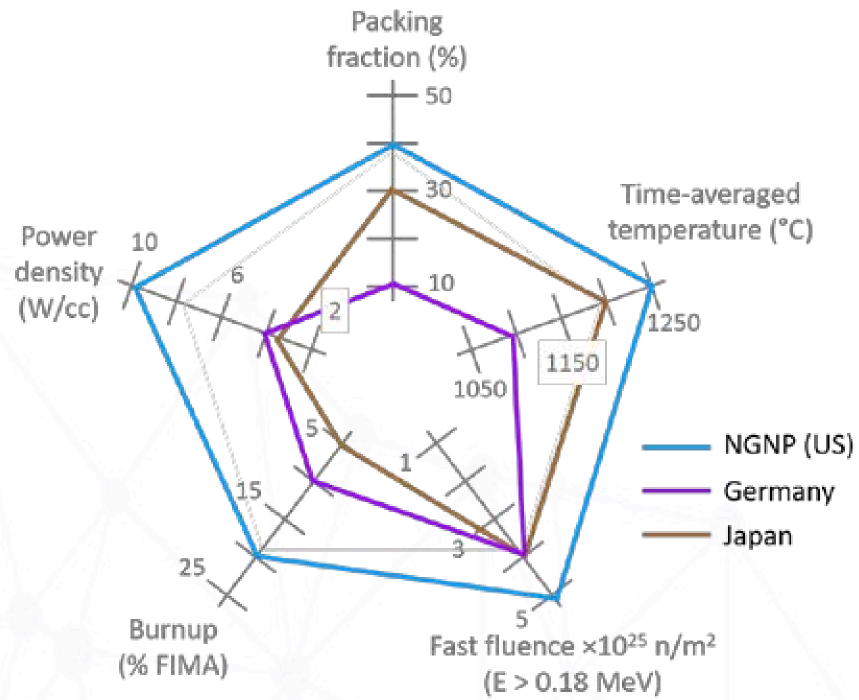
Cylindrical fuel compacts



Prismatic 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

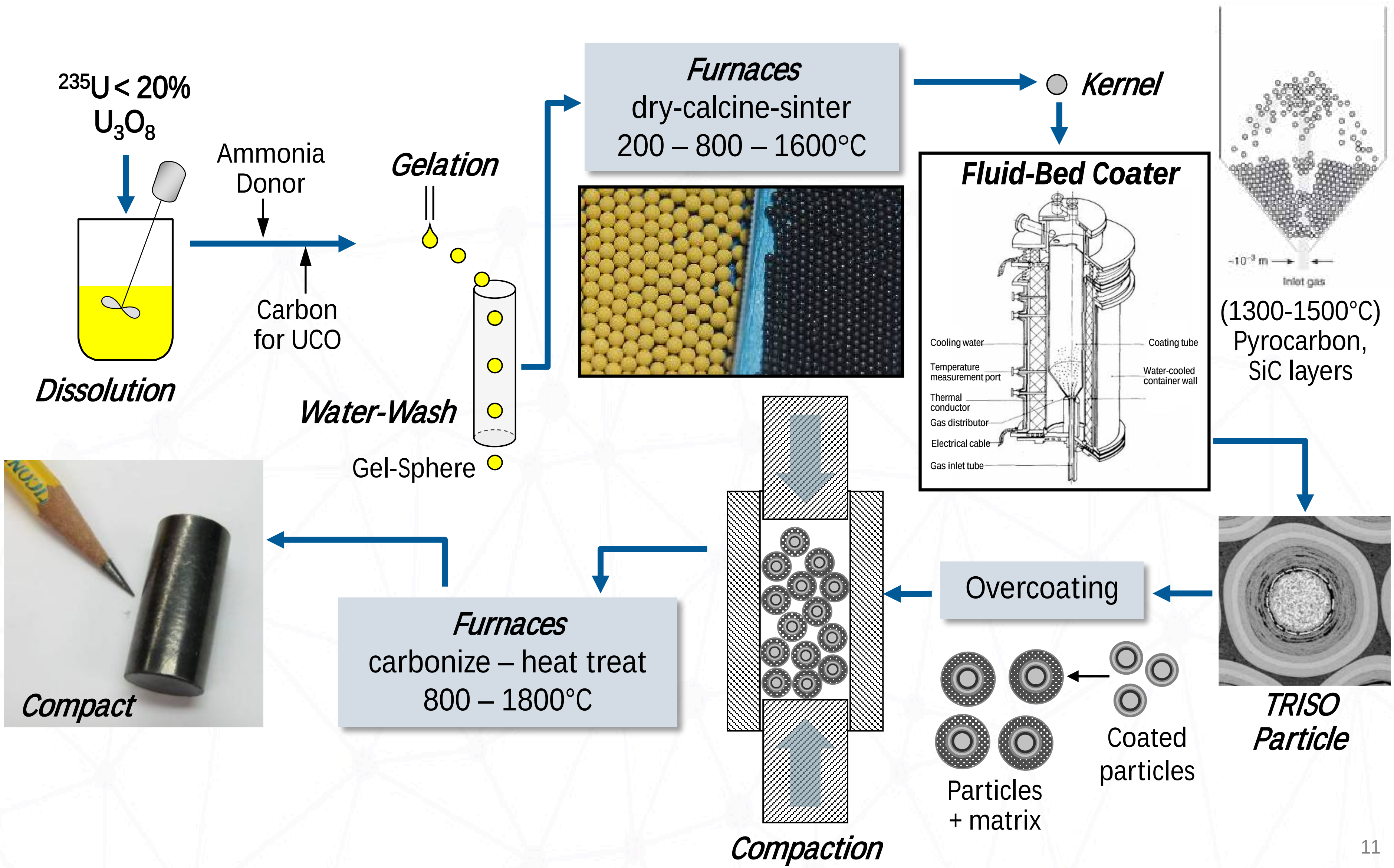


- Microreactors
  - Limited analyses on conceptual designs suggest that irradiation and accident conditions are less severe than larger gas reactor designs

Outline

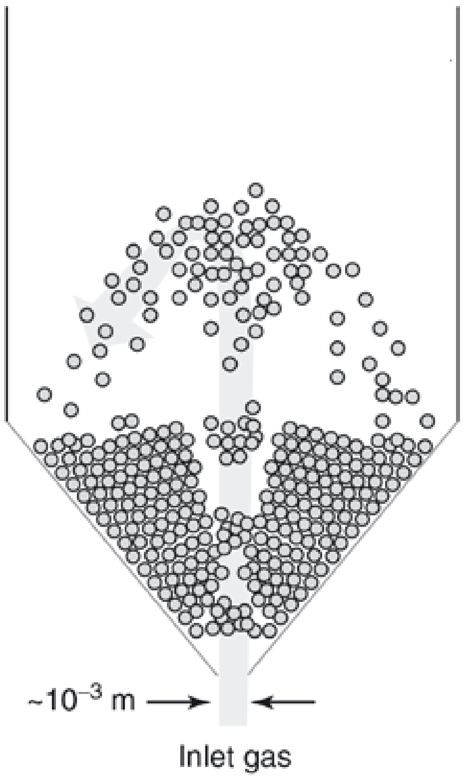
- TRISO fuel background and history
- Fuel fabrication and quality control
- Fuel irradiation performance
- Fuel accident performance
- Fuel performance and fission product transport modeling

TRISO Fuel Fabrication: Process Overview



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

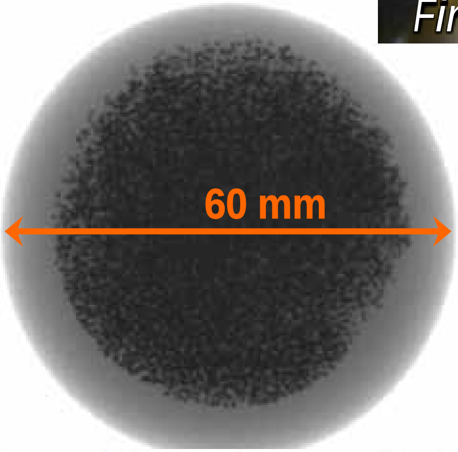
Industrial Scale 150 mm Coater (BWXT)

Fuel Elements

Spherical fuel elements

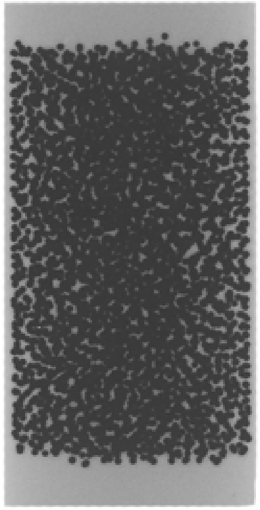

Fuel sphere press

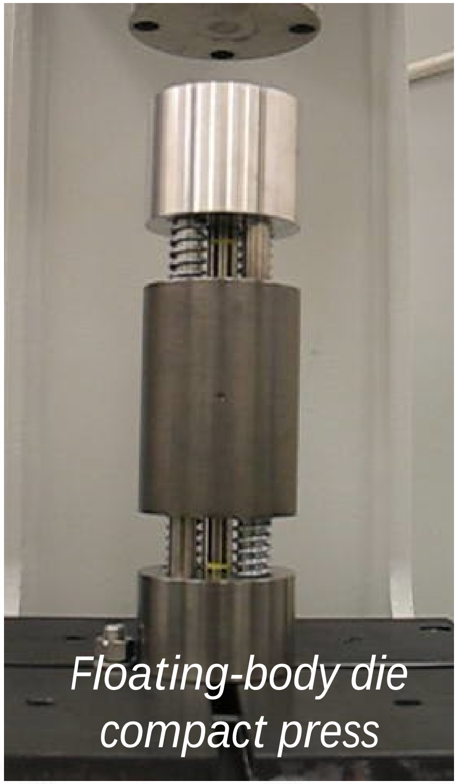

Finished fuel spheres

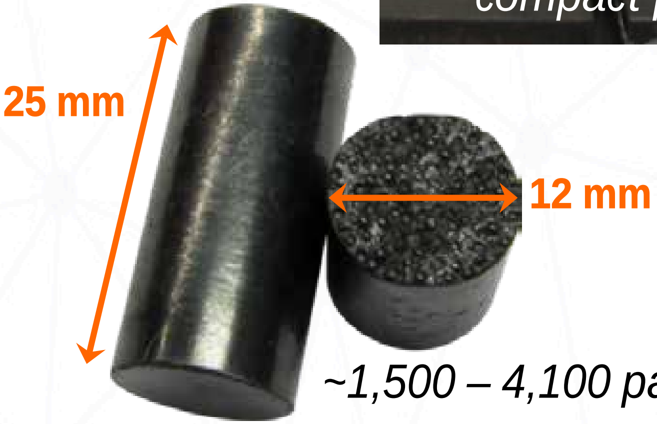


~9,000 – 18,000 particles

Cylindrical fuel elements



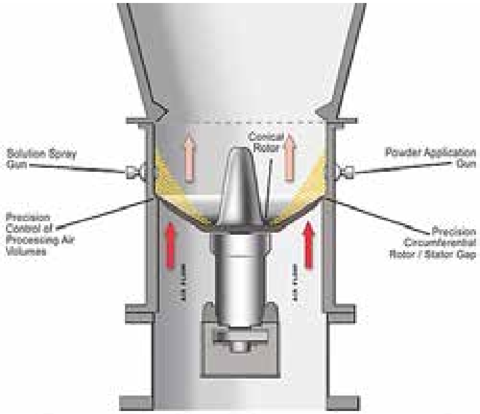

Floating-body die compact press



~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)

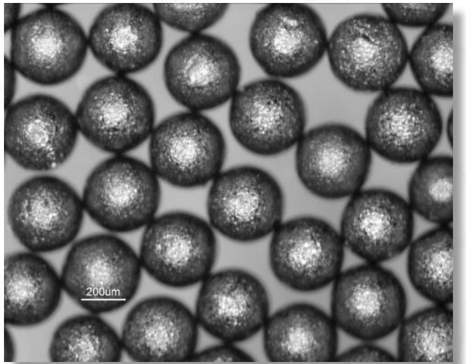


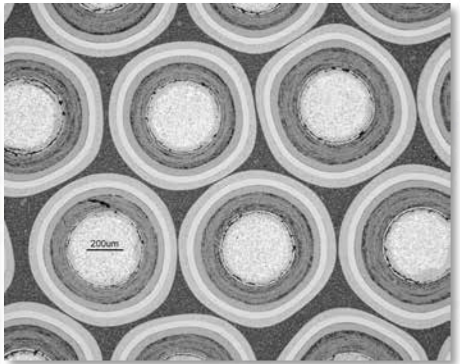
TRISO Fuel Quality Control

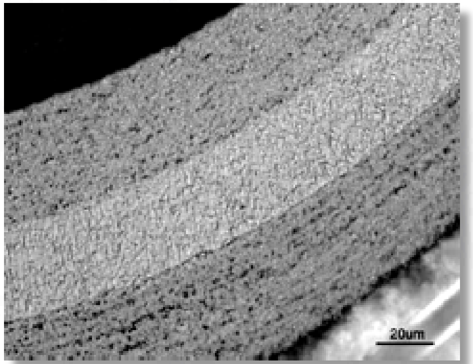
- Quality Control (QC) is the process used to verify that a product satisfies the design criteria
- QC for coated particle fuel includes:
  - Specifications on source materials, production processes, and process limits
  - Specifications on kernel, coating, and compact properties
  - Specifications on 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)

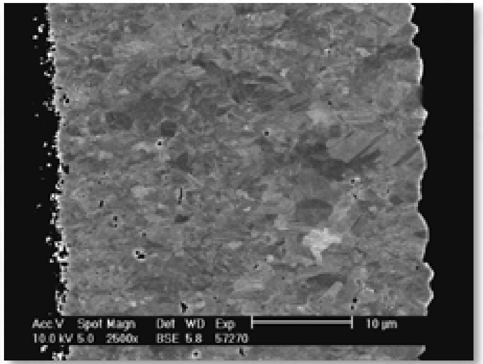
AGR Program Fuel Specifications for QC

- 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
  - SiC microstructure
  - 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

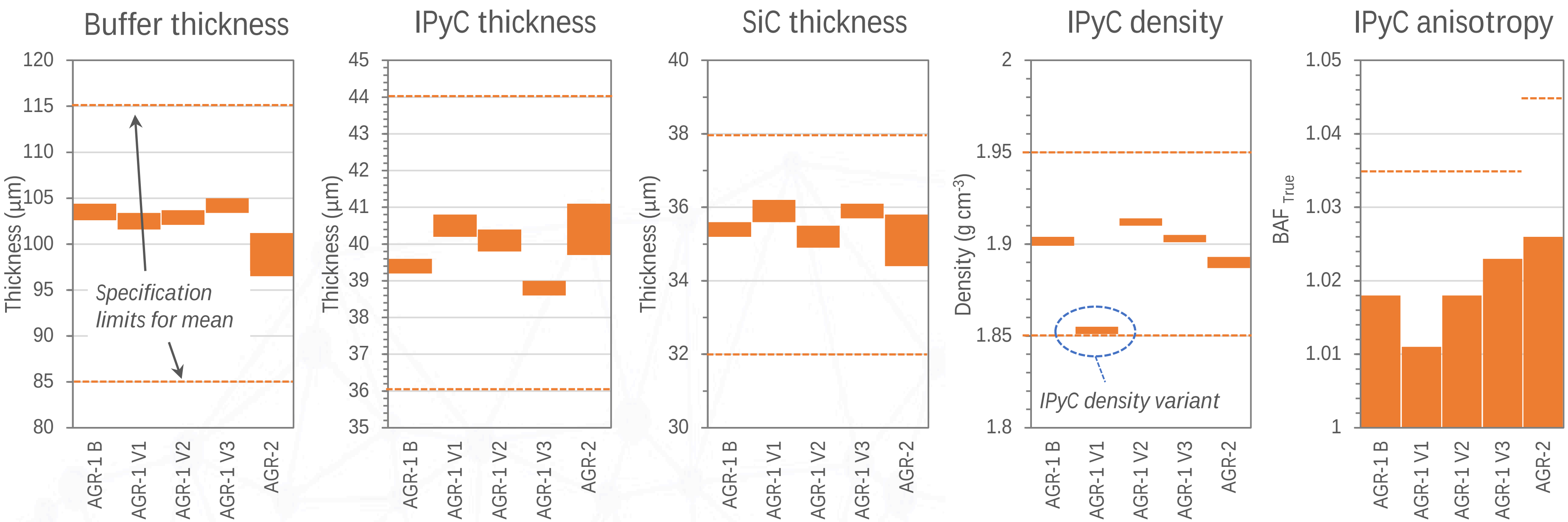






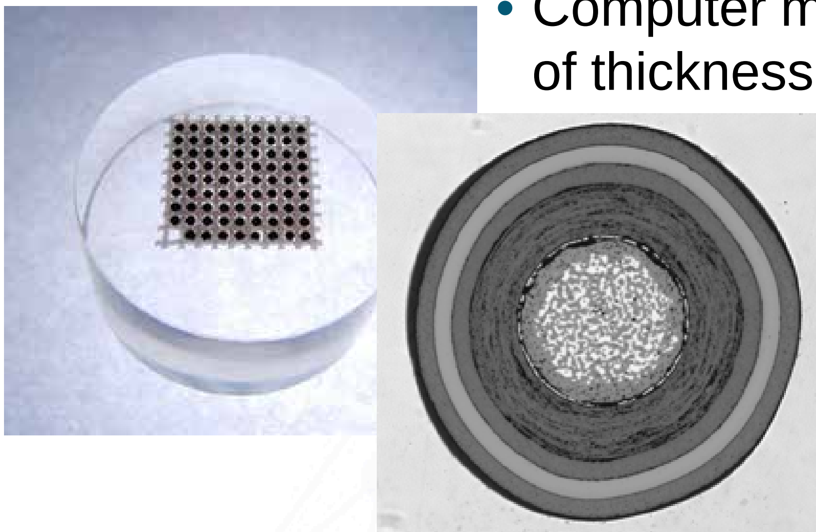


Selected AGR-1 and AGR-2 Fuel Property Means



- Mean must be within the specification limits at 95% confidence
- AGR-1 and AGR-2 measured values typically lie well within the specification range
- Note that some specifications were changed for AGR-2, 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

Fuel Fabrication Summary

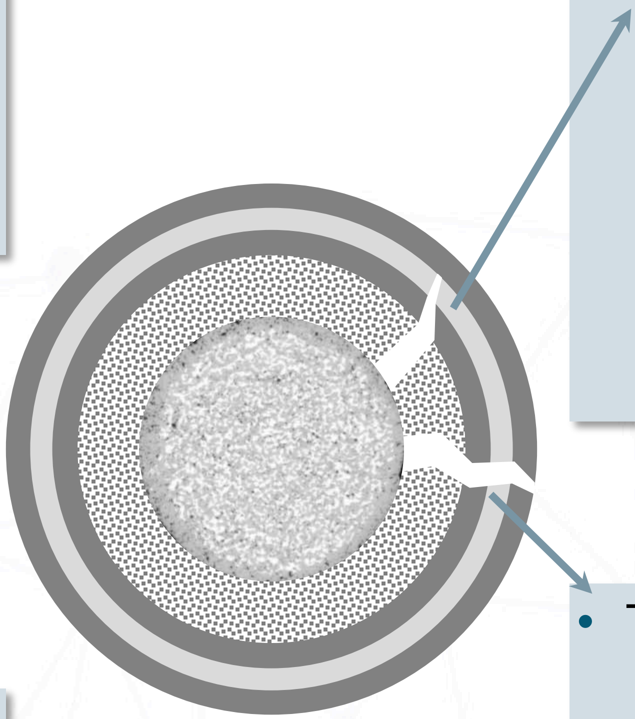
- TRISO fuel fabrication is a process that has matured over the last 50 years
- Statistical sampling is used to verify fuel quality
- Specifications are met to at least a 95% confidence level
- US AGR program has implemented numerous fuel fabrication process and characterization method improvements

Outline

- TRISO fuel background and history
- Fuel fabrication and quality control
- Fuel irradiation performance
- Fuel accident performance
- Fuel performance and fission product transport modeling

TRISO Fuel Performance

- Coating integrity
  - Layers remain intact to retain fission products



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

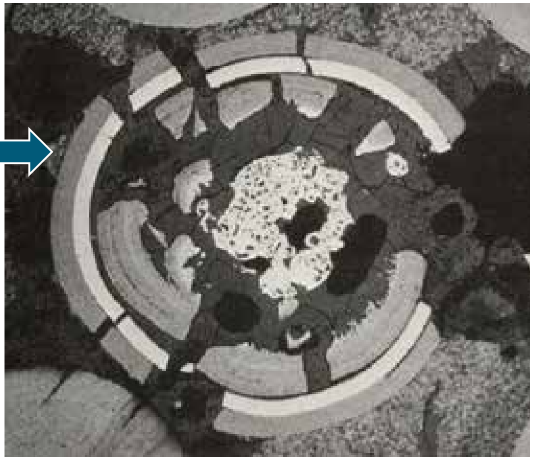
- TRISO layer failure:
  - All three dense coating layers breached
  - Release of fission gas and condensable fission products

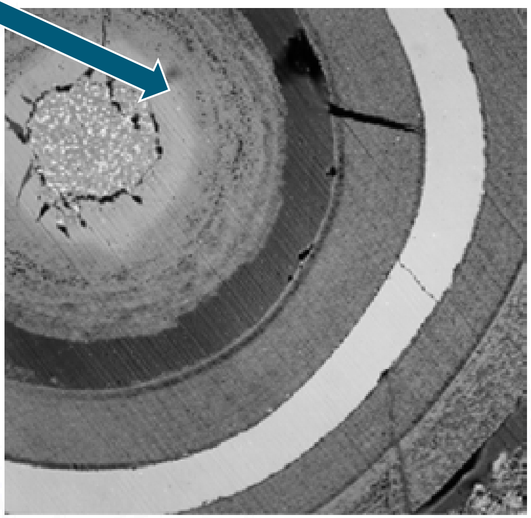
- Fission product retention
  - Coating integrity
  - Retention in kernel
  - Diffusive transport through layers
  - Matrix retention

Fuel Failure Mechanisms

Mechanical

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



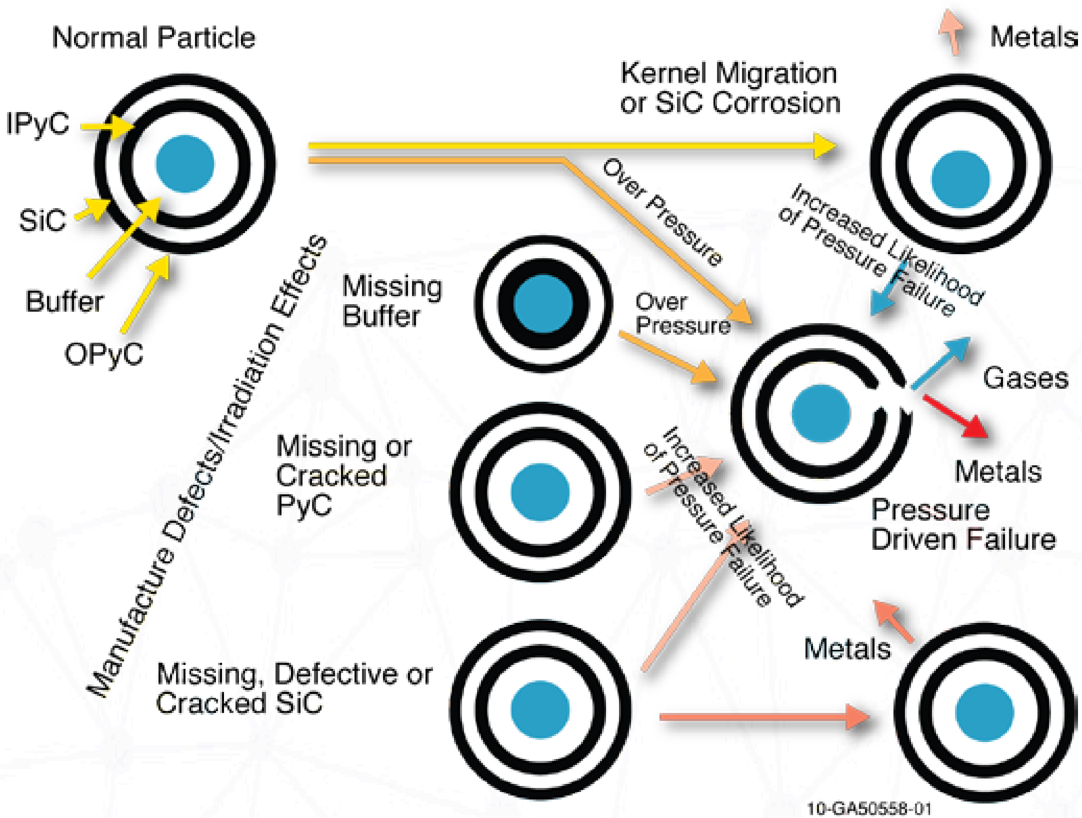


Thermochemical

- Kernel migration
- SiC thermal decomposition
- 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

Fuel Failure Mechanisms



- SiC corrosion by CO(g) (in UO_2 fuel) and fission products (in UO_2 and UCO fuel) is the primary cause of SiC layer failure observed in modern TRISO fuel
- High-quality fuel manufacture and limitations on irradiation conditions (performance envelope) reduce failure fractions to acceptable limits

Irradiation Testing

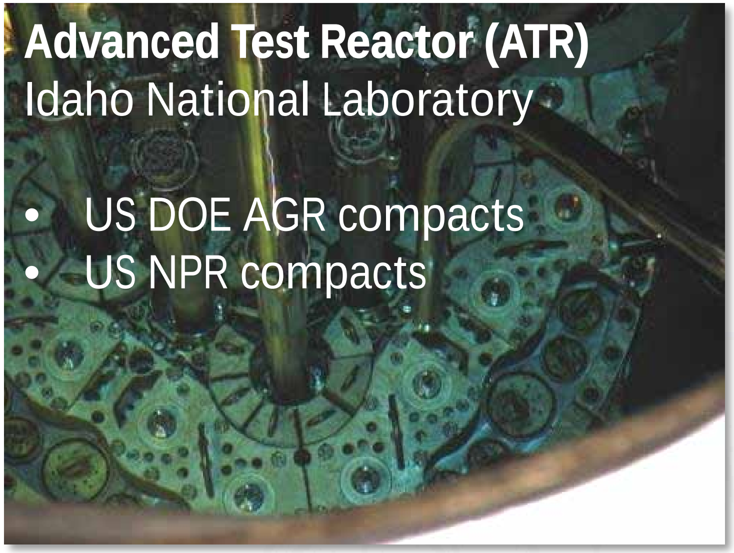
Prototype modular HTGRs

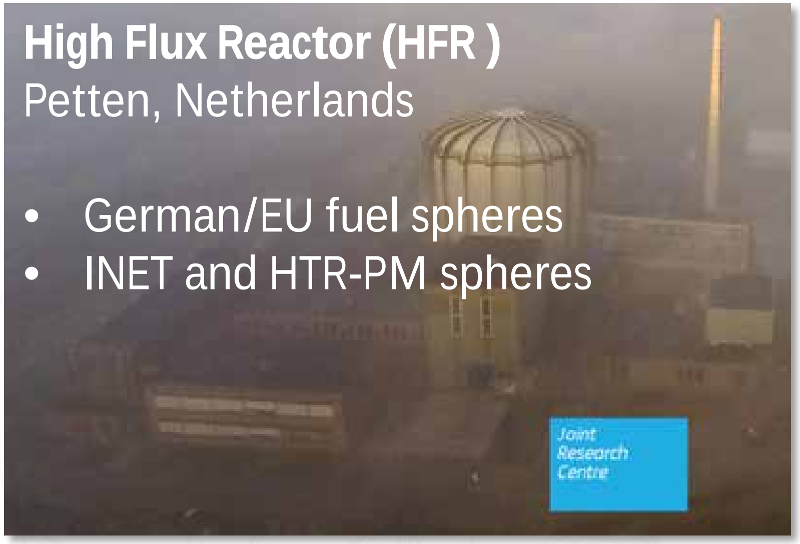
- Prototypical conditions (neutron spectrum and flux, burnup accumulation rate)
- Long duration
- Difficult online measurement of fuel performance
- Less certainty on fuel temperature

Materials Test Reactors (MTRs)

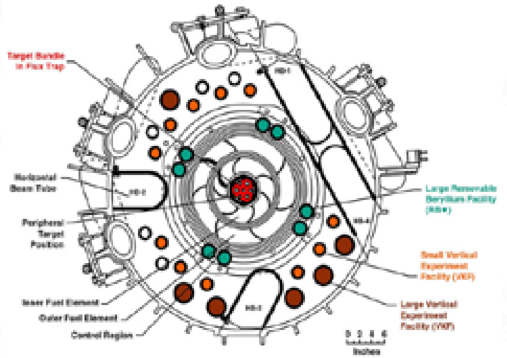
- Accelerated irradiation times
- Measurement and control of fuel temperature
- Real-time measurement of fission product release
- Conditions may differ somewhat from HTGRs (neutron spectrum and flux, burnup accumulation rate)

Irradiation Testing of TRISO Fuel in MTRs





High Flux Isotope Reactor (HFIR)
Oak Ridge National Laboratory



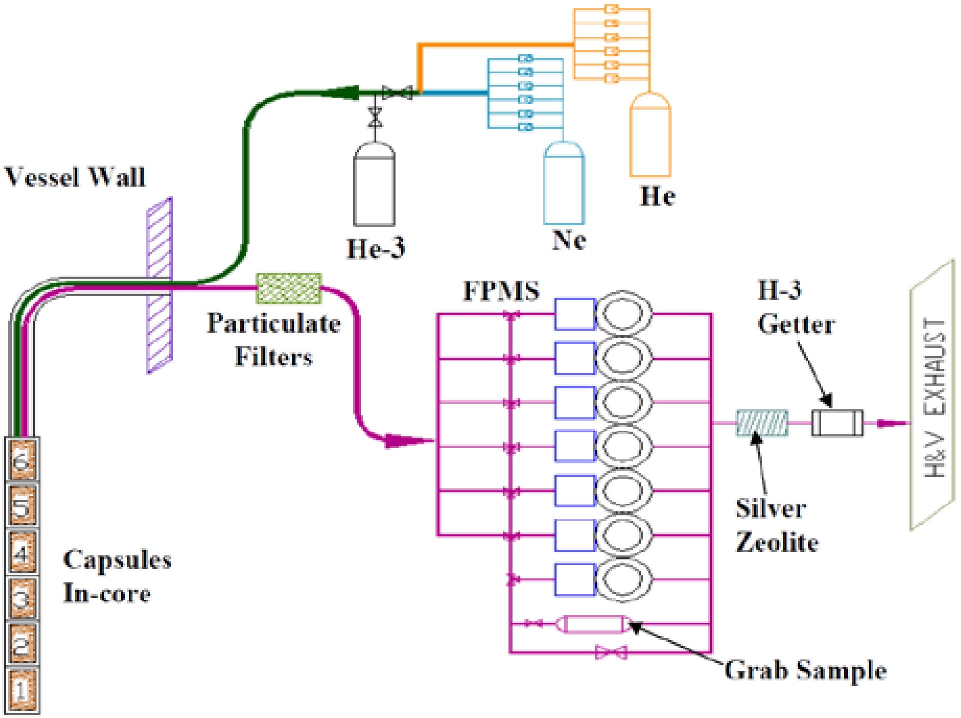
- US DOE TRISO fuels

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 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

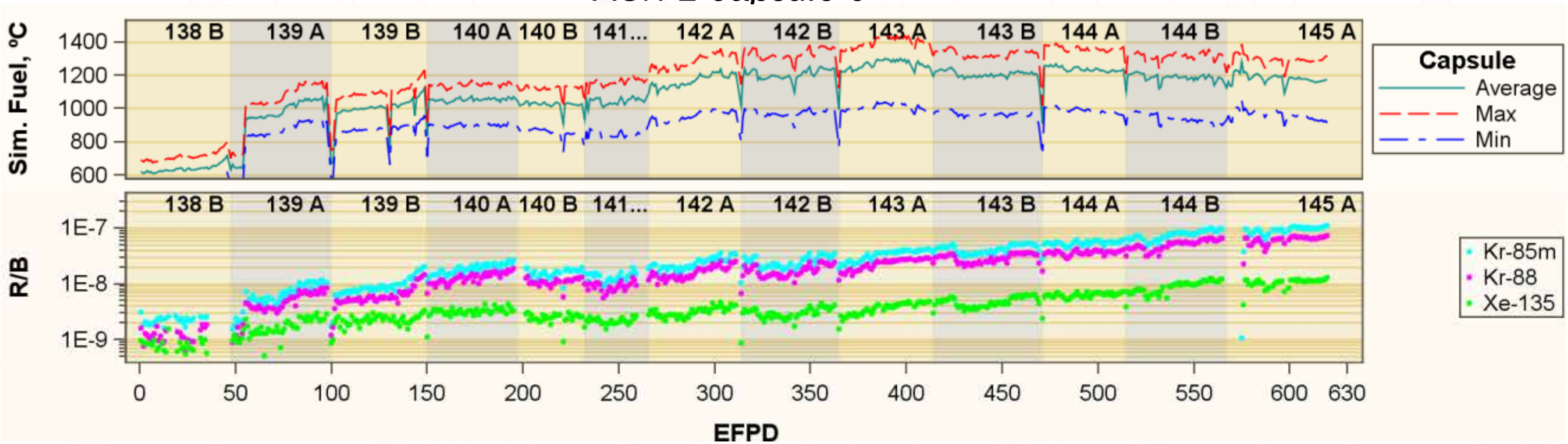


AGR-1 Fission Gas Monitoring System (FGMS)

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 half-life

AGR-1 Capsule 6



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

Recent TRISO Fuel Irradiation Tests (2000 – Present)

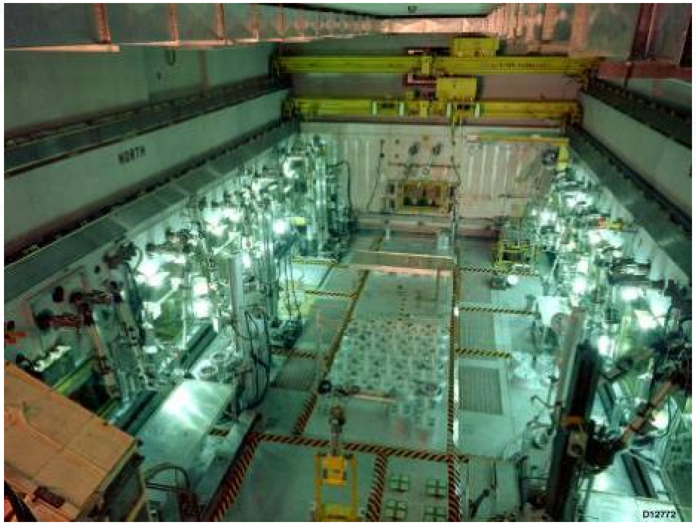
Irradiation test	Location	Fuel type	Spheres or compacts (particles)	Completed	Burnup (%FIMA)	Temperature (°C)[a]	EOL ^{85m}Kr R/B
US DOE/AGR (cylindrical compacts)							
AGR-1	ATR	UCO	72 (298,000)	Nov 2009	11.3 – 19.6	1069 – 1197	0.1 – 1×10^{-7}
AGR-2	ATR	UCO UO_2	36 (114,000) 12 (18,500)	Oct 2013	7.3 – 13.2 9.0 – 10.7	1080 – 1360 1072 – 1105	~10^{-6} [b] 10^{-7} [b]
AGR-5/6/7	ATR	UCO	194 (570,000)	In progress	7.4 – 18.6	~600 – 1500	*TBD*
Germany/EU (spheres)							
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 (spheres)							
HTR-10/ IVV-2M	IVV-2M	UO_2	4 (33,200)	Feb 2003	11.6 – 13.1	1000 ±50	0.1 – 8×10^{-5}
HFR-EU1	HFR	UO_2	2 (16,600)	Feb 2010	9.3, 11.6	900 – 940[c]	7×10^{-8}
HFR-PM	HFR	UO_2	5 (60,000)	Dec 2014	10.1 – 12.7	1050 ±50	~3×10^{-9}

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

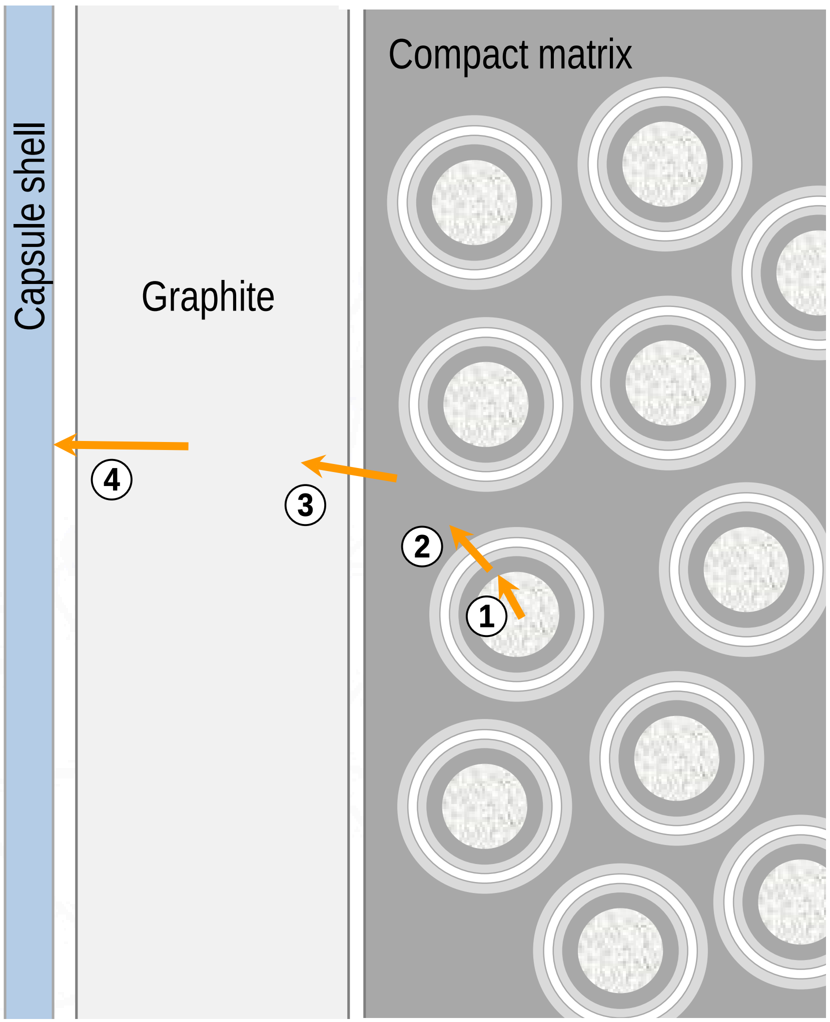
Excellent performance within intended fuel performance envelope

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



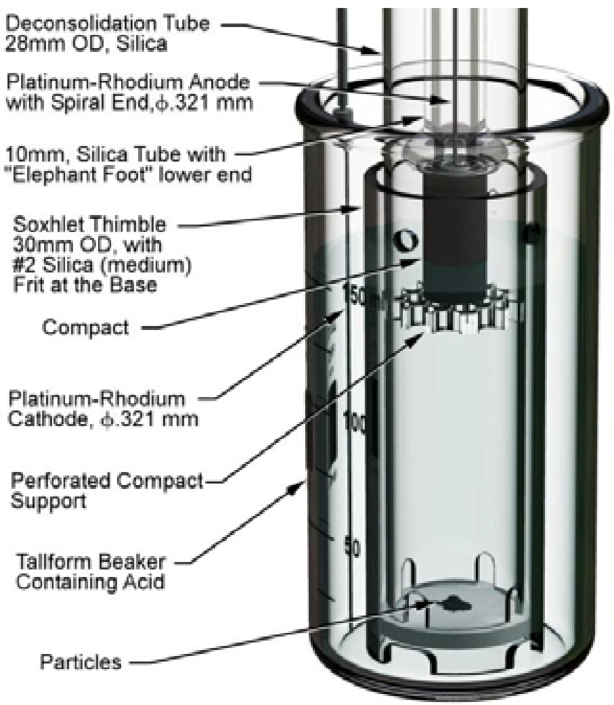
1. Release from kernel to coating layers
2. Release from coating layers to compact matrix
3. Release from compact matrix to structural graphite
4. Release from structural graphite to capsule shell (or reactor vessel)

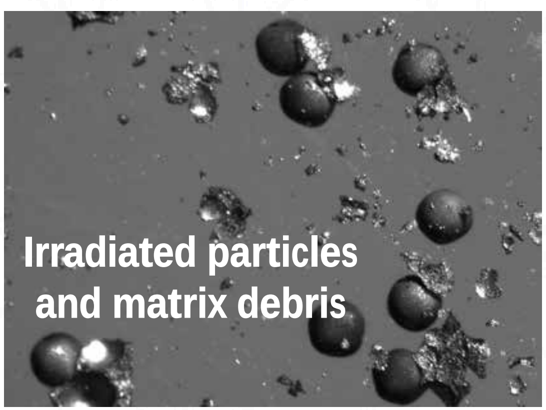
Look for fission products:

- 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

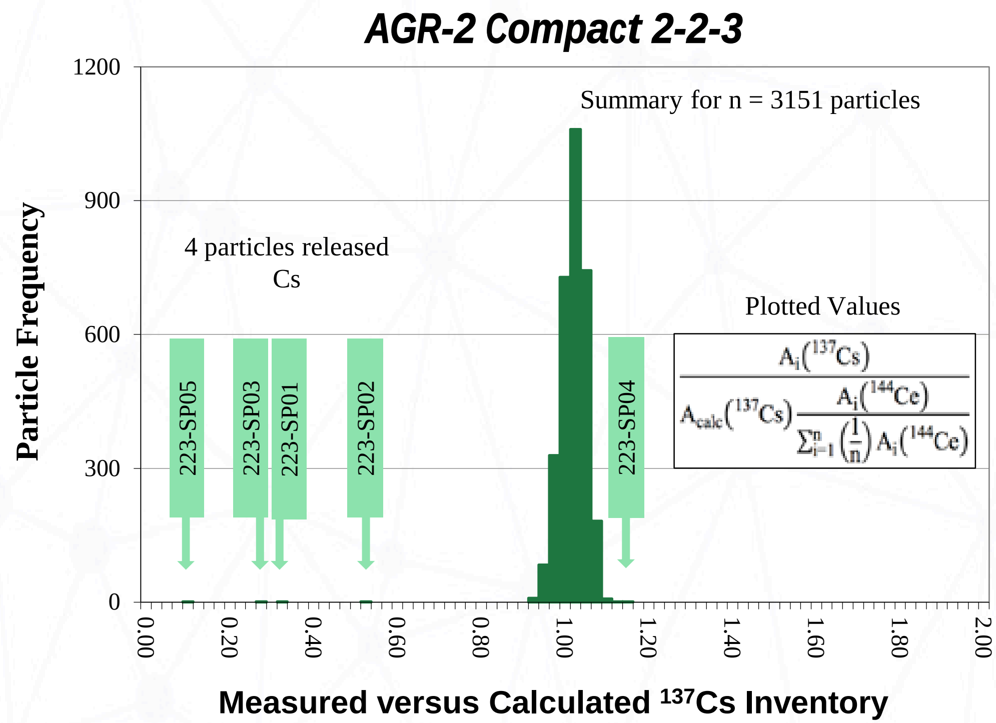
- **Process provides inventory of FPs and actinides in matrix outside of intact SiC**

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



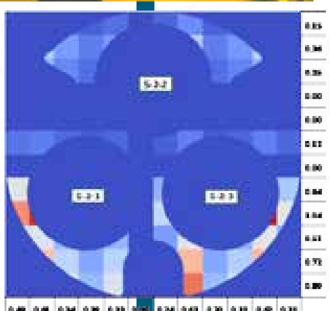
Studying failed particles greatly improves understanding of fuel performance

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

AGR-1 Test Train Vertical Section

Identify compacts with leakers

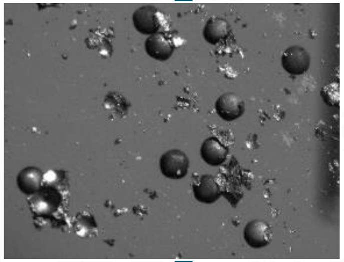
Capsule disassembly



Gamma scan to identify cesium hot spots and compact location

Identify particles with failed coatings

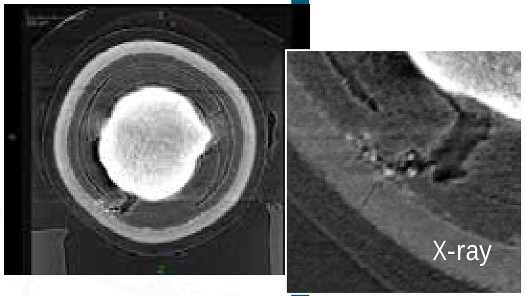
Deconsolidation to obtain ~4,000 particles from compact



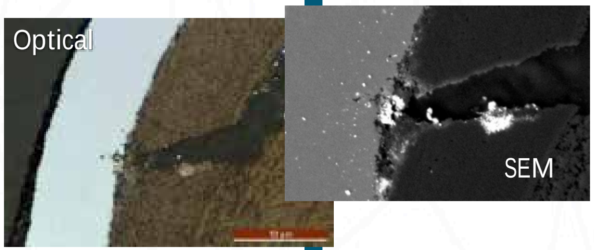
Gamma count to find particles with low cesium retention

Study particles with failed coatings

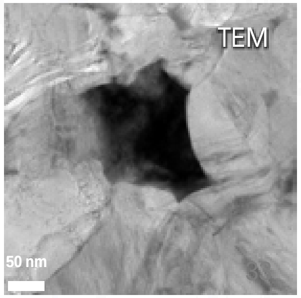
X-ray tomography to locate failures



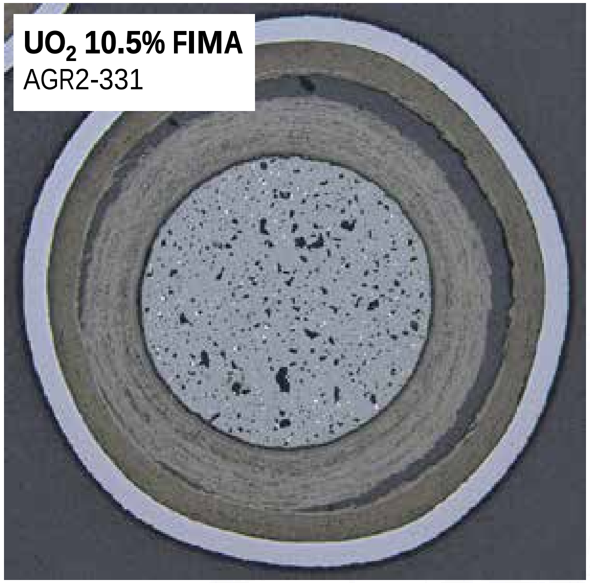
Materialography to expose defective region for analysis



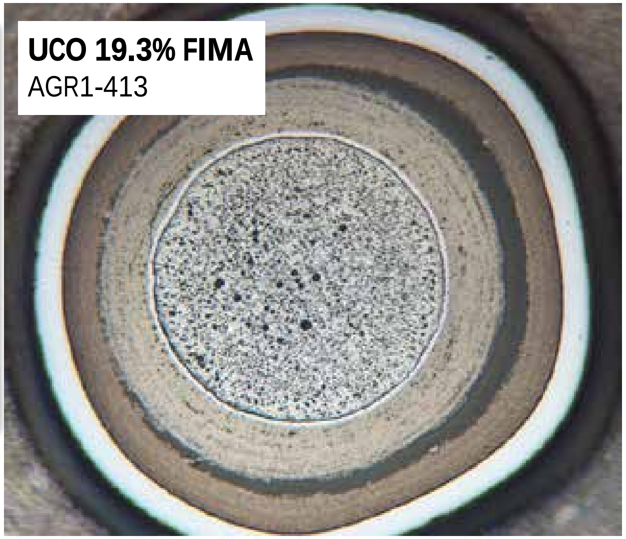
Advanced microscopy to study coating layers in detail

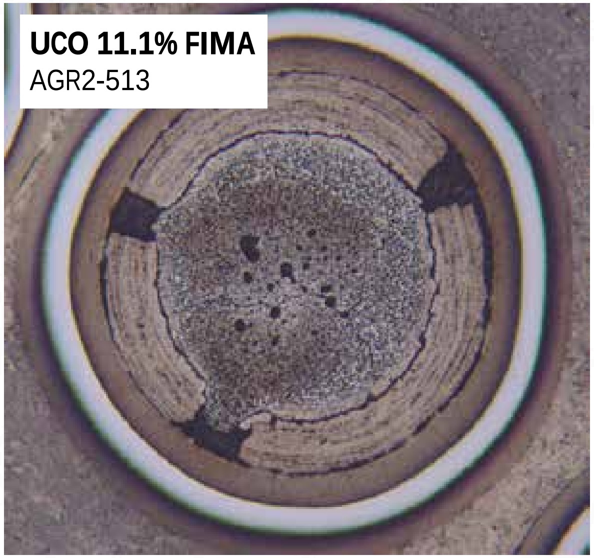


Kernel and Coating Behavior During Irradiation: AGR Particles



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



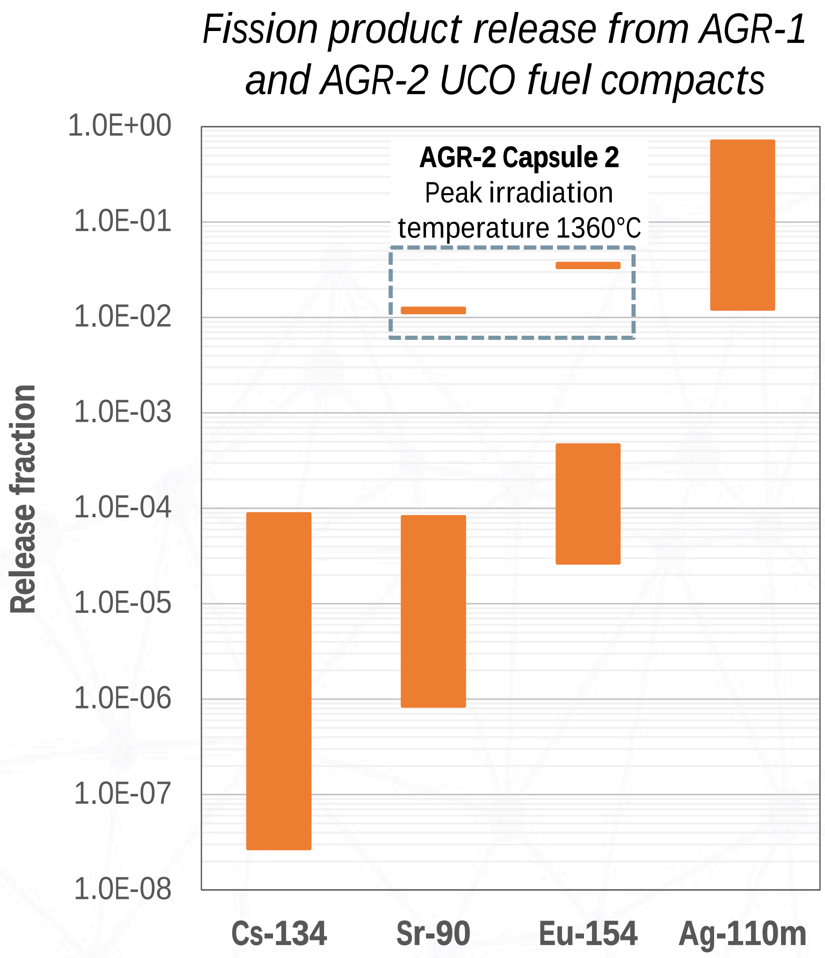


- Buffer fracture relatively common in UCO fuel particles
- Kernel can swell into gap
- Dependent on irradiation temperature and fast neutron fluence
- When buffer separates from IPyC, buffer fracture appears to have no detrimental effect on dense coating layers

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



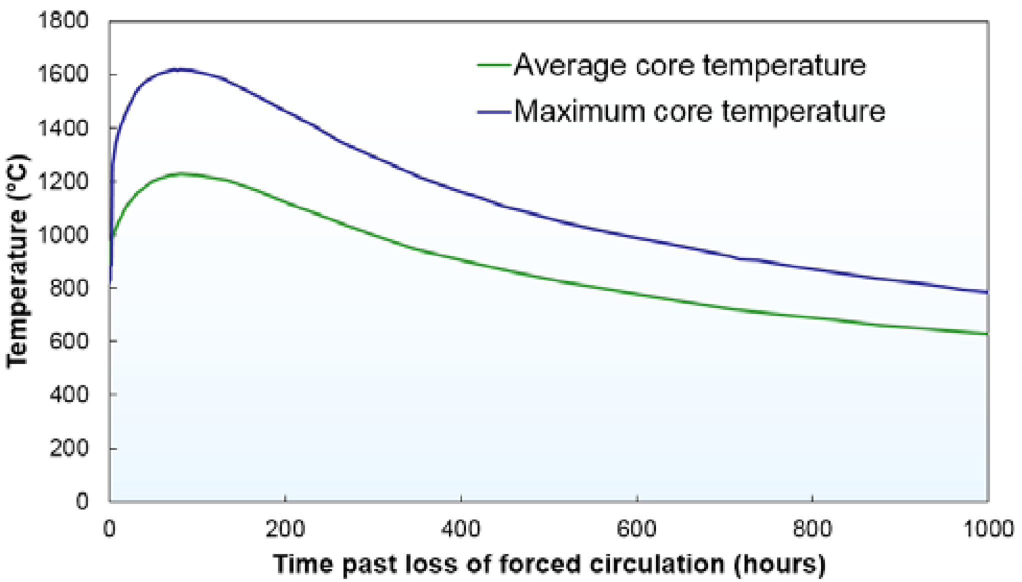
- Cs release is very low with intact SiC; higher releases are associated with a limited number of particles with failed SiC
- Sr and Eu can exhibit modest release; release is much higher with high in-pile temperatures (AGR-2 Capsule 2 time-average peak temperatures 1360°C)
- High Ag release

Outline

- TRISO fuel background and history
- Fuel fabrication and quality control
- Fuel irradiation performance
- Fuel accident performance
- Fuel performance and fission product transport modeling

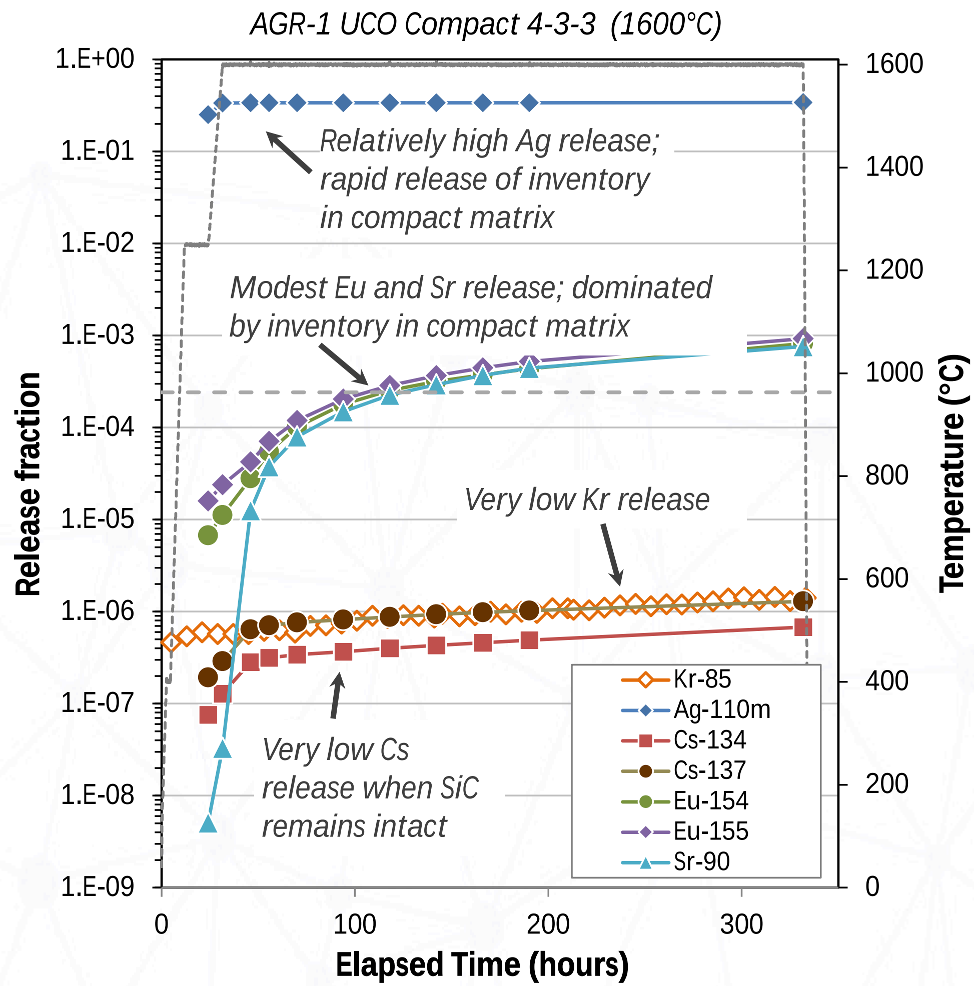
HTGR Accident Safety Testing of TRISO Fuel

- 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, and only a small fraction of the fuel in the core experiences temperatures near the peak.
- Assess fuel performance by post-irradiation heating tests while measuring fission product release at 1600—1800°C

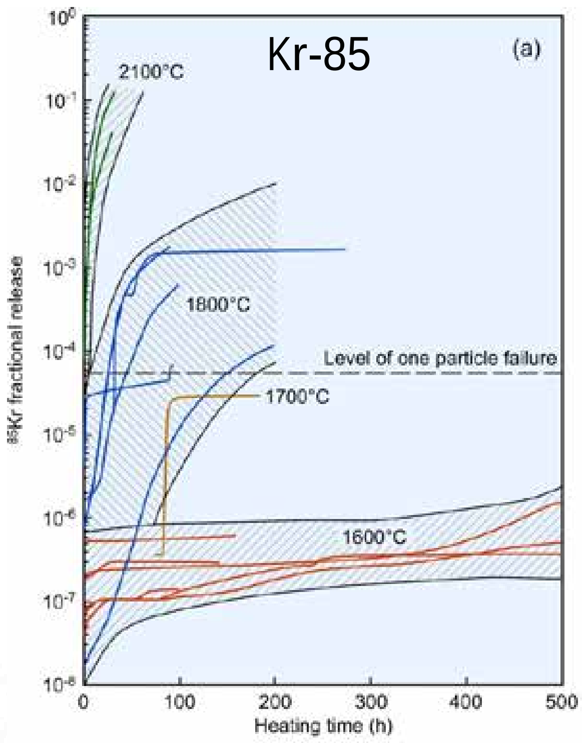


AGR-1 and AGR-2 Safety Test Performance

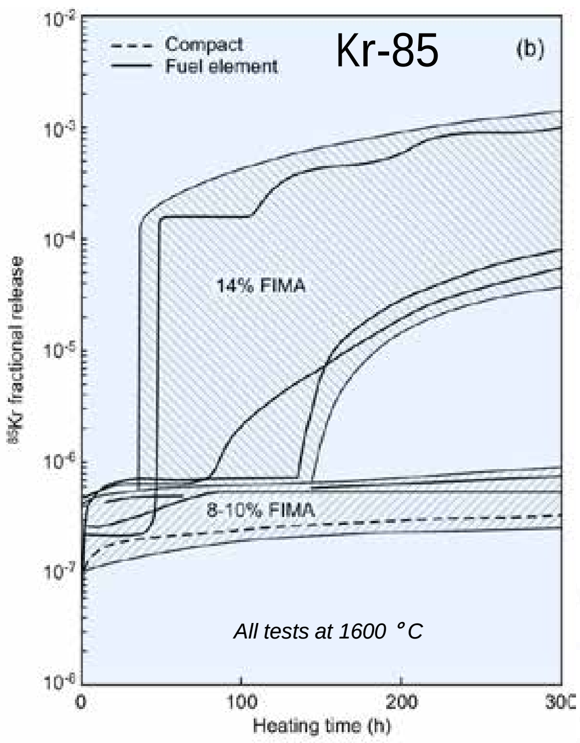
- **Low Cs release** (dependent on intact SiC)
- **Low Kr release**
- **Modest Sr and Eu release** (influenced by irradiation temperature)
- **High Ag release** (dominated by in-pile release from particles)
- **Excellent UCO performance up to 1800°C**
- **Low coating failure fractions** (UCO)
- **UO_2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



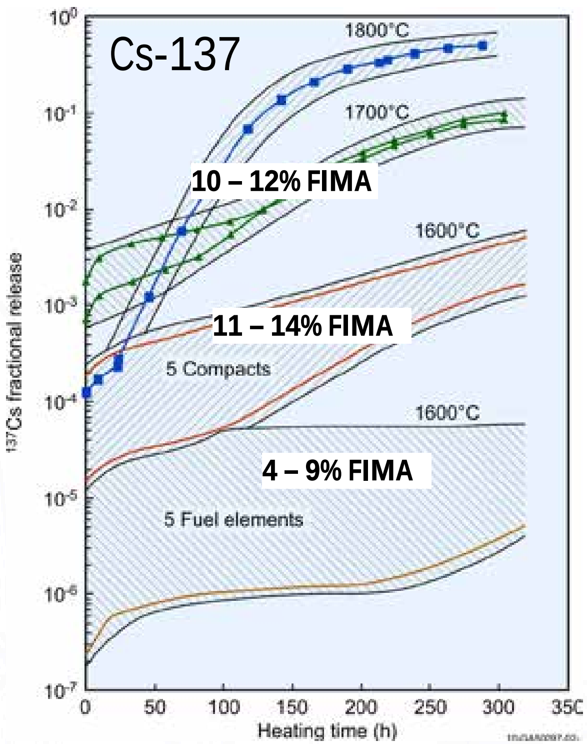
Safety Test Data: German UO_2 Results



- No TRISO failures at 1600°C
- TRISO failures occur after short periods at 1800°C



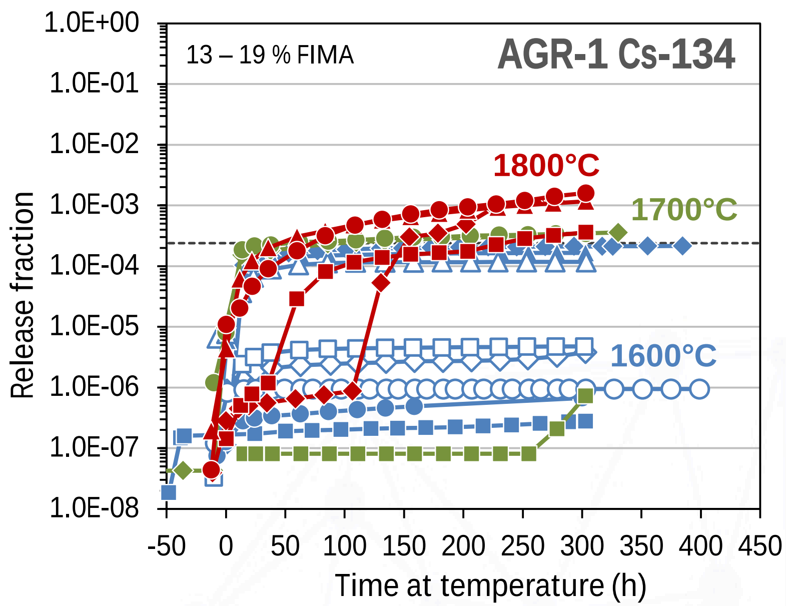
- No TRISO failures at 1600°C with burnup ≤10%
- TRISO failures occur at 1600°C with burnups ~14%

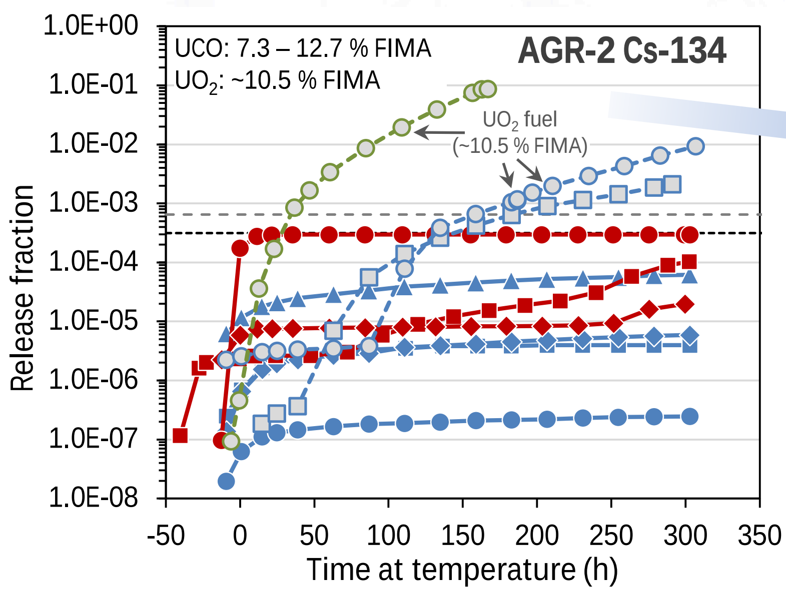


- At 1600°C and burnup <10% FIMA, Cs release remains relatively low
- Increasing burnup and temperature increases SiC layer degradation and Cs release

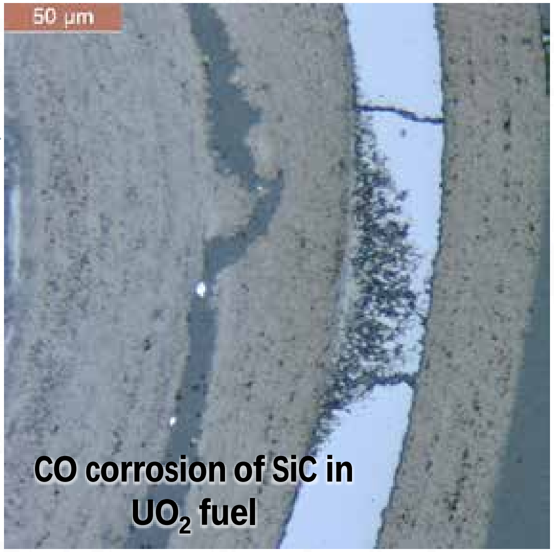
D.A. Petti et al., TRISO-Coated Particle Fuel Performance, in Konings R.J.M.,(ed.) Comprehensive Nuclear Materials (2012), vol. 3, pp. 151-213 Amsterdam: Elsevier.

Cesium Release Results: AGR Program Safety Testing



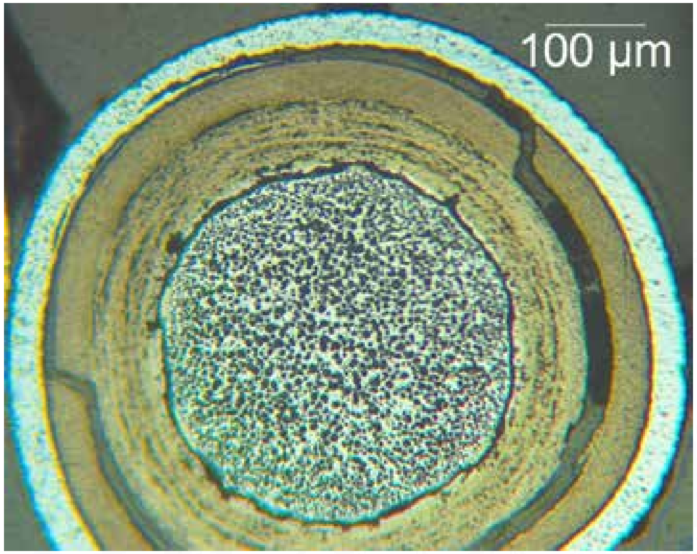


- **UCO fuel**: relatively low Cs release; release >10^{-4} results from discrete SiC layer failure in 1 or more particles
- **UO_2 fuel**: higher Cs release compared to UCO; driven by CO attack on the SiC layer causing more widespread SiC failure

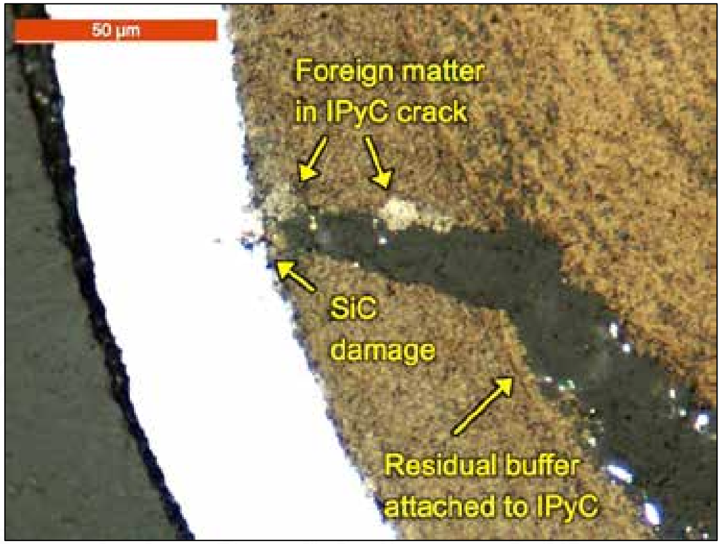


AGR UCO Particle SiC Failure

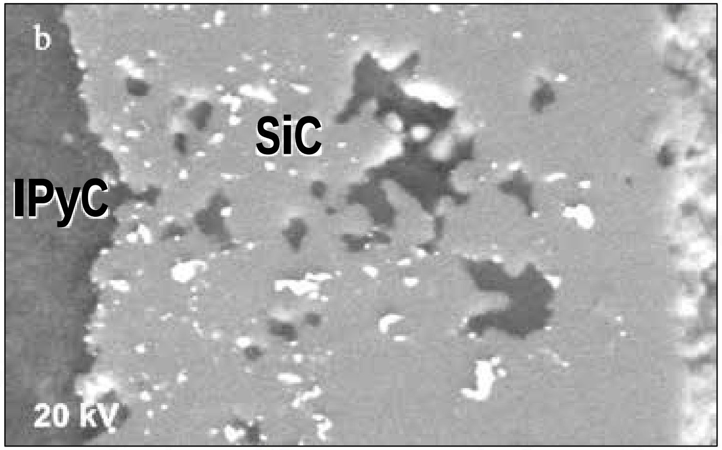
IPyC cracking and SiC separation during irradiation; no SiC failure



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

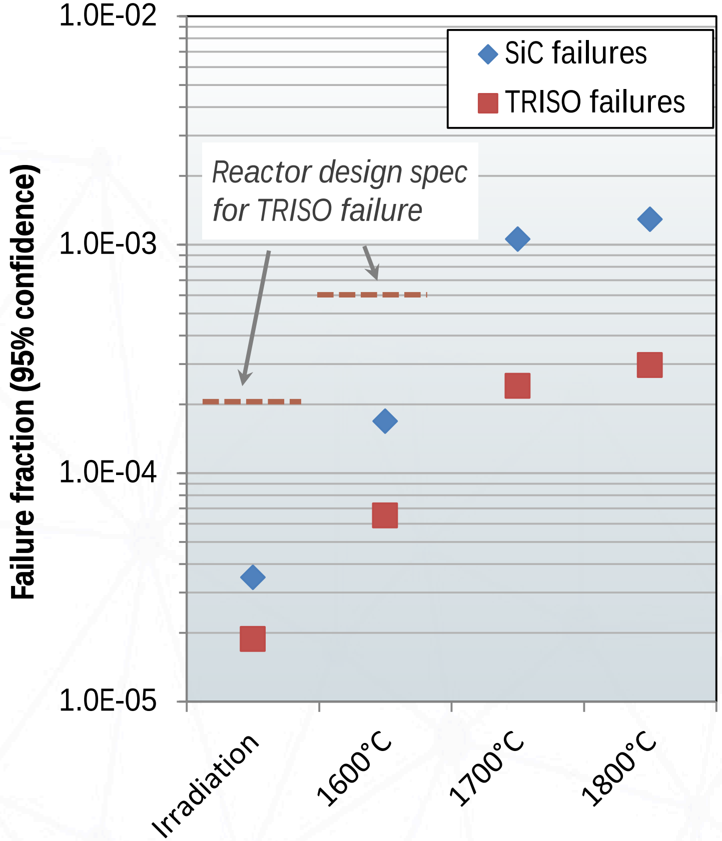
Fuel Design Safety Approach

Specifications for particle defects and failure fractions

Parameter	NGNP – 750°C Core Outlet Temperature	
	"Maximum Expected"	"Design"
As-Manufactured Fuel Quality		
HM contamination	≤ 1.0×10^{-5}	≤ 2.0×10^{-5}
Defective SiC	≤ 5.0×10^{-5}	≤ 1.0×10^{-4}
In-Service TRISO Failure		
Normal operation	≤5.0×10^{-5}	≤2.0×10^{-4}
Accidents	≤1.5×10^{-4}	≤6.0×10^{-4}

- Establish specifications for as-manufactured contamination levels and particle defects that can lead to fission product release
- Verify fuel quality with QC measurements
- Demonstrate failure fraction specifications are met during fuel qualification irradiation and safety testing

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



AGR-1 and -2 TRISO failure fractions meet historic design specifications with ~10X margin

Core Oxidation

- Accident scenarios in gas-cooled reactors can include air or steam ingress into the core
- Specific conditions should be defined to the extent possible through models (temperatures, durations, oxidant partial pressure)
- Core behavior under these conditions should be evaluated
  - Graphite and matrix oxidation
  - Fission product volatilization from matrix/graphite and exposed kernels
  - Coated particle integrity
- Graphite oxidation data is available in literature
- Limited data on matrix oxidation is available from previous tests
- US AGR program is performing dedicated testing to obtain necessary data:
  - Matrix oxidation tests
  - Irradiated fuel heating tests in air and steam environments (starting ~2020)

Fuel 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 R/B values during irradiation (low coating failures)
- TRISO fuel FP release behavior is well-characterized
- Extensive accident testing database
  - Fuel withstands 300 h at temperatures of 1600°C and above with low failure rates
- Observed failure fractions are well below historic reactor design specs

Outline

- TRISO fuel background and history
- Fuel fabrication and quality control
- Fuel irradiation performance
- Fuel accident performance
- Fuel performance and fission product transport modeling

Fuel Performance and Fission Product Transport Modeling

- Predict coating behavior as a function of particle properties and irradiation conditions à *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

PARticle FUel ModEl

PARFUME

AGR program fuel performance modeling and analysis code

Mechanistic code

Thermal, mechanical, physico-chemical behavior of TRISO fuel particles

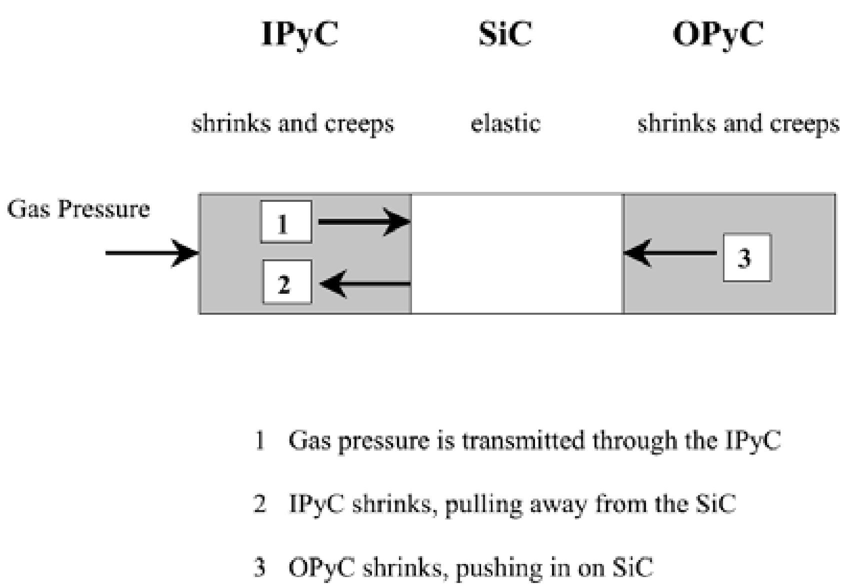
Probability of particle failure

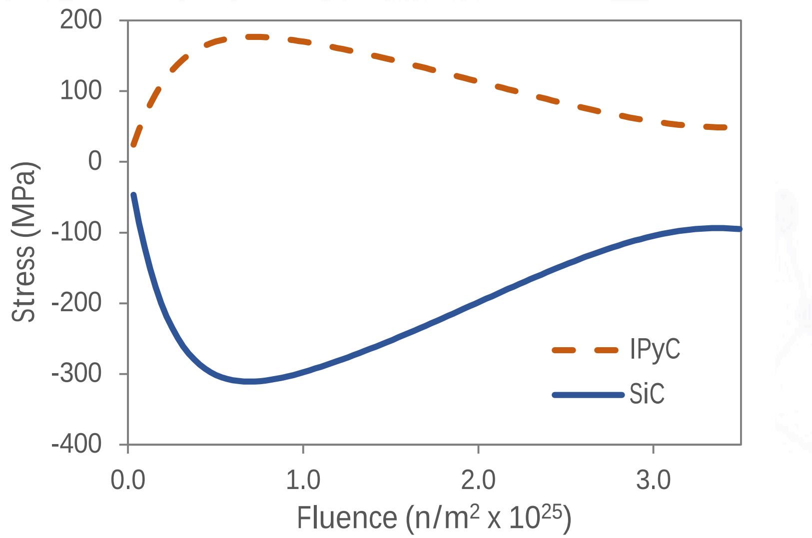
Fission product fractional release

Coating Stress Calculations and Particle Failure Analysis

- Key inputs:
  - Fuel temperature, burnup, fast neutron fluence
  - PyC irradiation-induced creep and strain
  - SiC tensile strength and Weibull modulus
  - (Sensitivity studies indicate that many properties have little effect on particle failure)
- Particle failure probability based on Weibull statistics

$$P_f = 1 - e^{-\int_V \left(\frac{\sigma}{\sigma_o}\right)^m dV}$$

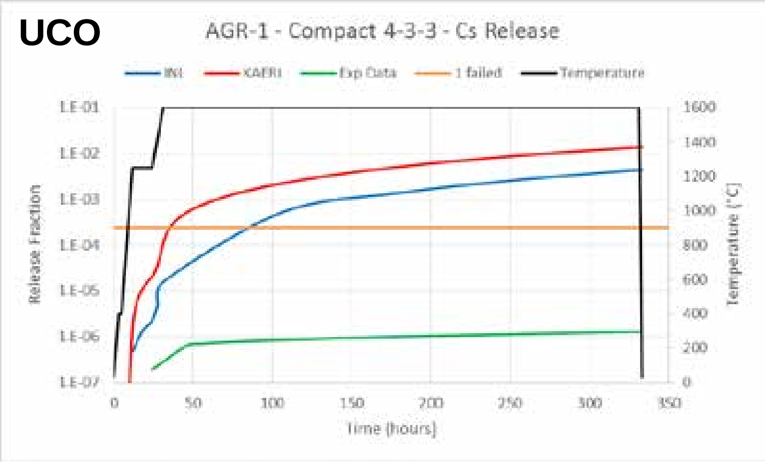


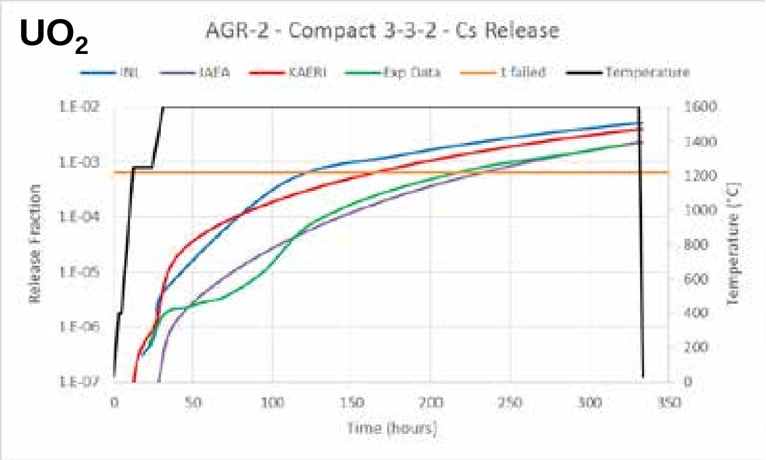


Stress histories at inner radii of the IPyC and SiC layers for an uncracked particle.

Fission Product Transport Modeling

- Fission product transport includes:
  - Release from failed particles
  - Release from uranium contamination in the compact
  - Diffusive release through intact coatings
- Requires FP diffusivities in:
  - Kernel
  - PyC
  - SiC
- Historic diffusivities come from UO_2 fuel fission product release observations
- Current models tend to overpredict fission product release by a significant margin





Results of computational modeling code benchmark of fission product release during high-temperature accident tests

(B. Collin et al., *Generation IV Benchmarking of TRISO Fuel Performance Models under Accident Conditions: Final Report*, *DRAFT*)

Summary

- TRISO fuel has a history spanning over 50 years
- High quality fuel can be fabricated to meet product specifications
- TRISO fuel has excellent performance during normal operation and accidents
- Fuel performance models predict behavior and tend to be conservative with respect to FP release

Suggested Reading

General TRISO Fuel

- 2010 HTGR Technology Course for the Nuclear Regulatory Commission
- P.A. Demkowicz et al., Coated particle fuel: Historical perspectives and current progress, J. Nucl. Mater. 515 (2019) 434-450
- M.J. Kania, H. Nabielek, H. Nickel, Coated Particle Fuels for High-Temperature Reactors, in Materials Science and Technology, Wiley 2015.
- D.A. Petti et al., TRISO-Coated Particle Fuel Performance, in Konings R.J.M.,(ed.) Comprehensive Nuclear Materials (2012), vol. 3, pp. 151-213 Amsterdam: Elsevier.
- High Temperature Gas Cooled Reactor Fuels and Materials, IAEA, TECDOC-1645 (2010).
- K. Verfondern, H. Nabielek, J.M. Kendall, Coated particle fuel for high temperature gas cooled reactors, Nucl. Eng. Tech. 39 (2007) 603-616.
- D.A. Petti et al., Key differences in the fabrication, irradiation and high temperature accident testing of US and German TRISO-coated particle fuel, and their implications on fuel performance, Nucl. Eng. Des. 222 (2003) 281-297.
- Fuel performance and fission product behavior in gas cooled reactors, IAEA, TECDOC-978 (1997).

AGR Program Results

- P.A. Demkowicz et al., “Key results from irradiation and post-irradiation examination of AGR-1 UCO TRISO fuel,” Nucl. Eng. and Des. 329 (2018) 102–109.
- P.A. Demkowicz et al., AGR-1 Post Irradiation Examination Final Report, INL/EXT-15-36407, Idaho National Laboratory, 2015.
- J.D. Hunn et al., “Post-Irradiation Examination and Safety Testing of US AGR-2 Irradiation Test Compacts,” Paper 10 in Proceedings of the 9th International Topical Meeting on High Temperature Reactor Technology (HTR-2018), Warsaw, Poland, October 8–10, 2018. Available at https://www.osti.gov/biblio/1489588
- J.D. Hunn et al., “Initial Examination of Fuel Compacts and TRISO Particles from the US AGR-2 Irradiation Test,” Nucl. Eng. and Des., 329 (2018) 89–101.

Suggested Reading (cont.)

HTR-PM Fuel

- C. Tang et al., Comparison of two irradiation testing results of HTR-10 fuel spheres, Nucl. Eng. Des. 251 (2012) 453-458.
- S. Knol et al., HTR-PM fuel pebble irradiation qualification in the high flux reactor in Petten, Nucl. Eng. Des. 329 (2018) 82-88.
- D. Freis et al., Burn-up Determination and Accident Testing of HTR-PM Fuel Elements Irradiated in the HFR Petten, Proceedings of the 9th International Topical Meeting on High Temperature Reactor Technology (HTR-2018), 8-10 Oct. 2018, Warsaw, Poland

Fuel Performance and Fission Product Transport Modeling

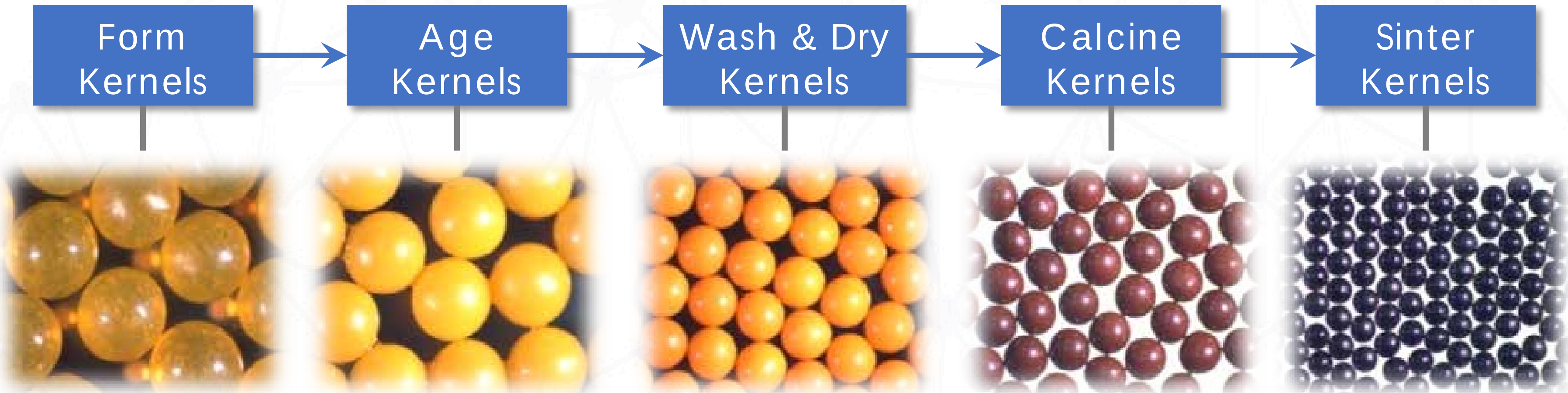
- J.J. Powers, B.D. Wirth, A review of TRISO fuel performance models, J. Nucl. Mater. 405 (2010) 74-82
- G.K. Miller et al., PARFUME Theory and Model Basis Report, INL/EXT-08-14497, September 2018
- W. F. Skerjanc, B. P. Collin, Assessment of Material Properties for TRISO Fuel Particles used in PARFUME, INL/EXT-18-44631, August 2018

INL

Idaho National Laboratory

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



Fuel Compact/Sphere Fabrication