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AGR Program TRISO Fuel Topical Report Dialog

February 2022

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Changing the World's Energy Future

Idaho National Laboratory

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AGR Program TRISO Fuel Topical Report Dialog

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February 10, 2022

GAIN
Gateway for Accelerated Innovation in Nuclear

Outline

- AGR Program Overview and Current Activities
- Fission Product Transport Data
- Short-Lived Fission Product Release
- Fuel Performance Margin Data
- Oxidation Testing Data

GAIN Gateway for Accelerated Innovation in Nuclear

Advanced Gas Reactor Fuel Development and Qualification Program

Objectives and Motivation

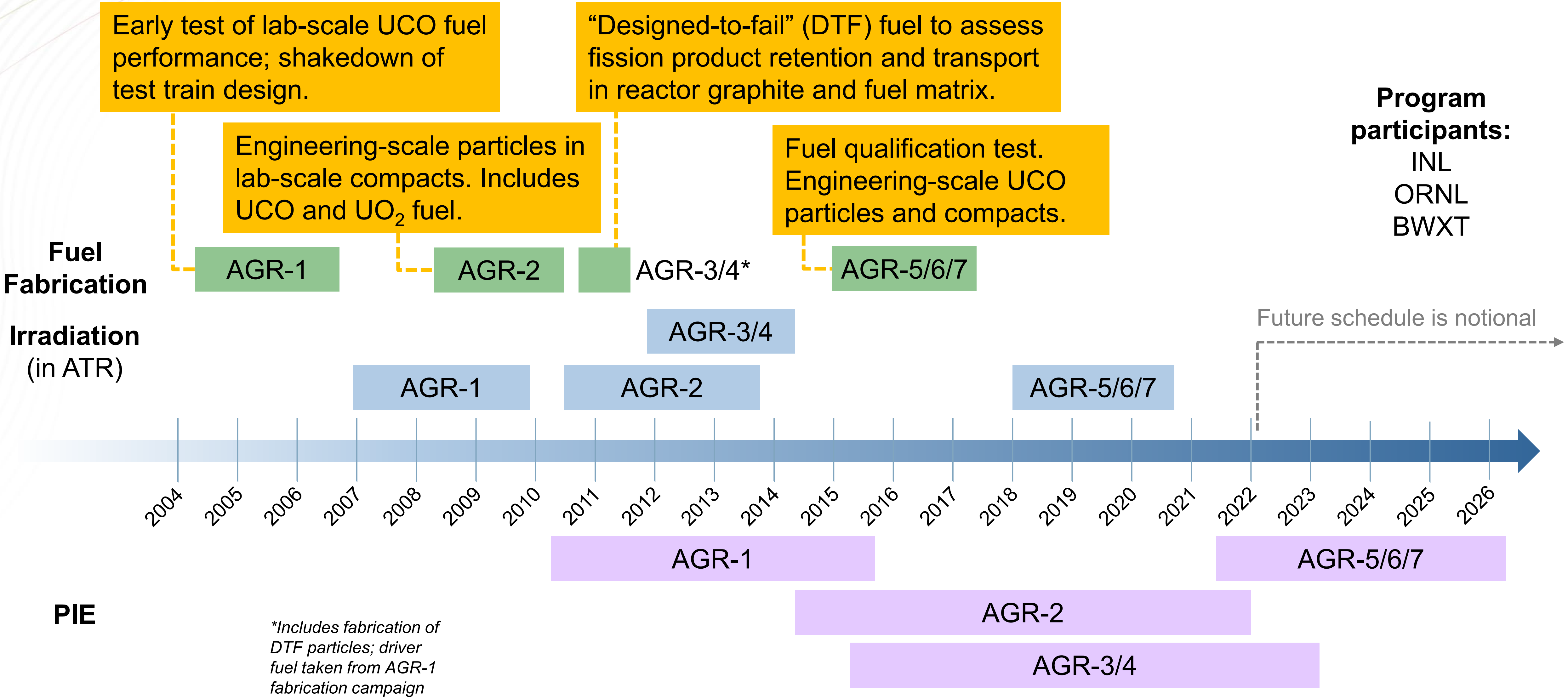
- Provide data for fuel qualification in support of reactor licensing
- Establish a domestic commercial TRISO fuel fabrication capability

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



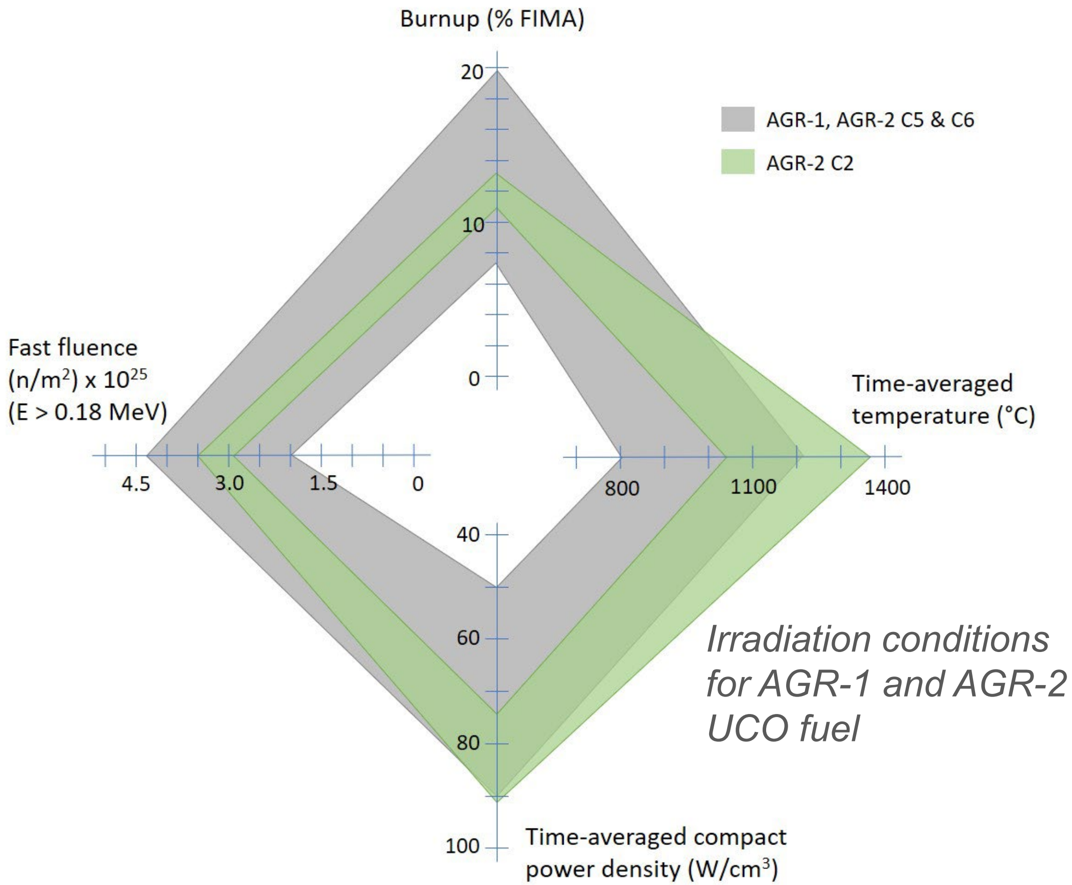
Program participants:
INL
ORNL
BWXT

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

AGR-1 and AGR-2 Experience

Exp	Kernel	^{235}U wt%	Kernel dia (µm)	Particle fab	Compact fab	# particles
AGR-1	UCO	19.7	349	Lab scale	Lab scale	298,000
AGR-2	UCO	14.0	427	Pilot scale	Lab scale	114,000
AGR-2	UO_2	9.6	508	Pilot scale	Lab scale	18,500

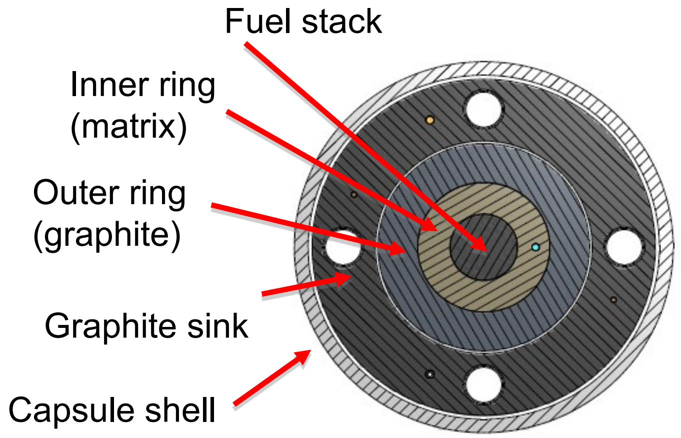
- Successful demonstration of UCO TRISO particle performance
- Large amount of fission product release data
- Highlighted key differences between UCO and UO_2
- Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO)-Coated Particle Fuel Performance—Topical Report EPRI-AR-1(NP)-A – Nov 2020
- AGR-2 Final PIE Report (INL/EXT-21-64279) – Sep 2021



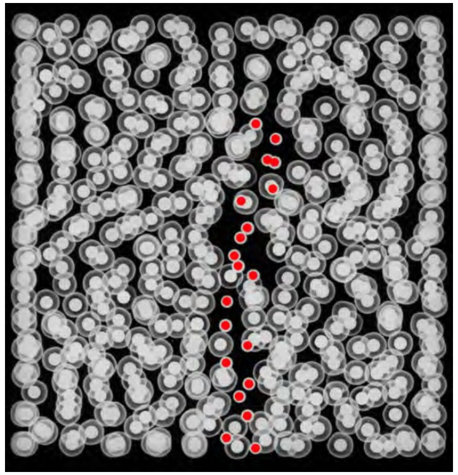
Irradiation conditions for AGR-1 and AGR-2 UCO fuel

AGR-3/4 Overview

- Focused on fission product transport in matrix and graphite (PCEA, IG-110)
- Irradiation in ATR Northeast Flux Trap for 369 EFPD from Dec 2011 to Apr 2014
- Burnup 4.9 – 15.3%
- Capsule time-average vol-average temperatures 845 – 1345°C
- Uses ~1% "designed-to-fail" (DTF) particles as fission product source
- Post-irradiation examination focused on understanding fission product transport during irradiation and during heating tests



AGR-3/4 Capsule Cross Section

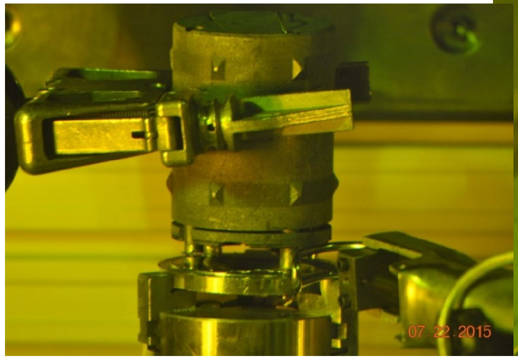


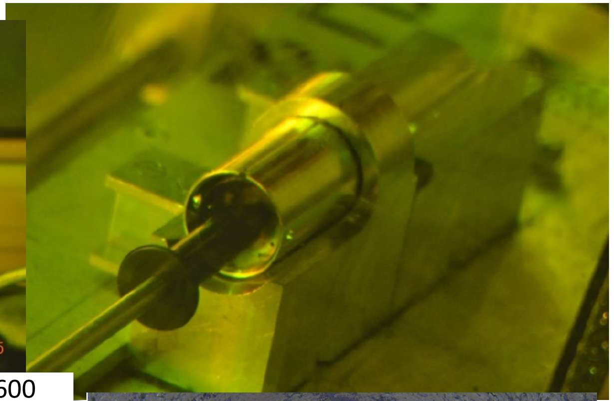
AGR-3/4 Compact X-radiograph; DTF particles highlighted red

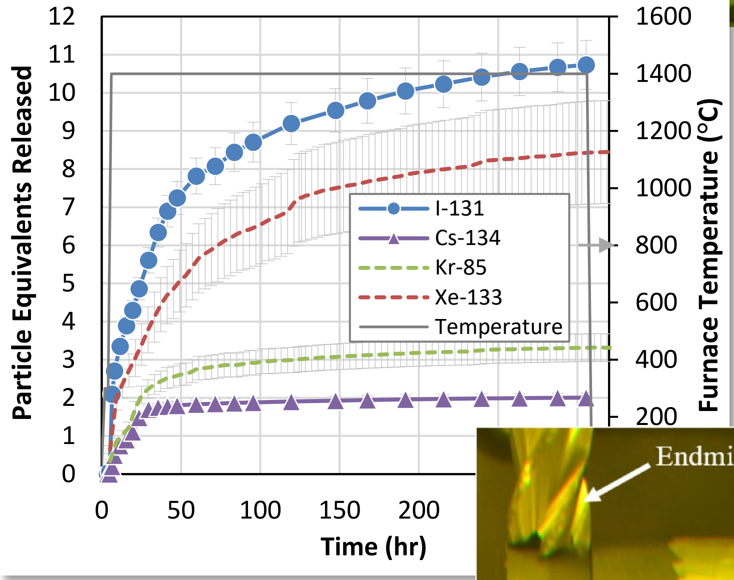
AGR-3/4 PIE Activities Summary

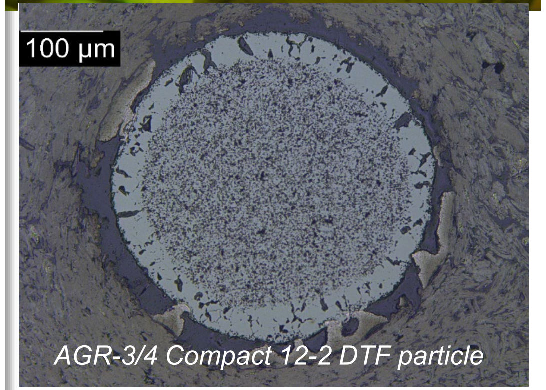
- Capsule disassembly and metrology (INL/EXT-16-38005)
- Capsule fission product mass balance (INL/EXT-18-46049)
- Compact cross-section microscopy (INL/EXT-20-57610)
- Compact post-irradiation heating tests
- Fission product distribution in graphite and matrix rings (INL/EXT-21-62863)
- Compact destructive exams to determine FP inventory
- Data analysis and comparison with models
- Oxidation testing of compacts and fuel bodies

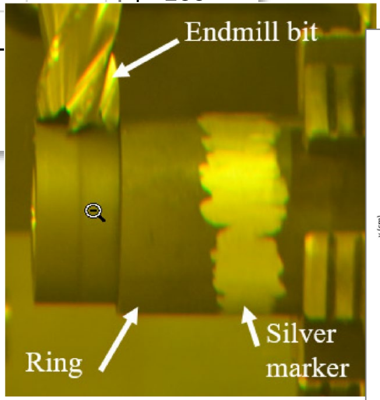
In progress

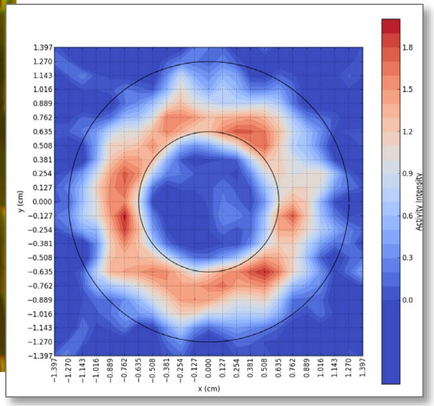








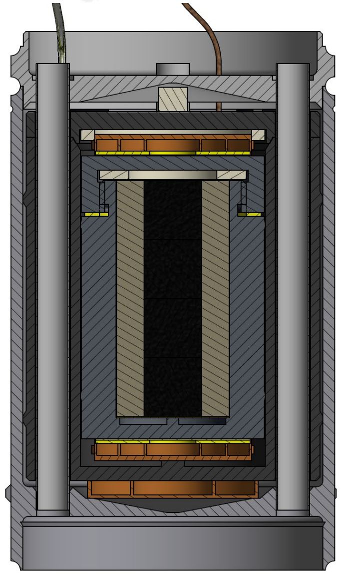




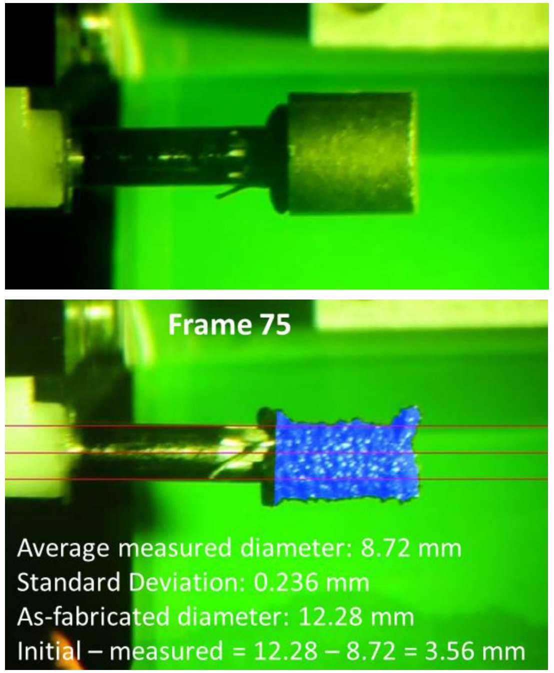
AGR-3/4 Current Work

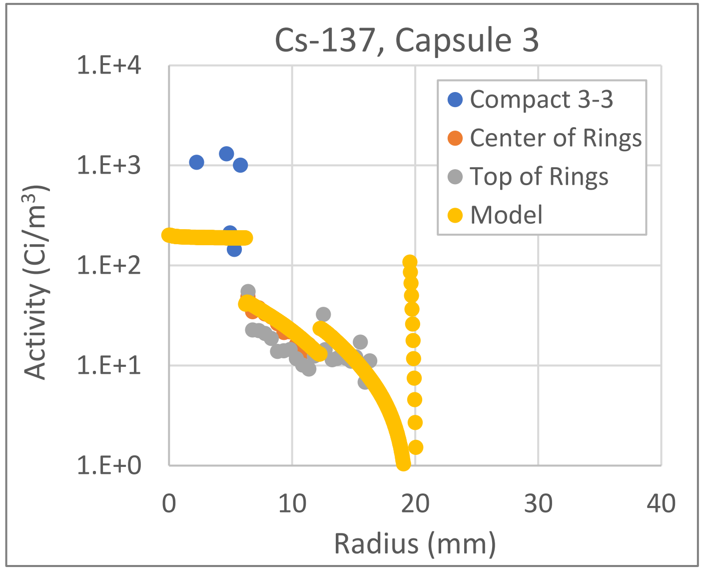
- Ring sampling – Capsule 4 fuel body
  - Supplement existing data from 6 other capsules
- Compact radial deconsolidation-leach-burn-leach (RDLBL)
  - Evaluate fission product inventory in the compact matrix without disturbing DTF particles
- Data analysis and model comparisons
  - Fit fission product behavior with 1D, 2D, or 3D models
  - Derive transport coefficients based on data comparison

AGR-3/4 Fuel Body cross section



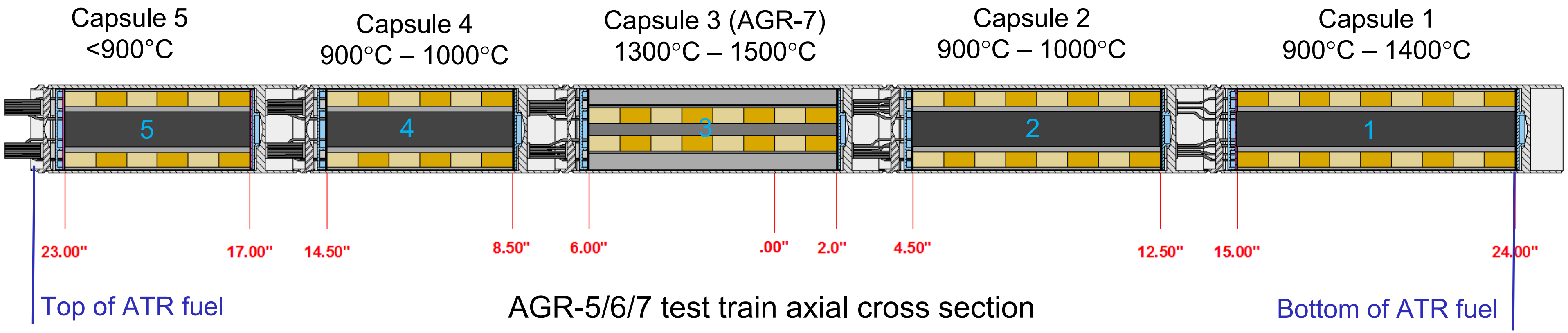
AGR-3/4 fuel compact radial deconsolidation





AGR-5/6/7 irradiation

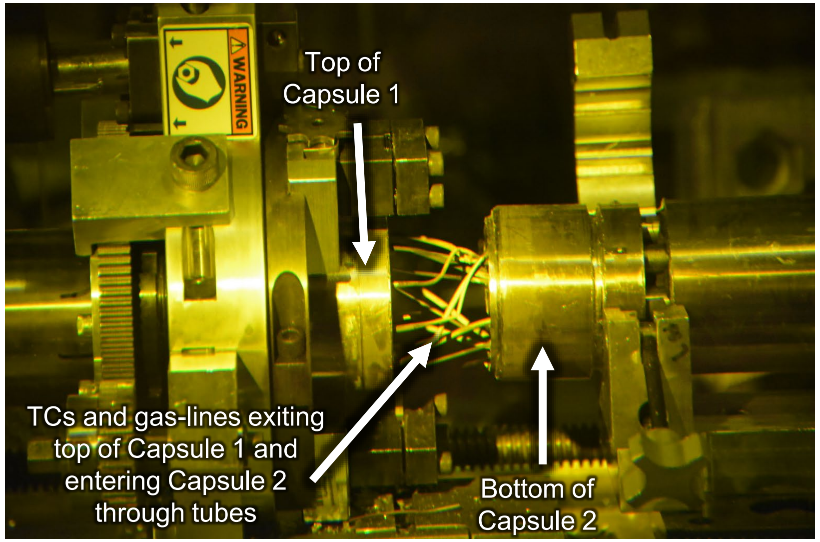
- Final fuel qualification irradiation and performance margin test
- 194 UCO fuel compacts (~570,000 particles)
- Burnup 5.7 – 15.3% FIMA; time-average temperatures 467 – 1432°C
- Significant particle failures in Capsule 1 at ~240 EFPD
  - Cause remains unknown; PIE needed to fully understand this behavior
  - **Capsule 1 PIE is considered highest priority activity**
- PIE began in Spring 2021



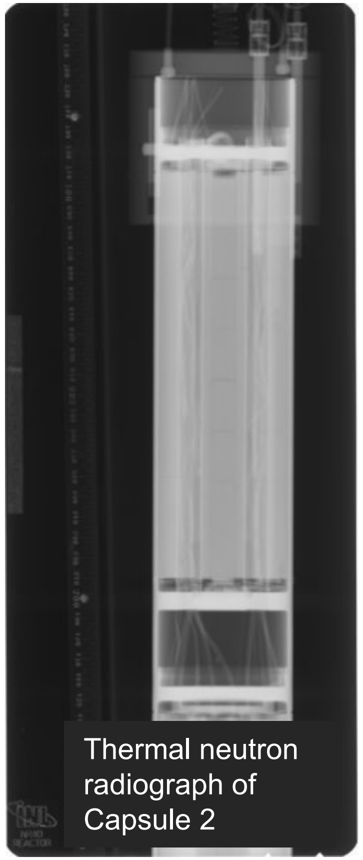
AGR-5/6/7 test train axial cross section

AGR-5/6/7 Completed and Current Activities

- NDE of test train completed
  - Gamma spectrometry
  - Neutron radiography
- Capsule disassembly
  - Capsule 1 and 2 complete
- Component metrology
  - Capsule 1 and 2 compacts complete
  - Capsule 1 and 2 graphite holders partially complete
- Starting separation of Capsules 3 – 5 and disassembly of Capsule 3



Separation of Capsules 1 and 2



AGR-5/6/7 Planned PIE and Safety Testing

- Complete disassembly and metrology for all capsules
- Perform fission product mass balance for all capsules (quantify fission products outside of fuel compacts)
- Gamma scanning:
  - Fuel compacts
  - Graphite fuel holders
- Fuel compact cross section analysis
- Extensive fuel compact destructive examination
  - Deconsolidation-leach-burn-leach (DLBL)
  - Particle gamma counting and sorting
  - Particle x-ray analysis
  - Particle microanalysis
- Fuel compact isothermal safety testing in He at 1600 – 1800°C
- Fuel compact heating tests in oxidizing gas mixtures at T ≤1600°C

Topical Reports – Some Observations

- EPRI TRISO topical report was a successful model for future regulatory interactions
- Original scope underwent significant modification based on industry feedback
- High-level AGR program scope is established in the Technical Program Plan; this is not a solicitation for major new program scope (note that AGR-5/6/7 outcomes could influence planned scope)
- *Technical reports* on all AGR program scope will be issued as work is completed
- Topical report preparation represents significant effort; need to determine where this effort is best focused
- The topics discussed today are suggestions based on planned scope; looking for input on the priority and utility of these

Outline

- AGR Program Overview and Current Activities
- Fission Product Transport Data
- Short-Lived Fission Product Release
- Fuel Performance Margin Data
- Oxidation Testing Data

Fission Product Transport – Background

- Empirical data on fission product transport in irradiated graphite and fuel matrix materials are limited
- Data for release from UCO kernels is also very limited
- Most diffusion data currently in use are summarized in IAEA TECDOC-978 (1997)
- Accurate fission product transport data are needed for radionuclide source term models that support reactor safety analyses

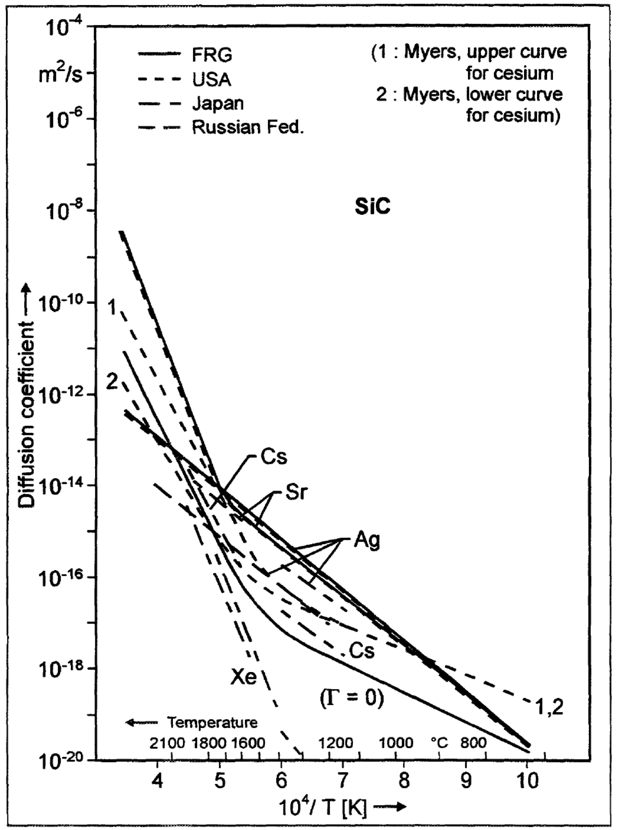


Fig. A-3: Diffusion coefficients of fission product species in silicon carbide as function of temperature

AGR Program Data – AGR-3/4

Data from irradiation and PIE includes:

- Fission gas release from exposed kernels during irradiation
- Total compact release during irradiation
- Ag, Cs, Eu, Sr profiles in matrix and graphite and inventory in compact matrix
- Fission product release from AGR-3/4 compacts during post-irradiation heating

Computational analysis:

- Results of fitting FP profiles to 1D and 2D transport models
- Refined diffusion data

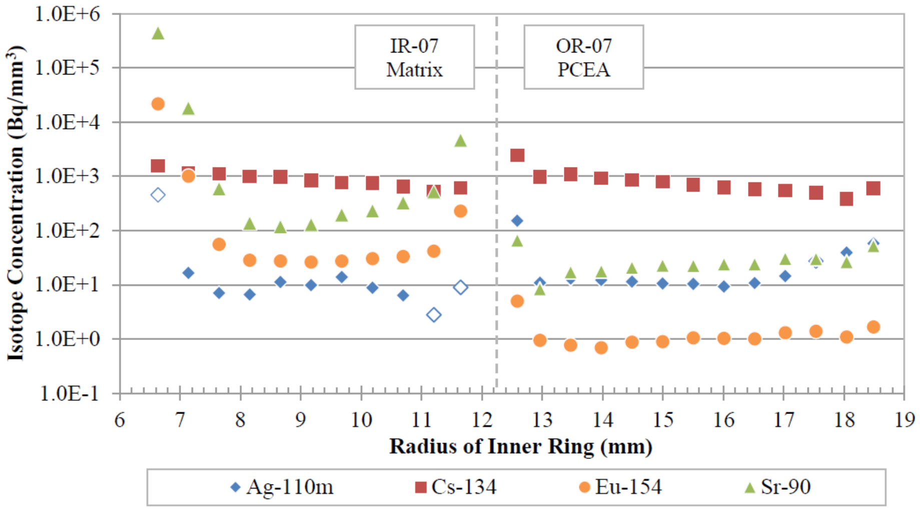
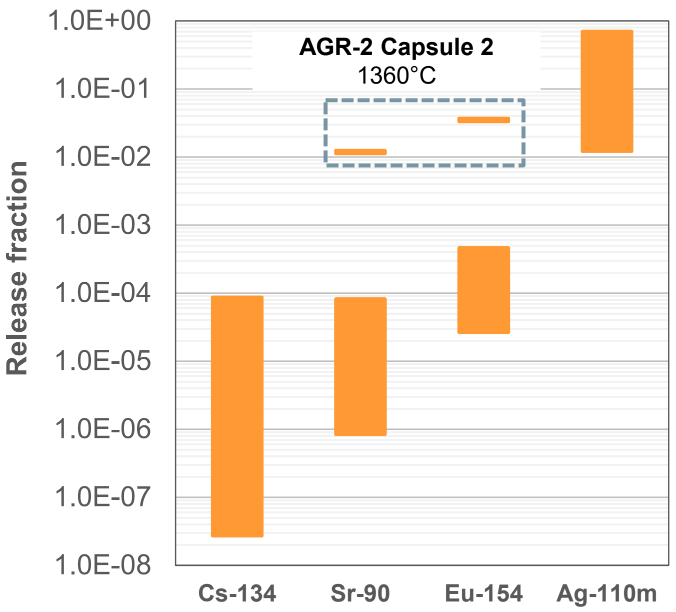


Figure 27. Radial profiles for select fission products at the axial center of the Capsule 7 IR and OR. The open symbols denote values derived from MDAs.

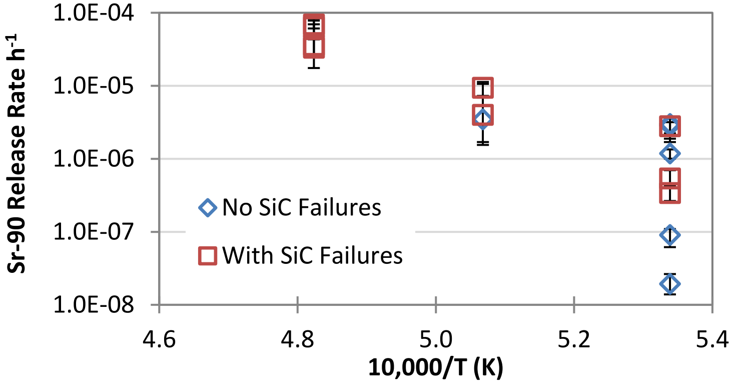
AGR-1 and AGR-2

- Total release from fuel compacts during irradiation and post-irradiation safety tests
- Matrix fission product inventory following irradiation and safety tests
- Individual particle fission product inventory following irradiation and safety tests
- Comparison of Ag, Cs, Sr release to existing models was performed to assess accuracy of diffusion coefficients

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



AGR-1 ^{90}Sr release rate during safety tests



Content and Timeline

- Need to complete AGR-3/4 PIE and analyses
- Need to integrate all fission product release data and analyses and draw conclusions about transport behavior

Notional Schedule

- AGR-3/4 PIE and analyses are expected to be completed in FY23
- Report preparation could begin in FY23 – FY24 timeframe

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Short-lived fission product release - Background

- ^{131}I ($t_{1/2}$ = 8.02 d) is a risk-dominant isotope in historical HTGR accident source term evaluations
- ^{131}I inventory is decayed by the time PIE commences following MTR irradiations; there is a need to regenerate inventory prior to heating tests to evaluate ^{131}I release behavior
- Previous work by W. Schenk in the German UO_2 TRISO program (1980s) involved reirradiation of specimens in the FRJ1 reactor prior to heating in KüFA
  - Loose UO_2 kernels, defective TRISO particles, and intact TRISO particles
- KüFA testing on “fresh” AVR spheres to compare ^{133}Xe and ^{85}Kr release

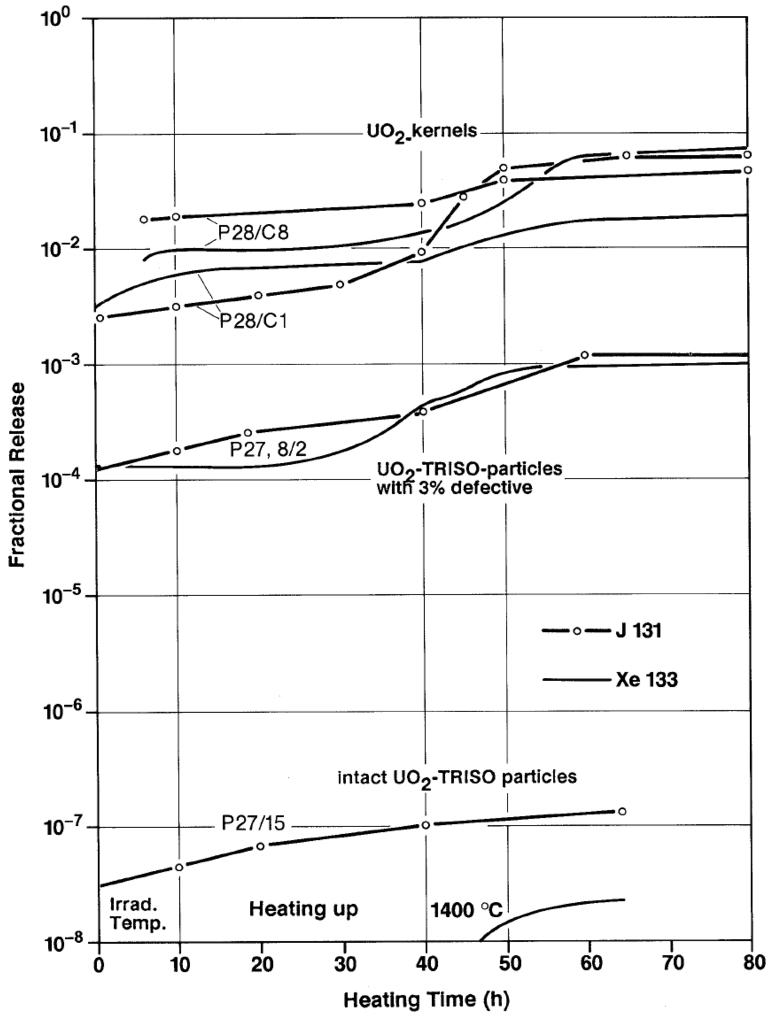
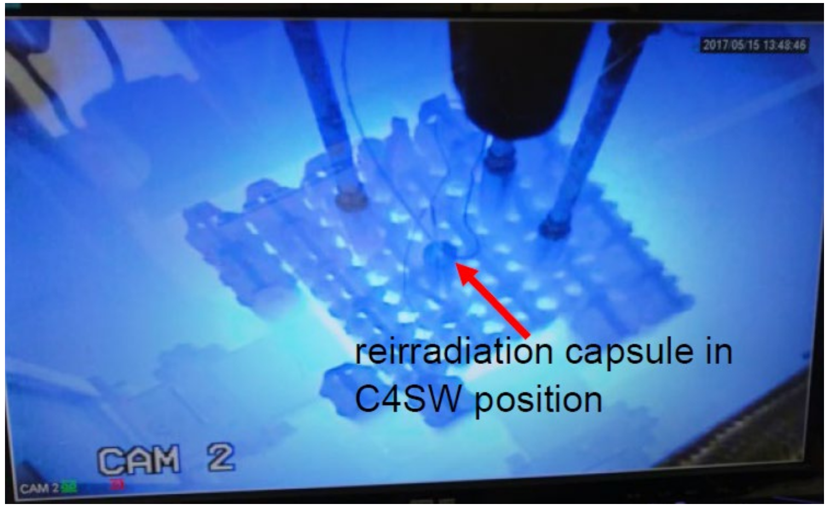


Fig. 39: I 131 and Xe 133 release during heating tests up to 1400 °C from UO_2 kernels and UO_2 TRISO particles

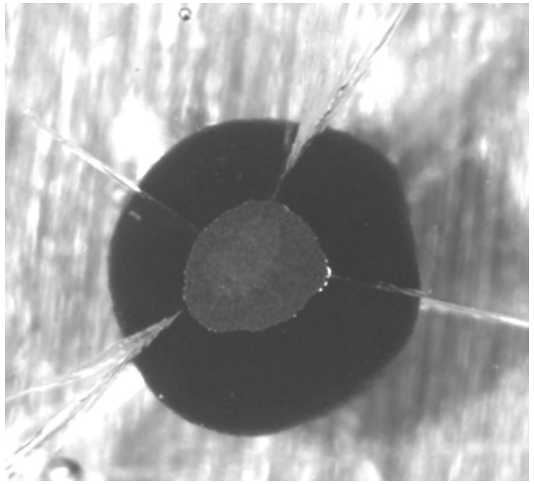
- *Schenk et al., Fission Product Release Profiles from Spherical HTR Fuel Elements at Accident Temperatures, Jül-2234, 1988*
- *H. Hantke, “Performance of High Quality HTR LEU Fuel Elements with TRISO Coated Particles,” Forschungszentrum Jülich Internal Report HTA-IB-7/92, 1992*

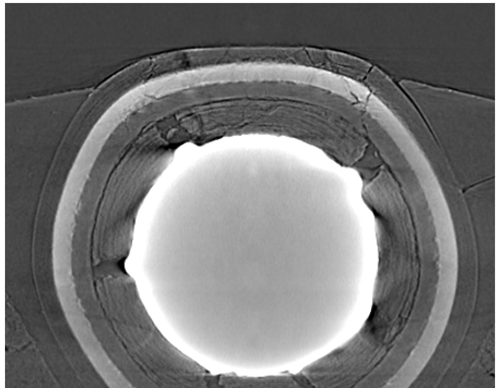
AGR Program Activities

- ^{131}I release measurement is being pursued at INL by irradiation of previously irradiated specimens in the NRAD reactor (HFEF) and subsequent heating tests in pure He
- ^{133}Xe ($t_{1/2}$ = 5.2 d) is also generated, and its release can be compared to ^{131}I and long-lived ^{85}Kr
- AGR-2 program has performed reirradiation+heating tests on:
  - Bare kernels (coatings removed)
  - AGR-2 loose particles with introduced coating failure
  - AGR-3/4 compacts
- Additional tests may be performed using selected AGR-5/6/7 compacts with failed TRISO particles



AGR specimen inserted into the Neutron Radiograhy (NRAD) TRIGA reactor





AGR-2 particle with introduced coating cracks

Test Matrix and Selected Results

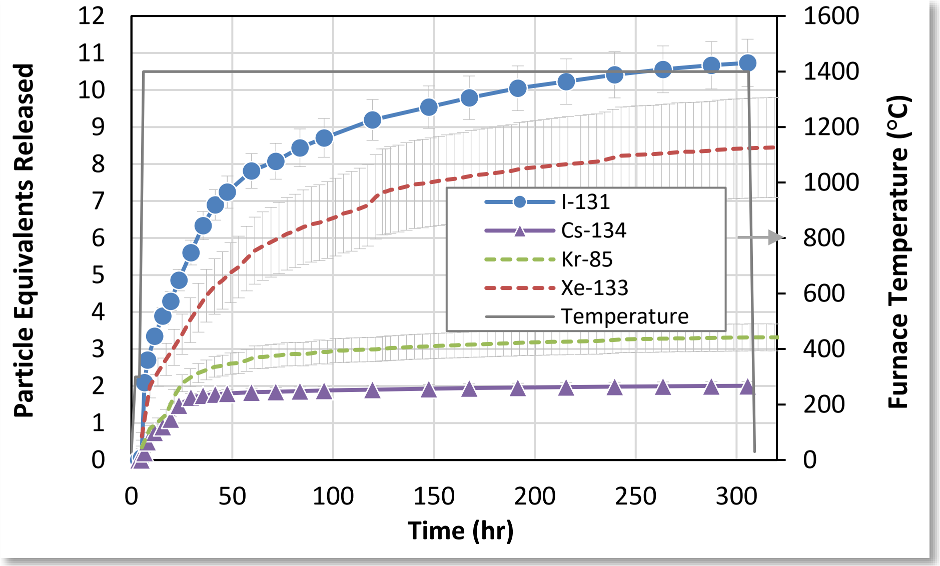
AGR-3/4 compact heating tests

AGR-3/4 Compact	Burnup (% FIMA)	TAVA Irradiation Temp (°C)	Heating Test Temp (°C)
3-1	12.2	1138	1600
8-1	14.5	1165	1200
10-1	12.1	1172	1400
4-3	14.3	1035	1000
1-2	5.9	941	1400

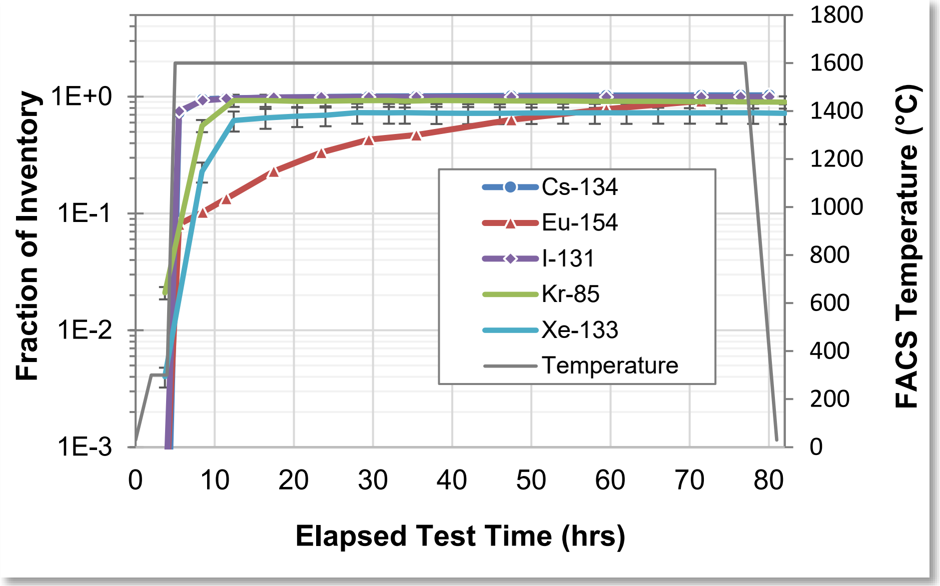
AGR-2 particle/kernel heating tests

AGR-2 Compact	Burnup (% FIMA)	TAVA Irradiation Temperature (°C)	Test #	FACS Temperature (°C)	Sample Type	Status
6-4-1	9.24	1018	1	1600	Bare kernels	Complete
5-4-2	12.03	1071	2	1600	Cracked particles	Complete
			3	1400	Cracked particles	Complete
			4	1200	Cracked particles	Complete
2-2-1	12.47	1287	5	1000	Cracked particles	Complete
			6	1200	Cracked particles	Planned FY22
			7	1400	Cracked particles	Planned FY22

Compact AGR34-10-1, 1400°C



Compact AGR2-542 cracked particles, 1600°C



Content and Timeline

- ^{131}I and ^{133}Xe release data from kernels, cracked particles, DTF particles/compacts, and failed particles
- Comparisons with long-lived fission product releases
- Combine with AGR-2 and AGR-3/4 fission product transport data in single topical report

Notional Schedule

- AGR-2 and AGR-3/4 heating tests will be completed in FY23; report preparation starting in ~FY24
- Inclusion of AGR-5/6/7 tests would extent the completion for several years; report preparation starting in ~FY25 – FY26?

Outline

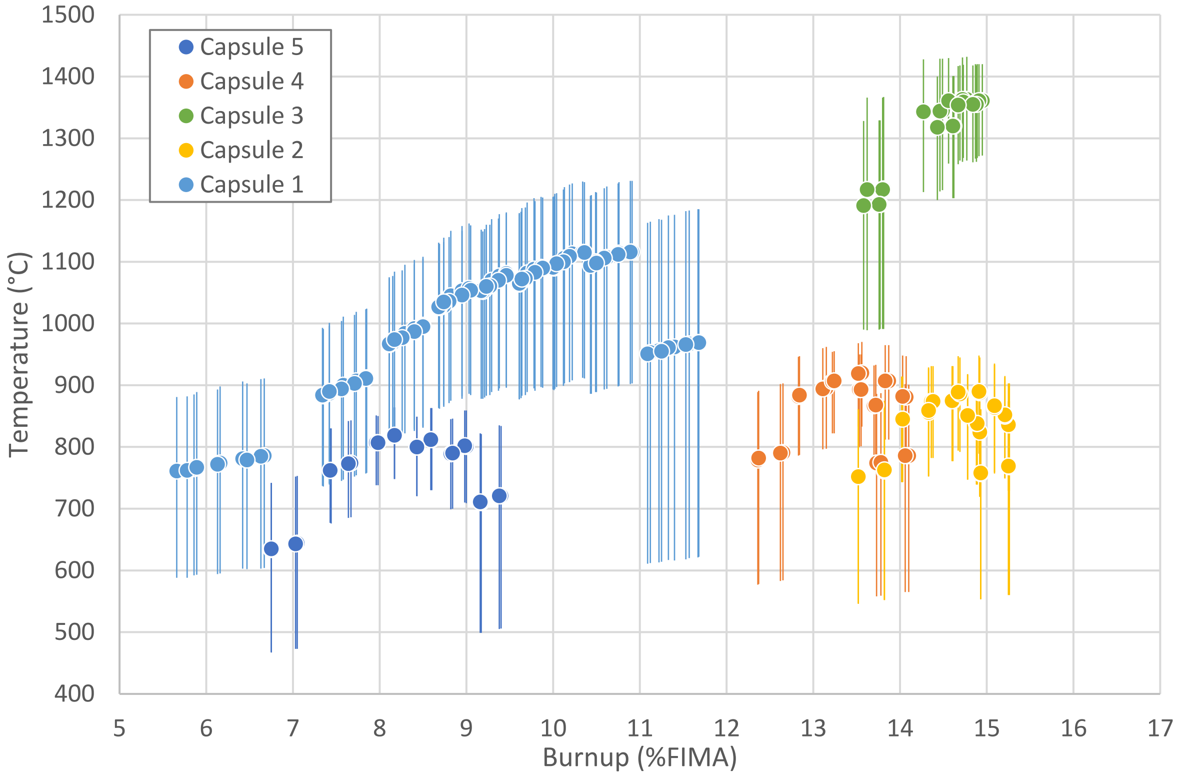
- AGR Program Overview and Current Activities
- Fission Product Transport Data
- Short-Lived Fission Product Release
- Fuel Performance Margin Data
- Oxidation Testing Data

Fuel Performance Margin (or “Expanded Performance Envelope”) – Background

- AGR-1 and AGR-2 particle performance was demonstrated over a wide range of conditions and results are summarized in EPRI topical report and elsewhere
- AGR-5/6/7 further expanded the performance envelope in terms of temperature and fast neutron fluence
- Both *higher* and *lower* temperatures may challenge the particles and the results are therefore important for various reactor designs

Fuel Performance Envelope in AGR-5/6/7

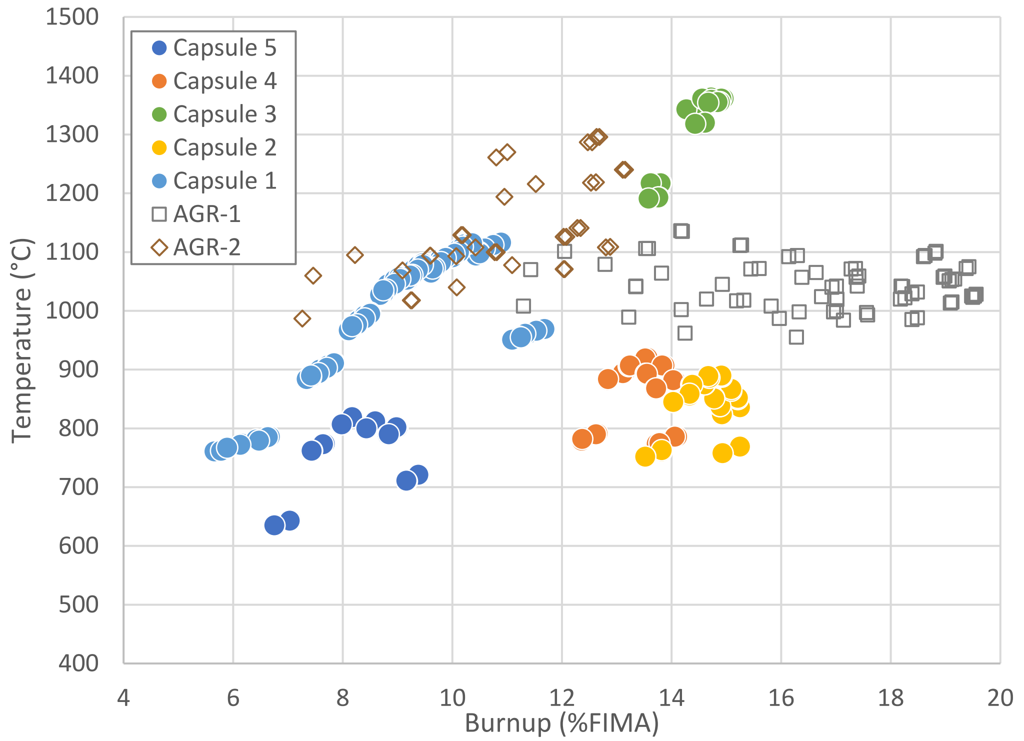
- AGR-5/6/7 Final Irradiation As-Run Report (INL/EXT-21-64221)
- Notes on in-pile fuel performance:
  - **Capsule 1**: Many particle failures, with cause unknown; fission gas release from this capsule impacted R/B measurements in other capsules
  - **Capsules 4 and 5** experienced zero particle failures
  - **Capsule 2**: Up to four estimated failures
  - **Capsule 3**: Up to 15 estimated failures
- Will rely on PIE to help understand behavior and reduce uncertainty on fuel failure numbers

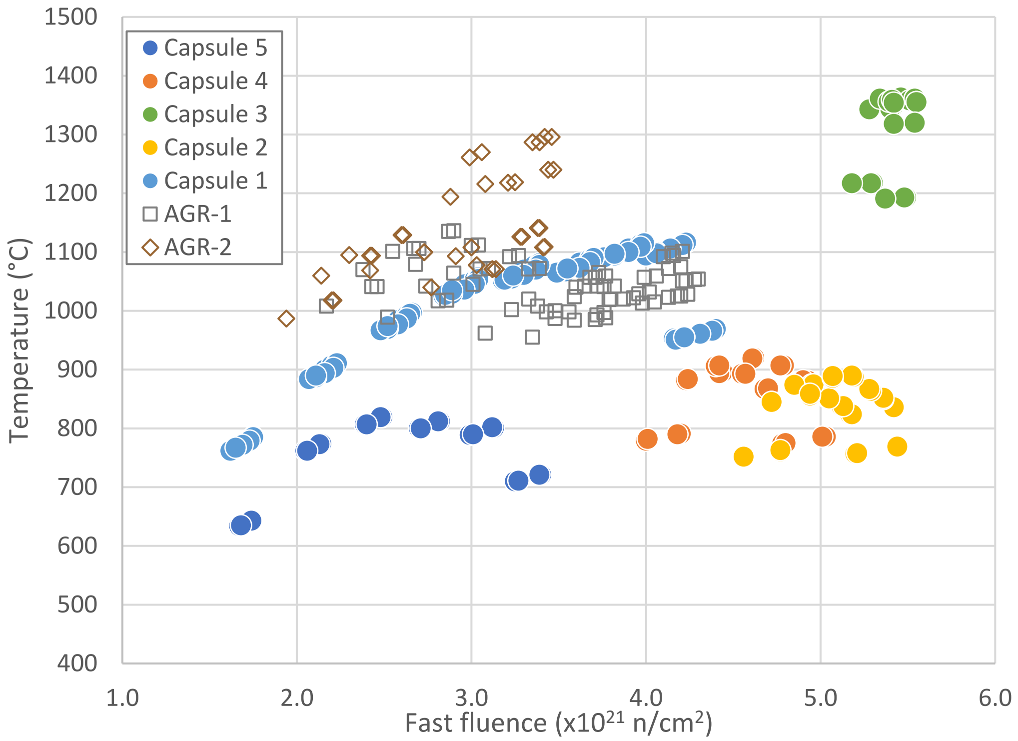


- *Data points are time-average, volume-average (TAVA) temperatures*
- *Lines represent time-average minimum and maximum values for each compact*

AGR-5/6/7 Compared to AGR-1 and AGR-2 UCO

- AGR-5/6/7 had significantly broader temperature and fast fluence range compared to AGR-1 and AGR-2





Data points are time-average, volume-average (TAVA) temperatures

Content and Timeline

- Expect significant volume of data on fuel performance beyond the envelope demonstrated with AGR-1 and AGR-2
  - Expand upper temperature margin and/or elucidate conditions that begin to degrade particle performance
  - Expand lower temperature performance range
  - Additional data on performance at fluences 30% higher than AGR-1/2
- Relevance for topical report may depend heavily on the data and causes of Capsule 1 fuel behavior

Notional Schedule

- Assuming the need to include the majority of AGR-5/6/7 fuel compact PIE and safety testing results, report preparation would commence in the 2026 timeframe

Outline

- AGR Program Overview and Current Activities
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- Fuel Performance Margin Data
- Oxidation Testing Data

Oxidation Testing of TRISO Fuel - Background

- Depressurized conduction cooldown accidents in HTGRs historically have resulted in the highest predicted peak fuel temperatures and led to extensive fuel testing in inert helium at temperatures ≥1600°C
- Accidents involving ingress of air or moisture into the core are also considered in safety analyses and comparatively little data has been collected on fuel behavior under these conditions
- Past experiments:
  - In-pile tests of kernel hydrolysis and fission gas release (HFR-B1, HRB-17/18)
  - German KORA furnace tests (air and water effects)
  - JAERI tests (air oxidation of fuel compacts and fuel compacts in graphite)
- Reference: IAEA TECDOC-978 (1997) “Fuel performance and fission product behavior in gas cooled reactors,” Chapter 5: *Fuel performance and fission product behavior under oxidizing conditions*

German KORA tests in air

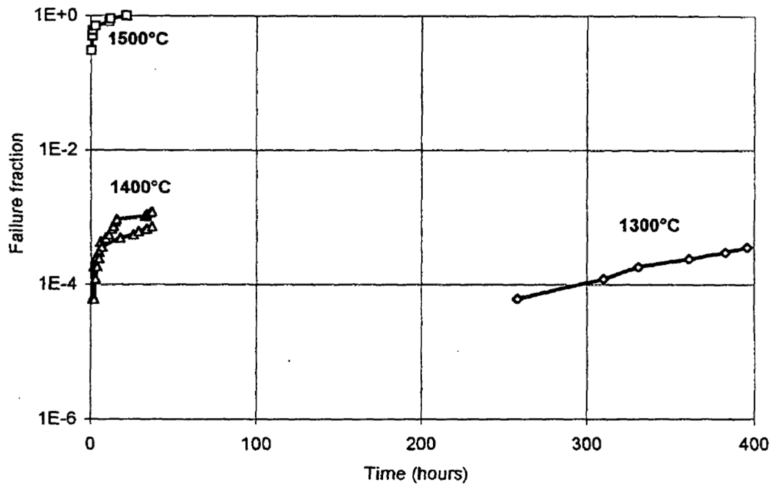
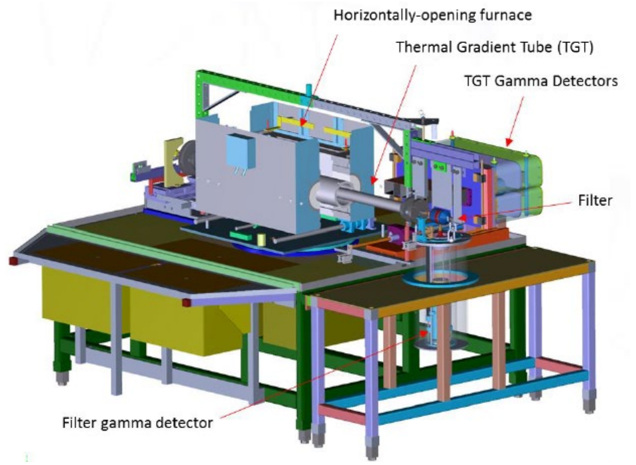


Fig. 5-21: Failure fraction of fuel particles within fuel spheres during heating in air at 1300 °C and of 10 intact, unbonded particles at 1500 °C

AGR Program Oxidation Testing Plans

- Current work and plans:
  - Scoping studies – Oxidation of loose irradiated particles (ORNL FITT [Furnace for Irradiated TRISO Testing]) ***In progress***
  - Extensive testing of irradiated fuel compacts and other specimens in air or steam gas mixtures – INL AMIX (Air/Moisture Ingress Experiment) ***Planned***
- AMIX furnace
  - Test in atmospheres containing air or H_2O
  - Temperatures to 1600°C
  - Continuous monitoring of condensable and gaseous fission product release



- Test objectives:
  - Determine impact of oxidation on TRISO particle integrity
  - Determine impact of oxidation on fission product release from exposed kernels
  - Determine impact of oxidation on fission product release from graphite and fuel matrix
- Specimens:
  - AGR-3/4 fuel compacts –Exposed kernels (DTF particles)
  - AGR-3/4 fuel bodies – Fuel compacts in graphite
  - AGR-5/6/7 fuel compacts

Content and Timeline

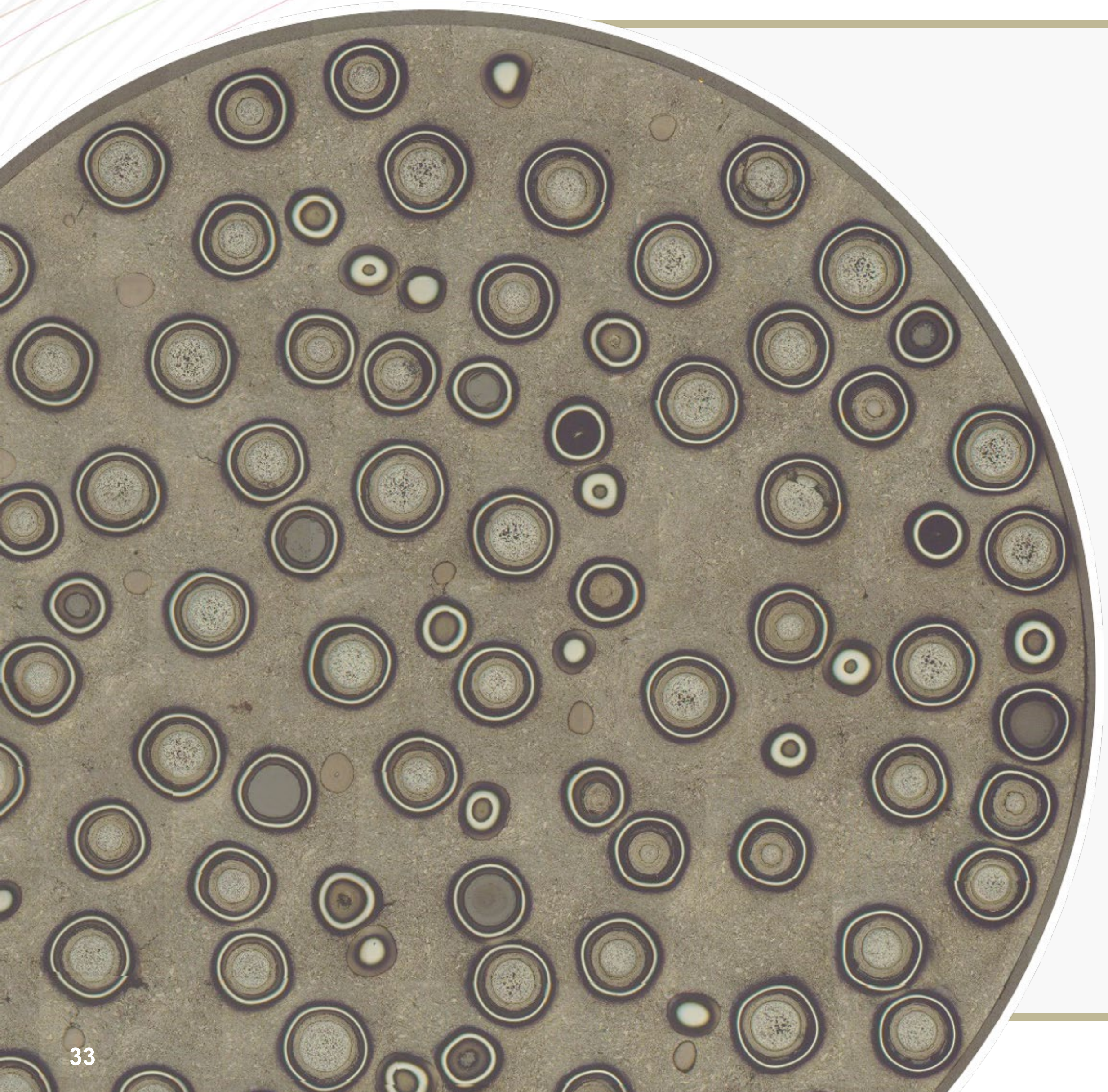
- Results will include:
  - Effect of PO_2/PH_2O and temperature on:
    - TRISO failure
    - Kernel hydrolysis and FP release
    - FP volatilization and release from graphite/matrix
  - Impact of graphite reservoir on particle behavior in oxidizing environments
  - FP plateout behavior as a function of temperature (thermal gradient collection tube)
  - Post-irradiation analysis of oxidized specimen to understand kernel/coating behavior

Notional schedule

- Oxidation testing is scheduled for FY22 – FY26
- Report preparation likely in the FY26 – FY27 timeframe

Discussion and Feedback

- Utility of these topics for licensing interactions?
- Applicability for Topical Reports?
- Schedule implications?



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