HTR (TRISO) Fuel Safety Research Activities and Needs

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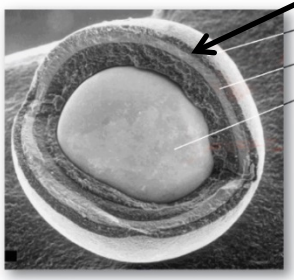
TRISO fuel morphology

UO_2 or UCO 'kernels' coated with pyrolytic carbon and SiC, embedded in a graphitic matrix

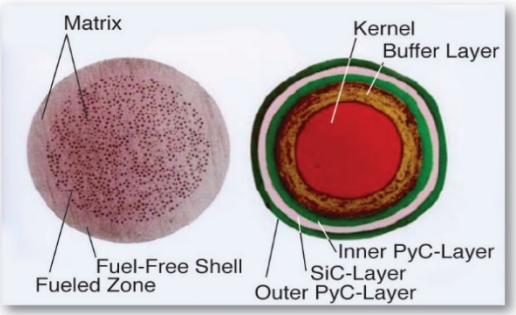
SiC is the pressure boundary



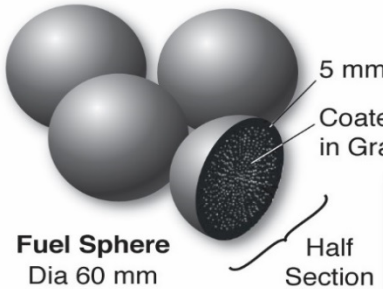
Prismatic

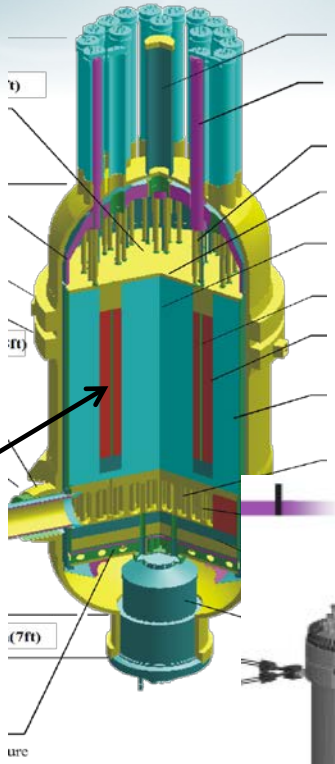
TRISO-coated fuel particles (left) are formed into fuel compacts (center) and inserted into graphoite fuel elements (right) for the prismatic reactor

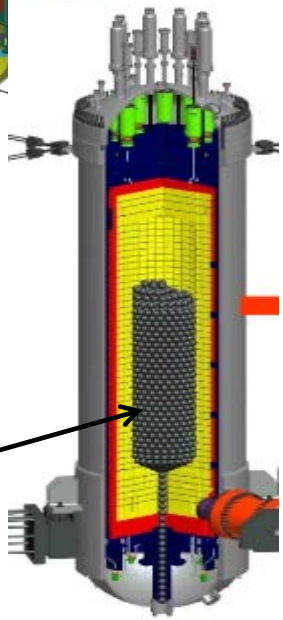
Pebble



TRISO-coated fuel particles are formed into fuel spheres for pebble bed reactor







Prismatic or Pebble Bed Core

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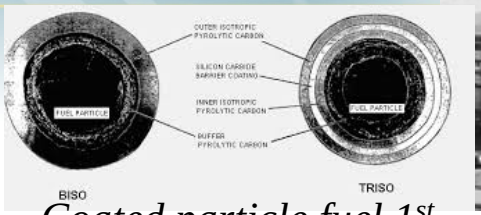
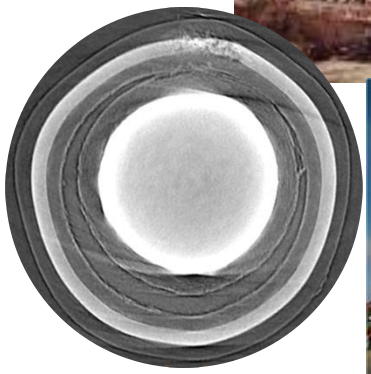
HTGR ⟷ TRISO fuel



Coated particle fuel 1st
1st proposed in 1957

DRAGON (UK 1964-1975)
experimental HTGR

- *The development of the HTGR is inter-linked with the development of coated particle fuel…*
- *Historically*
  - *BISO→1st gen TRISO → 2nd gen TRISO (UCO) → ?*
  - *AVR, Peach Bottom → THTR, FSV →*
  - *→ modular HTR → VHTR → ?*
- *Physically*
  - *Graphite matrix conducts away fission heat and moderates the spectrum, reducing the fluence and thermal stresses*
  - *Temperatures in tiny kernels stay well below solidus and SiC decomposition temperatures*
  - *Graphite provides a thermal buffer that slows transients (wide reactivity pulses)*
  - *TRISO coatings retain fission products – withstanding stresses under all steady state and transient conditions and to very high burnups*



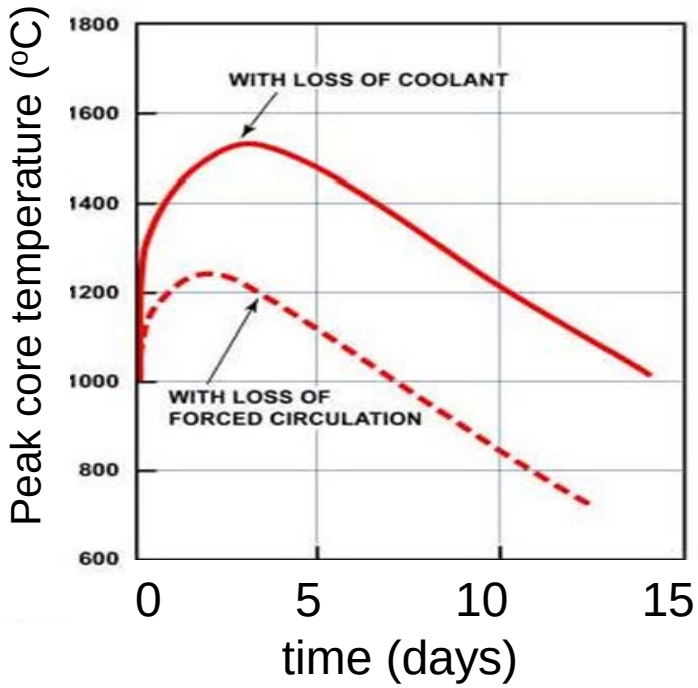
HTGR fuel safety/testing considerations

Fuel/Core attributes

- Low power density and high heat capacity of the core
- Phenomena are not highly coupled in either space or time as they are in other reactor systems
- Long time constants for heat removal upset events accidents

Consequences

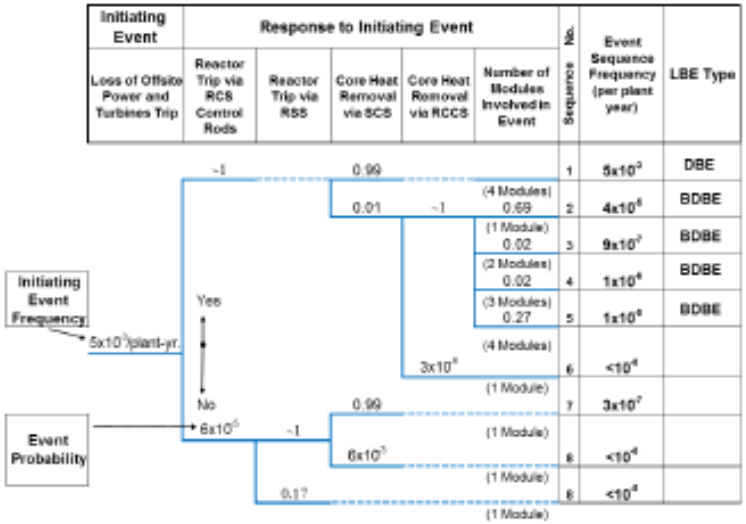
- Can use furnaces to simulate heatup accidents; even for those associated with moisture or air ingress
- No need for in-pile safety testing
- Need to re-activate irradiated fuel to obtain data on shorter-lived fission products (e.g., I-131)



Core melt is eliminated in the HTGR but attempts to use TRISO particles in other fuel forms have met with limited success. TRISO coatings are vulnerable to the fast reactivity transients and fast fluence to which LWR and fast reactor fuels are subjected

What to test?

- Conceptual design of modular HTGRs (both prismatic and pebble bed) have been completed
- PRA for prismatic MHTGR has also been completed
- Thus, vendors have defined risk dominant sequences, the associated service conditions expected during the event and the concomitant source term
- This leads to accepted levels of failure and fission product release that can be used to compare to testing results, and
- Allows for a very focused qualification program because requirements have been established by the vendors working backwards to ensure that accident failure rates meet (or are better than) design requirements and fission product release limits are not exceeded



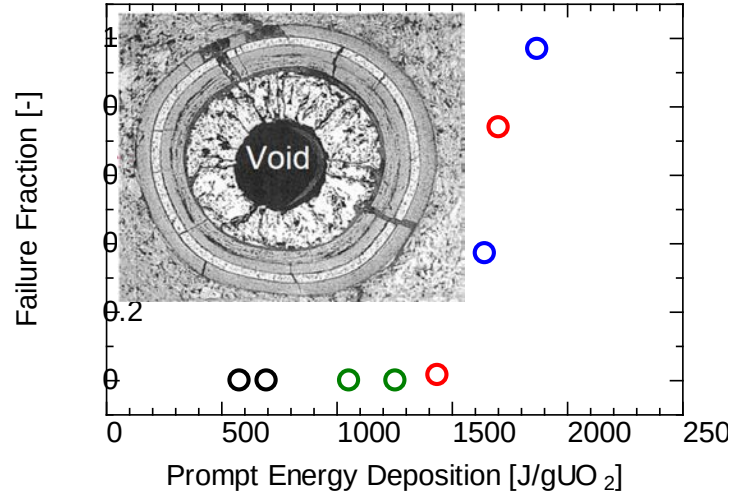
Event Tree for MHTGR Loss of Offsite power and turbine trip

Reactivity testing

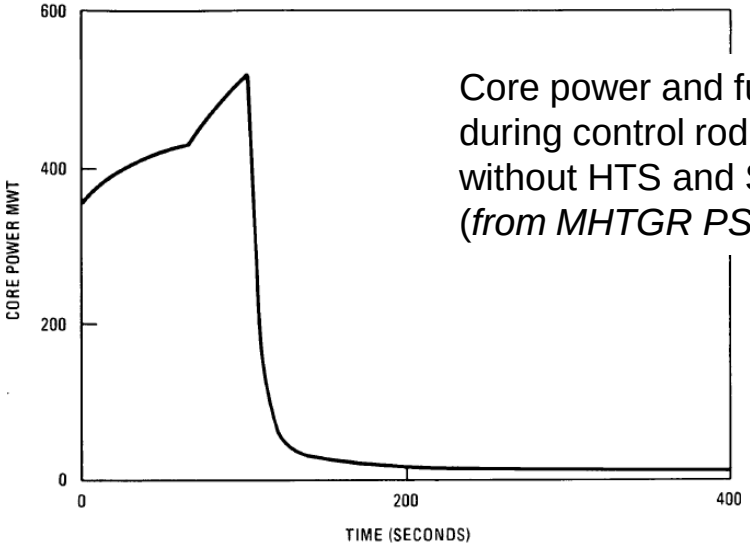
- Numerous reactivity tests have been performed in Japan and Russia and are well documented in IAEA TECDOCs and other relevant publications.
  - *These tests tend to have periods that are much shorter than typical of an HTGR (more typical of an LWR given the nature of the burst reactors used in the testing).*
  - *They also can inject enough reactivity to induce particle failure, over timescales typical of LWRs.*
- Severe reactivity events are precluded by the design in the HTGR.
  - *The thick bioshield above the reactor vessel and the design of the control rods (not actually rods but links) are such that rapid ejection is not possible.*
  - *Large, negative temperature coefficient and single phase coolant*
  - *General Atomics calculations show that in the worst reactivity transients in HTGRs, the fuel temperatures and stresses stay well below failure values*

Reactivity insertion considerations

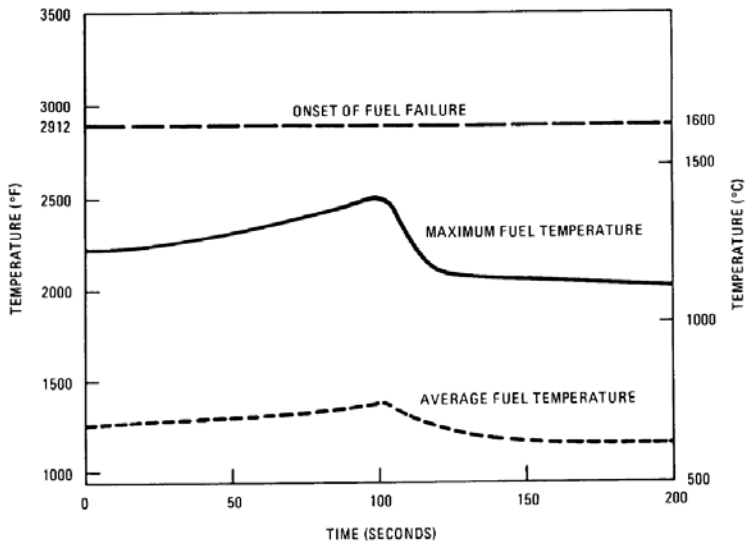
- Pulse testing of TRISO fuel in Japan has indicated particle failure thresholds



- HTGR reactor analysis indicates that the most rapid reactivity insertion DBEs take place on much longer time scales

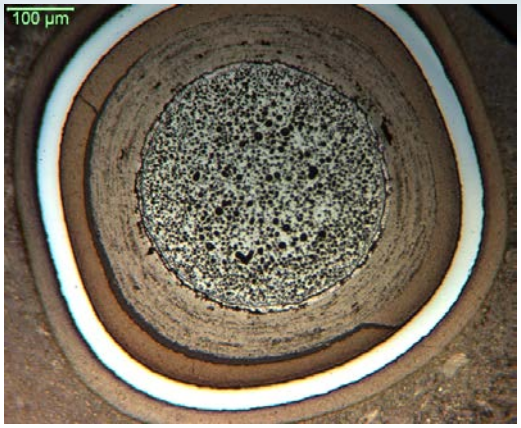


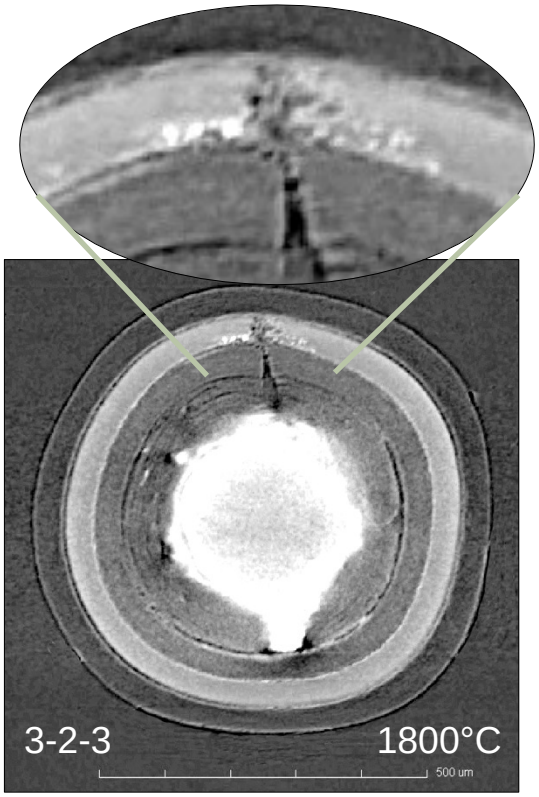
Core power and fuel temperatures during control rod withdrawal without HTS and SCS cooling (*from MHTGR PSID, HTGR-86-024*)



Fuel safety design criteria

- Are being developed for the HTGR (LWR criteria are not applicable)
- We understand TRISO fuel failure modes. We have design limits on failure fractions and fission product releases (much lower than LWRs given the robustness of TRISO fuel) under both normal operation and accident conditions.
- Instead of a SAFDL (specified acceptable fuel design limit) we will implement a SARRDL (specified acceptable radionuclide release design limit) for the modular HTGR because the SARRDL is directly related to the overall fuel performance in the reactor core and is directly related to potential offsite dose during and following postulated accidents

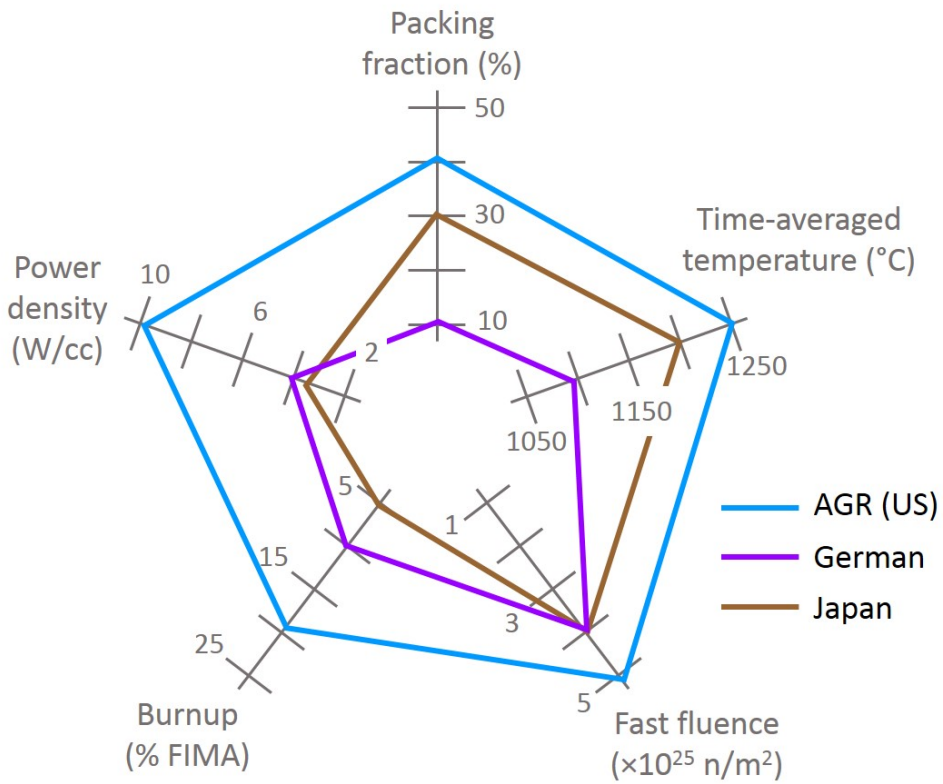




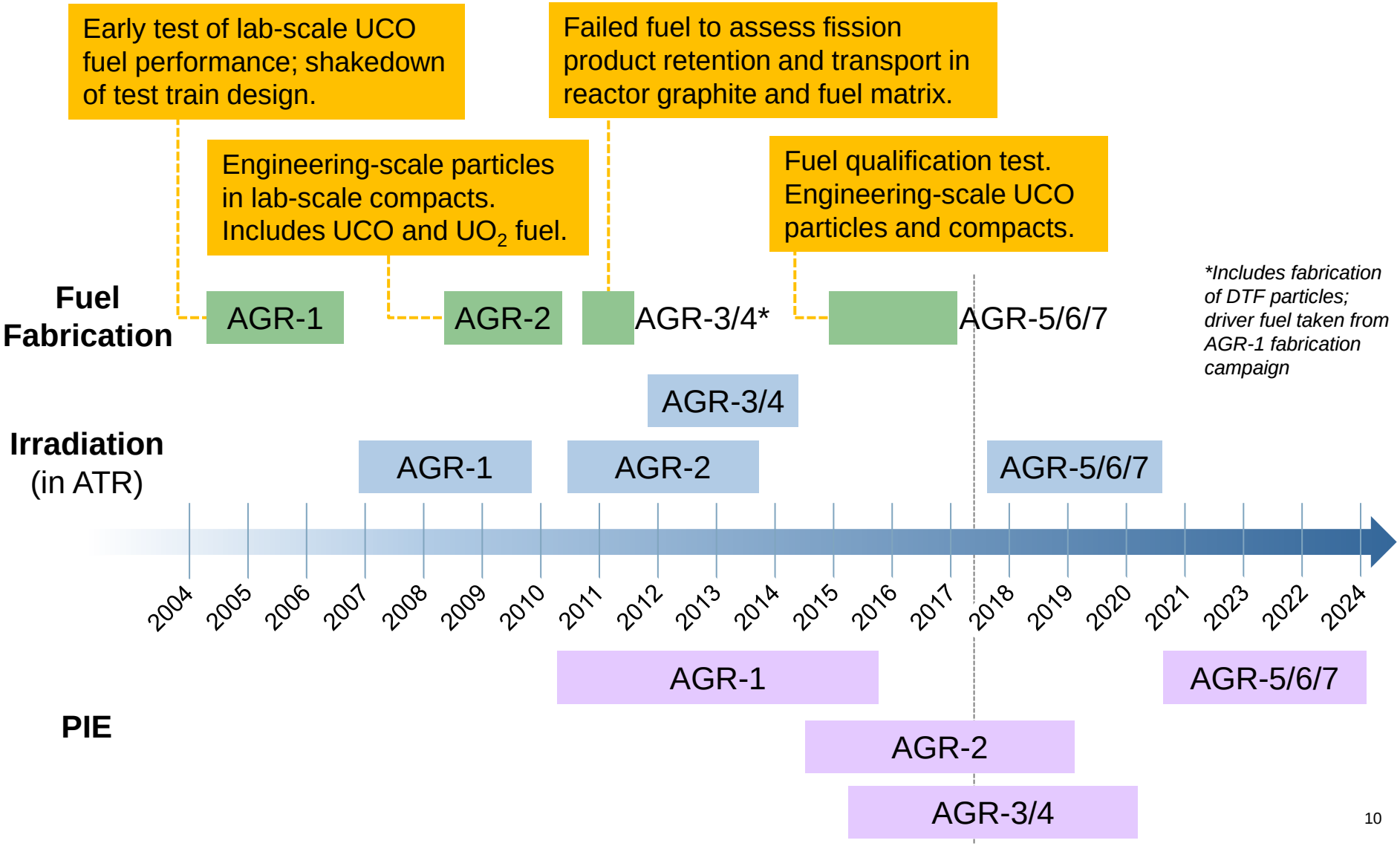
Gaps

- The AGR program was specifically designed to respond to gaps in our understanding of TRISO fuel using a top down approach
  - Vendor with greatest fuel experience, GA, produced Fuel and Fission Product Design Data Needs (DDNs) during the NGNP Project (2005-2010)
  - We designed the AGR Fuel Qualification program to meet those needs
- This approach allowed for a focused and limited technology development program

Targeted performance envelope



AGR Program Timeline



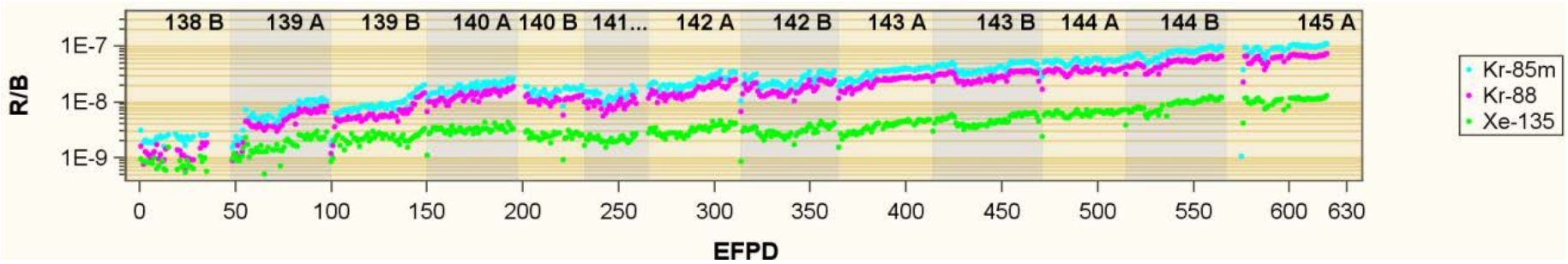
How the AGR Program addresses the gaps

- Establish capability to produce high quality UCO TRISO and prove performance under VHTR normal operation and accident conditions: **AGR-1 irradiation and safety testing**
- Prove performance of UCO TRISO fabricated at engineering scale under normal operation and accident conditions: **AGR-2 irradiation and safety testing**
- Develop data to fill gaps in existing database on fission product release and transport in fuel, matrix and graphite fuel element during normal operation and accident conditions: **AGR-3/4 irradiation and post-irradiation heating tests**
- Formal qualification of TRISO fuel produced at engineering scale to meet in-service failure requirements for VHTR design: **AGR-5/6 irradiation and safety testing**
- Understand margins in this fuel form: **AGR-7 irradiation and safety testing**
- Characterize behavior of fuel and release of fission products under moisture and air ingress scenarios: **AGR-5/6/7 oxidizing furnace heating tests**
- Verification and validation of fuel and fission product transport codes used by the designer: **AGR-8 (dropped from the AGR program when NGNP ended)**

In-pile fission gas release and TRISO failure

- Each capsule is monitored during irradiation to determine release of fission gases; significant release is an indication of TRISO failure
- Very low release-to-birth (R/B) ratios during the AGR-1 irradiation ($<10^{-7}$ for majority of test; peak value of 2×10^{-7})
  - Indicates no particles with failed TRISO layers (i.e., all three outer layers) out of 300,000 particles
  - Indicates very limited release through intact coatings

AGR-1 Capsule 6 R/B ratios

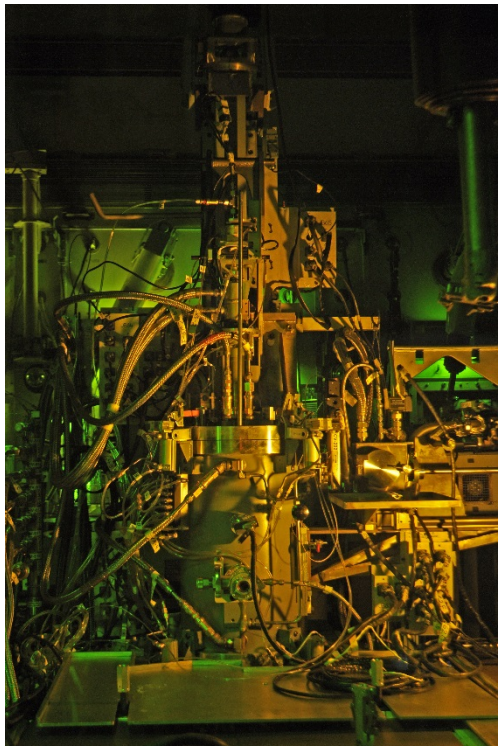


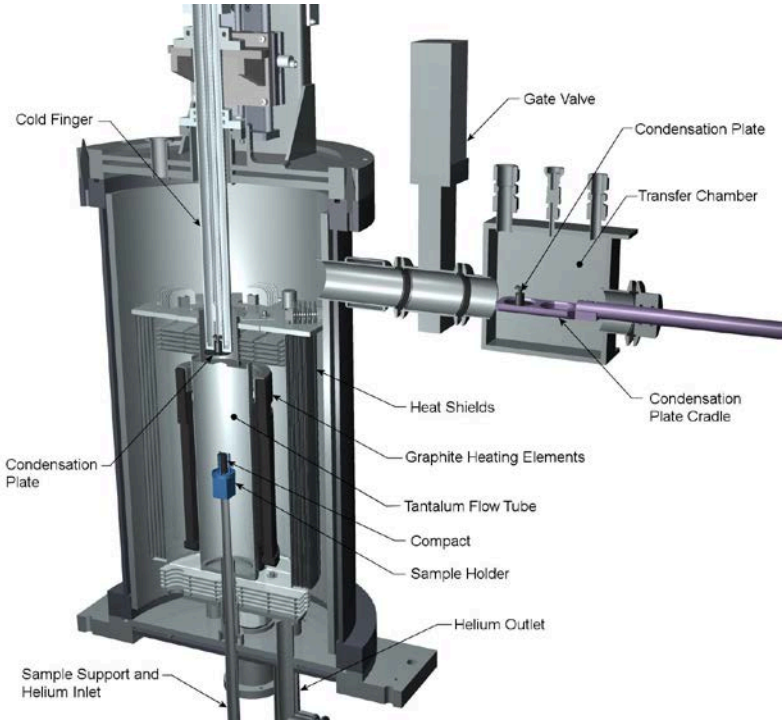
TRISO fuel post-irradiation safety testing

- Evaluate fuel performance under depressurized conduction cooldown reactor accident conditions
  - Measure fission product release from fuel elements (i.e., fuel compacts)
  - Examine fuel following tests to assess impact to particle microstructures
- Heat fuel specimens in flowing helium to **1600-1800°C** for ~300 h
- Measure real-time release of fission gases (**Kr, Xe**) using cryo-traps and gamma detectors
- Capture condensable fission products (**Ag, Cs, I, Sr, Eu**) released from the fuel on removable condensation surfaces and analyze released inventory
- Furnaces developed at INL and ORNL for TRISO fuel safety testing (both systems modeled after the German KüFA system)

INL Fuel Accident Condition Simulator (FACS)

- System installed in the HFEF Main Cell at Window 6M
- Tantalum hot zone
- Graphite heating element designed for max 2000°C operation
- Fission gas monitoring system to collect and measure fission gases (Kr, Xe)

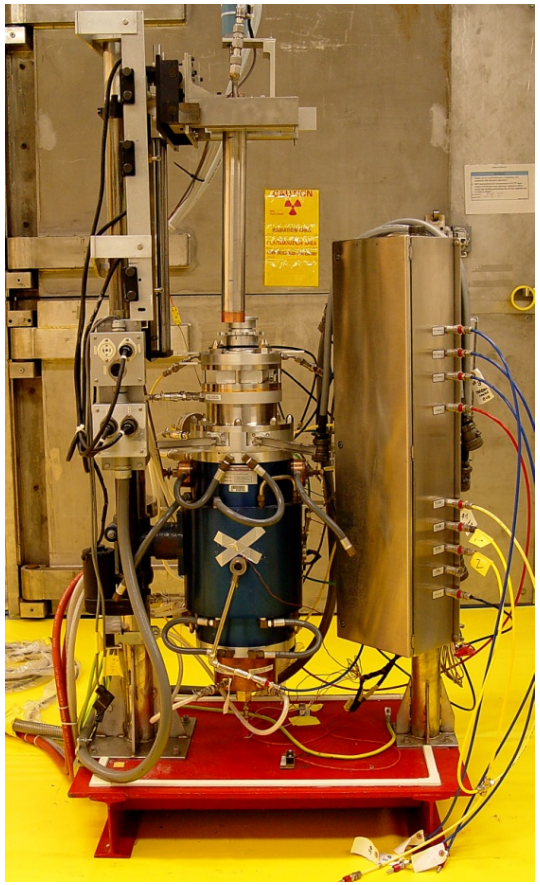


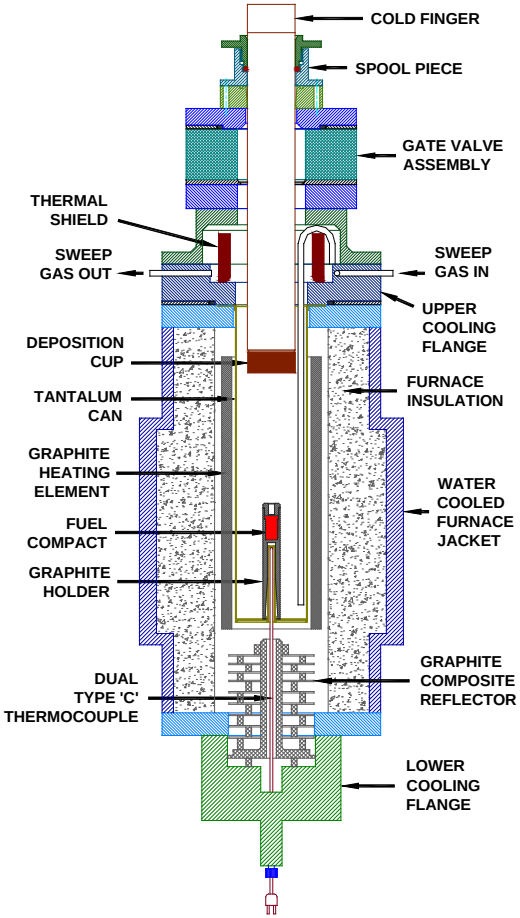


- Water-cooled cold finger with detachable condensation plates to collect solid fission products (e.g., Ag, Cs, Eu, Sr)
- System used for AGR-1 safety testing campaign; AGR-2 and AGR-3/4 safety tests in progress

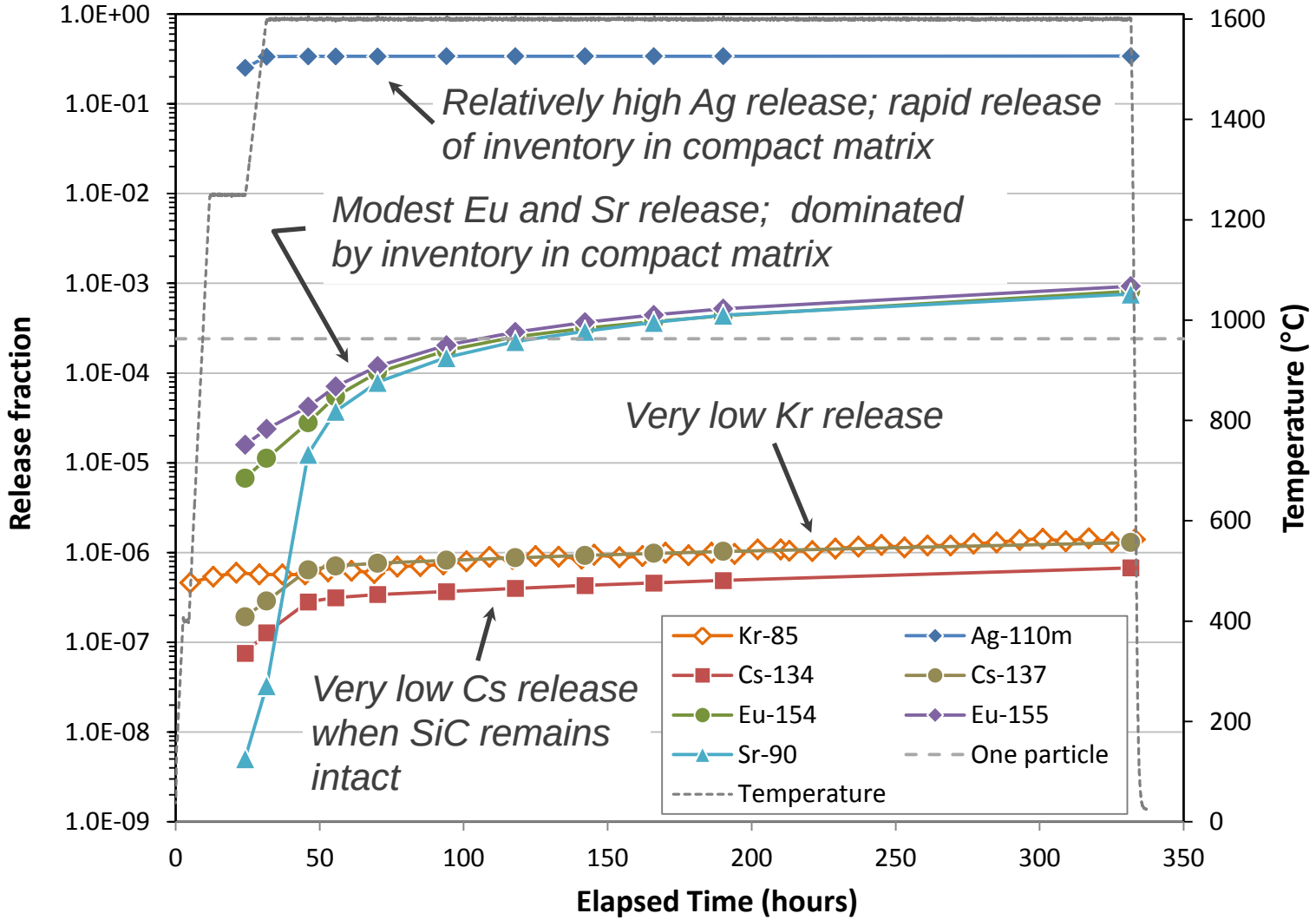
ORNL Core Conduction Cooldown Test Facility

- Built previously for TRISO particle heating tests and refurbished for the AGR program
- Graphite resistance furnace for heating fuel compacts in flowing He
- Liquid nitrogen-cooled carbon traps for detecting Kr-85 release
- Water-cooled deposition cup for collecting condensable fission products
- Airlock for periodic exchange of deposition cups



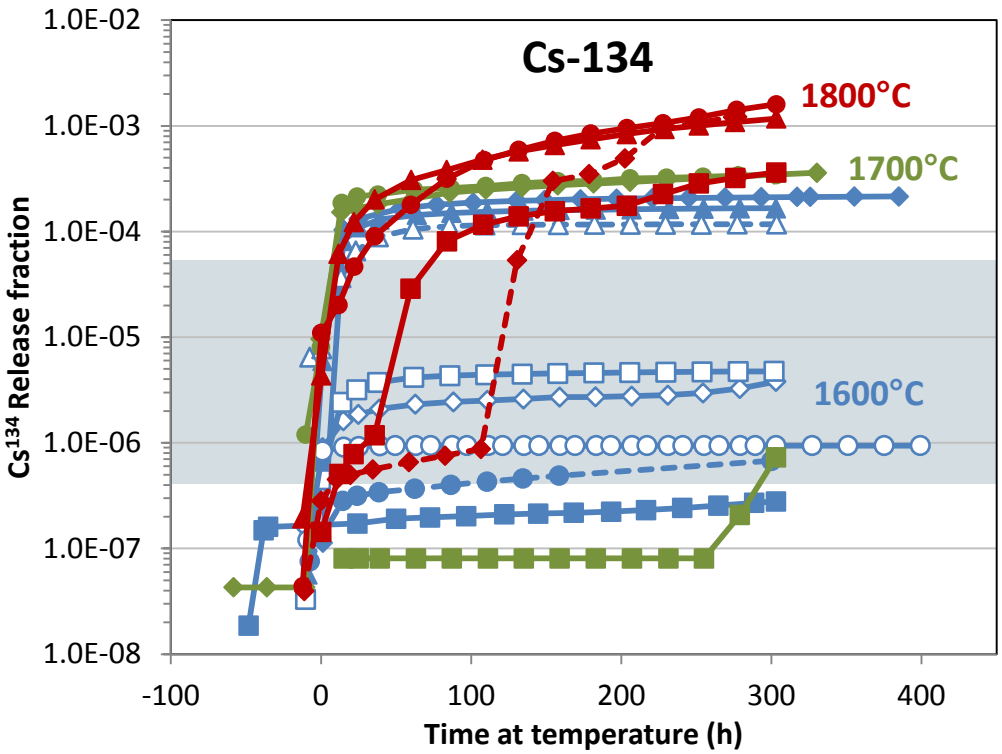


AGR-1 Compact 4-3-3 safety test results



AGR-1 high temperature cesium release behavior

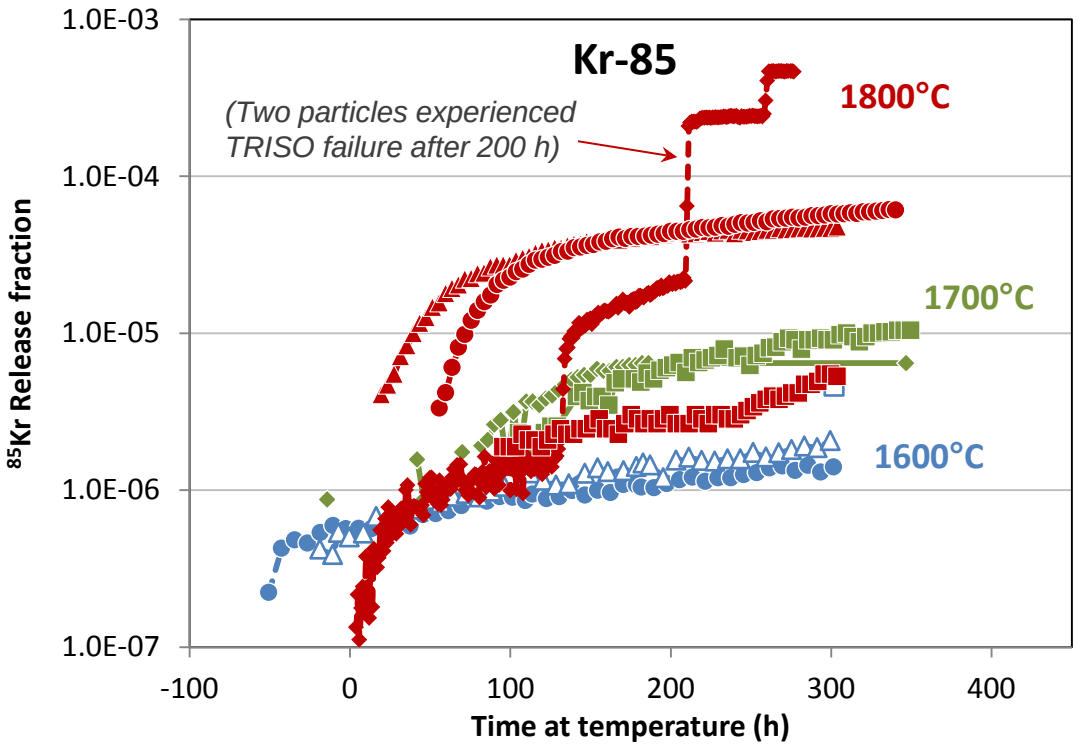
- Cs release through intact SiC was very low ($<5 \times 10^{-6}$) during post-irradiation safety tests up to 1800°C
- Total releases lower on average compared to historic UO_2 results, likely due to the lack of CO corrosion of the SiC layer in UCO fuel
- Elevated Cs release traced to failed SiC layers (i.e., failure of SiC layer with at least one intact PyC layer)
- Total Cs release is strongly related to SiC failure fraction
- Peak Cs releases ~10^{-3} after 300 h at 1800°C.



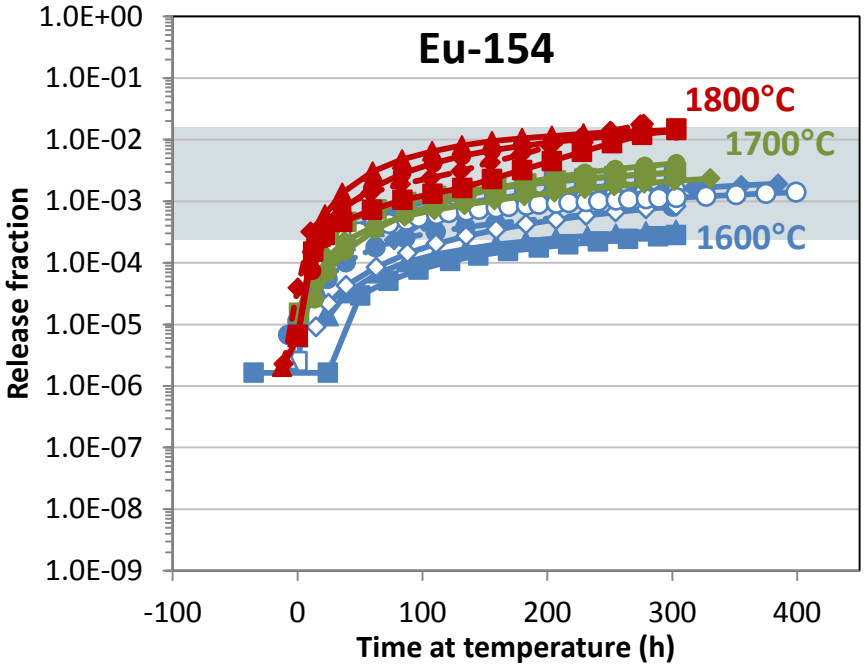
Shaded region: Cs-134 inventory in the matrix of irradiated compacts

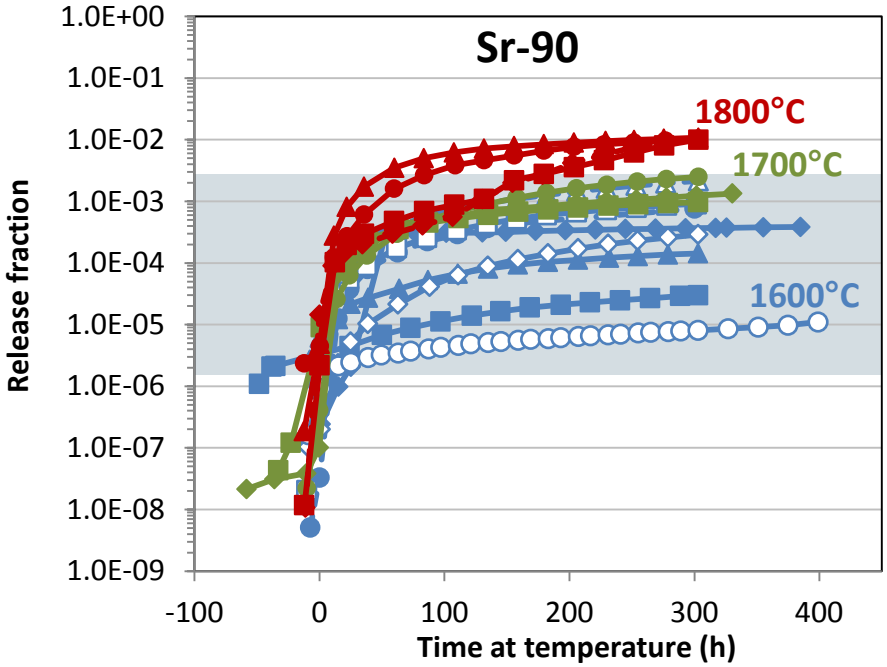
AGR-1 high temperature krypton release behavior

- Peak release after 300 h at 1600°C was 5×10^{-6}
- Kr-85 release increases with increasing temperature due to (a) increased incidence of SiC layer failure and (b) more rapid diffusion of Kr through the OPyC layer
- Post-irradiation safety testing up to 1800°C for 300 h in helium indicates very low Kr release in the absence of TRISO failure ($<6 \times 10^{-5}$)
- One compact out of four compacts tested at 1800°C experienced 2 TRISO failures after >200h at 1800°C with subsequent Kr release



AGR-1 high temperature Eu and Sr release behavior





- Levels of Eu and Sr released at 1600–1700°C are equivalent to that found in as-irradiated compacts outside of the SiC layer
- Likely that a significant portion of the release during safety testing is from the compact matrix (cannot discern low-level releases from particles)
- Elevated release at 1800°C likely from intact particles

Shaded region: Sr-90 inventory in the matrix of irradiated compacts

AGR-1 coating failure fractions

- AGR-1 particle failure statistics based on PIE and safety testing

Test conditions	# particles	SiC failures			TRISO failures		
		# failures	Failure fraction	Failure fraction (95% Conf)	# failures	Failure fraction	Failure fraction (95% Conf)
Irradiation	298000	4	1.3E-05	≤3.1E-05	0	0	≤1.1E-05
1600°C	33100	3	9.1E-05	≤2.4E-04	0	0	≤9.1E-05
1700°C	12450	7	5.6E-04	≤1.1E-03	0	0	≤2.5E-04
1800°C	16500	23	1.4E-03	≤2.0E-03	2	1.2E-04	≤3.9E-04

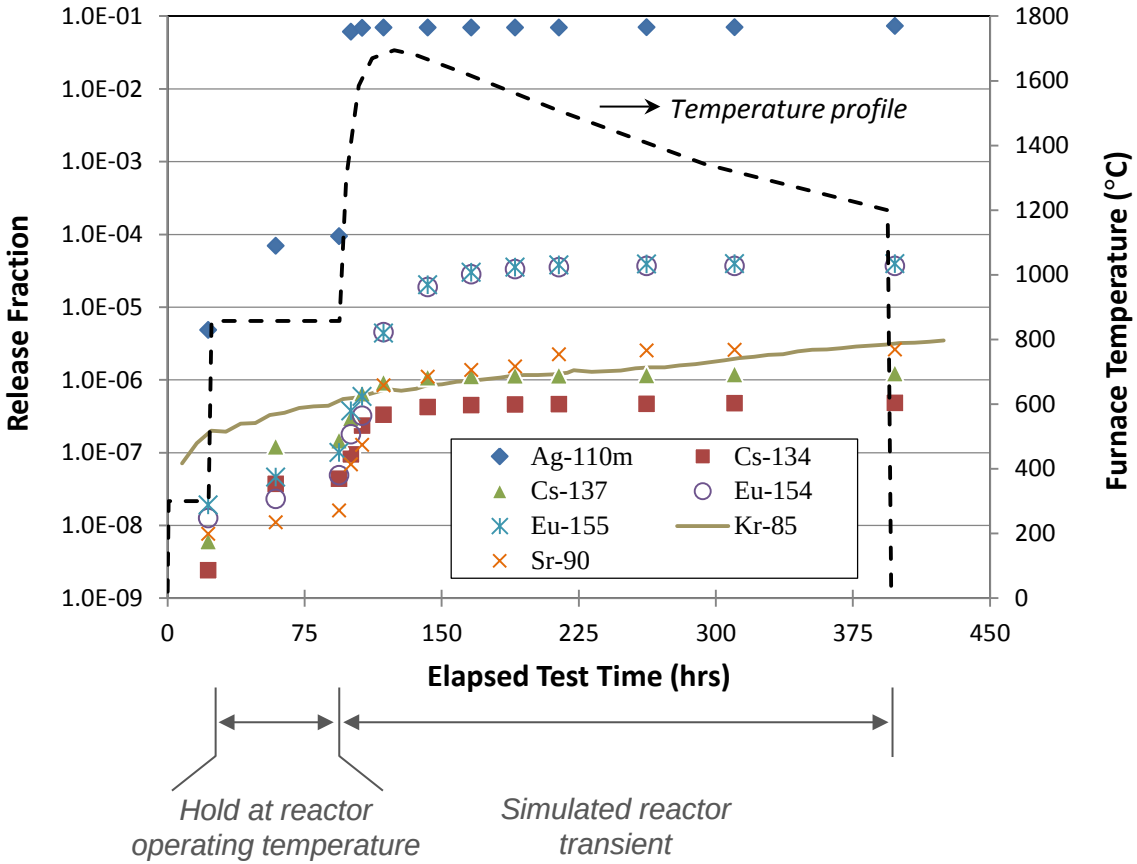
- TRISO failure fractions are better than existing reactor design specifications, often under more severe accident conditions (temperatures, durations)

Condition	Design specifications for TRISO failure fraction		AGR-1 95% confidence
	NGNP[a]	HTR-Modul[a]	
In-service	$\leq 2.0\times10^{-4}$	$\leq 1.6\times10^{-4}$	$\leq 1.1\times10^{-5}$
1600°C accident	$\leq 6.0\times10^{-4}$	$\leq 6.6\times10^{-4}$	$\leq 6.6\times10^{-5}$ [b]

[a] Values for NGNP and HTR-Modul taken from NGNP Fuel Qualification White Paper, INL/EXT-10-18610, Idaho National Laboratory, 2010.
[b] Value obtained by combining statistics from 1600 and 1700°C AGR-1 safety tests (0 failures out of 45,550 particles)

Transient temperature safety testing

- Temperature profile designed to mimic peak fuel temperature during a depressurized conduction cooldown even
  - Temperature profile adjusted ~100°C higer to match testing done in Germany on AVR spheres
- Results from first AGR-1 test (3 fuel compacts) indicate acceptable fuel performance with no unusual fuel behaviors
  - Kr release indicates no failed TRISO
  - Cs release indicates no failed SiC layers
  - Ag, Sr, and Eu release generally consistent with isothermal heating tests



Future safety testing needs and plans

- Reirradiation of fuel prior to out-of-pile safety testing in order to generate short-lived I-131 ($t_{1/2}$ = 8.02 d) and measure iodine release (I-131 is a major off-site dose contributor)
  - Current plans will utilize the NRAD reactor at HFEF
  - Testing will commence as part of the AGR-2 safety testing campaign
- High temperature safety testing in atmospheres containing air or moisture to expand the range of reactor accident scenarios (e.g., air ingress, steam generator tube rupture)
  - A key issue is the potential for oxidizing atmospheres to volatilize fission products in the fuel matrix and graphite
  - Furnace system is currently being designed and tested at INL, with planned deployment in the FCF air cell
  - Testing is planned for the AGR-5/6/7 fuel; earlier testing on AGR-2 and AGR-3/4 fuel will be performed if schedule allows

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