INL/MIS-22-67871-Revision-0

Exposed Kernel Heating Tests

July 2022

Changing the World's Energy Future

John D Stempien

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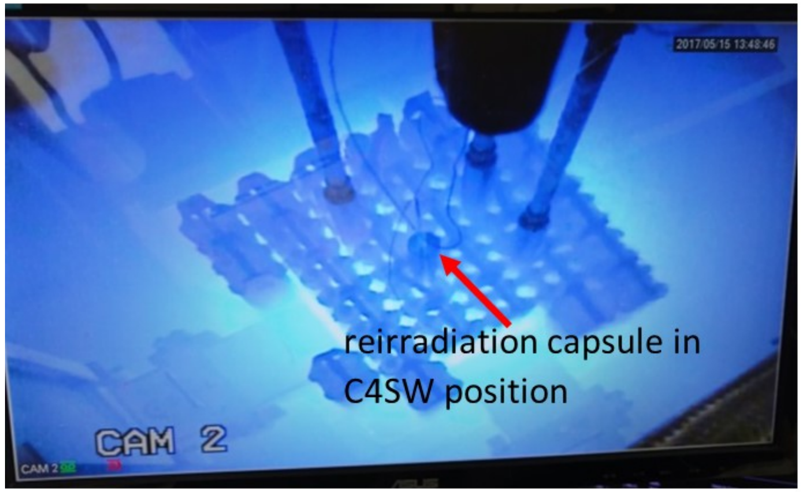
Exposed Kernel Heating Tests

Utilizing AGR-2 and AGR-3/4 Fuel

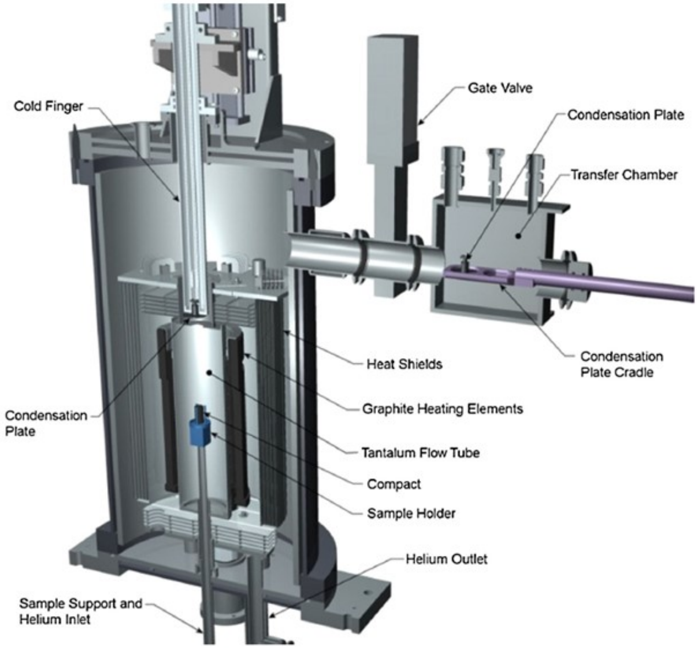
Use Heating Tests of Fuel with Exposed Kernels to Measure Release of Key Fission Products

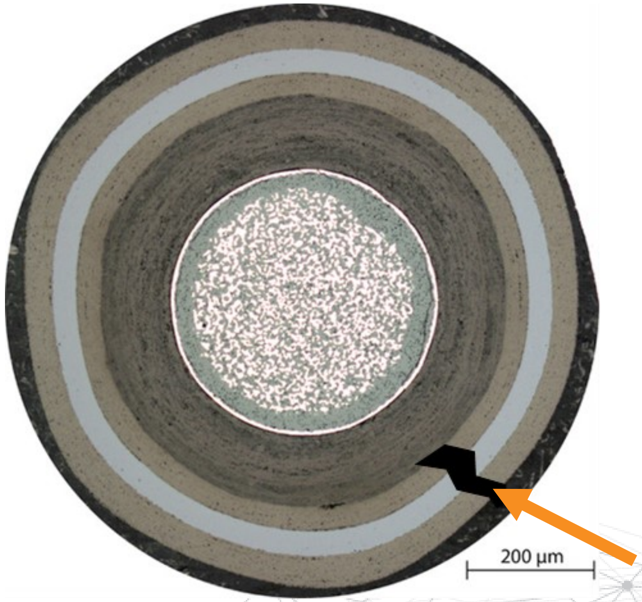
- Use as-irradiated fuel for long-lived fission products and reirradiated fuel for both long-lived and short-lived fission products
- Short-lived I-131 ($t_{1/2}$ = 8.02 d) and Xe-133 ($t_{1/2}$ = 5.2 d) will decay before PIE can begin
- Use short reirradiation in the Neutron Radiography (NRAD) reactor to produce I-131 and Xe-133
- Quickly transfer fuel from NRAD to the Fuel Accident Condition Simulator (FACS) furnace

Neutron Radiography Reactor (NRAD)



Fuel Accident Condition Simulator (FACS) Furnace

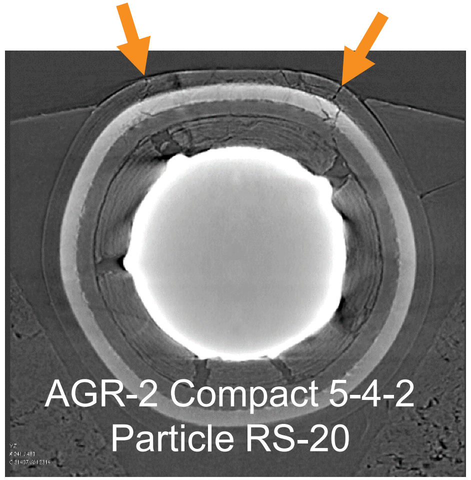




For Exposed Kernels, Employ Loose-cracked AGR-2 Particles and AGR-3/4 Compacts

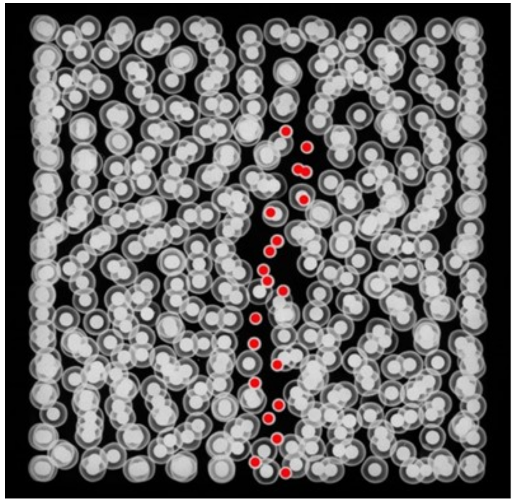
AGR-2 Compact 6-4-1 bare kernel with TRISO coating removed at INL

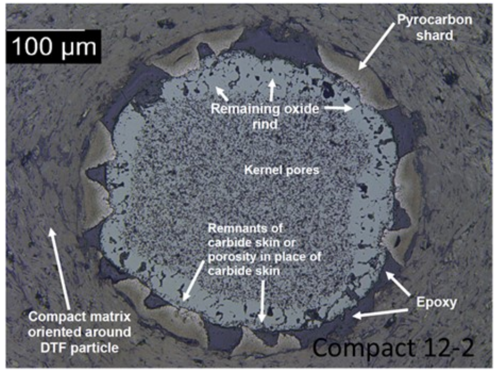
- Deconsolidated particle deliberately cracked at ORNL and shipped to INL
  - Cracking extends through OPyC, SiC, and IPyC
  - Avoid significant SiC shearing
  - Avoid SiC cracks at bottom of hemisphere

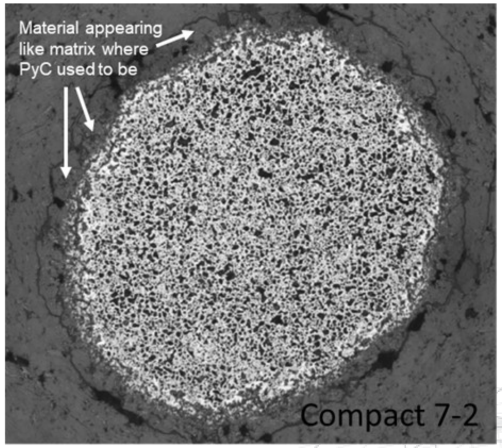


AGR-2 Compact 5-4-2
Particle RS-20

X-ray of Unirradiated AGR-3/4 Compact







Irradiated AGR-3/4 DTF particles in compact cross section

Particle Reirradiation Heating Tests – Status and Purpose

Tests serve four purposes:

- Determine I-131 and Xe-133 retention in exposed kernels to address scarcity of data
- Provide FACS condensation plate collection efficiencies for temperatures other than 1600°C
  - Needed for AGR-3/4 testing and upcoming AGR-5/6/7 testing
  - Challenge: Ag-110m in AGR-2 fuel has already decayed through ~10 half-lives.
- Provide data for use in source term estimates
- Investigate kernel diffusivity

AGR-2 Compact	Burnup (% FIMA)	TAVA Irradiation Temperature (°C)	Test Number	FACS Temperature (°C)	Sample Type	Status
6-4-1	9.24	1018	1	1600	Bare kernels	Complete FY18
5-4-2	12.03	1071	2	1600	Cracked loose particles	Complete FY18
			3	1400	Cracked loose particles	Complete FY19
			4	1200	Cracked loose particles	Complete FY19
2-2-1	12.47	1287	5	1000	Cracked loose particles	Complete FY20
			6	1200	Cracked loose particles	Completed FY22
			7	1400	Cracked loose particles	Completed FY22

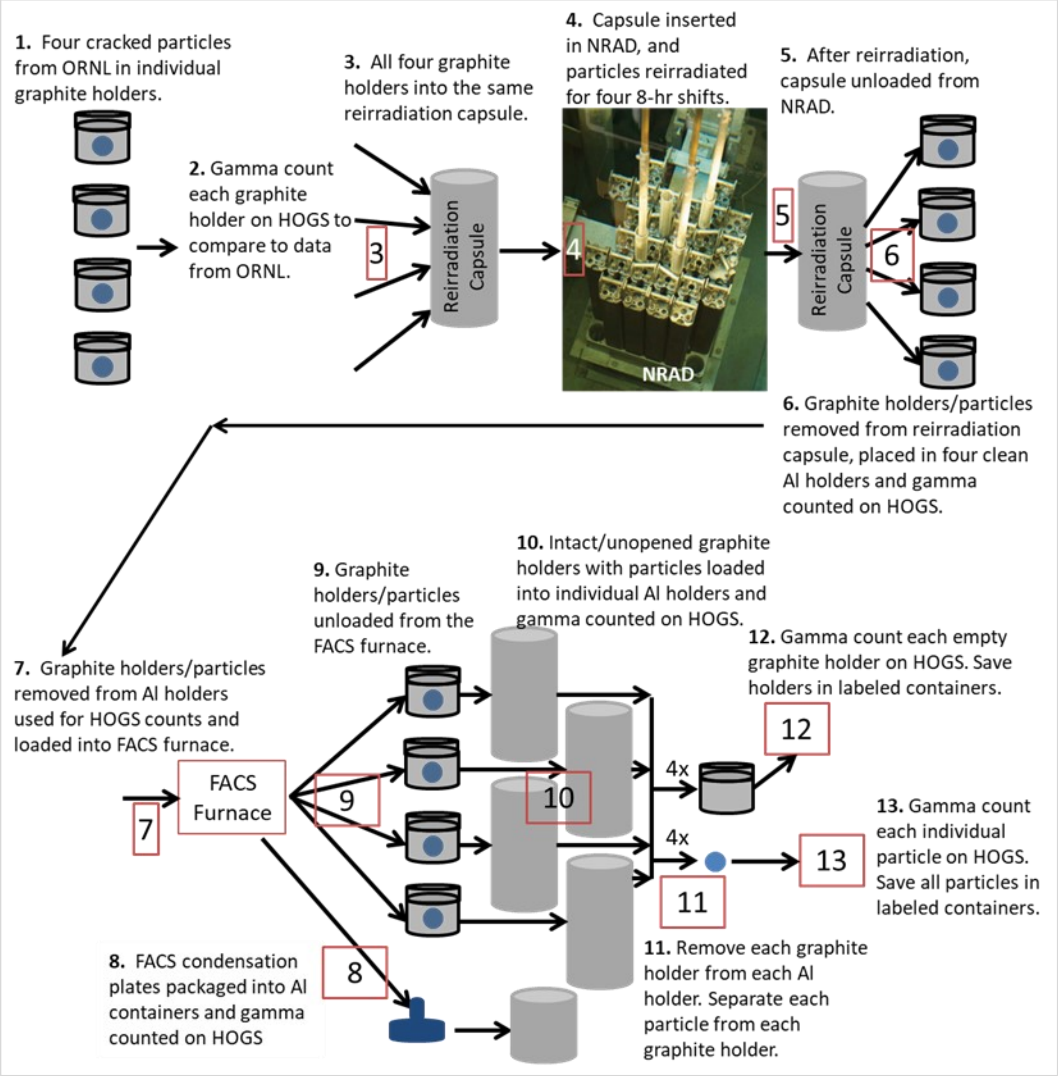
Completed all Planned AGR-3/4 Compact As-irradiated and Reirradiation-Heating Tests

- Determine release of residual long-lived fission products
- Determine integral release of short-lived fission products from exposed kernels in compacts
- Tests covered a wide range of temperatures and irradiation histories

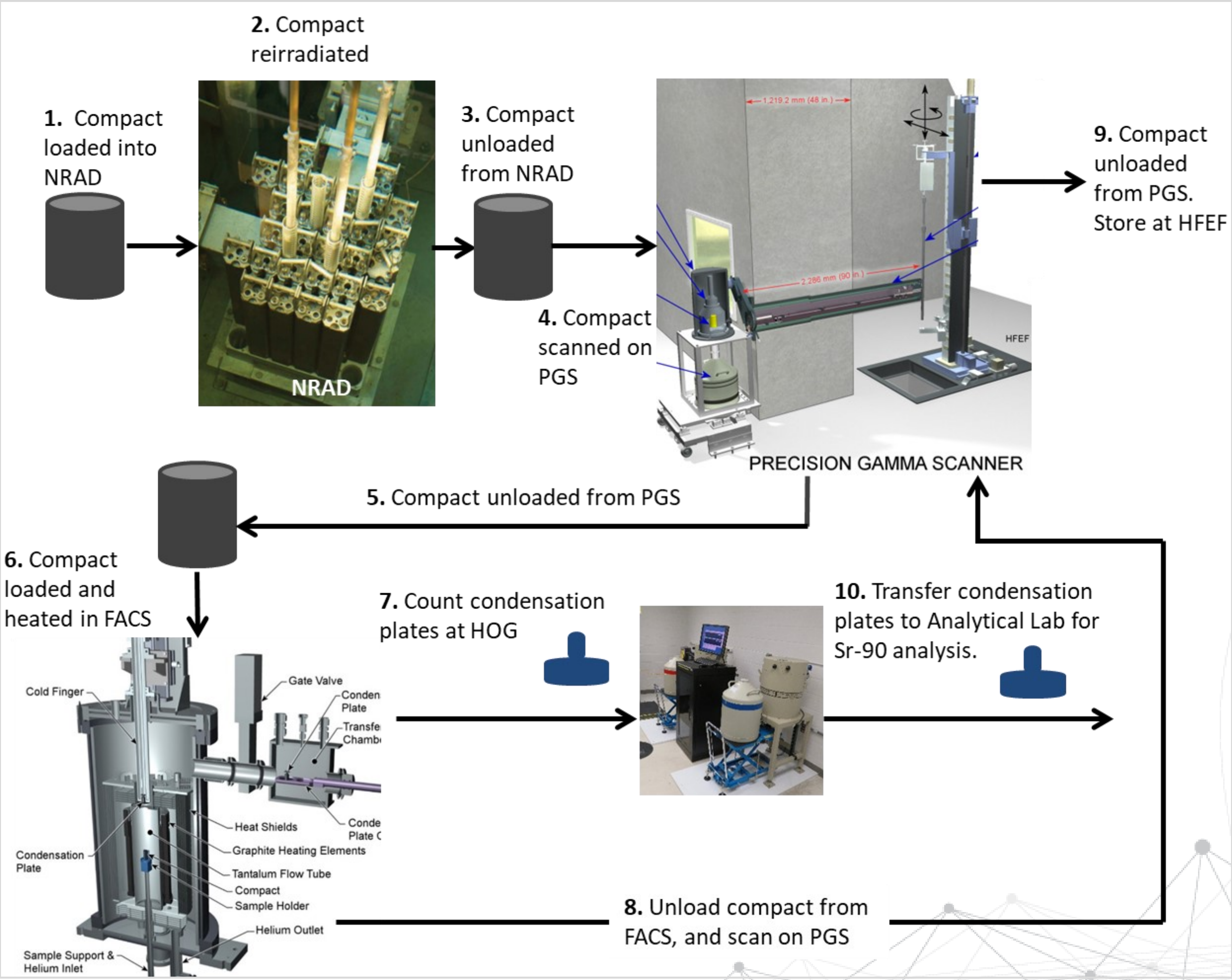
Compact ID	Condition	Status	Burnup (% FIMA)	TAVA Temp (°C)	FACS Furnace Temp (°C)
3-1	Reirradiated	Complete	12.2	1138	1600
8-1	Reirradiated	Complete	14.5	1165	1200
10-1	Reirradiated	Complete	12.1	1172	1400
4-3	Reirradiated	Completed late FY21	14.3	1035	1000
1-2	Reirradiated	Completed late FY21	5.9	941	1400
3-2	As-irradiated	Complete	12.5	1196	1600/1700
8-2	As-irradiated	Complete	14.6	1213	1400
10-2	As-irradiated	Complete	12.0	1213	1200
10-4	As-irradiated	Complete	11.4	1168	1400

Reirradiation Test Process

AGR-2 Particle Reirradiation Tests

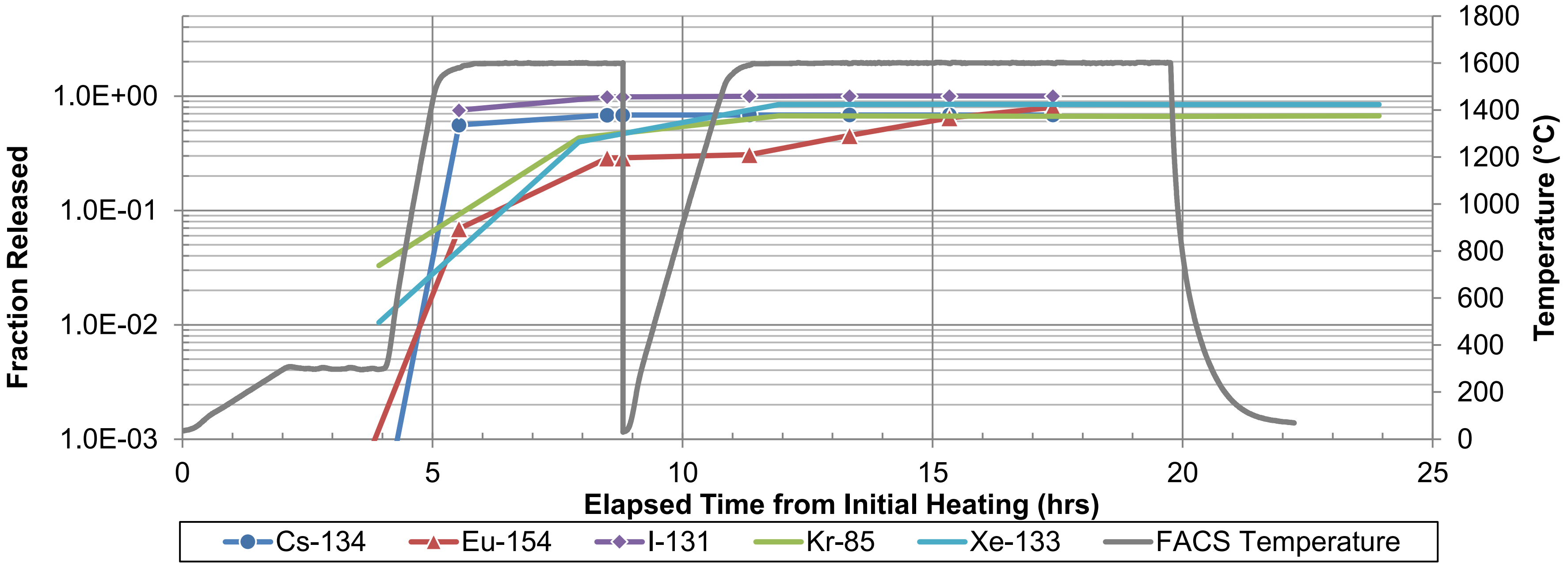


AGR-3/4 Compact Reirradiation Tests



1600°C Test of Reirradiated AGR-2 6-4-1 Four Bare Kernels

- I-131 and Xe-133: Releases similar; Supports assumption that I-131 behaves like Xe-133
- Kr-85: release indicates most (~70%) Kr-85 is in kernel when TRISO coatings intact
- Eu-154: ~20% retention in kernel

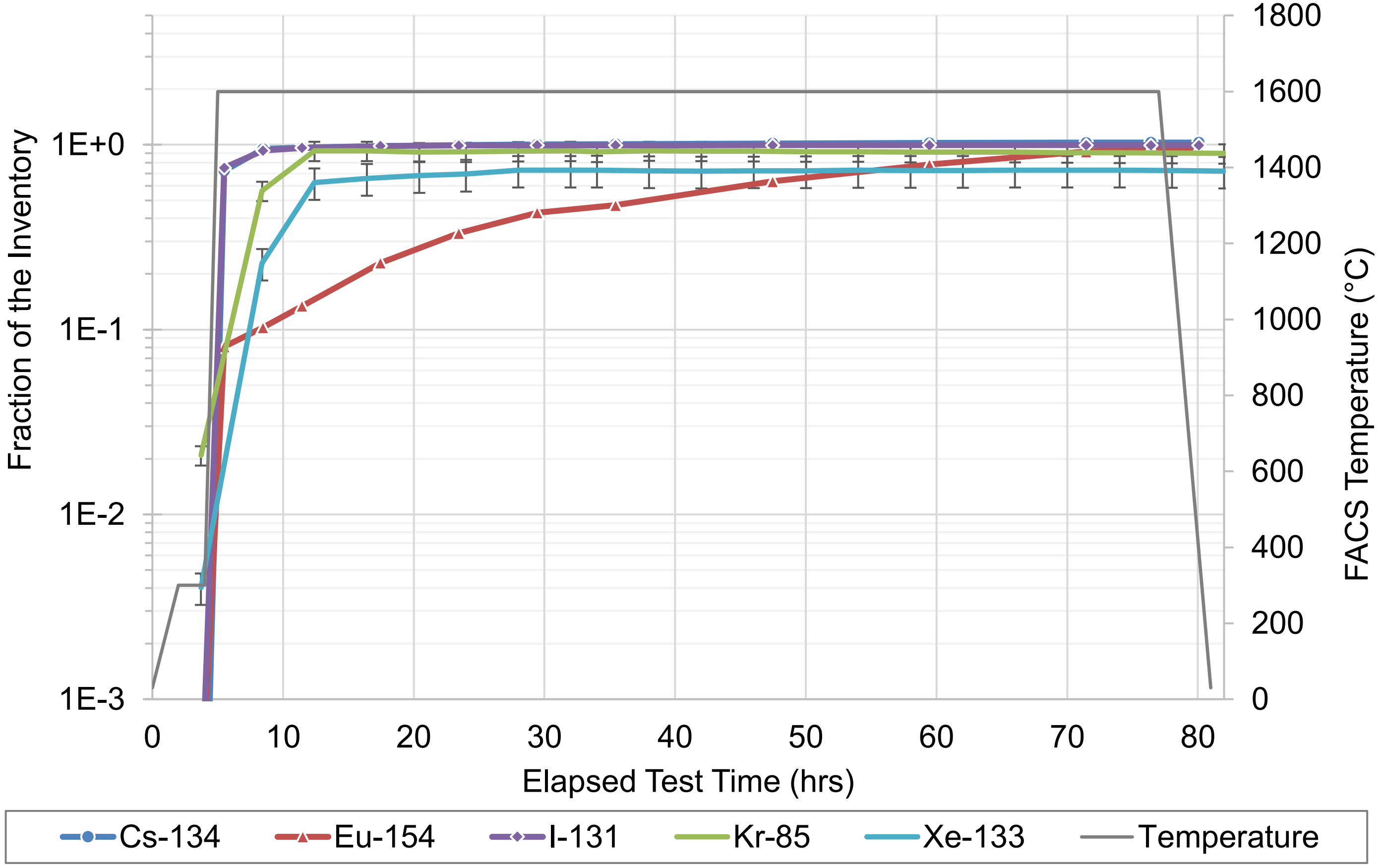


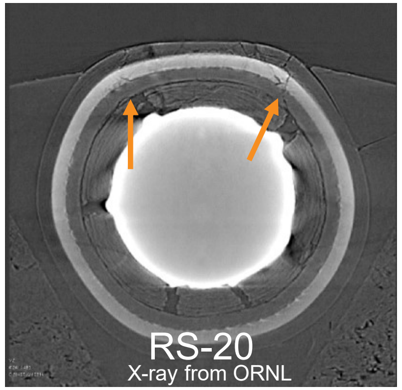
Isotope	Total Fraction Released
Cs-134	0.852
Eu-154	0.795
I-131	1.00
Kr-85	0.671
Xe-133	0.842

Fractions based on measured/calculated ratio.

1600°C Test of Four Reirradiated Cracked 5-4-2 Particles

- This test ~ 4 times longer than test with 6-4-1 bare kernels. At longer time, shows additional Eu-154 release compared to short test.
- Potentially an underestimate of Xe-133 production from the physics calculations



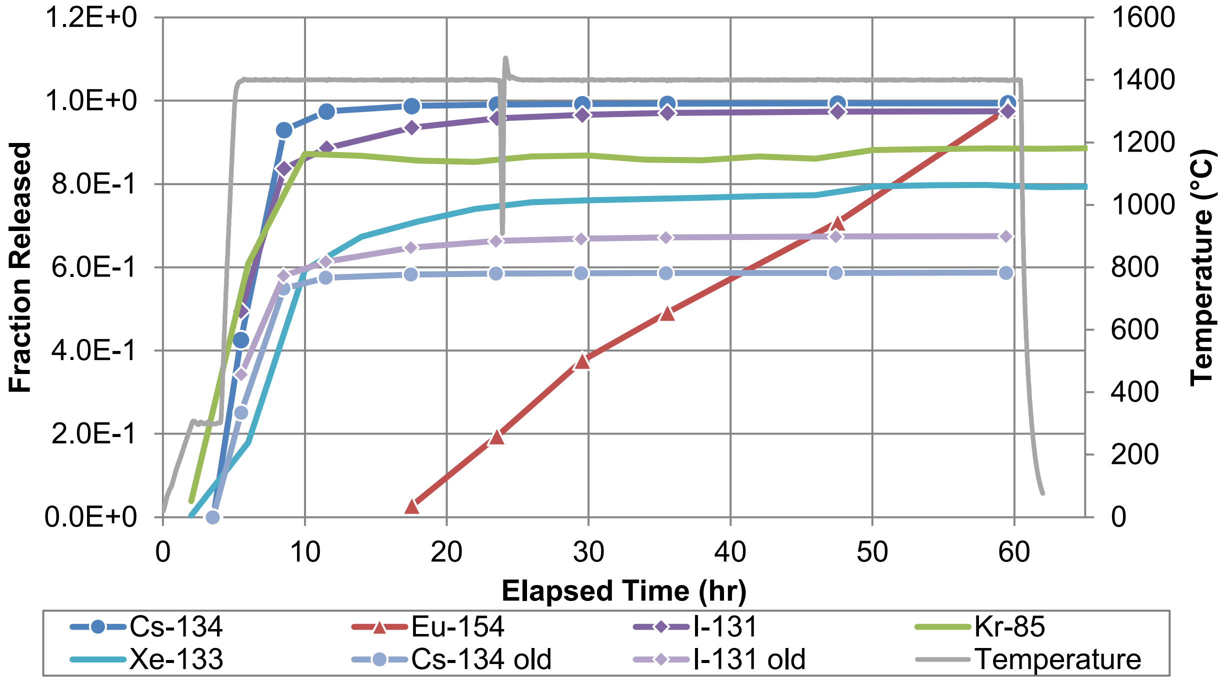


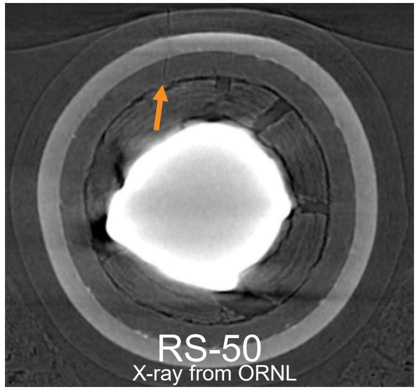
Isotope	Total Fraction Released
Cs-134	1.03
Eu-154	0.964
I-131	0.996
Kr-85	0.898
Xe-133	0.720

Fractions based on measured/calculated ratio.

1400°C Test of Four Reirradiated Cracked 5-4-2 Particles

- Kr-85 and Xe-133 releases like prior 1600°C tests
- Cs-134 and Eu-154 releases like 5-4-2 cracked particle 1600°C test
- I-131 release is slightly less than at 1600°C



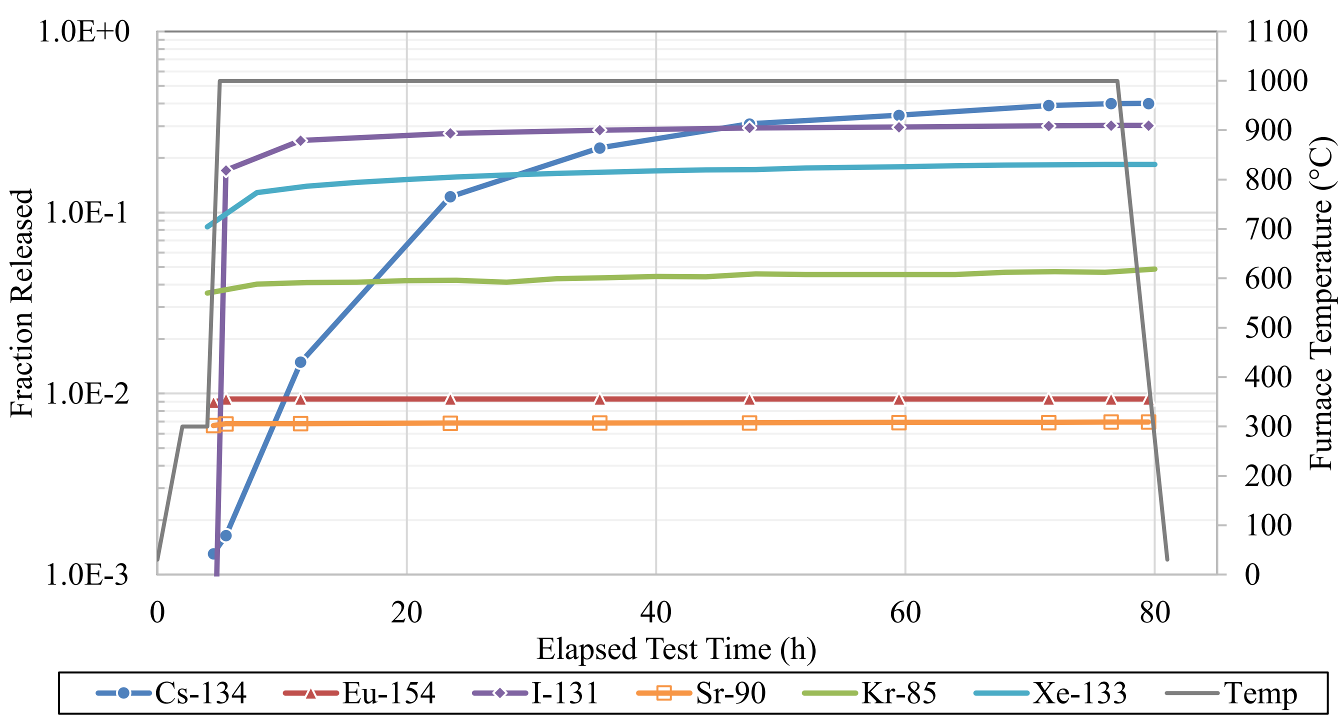


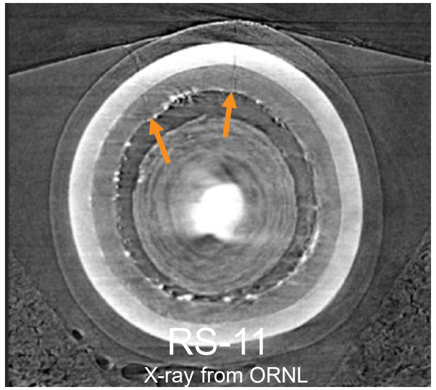
Isotope	Total Fraction Released
Cs-134	0.994
Eu-154	0.982
I-131	0.975
Kr-85	0.884
Xe-133	0.793

- Fractions based on measured/calculated ratio.
- Cs-134 and I-131 “old” used original FACS 1600°C efficiencies. Others used efficiencies calculated for this particular test.

1000°C Test of Four Reirradiated Cracked 2-2-1 Particles (Preliminary)

- Releases 3 to 1000 times less than at 1400°C with 5-4-2 particles

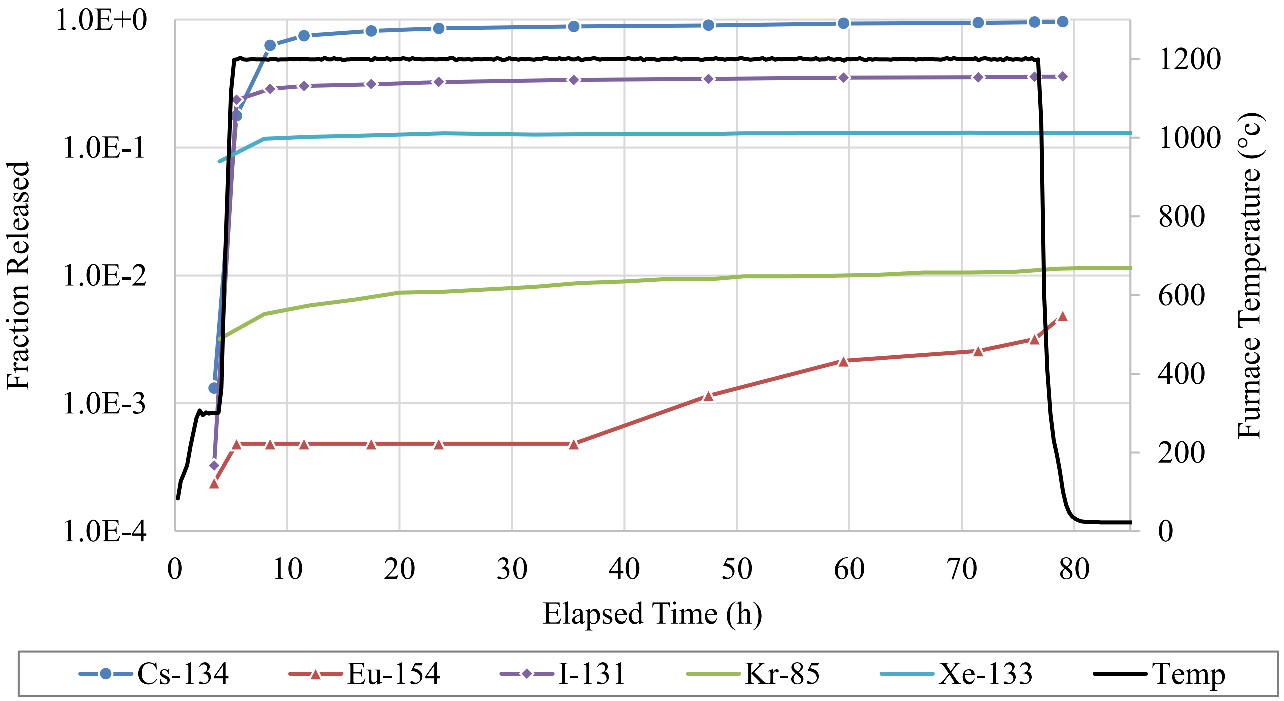


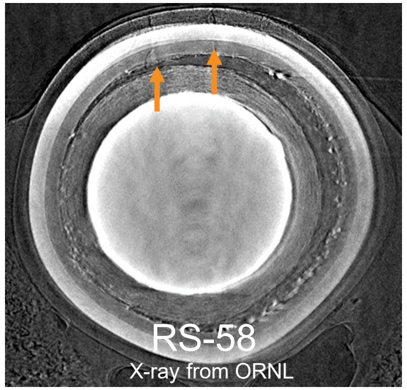


Isotope	Total Fraction Released
Cs-134	0.401
Eu-154	0.009
Sr-90	0.007
I-131	0.302
Kr-85	0.049
Xe-133	0.185

1200°C Test of Four Reirradiated Cracked 2-2-1 Particles (Preliminary)

- Cs release ~ 3 times higher than at 1000°C
- I-131 release ~20% higher than at 1000°C
- Other releases are similar to those seen at 1000°C, but new efficiencies still need to be applied

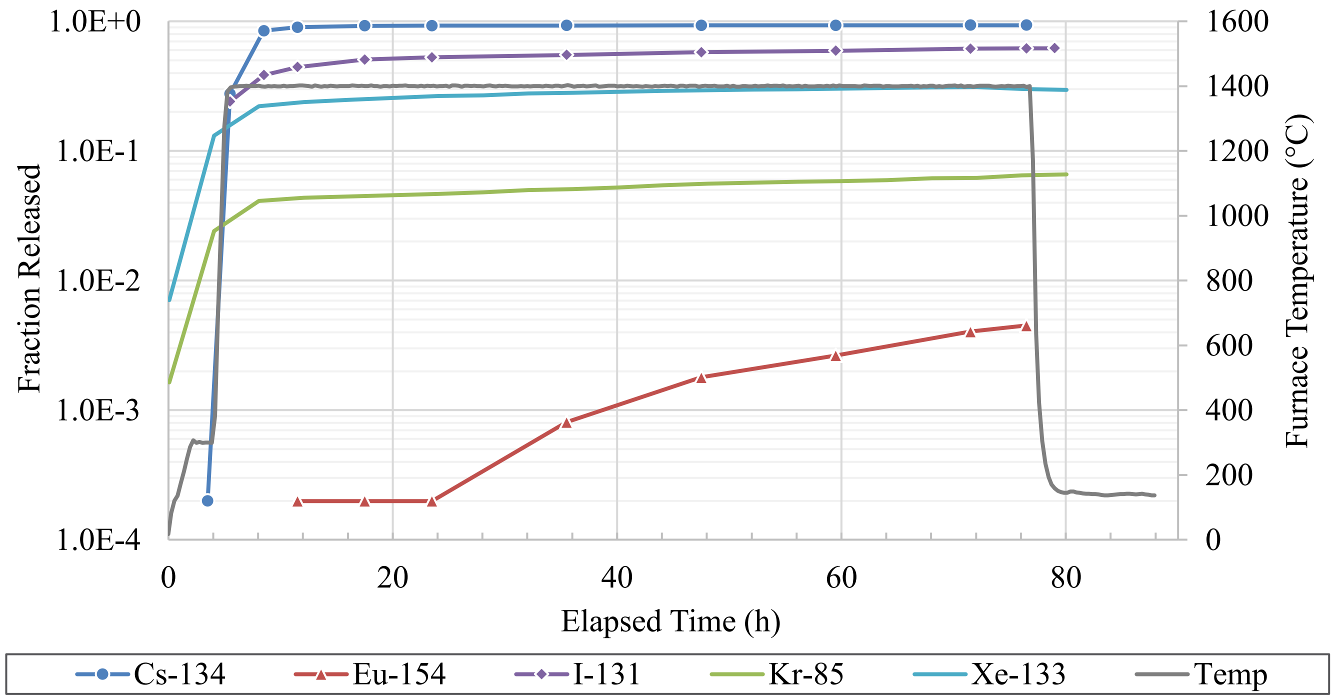


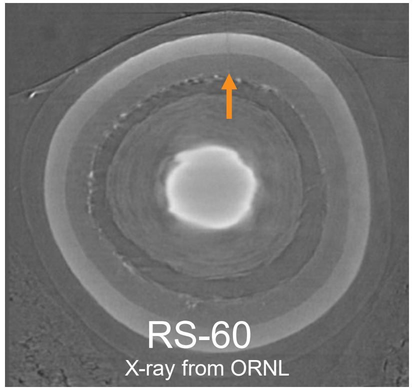


Isotope	Total Fraction Released
Cs-134	0.963
Eu-154	0.005
I-131	0.359
Kr-85	0.012
Xe-133	0.130

1400°C Test of Four Reirradiated Cracked 2-2-1 Particles (Preliminary)

- Releases of Cs and Eu similar to 1200 and 1000°C
- Releases of other nuclides are noticeably higher than at 1000 and 1200°C
- Some new 1400°C collection efficiencies exist, but the results from 1000 and 1200°C still need correction from new FACS plate collection efficiencies

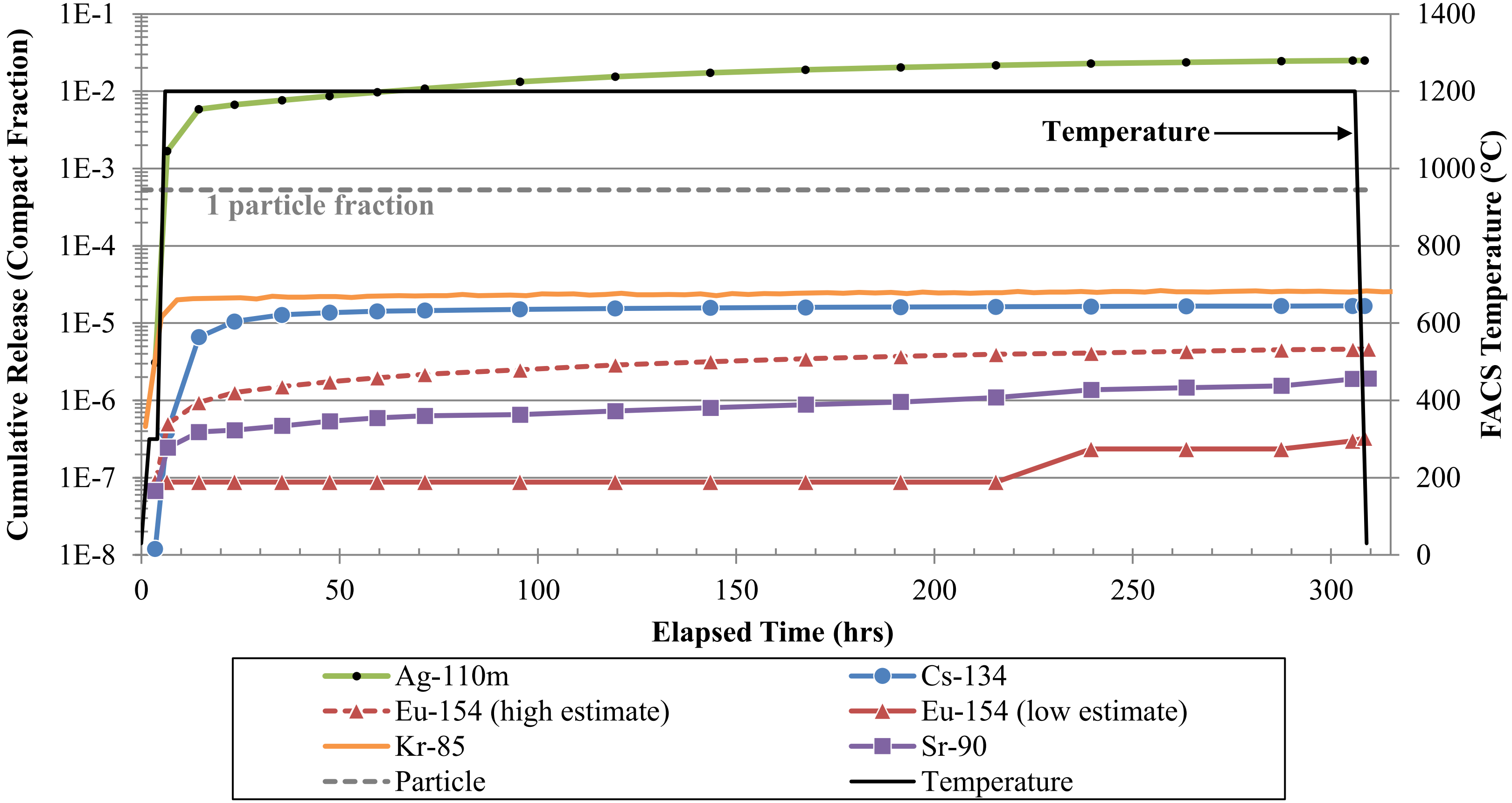




Isotope	Total Fraction Released
Cs-134	0.933
Eu-154	0.0045
I-131	0.619
Kr-85	0.066
Xe-133	0.297

All AGR-3/4 Compact Inert Heating Tests Have Been Completed

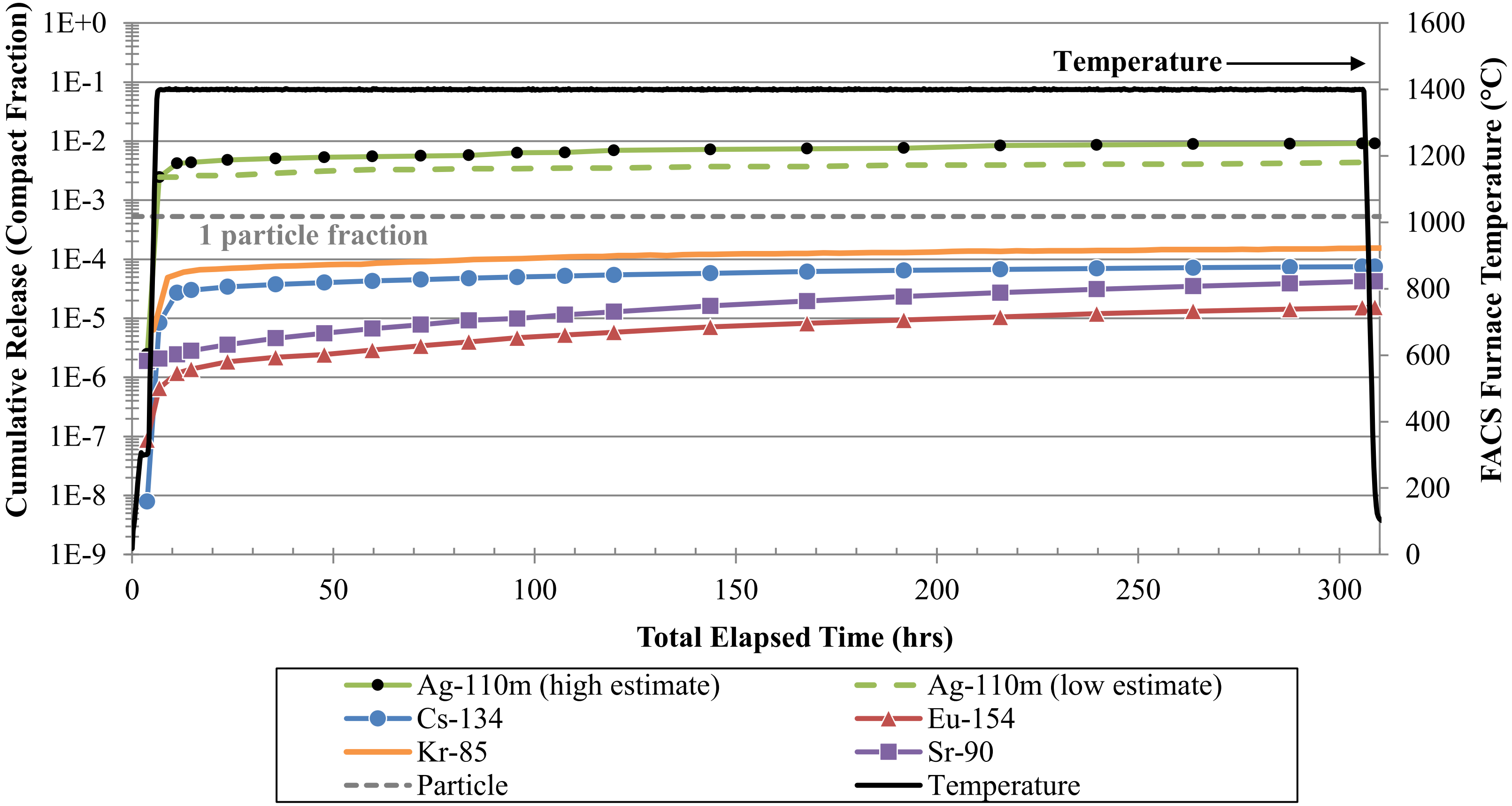
As-irradiated Compact 10-2: 1200°C Test



	DTF Inventory Released (%)
Ag-110m	240.7
Cs-134	0.160
Eu-154	0.003
Kr-85	0.244
Sr-90	0.18

Notes:
- 1 particle equates to a compact fraction of 5.29E-4
- “high estimate” includes values determined from minimum detectable activities (MDA)
- “low estimate” takes MDAs to be zero

As-irradiated Compact 10-4: 1400°C Test

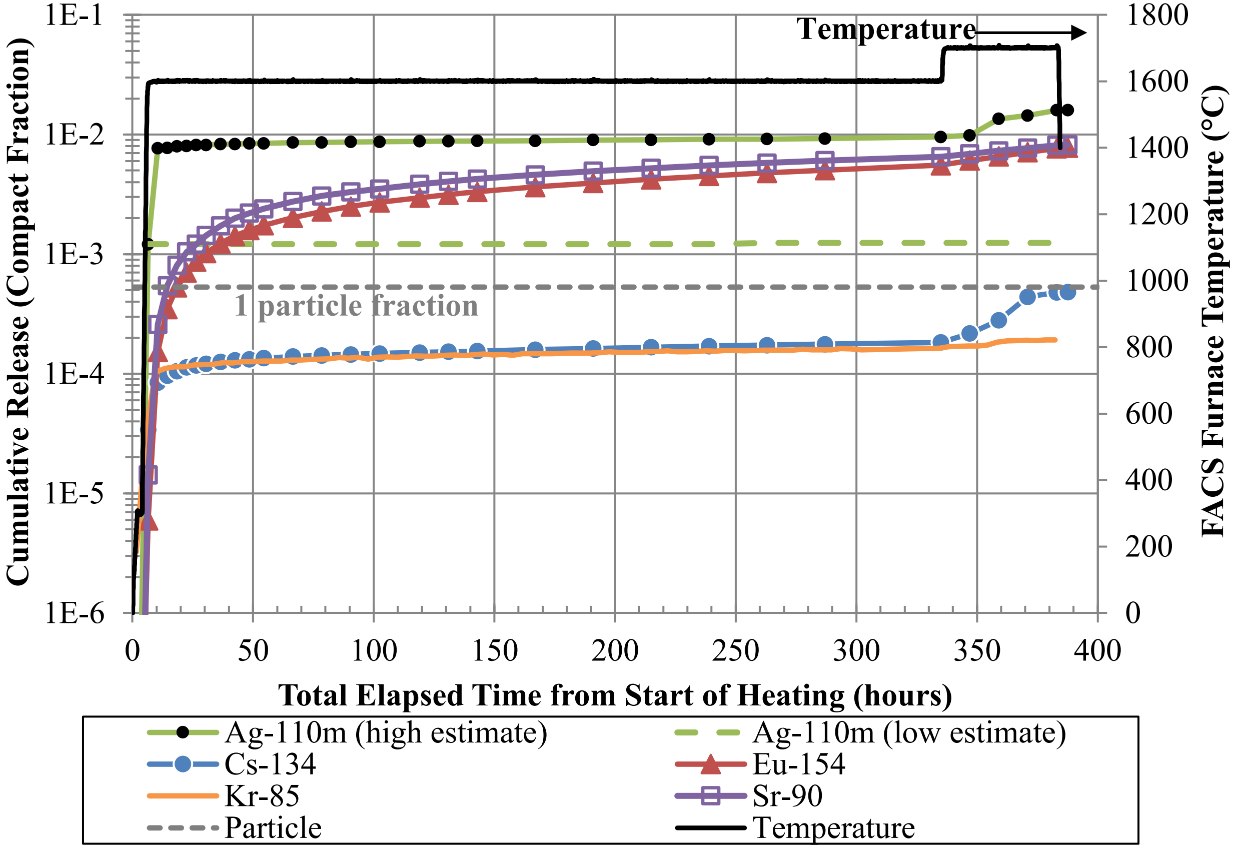


	DTF Inventory Released (%)
Ag-110m (low)	42.2
Cs-134	0.720
Eu-154	0.148
Kr-85	1.48
Sr-90	0.405

Notes:

- 1 particle equates to a compact fraction of 5.29E-4
- “high estimate” includes values determined from minimum detectable activities (MDA)
- “low estimate” takes MDAs to be zero

As-irradiated Compact 3-2: 1600/1700°C Test



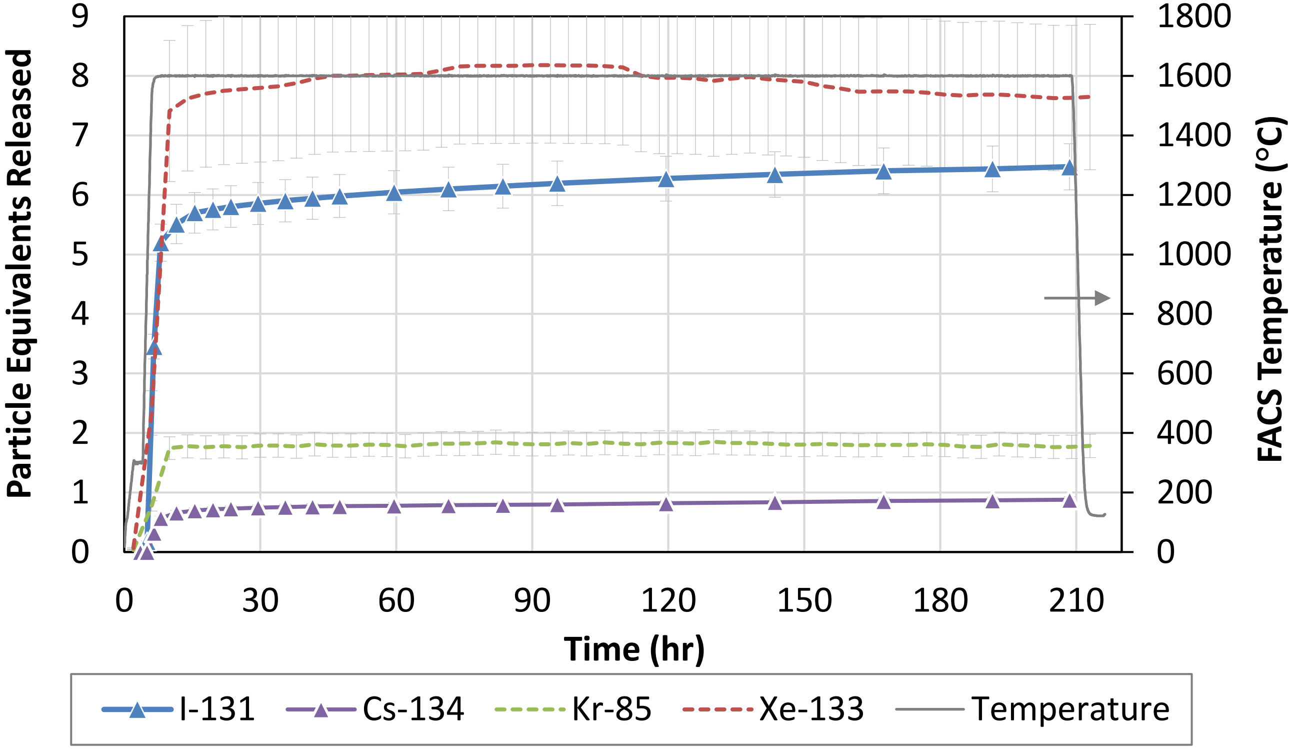
	Particle Equivalents Released		
	1600°C	1700°C	Total
Ag-110m (low)	2.3	0.0	2.3
Ag-110m (high)	18.0	12.2	30.3
Cs-134	0.3	0.6	0.9
Eu-154	10.5	4.2	14.7
Kr-85	0.3	0.1	0.4
Sr-90	12.3	3.2	15.5

Notes:

- 1 particle equates to a compact fraction of 5.29E-4
- “high estimate” includes values determined from minimum detectable activities (MDA)
- “low estimate” takes MDAs to be zero

Reirradiated Compact 3-1 1600°C Test Summary

- Fission gases and iodine released fastest. I-131 and Xe-133 releases are similar
- Kernels may retain some iodine and xenon
- Compact retained Cs-134 after irradiation that was released in heating test. Based on DLBL and measured releases, up to several particles' worth may remain in compact even after heating.

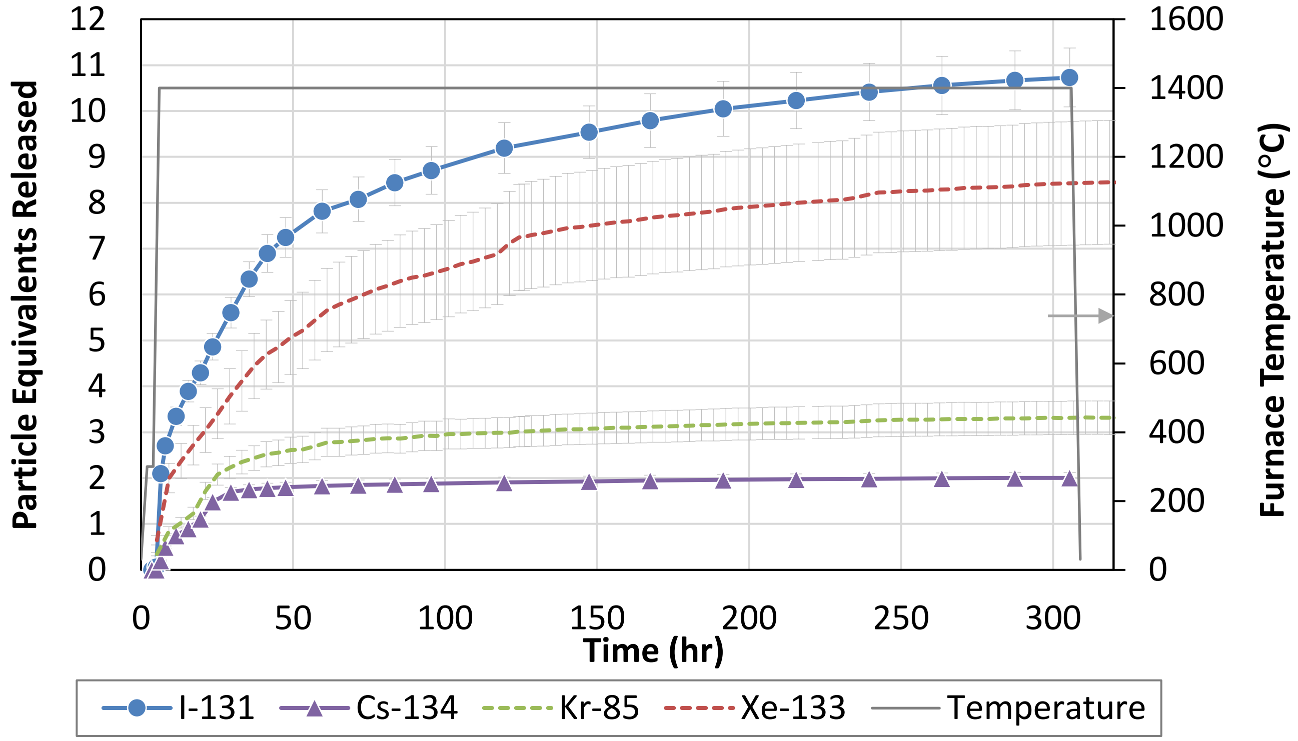


Reirradiation: ~114 hr
Heating test: 1600°C for 202 hr

	DTF Inventory Released (%)
Cs-134	4.4
I-131	32
Kr-85	9.3
Xe-133	41

Reirradiated Compact 10-1 1400°C Test Summary

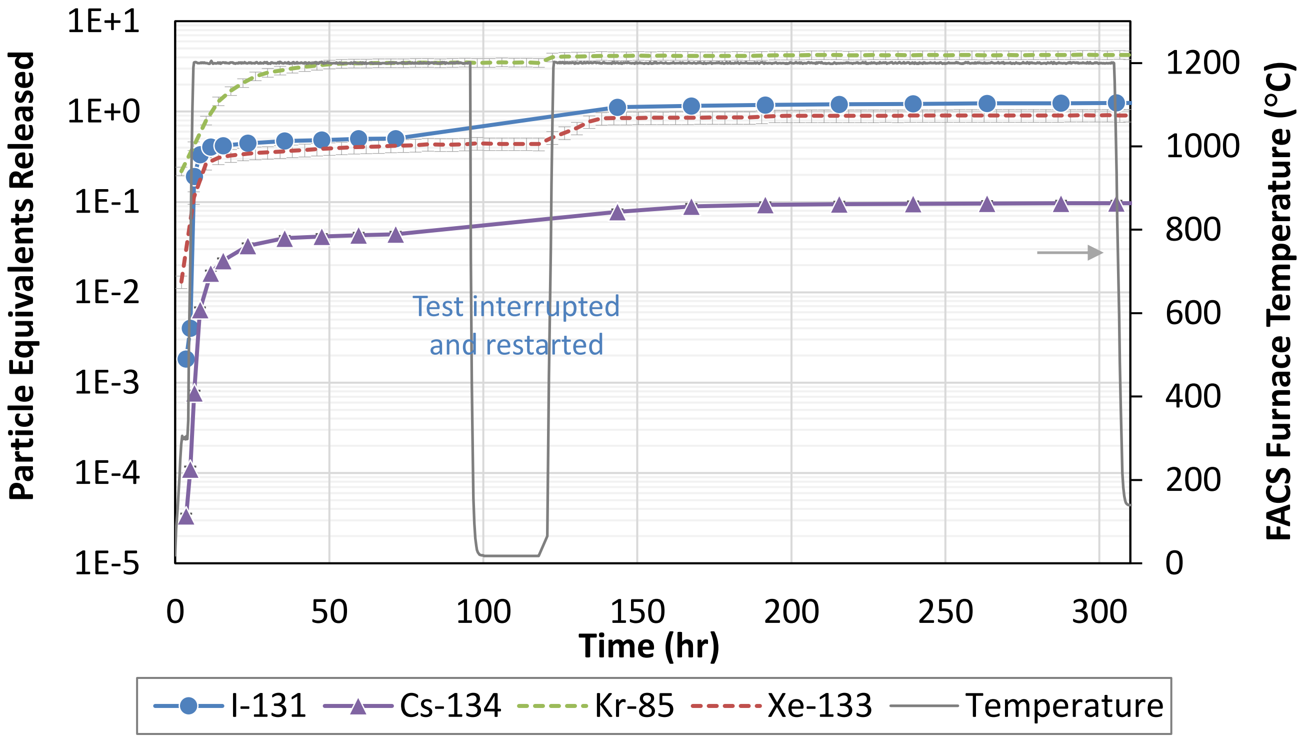
- Fission gases and iodine released fastest: I-131 and Xe-133 releases are similar
- Kernels seem to retain some iodine and xenon



	DTF Inventory Released (%)
Cs-134	10
I-131	54
Kr-85	17
Xe-133	43

Reirradiated Compact 8-1 1200°C Test Summary

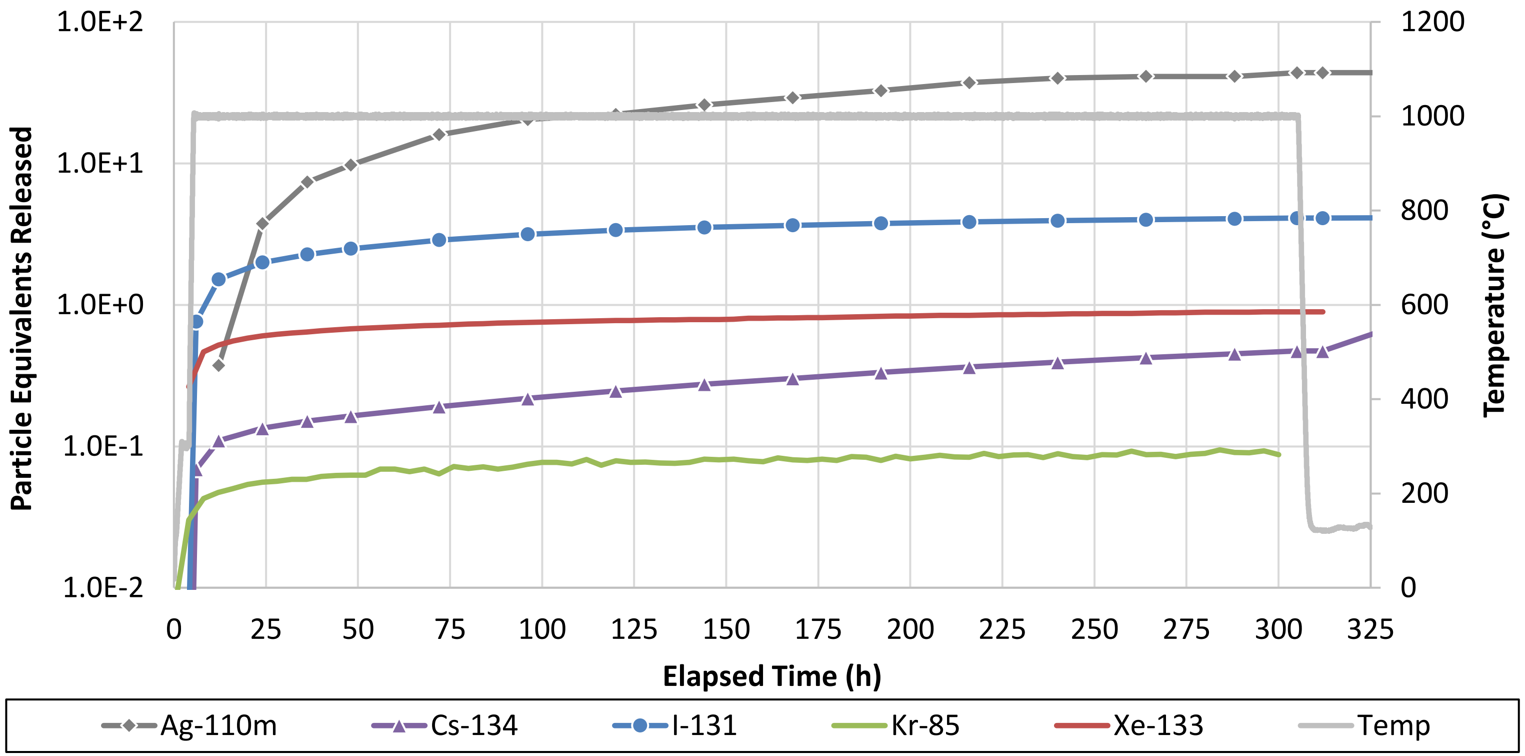
- After about 200 hr, 9x less Xe-133 and 5x less I-131 released at 1200°C than at 1600°C
- Temperature cycle from test interruption may have caused a little more release upon reheat phase



	DTF Inventory Released (%)
Cs-134	0.49
I-131	6.2
Kr-85	21
Xe-133	4.6

Reirradiated Compact 4-3 1000°C Test Summary (Completed late FY21)

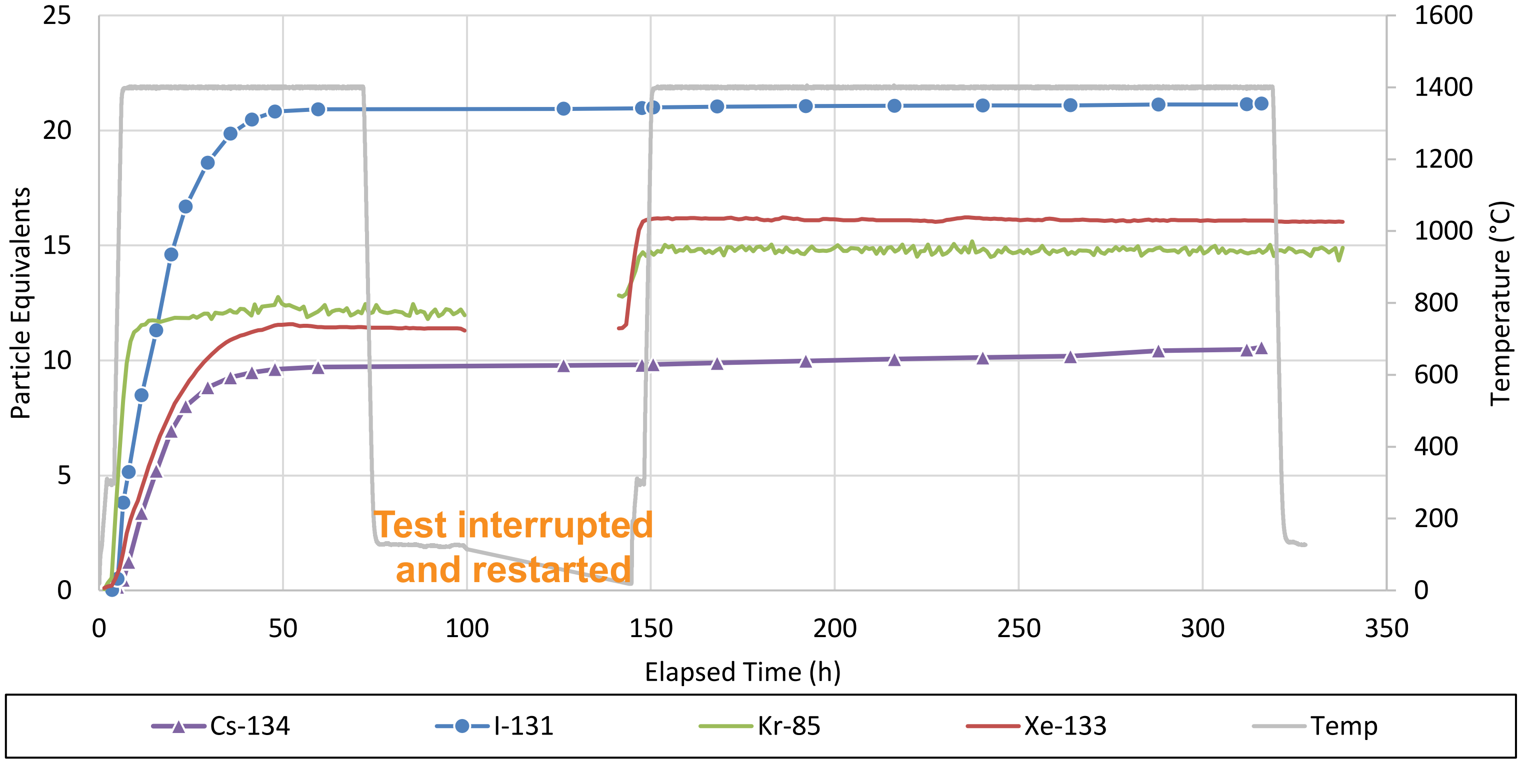
- Compact reirradiated in NRAD for 120 h
- Heated in FACS for 300 h at 1000°C



Releases after 210 h at temp (plate removed at 216.05 h)		
	Particle Equivalents	Percentage of DTF
Cs-134	0.363	1.8%
Eu-154	2.00E-04	0.001%
Kr-85	0.084	0.4%
I-131	3.853	19.3%
Xe-133	0.844	4.2%

Reirradiated Compact 1-2 1400°C Test Summary (Completed Late FY21)

- Test interruption and restart caused additional fission gas release, a seemingly typical response
- Considerably more condensable and gaseous fission products released from this low-burnup compact that had a low irradiation temperature prior to testing



Releases after 204 h at temp (plate removed at 288 h)		
	Particle Equivalents	Percentage of DTF
Cs-134	10.4	52%
Eu-154	4.5E-02	0.22%
Kr-85	14.9	74%
I-131	21.2	106%
Xe-133	16.1	81%

Value > 100% possibly due to underestimate of collection efficiency

Conclusions

- All AGR-3/4 compact and particle reirradiation heating tests have been completed
- Prior irradiation history (e.g., temperature and burnup) affects releases in heating tests.
- Kernels may retain some I-131 and Xe-133: 9x less Xe-133 and 5x less I-131 are released at 1200°C than at 1400°C and 1600°C. Retention of condensable fission products is even greater at 1000°C.
- Short-lived fission product retention in exposed kernels in compacts seems to be better than in deconsolidated exposed kernels.
- Several DTF particles worth of Cs-134 may remain in compacts outside of SiC layers even after heating.
- There may be be a calculational bias that overpredicts Xe-133, thus making its release fraction appear to be smaller than I-131.

Future Work

- Compare fuel performance predictions to these experiments
- Consider applications of the data in empirically based source term analyses
- Some post-test sample analyses from R-DLBL of tested compacts are still in progress
- May be possible to determine effective diffusion coefficients from the release data
- Tests at temperatures of 1400, 1200, and 1000°C still need to be adjusted with new collection efficiencies determined from tests completed in FY22.

INL

Idaho National Laboratory