July 12, 2022

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TRISO Fuel PIE Technical Lead

AGR-3/4 Post-Irradiation Examination

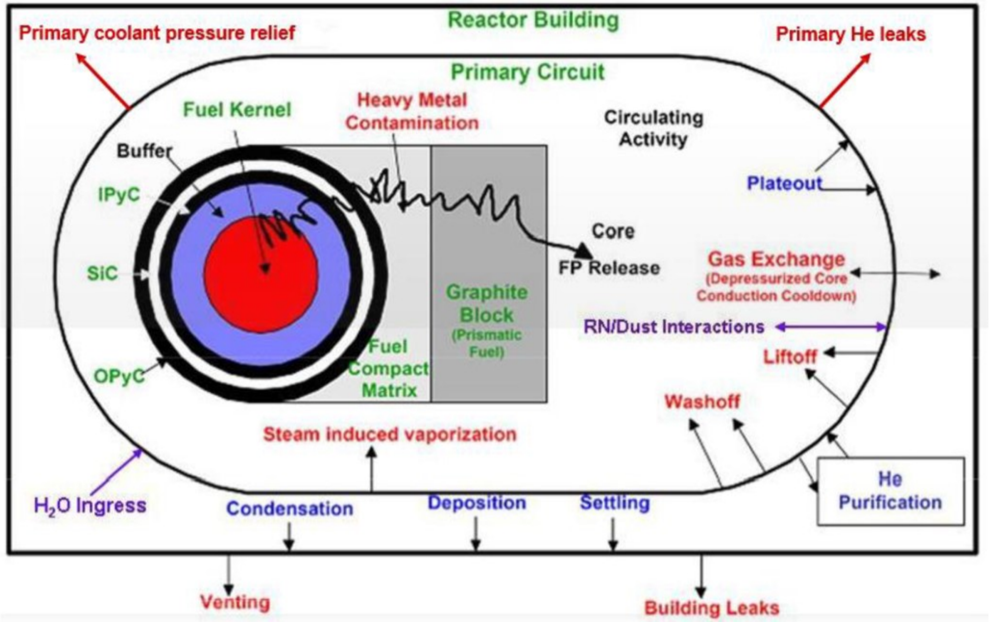
ART Advanced Reactor Technologies
GAS-COOLED REACTORS

AGR-3/4 Goals

- Improve reactor source term predictions
- Provide some data for validation of source term calculations
- Accomplish this by:
  - Observing metallic fission product (e.g., Ag, Cs, Eu, and Sr) transport within graphitic matrix and nuclear grade graphites (IG-110 and PCEA)
  - Measuring fission product inventories and spatial distributions within fuel compacts and graphite
  - Determinizing diffusion coefficients of metallic fission products within graphitic materials

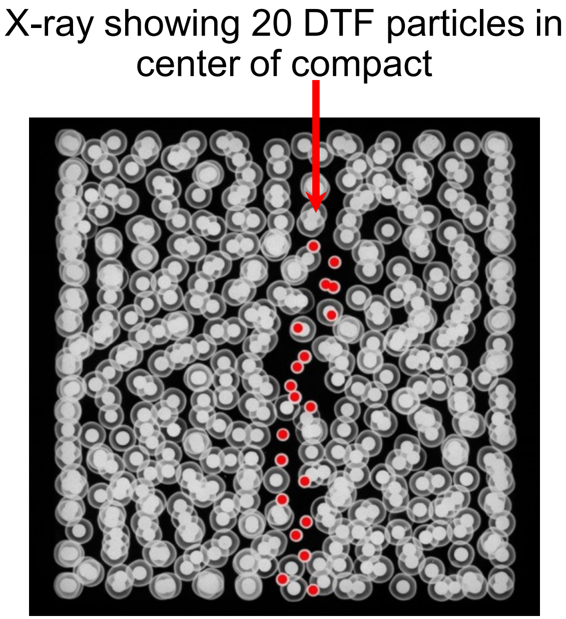
TRISO Fuels and High-Temperature Reactor Source Term

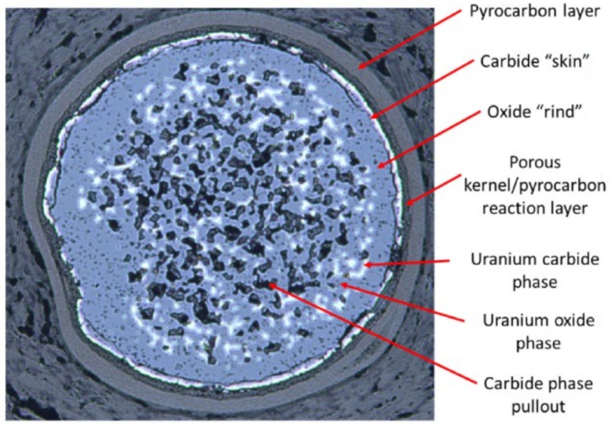
Fission product retention in TRISO fuels starts with the kernel, then the coatings, then the fuel element matrix, then any surrounding structural graphite. AGR-3/4 looks at kernel, matrix and graphite.

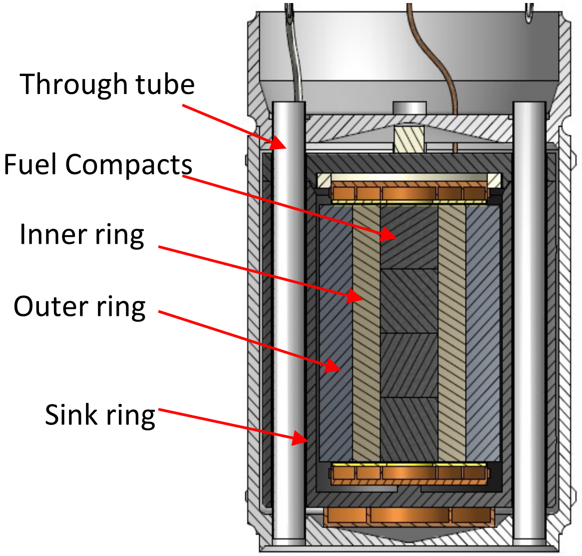


- Philosophy:
  - Integrated mechanistic models: can be very detailed, but fundamental physical constants and validation data are sparse
  - Empirical relationships: grounded in data, but could be harder to justify extension beyond the envelope of data or to modified fuels and conditions (e.g., different kernel chemistries, fuel element matrix, temperatures)
  - A combination of the two?
- Possible simplifications:
  - Add complexity to a source term analysis only as needed
  - For example: Is source term from fuel elements low enough that taking credit for other phenomena, e.g., holdup in reactor building is not necessary?

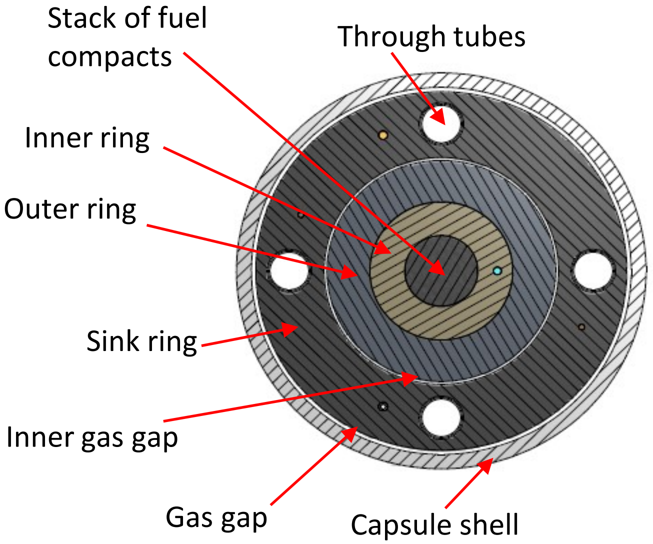
Besides Fuel, Carbon Rings are Key AGR-3/4 Samples







Axial cutaway of an AGR-3/4 capsule



AGR-3/4 capsule cross section

AGR-3/4 Mass Balance Outside of Driver Fuel SiC

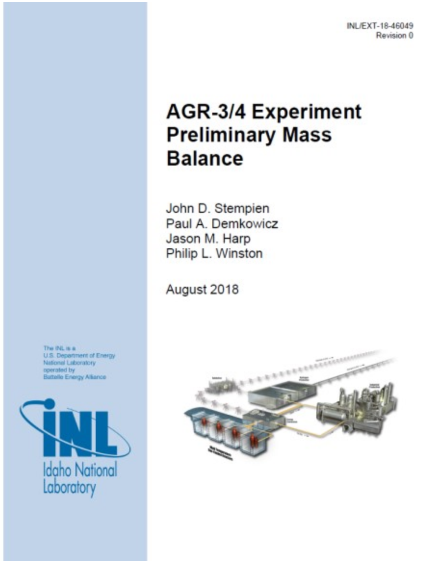
How Much is Released From Compacts During Irradiation? – Mass Balance Completed in 2018

Use this information to adjust the source from PARFUME used in the AGR-3/4 transport model.

Particle Equivalents		Ag-110m	Ce-144	Cs-134	Cs-137	Eu-154	Eu-155	Ru-106	Sr-90[b]
1	Low	2.23E+1	0.00E+0	5.11E+0	9.53E+0	8.10E+0	1.28E+1	0.00E+0	3.51E-2
	High	9.33E+2	1.55E-1	5.14E+0	9.53E+0	4.53E+1	1.38E+1	8.10E-1	3.51E-2
2[a]	Low	0.00E+0	0.00E+0	4.18E+0	9.55E+0	0.00E+0	9.91E+0	0.00E+0	5.58E-2
	High	4.90E+1	1.47E-1	4.18E+0	9.55E+0	1.06E+0	1.32E+1	5.70E-1	5.58E-2
3	Low	5.25E+3	5.54E-2	3.59E+1	4.11E+1	3.53E+1	1.26E+1	0.00E+0	2.33E+0
	High	5.26E+3	2.23E-1	3.59E+1	4.11E+1	4.49E+1	1.58E+1	6.55E-1	2.33E+0
4	Low	5.60E+2	0.00E+0	7.21E+1	7.32E+1	0.00E+0	1.88E+1	0.00E+0	7.75E-2
	High	5.67E+2	2.33E-1	7.21E+1	7.32E+1	1.44E+1	1.92E+1	2.08E-1	7.75E-2
5	Low	3.36E+1	8.69E-2	6.34E+1	6.05E+1	0.00E+0	0.00E+0	0.00E+0	3.51E-2
	High	4.63E+1	1.86E-1	6.34E+1	6.05E+1	1.27E+1	3.03E+0	3.25E-1	3.51E-2
6[a]	Low	1.29E+1	0.00E+0	3.28E+0	4.74E+0	2.33E-3	0.00E+0	0.00E+0	2.57E-2
	High	3.47E+1	1.95E-1	3.29E+0	4.74E+0	6.47E-1	3.41E+0	4.74E-1	2.57E-2
7	Low	7.65E+3	0.00E+0	4.52E+1	4.96E+1	2.33E+2	4.17E+0	7.75E-3	3.33E+0
	High	7.65E+3	1.10E-1	4.52E+1	4.96E+1	2.40E+2	6.52E+0	3.83E-1	3.33E+0
8	Low	6.67E+3	1.69E-2	5.23E+1	6.02E+1	1.11E+1	2.96E+0	2.11E-2	7.09E-1
	High	6.68E+3	1.32E-1	5.23E+1	6.02E+1	1.92E+1	5.87E+0	3.41E-1	7.09E-1
9[a]	Low	3.14E+1	0.00E+0	2.20E+0	5.07E+0	2.22E+0	1.05E+1	1.43E-2	3.56E-2
	High	6.43E+1	1.83E-1	2.20E+0	5.07E+0	3.78E+0	1.14E+1	9.48E-1	3.56E-2
10	Low	5.52E+3	7.50E-3	4.34E+1	5.03E+1	9.15E+0	4.61E+0	2.44E-2	2.10E+0
	High	5.52E+3	1.32E-1	4.34E+1	5.03E+1	9.96E+0	7.54E+0	4.11E-1	2.10E+0
11[a]	Low	4.12E+2	8.81E-3	2.65E+1	3.18E+1	1.99E+1	2.28E+1	0.00E+0	1.14E-1
	High	2.17E+3	2.52E-1	2.65E+1	3.18E+1	2.16E+1	2.36E+1	7.59E-1	1.14E-1
12	Low	0.00E+0	0.00E+0	3.25E+0	1.65E+1	1.69E+1	5.61E+0	6.21E-4	1.38E-1
	High	3.07E+3	2.45E-1	4.67E+0	1.65E+1	1.35E+2	1.18E+1	1.41E+0	1.38E-1

a. Capsules 2, 6, 9, and 11 were intact fuel bodies. The inner and outer ring inventories have not been determined. The mass balance is incomplete in these capsules.
b. Does not include inner and outer ring Sr-90 inventory.

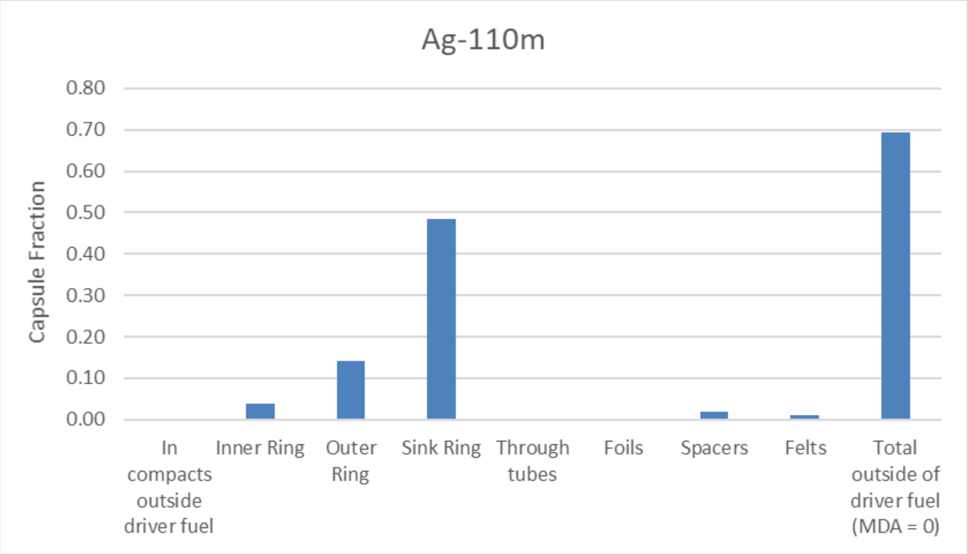
Summary of the fission product inventory measured outside of the fuel expressed units of particle equivalents. "Low" includes measured values only. "High" represents measured values plus particle equivalents calculated from MDAs.

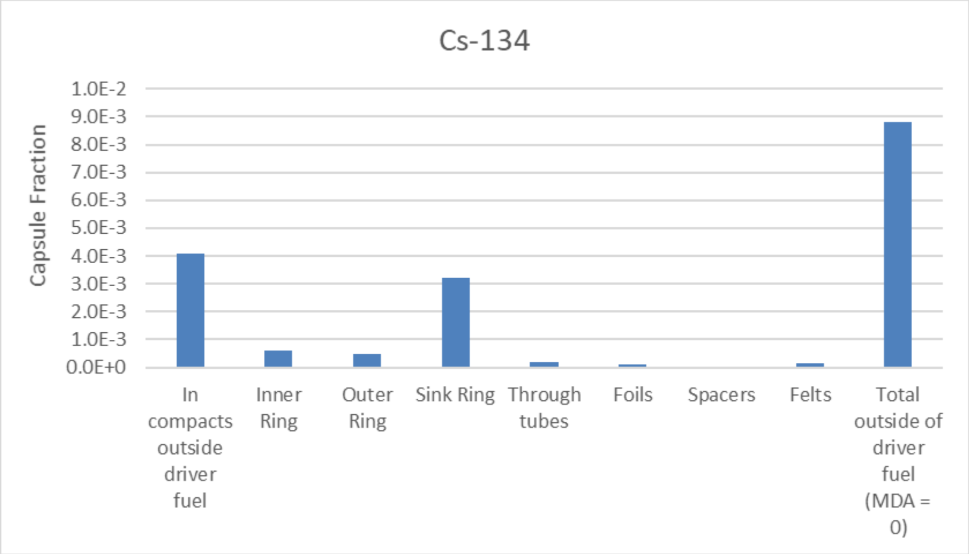


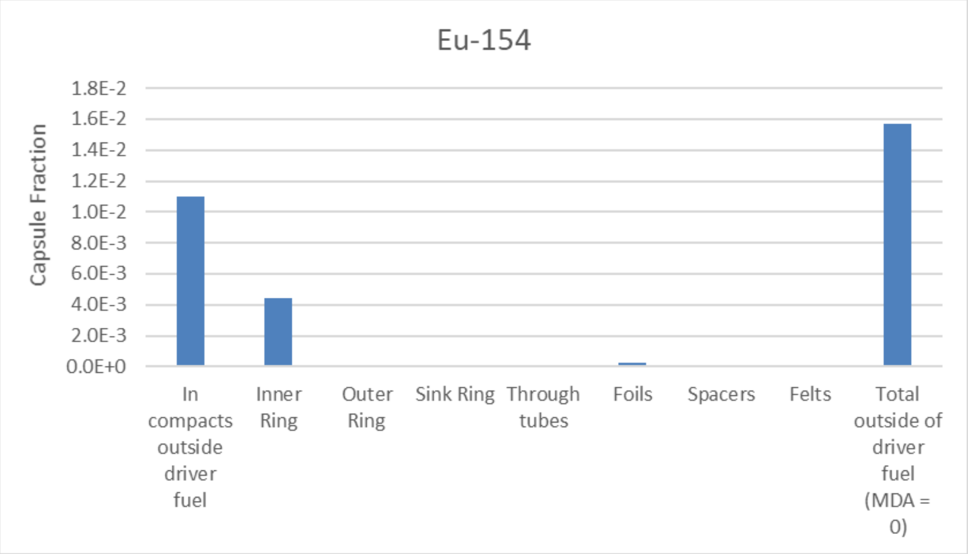
Capsule 3 Selected Summary

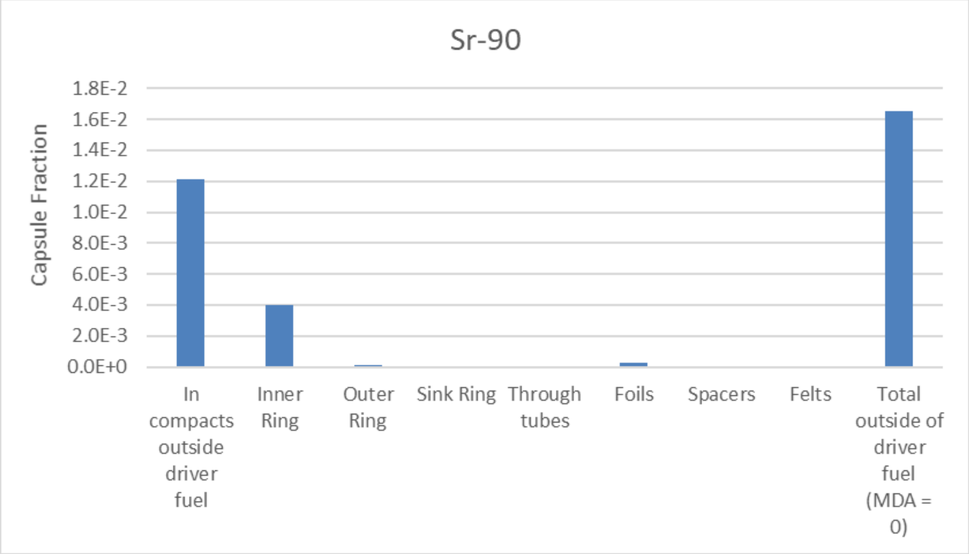
Capsule	Ring	TAVA (ºC)	TA Min (ºC)	TA Peak (ºC)
Capsule 03	Inner	1026	984	1050
	Outer	962	945	976
	Sink	539	504	569

Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
All Capsule 3 compacts		1041	1177	1242





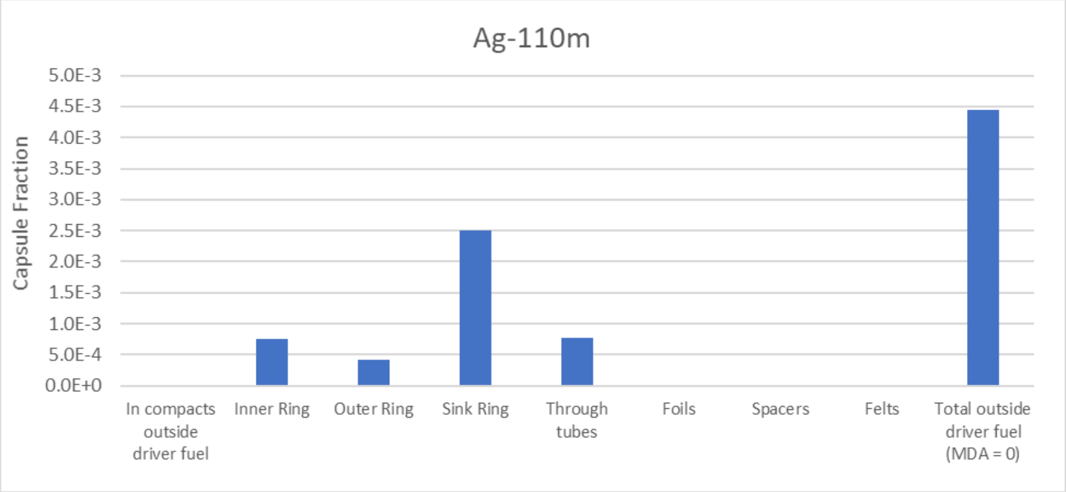


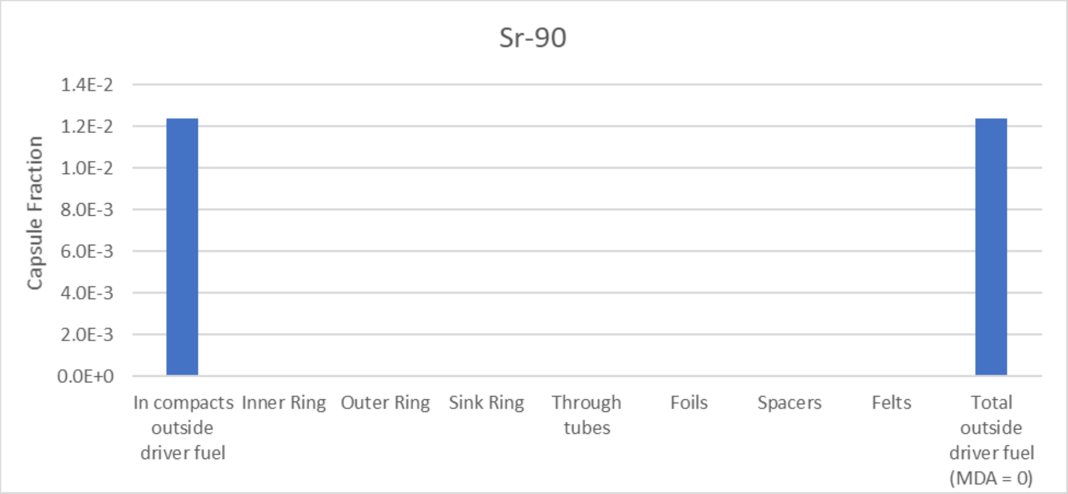


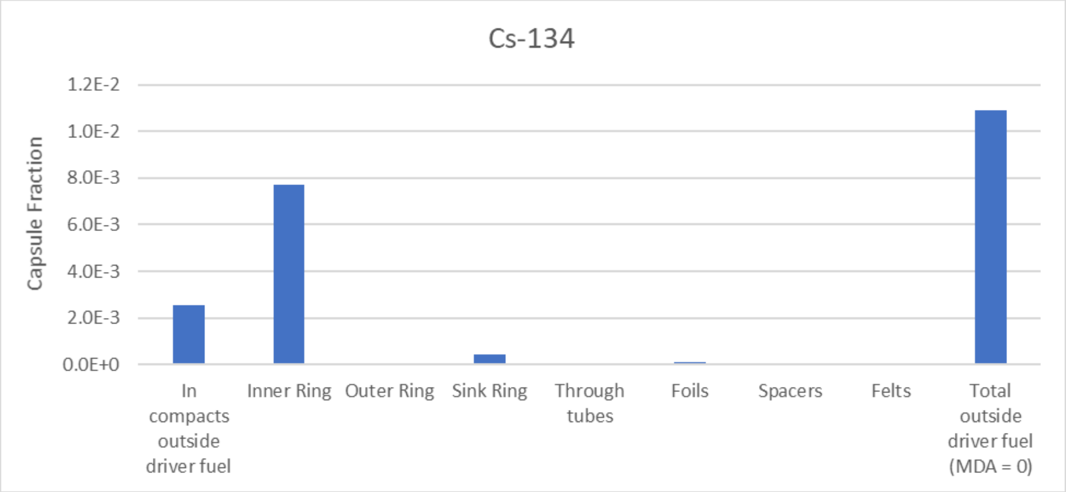
Capsule 5 Selected Summary

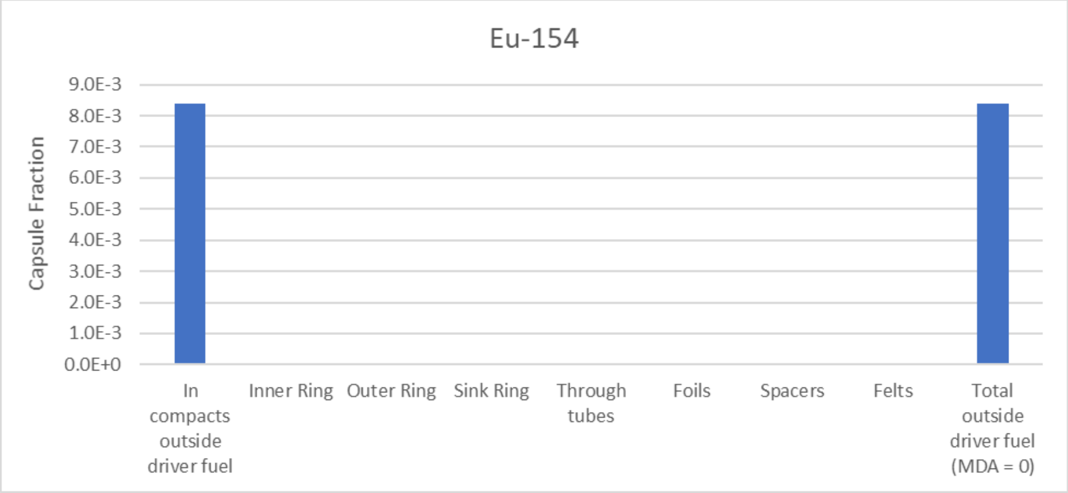
Capsule	Ring	TAVA (°C)	TA Min (°C)	TA Peak (°C)
Capsule 05	Inner	800	732	858
	Outer	677	661	706
	Sink	546	501	589

Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
All Capsule 5 compacts		838	1015	1102





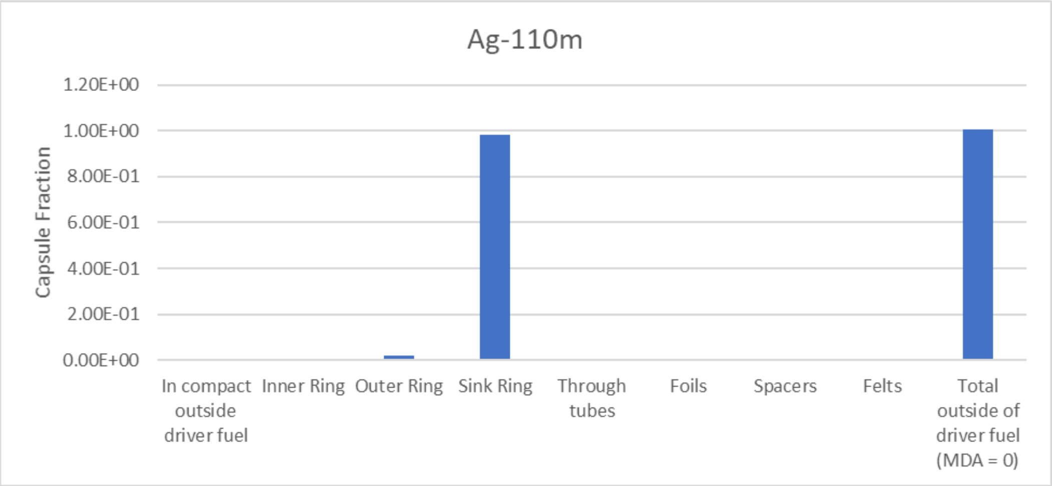


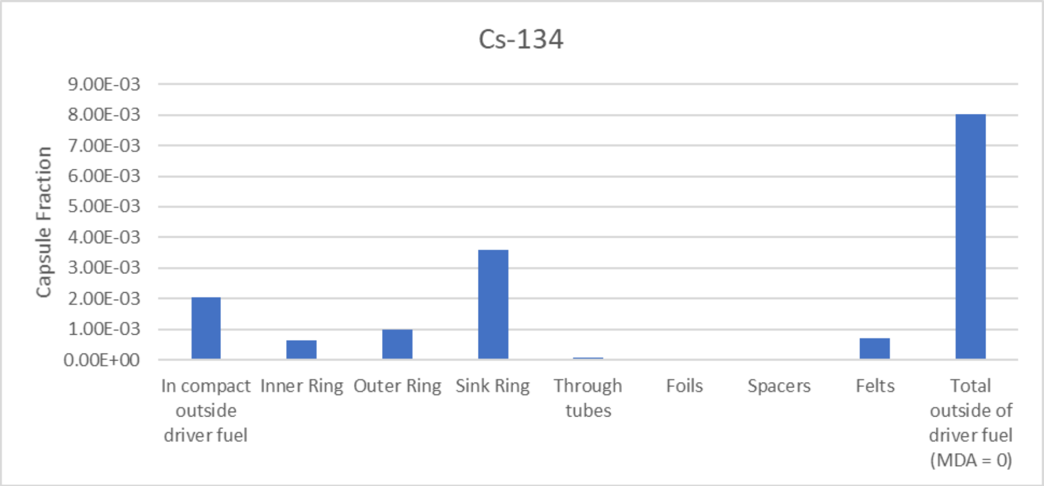


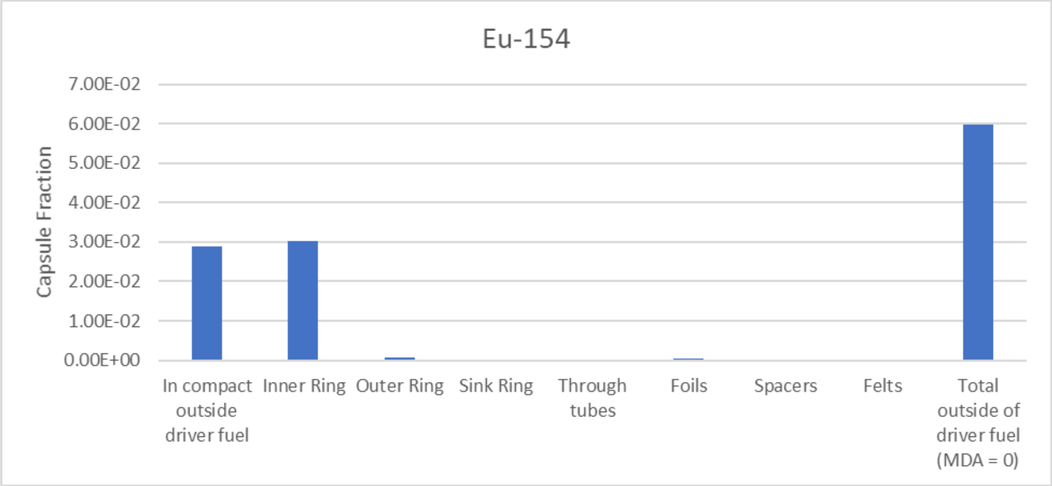
Capsule 7 Selected Summary

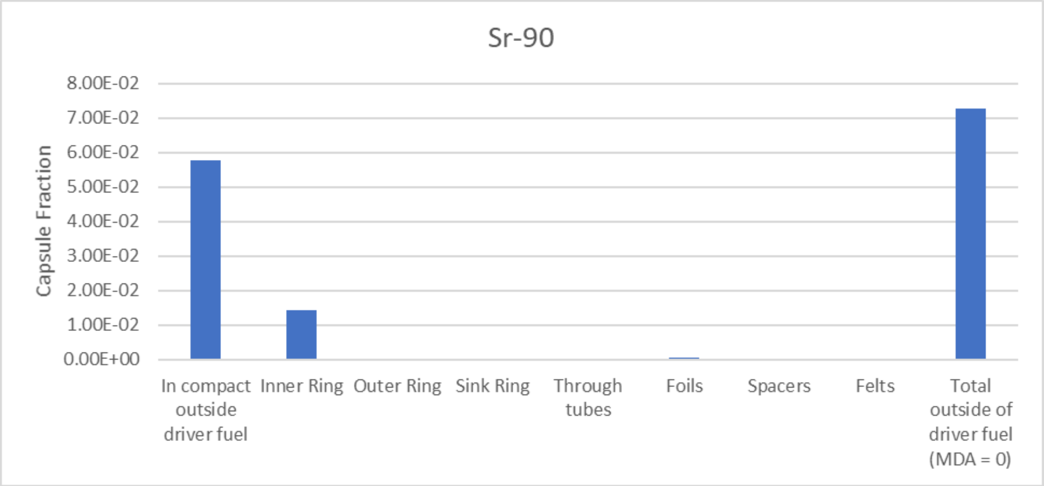
Capsule	Ring	TAVA (°C)	TA Min (°C)	TA Peak (°C)
Capsule 07	Inner	1151	1084	1203
	Outer	1025	1014	1045
	Sink	617	573	659

Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
All Capsule 7 compacts		1197	1345	1418





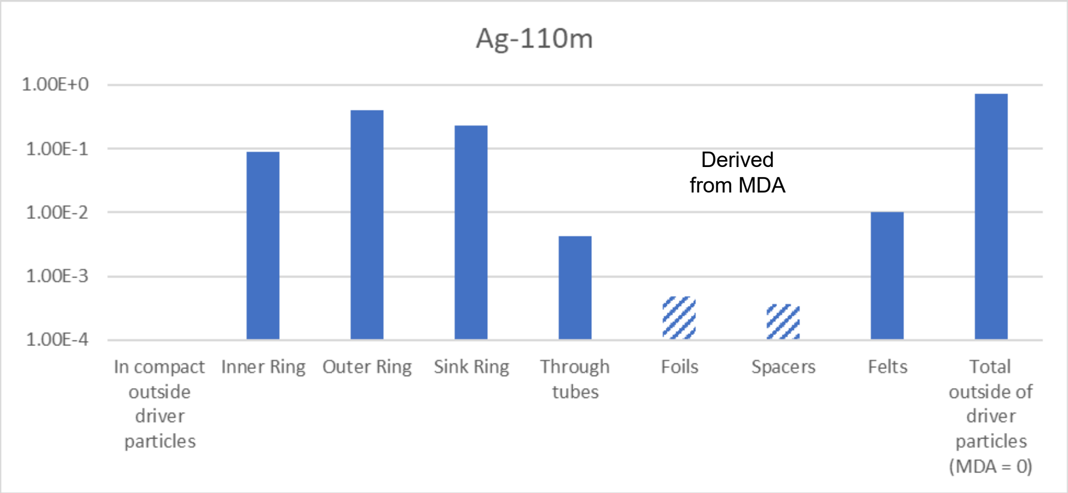


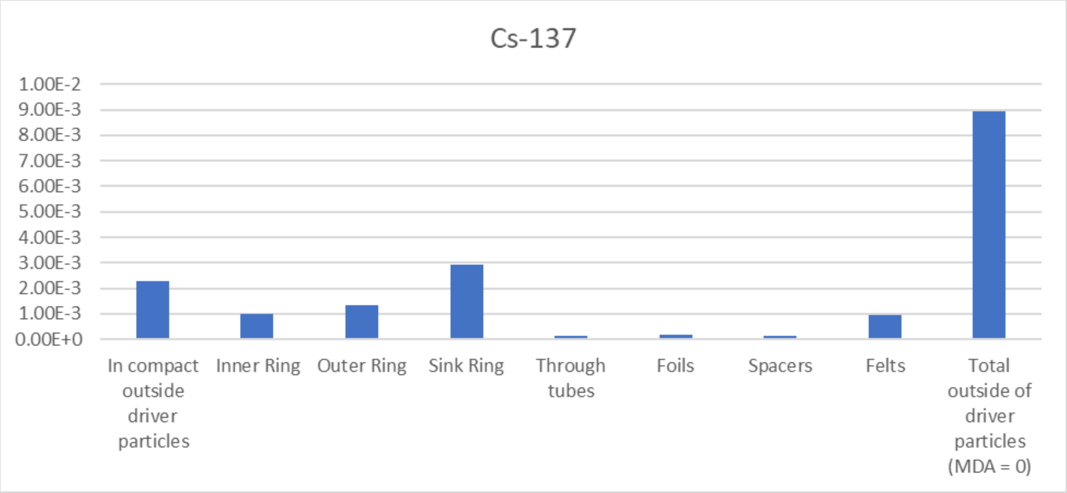


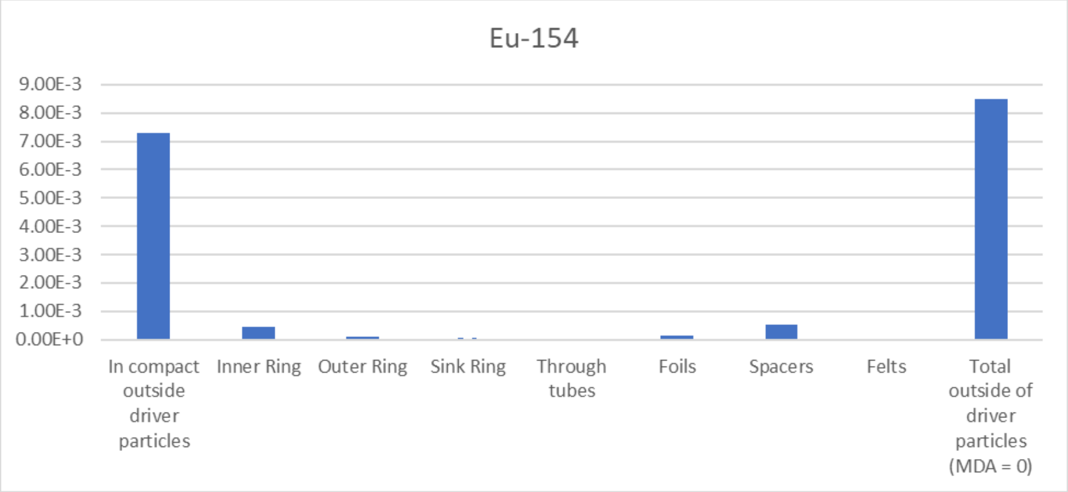
Capsule 10 Selected Summary

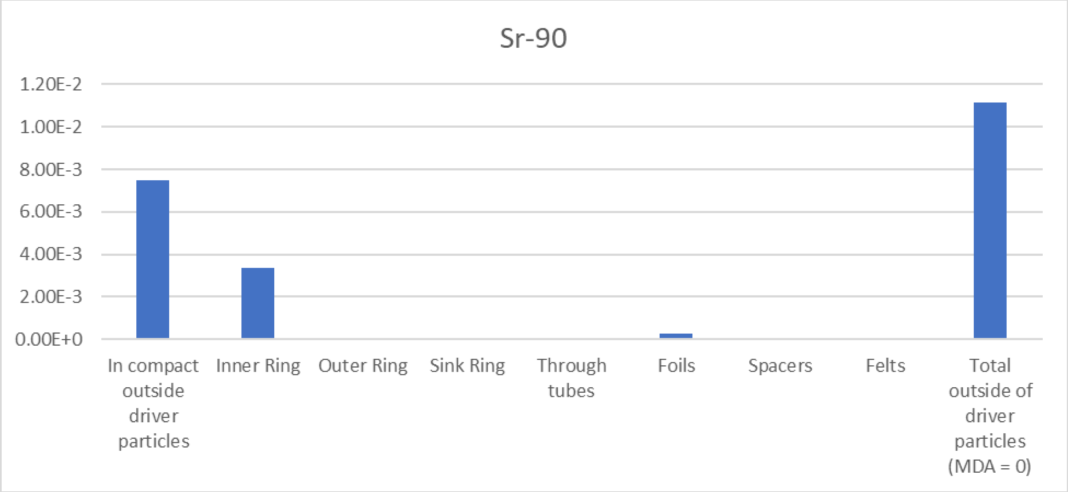
Capsule	Ring	TAVA (°C)	TA Min (°C)	TA Peak (°C)
Capsule 10	Inner	1038	1014	1055
	Outer	971	962	986
	Sink	646	609	678

Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
All Capsule 10 compacts		1079	1191	1249





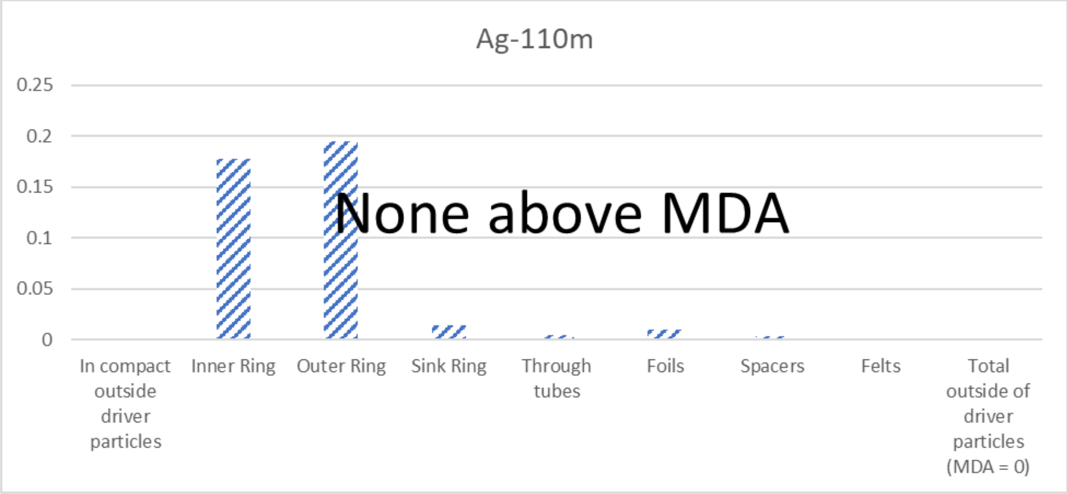


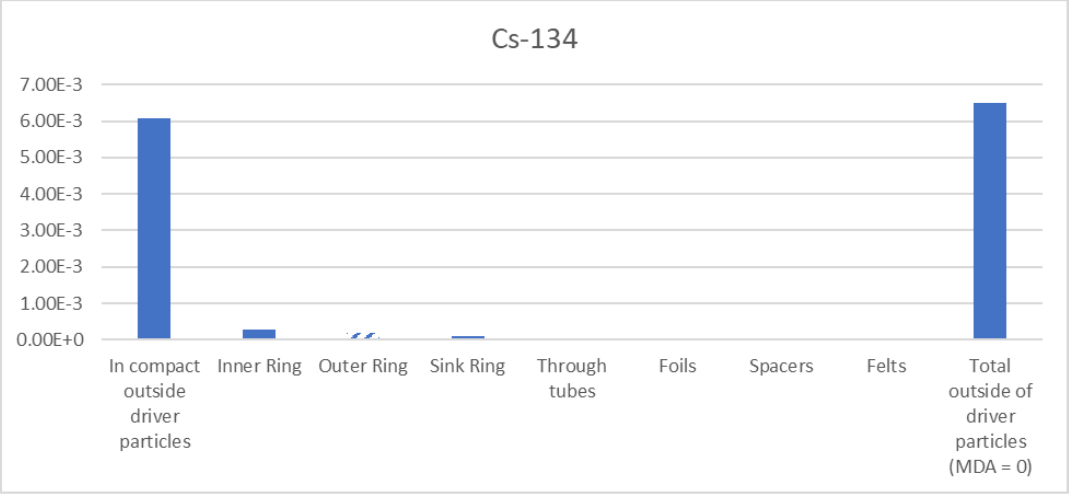


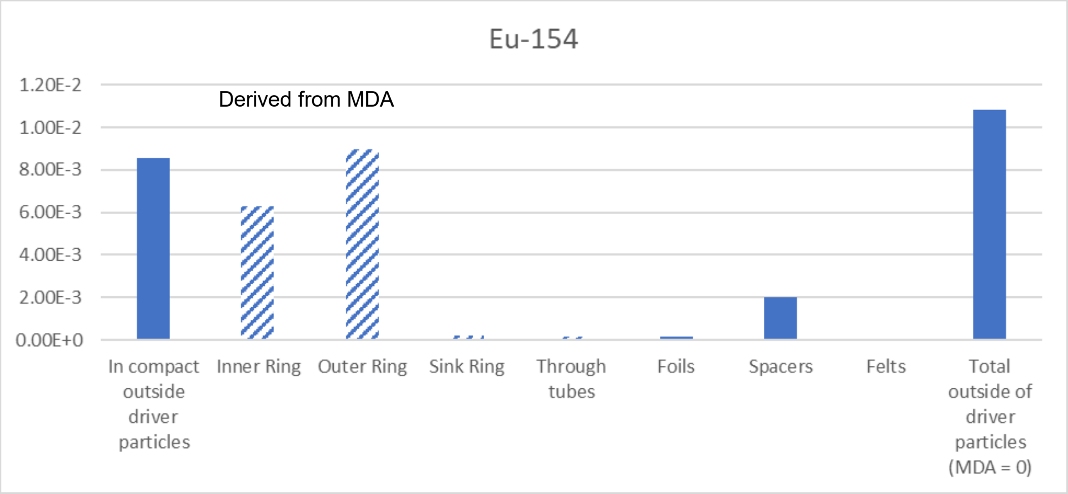
Capsule 12 Selected Summary

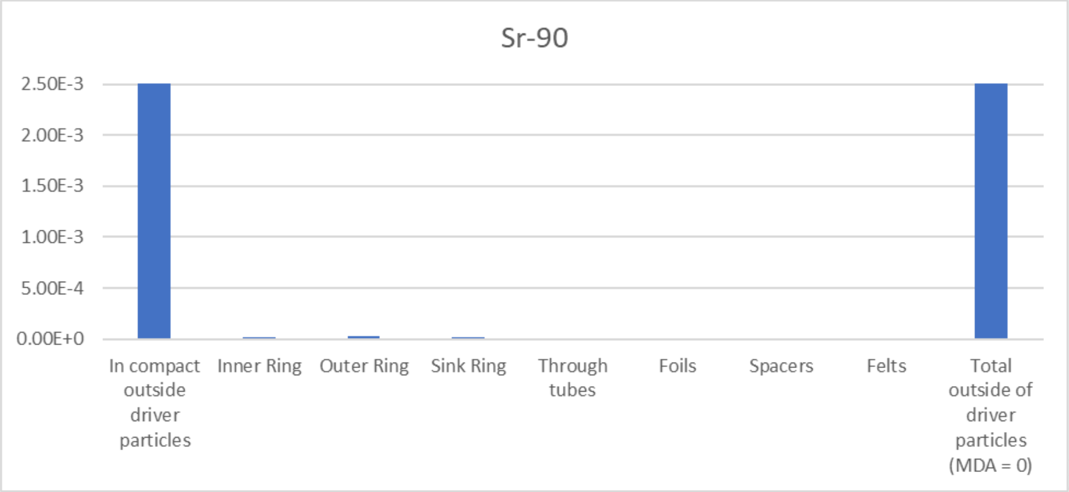
Capsule	Ring	TAVA (°C)	TA Min (°C)	TA Peak (°C)
Capsule 12	Inner	782	754	802
	Outer	741	735	748
	Sink	505	483	519

Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
All Capsule 12 compacts		790	854	888



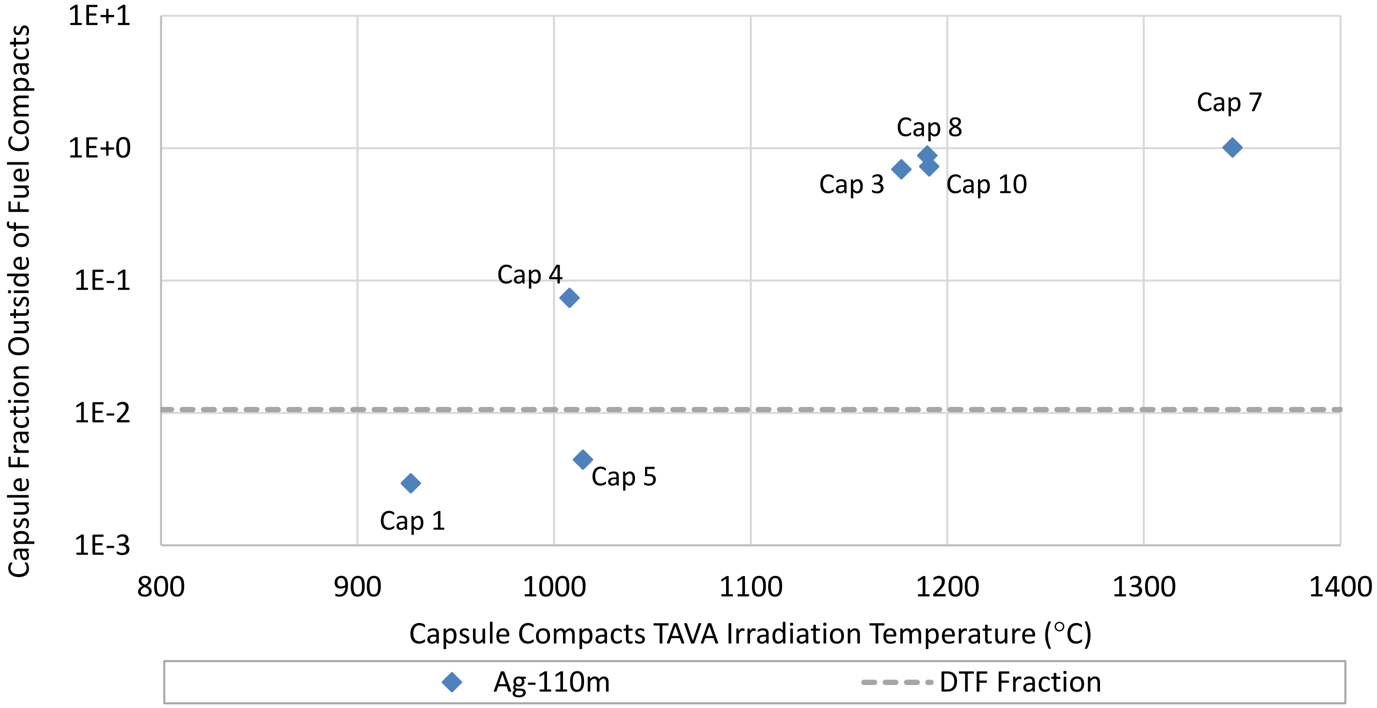






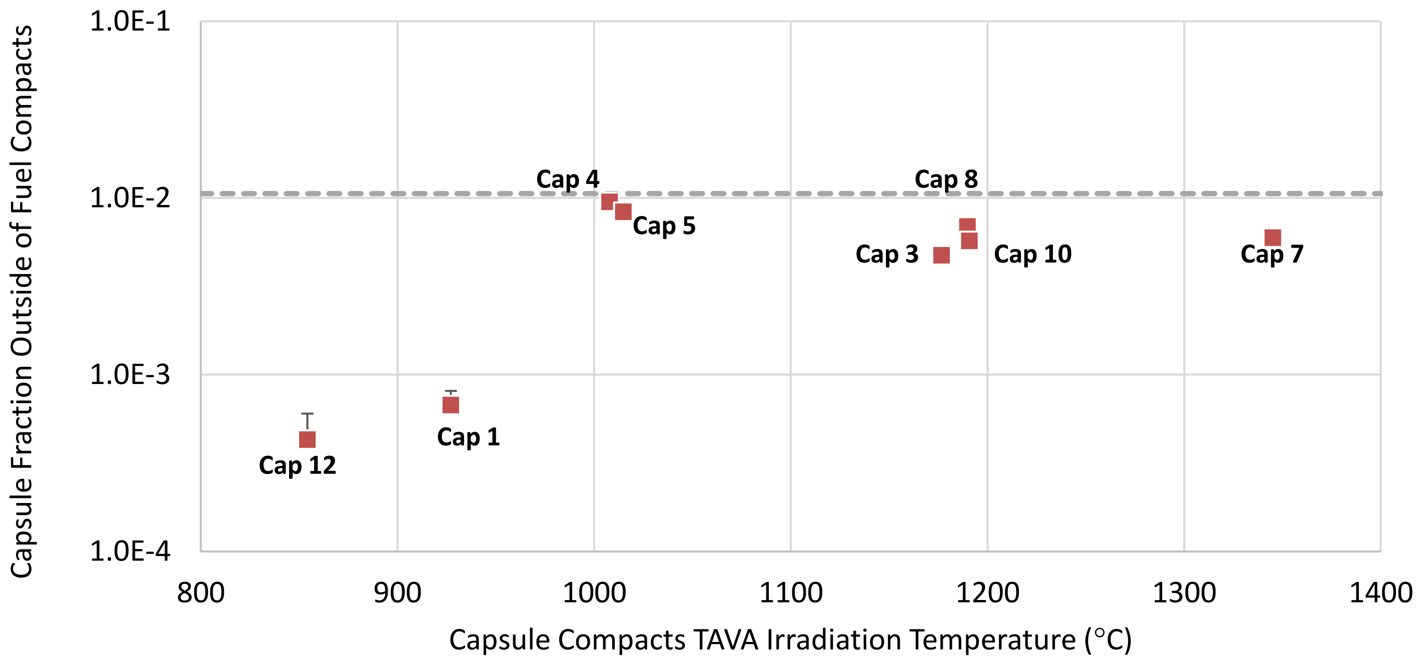
Ag-110m Release Versus Temperature

- Total release increases with temperature, 70-100% compact release at T ≥1200°C
- Total release increases sharply above irradiation temperatures ~1100°C
- Exceeds DTF fraction meaning release through intact TRISO driver particles contribute to release



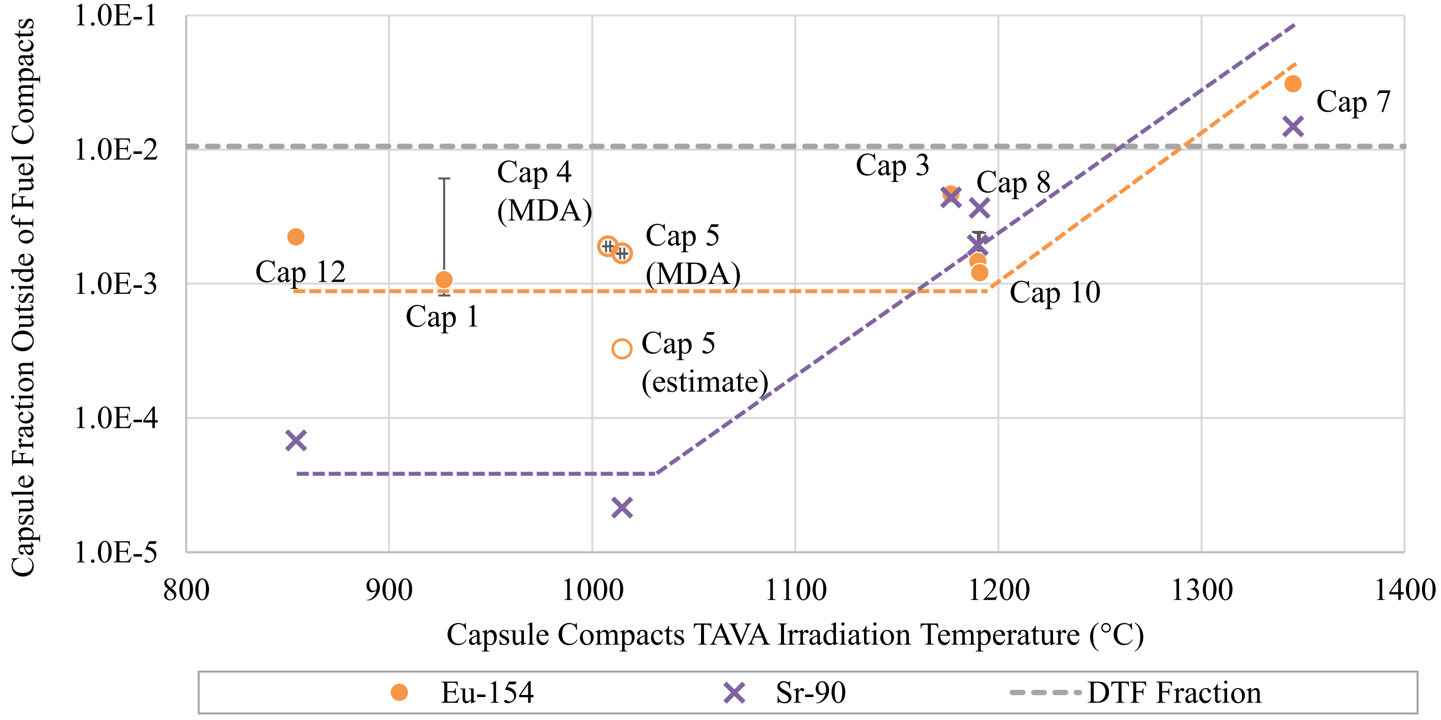
Mass Balance of Cs-134 Outside of Fuel Compacts

- Cs release from compacts is 55-95% of the DTF inventory for irradiation temperatures T ≥ 1000°C
- For T < 1000°C the compact retains about 90% of the DTF inventory



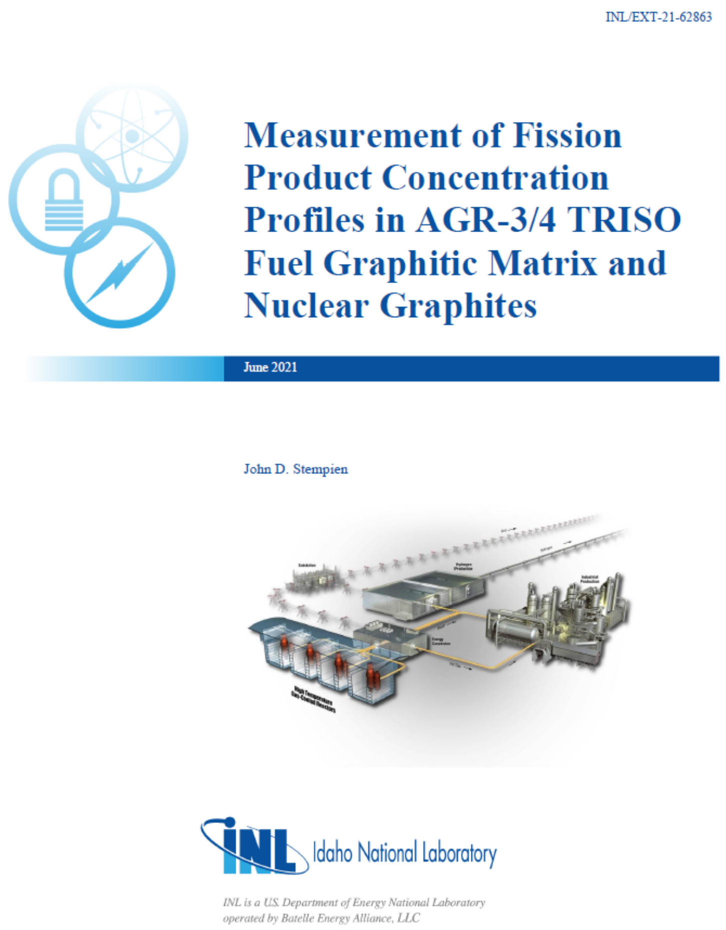
Mass Balance of Sr-90 and Eu-154 Outside of Fuel Compacts

- Capsule 7 releases > DTF fraction means release through intact driver particles.
- Accelerated Eu-154 release starting above ~1200°C (also seen in AGR-2)
- Sr-90 and Eu-154 releases similar in Capsules 3, 8, and 7
- Both Sr-90 and Eu-154 seem to have somewhat of a temperature threshold for faster release.



Physical Sampling of Irradiated Rings to Measure Fission Product Concentration Profiles

Completed Report on Measurement of Fission Product Concentration Profiles in all Carbon Rings in FY2021*



INL/EXT-21-62863

Measurement of Fission Product Concentration Profiles in AGR-3/4 TRISO Fuel Graphitic Matrix and Nuclear Graphites

June 2021

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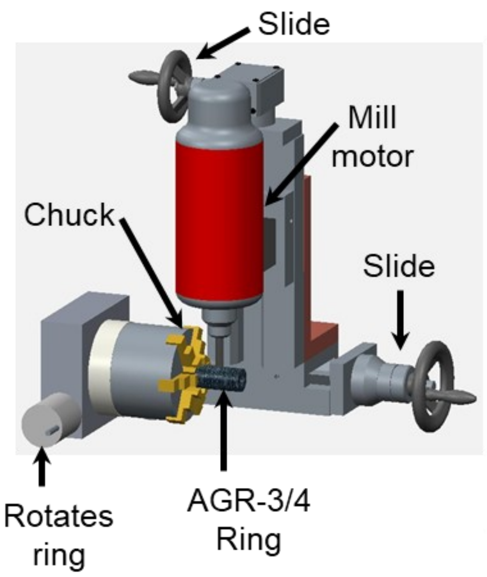
Idaho National Laboratory

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

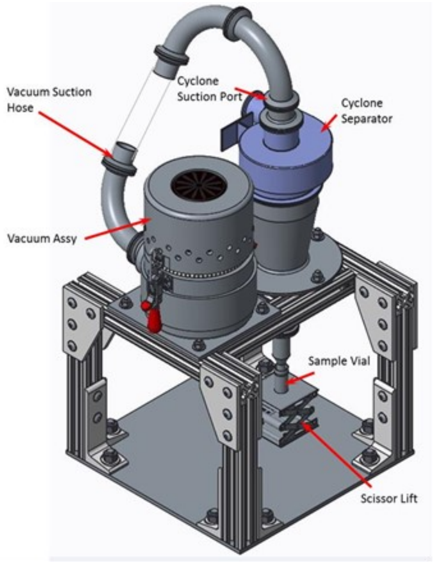
*added 1 additional ring for analysis of possible axial transport

Physical Sampling for Fission Product Concentration Profiles in Graphite and Graphitic Matrix

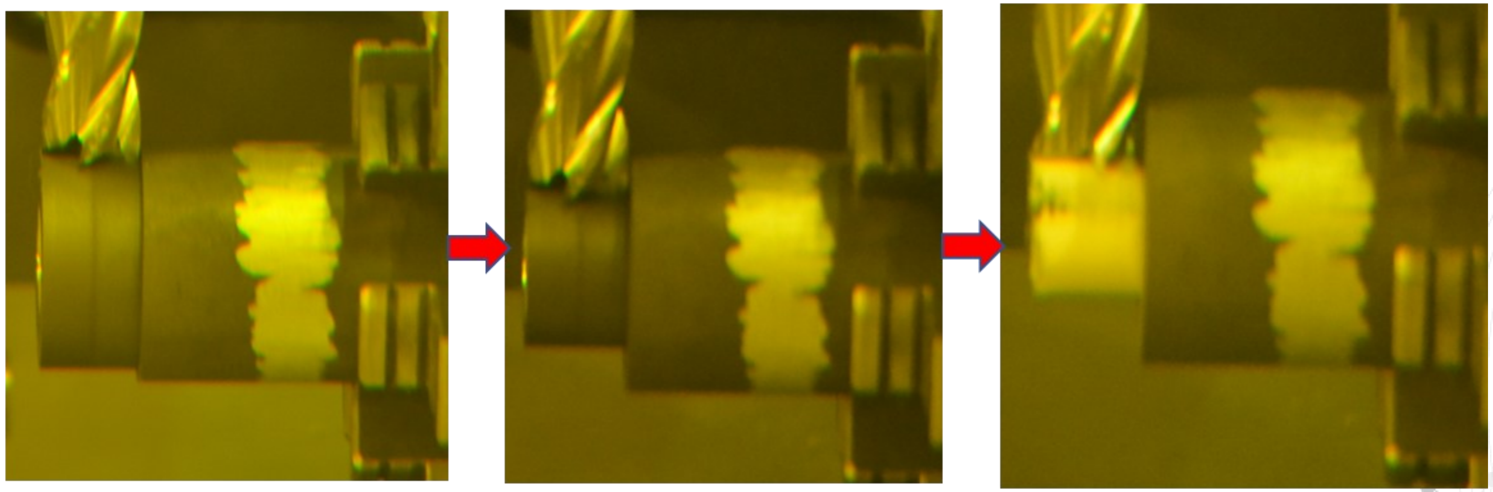
- Machining samples from the graphite rings to measure fission product radial profiles within rings
  - Progressively remove radial segments from rings at one or two axial locations
  - Collected material is gamma scanned and burn-leached for Sr-90 analysis
  - Refine models, compare to PGS, and derive transport parameters (e.g., diffusion coefficients) for FPs in graphite



Material Removal



Fines Collection



Images of IR-08 at beginning, middle, and end of sampling

Capsule 3 Ring Profiles

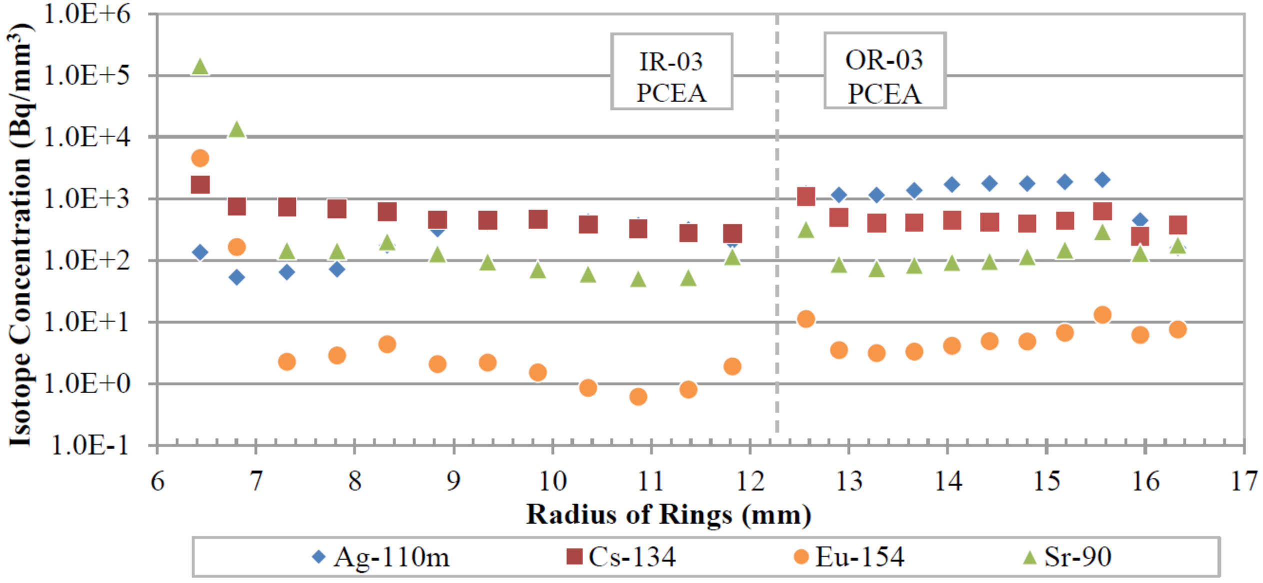


Figure 15. Radial profiles for select fission products at the axial top of the Capsule 3 rings.

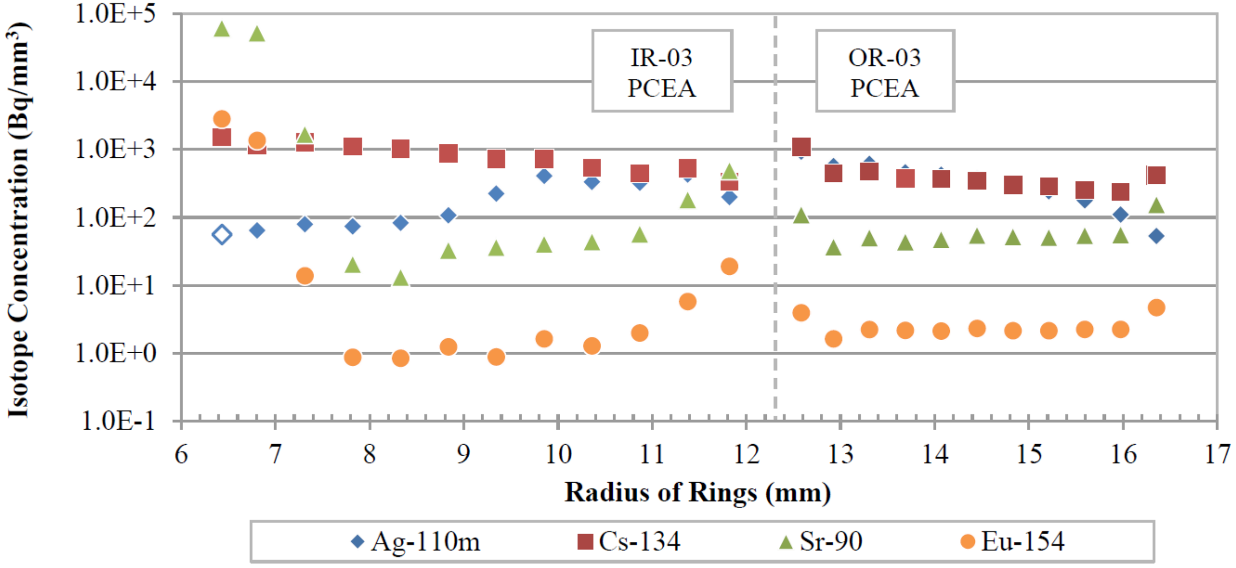


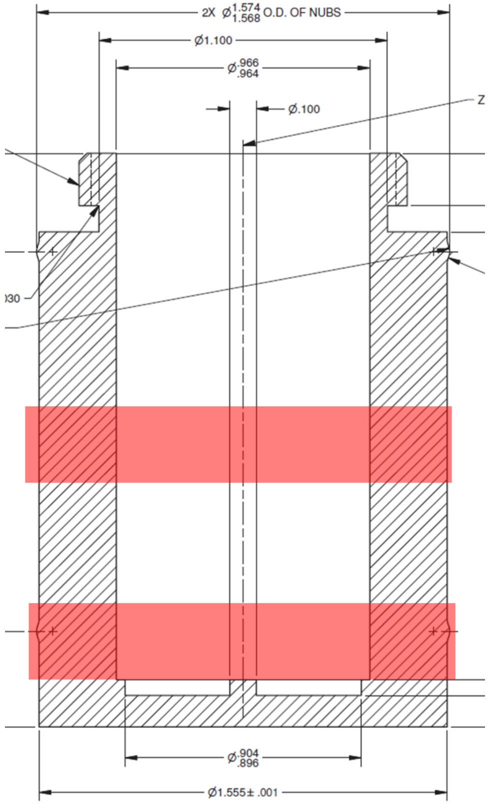
Figure 16. Radial profiles for select fission products at the axial center of the Capsule 3 IRs and ORs. The open symbol for Ag-110m at x = 6.4 mm denotes a value derived from an MDA.

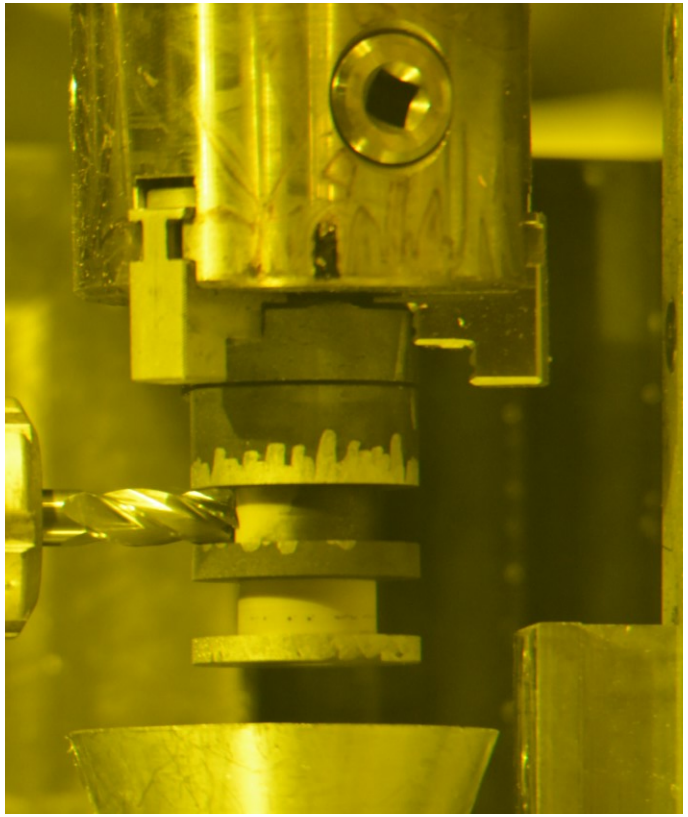
- Compacts TAVA temp: 1177°C
- Inner ring:
  - PCEA
  - TAVA temp: 1026°C
- Outer ring:
  - PCEA
  - TAVA temp: 962°C

Capsule 4 Rings (disassembled fuel body)

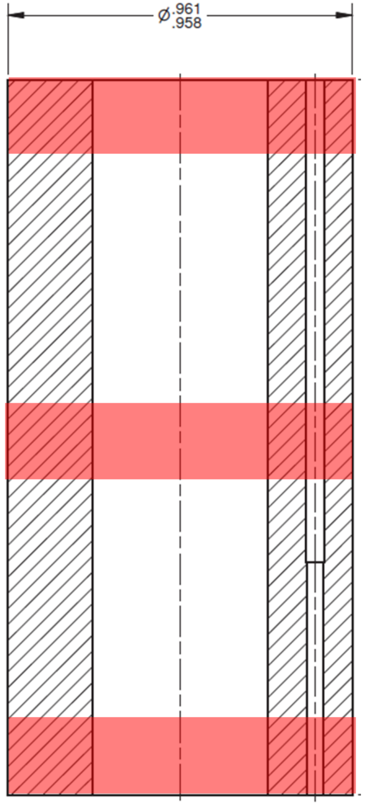
- Destructively sampled in FY22 after recommendation in Summer 2021 to analyze for axial transport
- Samples sent to Pacific Northwest National Laboratory in April 2022
- Expect results in late FY22 or Q1 in FY23

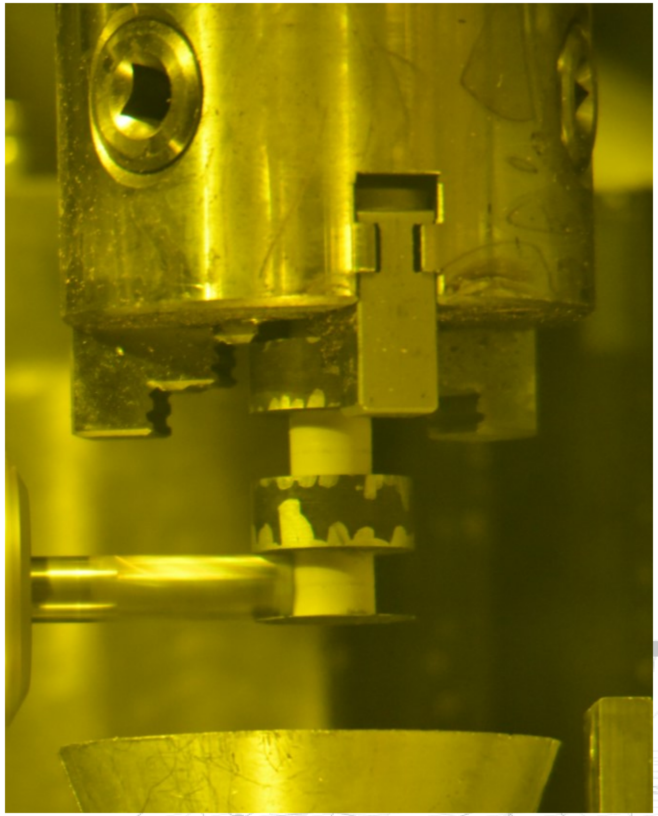
Outer Ring Samples Taken at Two Locations





Inner Ring Samples Taken at Three Locations





Capsule 5 Ring Profiles

- Compacts TAVA temp: 1015°C
- Inner ring:
  - Matrix A3-27
  - TAVA temp: 800°C
- Outer ring:
  - PCEA
  - TAVA temp: 677°C

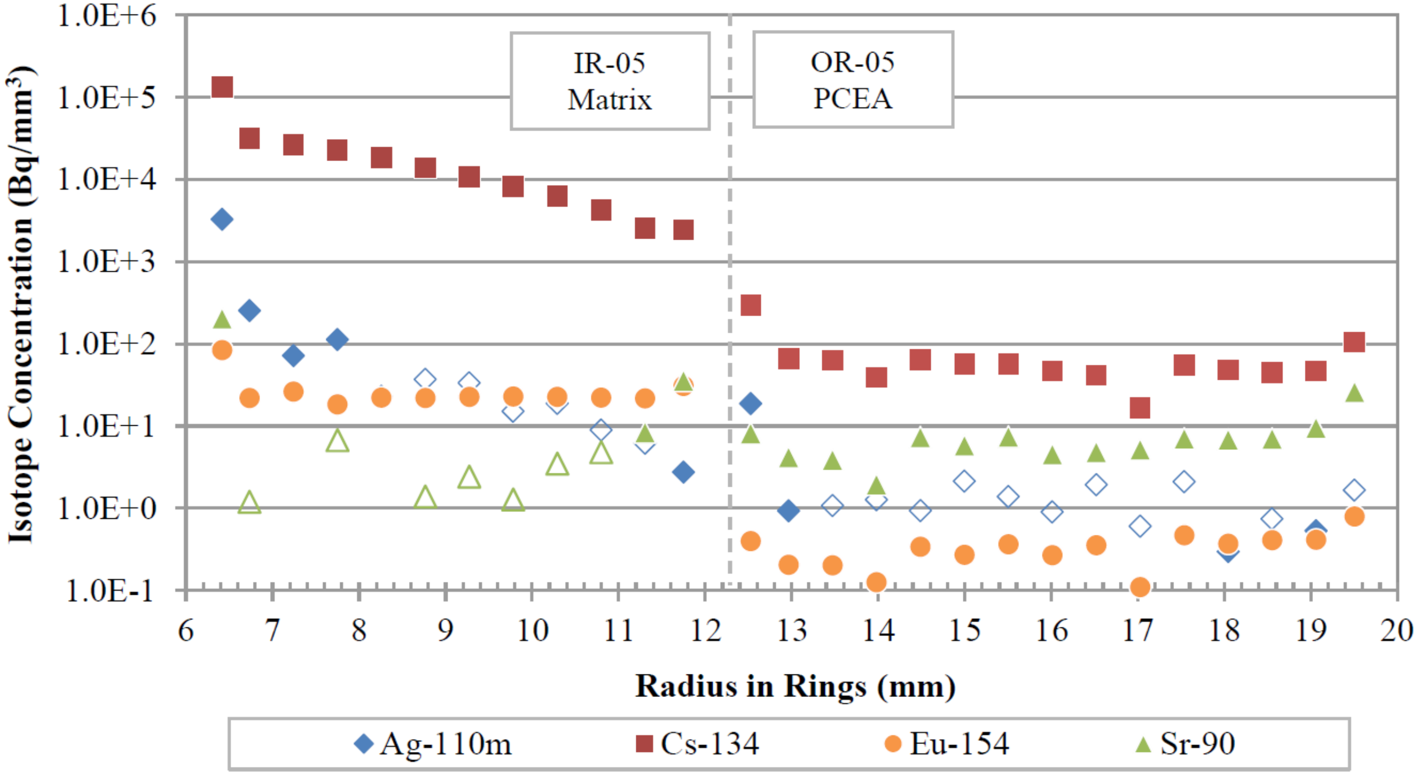


Figure 22. Radial profiles for select fission products at the axial center of the Capsule 5 IR and OR. The open symbols denote values derived from MDAs.

Capsule 7 Ring Profiles

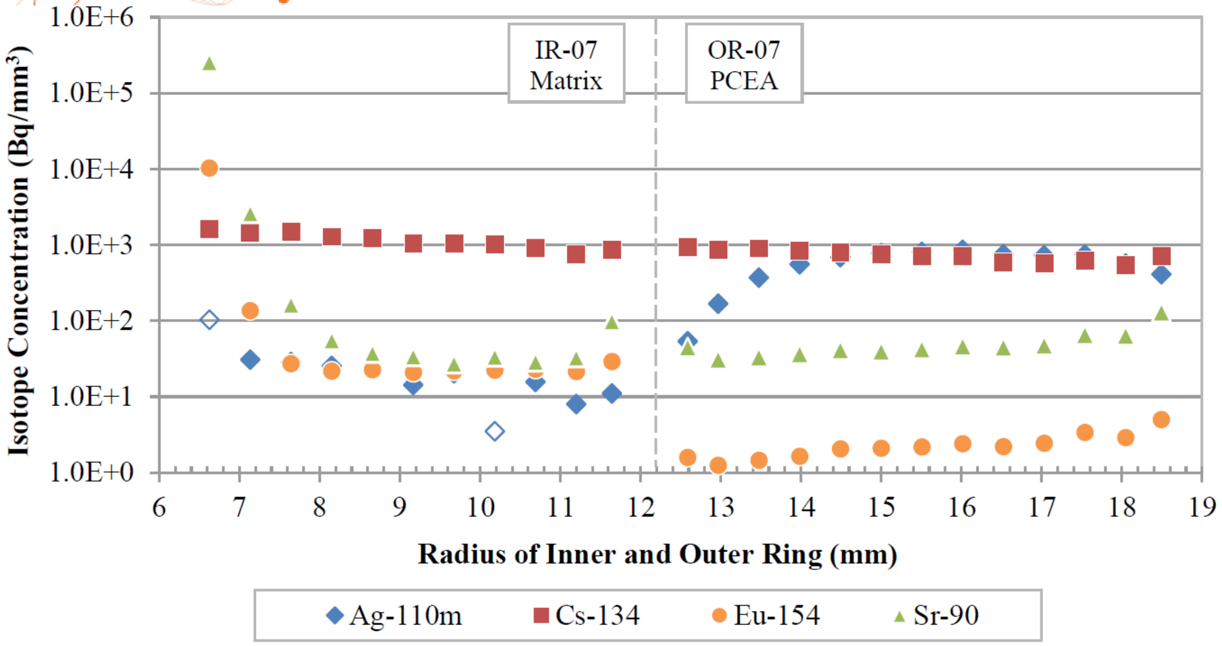


Figure 26. Radial profiles for select fission products at the axial top of the Capsule 7 IR and OR. The open symbols denote values derived from MDAs.

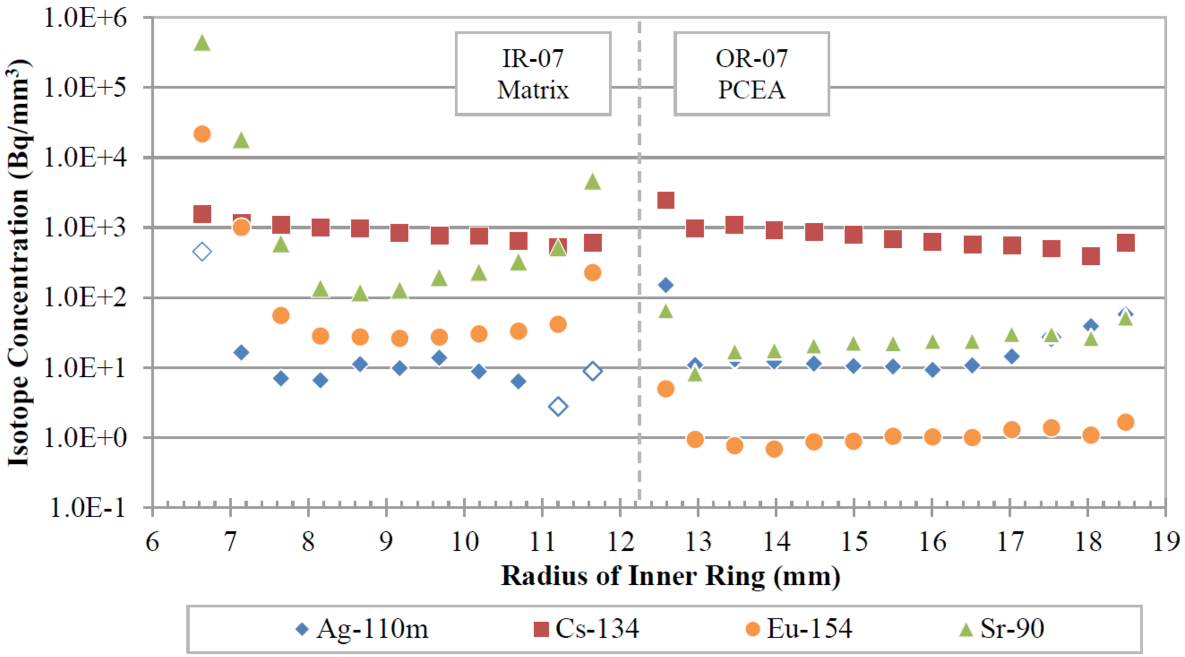


Figure 27. Radial profiles for select fission products at the axial center of the Capsule 7 IR and OR. The open symbols denote values derived from MDAs.

- Compacts TAVA temp: 1345°C
- Inner ring:
  - Matrix A3-27
  - TAVA temp: 1151°C
- Outer ring:
  - PCEA
  - TAVA temp: 1025°C

Capsule 8 Ring Profiles

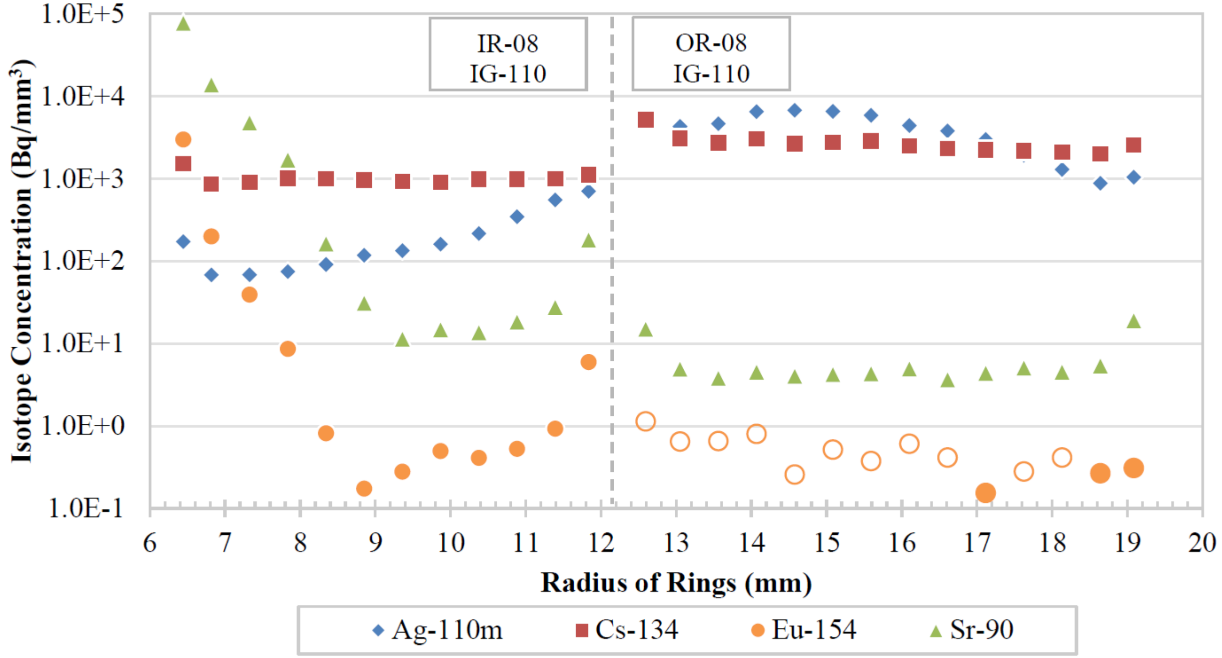


Figure 31. Radial profiles for select fission products at the axial center of the Capsule 8 IR and OR. The open symbols denote values derived from MDAs.

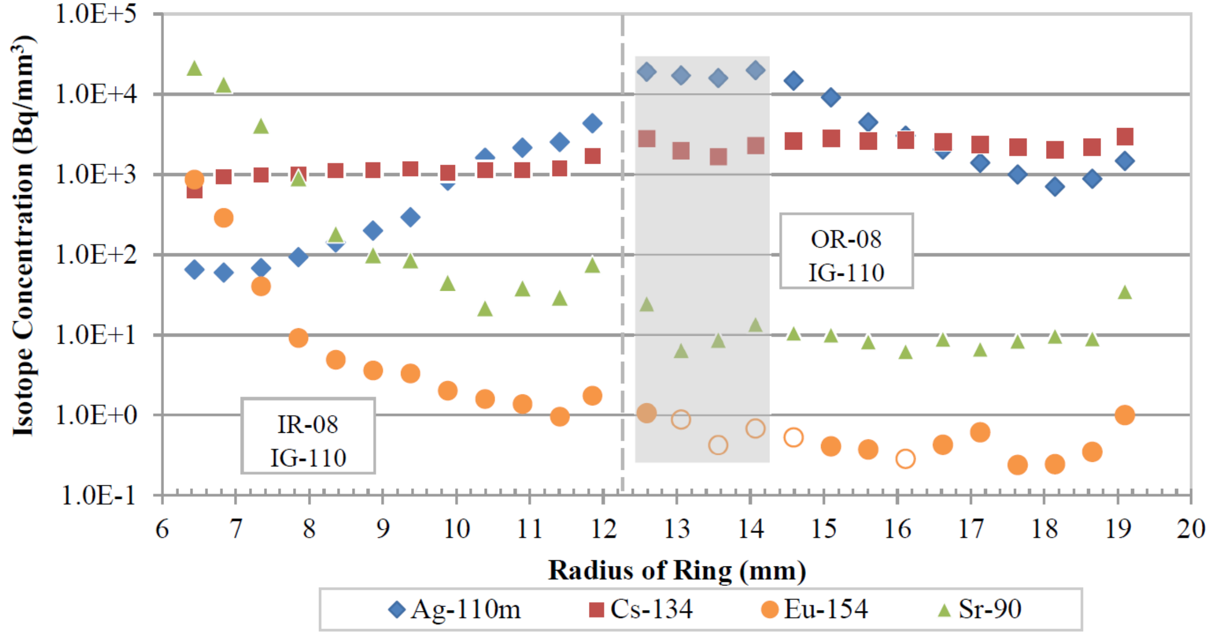


Figure 32. Radial profiles for select fission products at the axial bottom of the Capsule 8 IR and OR. The open symbols denote values derived from MDAs. Gray shading highlights points with greater uncertainty from ring cracking during sampling.

- Compacts TAVA temp: 1190°C
- Inner ring:
  - IG-110
  - TAVA temp: 1021°C
- Outer ring:
  - IG-110
  - TAVA temp: 917°C

Capsule 10 Ring Profiles

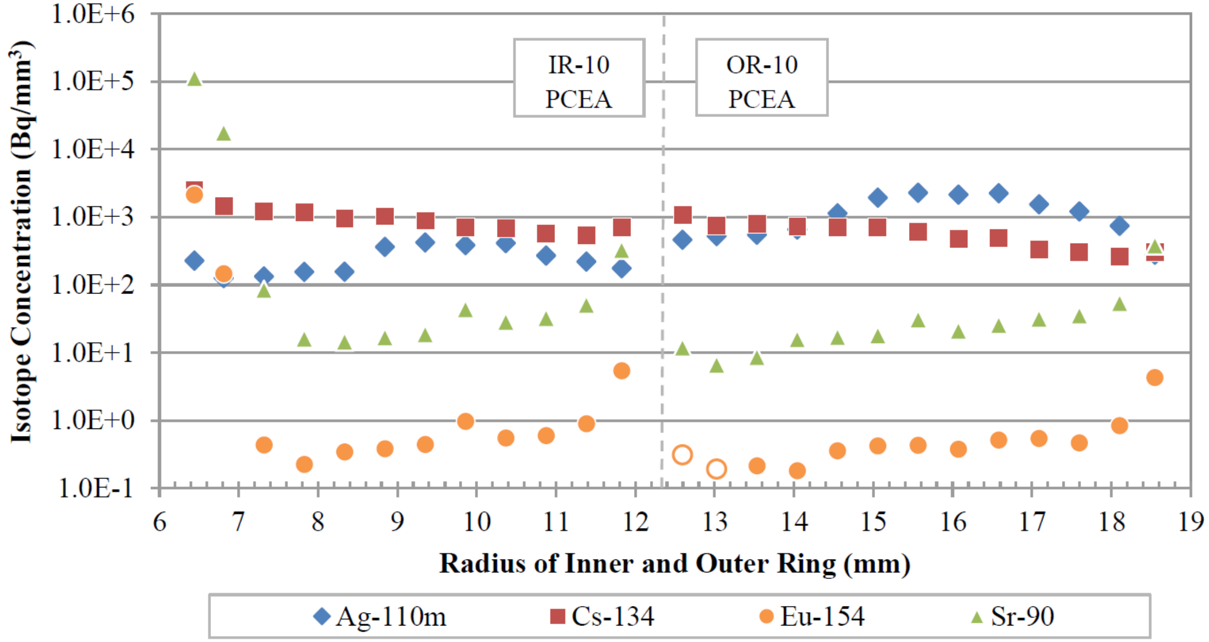


Figure 38. Radial profiles for select fission products at the axial center of the Capsule 10 IR and OR. The open symbols denote values derived from MDAs.

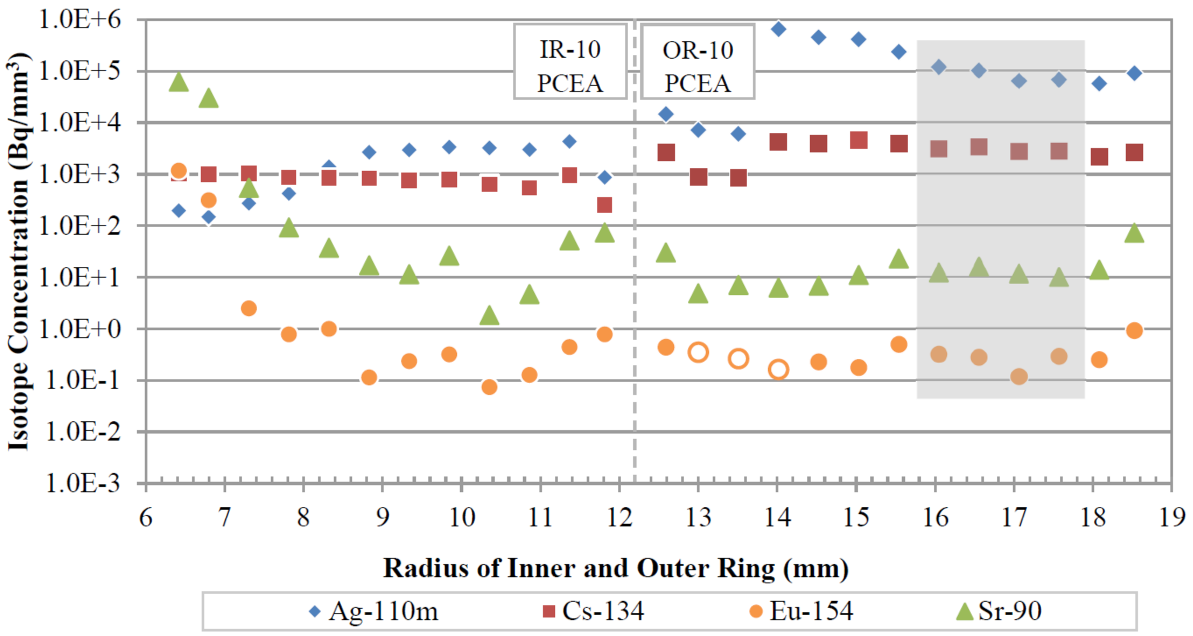


Figure 39. Radial profiles for select fission products at the axial bottom of the Capsule 10 IR and OR. The open symbols denote values derived from MDAs. Gray shading highlights the points with greater uncertainty from ring movement during sampling.

- Compacts TAVA temp: 1191°C
- Inner ring:
  - PCEA
  - TAVA temp: 1038°C
- Outer ring:
  - PCEA
  - TAVA temp: 971°C

Capsule 12 Ring Profiles

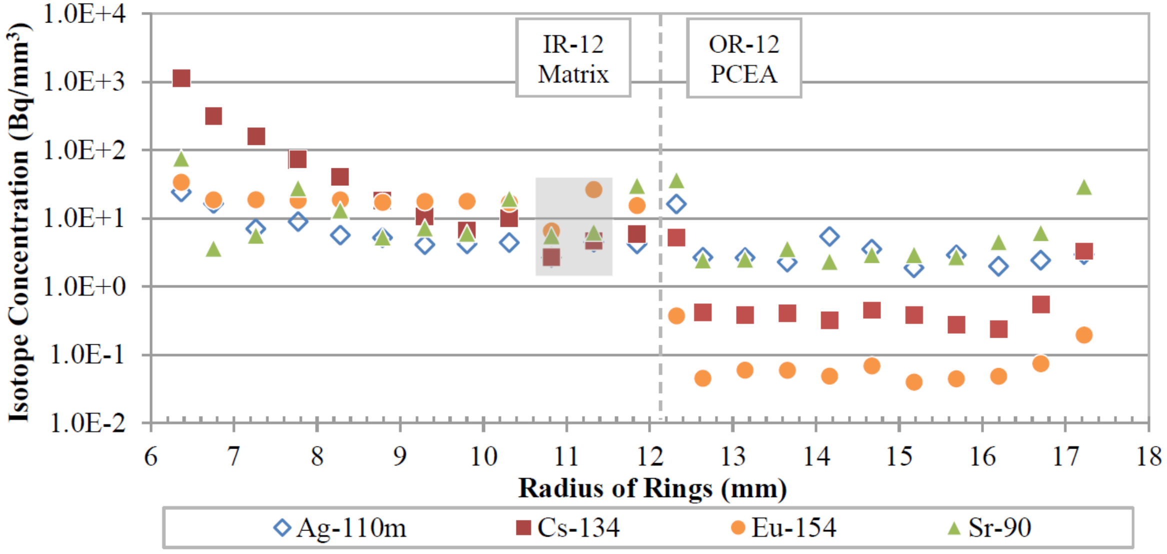


Figure 45. Radial profiles for select fission products at the axial center of the Capsule 12 IR and OR. The open symbols denote values derived from MDAs. Gray shading shows the IR-12 segments where roughly 60% of the third segment (around x = 10.8 mm) was collected in the vial for the second segment (around x = 11.4 mm).

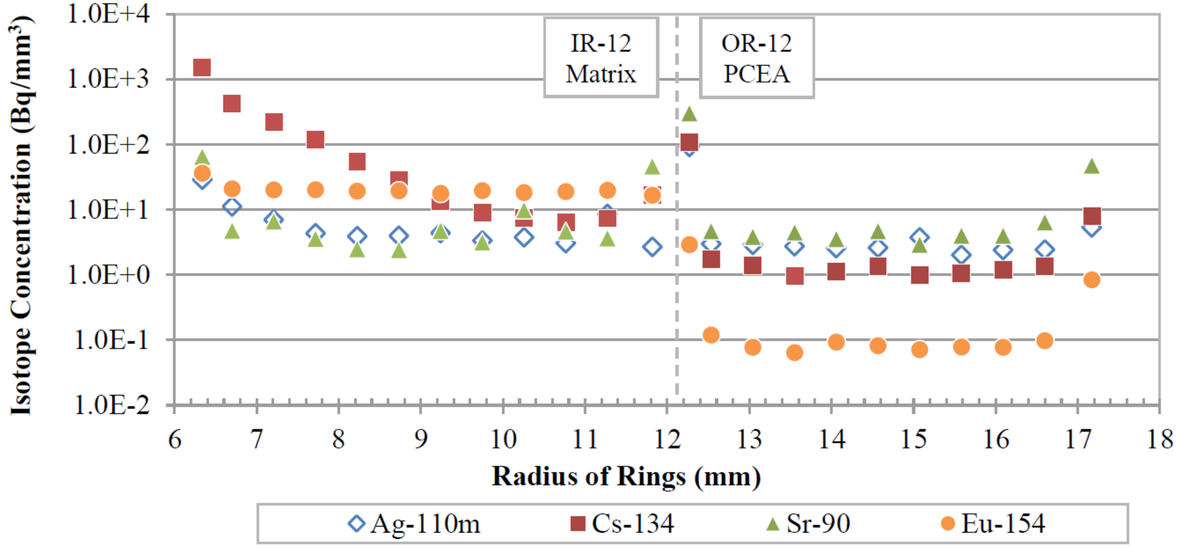


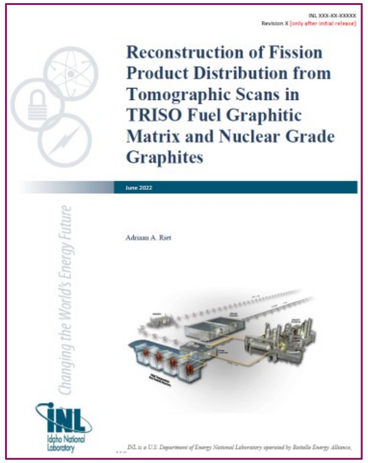
Figure 46. Radial profiles for select fission products at the axial bottom of the Capsule 12 IR and OR. The open symbols denote values derived from MDAs.

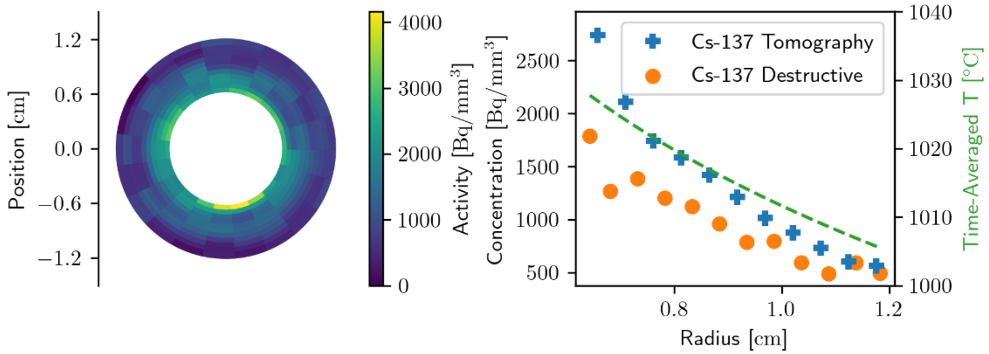
- Compacts TAVA temp: 854°C
- Inner ring:
  - Matrix
  - TAVA temp: 782°C
- Outer ring:
  - PCEA
  - TAVA temp: 741°C

Completed Improved Gamma Tomographic Reconstructions

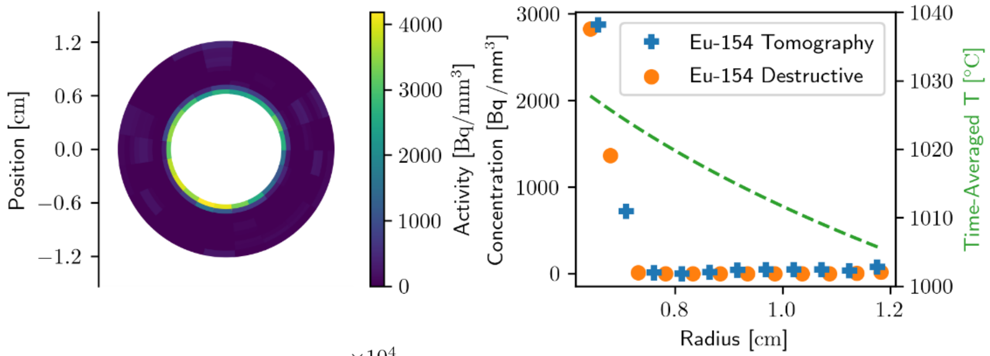
- Improved method of gamma tomographic reconstruction developed, applied to all AGR-3/4 data and compared to destructive sampling

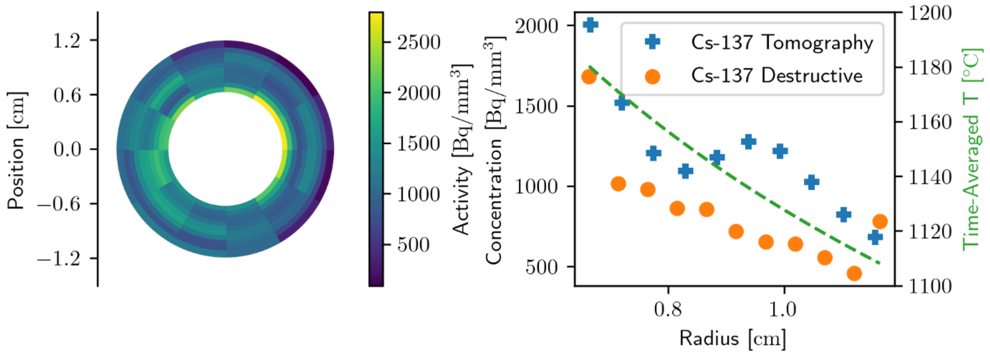
- Provides more data points for extracting diffusion coefficients



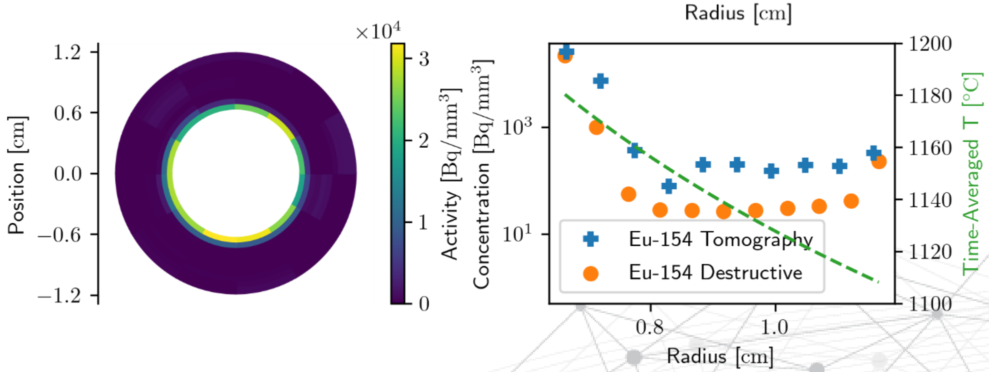


Capsule 3 Inner Ring



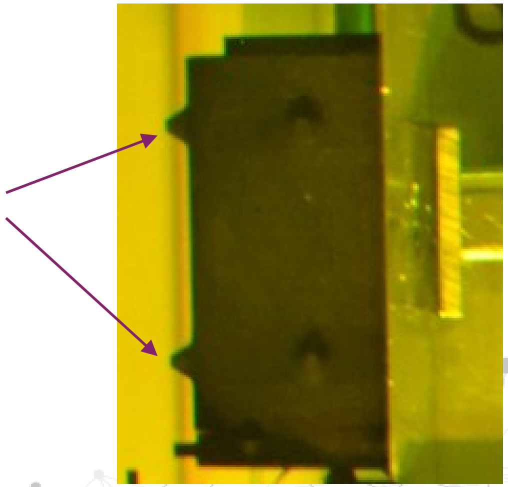


Capsule 7 Outer Ring



Selected Conclusions from Ring Sampling

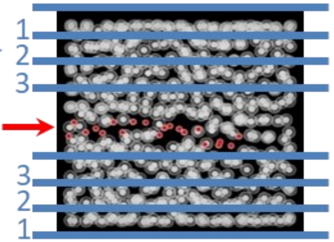
- Elevated concentrations of Ag, Cs, Eu, and Sr were detected on the outer surfaces of some IRs and ORs. Suggests a short-circuit pathway may exist whereby gas-phase fission product transport occurred in the gaps between the compacts and the rings.
- Ag-110m profiles had seemingly unpredictable shapes and significant variations from one sample to another. This will adversely affect the extraction of diffusivities.
- Cs-134 profiles compare reasonably with the AGR-3/4 model (more on that in A. Riet's presentation)
- Eu-154 and Sr-90 profiles have similar shapes suggesting transport is governed by similar mechanisms
- Outer ring nubs often had elevated fission product concentrations particularly of Sr-90. Suggests short-circuit transport. Also suggests some transport of Sr-90 as gaseous Kr-90 precursor and volatile intermediate Rb-90.
- Fundamental differences in transport within PCEA versus IG-110 versus graphitic matrix were not evident

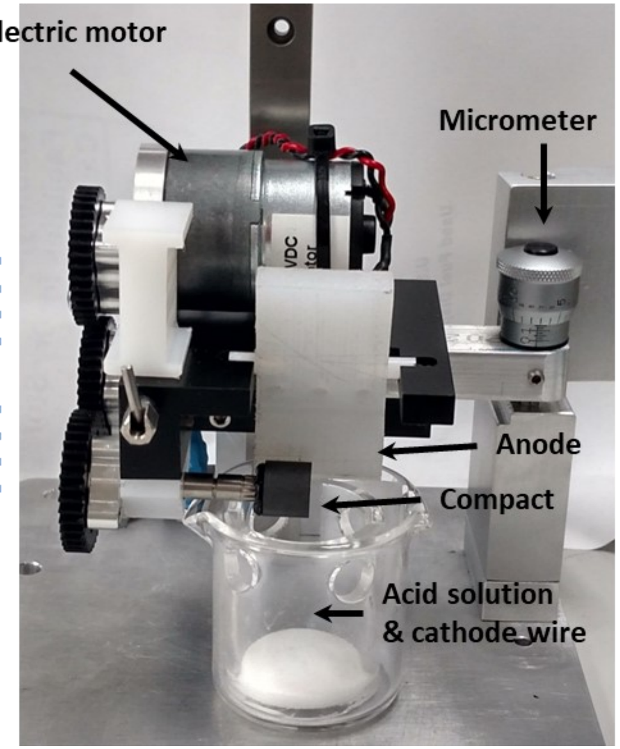


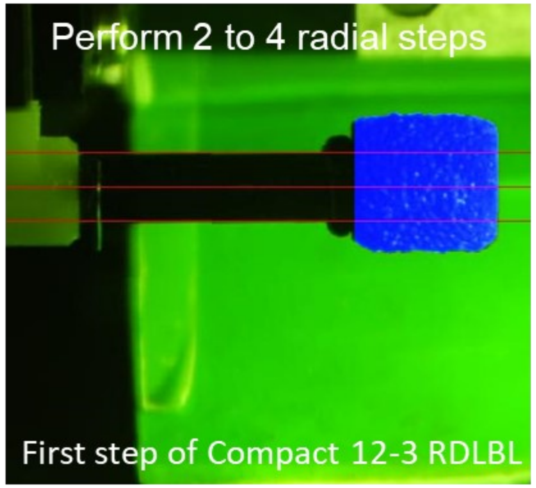
AGR-3/4 Compact Destructive Exams

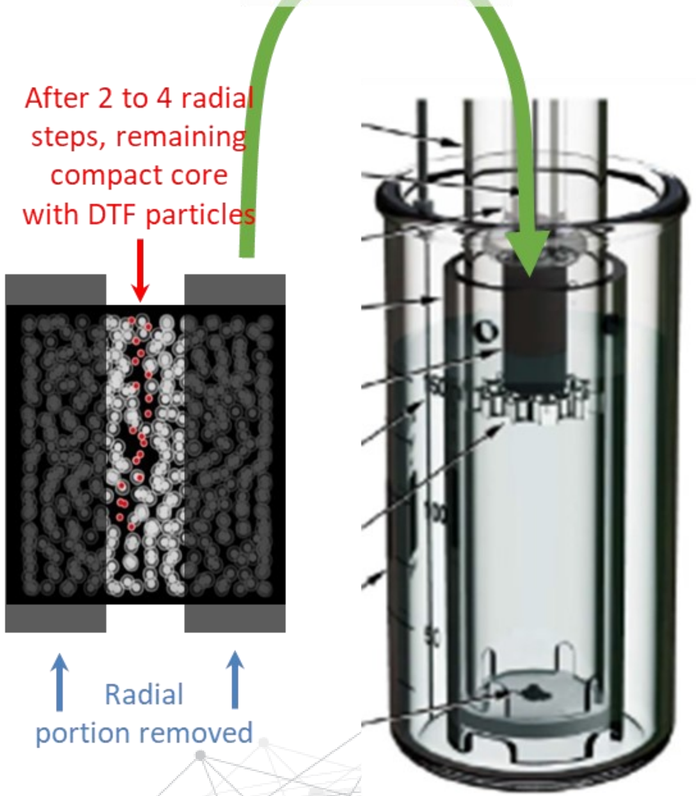
Radial Deconsolidation-Leach-Burn-Leach to Measure Fission Product Radial Concentration Profiles

- Radial deconsolidation-leach-burn-leach (R-DLBL)
  - Measure fission product inventory in compact outside of the SiC layer as a function of the radial position in the compact
  - Collect particles from specific radial portions of the compact for gamma counting and other PIE
  - Avoid deconsolidating DTF particles until the final axial step
  - Compare measured fission product profile with model predictions



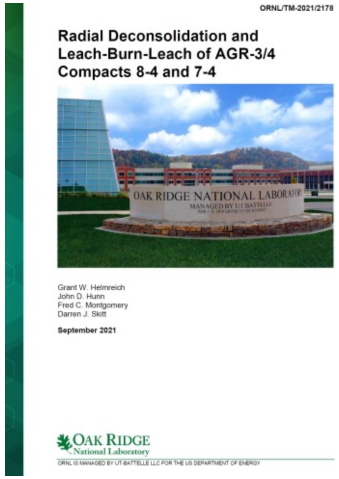


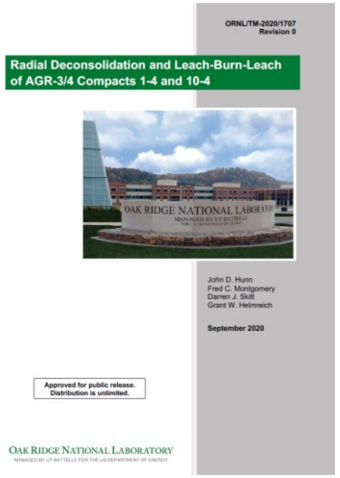




As-Irradiated Compacts R-DLBL Status

Compact ID	Burnup (% FIMA)	TAVA Irradiation Temp (°C)	R-DLBL
1-3	6.4	959	Completed ORNL in FY22
1-4	6.9	929	Completed ORNL
3-3	12.7	1205	Completed at INL
5-3	14.9	1050	Completed at INL
5-4	15.0	989	Completed at INL
7-3	15.0	1376	Completed at INL
7-4	14.9	1319	Completed ORNL in late FY21
8-3	14.5	1213	Completed at INL
8-4	14.4	1169	Completed ORNL in late FY21
10-3	11.8	1210	Decon completed FY21, radiochem still in progress at INL
12-1	5.9	849	Completed at INL
12-3	5.2	864	Completed at INL



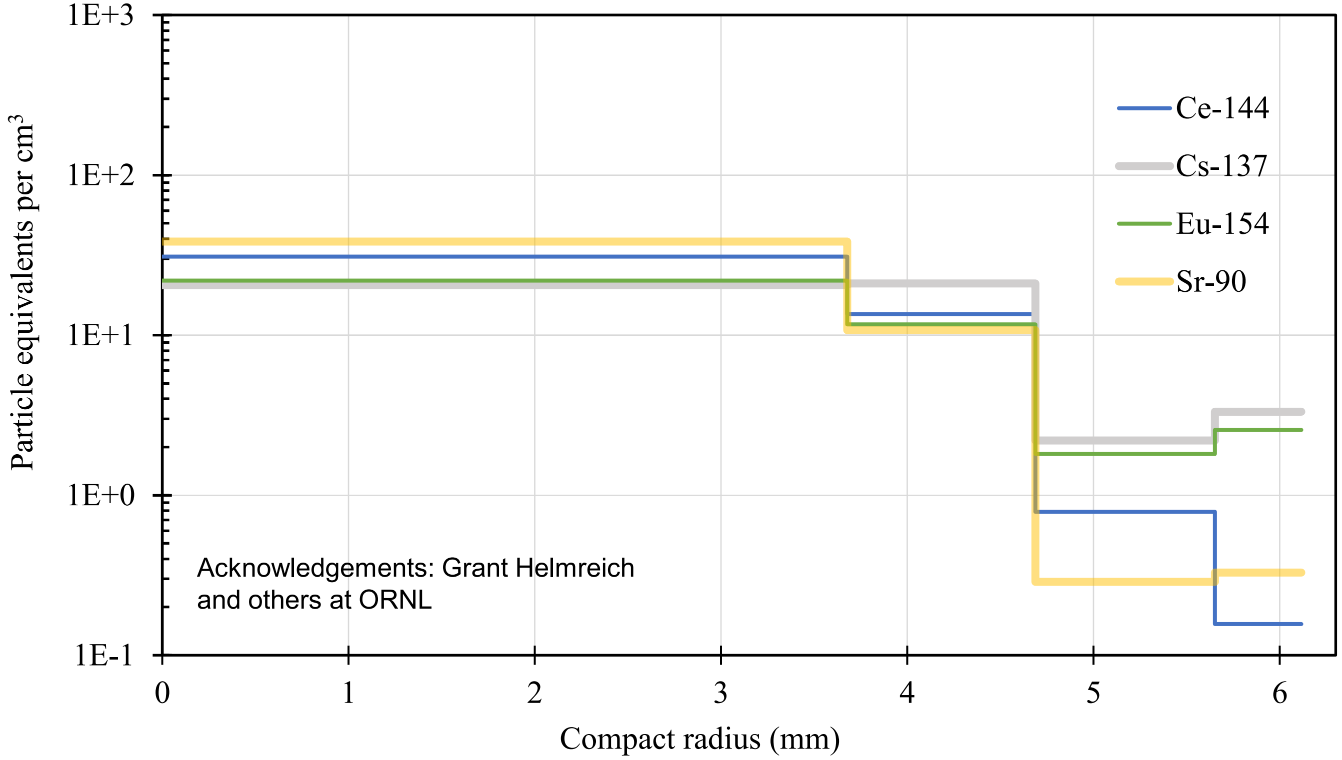


FACS-Tested Compacts R-DLBL Status

- In FY23: Only completion of some radiochemical analyses and particle gamma counting will remain

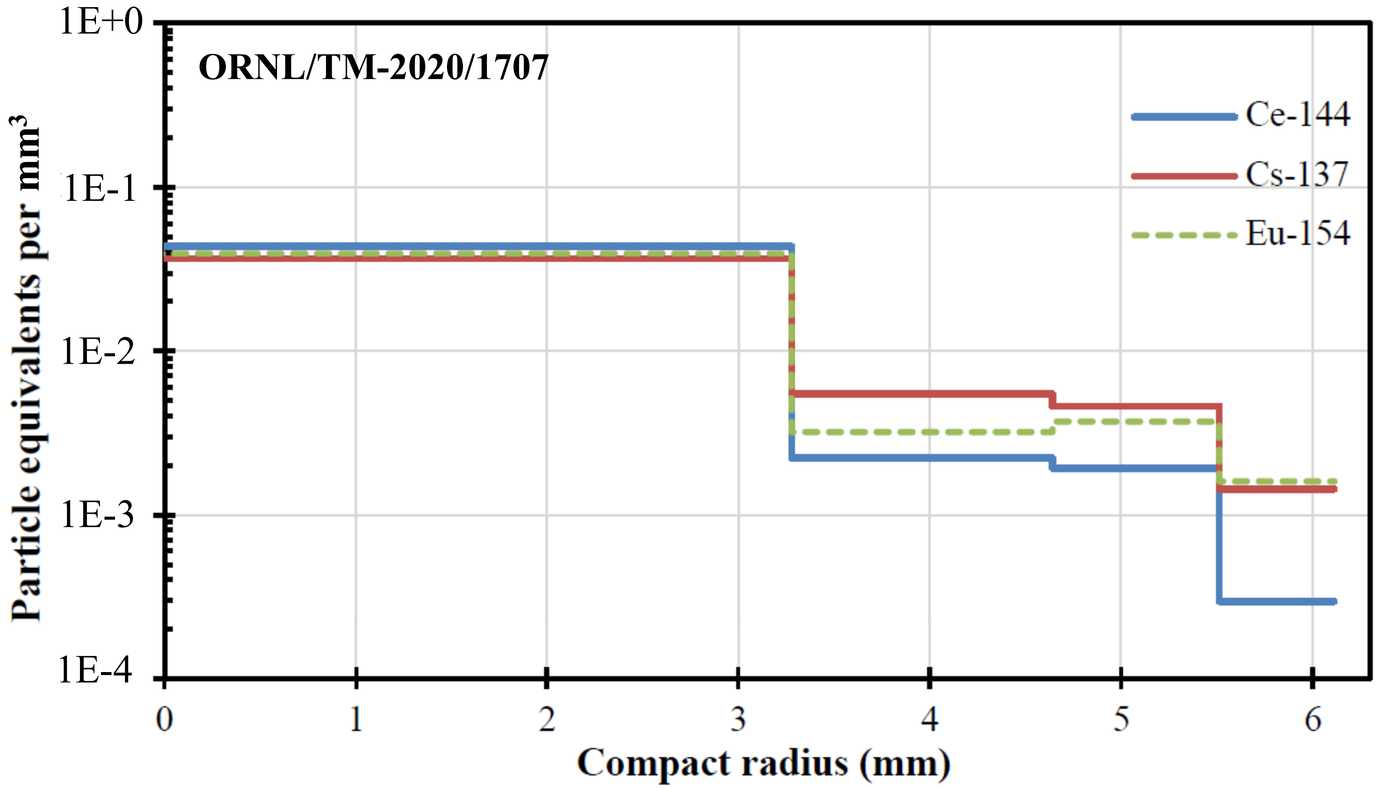
Compact	Burnup (% FIMA)	TAVA Irradiation Temp (°C)	FACS Temperature (°C)	Reirradiation	R-DLBL
1-2	5.9	880	1400	Late FY21	Decon completed at INL in FY22, radiochem in progress
3-1	12.2	1138	1600	Yes	Decon completed at INL late FY21, radiochem in progress
3-2	12.5	1196	1600	No	Completed at INL
4-3	14.3	1035	1000	Late FY21	Completed at ORNL in FY22
8-1	14.5	1165	1200	Yes	Decon completed at INL late FY21, radiochem in progress
8-2	14.6	1213	1400	No	Completed at INL
10-1	12.1	1172	1400	Yes	Completed at ORNL in FY22
10-2	12.0	1213	1200	No	Completed at ORNL in FY22
10-4	11.4	1168	1400	No	Completed at ORNL

As-irradiated Compact 1-3 – Completed FY22



Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
1	4	866	929	972
	3	942	959	978
	2	910	941	971
	1	817	880	932
All Capsule 1 compacts		817	927	978

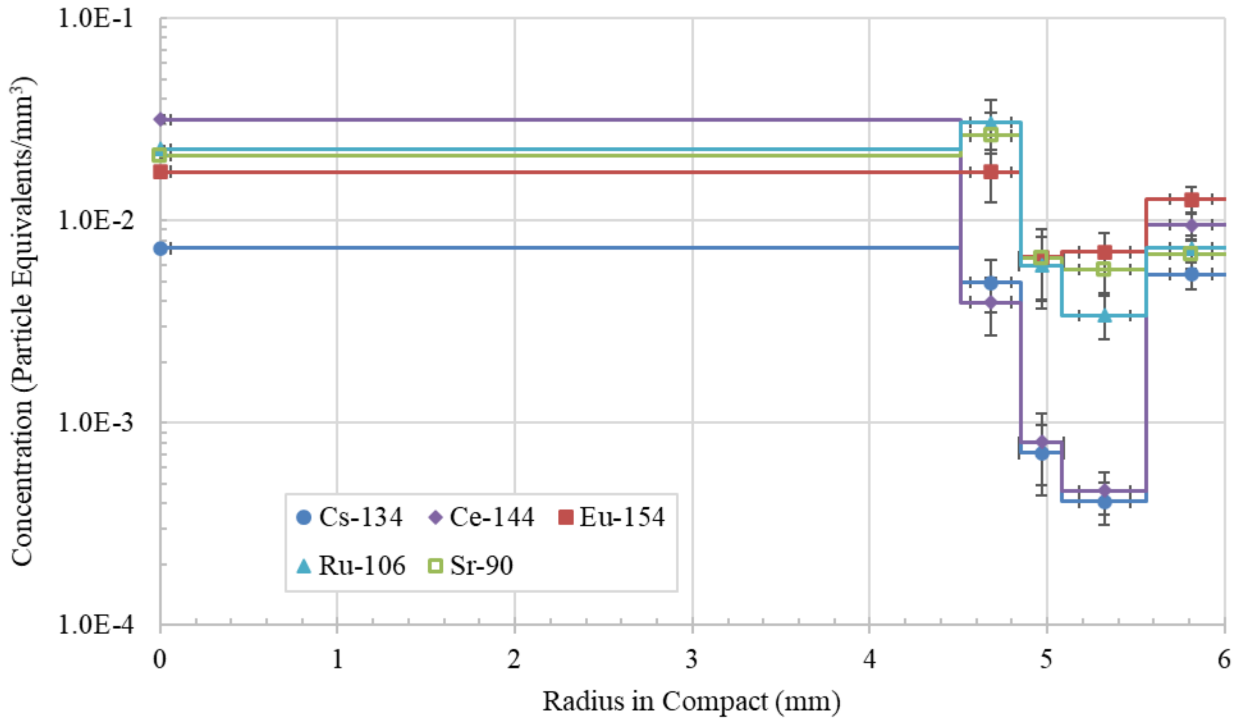
As-irradiated Compact 1-4



Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
1	4	866	929	972
	3	942	959	978
	2	910	941	971
	1	817	880	932
All Capsule 1 compacts		817	927	978

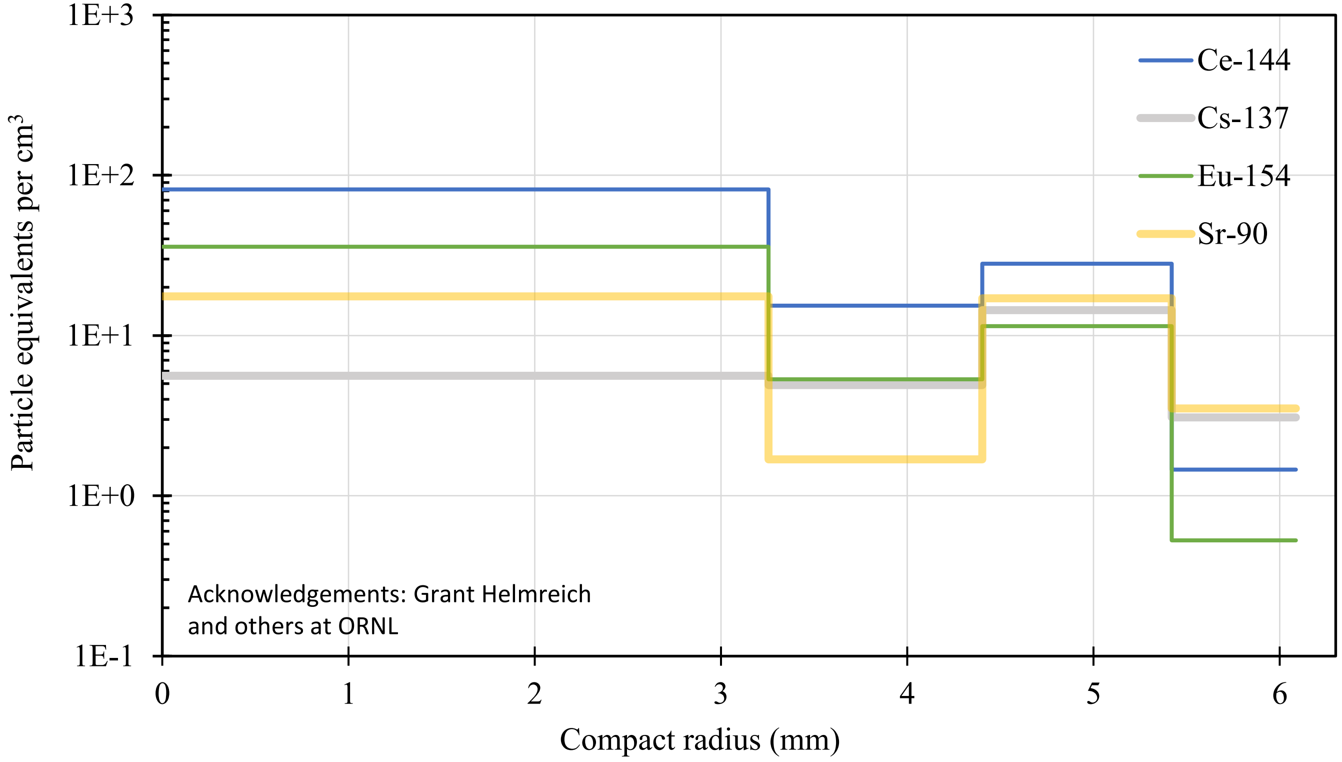
As-irradiated Compact 3-3

- **FACS-tested Compact 3-2 R-DLBL data being processed now.**



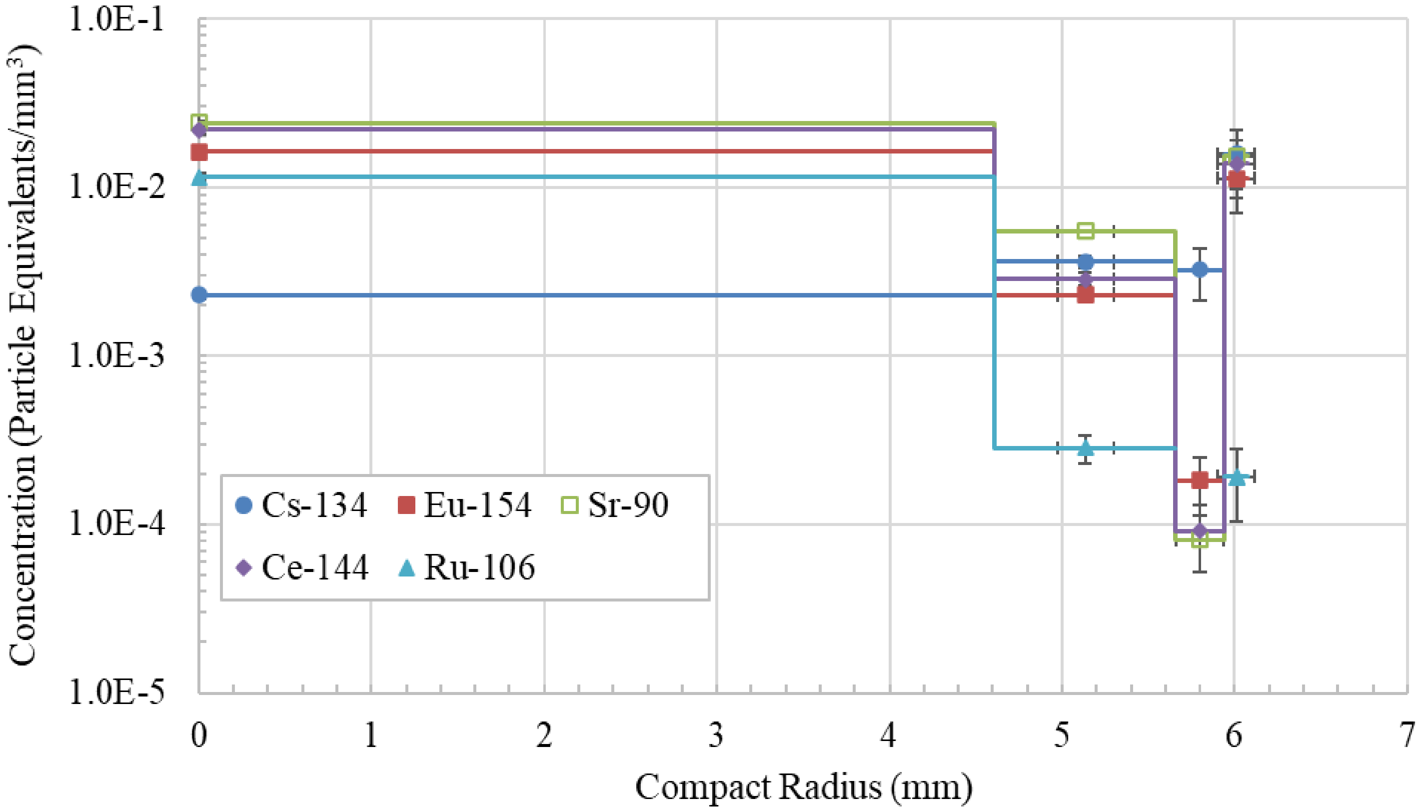
Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
3	4	1073	1168	1234
	3	1170	1205	1242
	2	1154	1196	1240
	1	1041	1138	1214
All Capsule 3 compacts		1041	1177	1242

Compact 4-3 – Reirradiated and FACS-tested at 1000°C at INL before R-DLBL Completed in FY22 at ORNL



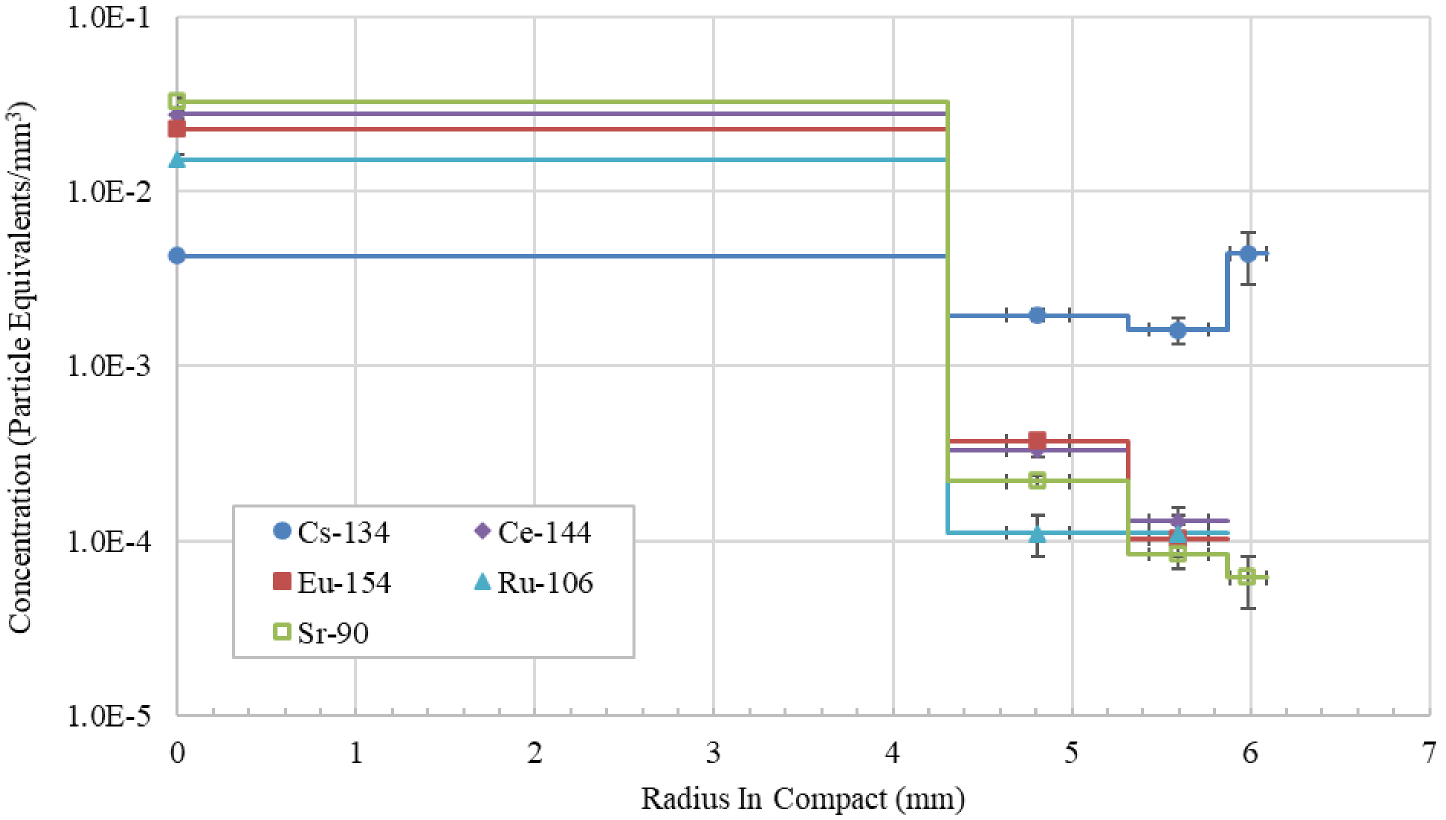
4	4	899	996	1073
	3	992	1035	1084
	2	980	1029	1082
	1	867	970	1058
All Capsule 4 compacts		867	1008	1084

As-irradiated Compact 5-3



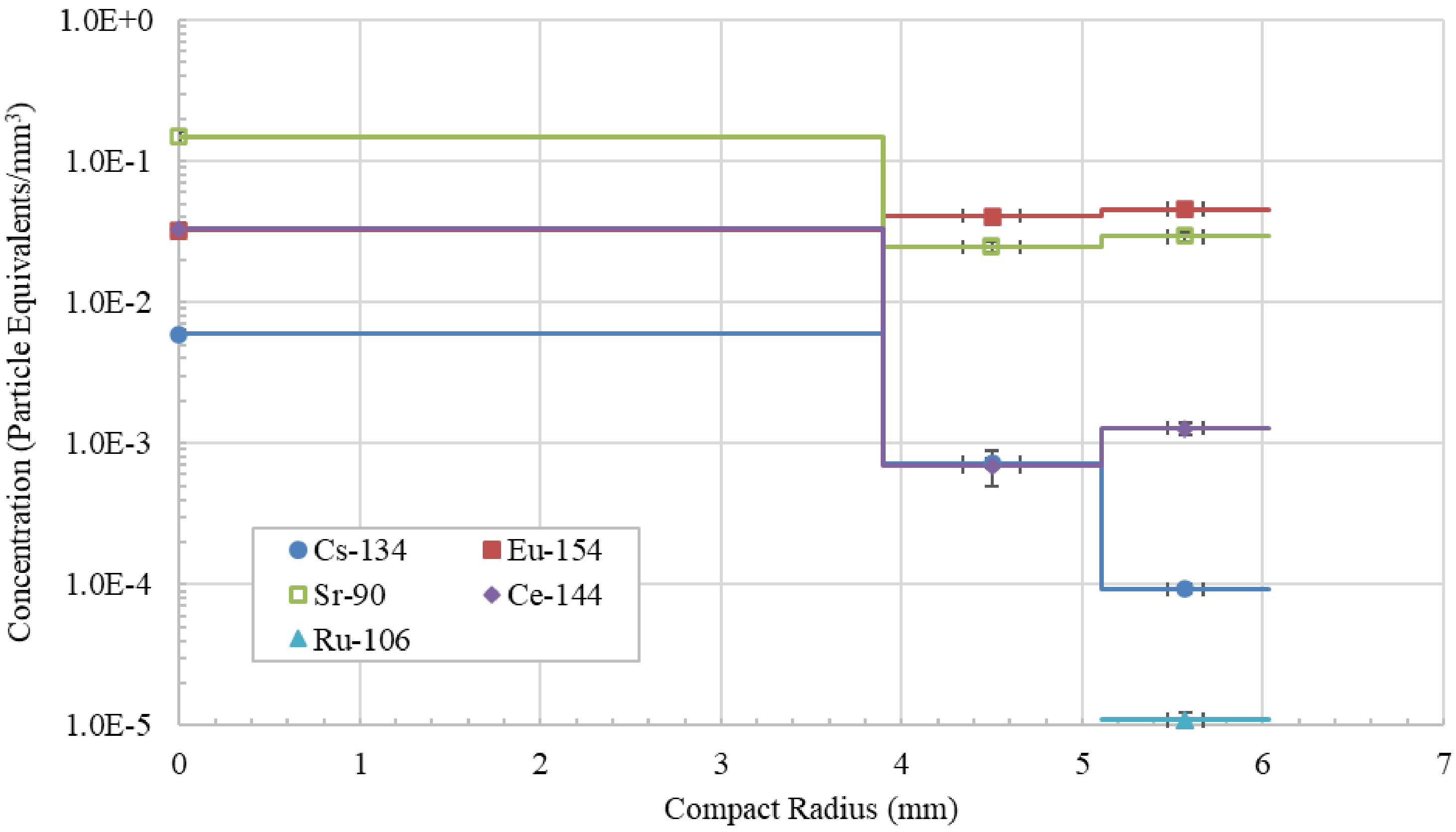
Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
5	4	858	989	1084
	3	1001	1050	1102
	2	995	1047	1101
	1	838	973	1075
All Capsule 5 compacts		838	1015	1102

As-irradiated Compact 5-4



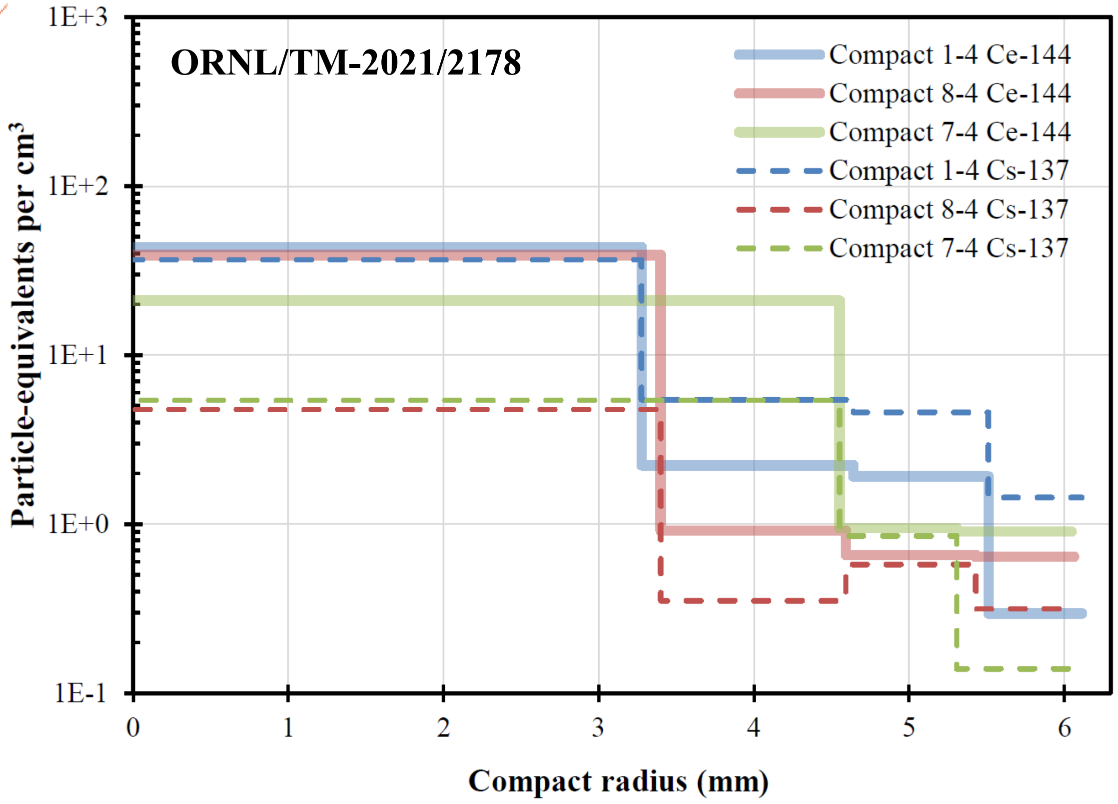
Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
5	4	858	989	1084
	3	1001	1050	1102
	2	995	1047	1101
	1	838	973	1075
All Capsule 5 compacts		838	1015	1102

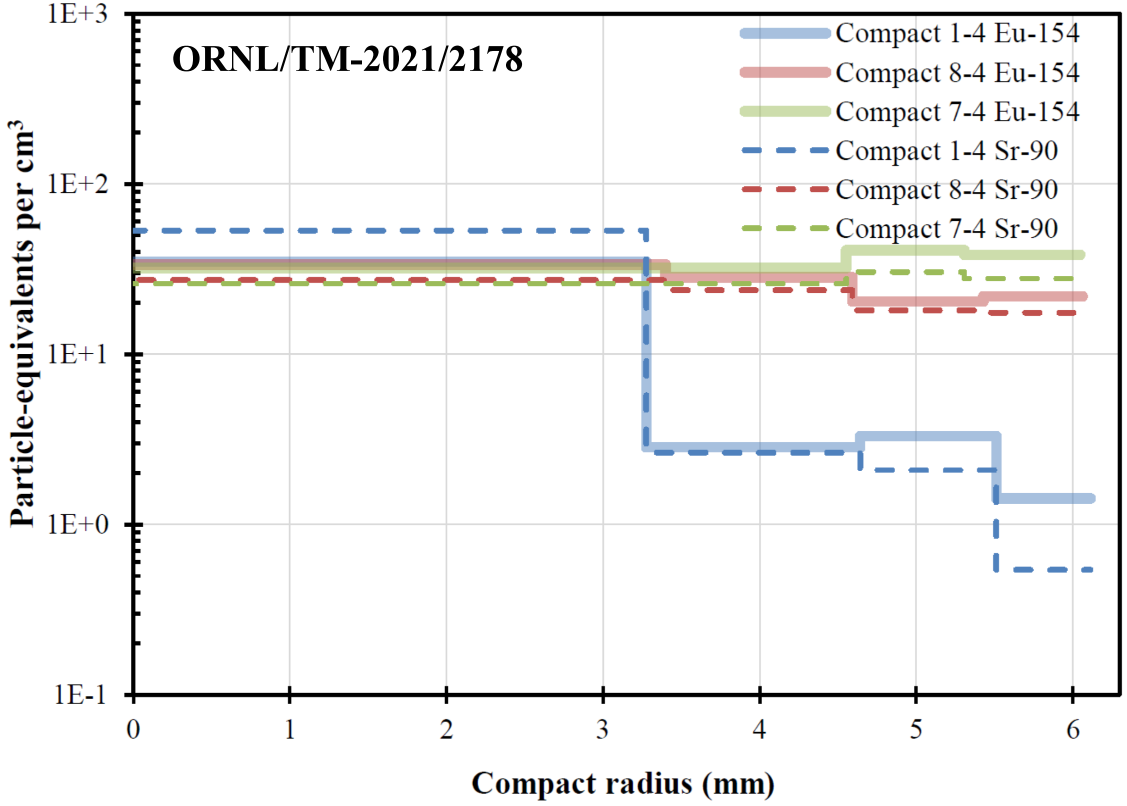
As-irradiated Compact 7-3



Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
7	4	1206	1319	1397
	3	1335	1376	1418
	2	1332	1375	1417
	1	1197	1311	1394
All Capsule 7 compacts		1197	1345	1418

As-irradiated Compacts 7-4 and 8-4 – Completed end of FY21

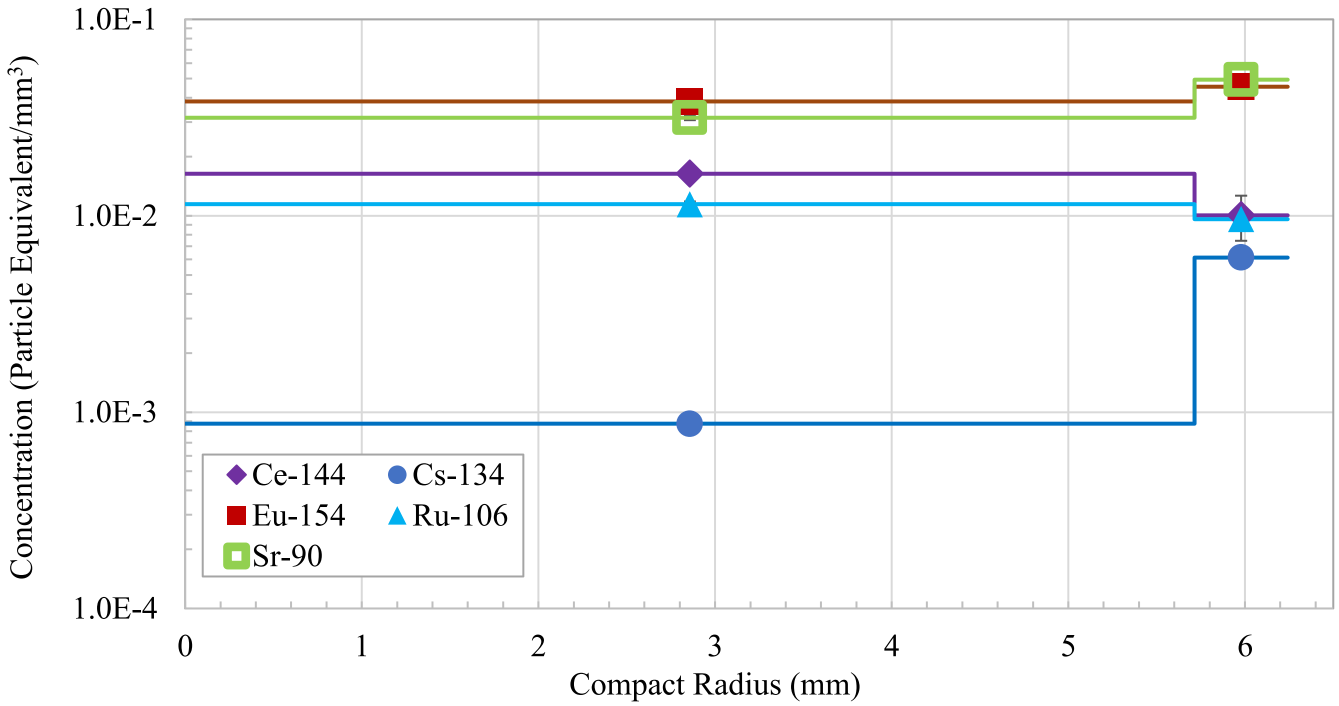




	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
All Capsule 1 compacts	817	927	978
All Capsule 7 compacts	1197	1345	1418
All Capsule 8 compacts	1063	1190	1257

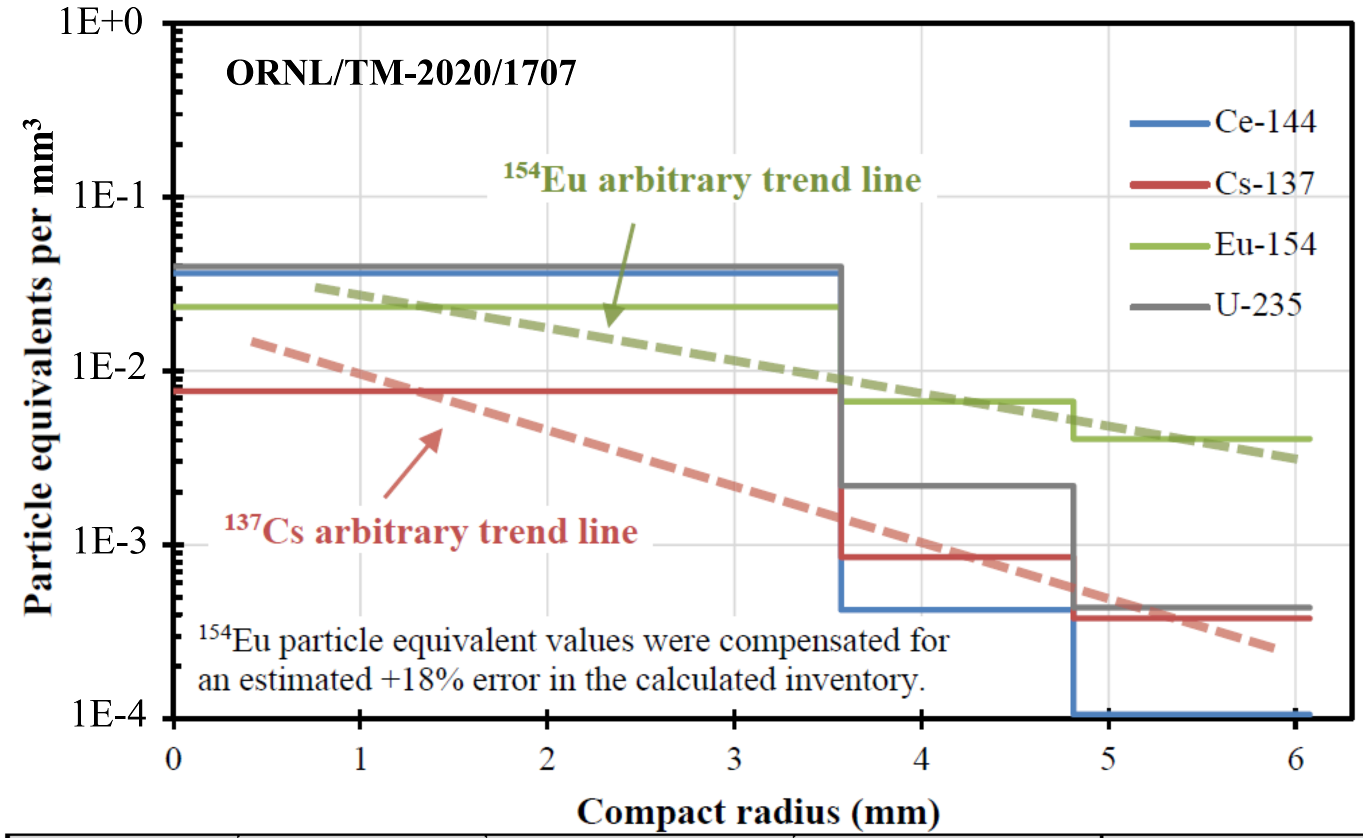
FACS-tested Compact 8-2 and As-irradiated Compact 8-3

- Compact 8-2 radiochemical analysis is complete, data currently being processed
- Compact 8-3 preliminary results are below. Compact fell from rod and complicated analysis.



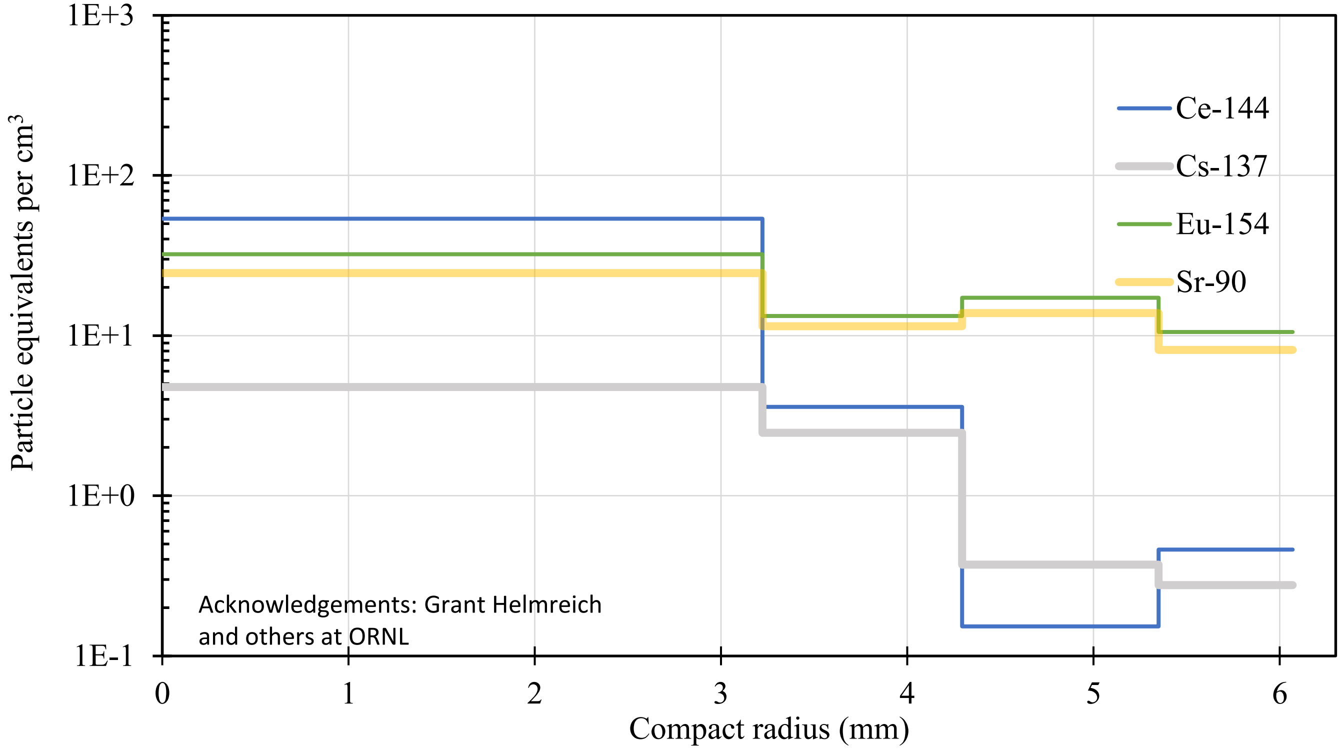
8	4	1068	1169	1242
	3	1171	1213	1257
	2	1171	1213	1257
	1	1063	1165	1242
All Capsule 8 compacts		1063	1190	1257

FACS-tested Compact 10-4



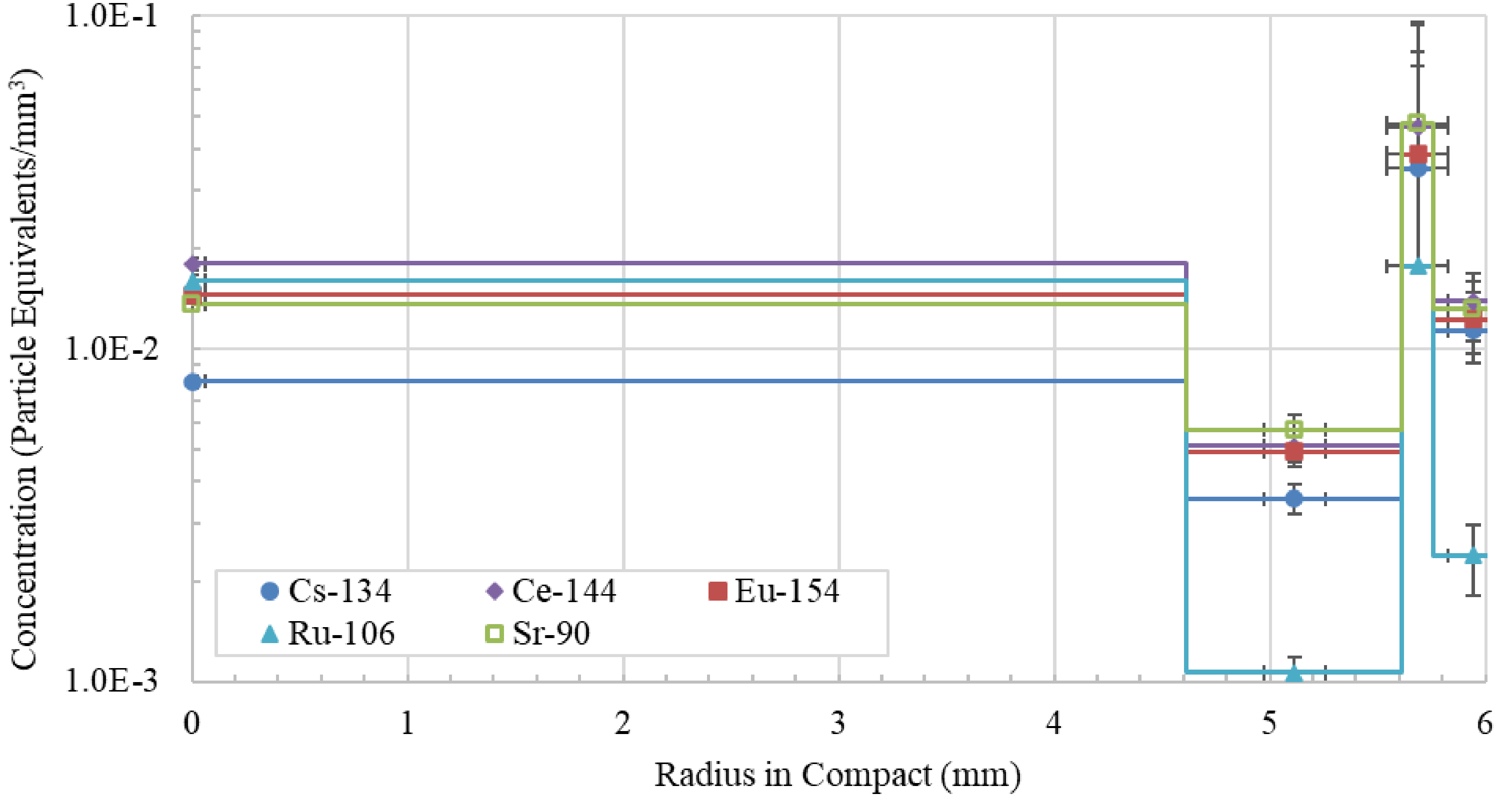
Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
10	4	1079	1168	1231
	3	1174	1210	1248
	2	1179	1213	1249
	1	1080	1172	1238
All Capsule 10 compacts		1079	1191	1249

FACS-tested Compact 10-2 – R-DLBL Completed FY22



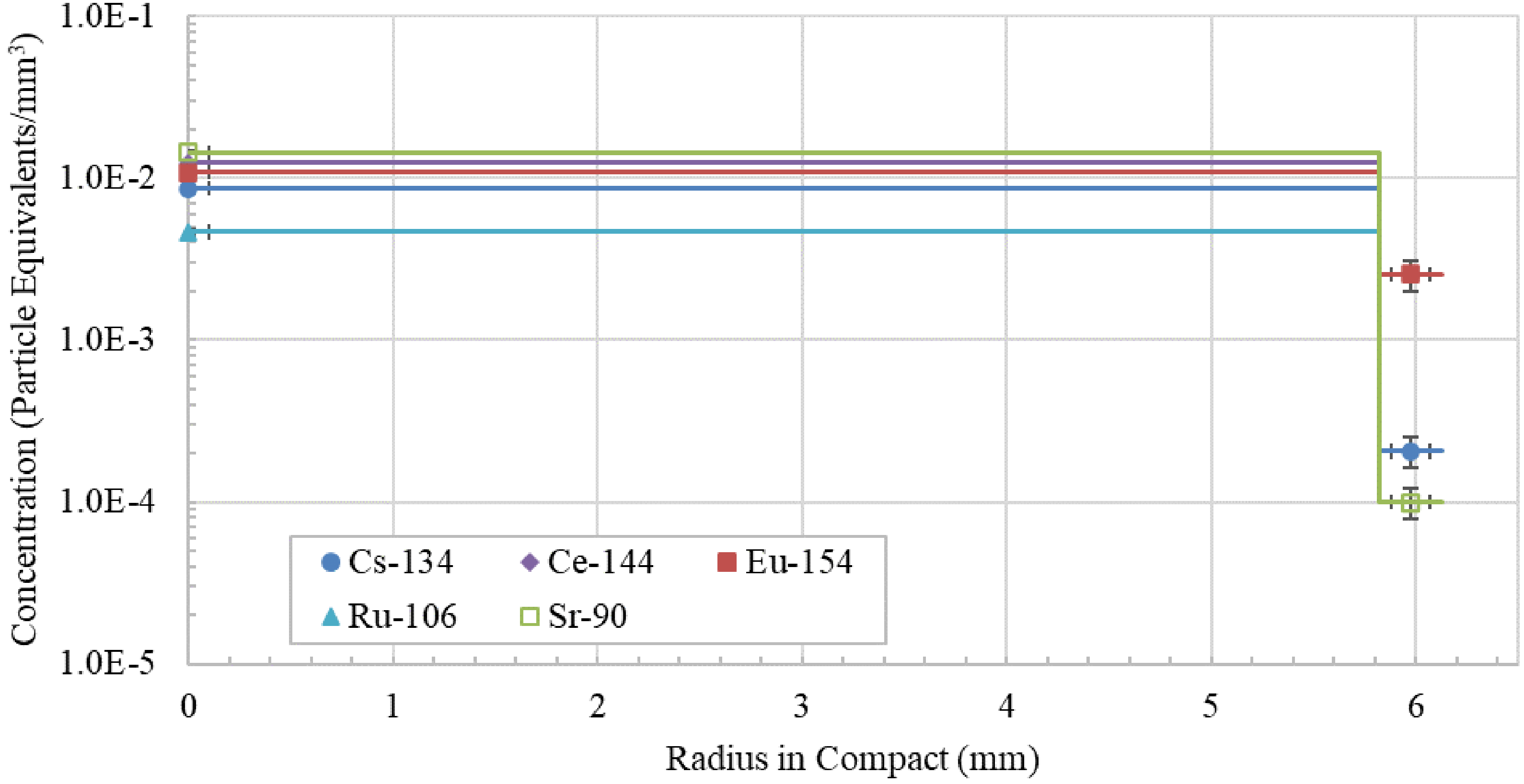
Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
10	4	1079	1168	1231
	3	1174	1210	1248
	2	1179	1213	1249
	1	1080	1172	1238
All Capsule 10 compacts		1079	1191	1249

As-irradiated Compact 12-1



Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
12	4	790	832	865
	3	844	864	884
	2	857	872	888
	1	802	849	883
All Capsule 12 compacts		790	854	888

As-irradiated Compact 12-3



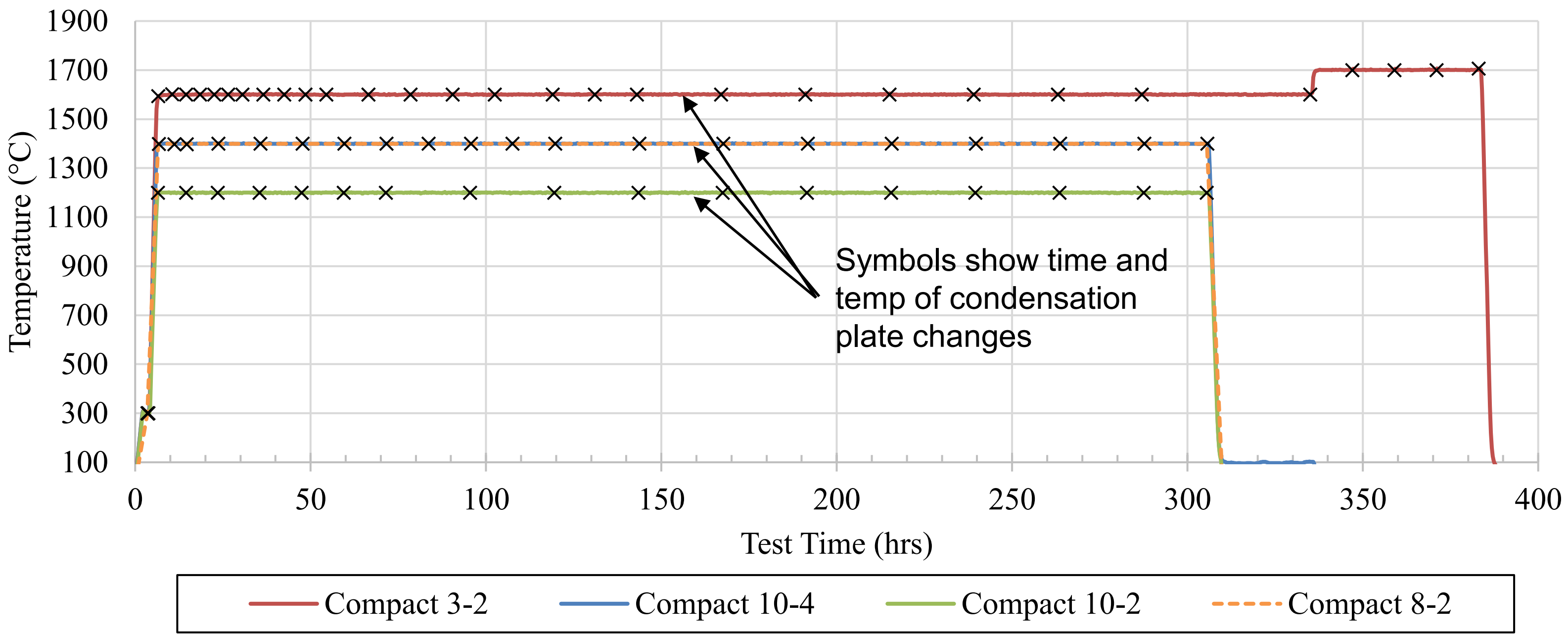
Capsule	Compact	Time-Average Minimum Temperature (°C)	Time-Average Volume-Average Temperature (°C)	Time-Average Peak Temperature (°C)
12	4	790	832	865
	3	844	864	884
	2	857	872	888
	1	802	849	883
All Capsule 12 compacts		790	854	888

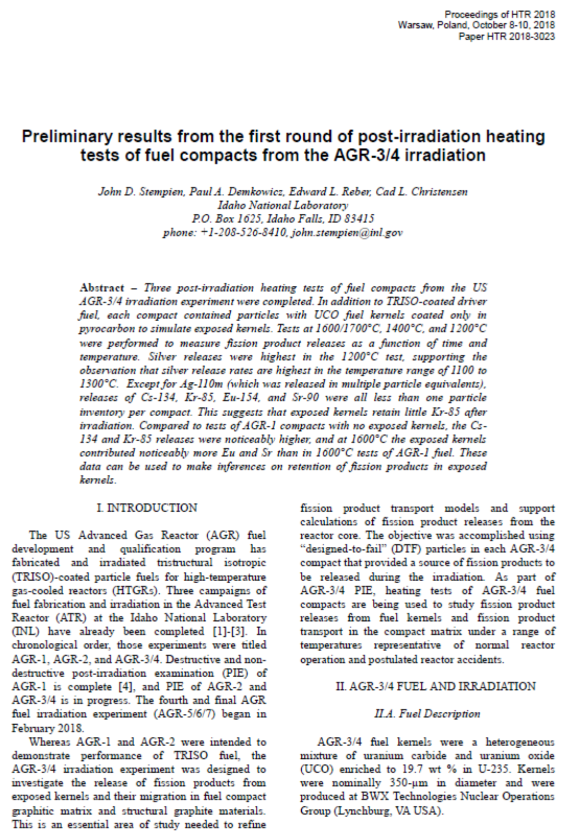
AGR-3/4 Compact Heating Tests

Tests of As-Irradiated Compacts Were Completed in 2018

Compact ID	Burnup (% FIMA)	Fast Fluence (n/m^2, E > 0.18 MeV)	TAVA Irradiation Temp (°C)	Heating Test Temp (°C)
3-2	12.5	4.17E+25	1196	1600/1700
8-2	14.6	5.11E+25	1213	1400
10-2	12.0	4.01E+25	1213	1200
10-4	11.4	3.75E+25	1168	1400

FIMA: fissions per initial metal atom
TAVA: time-averaged, volume-averaged





Proceedings of HTR 2018
Warsaw, Poland, October 8-10, 2018
Paper HTR 2018-3023

Preliminary results from the first round of post-irradiation heating tests of fuel compacts from the AGR-3/4 irradiation

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Abstract – *Three post-irradiation heating tests of fuel compacts from the US AGR-3/4 irradiation experiment were completed. In addition to TRISO-coated driver fuel, each compact contained particles with UCO fuel kernels coated only in pyrocarbon to simulate exposed kernels. Tests at 1600/1700°C, 1400°C, and 1200°C were performed to measure fission product releases as a function of time and temperature. Silver releases were highest in the 1200°C test, supporting the observation that silver release rates are highest in the temperature range of 1100 to 1300°C. Except for Ag-110m (which was released in multiple particle equivalents), releases of Cs-134, Kr-85, Eu-154, and Sr-90 were all less than one particle inventory per compact. This suggests that exposed kernels retain little Kr-85 after irradiation. Compared to tests of AGR-1 compacts with no exposed kernels, the Cs-134 and Kr-85 releases were noticeably higher, and at 1600°C the exposed kernels contributed noticeably more Eu and Sr than in 1600°C tests of AGR-1 fuel. These data can be used to make inferences on retention of fission products in exposed kernels.*

I. INTRODUCTION

The US Advanced Gas Reactor (AGR) fuel development and qualification program has fabricated and irradiated tristructural isotropic (TRISO)-coated particle fuels for high-temperature gas-cooled reactors (HTGRs). Three campaigns of fuel fabrication and irradiation in the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL) have already been completed [1]-[3]. In chronological order, those experiments were titled AGR-1, AGR-2, and AGR-3/4. Destructive and non-destructive post-irradiation examination (PIE) of AGR-1 is complete [4], and PIE of AGR-2 and AGR-3/4 is in progress. The fourth and final AGR fuel irradiation experiment (AGR-5/6/7) began in February 2018.

Whereas AGR-1 and AGR-2 were intended to demonstrate performance of TRISO fuel, the AGR-3/4 irradiation experiment was designed to investigate the release of fission products from exposed kernels and their migration in fuel compact graphitic matrix and structural graphite materials. This is an essential area of study needed to refine fission product transport models and support calculations of fission product releases from the reactor core. The objective was accomplished using "designed-to-fail" (DTF) particles in each AGR-3/4 compact that provided a source of fission products to be released during the irradiation. As part of AGR-3/4 PIE, heating tests of AGR-3/4 fuel compacts are being used to study fission product releases from fuel kernels and fission product transport in the compact matrix under a range of temperatures representative of normal reactor operation and postulated reactor accidents.

II. AGR-3/4 FUEL AND IRRADIATION

II.A. Fuel Description

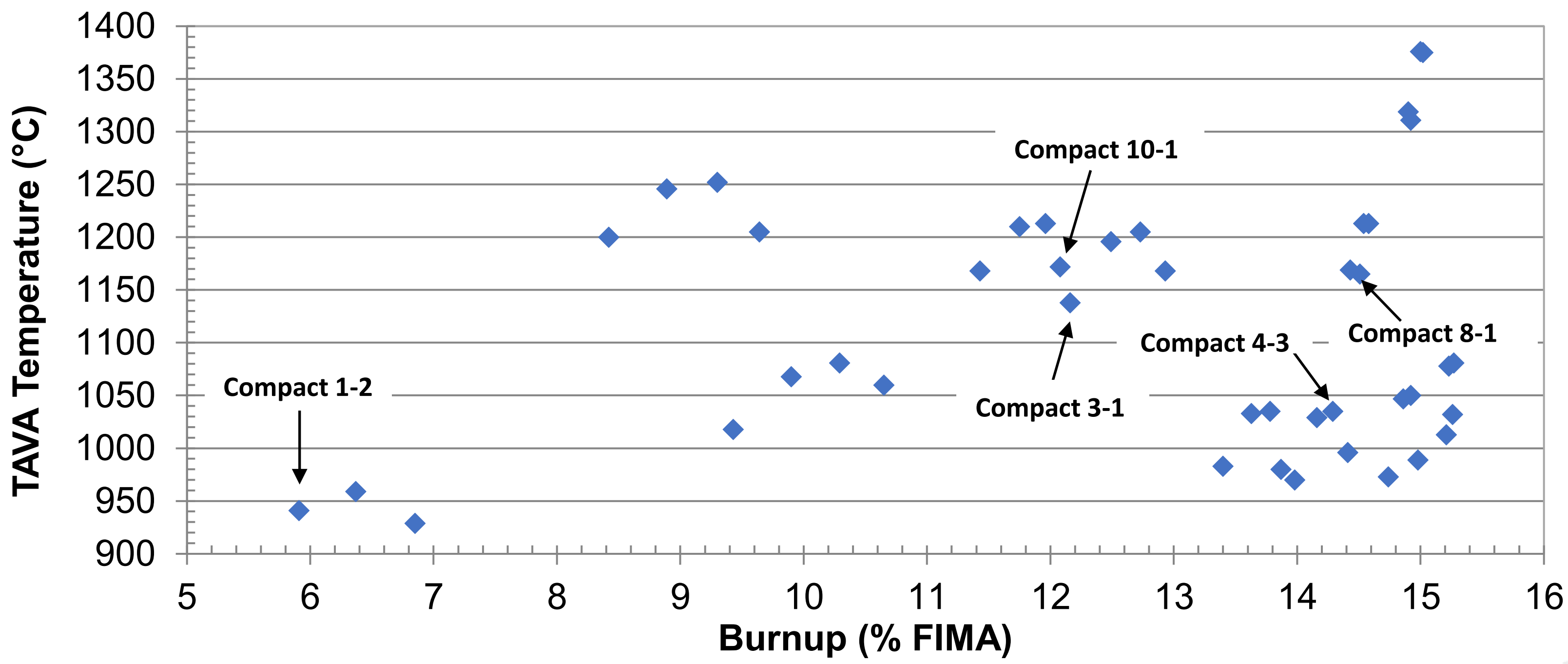
AGR-3/4 fuel kernels were a heterogeneous mixture of uranium carbide and uranium oxide (UCO) enriched to 19.7 wt % in U-235. Kernels were nominally 350-µm in diameter and were produced at BWX Technologies Nuclear Operations Group (Lynchburg, VA USA).

Completed all Planned Compact Reirradiation-Heating Tests

Compact ID	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
Completed late FY21: 4-3	14.3	1035	1000
Completed late FY21: 1-2	5.9	941	1400

HTR-2021 paper (3-1, 8-1, 10-1)

Future report or paper (4-3, 1-2)



Conclusions and Future Work

- Conclusions:
  - Many data points on spatial distributions of fission products have been collected
  - Work on how these measurements can be used in source term analyses is in progress (e.g., extraction of new transport parameters and development of empirical correlations)
  - A couple different transport models are being compared to the AGR-3/4 data
- Work in FY23:
  - Complete solutions analyses and particle gamma counting from AGR-3/4 compact radial deconsolidations
  - Complete radiochemical analysis from physical sampling of AGR-3/4 Capsule 4 rings
  - Begin final PIE report on experimental work
  - Complete report on modifications to AGR-3/4 fission product transport model and extraction of fission product diffusivities in carbonaceous materials

INL

Idaho National Laboratory