GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

AGR-5/6/7 Compact Destructive Exams and Safety Testing 2024

John Stempien, PhD

ART AGR TRISO FUEL Post-Irradiation Technical Lead

Collaborators in Post-Irradiation Examination (PIE)

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- Adriaan Riet
- Phil Winston
- Kelley Walker
- Cad Christensen
- Edward Reber
- Ryan Fronk
- BJ Camphouse
- Luiza Albuquerque
- Magen Coleman
- Irina Glagolenko
- Bill Chuirazzi
- Tanner Mauseth
- Ethan Hisle

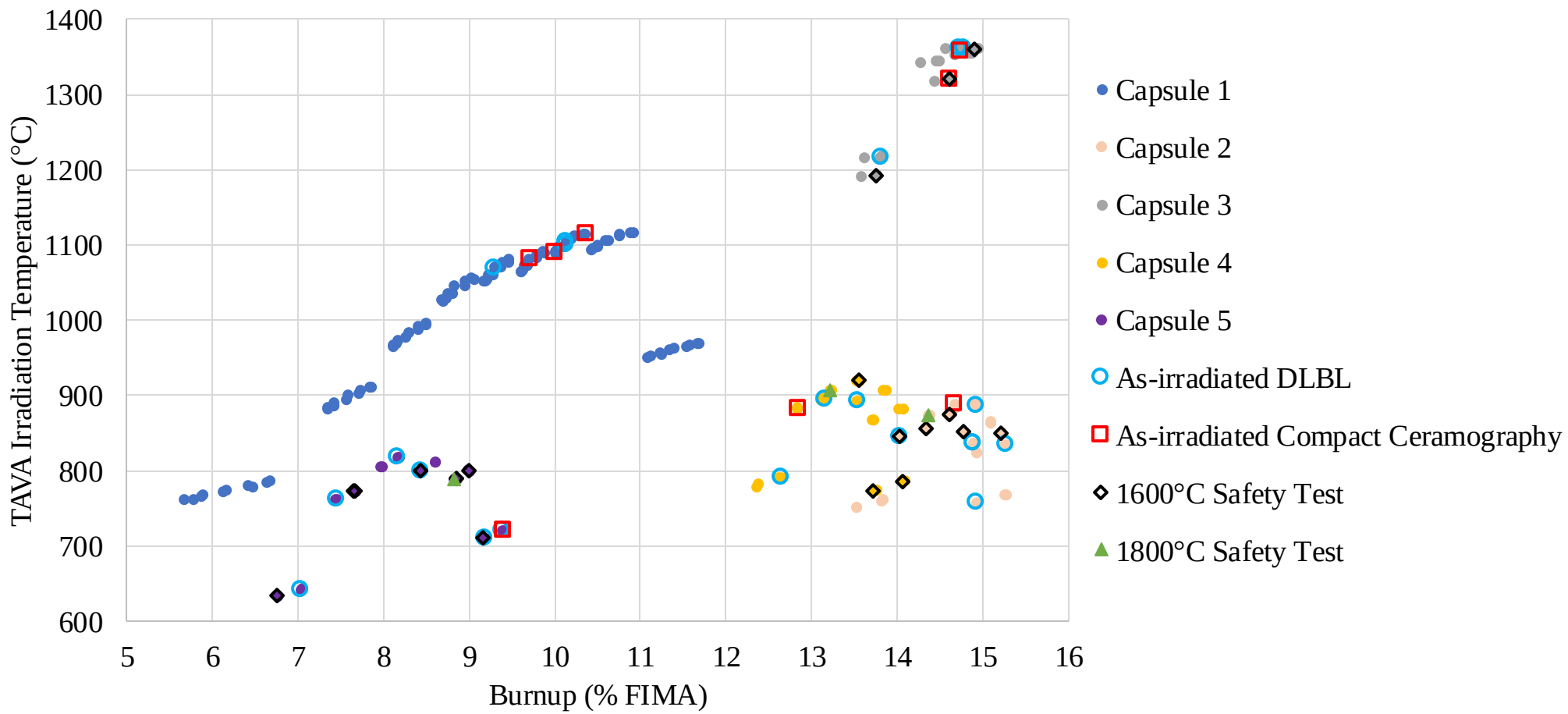
- John Hunn
- Tyler Gerczak
- Fred Montgomery
- Will Cureton
- Grant Helmreich
- Martino Hooghkirk
- Chuck Baldwin
- Matt Jones
- Stephen Trewhitt
- Jese Werden
- Bob Morris
- Darren Skitt (honorable mention!)

Major AGR-5/6/7 PIE Objectives

Overall: Establish acceptable nominal, margin, and accident performance of fuel produced at the pilot scale

1. Evaluate and characterize unexpected Capsule 1 behavior.
2. Determine if there was acceptable performance and behavior of the fuel under normal irradiation conditions (Capsules 2, 4, and 5).
3. Evaluate performance and characterize behavior of fuel under high irradiation temperatures (Capsule 3: TAVA 1360°C, TA Peak 1430°C).
4. Conduct post-irradiation high-temperature testing in helium to verify acceptable fuel performance under conduction cool-down accidents. (CCCTF and FACS)
5. Perform oxidation testing to characterize fuel behavior during exposure to air or moisture at nominal and accident temperatures

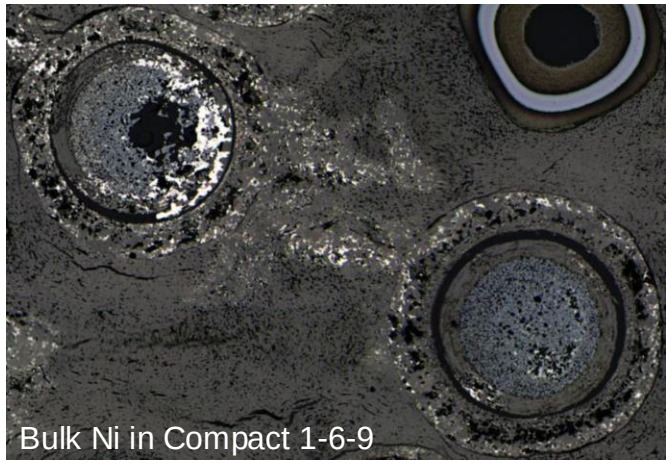
Compact Safety Tests and Exams Visual Status

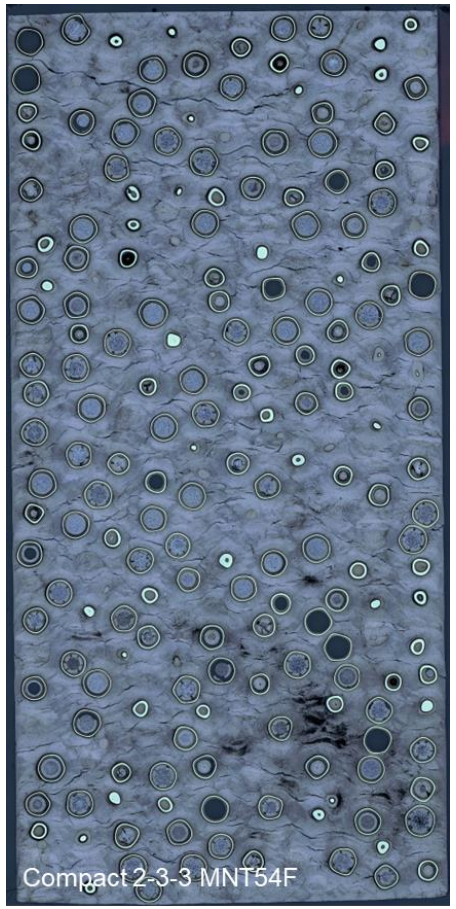


As-irradiated Compact Ceramography Complete. Some analyses still in progress.

Compact	Burnup	Fluence	TA Min	TAVA	TA Max	Lab	Year
1-6-9	9.7	3.62	889	1082	1196	INL	2022
2-3-3	14.67	5.07	794	889	947	INL	2022
3-4-1	14.73	5.41	1268	1359	1419	INL	2022
5-1-4	9.4	3.4	506	721	834	INL	2022
1-7-1	10	3.76	893	1091	1205	INL	2022/FY23
1-7-6	10.36	3.99	911	1115	1229	INL	2022/FY23
3-2-3	14.62	5.54	1203	1320	1401	INL	2022/FY23
4-5-1	12.84	4.24	787	884	947	INL	2022/FY23

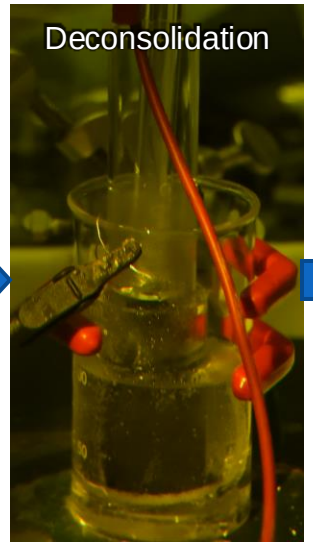

Kernel migration in Compact 3-4-1


Bulk Ni in Compact 1-6-9

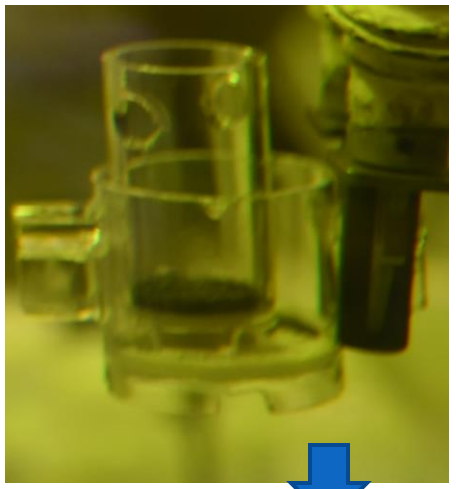

Compact 2-3-3 MNT54F


Compact 1-7-6 MNT82F

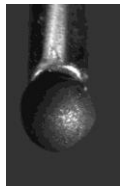
As-Irradiated Deconsolidation-Leach Burn-Leach (AI-DLBL)

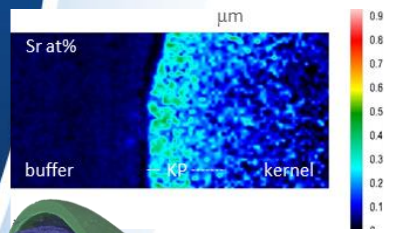


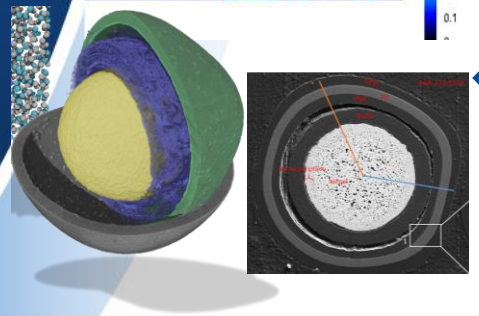
"Burn" at 750°C in air for 72 h

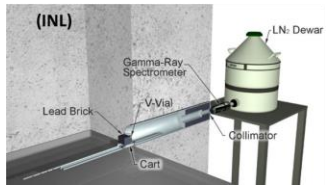


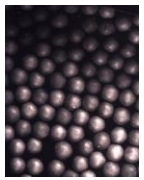
Analysis of solutions:
- gamma spec
- Sr-90 separation
- mass-spec











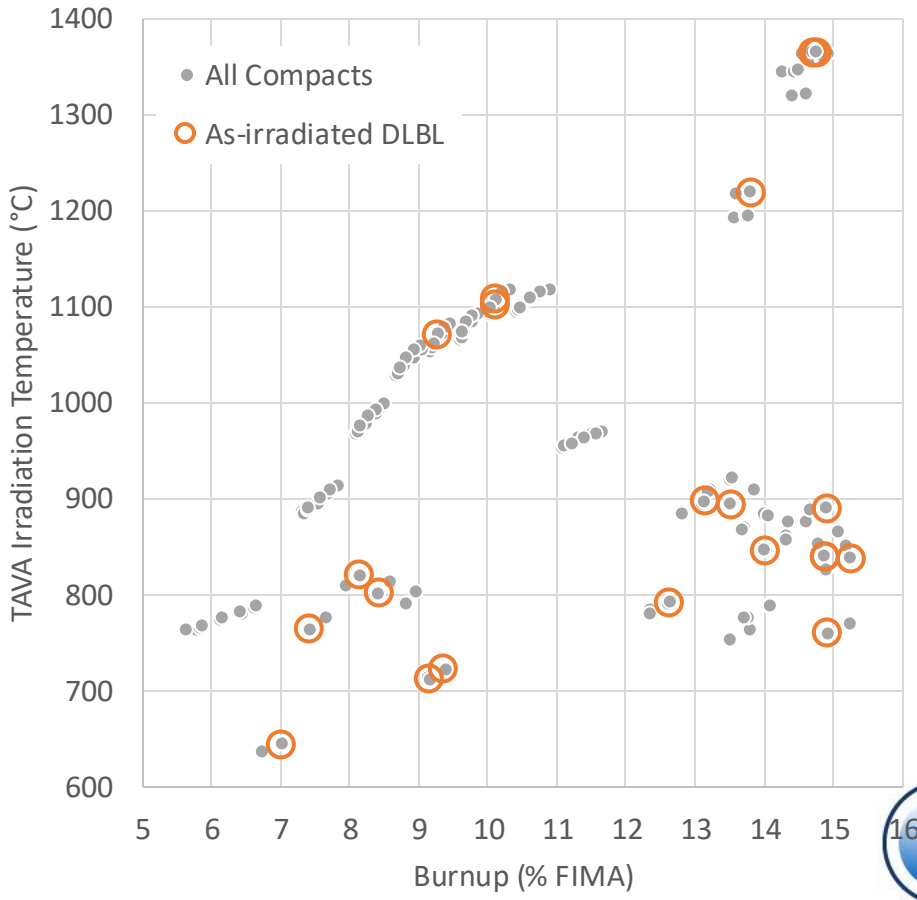
Particle Exams
- Gamma counting
- X-ray CT
- Microanalysis

As-Irradiated Deconsolidation-Leach Burn-Leach (AI-DLBL)

FY24 Milestones due 9/13/2024

1. **Complete four DLBLs at INL – one remaining to complete.**
2. **Complete five DLBLs at ORNL – One complete. Completing radiochemistry or particle burn-leach on the other four.**

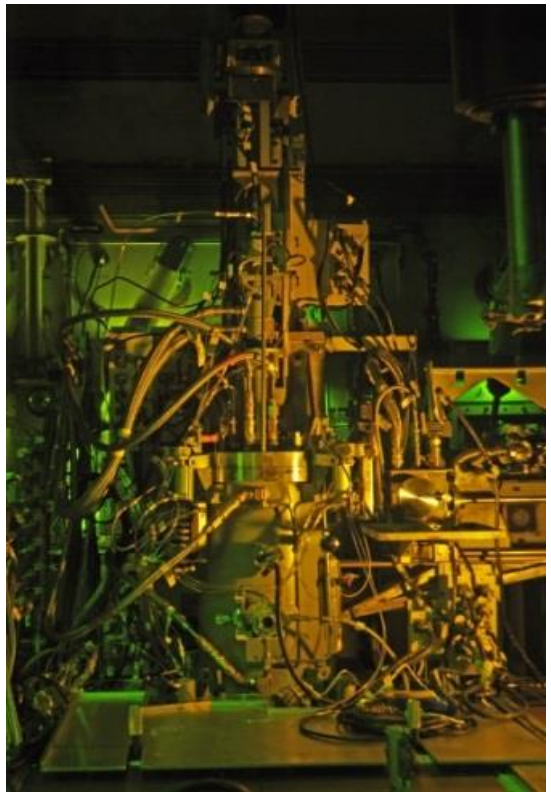
Compact	Burnup	Fluence	TA Min	TAVA	TA Max	Lab	Year
1-7-4	10.12	3.9	899	1100	1217	INL	2022
1-7-9	10.13	3.9	903	1106	1221	INL	2022
2-2-1	14.03	4.72	743	845	914	ORNL	2022
3-6-3	14.77	5.47	1264	1363	1432	ORNL	2023
5-1-2	9.17	3.25	499	710	821	INL	2022/FY23
1-5-9	9.29	3.3	889	1070	1169	ORNL	2022/FY23
3-6-2	14.72	5.46	1262	1363	1431	INL	2023
2-7-4	15.26	5.42	729	836	903	INL	2023
4-6-4	12.65	4.2	584	791	903	INL	2023
5-1-3	9.38	3.39	505	721	835	ORNL	2024
3-8-3	13.81	5.3	991	1218	1367	ORNL	2024
2-6-1	14.89	5.13	739	838	898	ORNL	2024
4-5-4	13.15	4.44	797	896	962	INL	2024
2-6-2	14.89	5.13	739	838	898	INL	2024
5-6-3	7.03	1.74	473	643	752	ORNL	TBD
5-5-2	7.44	2.05	676	762	830	INL	2024
5-3-1	8.43	2.71	721	800	849	INL	Planned FY24
5-4-3	8.16	2.48	748	819	864	ORNL	TBD, Shipment 7
4-3-2	13.53	4.55	800	893	950	ORNL	TBD, Shipment 7
2-8-1	14.93	5.21	554	758	861	ORNL	TBD, Shipment 8
2-4-4	14.92	5.19	788	888	945	INL	Planned FY24

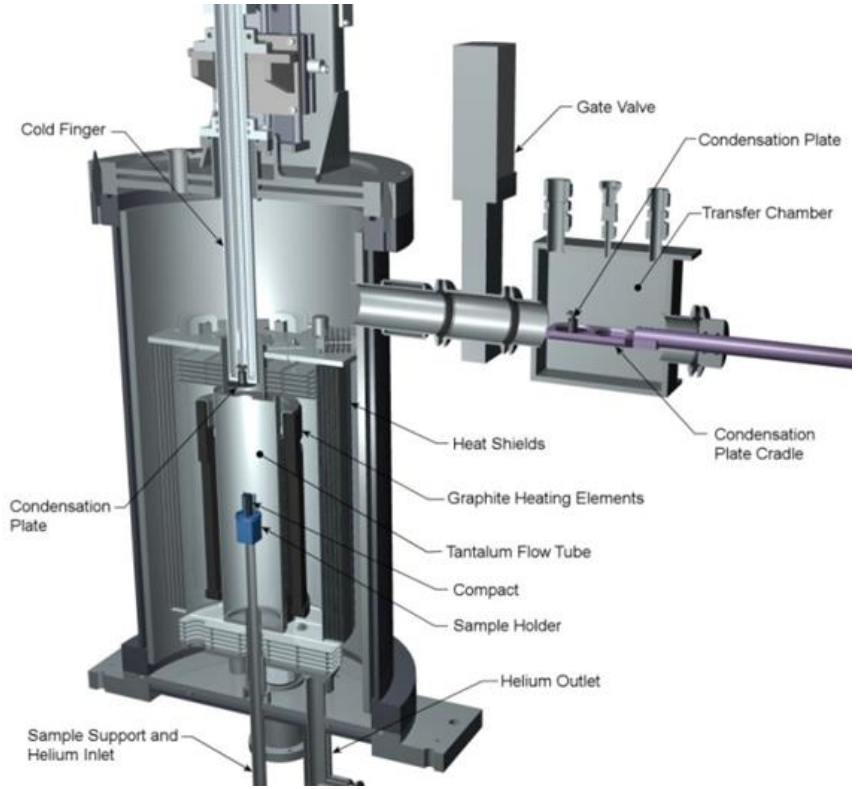


Completed since July 2023

Irradiated Compact Inert Safety Tests

- Determine SiC and TRISO failure rates in conditions like core-conduction-cooldown
- Typically hold temperature at 1600 and 1800°C for 300 h
- Measure fission product releases versus time and temperature
- Tests conducted in parallel at INL and ORNL





Irradiated Compact Inert Safety Tests

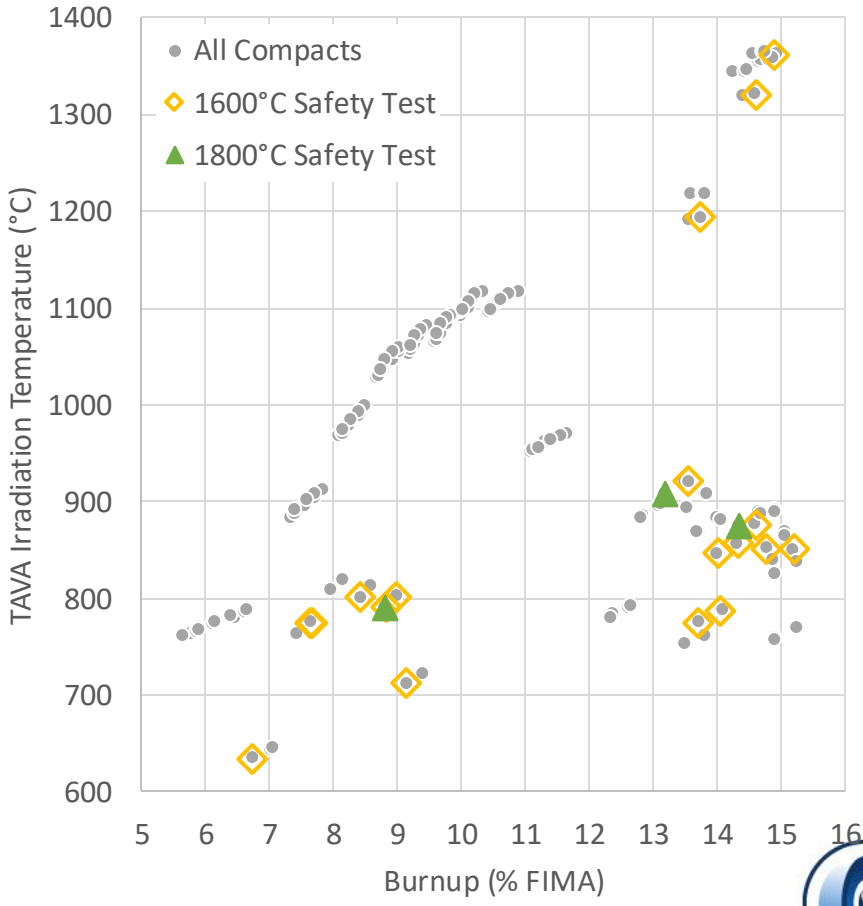
FY24 Milestones due 9/13/2024

1. **Complete three tests in FACS at INL – need two more**
2. **Complete four tests in CCCTF at ORNL – waiting on chemistry results from the 4th test**

	Compact	Burnup	Fluence	TA Min	TAVA	TA Max	Lab	Year
1600°C Safety Test	2-2-2	14.02	4.72	743	845	914	ORNL	2022
	2-2-4	14.33	4.94	752	856	927	ORNL	2022
	4-1-3	14.06	5.01	565	786	902	INL	2022
	5-5-4	7.67	2.14	686	774	843	INL	2022
	3-1-2	13.76	5.48	990	1193	1329	ORNL	2023
	5-5-3	7.64	2.13	685	773	842	ORNL	2022/FY23
	4-4-4	13.56	4.62	833	920	970	INL	2023
	4-1-2	13.72	4.78	558	774	886	ORNL	2023/FY24
	5-6-2	6.75	1.67	467	634	741	ORNL	FY23/FY24
	2-6-4	15.21	5.36	749	850	913	INL	2023/FY24
	5-2-1	8.84	3.01	700	790	846	ORNL	2024
	5-2-4	8.99	3.13	709	801	859		
	5-3-2	8.43	2.7	720	800	849		
	2-5-1	14.78	5.05	747	851	917	ORNL	FY23/FY24
	3-4-2	14.91	5.54	1271	1361	1420	INL	2023/FY24
	5-1-1	9.16	3.27	499	711	822	INL	2023/FY24
	3-2-2	14.61	5.54	1203	1320	1401	ORNL	Started 2024
	2-4-2	14.61	4.95	777	875	931	INL	Planned FY24

	Compact	Burnup	Fluence	TA Min	TAVA	TA Max	Lab	Year
1800°C Safety Test	2-3-2	14.36	4.85	782	874	931	ORNL	2022/FY23
	5-2-2	8.82	2.99	699	789	845	ORNL	2022/FY23
	4-4-2	13.21	4.4	822	906	954	ORNL	Planned FY24

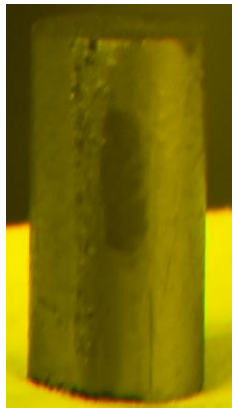
Completed since July 2023

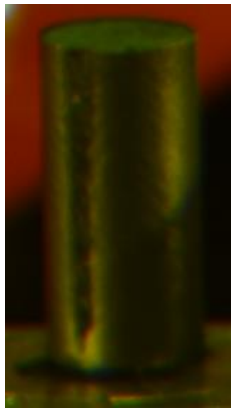


Results Summary (1/6): Compact 4-1-3

Compact		Kr-85	Ag-110m	Cs-134	Eu-154	Sr-90
4-1-3	Fraction	3.0E-3	3.6E-1	2.2E-3	1.5E-3	
TAVA 786°C, 14.1% FIMA	Peq	6.5	796.1	4.9	3.3	
5-5-4	Fraction	2.9E-4	3.1E-3	4.6E-4	1.8E-4	2.4E-4
TAVA 774°C, 7.7% FIMA	Peq	1.0	10.6	1.6	0.6	0.8
4-4-4	Fraction	2.1E-5	1.8E-1	4.7E-6	7.3E-4	8.0E-4
TAVA 920°C, 13.6% FIMA	Peq	0.05	406.1	0.01	1.6	1.8
2-6-4	Fraction	~4.2E-6	1.5E-1	7.3E-6	2.9E-3	2.0E-3
TAVA 850°C, 15.2% FIMA	Peq	~0.01	348.57	0.02	6.64	4.53
3-4-2	Fraction	5.7E-5	7.3E-3	1.3E-4	1.8E-2	3.9E-2
TAVA 1361°C, 14.9% FIMA	Peq	0.13	16.6	0.3	39.5	89.2
5-1-1	Fraction	N/A	4.0E-4	9.6E-6	1.4E-4	5.4E-5
TAVA 711°C, 9.16% FIMA	Peq	N/A	1.4	0.03	0.5	0.2

- Appears to have been damaged before FACS test started and NOT in-pile
- Particle failures apparent during ramp to 1250°C hold
- 6.5 particle equivalents (peq) Kr-85 and 4.9 peq Cs-134 released in FACS
- 8 peq U measured in DLBL at ORNL
- Suspect particles show mechanical damage
- **Compact not considered a valid safety test due to pre-test handling damage.**

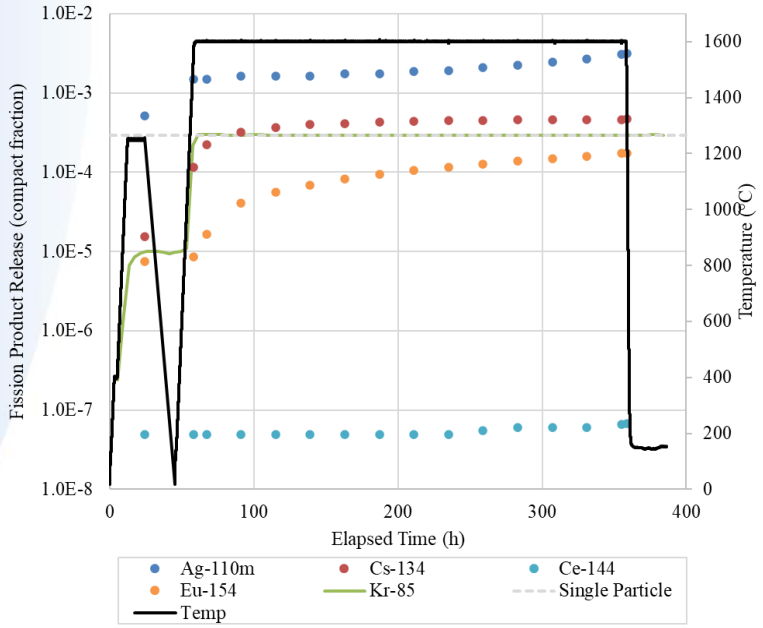


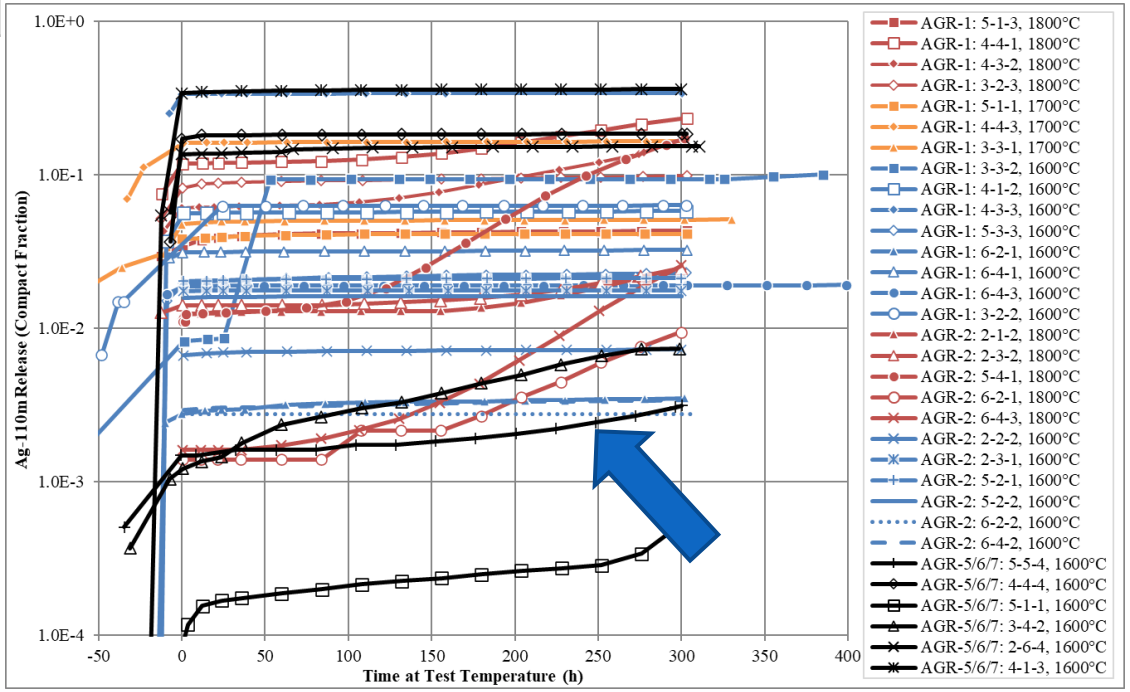


Results Summary (2/6): Compact 5-5-4

Compact		Kr-85	Ag-110m	Cs-134	Eu-154	Sr-90
4-1-3	Fraction	3.0E-3	3.6E-1	2.2E-3	1.5E-3	
TAVA 786°C, 14.1% FIMA	Peq	6.5	796.1	4.9	3.3	
5-5-4	Fraction	2.9E-4	3.1E-3	4.6E-4	1.8E-4	2.4E-4
TAVA 774°C, 7.7% FIMA	Peq	1.0	10.6	1.6	0.6	0.8
4-4-4	Fraction	2.1E-5	1.8E-1	4.7E-6	7.3E-4	8.0E-4
TAVA 920°C, 13.6% FIMA	Peq	0.05	406.1	0.01	1.6	1.8
2-6-4	Fraction	~4.2E-6	1.5E-1	7.3E-6	2.9E-3	2.0E-3
TAVA 850°C, 15.2% FIMA	Peq	~0.01	348.57	0.02	6.64	4.53
3-4-2	Fraction	5.7E-5	7.3E-3	1.3E-4	1.8E-2	3.9E-2
TAVA 1361°C, 14.9% FIMA	Peq	0.13	16.6	0.3	39.5	89.2
5-1-1	Fraction	N/A	4.0E-4	9.6E-6	1.4E-4	5.4E-5
TAVA 711°C, 9.16% FIMA	Peq	N/A	1.4	0.03	0.5	0.2

- Estimated 1 failed TRISO and 1 failed SiC upon restart of ramp to 1600°C from repairing FACS cold finger.
- Total Ag-110m release is low, but increases late in test. Only 1800°C tests showed this previously.

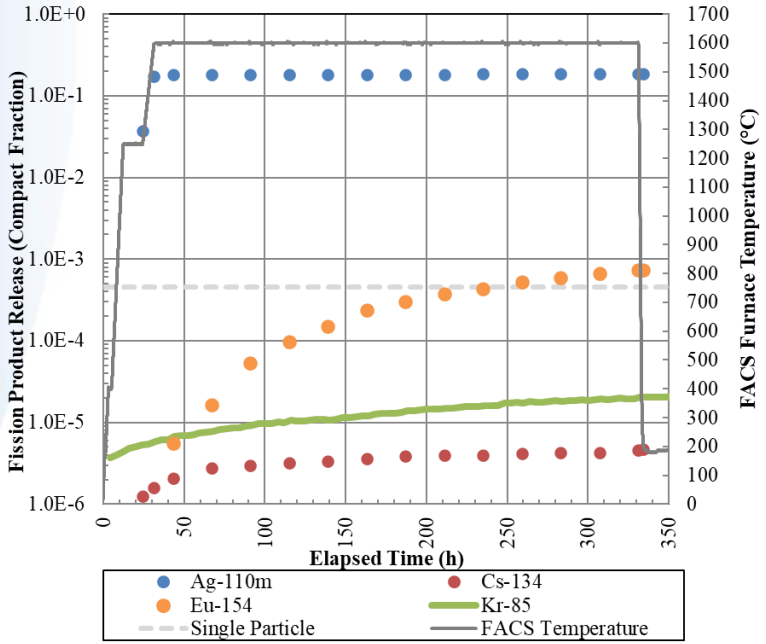


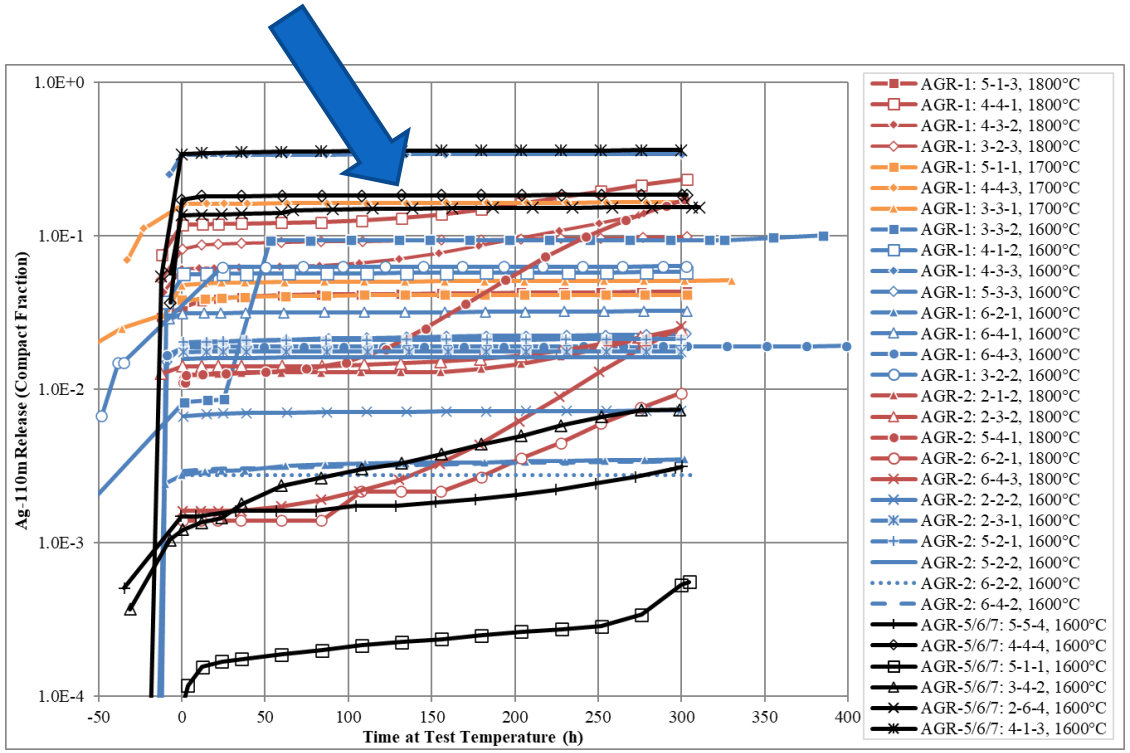


Results Summary (3/6): Compact 4-4-4

Compact		Kr-85	Ag-110m	Cs-134	Eu-154	Sr-90
4-1-3	Fraction	3.0E-3	3.6E-1	2.2E-3	1.5E-3	
TAVA 786°C, 14.1% FIMA	Peq	6.5	796.1	4.9	3.3	
5-5-4	Fraction	2.9E-4	3.1E-3	4.6E-4	1.8E-4	2.4E-4
TAVA 774°C, 7.7% FIMA	Peq	1.0	10.6	1.6	0.6	0.8
4-4-4	Fraction	2.1E-5	1.8E-1	4.7E-6	7.3E-4	8.0E-4
TAVA 920°C, 13.6% FIMA	Peq	0.05	406.1	0.01	1.6	1.8
2-6-4	Fraction	~4.2E-6	1.5E-1	7.3E-6	2.9E-3	2.0E-3
TAVA 850°C, 15.2% FIMA	Peq	~0.01	348.57	0.02	6.64	4.53
3-4-2	Fraction	5.7E-5	7.3E-3	1.3E-4	1.8E-2	3.9E-2
TAVA 1361°C, 14.9% FIMA	Peq	0.13	16.6	0.3	39.5	89.2
5-1-1	Fraction	N/A	4.0E-4	9.6E-6	1.4E-4	5.4E-5
TAVA 711°C, 9.16% FIMA	Peq	N/A	1.4	0.03	0.5	0.2

- No indications of particle failure or SiC failure.
- Significant Ag release. Similar to 2-6-4.

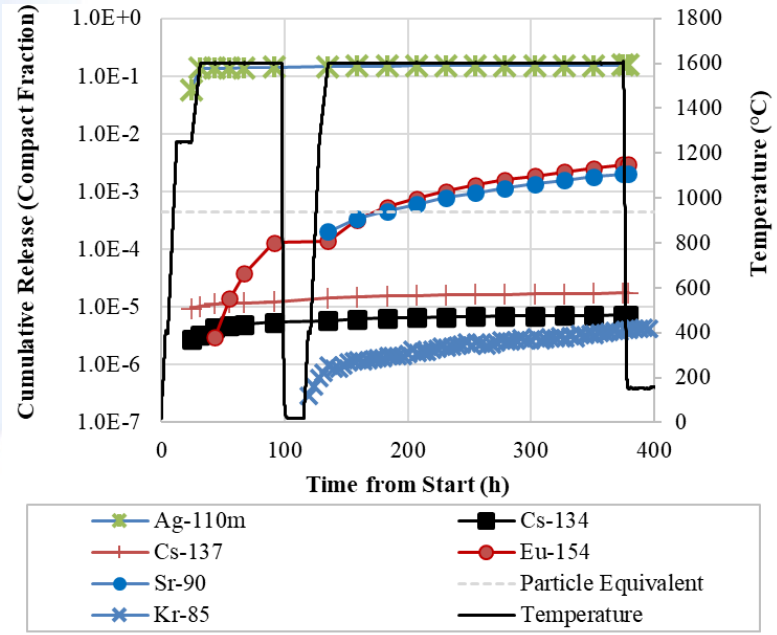


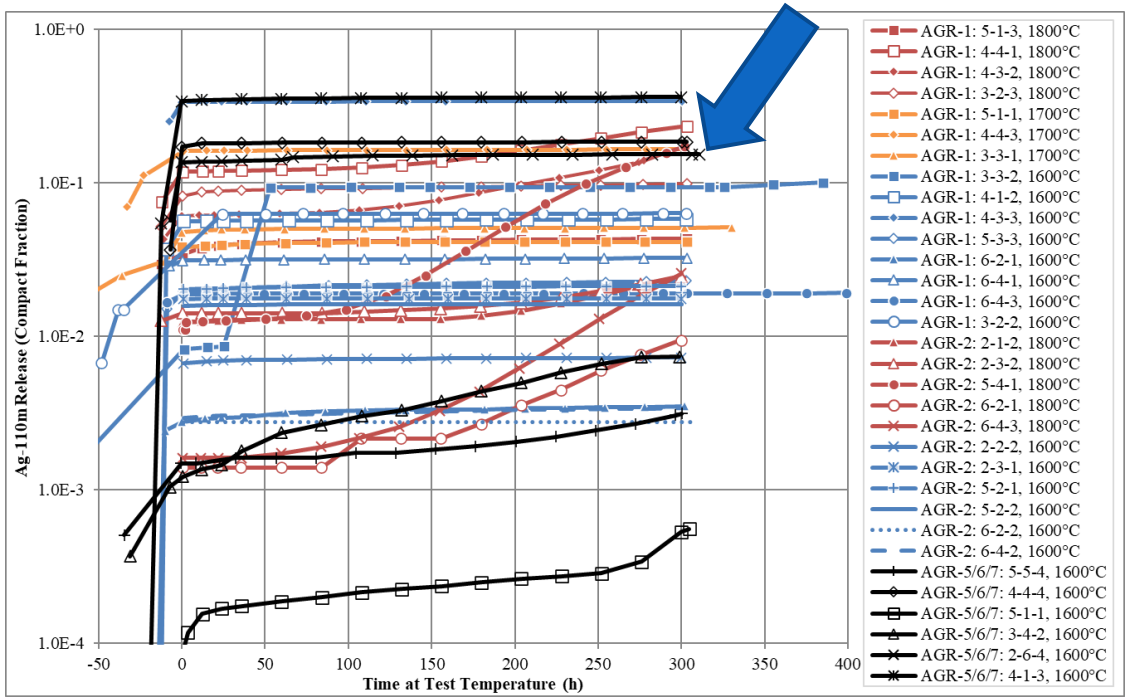


Results Summary (4/6): Compact 2-6-4

Compact		Kr-85	Ag-110m	Cs-134	Eu-154	Sr-90
4-1-3	Fraction	3.0E-3	3.6E-1	2.2E-3	1.5E-3	
TAVA 786°C, 14.1% FIMA	Peq	6.5	796.1	4.9	3.3	
5-5-4	Fraction	2.9E-4	3.1E-3	4.6E-4	1.8E-4	2.4E-4
TAVA 774°C, 7.7% FIMA	Peq	1.0	10.6	1.6	0.6	0.8
4-4-4	Fraction	2.1E-5	1.8E-1	4.7E-6	7.3E-4	8.0E-4
TAVA 920°C, 13.6% FIMA	Peq	0.05	406.1	0.01	1.6	1.8
2-6-4	Fraction	~4.2E-6	1.5E-1	7.3E-6	2.9E-3	2.0E-3
TAVA 850°C, 15.2% FIMA	Peq	~0.01	348.57	0.02	6.64	4.53
3-4-2	Fraction	5.7E-5	7.3E-3	1.3E-4	1.8E-2	3.9E-2
TAVA 1361°C, 14.9% FIMA	Peq	0.13	16.6	0.3	39.5	89.2
5-1-1	Fraction	N/A	4.0E-4	9.6E-6	1.4E-4	5.4E-5
TAVA 711°C, 9.16% FIMA	Peq	N/A	1.4	0.03	0.5	0.2

- Partial results shown last year. Test completed in early FY24
- No signs of TRISO or SiC failure
- Ag release fairly high. Similar to 4-4-4.

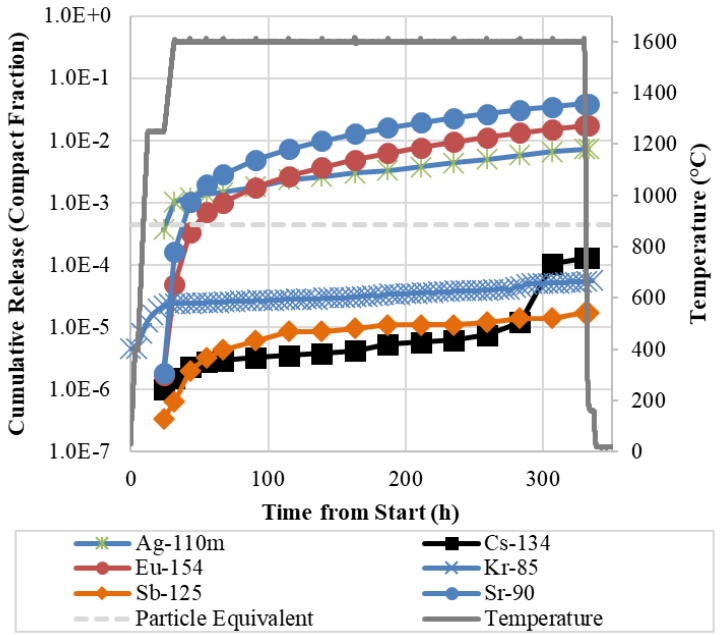


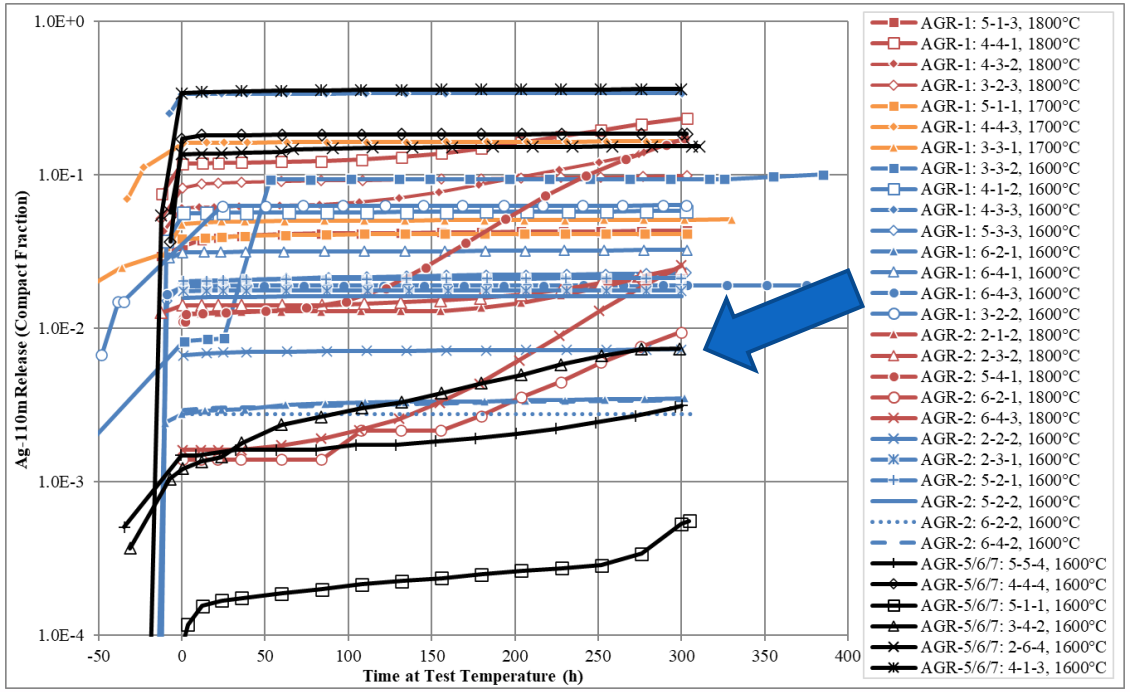


Results Summary (5/6): Compact 3-4-2

Compact		Kr-85	Ag-110m	Cs-134	Eu-154	Sr-90
4-1-3	Fraction	3.0E-3	3.6E-1	2.2E-3	1.5E-3	
TAVA 786°C, 14.1% FIMA	Peq	6.5	796.1	4.9	3.3	
5-5-4	Fraction	2.9E-4	3.1E-3	4.6E-4	1.8E-4	2.4E-4
TAVA 774°C, 7.7% FIMA	Peq	1.0	10.6	1.6	0.6	0.8
4-4-4	Fraction	2.1E-5	1.8E-1	4.7E-6	7.3E-4	8.0E-4
TAVA 920°C, 13.6% FIMA	Peq	0.05	406.1	0.01	1.6	1.8
2-6-4	Fraction	~4.2E-6	1.5E-1	7.3E-6	2.9E-3	2.0E-3
TAVA 850°C, 15.2% FIMA	Peq	~0.01	348.57	0.02	6.64	4.53
3-4-2	Fraction	5.7E-5	7.3E-3	1.3E-4	1.8E-2	3.9E-2
TAVA 1361°C, 14.9% FIMA	Peq	0.13	16.6	0.3	39.5	89.2
5-1-1	Fraction	N/A	4.0E-4	9.6E-6	1.4E-4	5.4E-5
TAVA 711°C, 9.16% FIMA	Peq	N/A	1.4	0.03	0.5	0.2

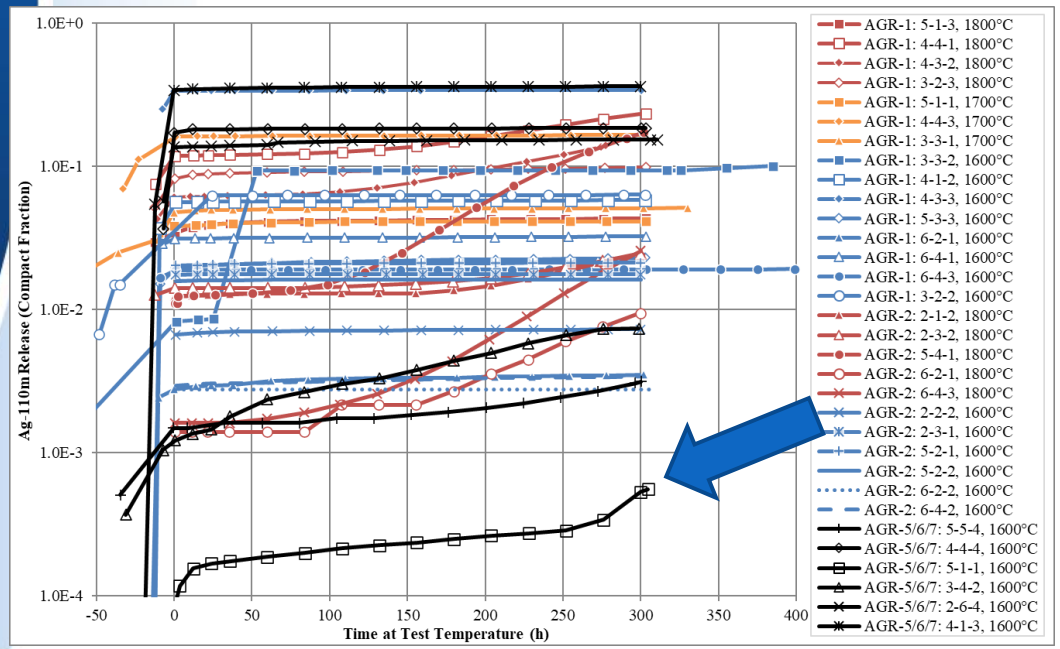
- Kr-85 was relatively low. No signs of TRISO failure.
- May have been SiC failure late in the test with ~0.3 peq
- Ag release relatively low (similar to compacts with lower irradiation temperatures, e.g., 5-5-4 and 5-5-3 [ORNL])



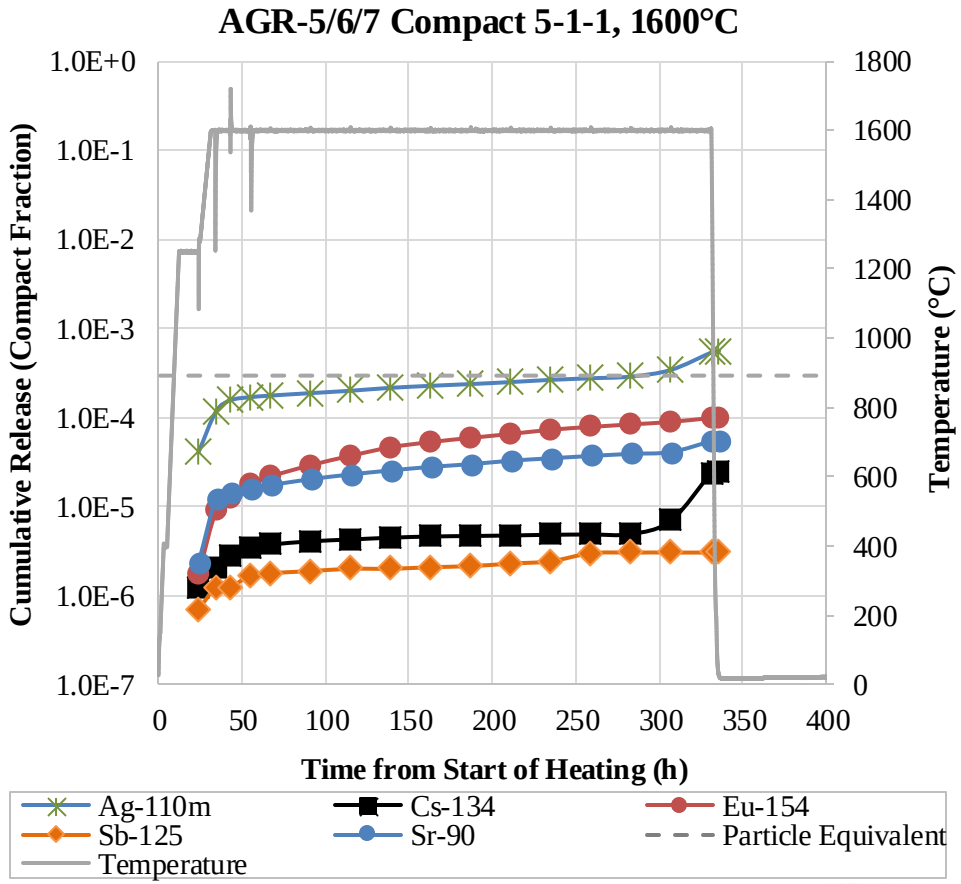


Results Summary (6/6): Compact 5-1-1

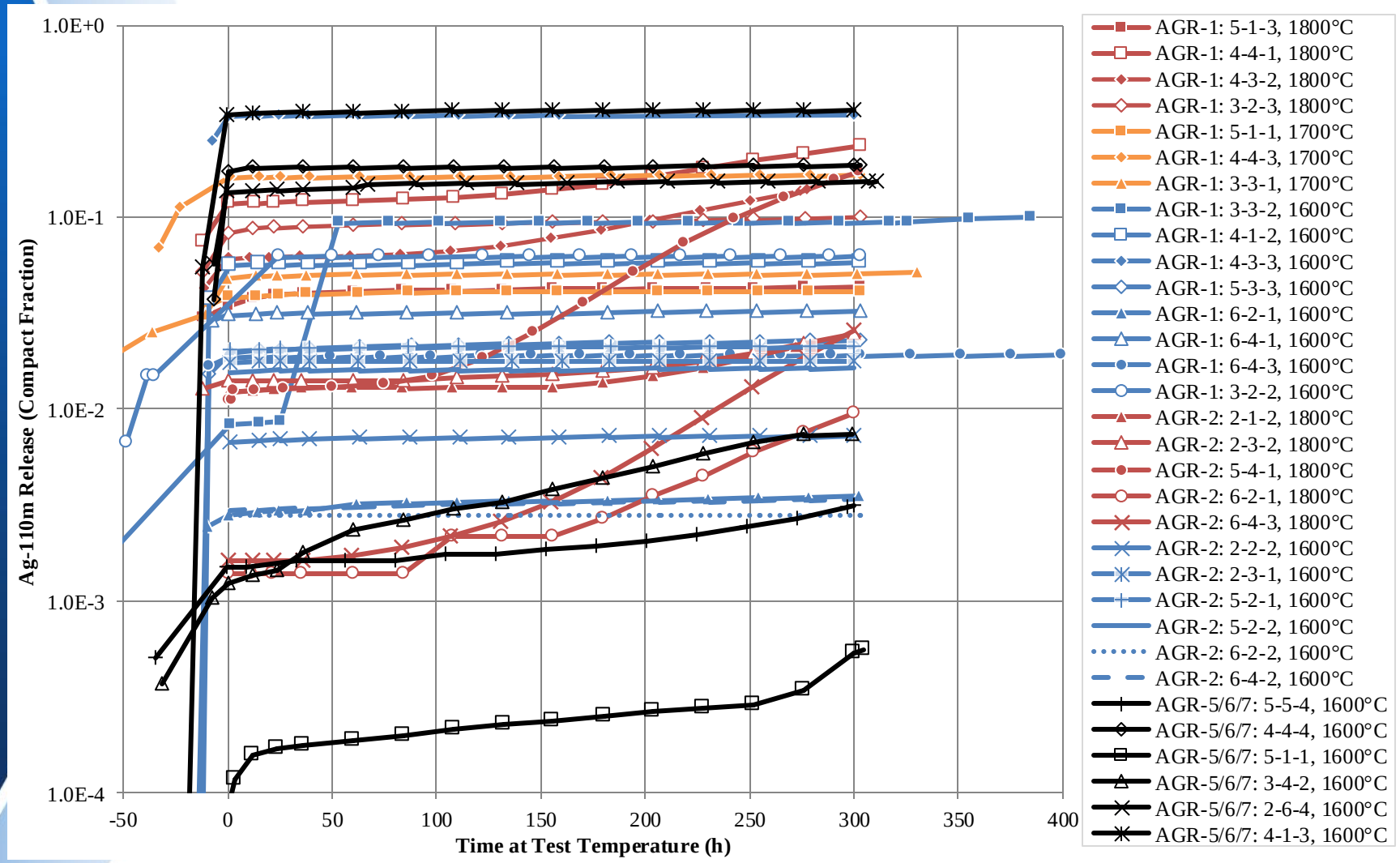
Compact		Kr-85	Ag-110m	Cs-134	Eu-154	Sr-90
4-1-3	Fraction	3.0E-3	3.6E-1	2.2E-3	1.5E-3	
TAVA 786°C, 14.1% FIMA	Peq	6.5	796.1	4.9	3.3	
5-5-4	Fraction	2.9E-4	3.1E-3	4.6E-4	1.8E-4	2.4E-4
TAVA 774°C, 7.7% FIMA	Peq	1.0	10.6	1.6	0.6	0.8
4-4-4	Fraction	2.1E-5	1.8E-1	4.7E-6	7.3E-4	8.0E-4
TAVA 920°C, 13.6% FIMA	Peq	0.05	406.1	0.01	1.6	1.8
2-6-4	Fraction	~4.2E-6	1.5E-1	7.3E-6	2.9E-3	2.0E-3
TAVA 850°C, 15.2% FIMA	Peq	~0.01	348.57	0.02	6.64	4.53
3-4-2	Fraction	5.7E-5	7.3E-3	1.3E-4	1.8E-2	3.9E-2
TAVA 1361°C, 14.9% FIMA	Peq	0.13	16.6	0.3	39.5	89.2
5-1-1	Fraction	N/A	4.0E-4	9.6E-6	1.4E-4	5.4E-5
TAVA 711°C, 9.16% FIMA	Peq	N/A	1.4	0.03	0.5	0.2



- Very low Ag release. Shows signs of increase at end of test like 5-5-4. Suggests evidence of diffusive release.
- Not believed to have SiC or TRISO failure, but abrupt increase in Cs at the end is curious



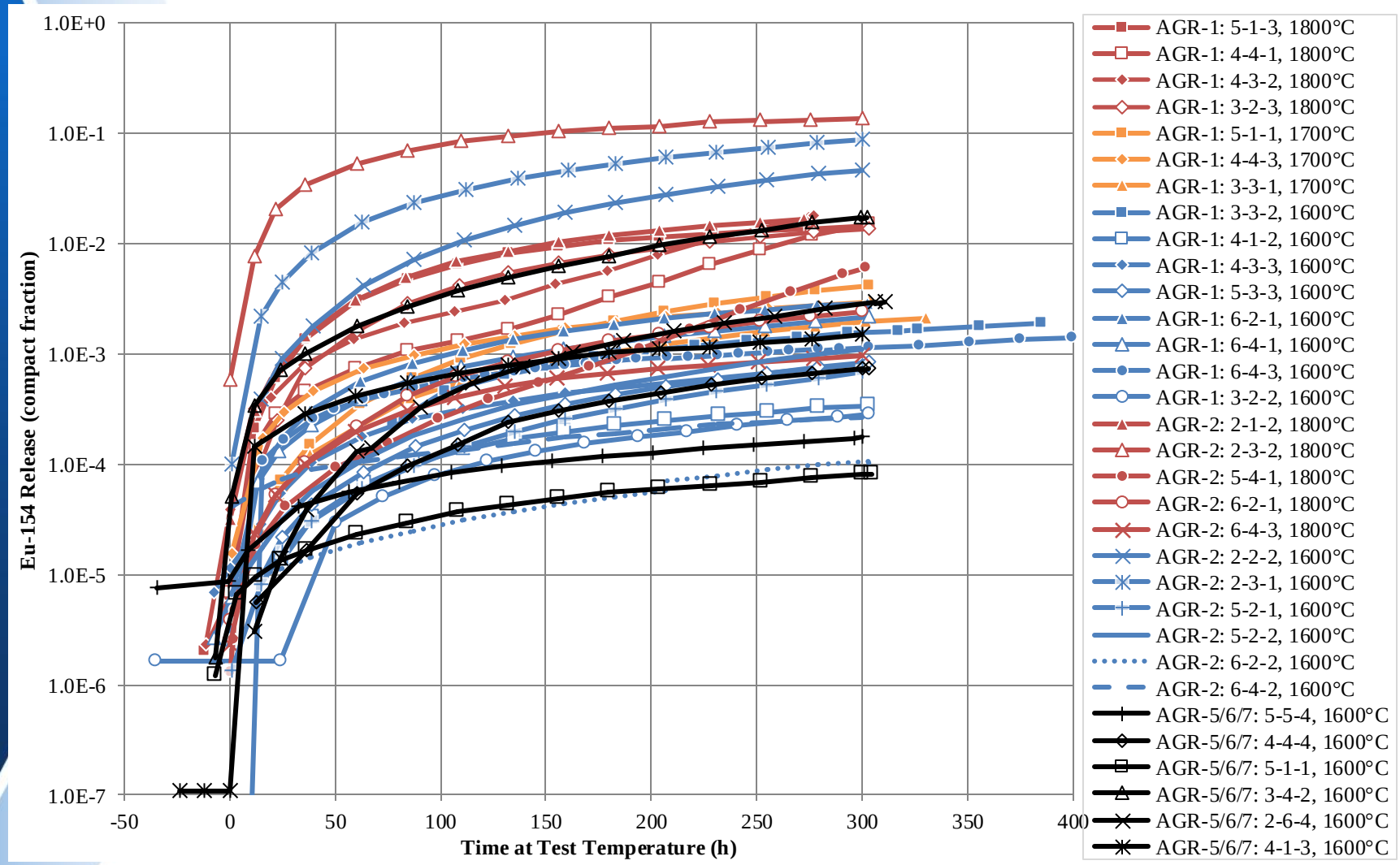
Ag Behavior



Increasing Safety Test Release

- 4-1-3 TAVA 786°C, 14.1% FIMA
- 4-4-4 TAVA 920°C, 13.6% FIMA
- 2-6-4 TAVA 850°C, 15.2% FIMA
- 3-4-2 TAVA 1361°C, 14.9% FIMA
- 5-5-4 TAVA 774°C, 7.7% FIMA
- 5-1-1 TAVA 711°C, 9.16% FIMA

Eu Behavior

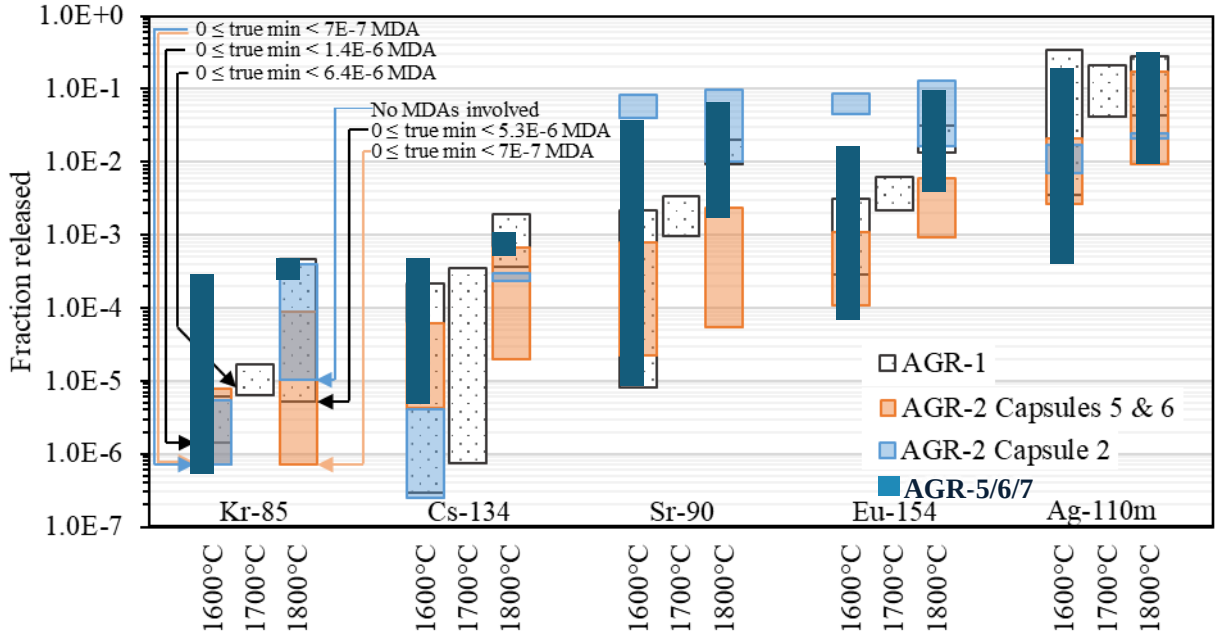


Increasing Safety Test Release

- 3-4-2 TAVA 1361°C, 14.9% FIMA
- 2-6-4 TAVA 850°C, 15.2% FIMA
- 4-1-3 TAVA 786°C, 14.1% FIMA
- 4-4-4 TAVA 920°C, 13.6% FIMA
- 5-5-4 TAVA 774°C, 7.7% FIMA
- 5-1-1 TAVA 711°C, 9.16% FIMA

Preliminary AGR-5/6/7 Safety Test Release Comparison

- Through 13 1600°C safety tests and 2 1800°C safety tests
- The upper range Kr from AGR-5/6/7 1600°C is from one TRISO failure
- Cs on high end at 1600°C because one SiC failure in 25% pf AGR-5/6/7 Compact 3-1-2.
- Cs on high end at 1800°C because all AGR-5/6/7 1800°C tests had a SiC or TRISO failure
- High-temperature Capsule 3 fuel accounts for upper range of Eu and Sr releases. (Like AGR-2 Capsule 2)
- AGR-5/6/7 Ag ~ normal. Highest Ag from Capsule 4 and 2 compacts.
- Lowest Ag releases from Capsules 3 and 5
- Bottom line: safety test release range is broader, but comparable to what was spanned by AGR-1 & 2 fuel



Preliminary Safety Test Statistics

- Roughly 44,000*,** particles tested at 1600°C
- Roughly 5,700 particles tested at 1800°C. More tests are planned.
- Some results may change if it is discovered these were damaged (either accidentally via handling or in-pile during irradiation). A few scenarios for 1600°C are presented.

1600°C	Observed SiC Failure	SiC Failure at 1600°C (95% Confidence, ≤)	Observed TRISO Failure	TRISO Failure at 1600°C (95% Confidence, ≤)
AGR-1	9.1E-5	2.4E-4	0	9.1E-5
AGR-2	0	2.4E-4	0	2.4E-4
AGR-5/6/7 (not including 3-compact test)	2.1E-4	3.9E-4	3.0E-5	1.4E-4
AGR-5/6/7 (including 3-compact test assuming no failures)	1.6E-4	3.0E-4	2.3E-5	1.1E-4
AGR-5/6/7 (including 3-compact test assuming 3 failures)	1.6E-4	3.0E-4	9.1E-5	2.1E-4

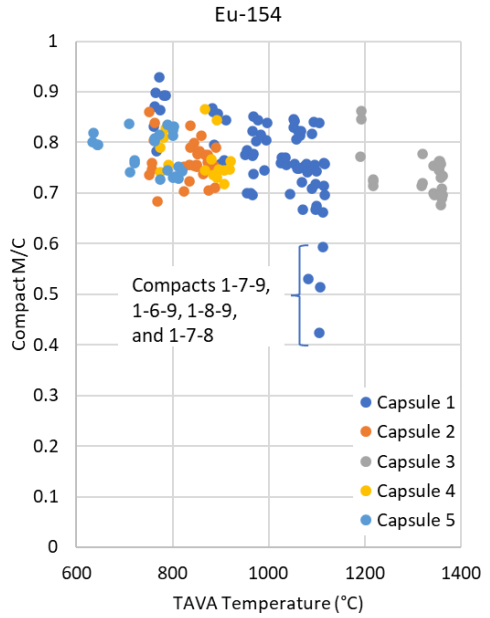
1800°C	Observed SiC Failure	SiC Failure at 1800°C (95% Confidence, ≤)	Observed TRISO Failure	TRISO Failure at 1800°C (95% Confidence, ≤)
AGR-1	1.4E-3	2.0E-3	1.2E-4	3.9E-4
AGR-2	1.0E-4	5.0E-4	1.0E-4	5.0E-4
AGR-5/6/7	3.5E-4	1.1E-3	5.3E-4	1.4E-3

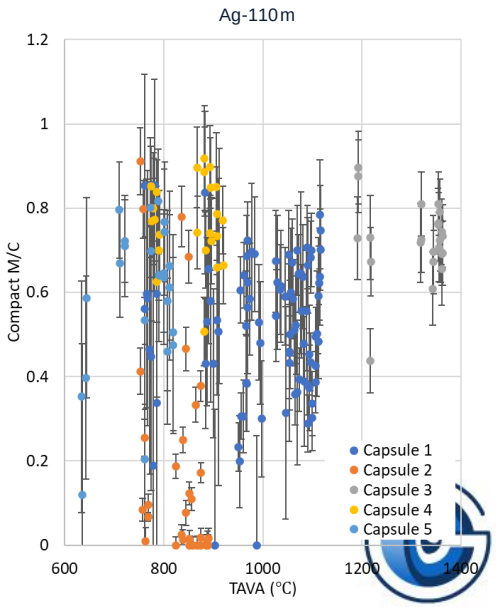
*Compact 4-1-3 was excluded due to pre-test damage
**Includes Compact 3-2-2. Test may be restarted.

Remaining AGR-5/6/7 Work (1 of 3)

- Inert tests
  - Two at 1700°C
  - Three to four at 1800°C
- Complete mass balance
  - Gamma counting spacers and foils and leach or burn-leach as appropriate
  - Burn-leach of graphite holders
- Look for explanations for different Eu and Ag behavior between Capsules 2, 4, and 5. Attempt use of SiC as EOI temperature indicator.

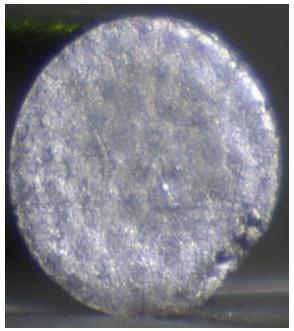
Capsule Fraction Outside of Fuel (Partial Mass Balance) Ordered by increasing Capsule TAVA					
	Capsule 5	Capsule 2	Capsule 4	Capsule 1	Capsule 3
Ag-110m	0.00E+00	4.18E-01	1.76E-02	1.09E-01	8.26E-02
Eu-154	0.00E+00	2.18E-04	0.00E+00	1.66E-02	1.78E-02
Sr-90	5.36E-06	1.03E-05	9.77E-06	1.20E-03	8.87E-06
Instant Peak Temp (°C)	983	1039	1091	1386	1536
Time-average Peak Temp	864	948	970	1267	1432
TAVA Temp (°C)	756	833	857	1041	1313
Time-average Min Temp (°C)	467	546	558	624	989

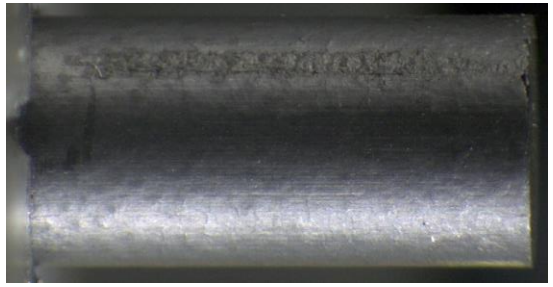




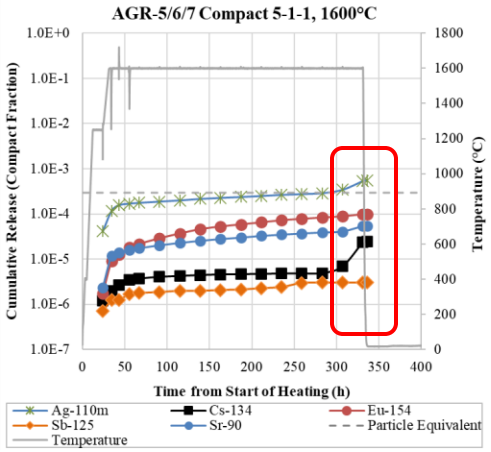
Remaining AGR-5/6/7 Work (2 of 3)

- Assessment of post-irradiation handling damage via acid leaching intact compacts (and perhaps XCT as well)





- Investigate some of the small releases from safety testing to see if it is some kind of incomplete failure (e.g., Compact 5-1-1)



Remaining AGR-5/6/7 Work (3 of 3)

- Attempt screening of Capsule 1 compacts (perhaps others as well) for failure using the Removable Assembly Providing TRISO Reirradiations (RAPTOR) and Screen Neutron Irradiated Fuel for Failure (SNIFF) devices
- Oxidation testing of irradiated fuel compacts in the Air Moisture Ingress Experiment (AMIX) system
- Reporting results

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Thank you for your attention

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