July 25, 2023

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2023 AGR-5/6/7 Safety Testing and Compact Destructive Exams

This presentation contains information that is preliminary in nature, and the results and conclusions may change as experiments and analyses continue.

DOE ART Gas-Cooled Reactor (GCR) Review Meeting
Virtual Meeting
July 25 – 27, 2023

ART Advanced Reactor Technologies
GAS-COOLED REACTORS

Collaborators in Safety Tests and Destructive Exams

- Cad Christensen
- Edward Reber
- Lu Cai
- David Laug
- Kelley Verner
- Phil Winston
- BJ Camphouse

- John Hunn
- Tyler Gerczak
- Grant Helmreich
- Darren Skitt
- Fred Montgomery

Topics

- Post-irradiation fuel compact safety testing (1600°C+)
- As-irradiated and post-safety test compact deconsolidation-leach-burn-leach (DLBL)
- Facility for fuels oxidation testing

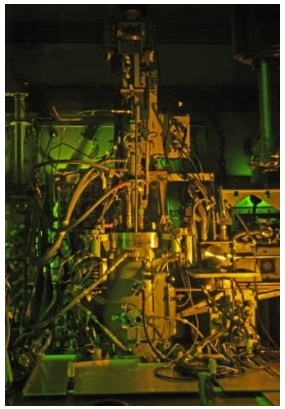
Compact Shipments to ORNL for PIE

Shipment	Date	Compacts	Use
1	Completed 3/2022	2-2-1	As-irradiated DLBL
		2-2-2	1600°C Safety Test
		2-2-3	~~Safety Test or As-irradiated DLBL~~
		2-2-4	1600°C CCCTF
2	Completed 10/2022	1-5-9	As-irradiated DLBL
		2-3-2	1800°C Safety Test
		4-1-3	Post-FACS DLBL
		5-5-3	1600°C Safety Test
3	Completed 12/2022	3-1-2	1600°C CCCTF
		3-6-3	as-irradiated DLBL
		5-1-3	as-irradiated DLBL
		5-2-2	1800°C CCCTF
4	Completed 4/2023	3-8-3	as-irradiated DLBL
		4-1-2	1600°C CCCTF
		5-2-1	Simultaneous 1600°C CCCTF
		5-6-2	1600°C CCCTF
5	Planned 7/2023	5-2-4	Simultaneous 1600°C CCCTF
		5-3-2	Simultaneous 1600°C CCCTF
		2-5-1	1600°C Safety Test
		2-6-1	As-irradiated DLBL

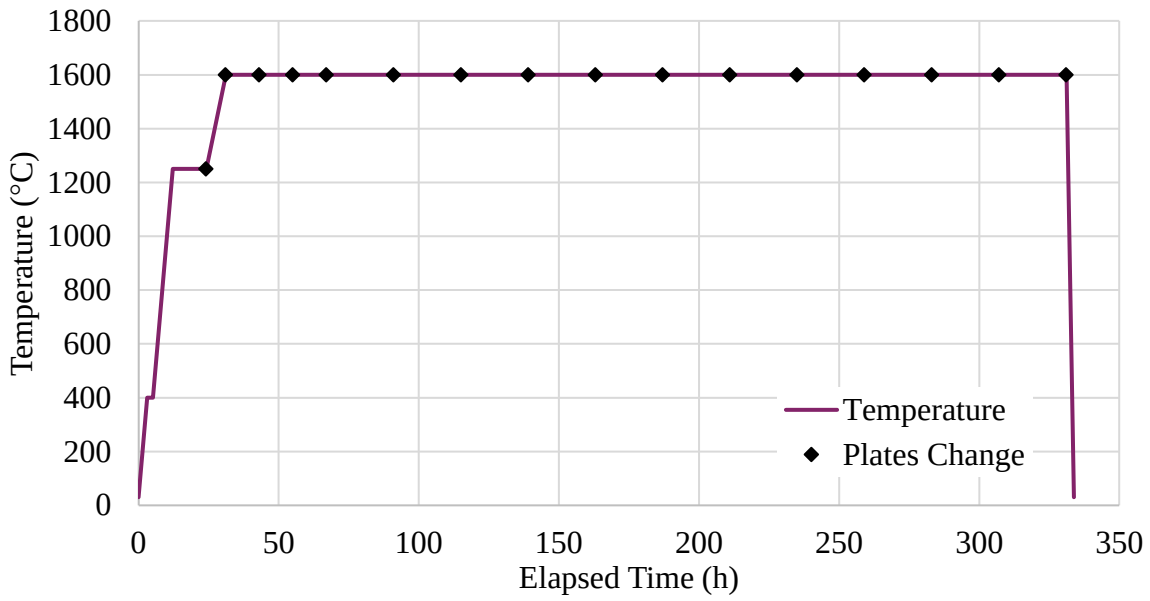
Need to complete Shipments 5 and 6 for L3 milestone.
Compacts for Shipment 6 TBD.

Inert Safety Tests

FACS Furnace (INL)



CCCTF Furnace (ORNL)



	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	planned FY23
	5-6-2	6.75	1.67	467	634	741	ORNL	planned FY23
	2-6-4	15.21	5.36	749	850	913	INL	In Progress
	5-2-1	8.84	3.01	700	790	846	ORNL	Planned simultaneous FY23
	5-2-4	8.99	3.13	709	801	859	ORNL	
	5-3-2	8.43	2.7	720	800	849	ORNL	

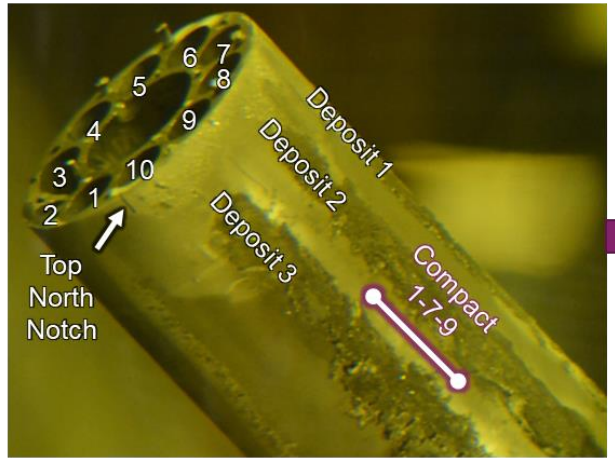
	Compact	Burnup	Fluence	TA Min	TAVA	TA Max	Lab	Year
1800°C Safety Test	2-3-2	14.36	4.85	782	874	931	ORNL	2022
	5-2-2	8.82	2.99	699	789	845	ORNL	2022

FY23 Milestones due 9/15/2023

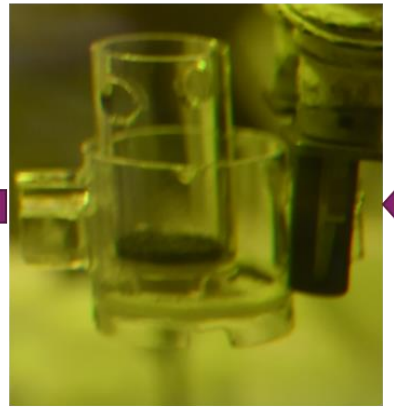
1. **Complete three tests in FACS at INL**
2. **Complete four tests in CCCTF at ORNL**

Compact Exams: Deconsolidation-Leach-Burn-Leach

	Compact	Burnup	Fluence	TAVA	Lab	Year
As-irradiated DLBL	1-7-4	10.12	3.9	1100	INL	2022
	1-7-9	10.13	3.9	1106	INL	2022
	2-2-1	14.03	4.72	845	ORNL	2022
	3-6-3	14.77	5.47	1363	ORNL	2023/FY23
	5-1-2	9.17	3.25	710	INL	2022/FY23
	1-5-9	9.29	3.3	1070	ORNL	2022/FY23
	3-6-2	14.72	5.46	1363	INL	2023/FY23
	2-7-4	15.26	5.42	836	INL	planned FY23
	4-6-4	12.65	4.2	791	INL	planned FY23
	5-1-3	9.38	3.39	721	ORNL	planned
	3-8-3	13.81	5.3	1218	ORNL	planned

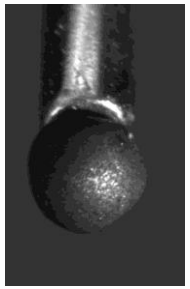


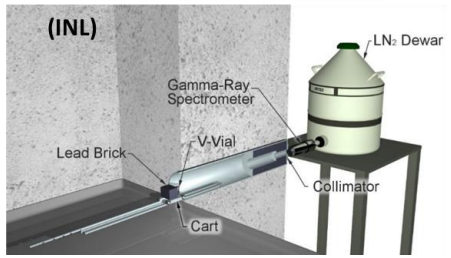
"Burn" at 750°C in air for 72 h



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

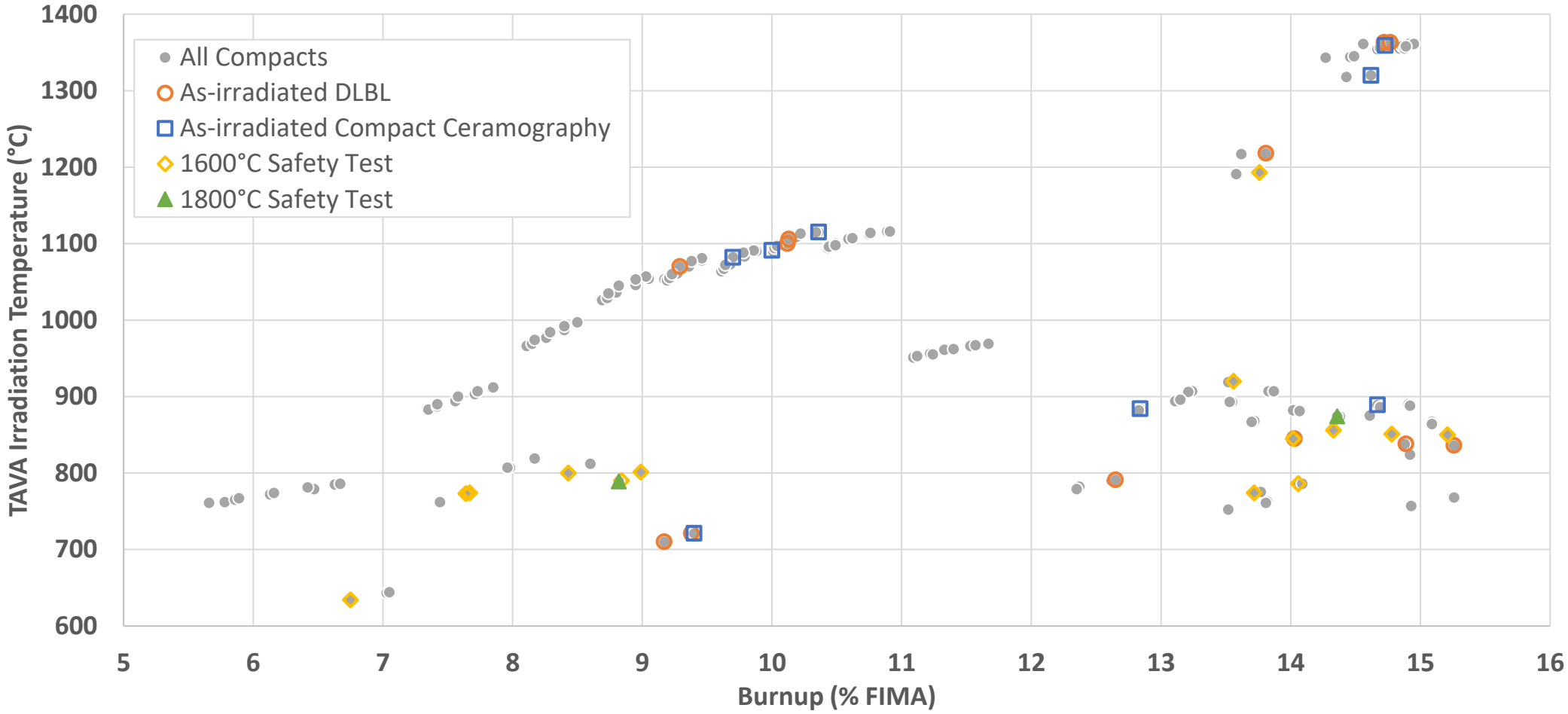
Particle Exams
- Gamma counting
- X-ray CT





Need to complete a total of four DLBL at INL and four at ORNL for two L2 milestones by 9/15/2023.

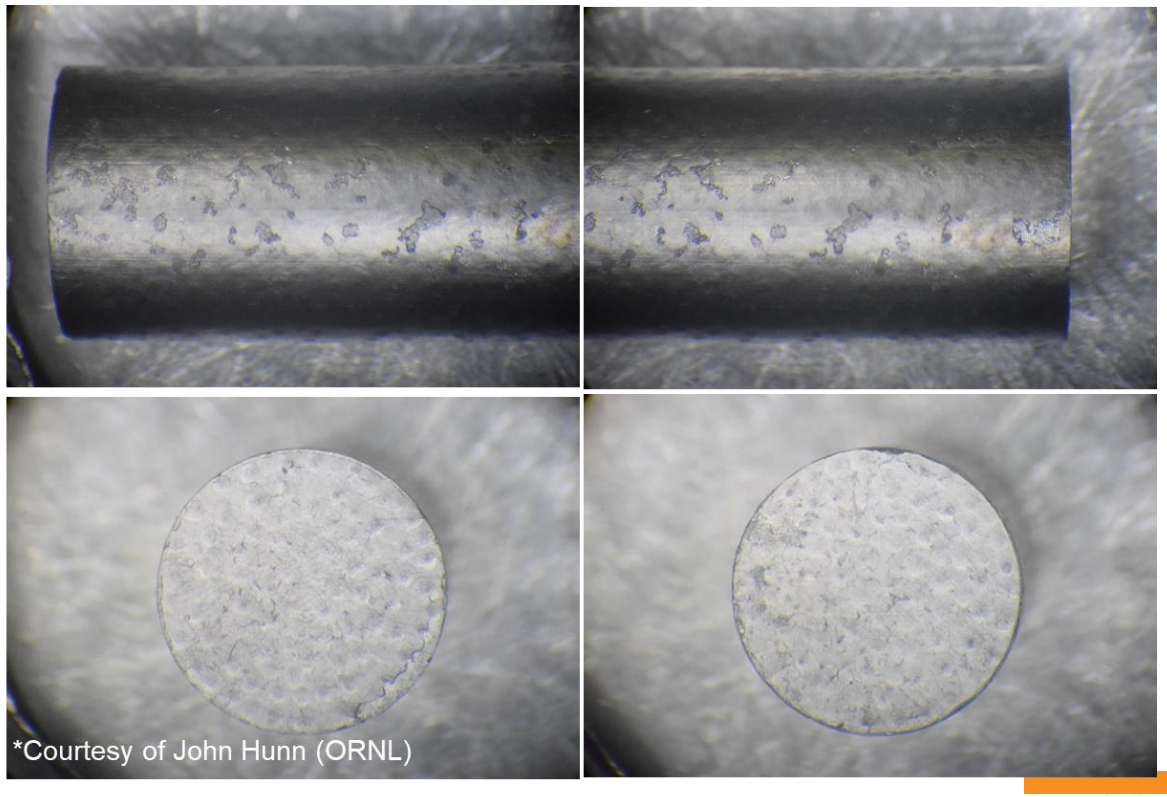
Compact Exams Planned and Completed

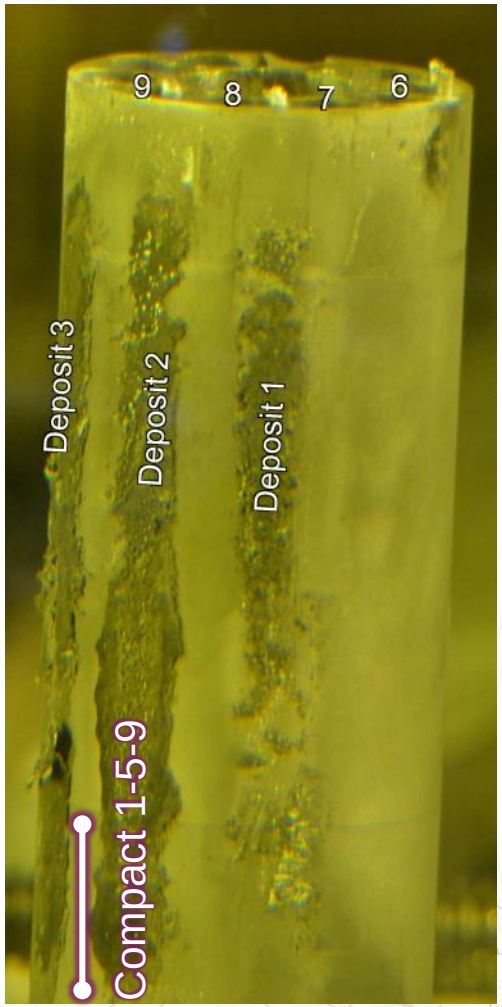


- Includes both completed and near-term planned tests and exams

AGR-5/6/7 DLBL Data from ORNL As-irradiated Deconsolidation of Compact 1-5-9

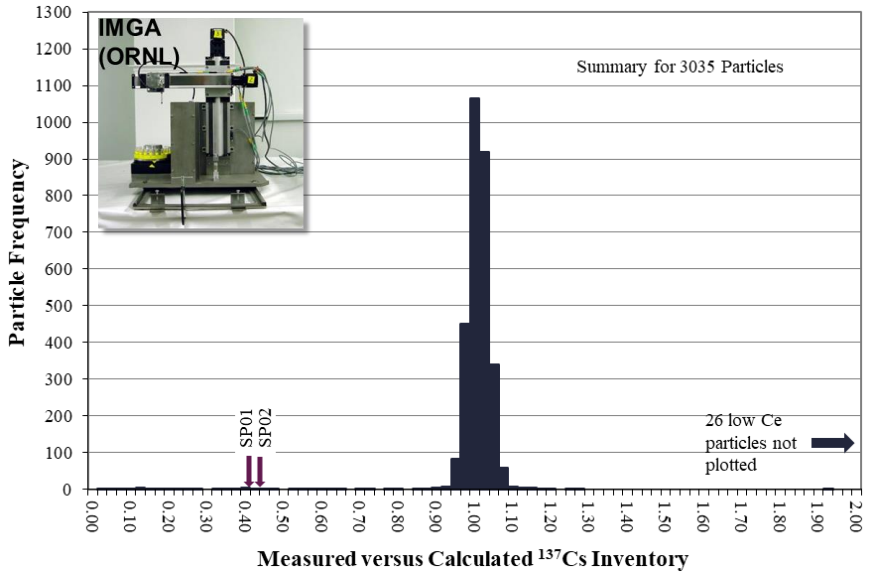
- Compact taken from in between deposits on Capsule 1 holder
- Compact shows external surface degradation
- 300–400 exposed kernels detected in the LBL
- 329 particle equivalent ^{238}U in pre-burn leach alone

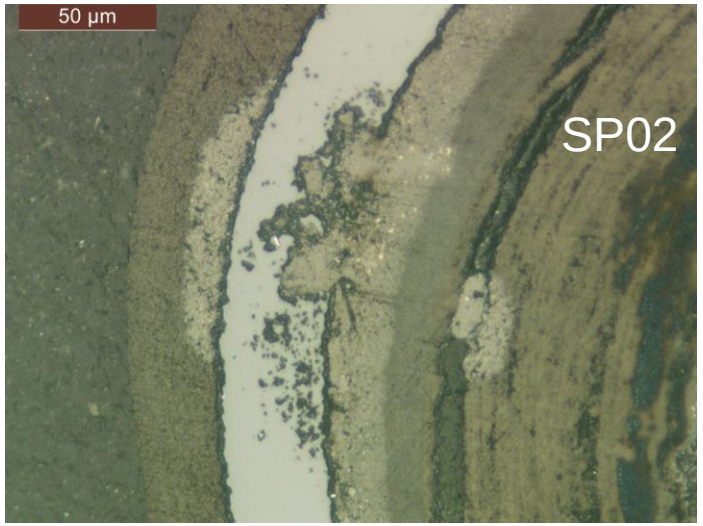


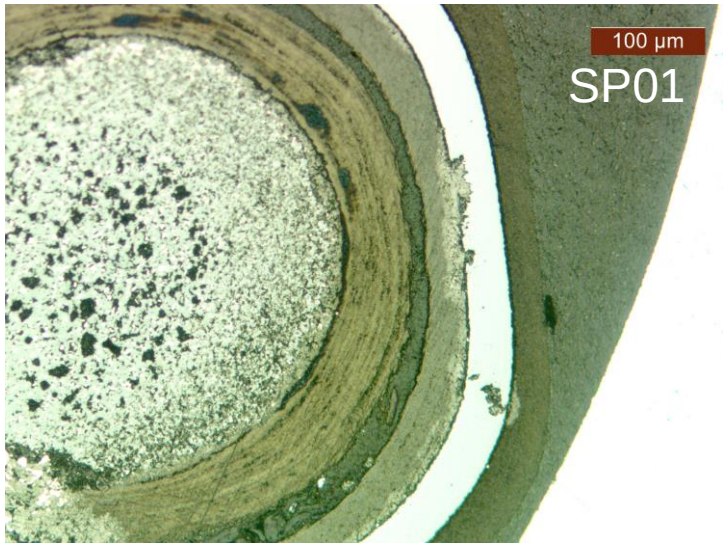


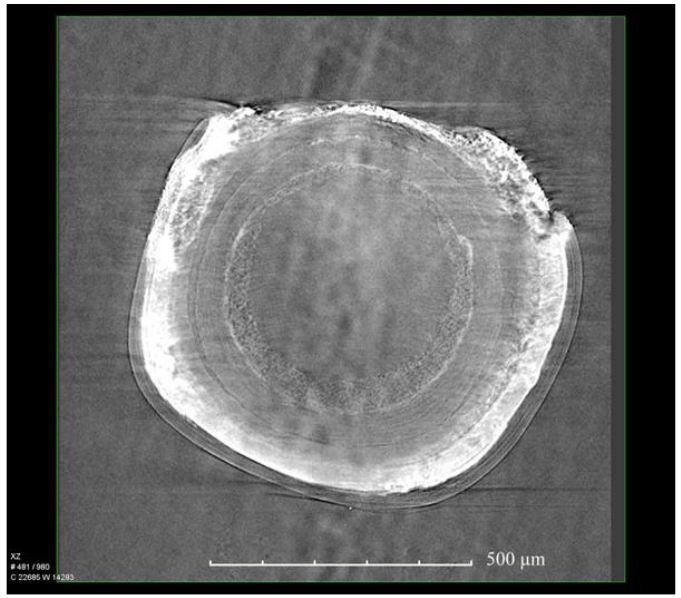
Compact 1-5-9 IMGA and Targeted Ceramography at ORNL

Numerous particles with low Ce and/or low Cs (103 particles < 0.85 ^{144}Ce M/A, 109 particles < 0.85 ^{137}Cs M/A)









SP22: 0.04 ^{144}Ce M/A, no measurable ^{134}Cs

Compact 1-6-9 example of inside-out-looking attack

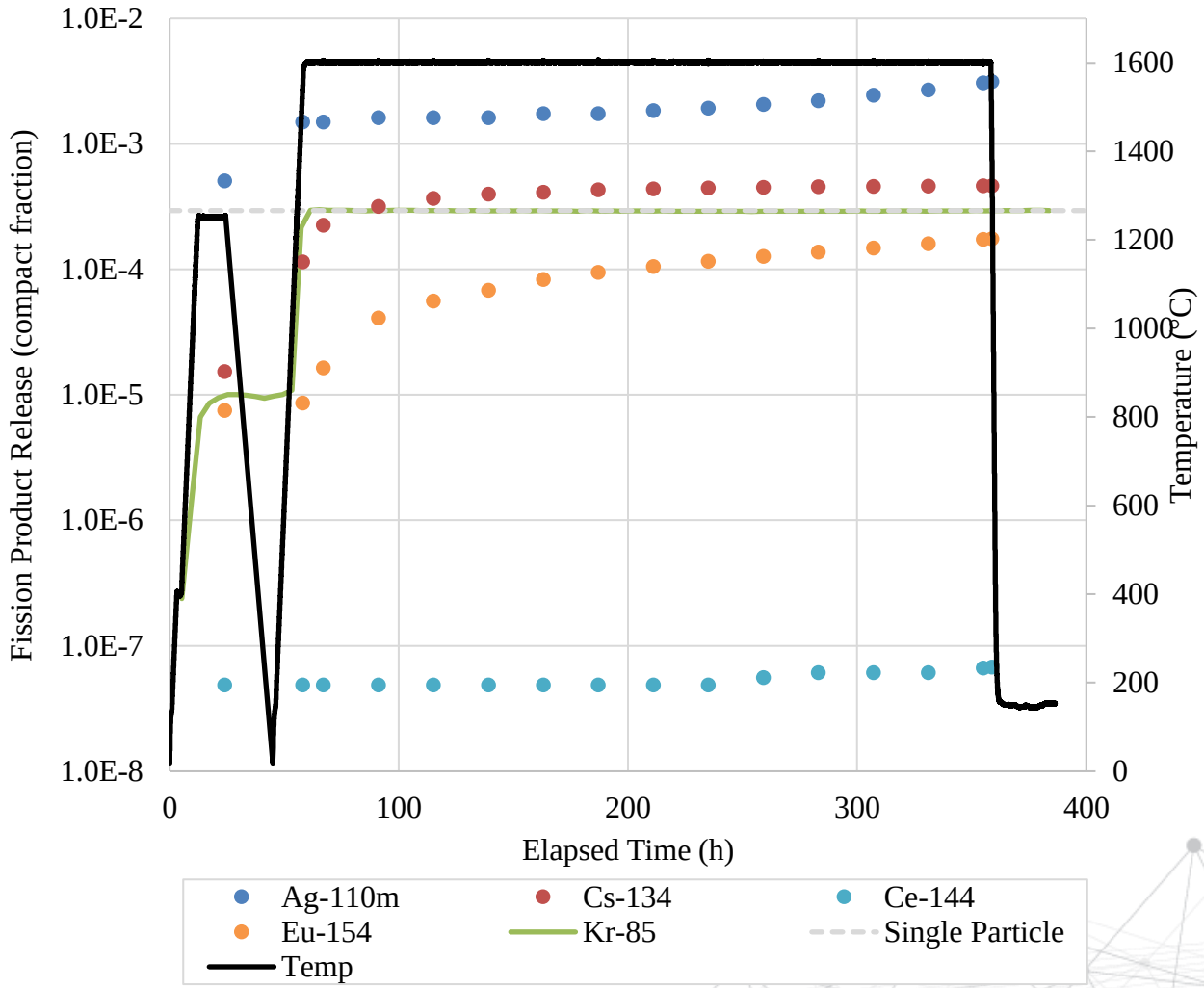
*Courtesy of John Hunn (ORNL)

1600°C FACS Test of Compact 5-5-4 Summary

Compact	Burnup	Fluence	TA Min	TAVA	TA Max
5-5-4	7.67	2.14	686	774	843

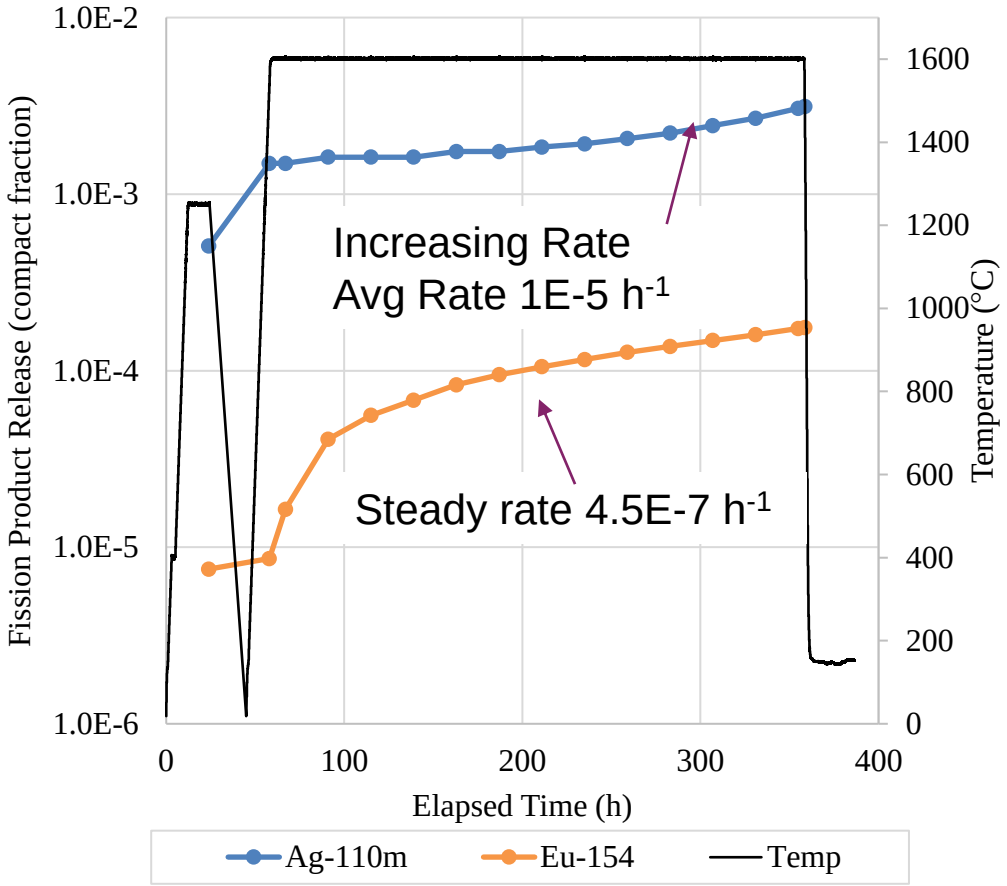
- Condensation plate change failed 30 minutes prior to ramp to 1600°C
- Furnace shutdown then restarted
- Estimated 1 failed TRISO and 1 failed SiC upon restart of ramp to 1600°C
- Low Ag and Eu release compared to AGR-1 and 2

Nuclide	Fraction Released	Particle Equivalents
Ru/Rh-106	1.01E-8	3.44E-5
Ag-110m	3.14E-3	1.06E+1
Sb-125	2.44E-4	8.28E-1
Cs-134	4.64E-4	1.57E+0
Cs-137	5.03E-4	1.71E+0
Ce-144	6.74E-8	2.29E-4
Eu-154	1.75E-4	5.94E-1
Eu-155	1.50E-4	5.09E-1
Kr-85	2.93E-4	9.95E-1



1600°C FACS Test of Compact 5-5-4 Ag and Eu

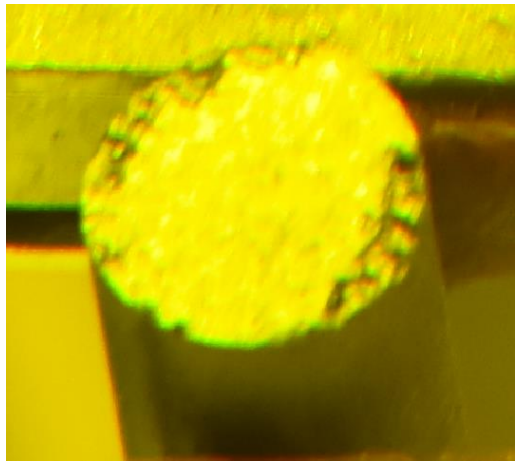
Compact	Burnup	Fluence	TA Min	TAVA	TA Max
5-5-4	7.67	2.14	686	774	843

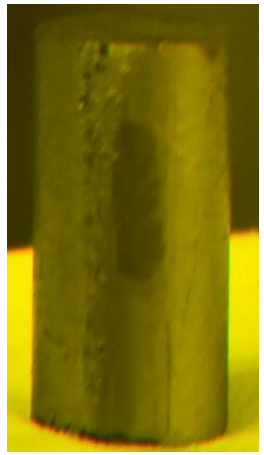


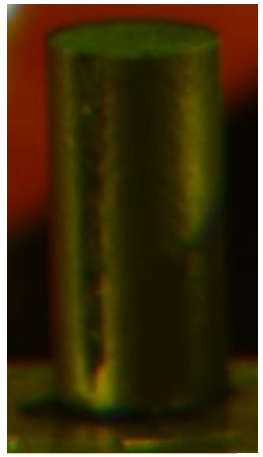
1600°C FACS Test of Compact 4-1-3 Summary

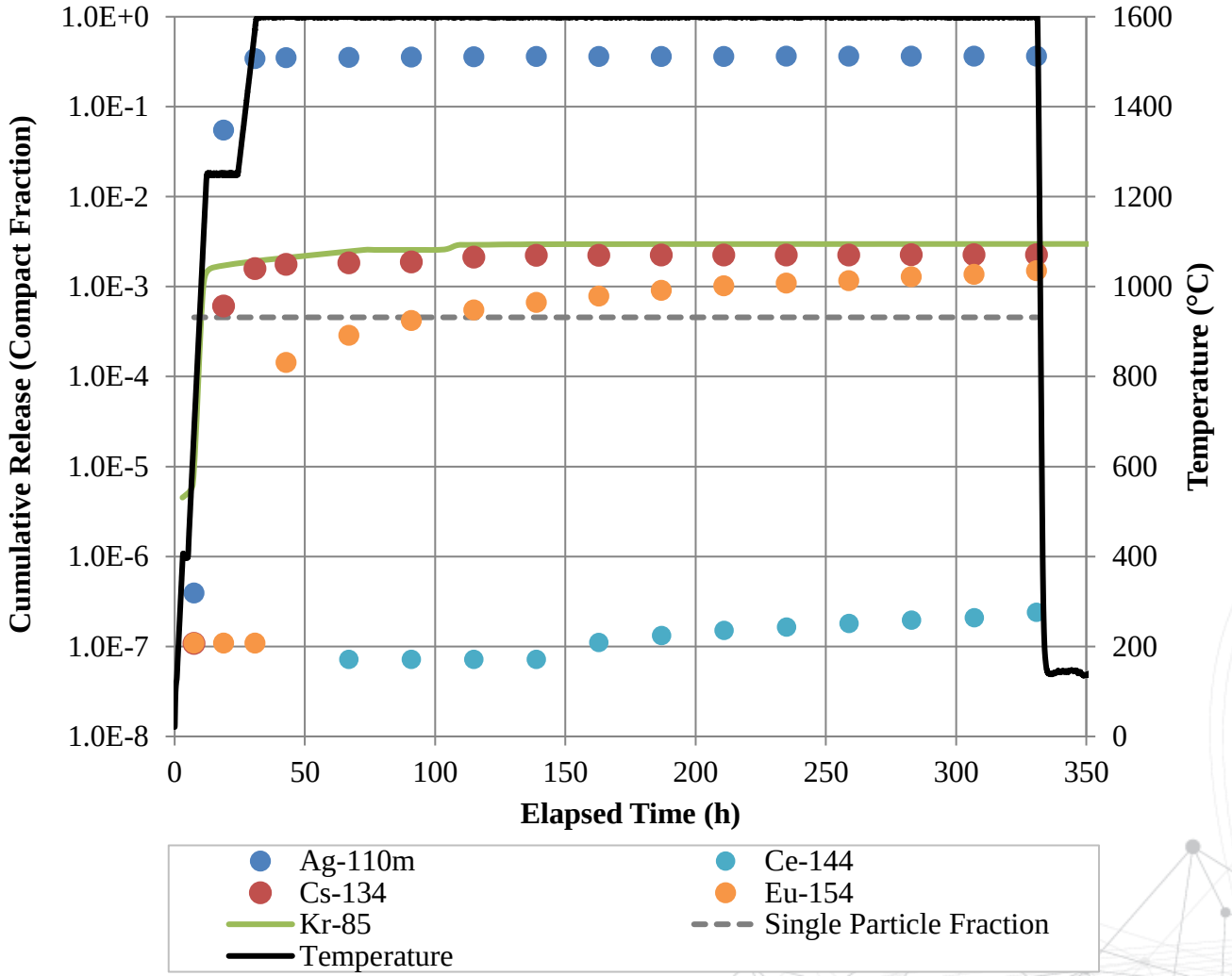
Compact	Burnup	Fluence	TA Min	TAVA	TA Max
4-1-3	14.06	5.01	565	786	902
5-5-4	7.67	2.14	686	774	843

- Particle failures apparent during ramp to 1250°C hold
  - 6.5 particle equivalents Kr-85
  - 4.9 particle equivalents Cs-134
- Appears to have been damaged before FACS test started and NOT in-pile
- High Ag-110m release ~36%. Higher than AGR-2. Similar to AGR-1.



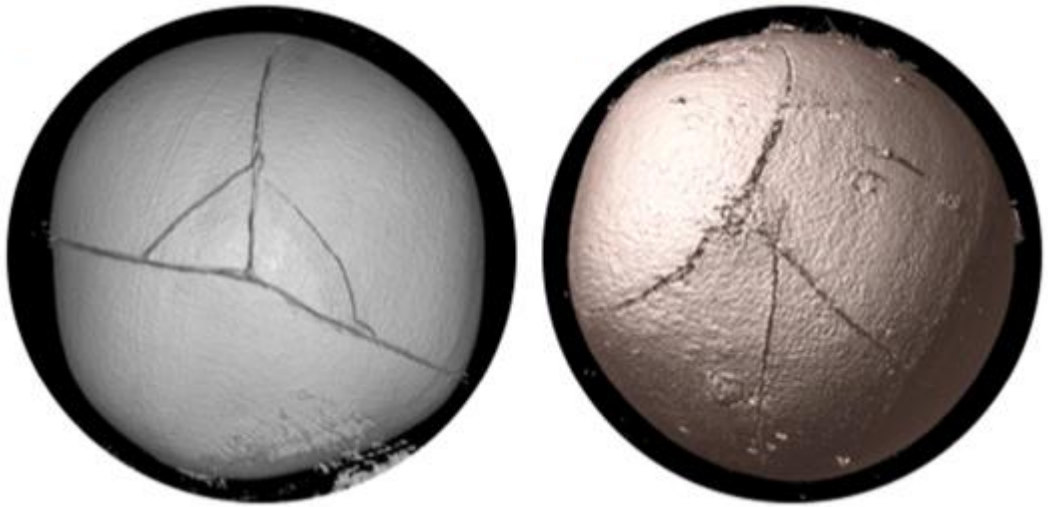






Pre-burn Leach Data from Compact 4-1-3 (FACS Test at INL, DLBL at ORNL)

- 6.8 particle equivalents U-238 in pre-burn leach
- Estimated 5-7 exposed kernels. Consistent with FACS measurements.
- XCT found particles with impact cracks (example below from AGR-2)



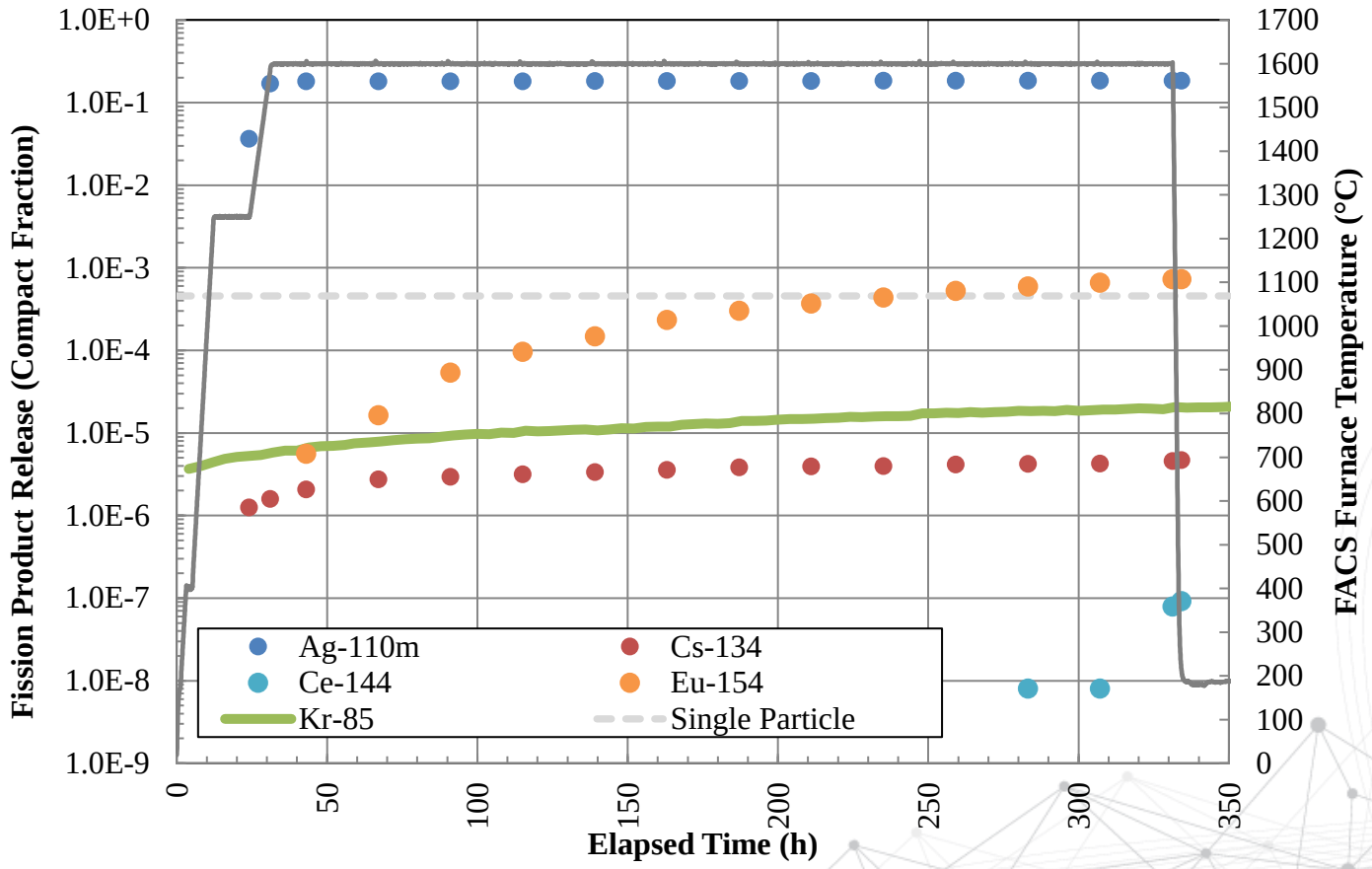
*Courtesy of John Hunn (ORNL)

1600°C FACS Test of Compact 4-4-4 Summary

Compact	Burnup	Fluence	TA Min	TAVA	TA Max
4-4-4	13.56	4.62	833	920	970
4-1-3	14.06	5.01	565	786	902
5-5-4	7.67	2.14	686	774	843

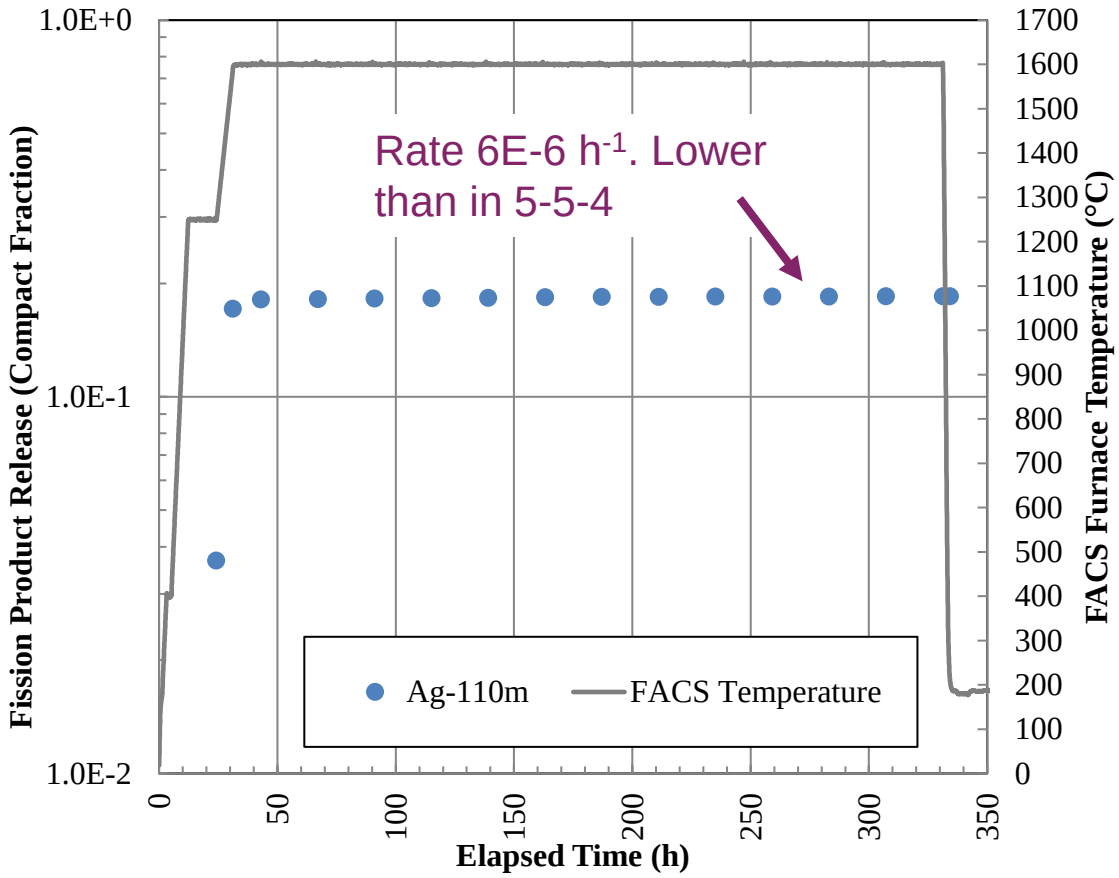
- No indications of particle failure
- ~0.04 particle equivalents of Kr-85 released
- Significant Ag-110m released here as with Compact 4-1-3.
- Eu and Cs release within ranges from AGR-1 and AGR-2

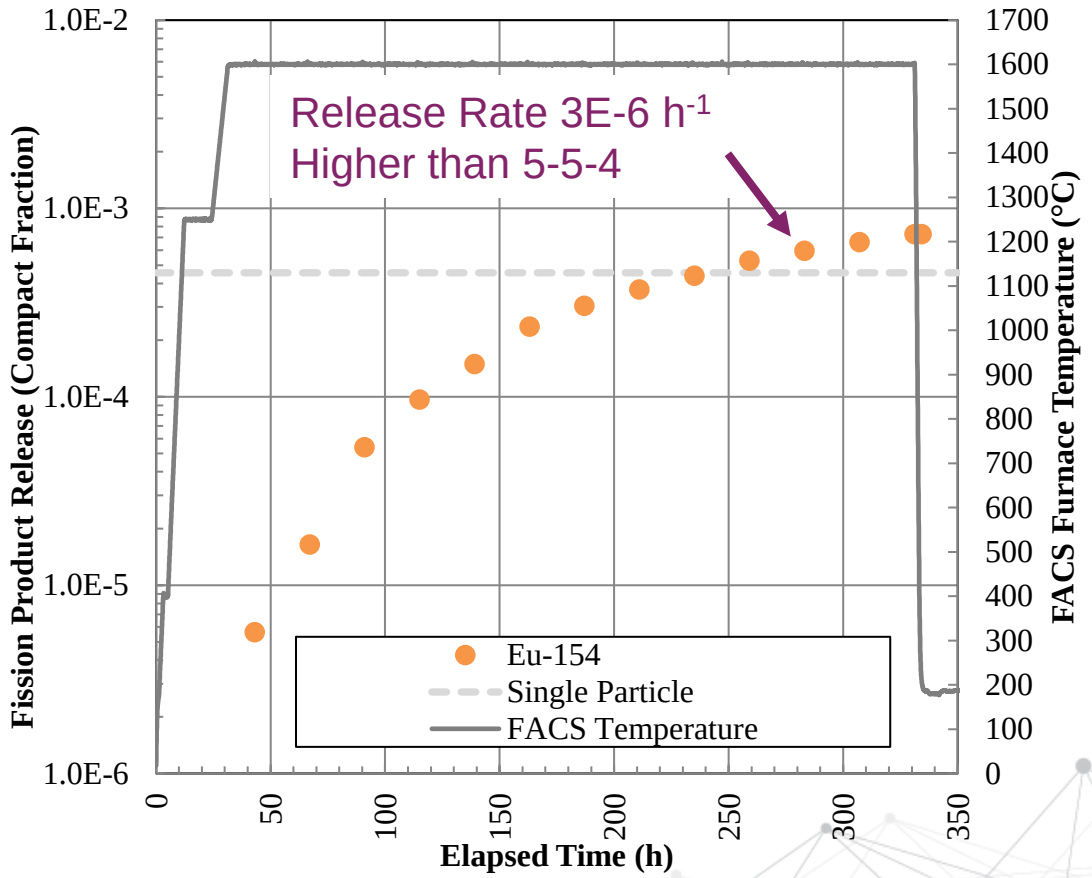
Nuclide	Fraction Released	Particle Equivalents
Ru/Rh-106	2.8E-7	6.2E-4
Ag-110m	1.8E-1	4.1E+2
Sb-125	2.3E-6	5.1E-3
Cs-134	4.7E-6	1.0E-2
Cs-137	6.6E-6	1.5E-2
Ce/Pr-144	9.3E-8	2.0E-4
Eu-154	7.3E-4	1.6E+0
Eu-155	6.8E-4	1.5E+0



1600°C FACS Test of Compact 4-4-4 Ag and Eu

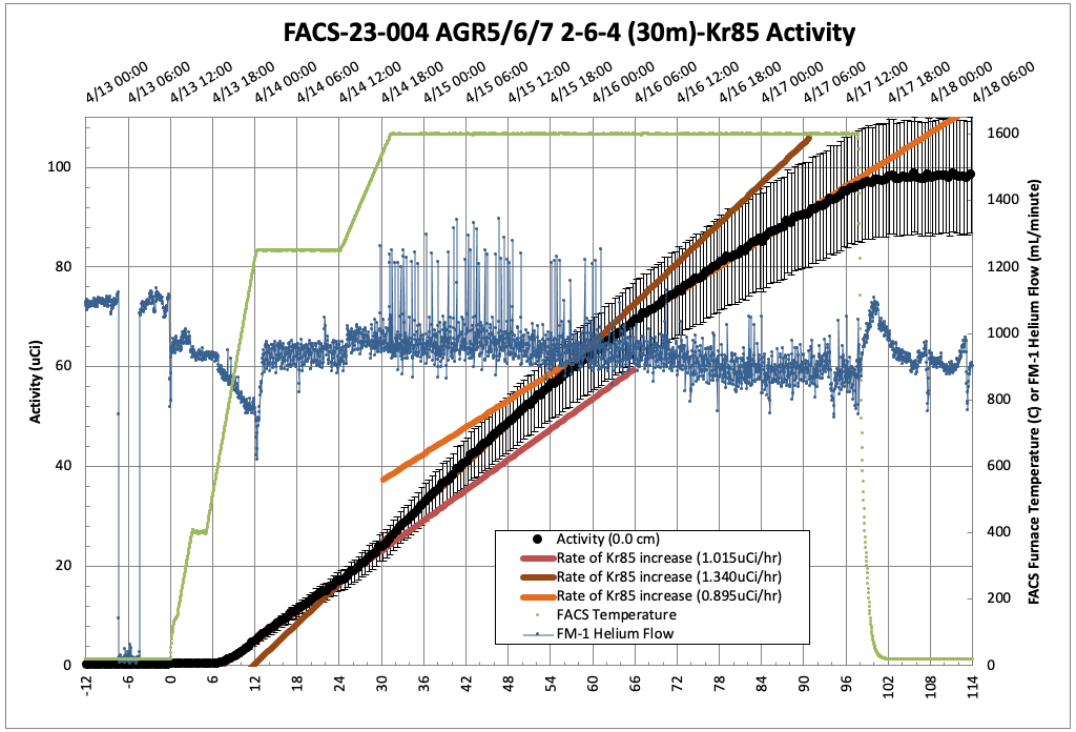
Compact	Burnup	Fluence	TA Min	TAVA	TA Max
4-4-4	13.56	4.62	833	920	970
4-1-3	14.06	5.01	565	786	902
5-5-4	7.67	2.14	686	774	843

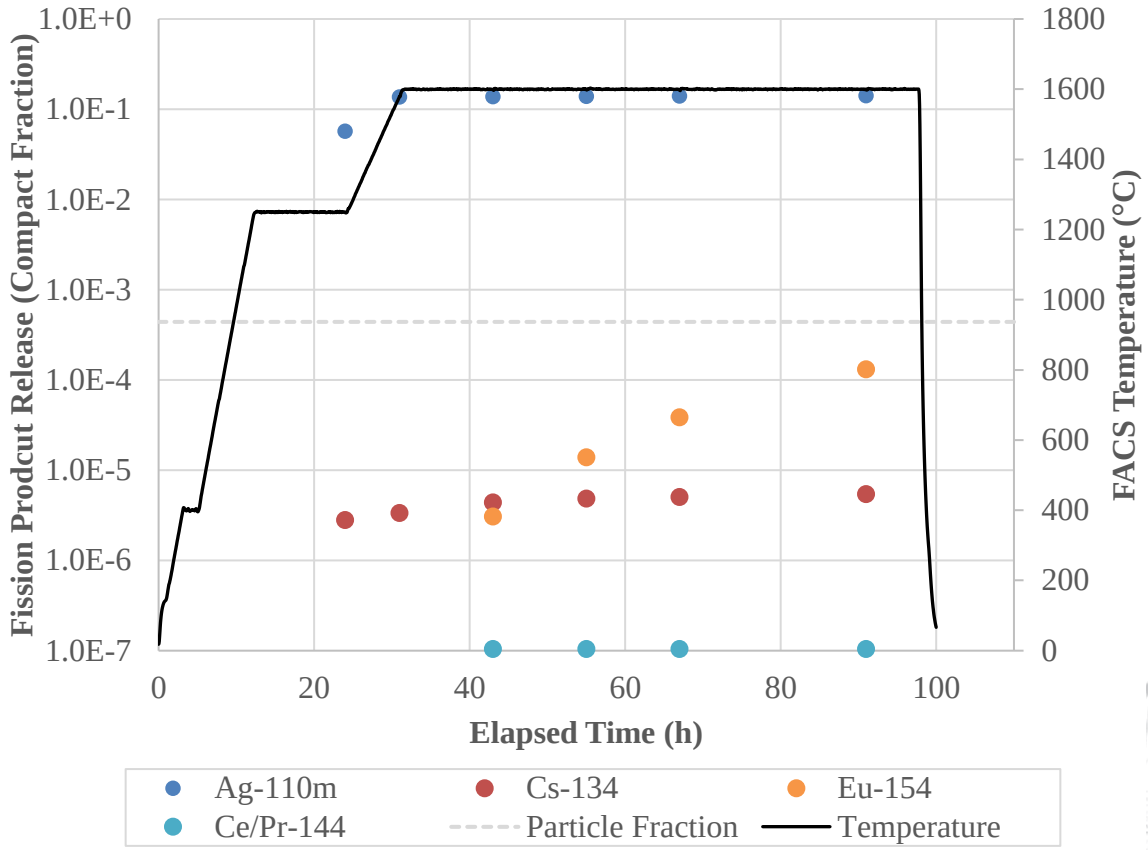




1600°C FACS Test of Compact 2-6-4 Interrupted – No Signs of Fuel Failure

- High steady rate of Kr-85 detection indicated in-leakage of contamination from HFEF hot cell
- Test interrupted and a failed pressure test confirmed FACS furnace leakage
- FACS bottom O-rings replaced for first time in ~10 years
- FACS passed pressure test
- Test will be restarted





Summary of FACS Safety Tests

	Compact	Kr-85	Ru/Rh-106	Ag-110m	Sb-125	Cs-134	Ce/Pr-144	Eu-154
Damaged before test	**4-1-3**	3.0E-3	9.4E-5	3.6E-1	3.0E-3	2.2E-3	2.4E-7	1.5E-3
	TAVA 786°C, 14.1% FIMA	(6.54)	(0.206)	(793.9)	(6.6)	(4.9)	(0.001)	(3.3)
One TRISO and one SiC failure upon restart	**5-5-4**	2.9E-4	1.0E-8	3.1E-3	2.4E-4	4.6E-4	6.7E-8	1.8E-4
	TAVA 774°C, 7.7% FIMA	(0.995)	(0.00003)	(10.6)	(0.8)	(1.6)	(0.0002)	(0.6)
No failures	**4-4-4**	2.0E-5	2.8E-7	1.8E-1	2.3E-6	4.7E-6	9.3E-8	7.3E-4
	TAVA 920°C, 13.6% FIMA	(0.726)	(0.001)	(406.1)	(0.005)	(0.010)	(0.0003)	(1.6)
200 h to go	**2-6-4**	N/A	<detection	1.4E-1	7.7E-6	5.4E-6	1.0E-7	1.3E-4
	TAVA 850°C, 15.2% FIMA	N/A		(320.5)	(0.017)	(0.012)	(0.005)	(0.297)

Fractional Release Ranges from all 1600°C Tests (INL & ORNL)	Ag-110m	Cs-134	Eu-154
AGR-1	3.5E-3 to 3.4E-1	2.9E-7 to 2.1E-4	2.8E-4 to 2.9E-3
AGR-2	2.7E-3 to 2.1E-2	**2.5E-7** to 6.2E-5	1.1E-4 to **8.8E-2**
AGR-5/6/7	**1.6E-3** to **3.6E-1**	4.7E-6 to **4.6E-4**	**3.9E-5** to 7.3E-4

Low; **High**

Preliminary AGR-5/6/7 Safety Test Failure Rates

1600°C	Observed SiC Failure Fraction	SiC Failure (95% Confidence, ≤)	Observed TRISO Failure	TRISO Failure (95% Confidence, ≤)
AGR-1	9.1E-05	2.4E-04	0	9.1E-05
AGR-2	0	2.4E-04	0	2.4E-04
AGR-5/6/7 (Excluding 4-1-3)	6.3E-05	3.5E-04	1.3E-04	4.6E-04

1800°C	Observed SiC Failure Fraction	SiC Failure (95% Confidence, ≤)	Observed TRISO Failure	TRISO Failure (95% Confidence, ≤)
AGR-1	1.4E-03	2.0E-03	1.2E-04	3.9E-04
AGR-2	1.0E-04	5.0E-04	1.0E-04	5.0E-04
AGR-5/6/7	3.5E-04	1.1E-03	3.5E-04	1.1E-03

Compacts Considered in Rates Above	
1600°C	2-2-2
	2-2-4
	5-5-4
	3-1-2
	5-5-3
	4-4-4
1800°C	2-3-2
	5-2-2

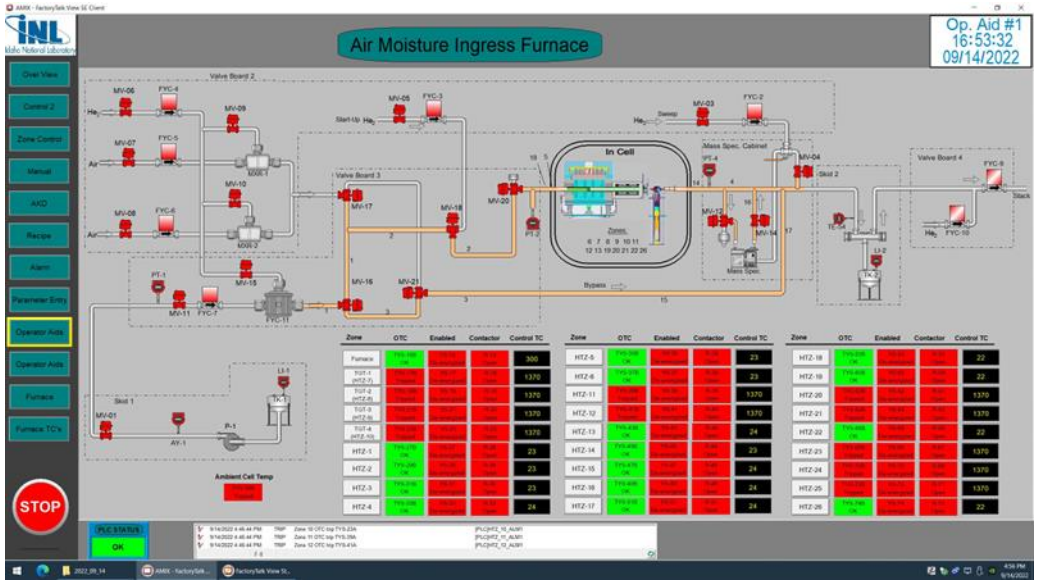
*Compact 4-1-3 excluded due to pre-test damage

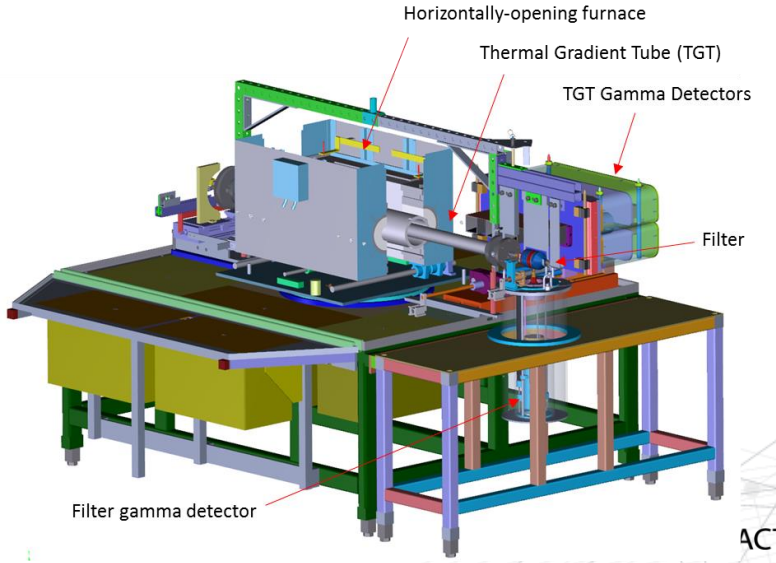
Air-Moisture Ingress Experiment (AMIX)

FY23 Milestones:
1. **Complete Phase IIA integrated systems qualifications**
2. **Complete Phase IIB remote qualification**

- AMIX Purpose:
  - To date, safety testing AGR fuel compacts has only been conducted under helium. AMIX will test irradiated TRISO fuels in oxidizing environments representative of air and moisture ingress accidents in HTGRs
  - Measure fission product releases as a function of time

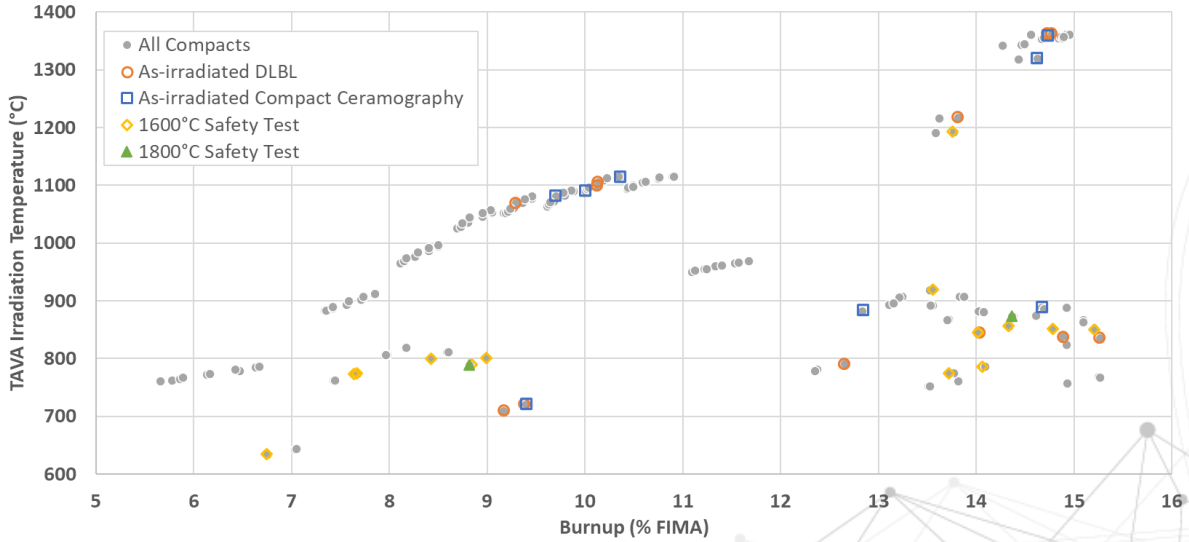
- Update:
  - System has been constructed
  - Software is 99.9% complete
  - 95% of integrated testing has been completed
  - Complete of all of Phase II (remote assembly and checkout) by January 2024
  - Complete AMIX installation in Fuel Conditioning Facility (FCF) hot cell by spring 2024





Major Work in Progress

- Complete installation of AMIX in hot cell to test fuels in oxidizing atmospheres
- Continue compact shipments to ORNL
- Continue working through safety tests at FACS and CCCTF
- Continue as-irradiated DLBLs at INL and ORNL
- Continue DLBL of safety-tested compacts



Idaho National Laboratory