July 12, 2022

John Stempien, PhD
AGR TRISO Fuel PIE Technical Lead

AGR-5/6/7 PIE

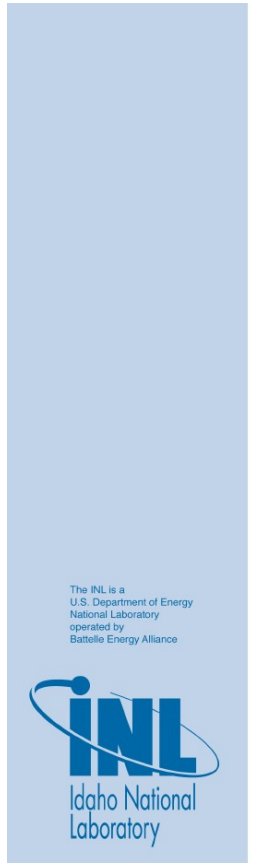
The Fuel Qualification Irradiation

ART Advanced Reactor Technologies
GAS-COOLED REACTORS

Major PIE Objectives

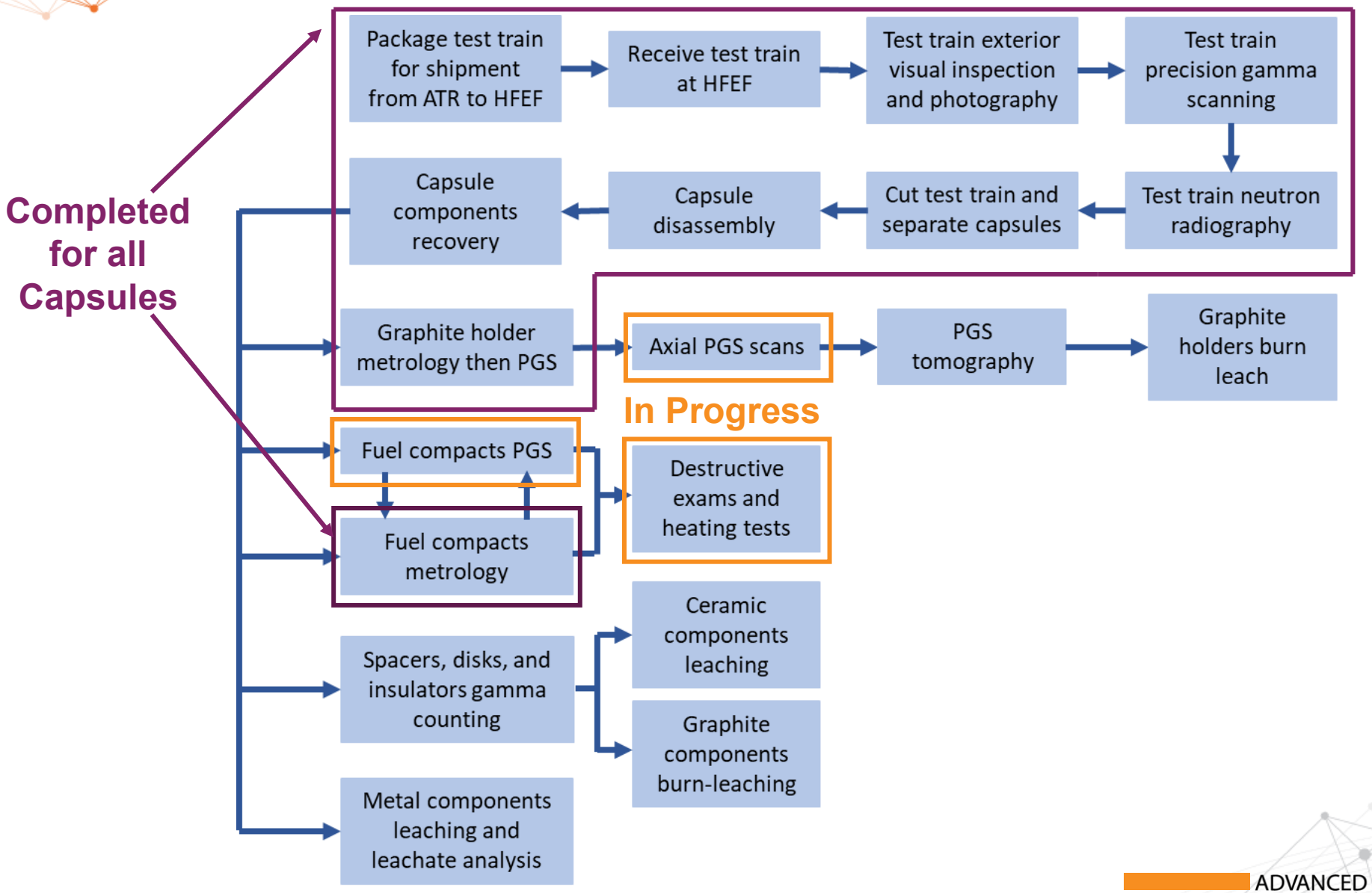
Overall: Establish acceptable nominal, margin, and accident performance of fuel produced at the pilot scale.

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 1380°C, TA Peak 1480°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.

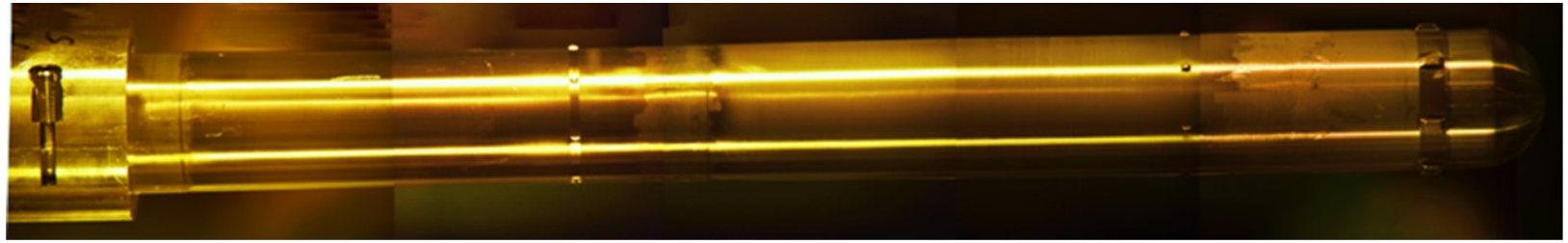


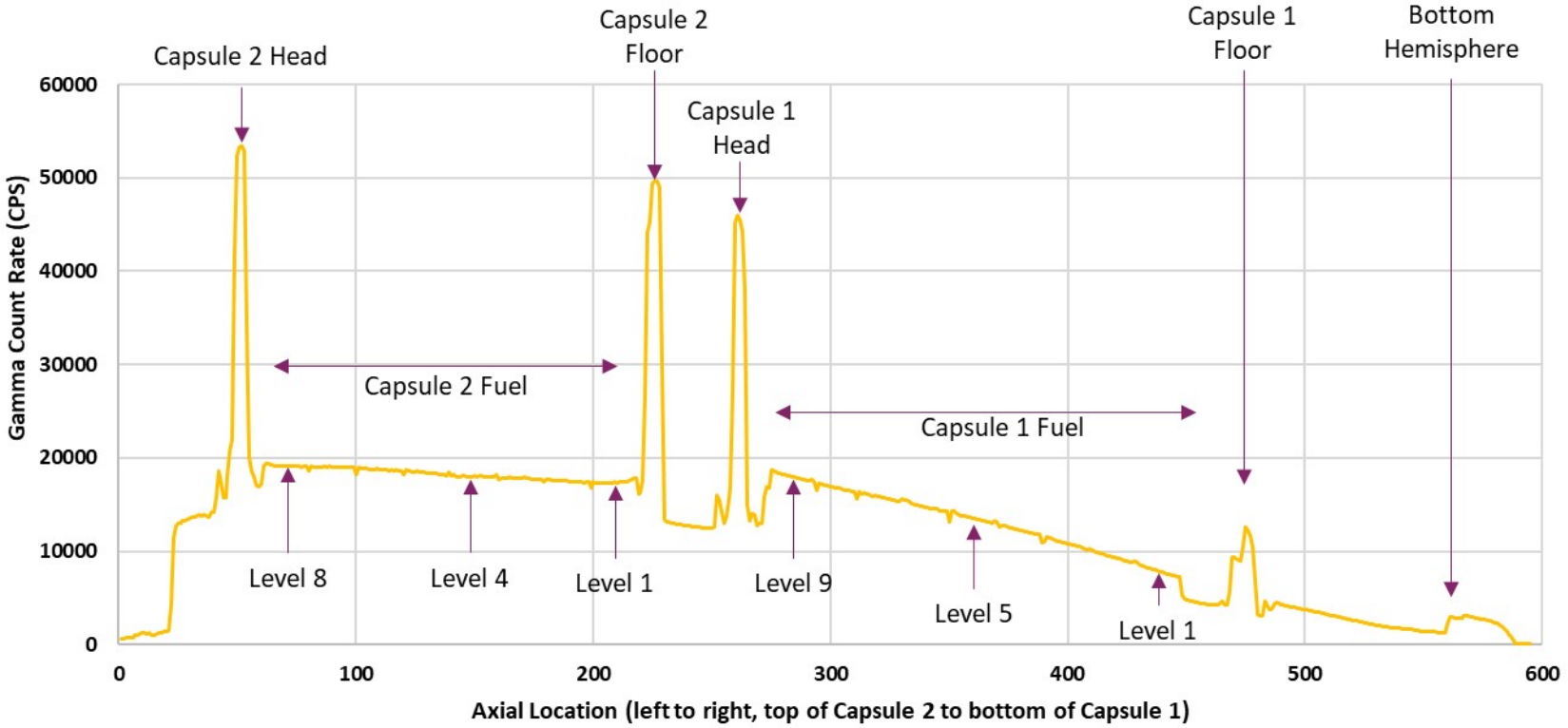
PIE Status

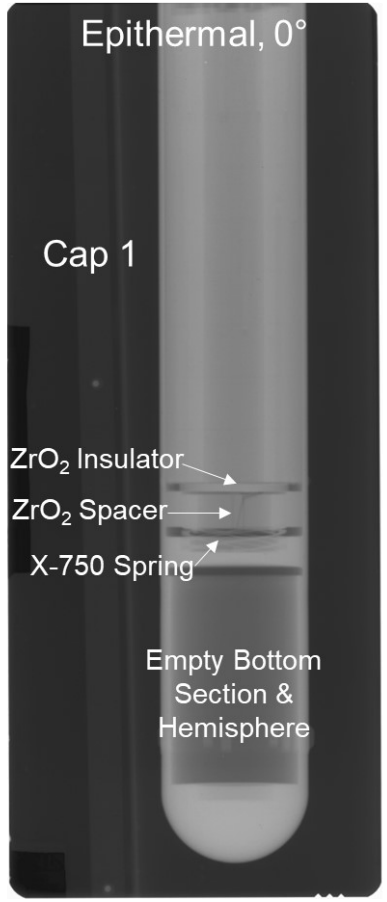
Process Flow of Major PIE Activities



Initial Test Train Exams (e.g., gamma scanning and radiography) Completed in FY21. Shown at July 2021 meeting.





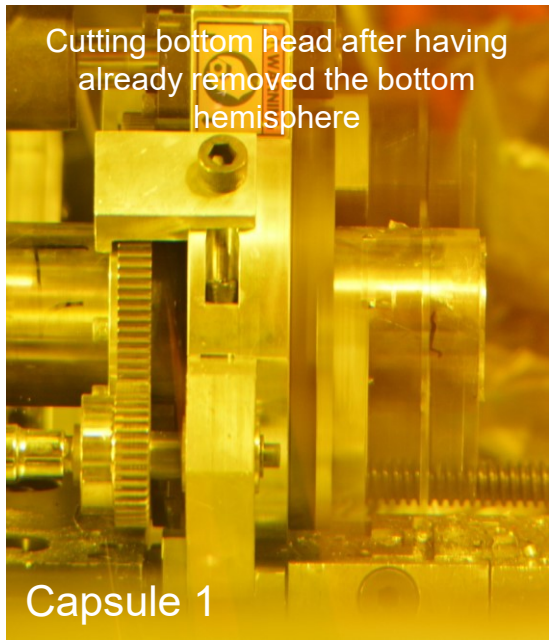


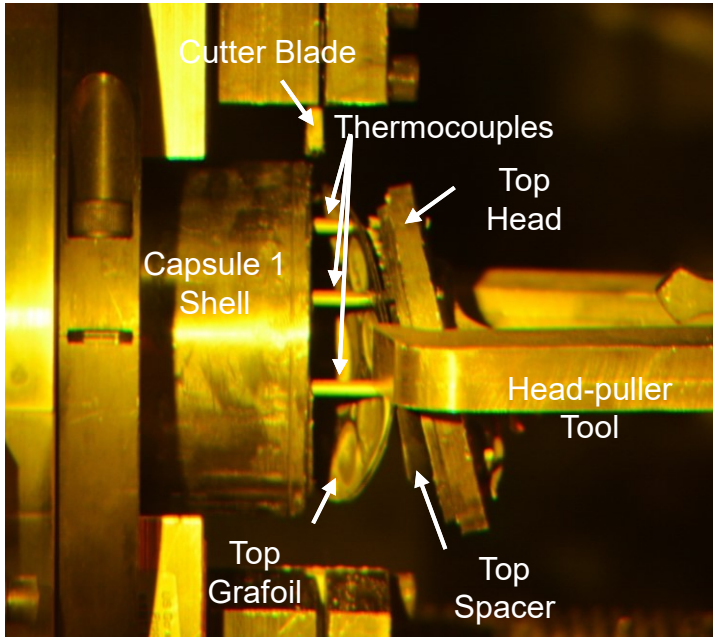
Disassembly and Metrology Complete

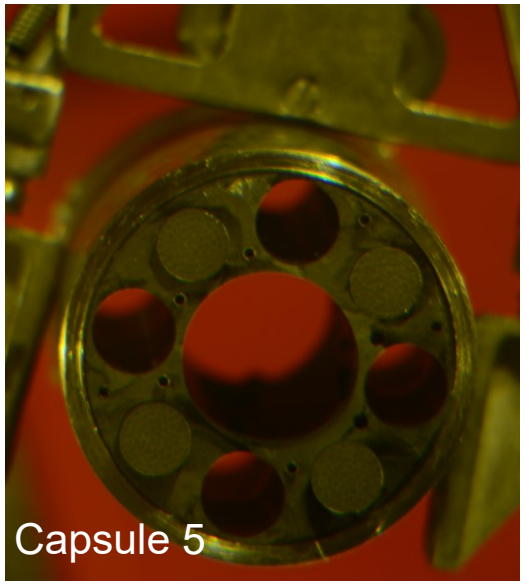
Level 2 Milestone due 8/19/2022

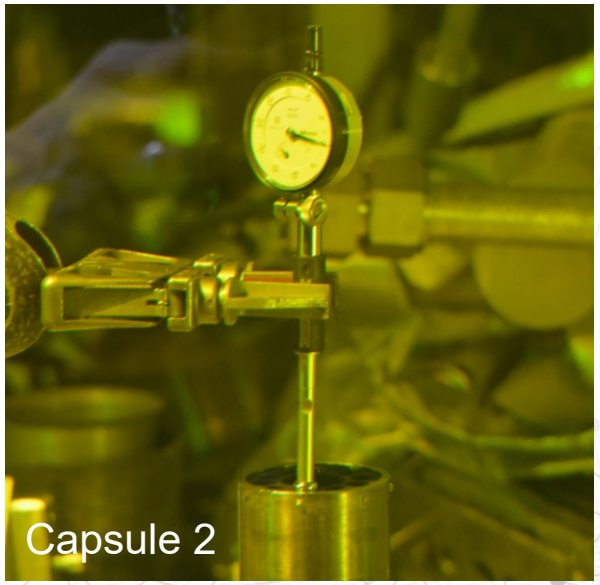
Components	Number
Capsules Disassembled	5/5
Holders Measured*	6/6
Compacts Recovered and Measured	194/194

*A few measurements being repeated to check consistency



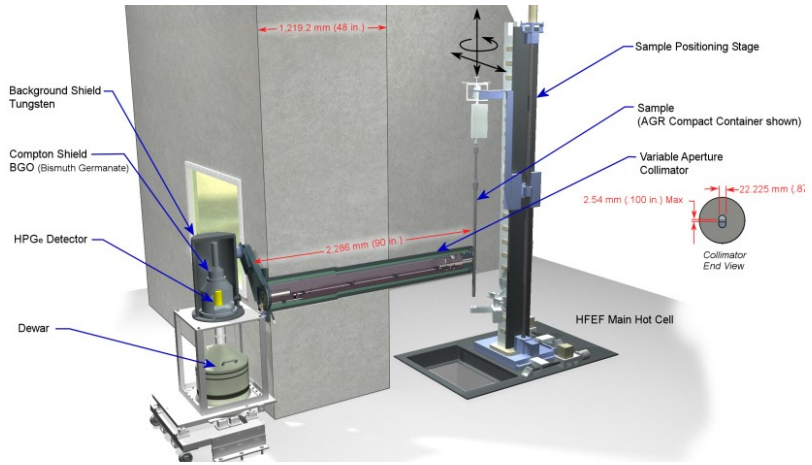






Precision Gamma Scanning is in Progress

Components	Number Complete
Compact Holders	
Axial Scan	1/6 (Capsule 1 holder counted)
Tomographic Scans	0/6
Compacts	
Overall	87/194
Capsule 1	48/90
Capsule 2	32/32
Capsule 3	1/24
Capsule 4	2/24
Capsule 5	4/24



Precision Gamma Scanner (PGS)

Fulfilled Level 2 Milestone on 5/11/22 (due 9/15/2022)

Safety Testing in Progress

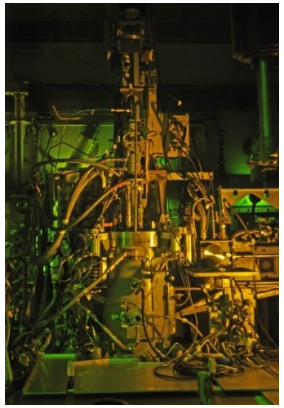
Estimated numbers of compacts for safety testing to demonstrate failure rate ≤2E-4 at 95% confidence. Values in parentheses assume Capsule 1 fuel cannot be used.

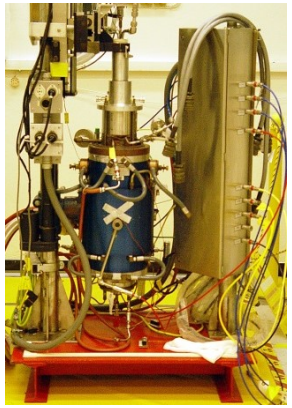
Capsule	Packing Fraction (%)	TA Peak (°C)	TAVA (°C)	TA Min (°C)	Burnup (% FIMA)	1600°C Safety Tests	1700°C Safety Tests	1800°C Safety Tests
1	40	1231	1001	588	9.12	6 (0)	–	2 (0)
2	25	948	833	546	14.66	2 (2)	–	1 (1)
3	25	1432	1313	989	14.46	3 (4)	2 (2)	2 (3)
4	25	970	857	558	13.39	2 (2)	–	–
5	40	864	756	467	8.2	2 (8)	–	1 (2)
					TOTALS	15 (16)	2 (2)	6 (6)

Compact	Burnup (% FIMA)	TAVA Irradiation Temperature (°C)	Safety Test Temperature (°C)	Status
4-1-3	14.06	786	1600	Done 6/17/2022 in FACS
4-4-3	13.52	901	1600	Planned July 2022 in FACS
2-2-2	14.02	845	1600	Planned in July 2022 in CCCTF
Capsule 2 or 5		**TBD**		Two more CCCTF tests. May use multiple compacts at once.

Need to complete 2 CCCTF tests for L2 milestone due 9/15/2022

FACS Furnace at INL



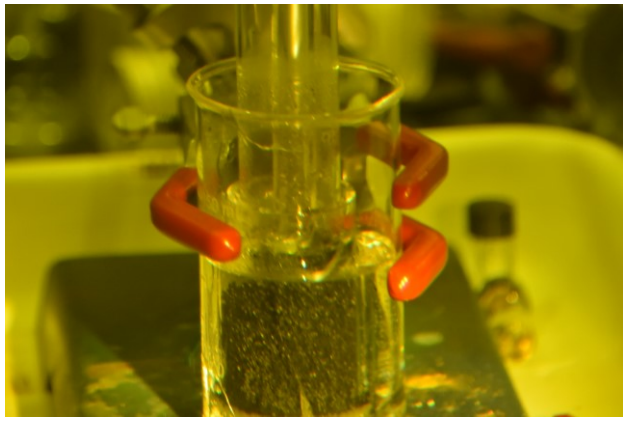


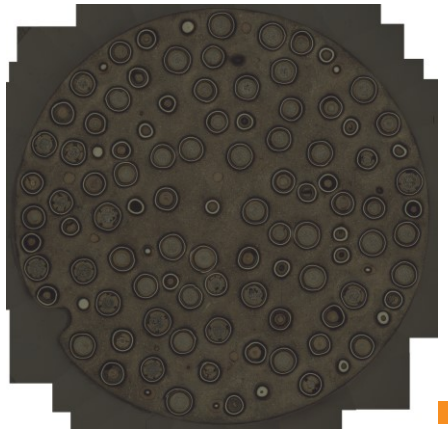
CCCTF Furnace at ORNL

Destructive Exams have Begun

Compact	Condition	DLBL	Compact Ceramography	Notes
1-7-9	As-irradiated	Complete at INL	N/A	Fulfilled FY22 Level 3 Milestone Supports 9/15 L2 for particle X-ray
1-7-4	As-irradiated	Complete at INL	N/A	
2-2-1	As-irradiated	In progress at ORNL	N/A	Supports 9/15 L2 for DLBL of 2 compacts
1-5-9	As-irradiated	Planned at ORNL	N/A	May select other based on timing of Shipment 2
2-2-2	Safety-tested	Planned at ORNL	N/A	
1-6-9	As-irradiated	N/A	In progress at INL	FY22 Level 2 Milestone Due 9/15
2-3-3	As-irradiated	N/A	In progress at INL	
3-4-1	As-irradiated	N/A	In progress at INL	
5-1-4	As-irradiated	N/A	In progress at INL	

AGR-5/6/7
Compact 1-7-9
DLBL





Cross section of AGR-2
Compact 2-1-3

Compact Shipments to ORNL

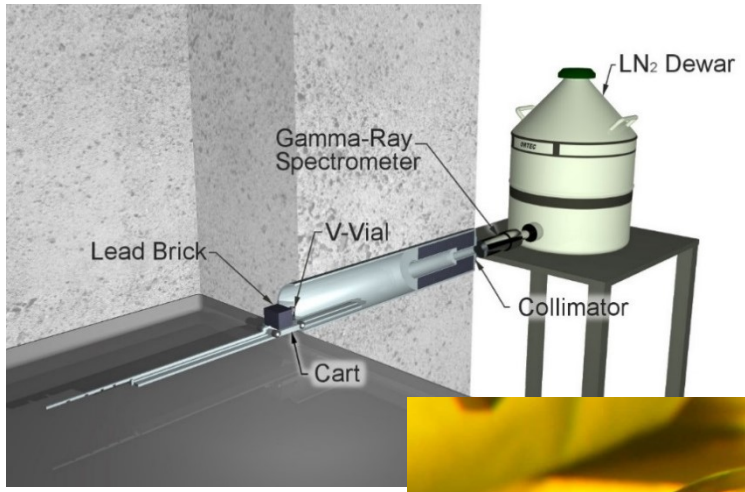
Shipment	Date	Compacts	Use
Shipment 1	Completed 3/25/2022	2-2-1	As-irradiated DLBL
		2-2-2	1600°C Safety Test
		2-2-3	Safety Test or As-irradiated DLBL
		2-2-4	Safety Test or As-irradiated DLBL
Shipment 2	Planned Summer 2022	1-5-9	As-irradiated DLBL
		2-3-2	1600°C Safety Test
		4-1-3	Post-safety Test DLBL
		5-5-3	1600°C Safety Test
Shipment 3	Late FY22		
Shipment 4	Early FY22		

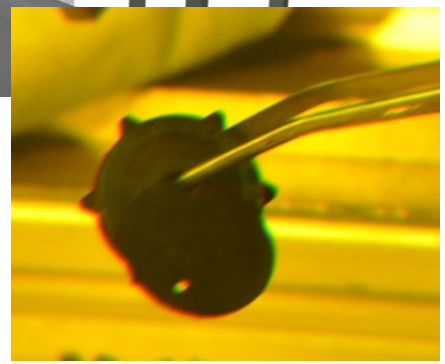
TBD

Need to complete for L3 milestone due 9/15/2022

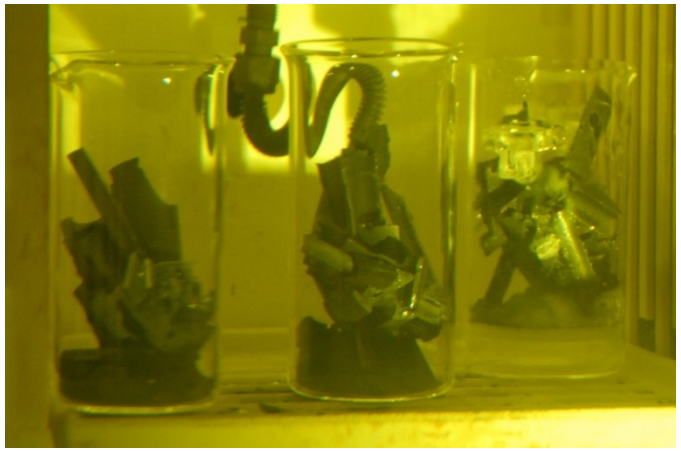
Planned Fission Product Analyses of Capsule Components

Component	Gamma Counting	Leaching	Burn-Leaching
Spacers, insulators, disks, springs	Yes (non-PGS)	Metallic and ceramic items only	Carbon items only
Stainless-steel capsule shells and through-tubes. Capsule 1 TCs and gas lines.	No	Yes	No
Compact holders	Yes (PGS)	No	Yes

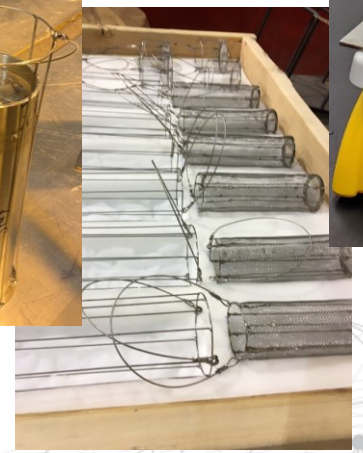


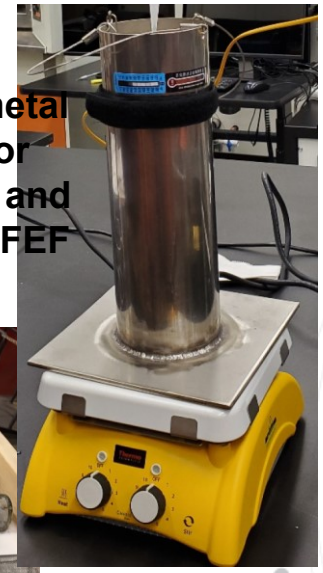


Spacers, foils, disks etc. gamma counting prior to leaching



Burn-leach of graphite with subsequent leaching for Sr-90





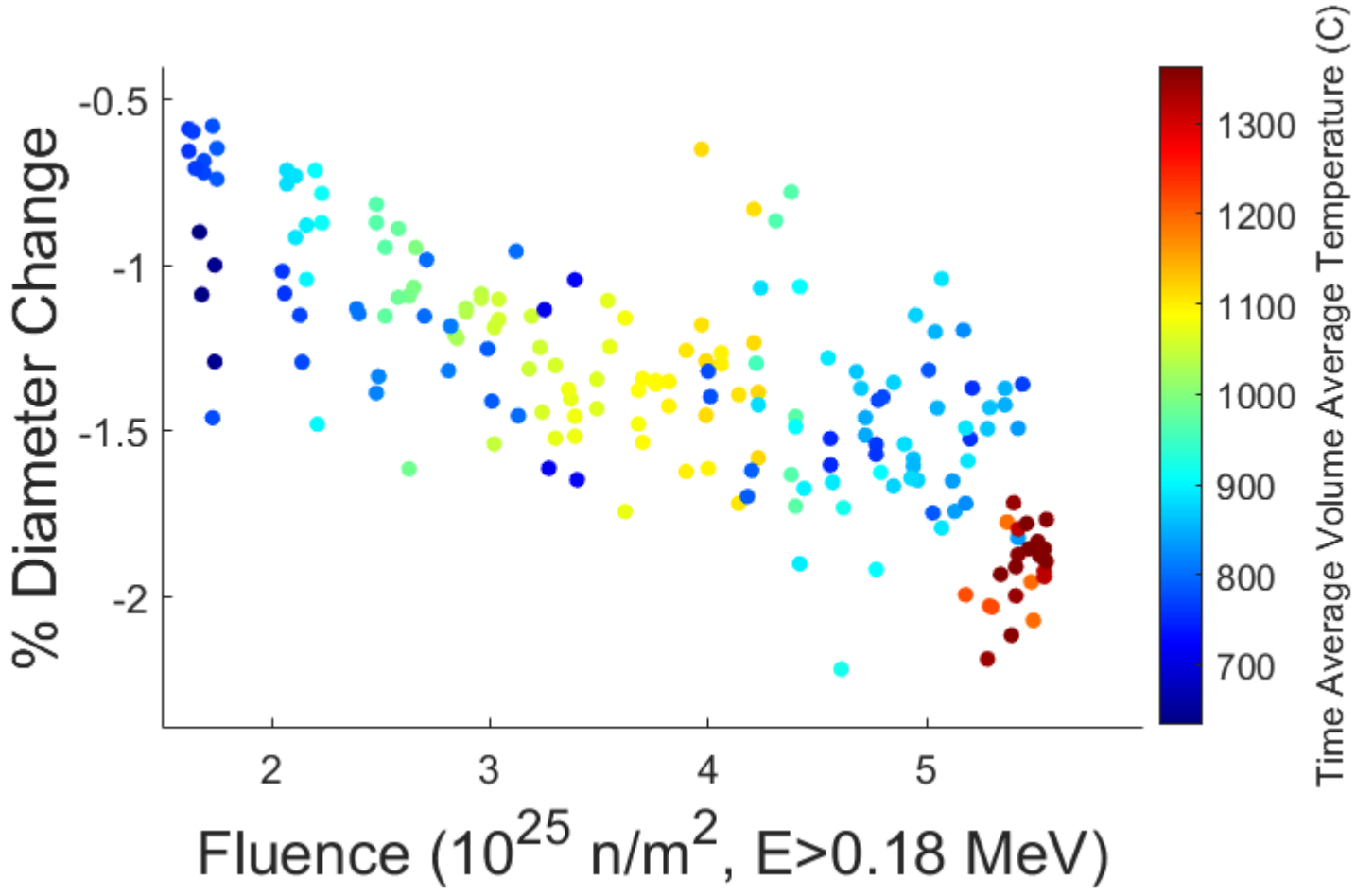
Leach of large metal components for gamma-emitters and Sr-90 in-cell at HFEF

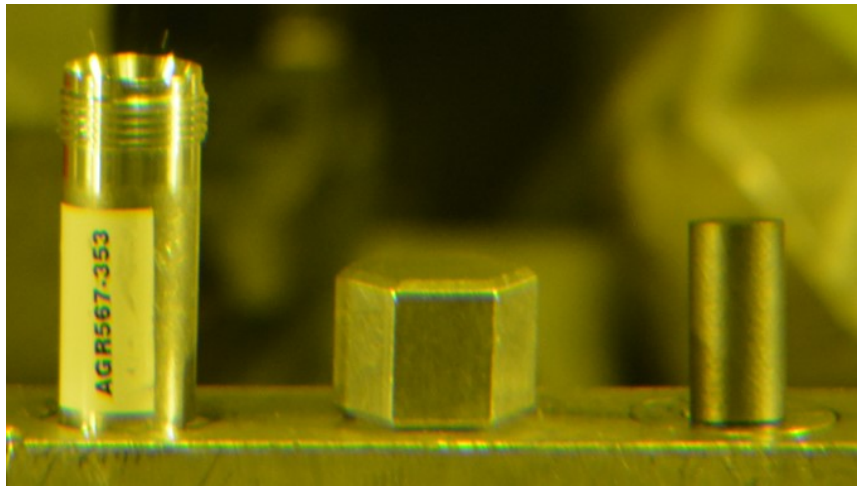
Need to complete for L2 milestone due 9/15/2022

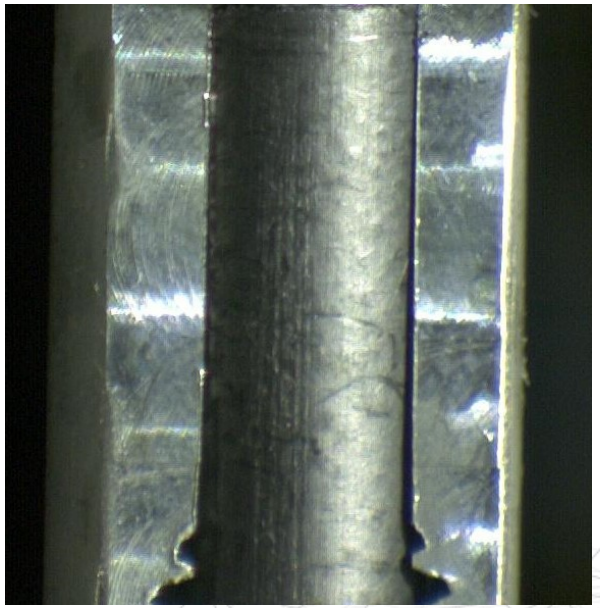
Recent Results

Compact Metrology (preliminary)

- Compact diameters decreased

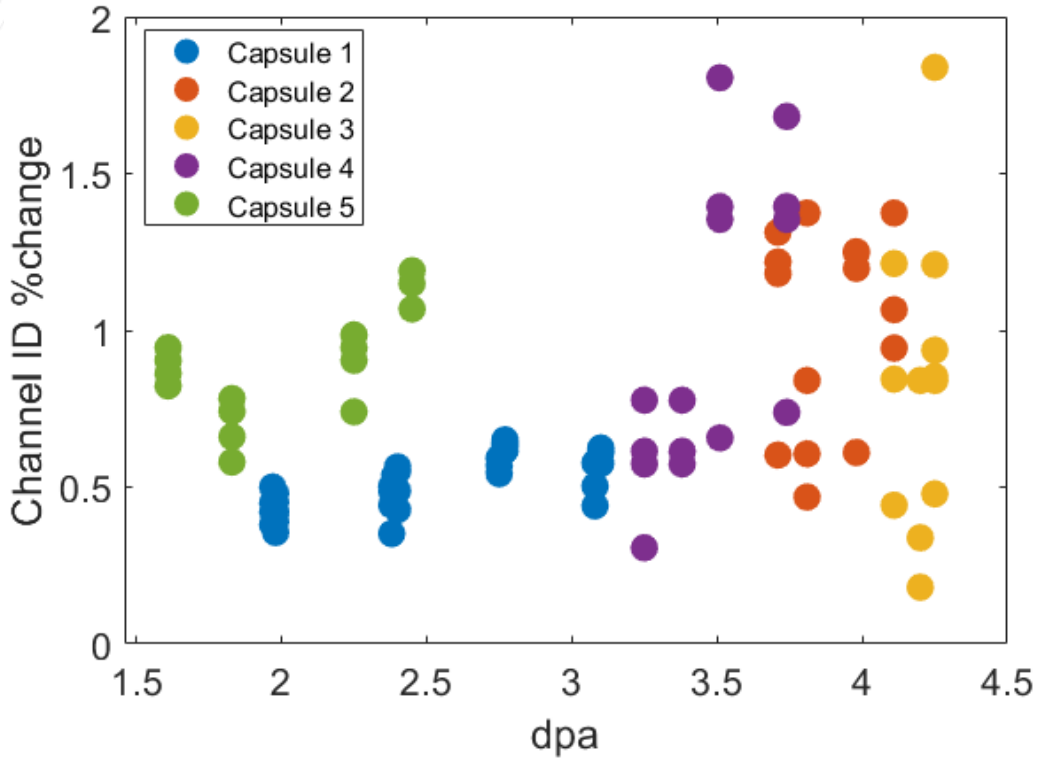


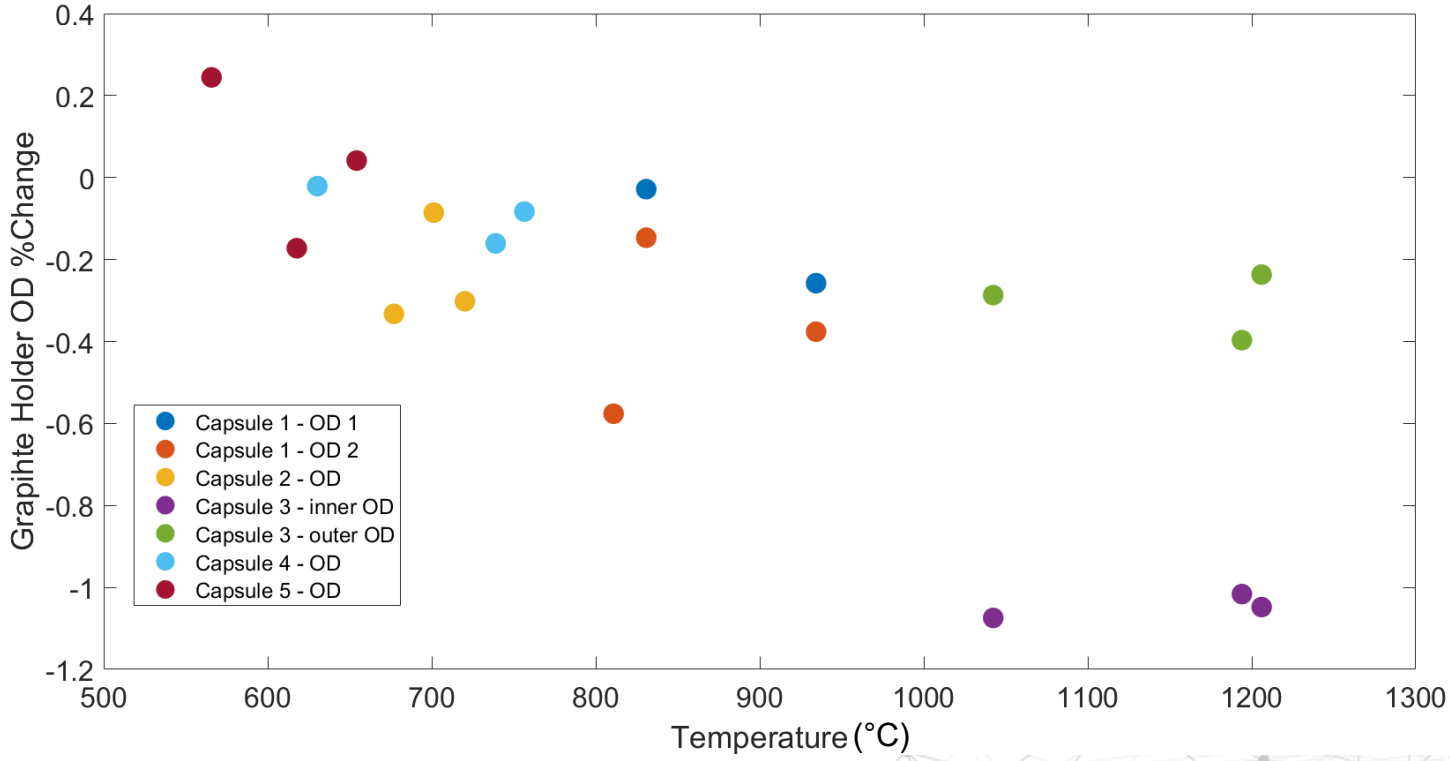




Graphite Holder Metrology (preliminary)

- Holder fuel channel diameters increased
- Overall fuel compact-to-holder gap increased
- Holder outer diameter generally decreased, suggesting an increase in the holder to stainless-steel shell gap
- Uncertainty analysis still needed

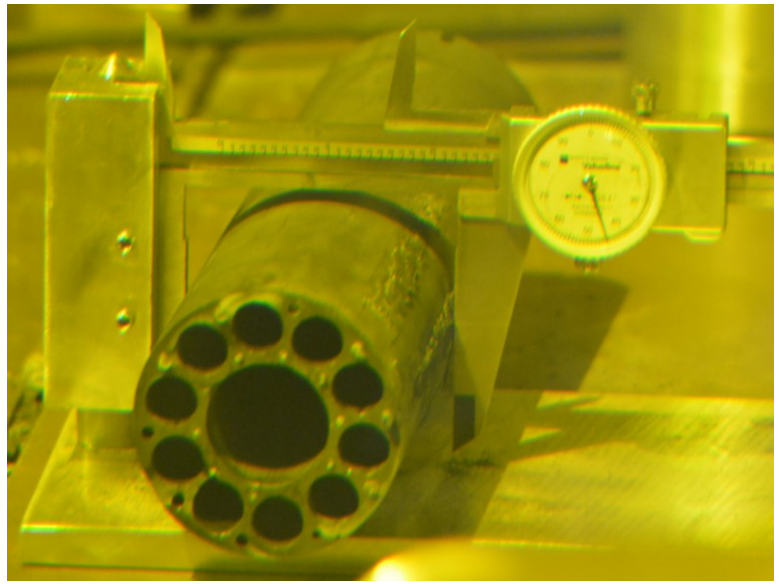


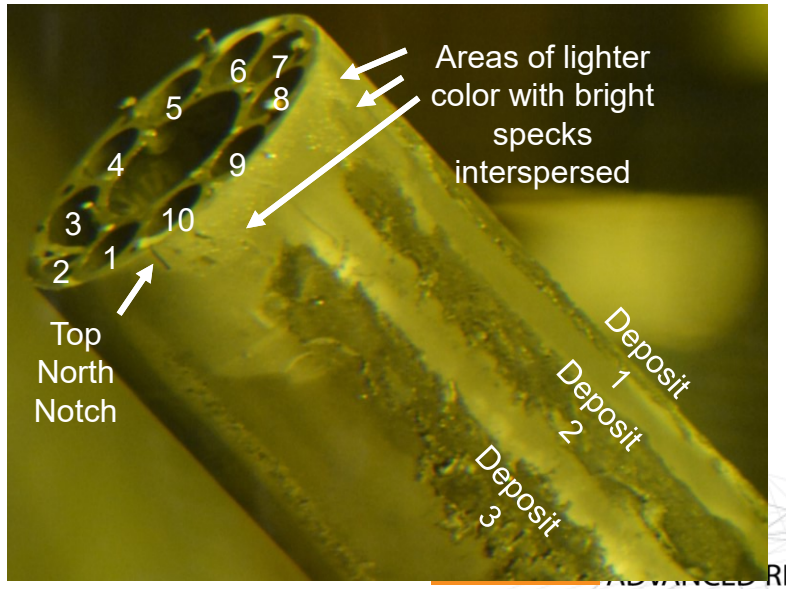


Capsule 1 Holder Deposit Thickness Measurements

- Suggests holder-shell gap was significantly greater than the intended 0.008-in design gap.
- Undersized nubs fabricated in error would have allowed up to ~0.013-in gap on one side of the holder
- Irradiation induced shrinkage of holder would allow for even larger gap size
- A 0.009-in gap was calculated to raise temperatures at TCs by ~50°C. Measurements indicate gaps ~2-3x that were possible.
- All else constant, larger gap = higher irradiation temperature, high enough to degrade TCs

	Deposit 3	Deposit 2	Deposit 1
Thickness @ Top (in)	0.030	0.019	0.012
Thickness @ Middle (in)	N/A	0.018	0.025
Thickness @ Bottom (in)	N/A	0.010	0.011

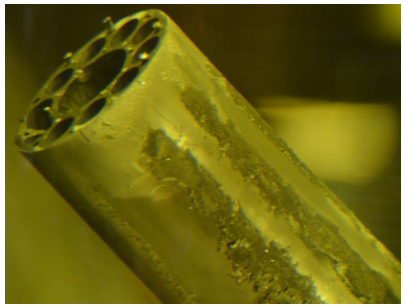




Holder Deposits Gamma Measurements

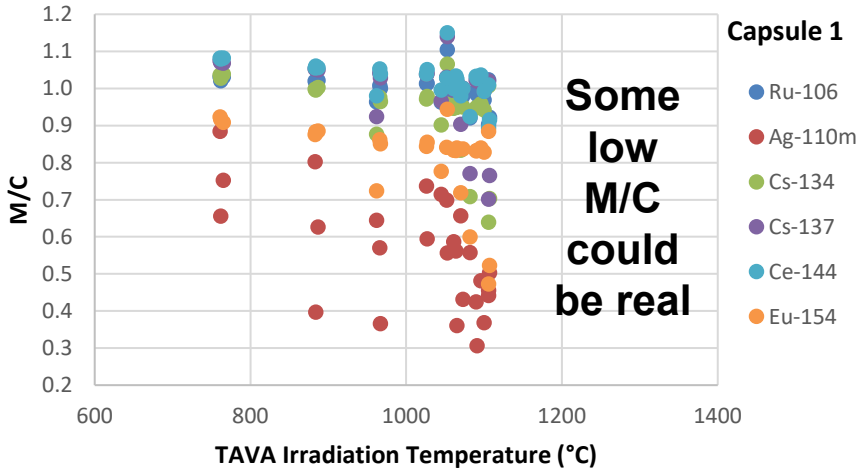
- Findings support assumption that TC melting/rupture caused fuel failure and formation of deposits on graphite holder
- Small samples of deposits (estimated to be ~0.04 to 0.08 cm^3 total) have substantial:
  - Activation products from foreign nickel: Co-60 concentration here ~26,000x higher than trace contamination in graphite
  - Fission products:
    - >2 particles worth of Cs, indicating nearby SiC failure
    - Substantial Eu suggests high temperatures and/or potential SiC degradation

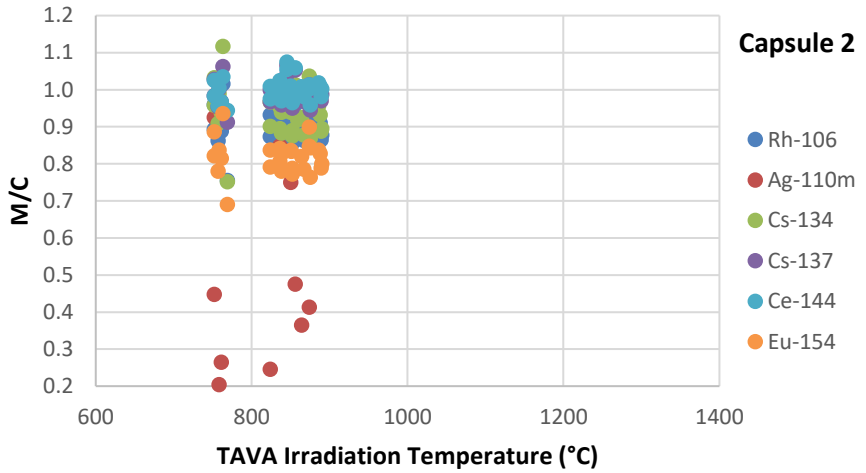
	Co-58	Co-60	Ag-110m	Sb-125	Cs-134	Cs-137	Eu-154	Eu-155
Measured Activity at EOI+1 (µCi)	2.63E+3	3.57E+1	5.18E+0	1.83E+1	2.61E+2	2.36E+2	2.72E+1	1.41E+1
Fraction of Capsule 1 Inventory	N/A		2.07E-5	7.51E-6	8.42E-6	7.04E-6	2.54E-5	1.90E-5
Number of Equivalent Average Capsule 1 Particles	N/A		6.39	2.32	2.60	2.17	7.85	5.86

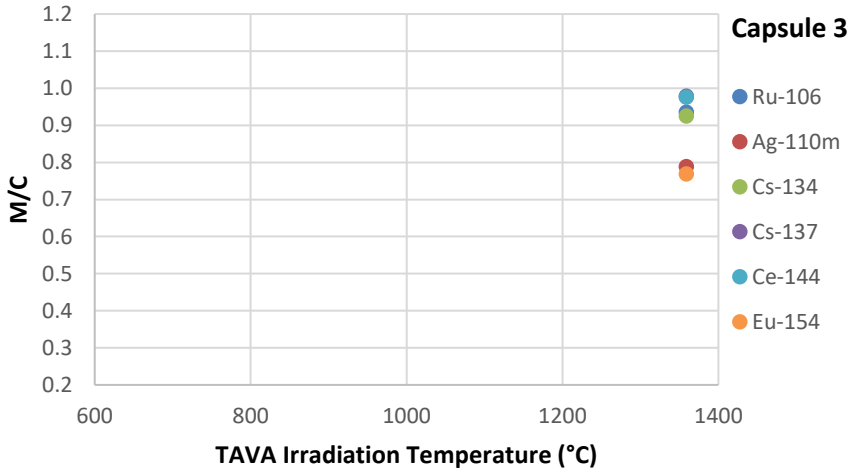


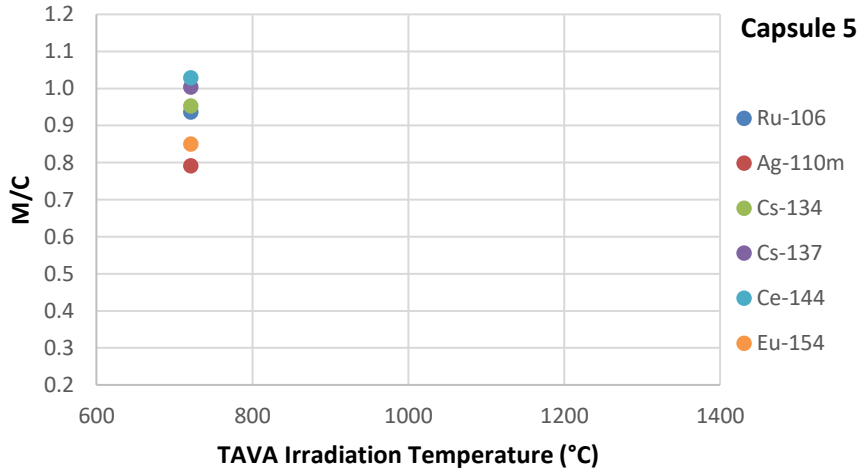
Compact PGS (preliminary, in progress)

- Generally, measured values (M) are comparable to calculated values (C)
- Some low Ag-110m M/Cs are expected, but some need improved peak fitting
- Eu-154 is often around 0.8 from calculational biases. Consistent with prior AGR irradiations.

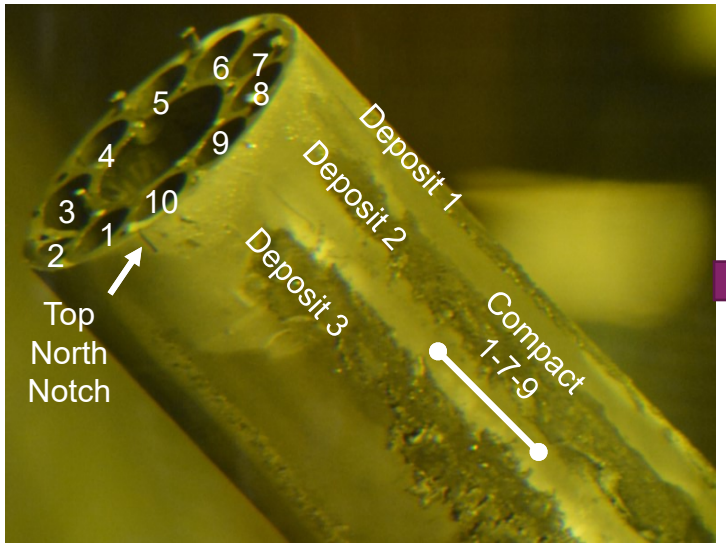


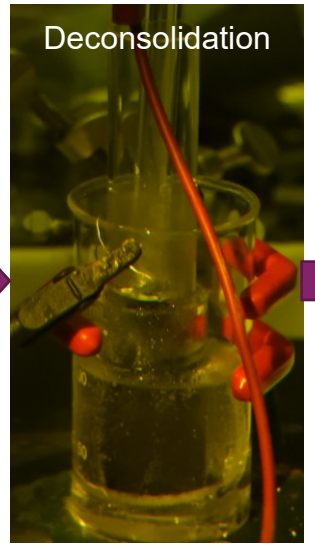


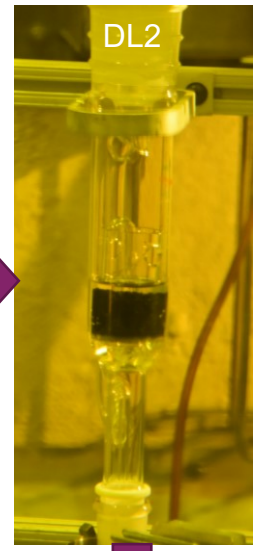




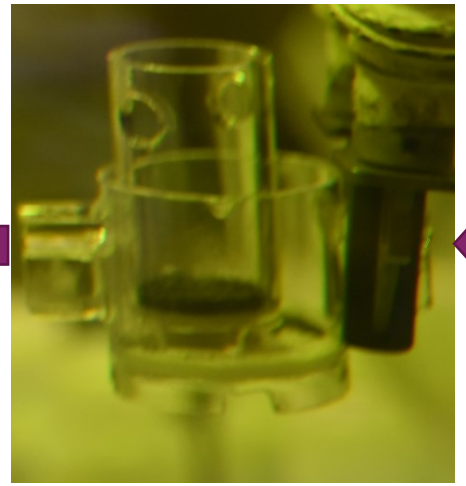
DLBL of Compact 1-7-9 Complete

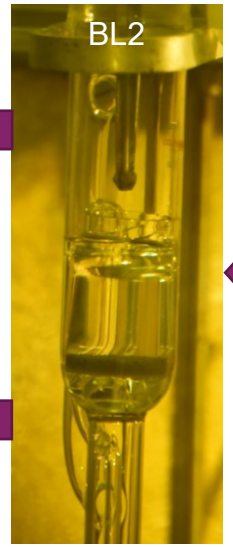






"Burn" at 750°C in air for 72 h



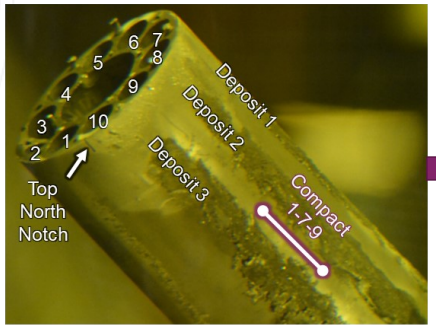


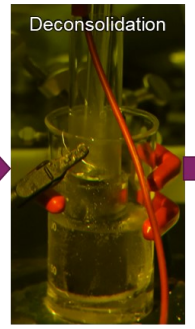
Analysis of solutions:
- **gamma spec**
- **Sr-90 separation**
- **mass-spec**

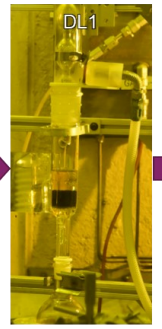
Particle Exams
- **Gamma counting**
- **X-ray CT**

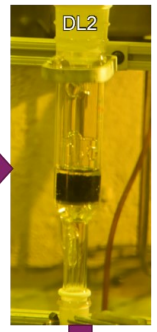
DLBL of Compact 1-7-9 – Photos after DL2

- Reflective material among the matrix “debris”
- Possible piece of SiC coating









“Burn” at 750°C in air for 72 h

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- mass-spec

Particle Exams
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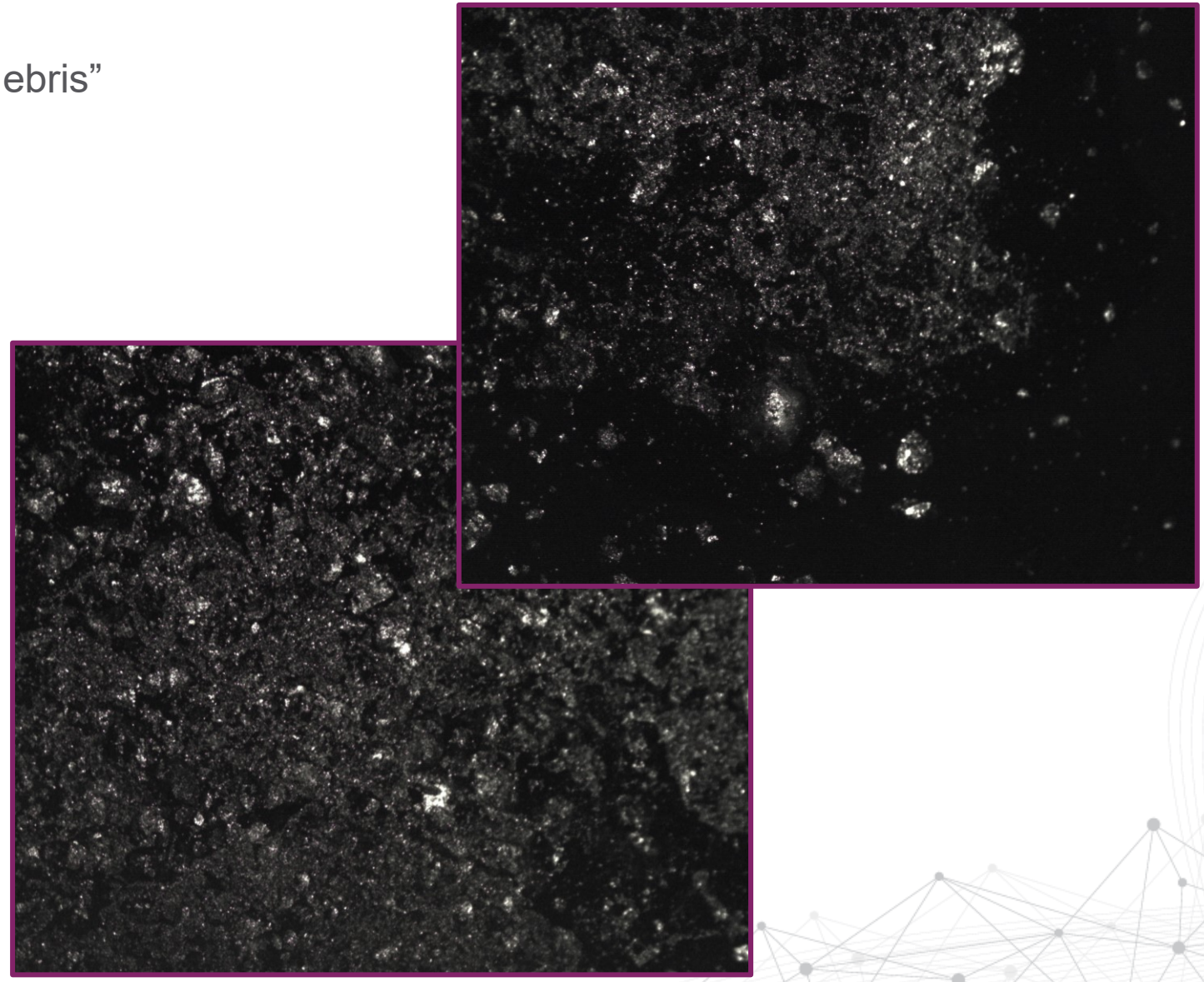
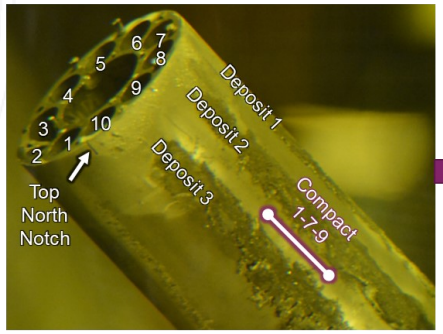
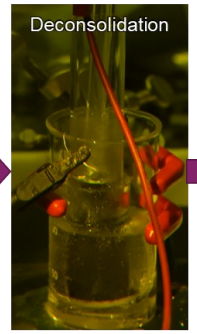
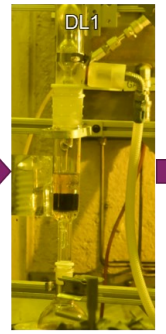


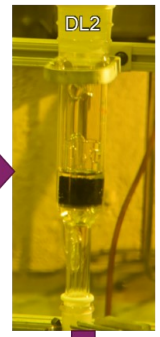
DLBL of Compact 1-7-9 – Photo after Burn/Before BL2

- Many SiC shell fragments that appear rough/charred
- Possible loose buffer/kernel

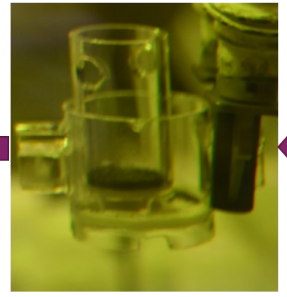






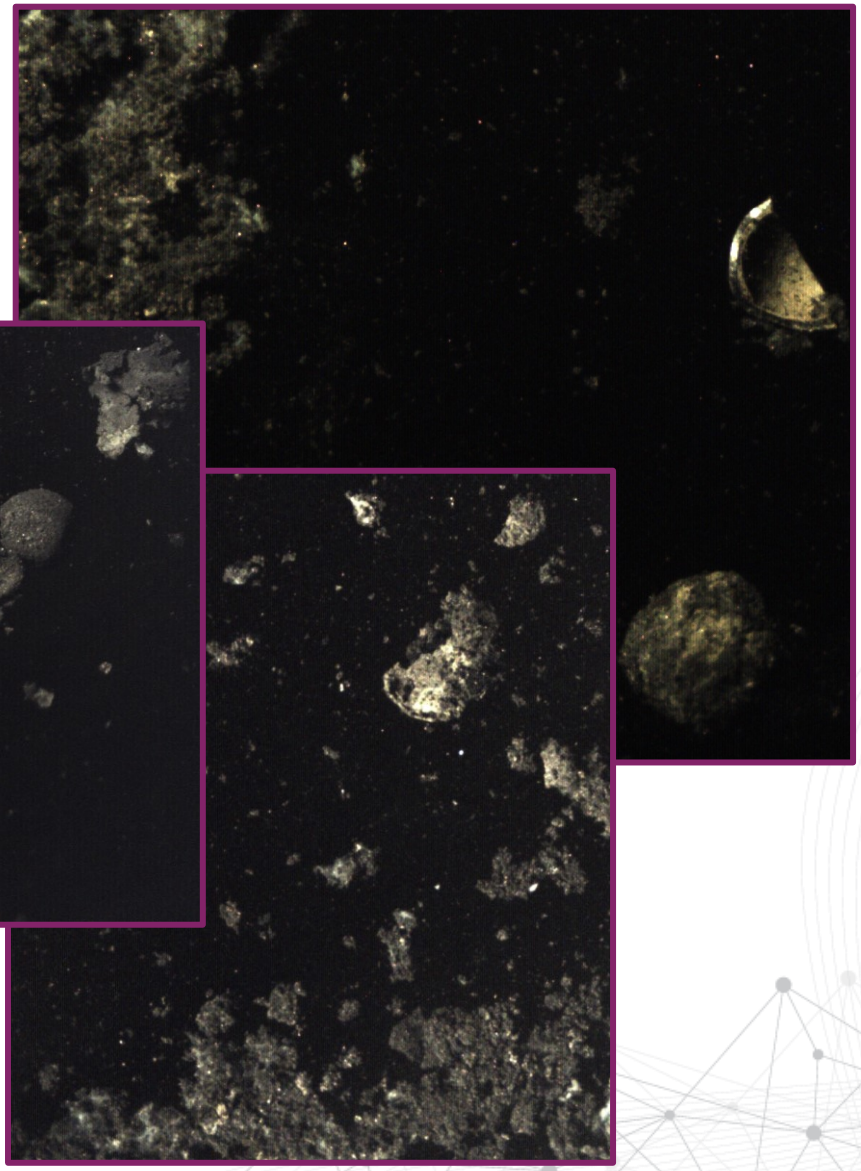


"Burn" at 750°C in air for 72 h



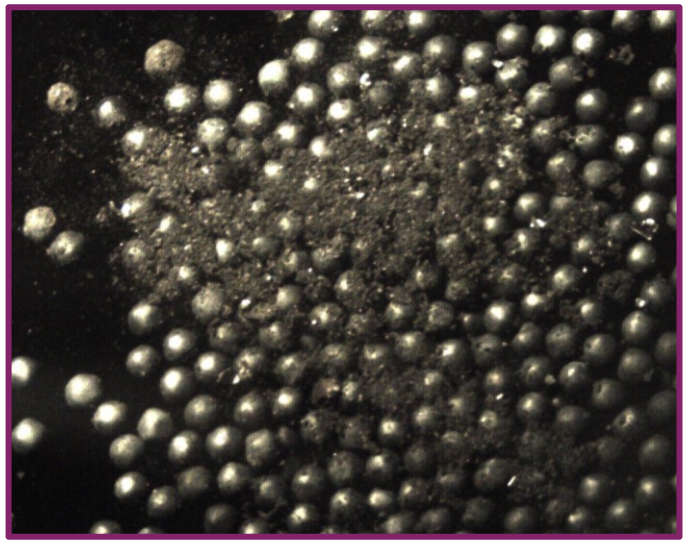
Analysis of solutions:
- gamma spec
- Sr-90 separation
- mass-spec

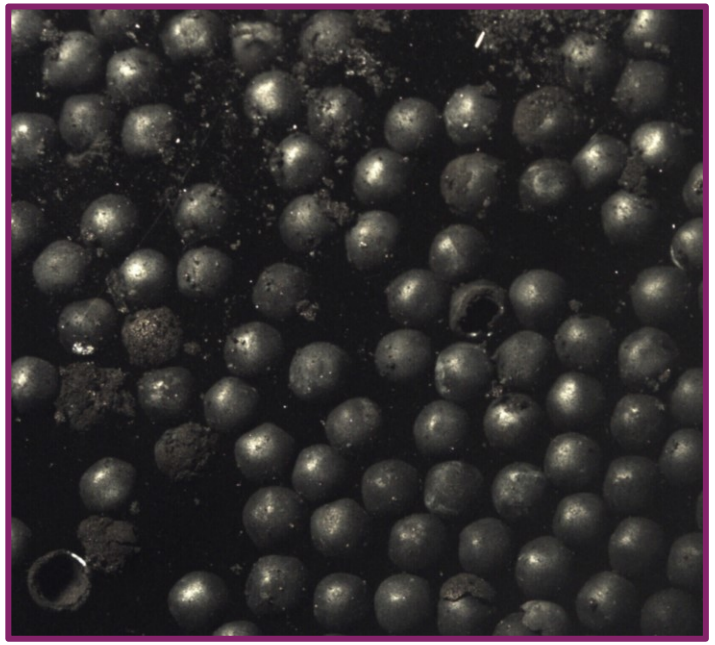
Particle Exams
- Gamma counting
- X-ray CT

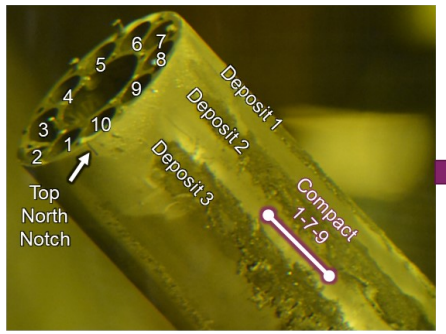


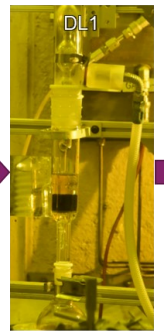
DLBL of Compact 1-7-9 – Photo after BL2

- SiC shell fragments
- Rough SiC surfaces
- Reflective nodules on SiC
- Insoluble fines with some reflective nodules





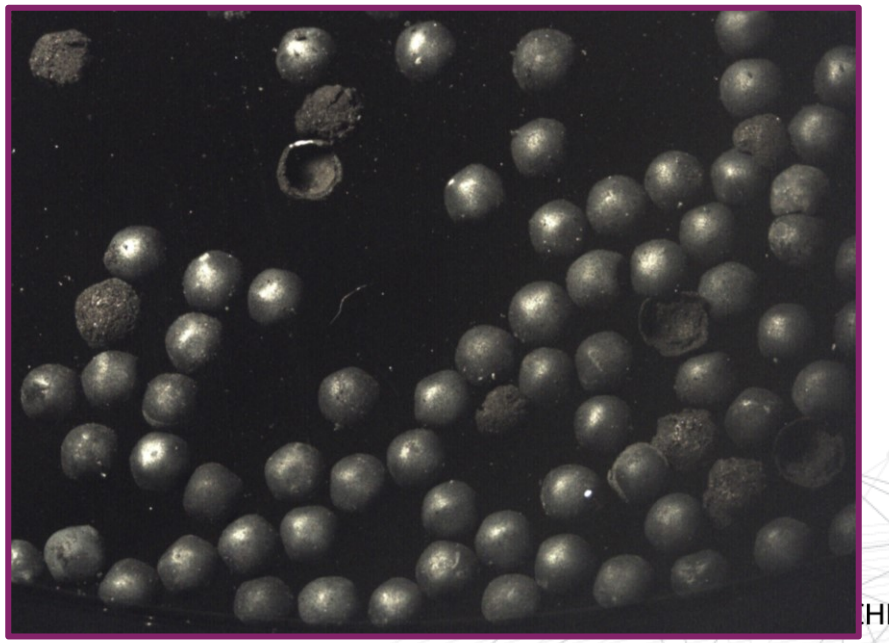




"Burn" at 750°C in air for 72 h

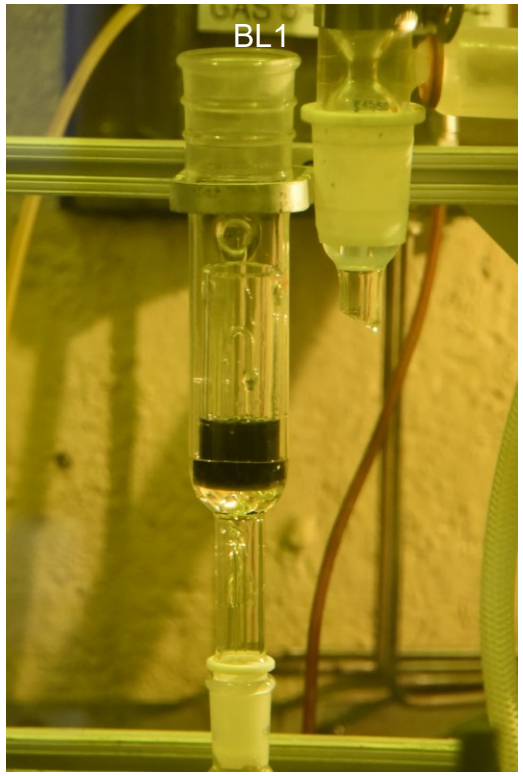
Analysis of solutions:
- gamma spec
- Sr-90 separation
- mass-spec

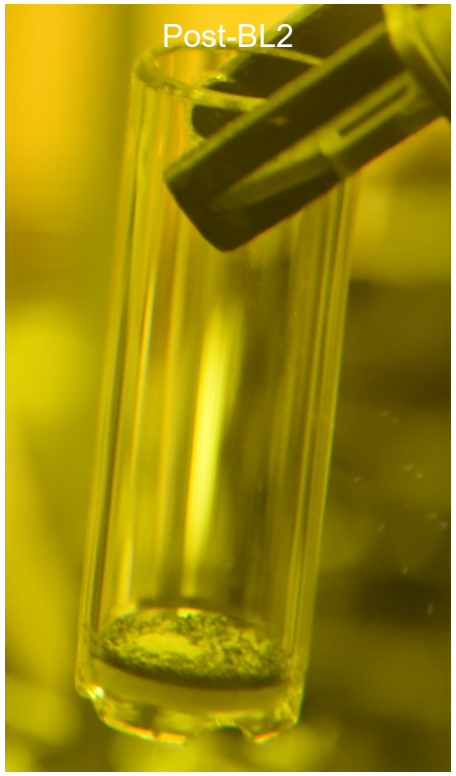
Particle Exams
- Gamma counting
- X-ray CT



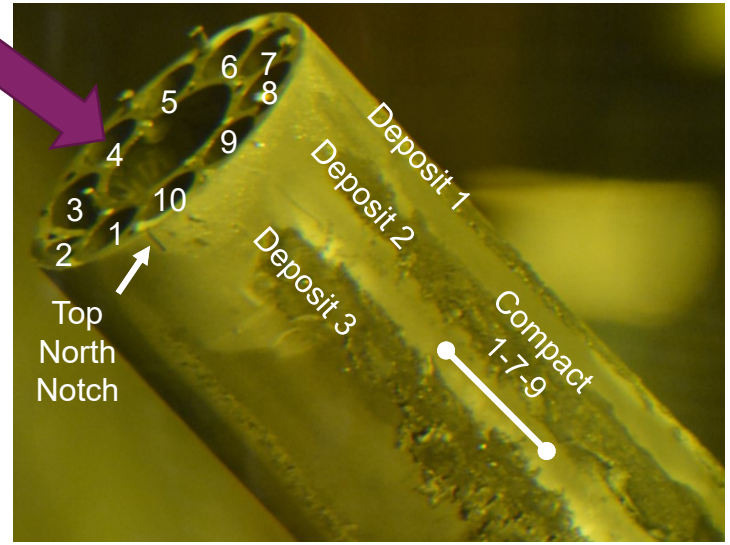
DLBL of Compact 1-7-4 Complete

- Compact selected from region opposite the deposits
- Solutions clearer (less fines)
- No discernable color (yellow or otherwise) in solutions
- Particles and matrix debris appear to be ~normal (images not available)
- Some white substance present after 750°C burn. Unclear what this is.





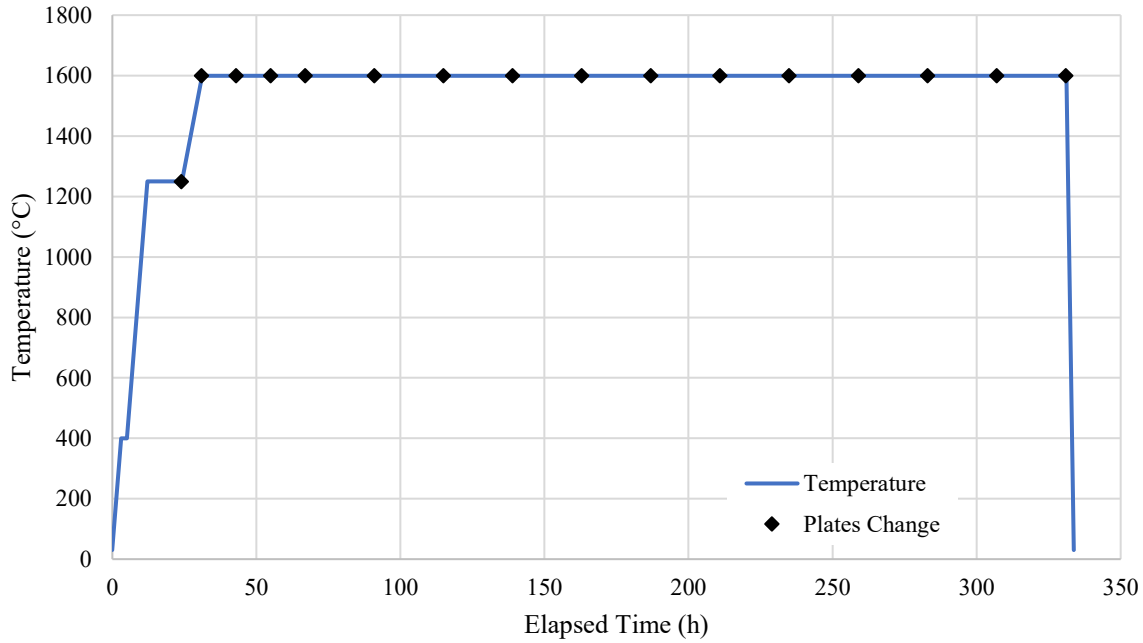
Compact 1-7-4 from Level 7 of Stack 4



Completed 1600°C FACS Test of Compact 4-1-3 for 300 h

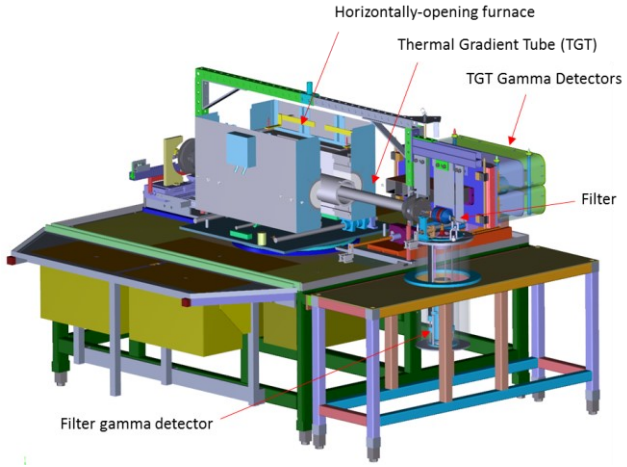
- Lowest-temp, highest-burnup compact safety tested so far in all AGR
- Data incomplete at this time

Compact	4-1-3
Nominal Packing Fraction[a]	25%
Compact Average Burnup (% FIMA)[b]	14.06
Compact average Fast Fluence (n/m^2, E > 0.18 MeV)[b]	5.01×10^{25}
TAVA Irradiation Temperature (°C)[c]	786
TA Peak Irradiation Temperature (°C)[d]	902
TA Minimum Irradiation Temperature (°C)[d]	575



Air-Moisture Ingress Experiment (AMIX)

- 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 ~80% complete
  - FY22 Milestone: Complete Phase II-a qualifications by 9/15/2022
  - Complete of all of Phase II (remote assembly and checkout) at mockup by April 2023
  - Complete AMIX installation in Fuel Conditioning Facility (FCF) hot cell by end of FY23



Selected Conclusions and Future Work

Conclusion:

- Very likely Capsule 1 fuel failures are attributed to error in test train design/construction that allowed Ni from over-heated TCs to attack the fuel. Failures NOT from inherently poor fuel performance
- Rest of test train seems to have performed nominally as intended

Future work:

- Assay irradiation test train components for fission products and determine mass balance
- Continue safety testing fuel
- Continue destructive exams of as-irradiated and safety-tested fuel
- Evaluate Capsule 1 fuel to elucidate cause of unexpected behavior via:
  - DLBL
  - Particle X-ray
  - Compact cross-sectioning
  - Additional holder exams including gamma tomography and possible cross-sectioning
- Install AMIX at FCF


INL
Idaho National Laboratory