

The Role of Separate Effects Irradiation Testing: Bridging Gap Between Physic-based Modeling and AFQ

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Understand Relevant Physical Mechanisms that Link **Model Predictions, Accelerated Irradiations, and Integral Performance**

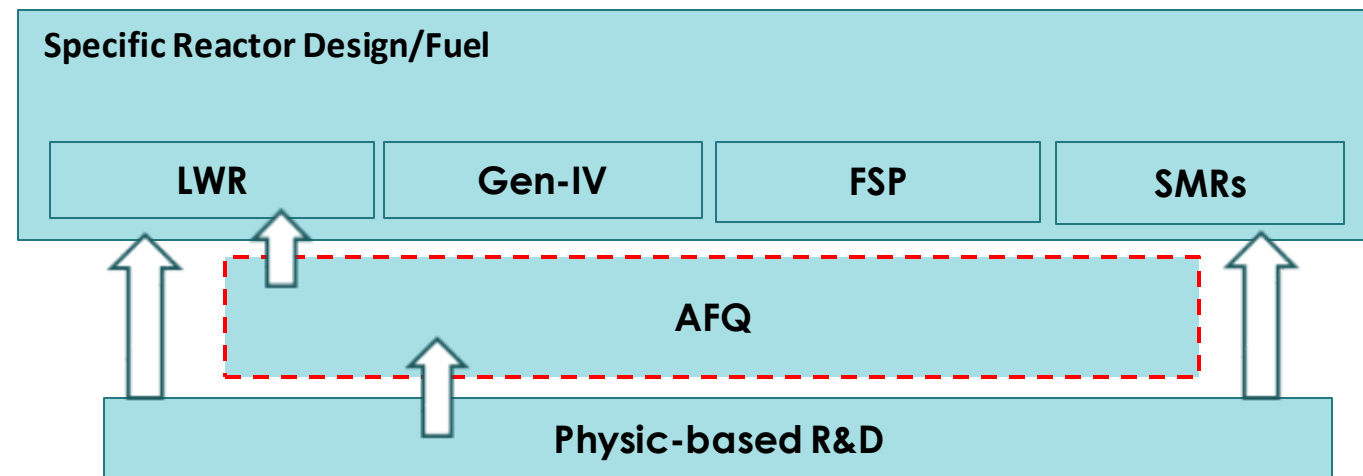
❑ **Requires** creation of interfaces between different research frameworks:

- ❑ Physics-base R&D
- ❑ AFQ
- ❑ Reactor Design, etc...

❑ Model predictions are **benchmarked** using testing of increasing complexity

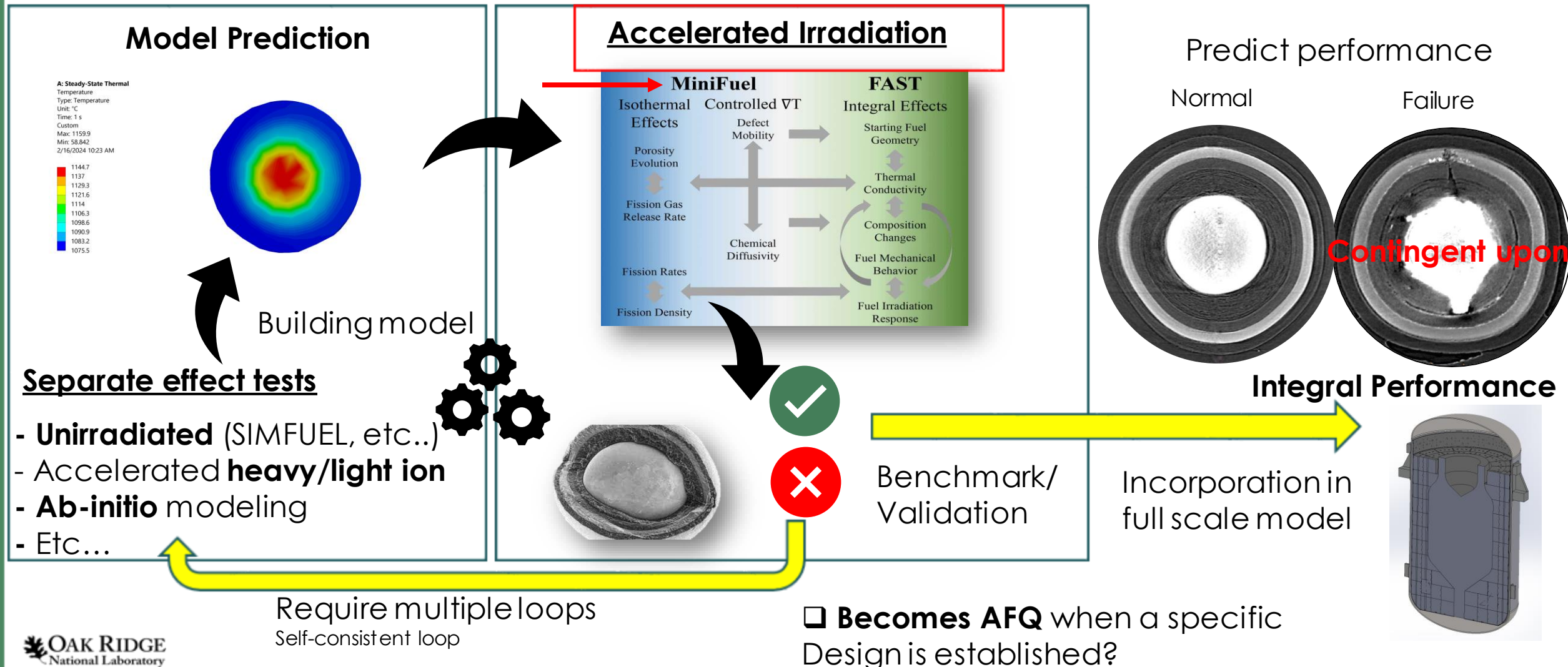
❑ **Unirradiated** ... accelerated swift **heavy ion**... **MiniFuel**... FAST... **Integral**

❑ Still to be define the **boundaries of AFQ**.

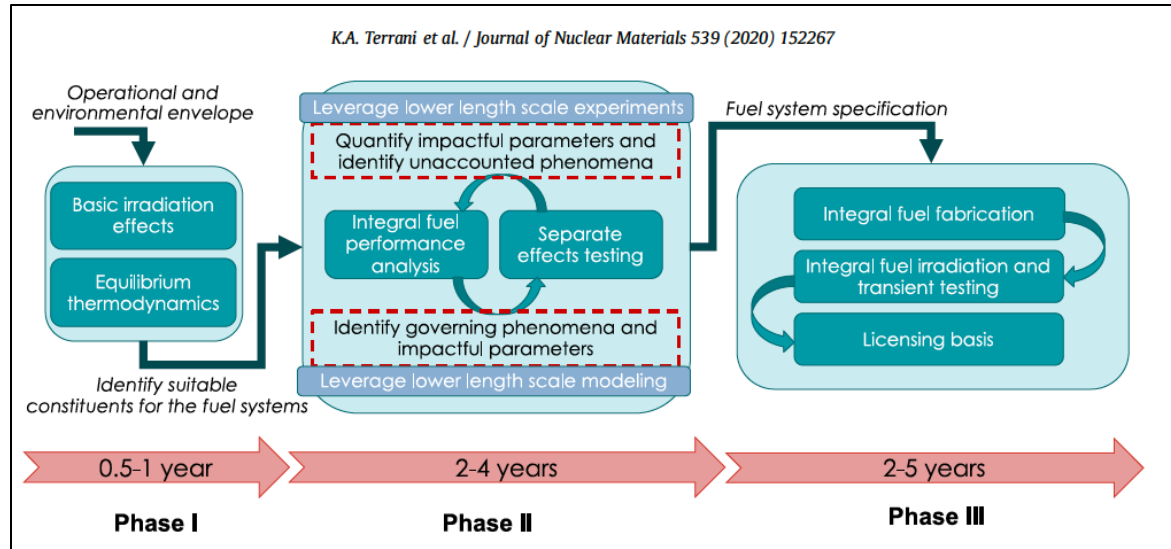


Different research framework interfacing

Understand Relevant Physical Mechanisms that Link **Model Predictions, Accelerated Irradiations, and Integral Performance**

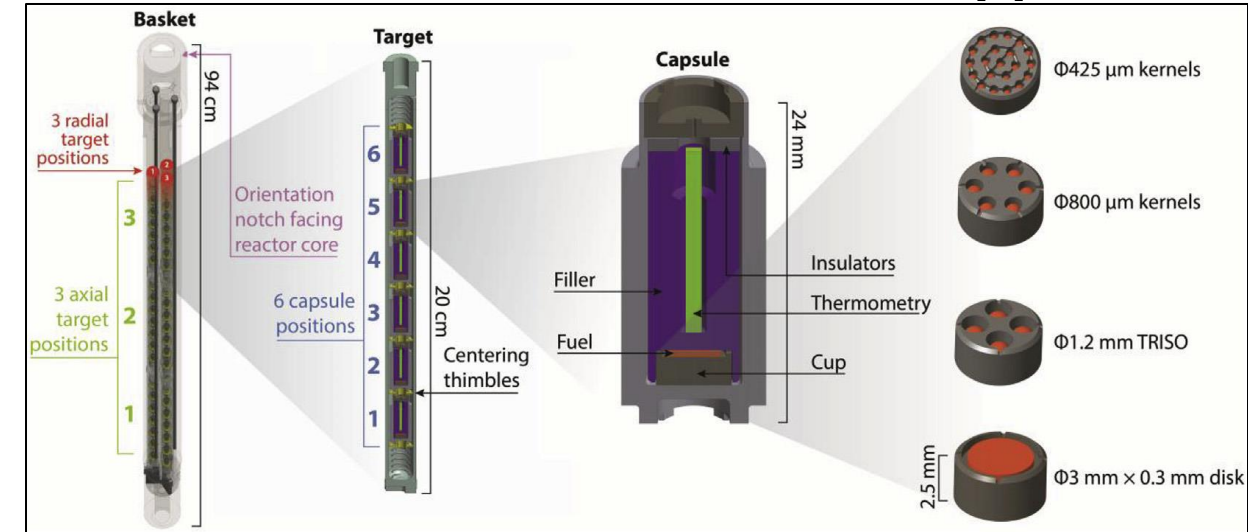


Separate Effects Irradiation Testing: The **MiniFuel** Vehicle



Process workflow for Accelerated Fuel Qualification - AFQ [1]

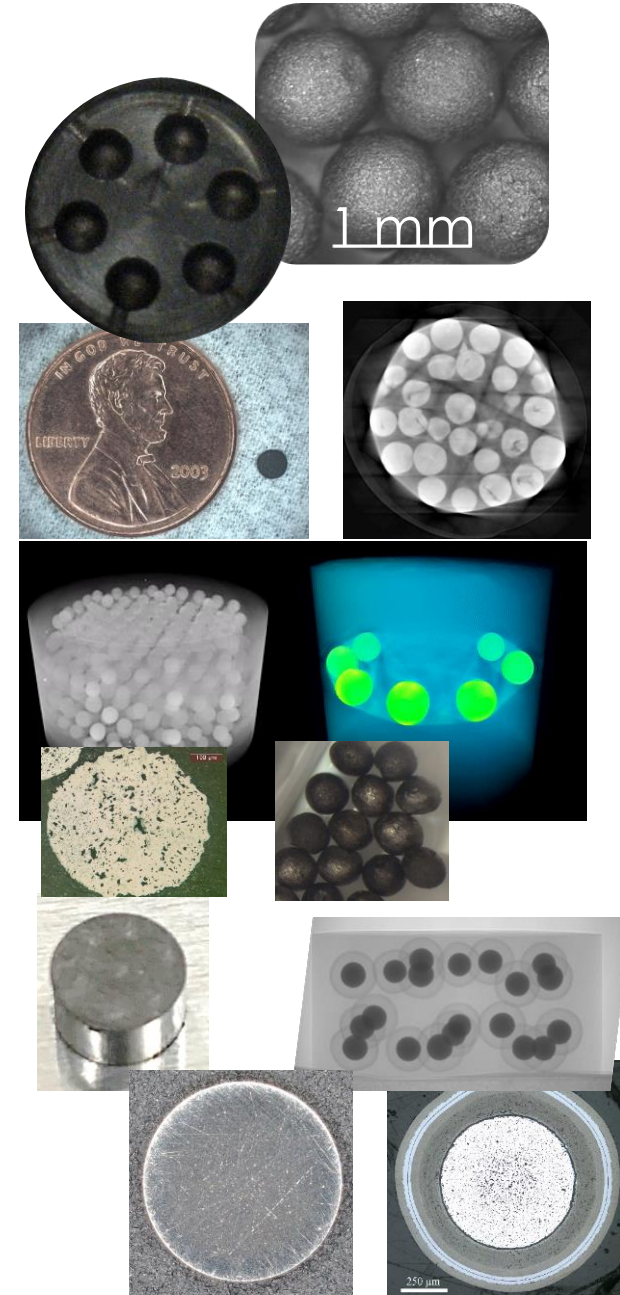
MiniFuel Test Vehicle [2]



- High flux from **HFIR accelerates testing**. **Natural and depleted U-samples** can be used.
- Gamma heating generated by the high Z tube and filler controls fuel temperature (small fuel volumes).
- Standard geometries can **reduce design costs**
- Putting into practice **new perspectives** on fuel development to determine feasibility of operating in well control parameters → **“if results are positive”** consider moving forward in workflow

MiniFuel Experiments: Completed, Ongoing and Planned

Targets	Fuel type	Enrichment (wt.%)	Target temperature (°C)	Target burnup (% FIMA)	HFIR Facility
MF01/02	UCN/UGdCN kernels, TRISO	0.22 or 0.71	600	1-6	VXF
LA01/02	U₃Si₂ , UO ₂ disks	0.19 or 0.35	500	1-3	VXF
FC01-04	UCN/UCO TRISO compacts	0.22 or 0.71	500	1-3	VXF
GA FOA 201/202	UC and UO ₂ kernels	2.38	800	2-3	VXF
KP01 thru KP05	UCO/UO ₂ TRISO compacts	0.71, 9.58, or 14.17	500-900	2-12	VXF
ALEU-1 thru -3	U-Mo disks	1.20	250-500	0.5-2	VXF
IF-1 thru -3	Ni, Mo, W-doped UO₂ disks	0.71	600	1-3	VXF
RB01/02	Cr-doped UO₂ disks	0.34	1100	5-10	RB
UCN1-6	UN, UC, UO ₂ kernels	0.71	900-1300	3-6	RB
HBU1-5	UO ₂ disks	0.71	600-1100	6+	RB
Mini99-1 thru -3	Na-bonded U metal disks	8	150-400	2	VXF

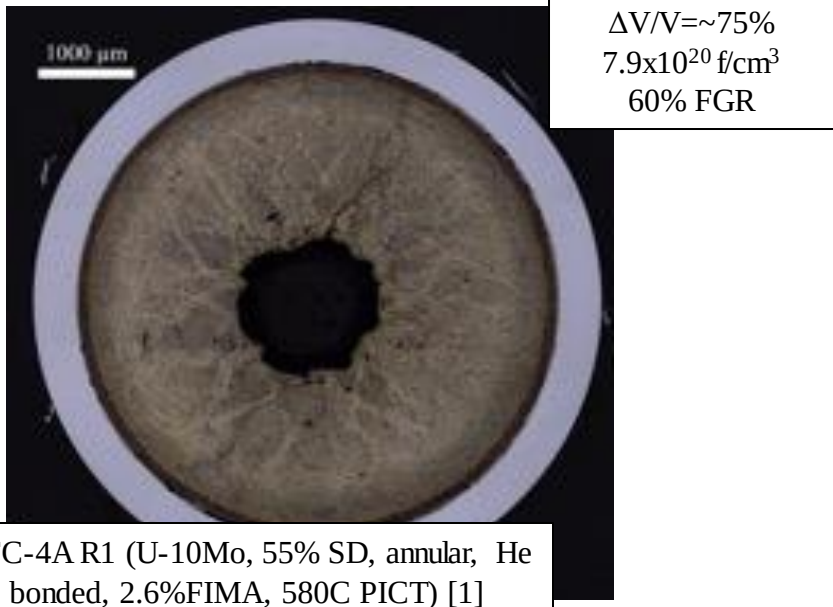
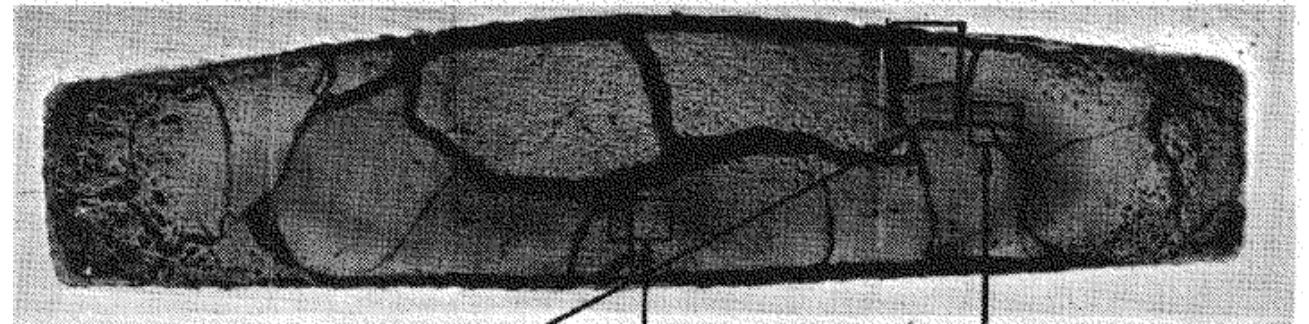


MiniFuel Irradiation Application Cases:

- **U-Mo** fuel screening study
- **TRISO** Kairos AFQ case

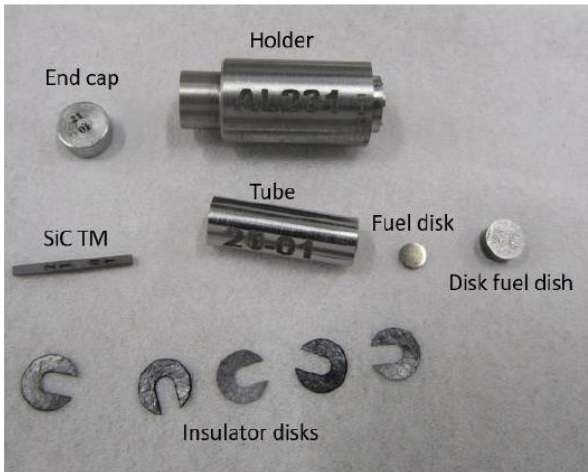
Basic Use of Accelerated Fission Rate Testing: Determination of Swelling of U-10Mo for LWR Service

- U-10Mo performs well in **research reactor** conditions ($<200^{\circ}\text{C}$), but experiences significant swelling at **SFR conditions** ($>600^{\circ}\text{C}$)
- Swelling behavior in **intermediate temperature range** determines viability as a monolithic LWR fuel
- **MiniFuel and FAST** irradiations were performed to explore this temperature regime

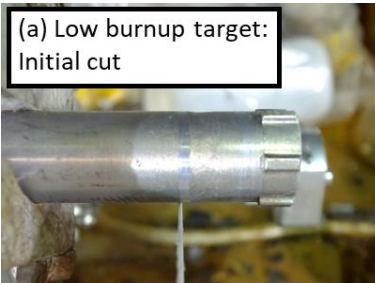
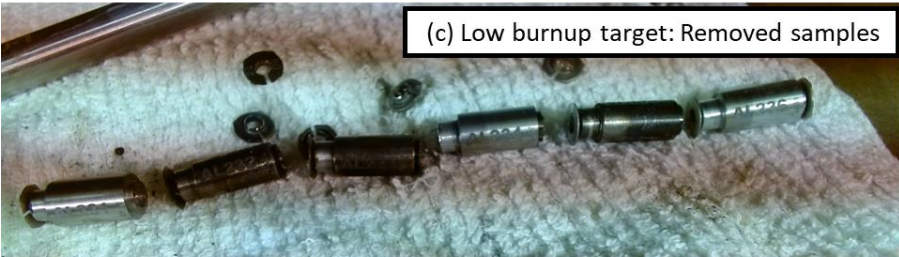
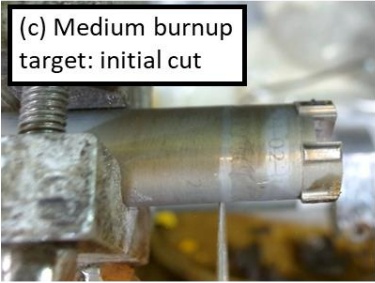
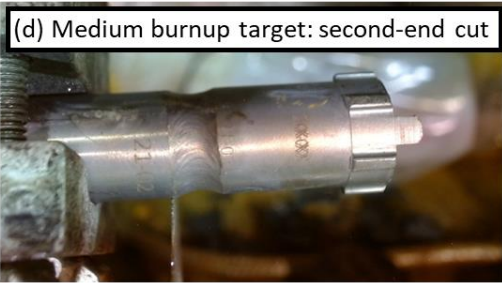


Example of UO_2 -6 wt% ZrO_2 fuel that failed due to excessive swelling ($\Delta t/t \sim 15\%$, $1.9 \times 10^{21} \text{ f/cm}^3$, Internal cladding temperature 315°C) [2]

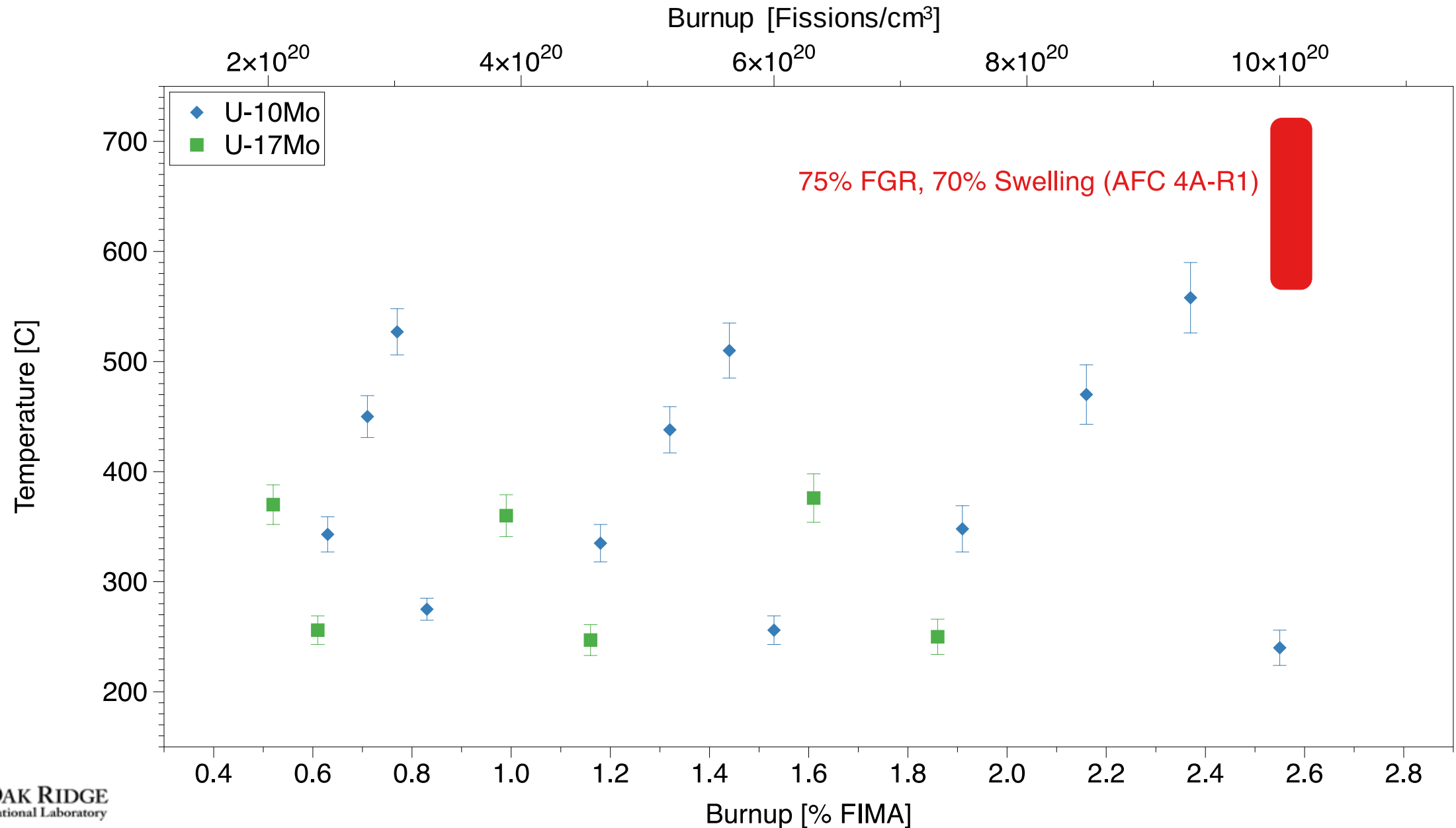
MiniFuel Subcapsule Assembly (FY21) & Disassembly (FY22)



January 2021

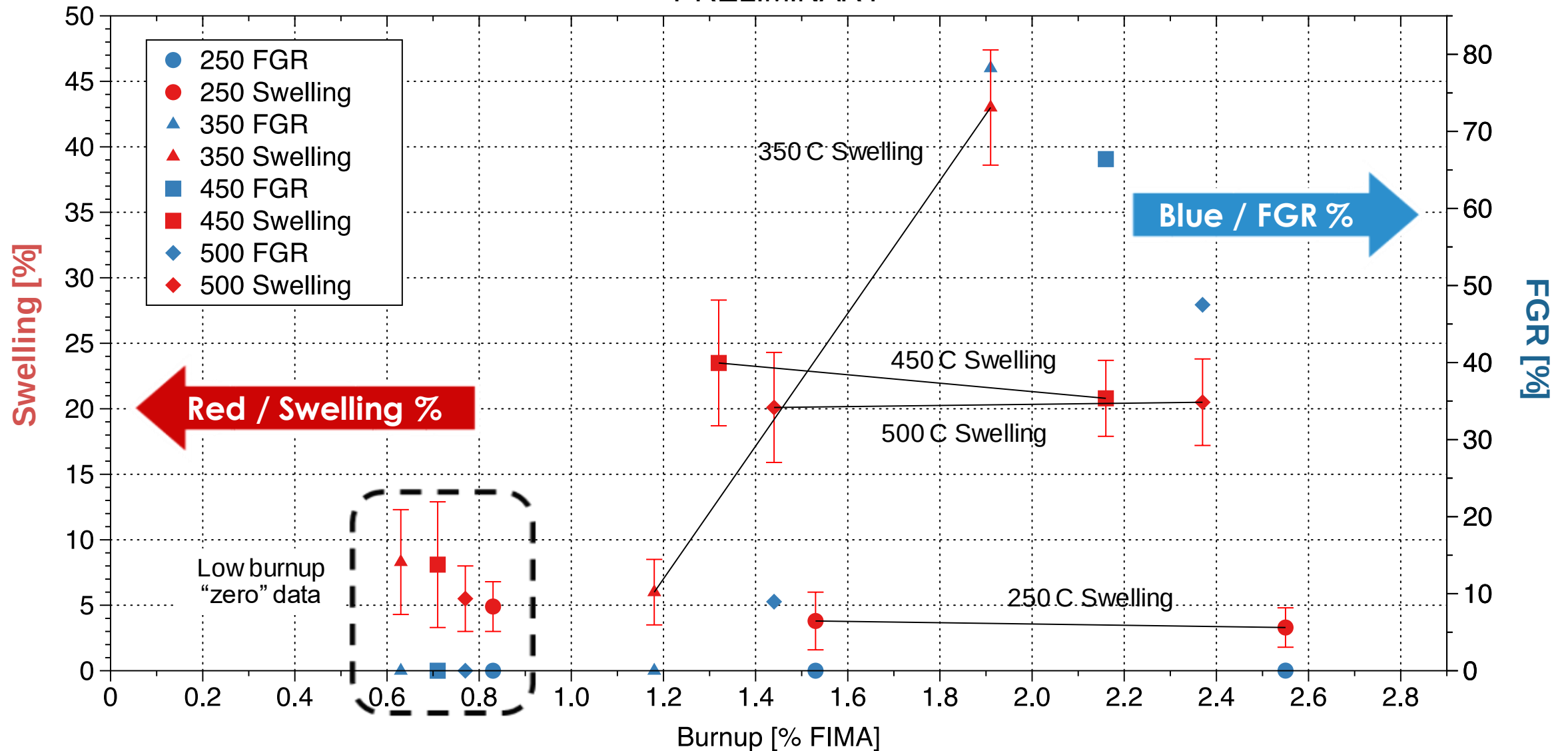


Summary of HFIR U-Mo MiniFuel Irradiations (2021-2022)



U-10Mo MiniFuel Swelling and Fission Gas Release

PRELIMINARY



Primary Takeaways from U-10Mo MiniFuel Campaign

- U-10Mo experiences significant swelling & fission gas release beginning at **~350°C and 2% FIMA**, challenging its use as a monolithic light water reactor fuel.
- Existing fuel performance models did not predict this behavior [1] (unsurprising since they were developed based on research reactor test conditions).
- **Comparison of microstructures / fission gas bubble morphologies** developed in U-10Mo irradiated in **MiniFuel** and **FAST** will provide insight into fission rate effects.

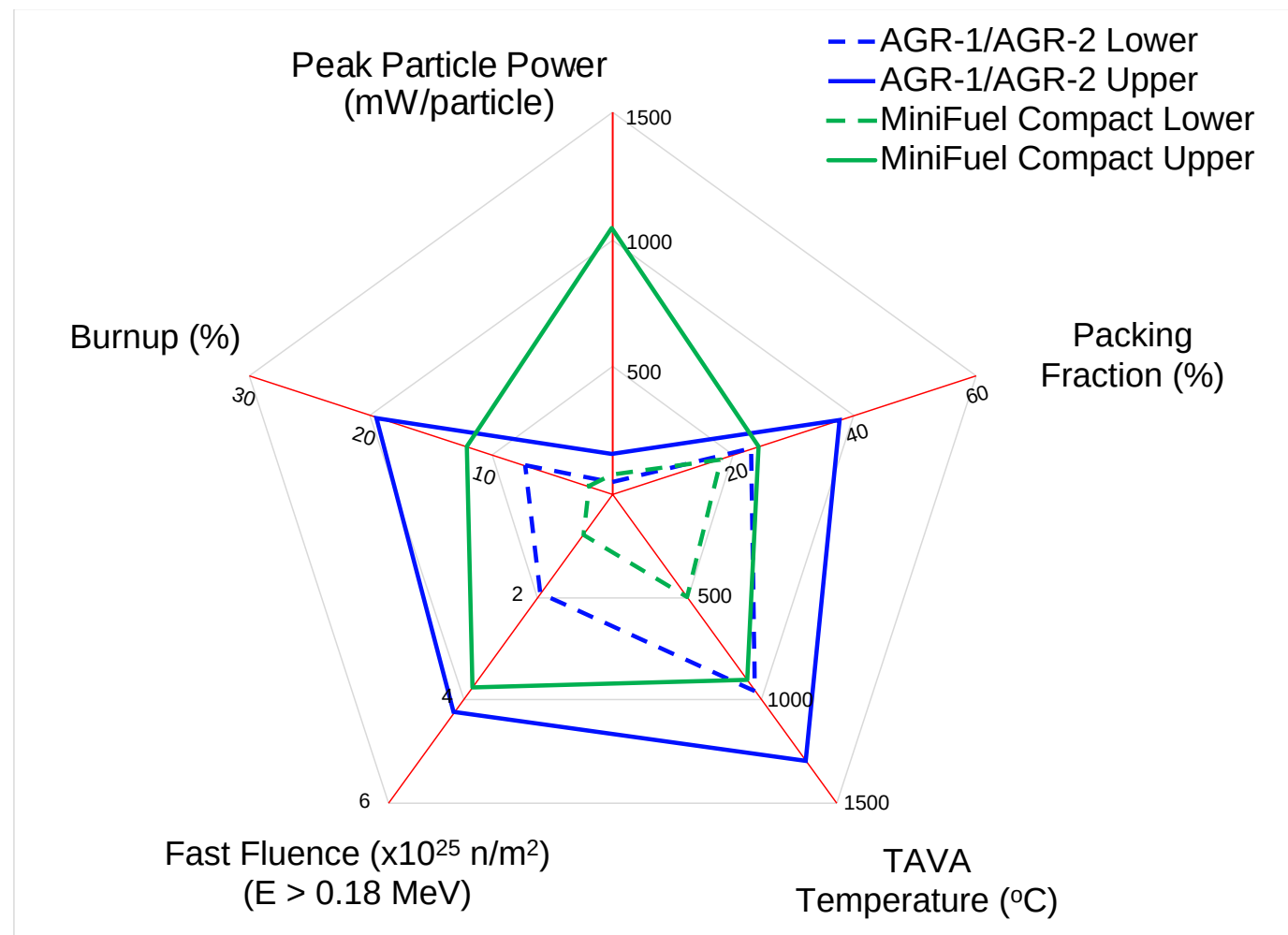
MiniFuel Irradiation Application Cases:

- U-Mo fuel screening study
- **TRISO** Kairos AFQ case

MiniFuel AFQ Kairos example

High particle power conditions are **well-outside of AGR** program bounds

- Bounding tests are needed to **understand feasibility of operating outside of AGR bounds** and identify “cliffs” in failure rate
 - A full integral fuel form irradiation campaign is unreasonable to survey feasibility of high particle powers
- Any experiment **should link to AGR** pedigree fuel with its known performance ($\sim 1E-5$ failure rate)^[1] to provide a baseline for determining impact of testing outside of AGR bounds



Time-average Volume-average (TAVA) Compact Temperature

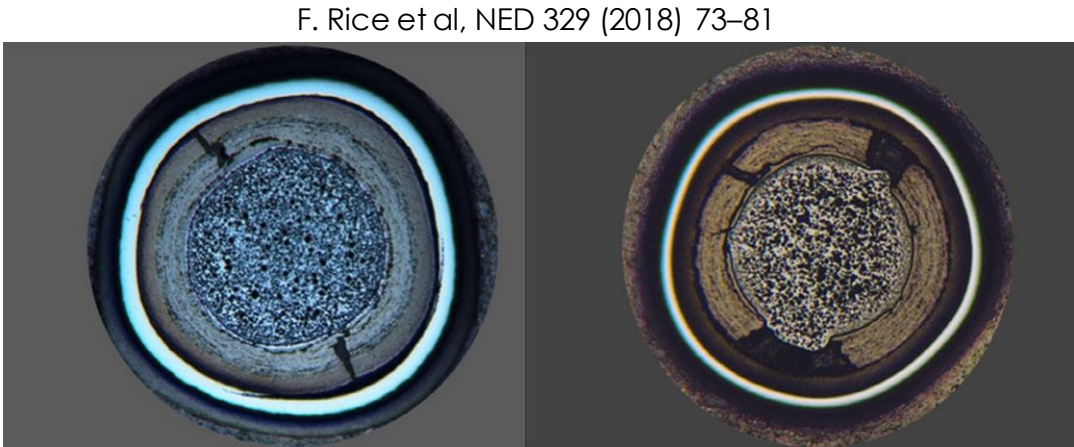
MiniFuel AFQ Kairos example

Targeted Experimental Conditions

LE = low enriched; NU = natural enriched
UCO = uranium oxide, uranium carbide kernels

Particles	Temp.	Peak Power (mW/particle)	Average Power (mW/particle)	Burnup (FIMA%)	Fast Fluence (10 ²⁵ n/m ² , E>0.18)
LEUCO/NUCO	500°C	80–1050	70–600	2–12	2–4
LEUCO/NUCO	700°C	80–1050	70–600	2–12	2–4
LEUCO/LEUO ₂	900°C	700–950	350–500	7–9	2–3

- Leverage AGR-2 pedigree TRISO fuel with significant pre-irradiation characterization data
- **Higher particle powers and low temperature particle response**
- Impact of kernel chemistry and particle power on kernel migration

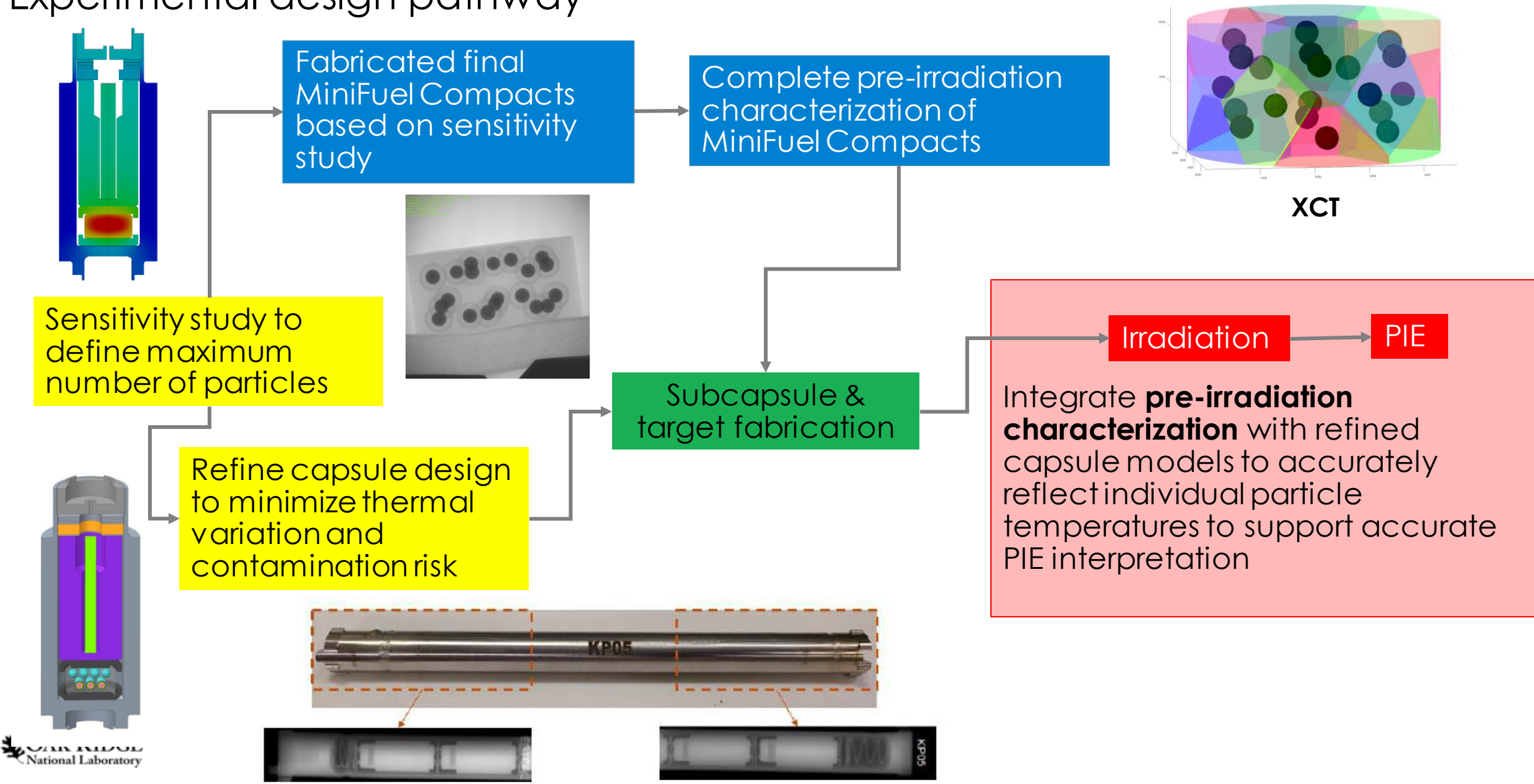


Low Temperatures: Speculated increased potential for unwanted internal layer cracking

Two simultaneous experiments

MiniFuel AFQ Kairos example

Experimental design pathway



Multiphysics Models to Predict Performance and Support PIE Interpretation

Preliminary **HFIR MiniFuel** Performance from
BISON Modeling [1]

Compact	IPyC Cracking Probability (%)	Pd Penetration (μm)	SiC Failure Probability (%)	
			Failure from IPyC Cracking (%)	Pressure Vessel Failure
121 UCO – 900°C	25.6	0.23	1.5	1.3×10^{-8}
122 UO ₂ – 900°C	22.5	0.25	1.1	1.5×10^{-8}
221 UCO – 700°C	84.3	0.028	8.3	5.6×10^{-12}
222 NUCO – 700°C	91.1	0.029	16.2	5.9×10^{-14}
231 UCO – 700°C	87.3	0.029	8.7	2.3×10^{-12}
236 UCO – 700°C	79.6	0.026	1.8	1.0×10^{-12}
321 UCO – 500°C	85.6	0.0017	7.4	3.1×10^{-8}
322 NUCO – 500°C	91.5	0.0015	14.6	1.0×10^{-13}
331 UCO – 500°C	87.3	0.0016	7.6	9.5×10^{-9}
336 UCO – 500°C	77.2	0.0015	1.5	4.8×10^{-9}

Observable based
on particle statistics
(60 particles per
condition)

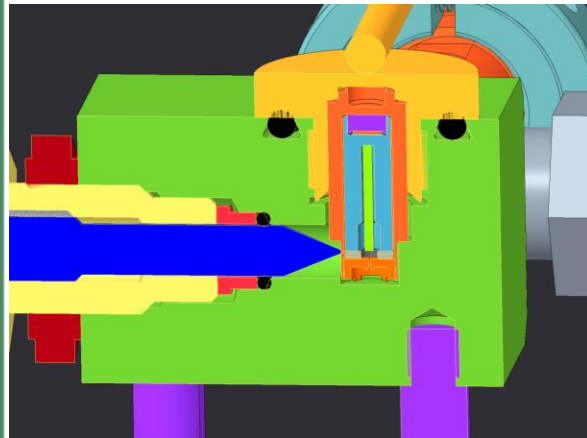
- Predict relevant phenomena based on irradiation conditions and known properties
 - Not all possible failure modes are identified (e.g. local corrosion by CO_(g) or degradation by Pd)

[1] B. Collin, R. Gardner, M. Hackett, R. Latta, R. Gallagher, T. Gerczak, A. Le Coq, K. Linton TRISO Fuel Performance Pre-test Predictions of HFIR MiniFuel High Power Irradiation, ANS Annual Meeting, 2022

MiniFuel AFQ Kairos example

PIE plans: Implementing a phased approach

Overall release behavior & failure fraction

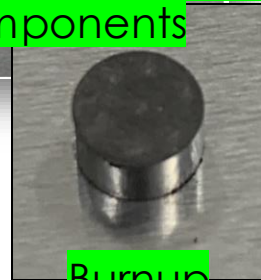


Gas puncture

Gamma Analysis

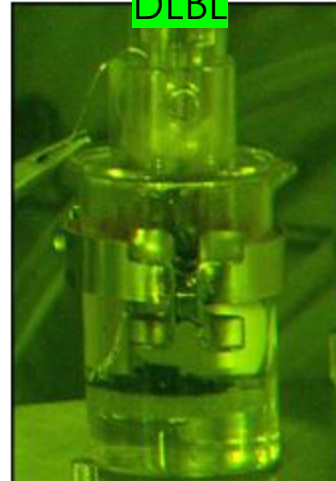


Plate out on capsule components



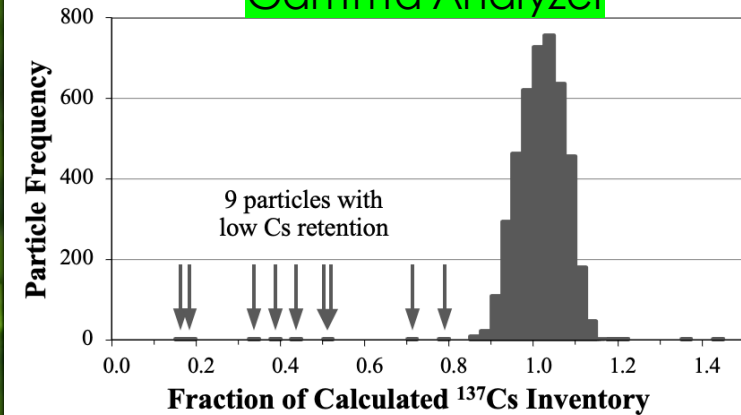
Burnup

DLBL

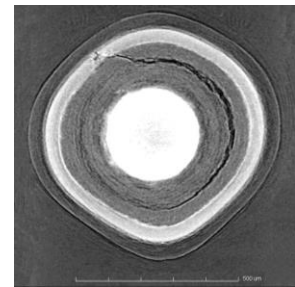


Capsule leaching

Irradiated Microsphere Gamma Analyzer



Mechanistic understanding



XCT

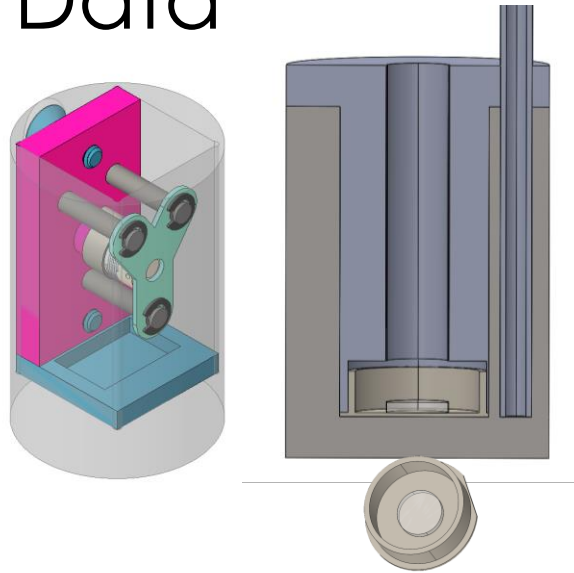
- **Phase 1 (current scope funded by NSUF):** gas puncture (failure, yes or no), FP sink ring and capsule leaching (failure/release, yes/no), burnup (gamma), select deconsolidation leach-burn-leach (DLBL) analysis (number of failures) and XCT – **can the particle survive high power irradiation?**
- Phase 2/3: mechanistic assessment of particle failure by leveraging multiscale PIE approach – **why did they fail**, if at all? Kernel Migration?

Primary Takeaways from TRISO MiniFuel Campaign

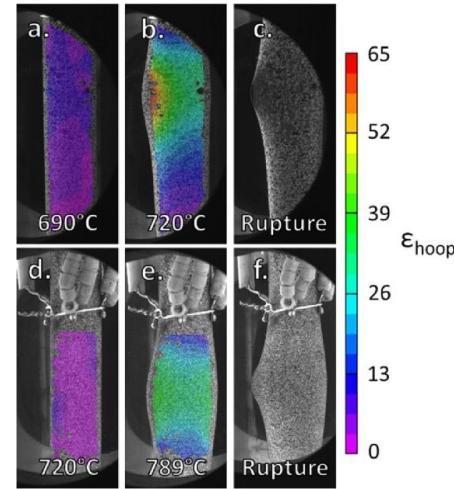
- A separate effects irradiation experiment has been undertaken to determine if **TRISO particles can perform at “high” particle powers and “low” temperatures** relative to HTGR operating conditions.
- **Supporting modeling efforts** were done using BISON platform to predict fuel performance at high particle powers and for comparison with PIE results.
- Capsule design, fuel fabrication, and pre-irradiation characterization were considered to refine and improve the experiment **fidelity to support final PIE interpretation.**
- Initial gas puncture results are inconclusive to date, comprehensive PIE to follow.

Other Platforms for **Separate Effects Vehicles Coming Up:** Working to do better than “Cook and Look”... Let's Get More / Better Data

- **MINITAURE**
- **SATS DIC**
- **WIRE-21**



Minitaure Thermal conductive capsule (TCC)
and Dimensional change capsule(DCC)



Severe Accident Test Station (SATS)
3D digital image
correlation for
cladding analysis



Wire-21 – wireless in-rod
sensors. More data from
LTR/LTAs

- Using data from these kinds of tests to validate predictions will require regulator understanding & acceptance (e.g. LWR industry's use of Halden in situ data)

**More platform for access throw
NSUF program !**

Summary

- Separate Effects Irradiation Testing attempt to bridge the gap between:
 - Physic-based R&D
 - AFQ
 - Reactor Design.

Makes necessary interaction of **multiple DoE labs**.

- **MiniFuel** vehicle design was demonstrated flexible and can support AFQ initiatives.
- **Other** Separate Effects **Irradiation Testing Vehicle** are in development. Continues financial support is necessary.
- **The use of NSUF facility through program from DoE** will be beneficial to support multiple fuel qualification.