July 13, 2021

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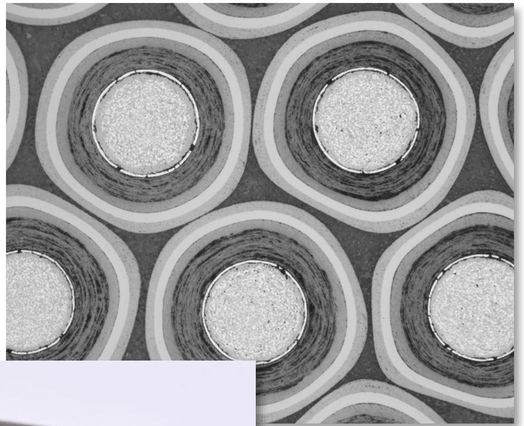
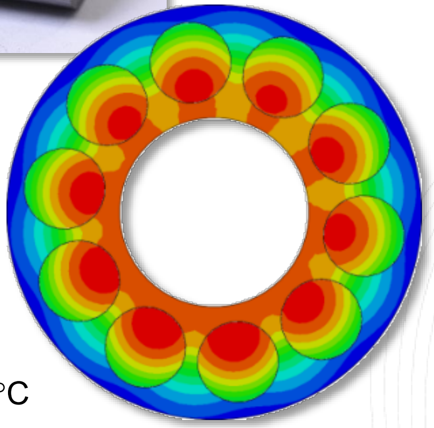
AGR-5/6/7 Irradiation Results and Reporting

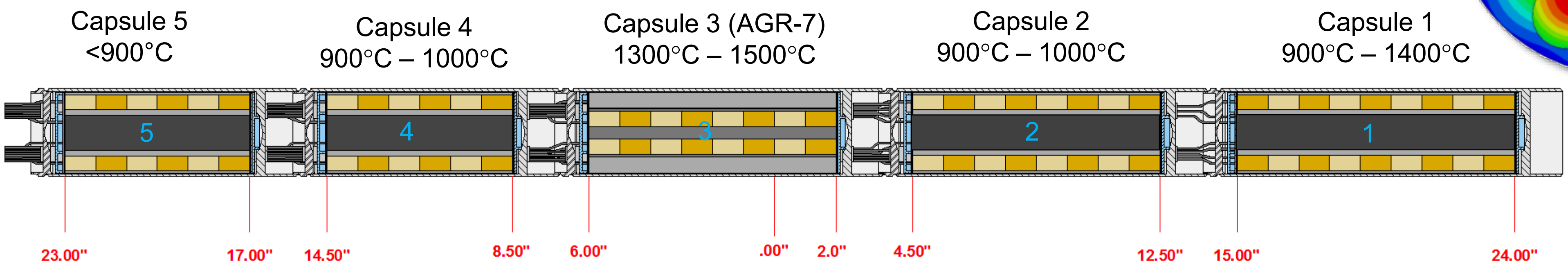
ART
Advanced Reactor Technologies

AGR-5/6/7 Irradiation

- Final fuel qualification irradiation (AGR-5/6) and performance margin test (AGR-7)
- 425 µm diameter UCO kernels with 15.5% ^{235}U enrichment
- Target time-average peak fuel temperatures ~1500°C
- Target peak burnup 18% FIMA
- 194 fuel compacts (~570,000 particles) in five capsules
- Irradiation started Feb 2018 in ATR Northeast Flux Trap







AGR-5/6/7 test train axial cross section

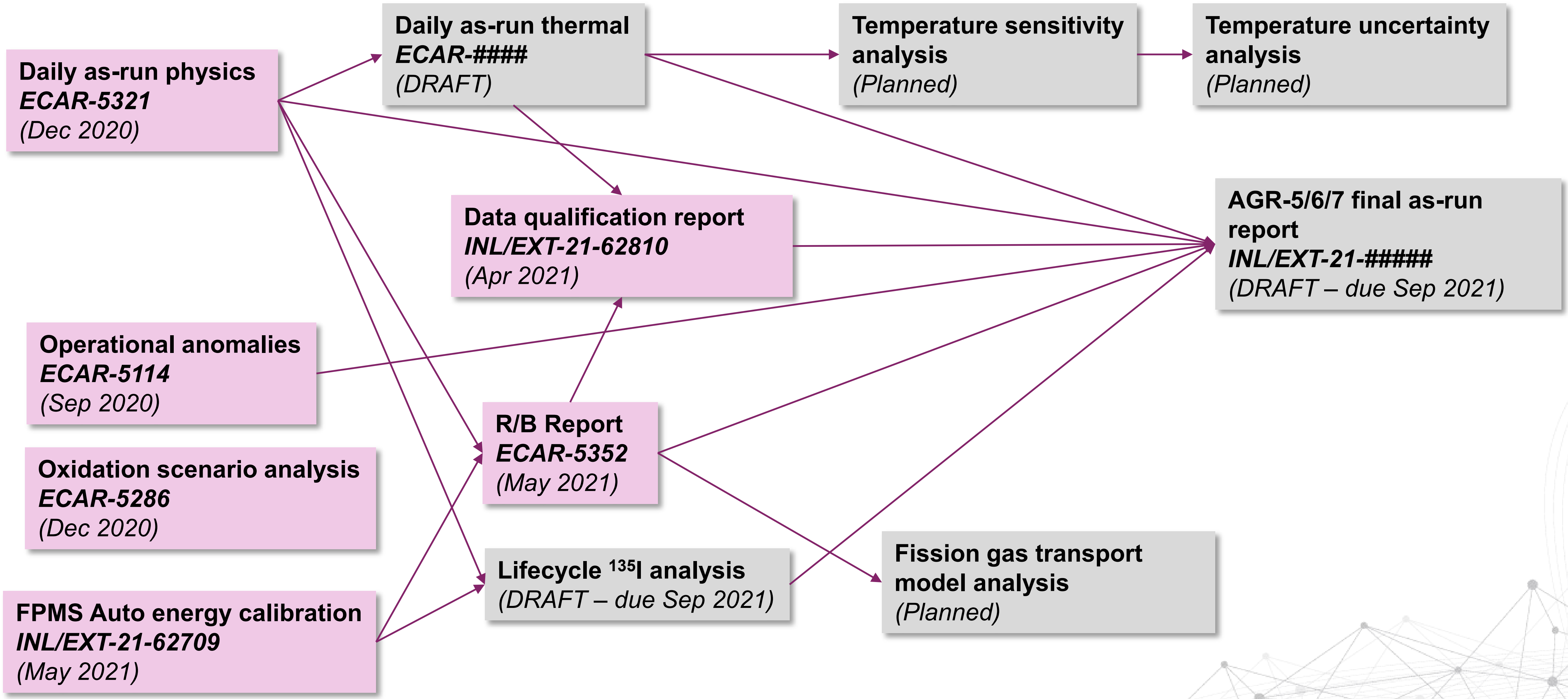
AGR-5/6/7 Status

- Large increase in fission gas from Capsule 1 observed in October 2019 (~235 EFPD, peak burnup ~8% FIMA)
- Experiment terminated early (July 2020) after 361 EFPD and peak burnup 15.3% FIMA
  - Primarily to ensure timely shipment to MFC and avoid conflicts with ATR Core Internals Changeout (CIC)
- Expedited shipment from ATR to MFC was not realized in late 2020; experiment shipped to MFC in March/April 2021 (two sections)
- Conflicts at HFEF with ART-AGC work and other DOE programs, as well as facility maintenance outages, have delayed the start of destructive capsule examination
- Capsule 1 PIE remains the top priority

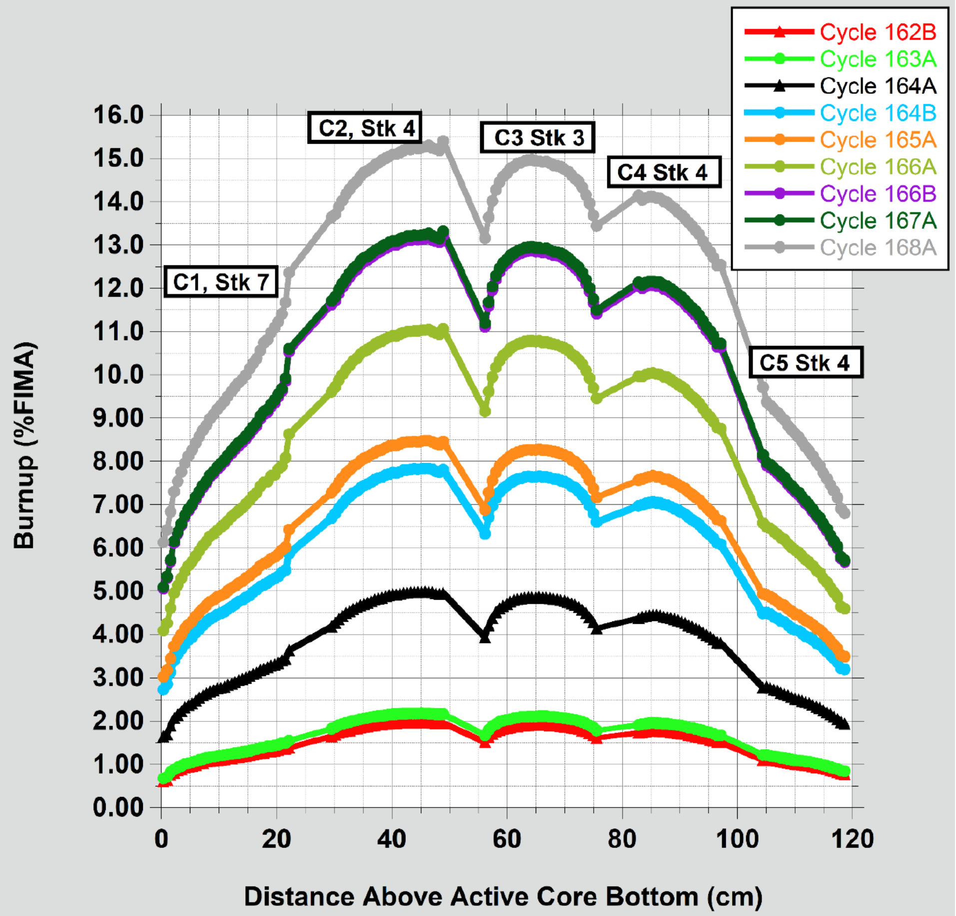
AGR-5/6/7 Operational Issues

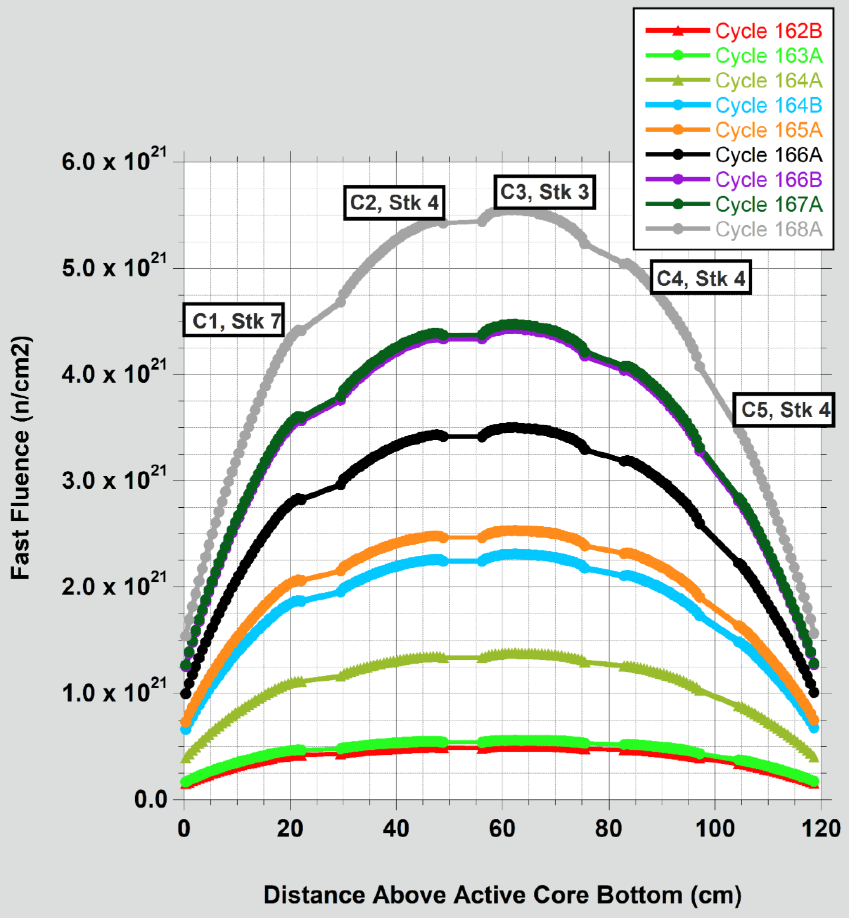
- Gas line integrity in Capsule 1 was compromised starting with the 4th cycle (Cycle 164B)
  - M. Nelson, “AGR-5/6/7 Gas System – Analysis of Various Anomalies Encountered During Irradiation,” ECAR-5114, September 2020
  - J. Palmer, “AGR-5/6/7 Irradiation Summary as of the End of Cycle 167A,” Presentation at 2020 ART-GCR Annual Program Review, July 2020
- These issues persisted and worsened throughout the irradiation and including occlusion (abnormally low flow) and breaks (gas flow leaking into and out of gas lines)
- Fission gas leaking from Capsule 1 to the leadout entered other capsules and complicated fission gas R/B analysis for Capsules 2 – 5
- Challenged ability to maintain fuel temperatures in Capsule 1

AGR-5/6/7 Reporting



AGR-5/6/7 Burnup and Fast Fluence

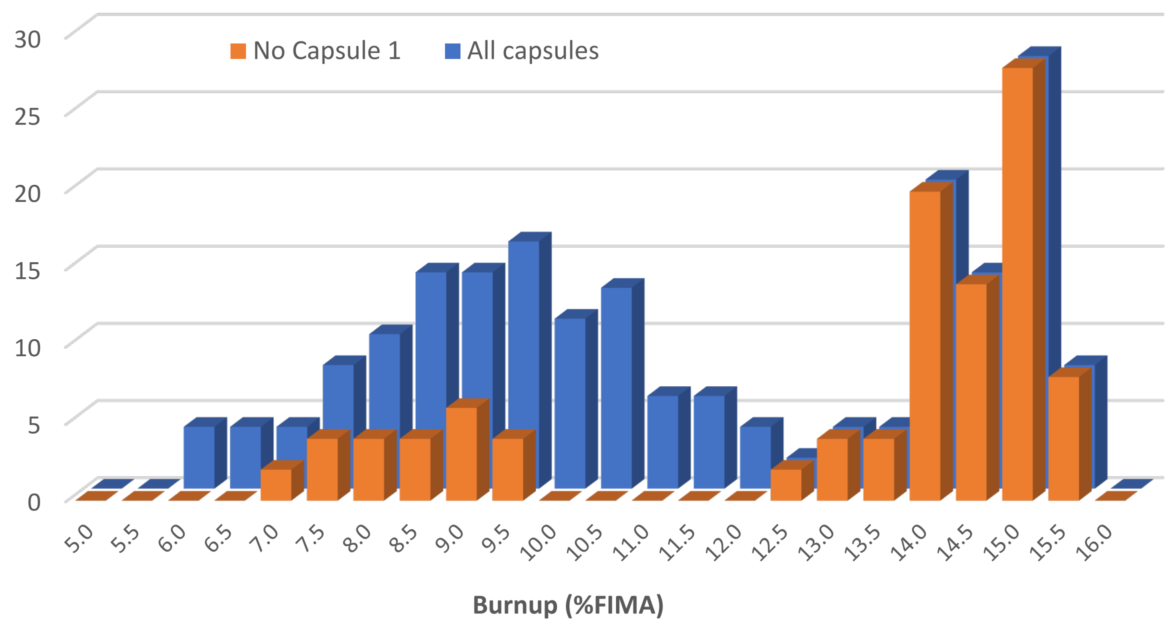




- Burnup (%FIMA)
  - Min: 5.7
  - Max: 15.3
  - Target: Max >18
- Fast fluence (n/cm^2)
  - Min: 1.6×10^{21}
  - Max: 5.6×10^{21}
  - Target: Max $>5\times10^{21}$

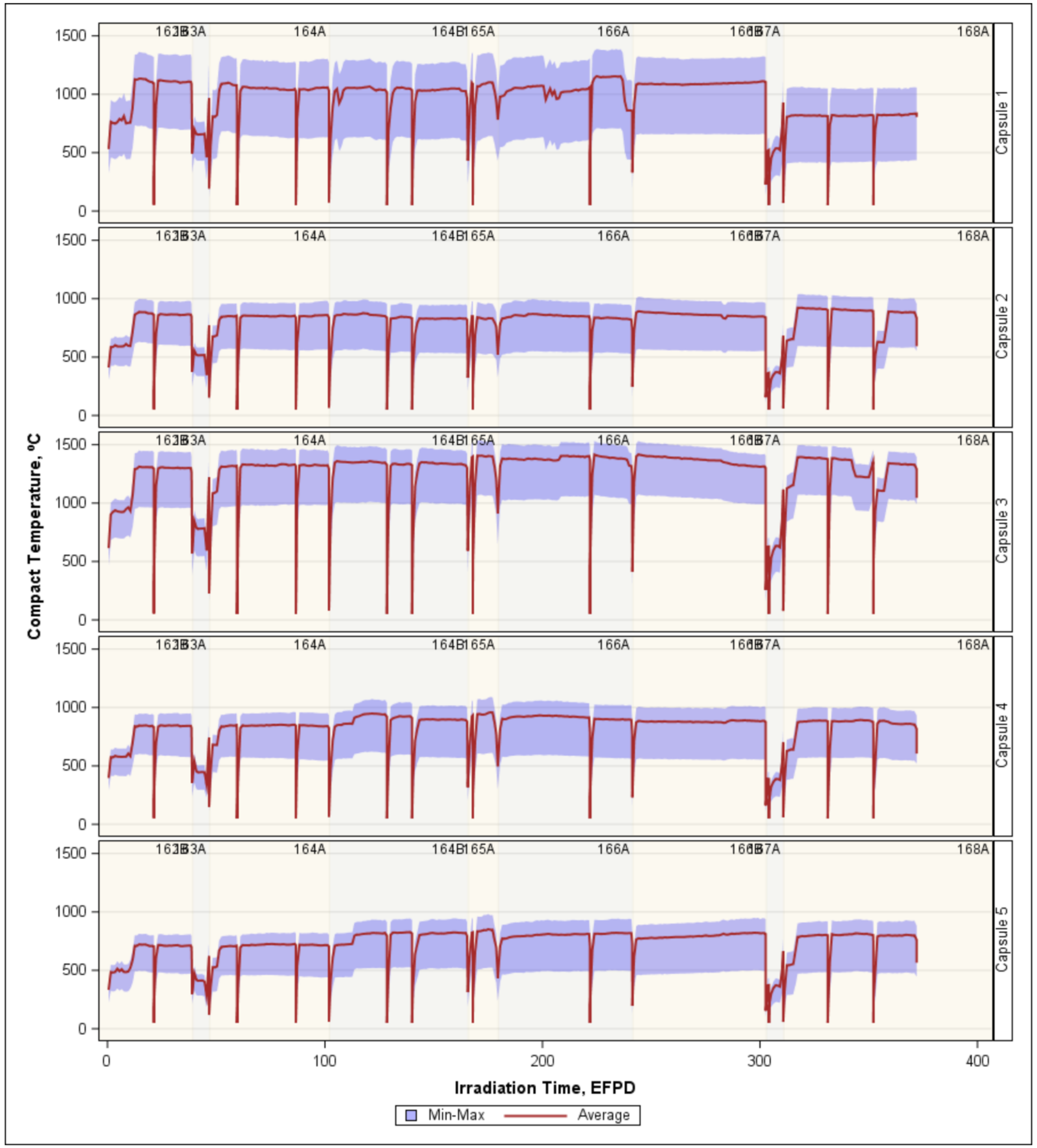
J. Sterbentz, "JMOCUP Physics Depletion Calculations for the As-Run AGR-5/6/7 TRISO Particle Experiment in ATR Northeast Flux Trap," ECAR-5321, December 2020

Burnup Distribution



- Limited compacts with intermediate burnup (11.5 – 13.5 %FIMA)
- Only Capsules 1 and 5 had burnup <12 %FIMA

AGR-5/6/7 Fuel Temperatures

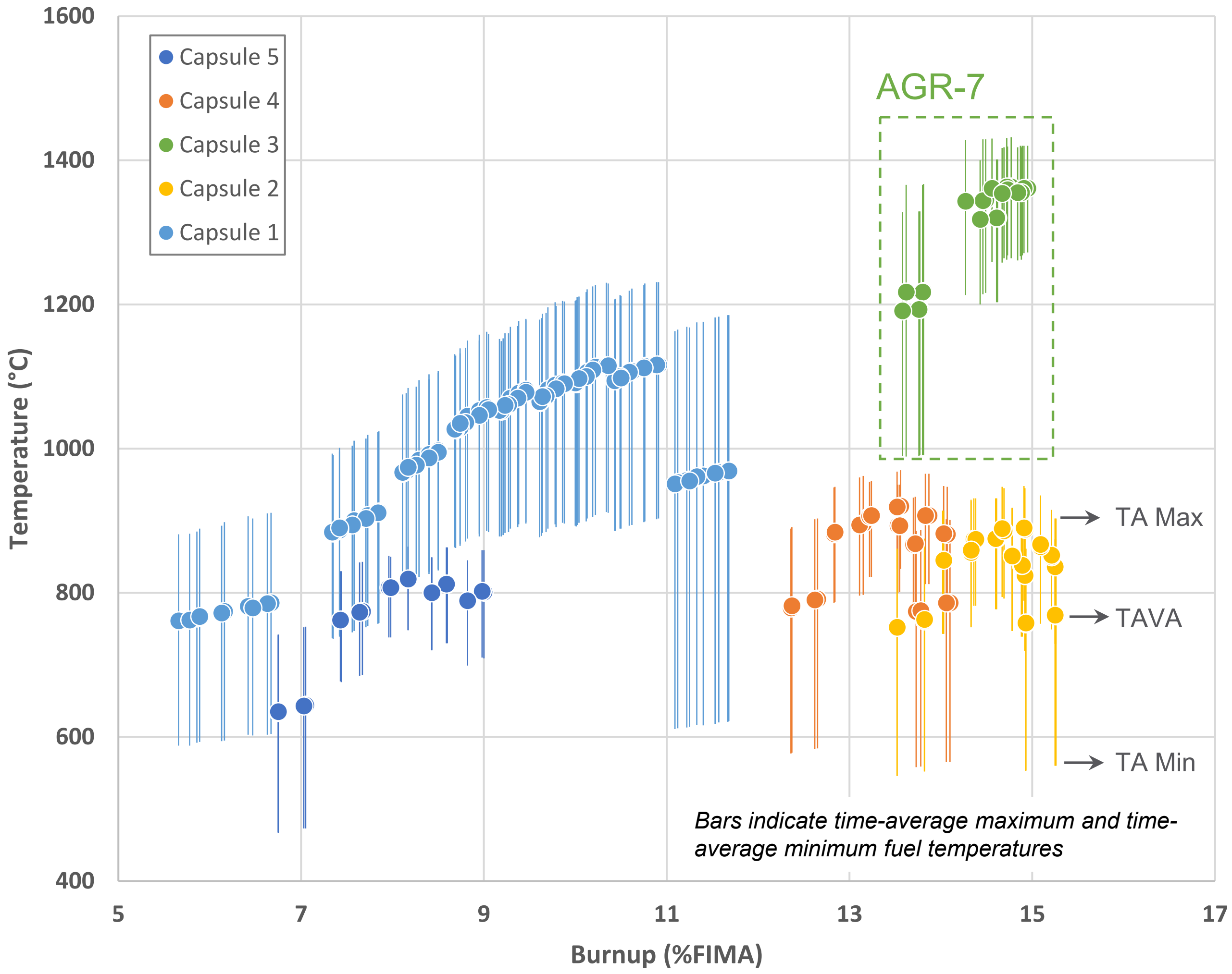


Thermal model assumes 100% He in Cycle 168A which gives lowest fuel temperatures

Low bias in predicted TC temperatures indicates possibility of higher fuel temperatures

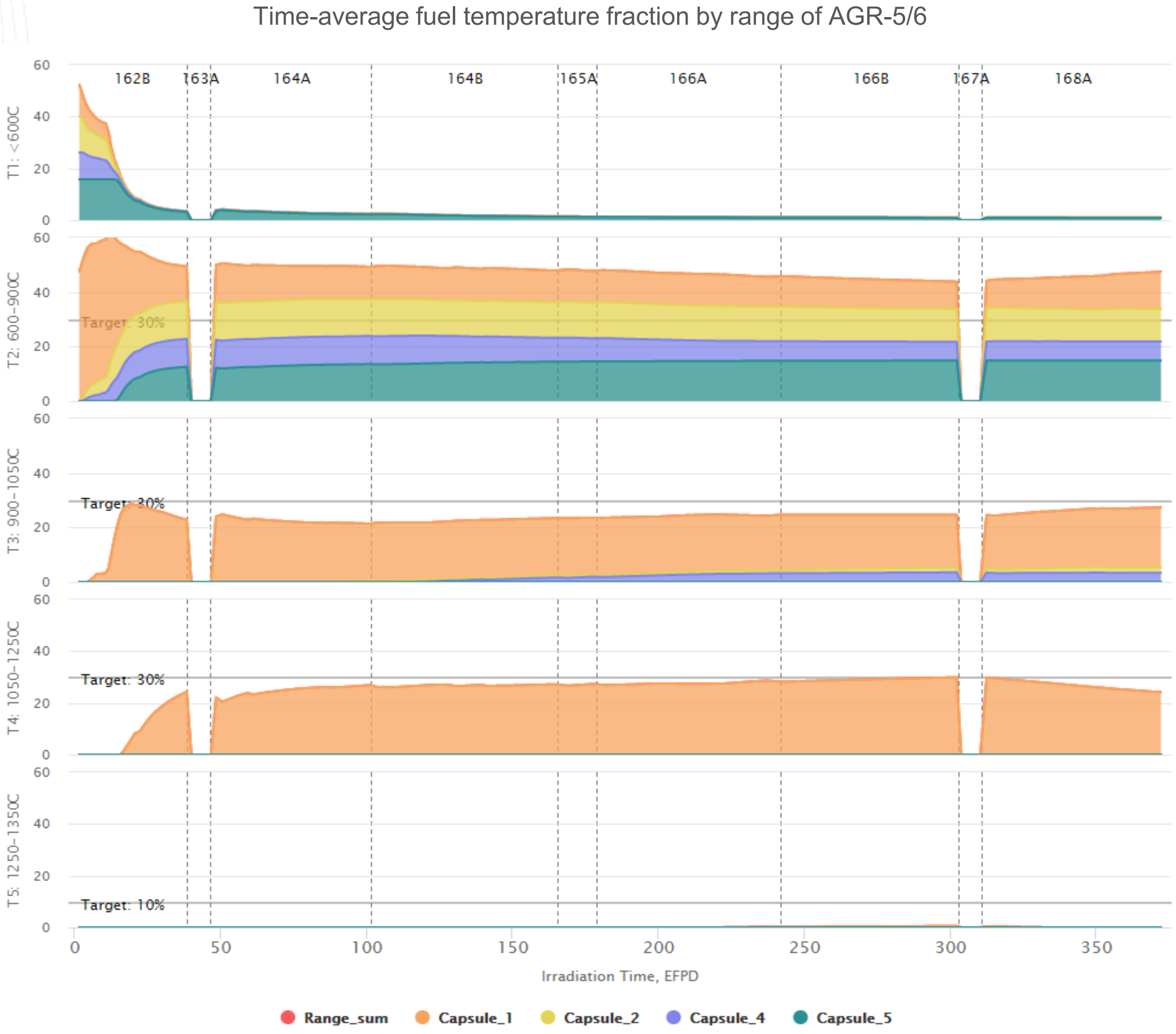
(J. Palmer et al., "Summary of Thermocouple Performance in the Advanced Gas Reactor Experiment AGR-5/6/7 During Irradiation in the Advanced Test Reactor," ANNIMA2021-04-196, June 2021)

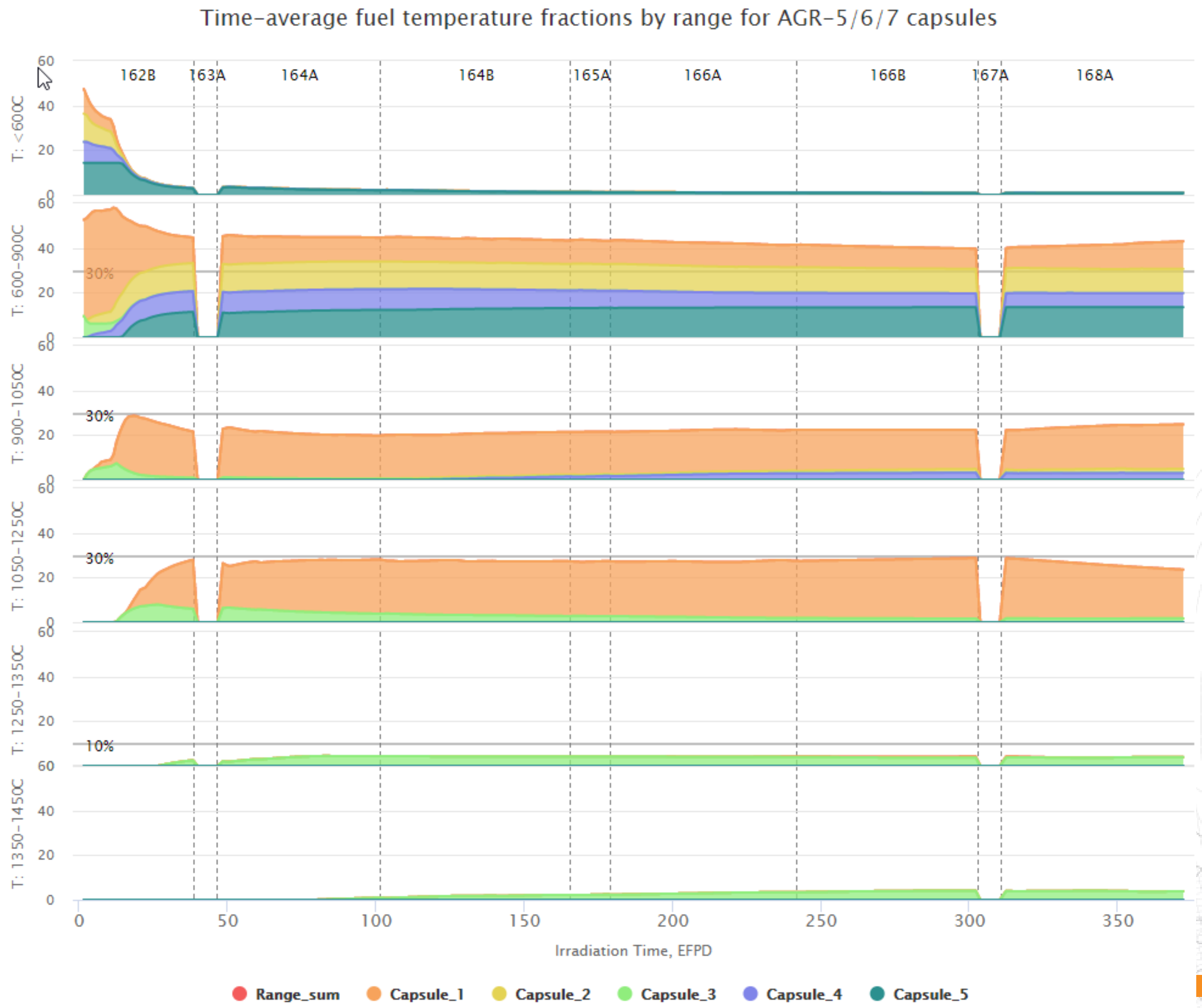
Time Averaged Fuel Temperatures



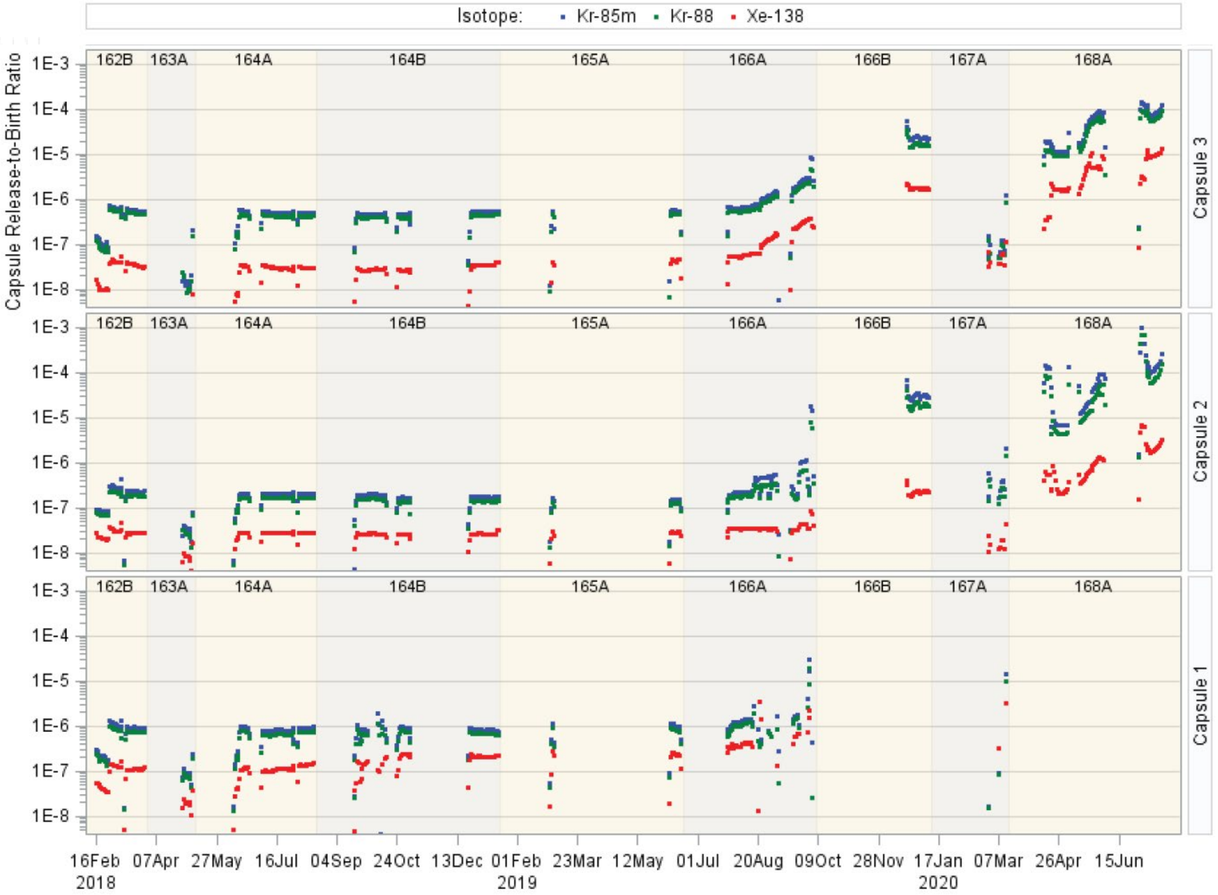
- Fuel temperature time averaging removes low-power PALM cycles (163A and 167A)
- Capsule 1 was relied upon for most of the upper temperature range for AGR-5/6
- Peak time-average temperature: 1432°C
  - Target: 1500 ±50°C
  - AGR-2: 1360°C

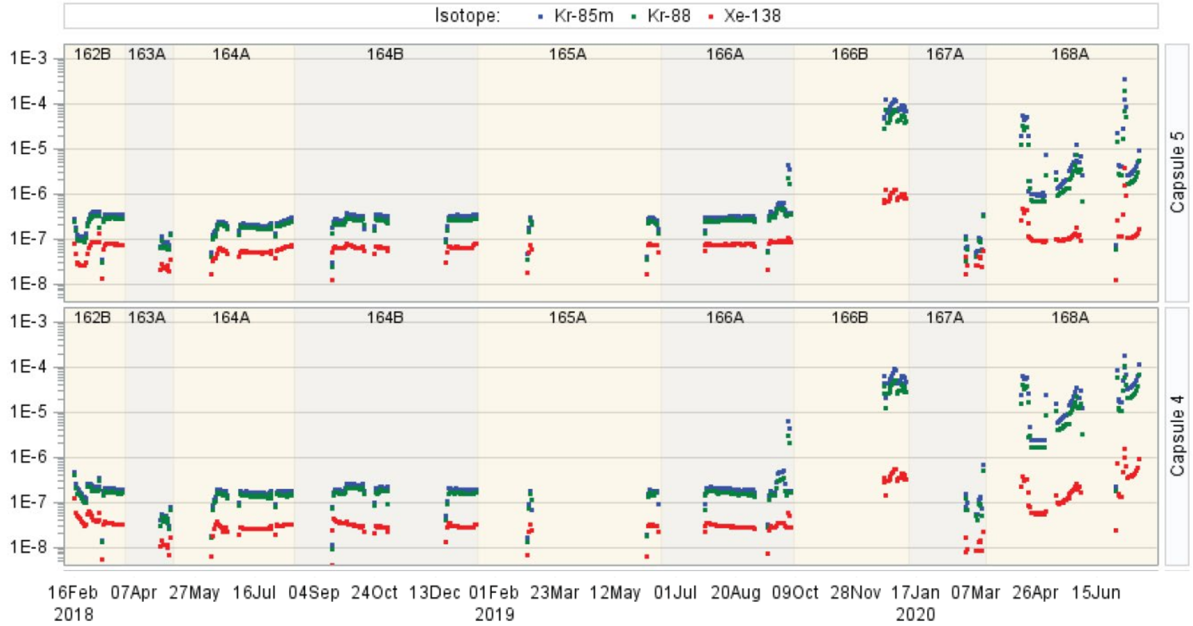
AGR-5/6/7 Temperature Distributions





Fission Gas Release-to-Birth Ratios





- Kr-85m R/B in early cycles was stable at ~10^{-7} to 10^{-6}
- Values unreliable from Cycle 166A onward due to leakage from Capsule 1

D. Scates, “Release-to-Birth Ratios for AGR-5/6/7 Operating Cycles 162B–168A,” ECAR-5352

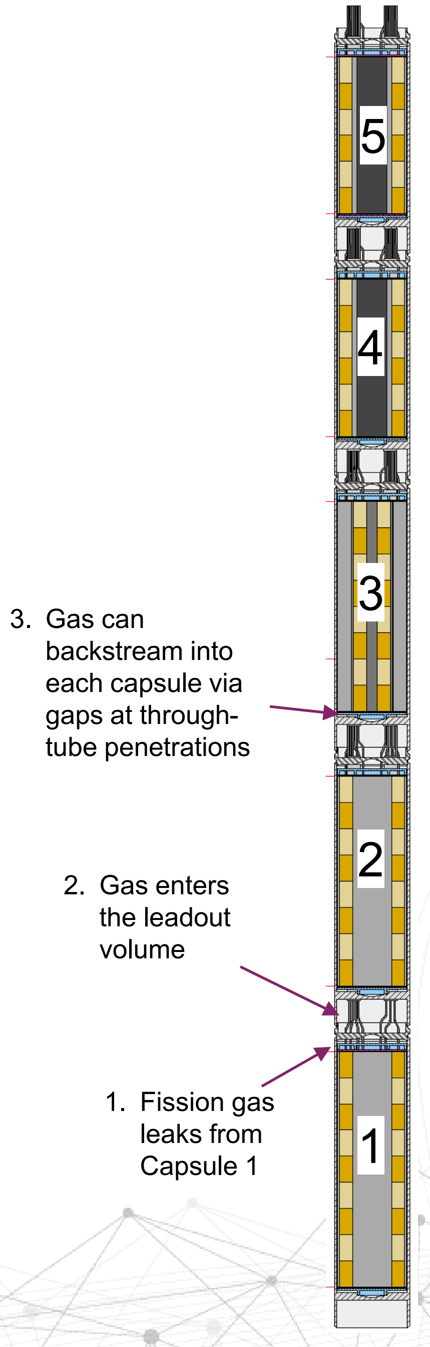
Quantifying In-Pile Particle Failure

Approach

- Utilize combined fission gas data streams to analyze for particle failures
  - Gross gamma spectra (peaks related to particle failure)
  - Isotopic gamma spectra peaks
  - R/B data (compare measured R/B with predicted values)

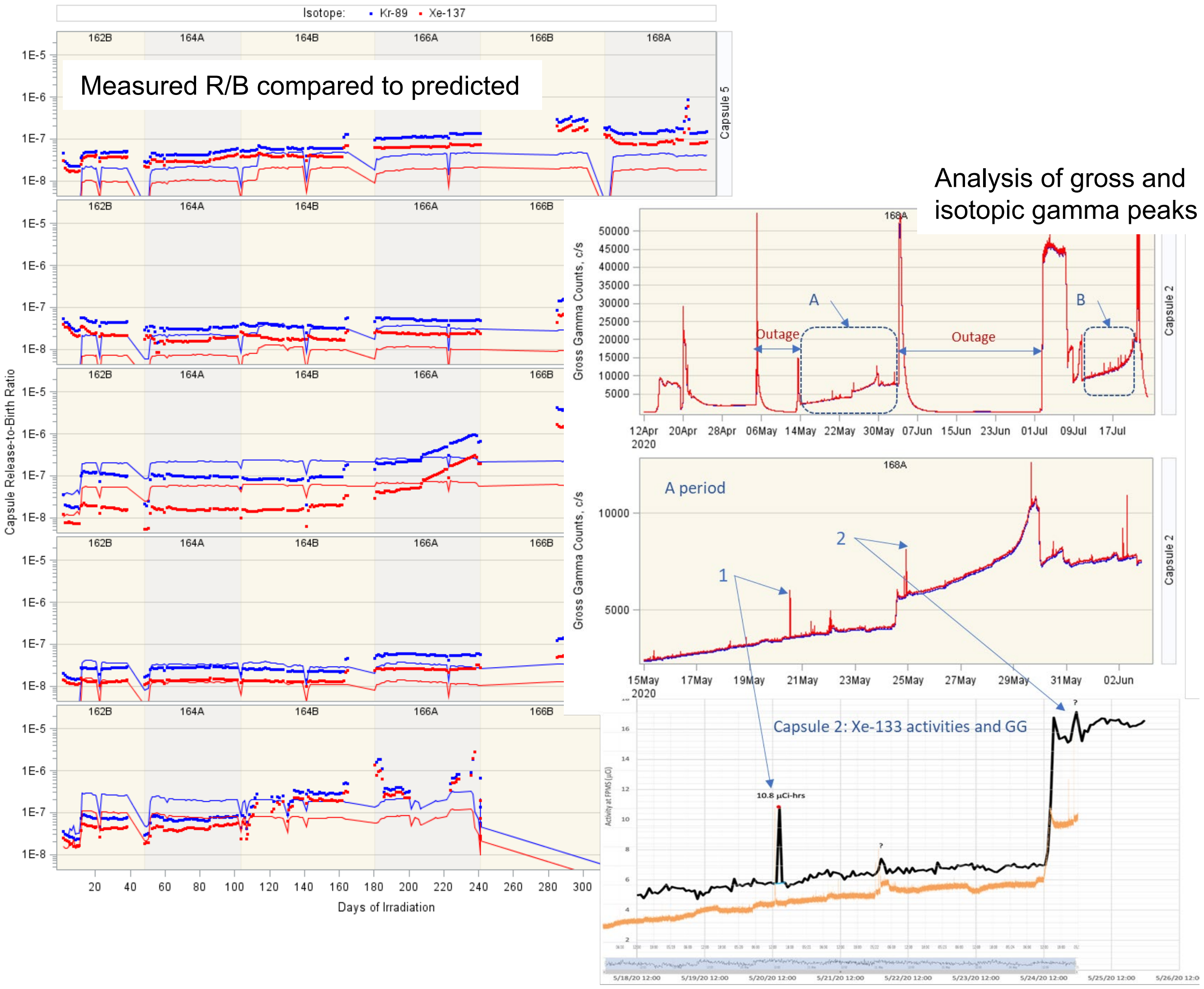
Challenges

- Capsule 1: No gas flow after Cycle 166A (no direct fission gas measurement)
- Capsules 2 – 5: In-leakage of gas from Capsule 1 impacts R/B analysis
- Uncertainty in starting number of exposed kernels
- Uncertainty in temperature of as-fabricated exposed kernel defects and in-pile failures, which impacts fission gas release
- Peaks in gamma spectra often appear to be unrelated to particle failure events



B. Pham et al., "AGR 5/6/7 Irradiation Test Final As-Run Report," INL/EXT-21-##### (DRAFT)

Particle Failure Analysis



Preliminary estimate of in-pile particle failures

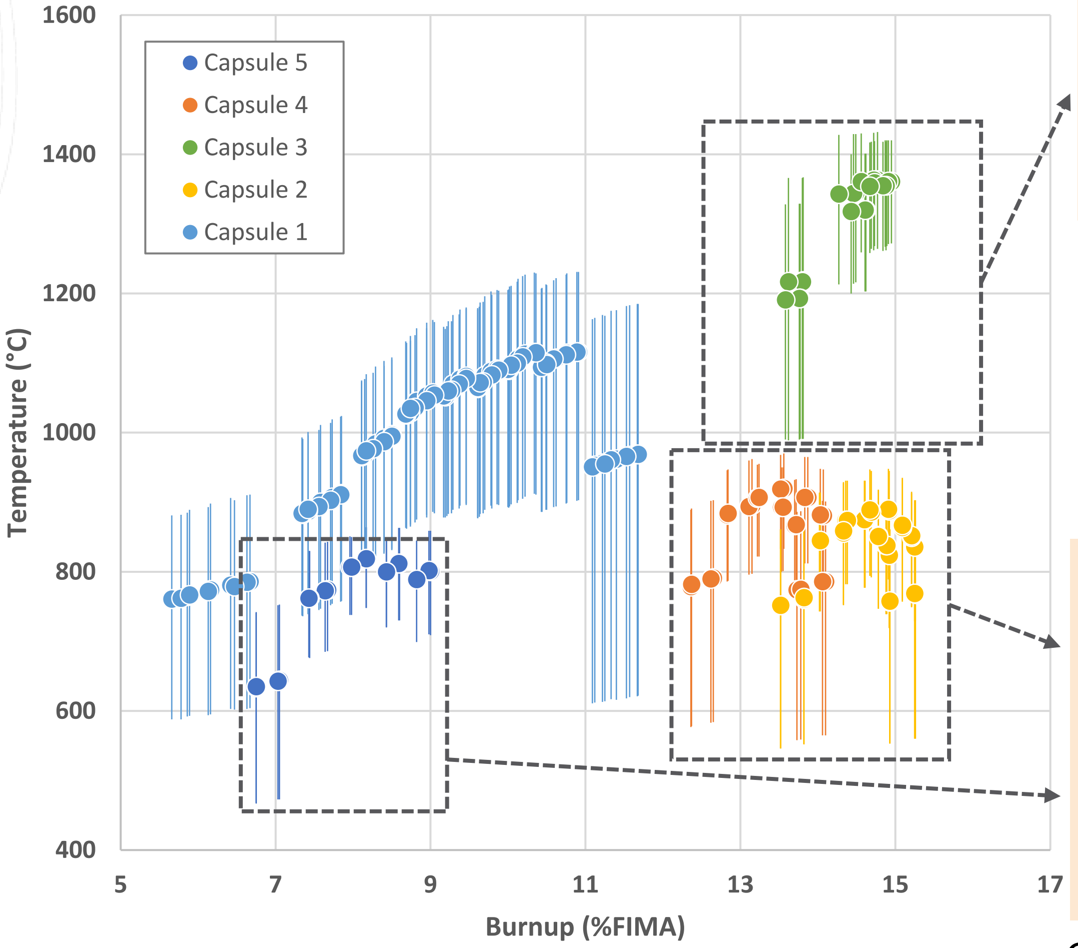
Capsule	# Failures
1	180 – 440 near the end of Cycle 166A; unknown thereafter
2	1 – 4 in Cycle 168A
3	≤15 in Cycle 168A
4	0
5	0

B. Pham et al., “AGR 5/6/7 Irradiation Test Final As-Run Report,” INL/EXT-21-##### (DRAFT)

Considerations for Postirradiation Examination

- Implications for Capsule 1 fuel use
  - Most/all compacts are likely highly contaminated with fission products (Cs, Sr, Eu) from failed particles
    - This capsule not useful for evaluating fission product release from intact fuel (capsule mass balance, DLBL, safety testing)
  - Particle gamma counting still useful
  - Particle microanalysis still useful
  - Safety tests to determine particle failure – need compacts with zero failures (still probably unsuitable for assessing fission product release from intact fuel)
- Can we screen specific compacts for particle failure and use the “good ones”?
  - Short-duration heating in FACS to assess presence of particle failures (pass/fail)
- Compromised compacts
  - Testing in AMIX to assess impact of oxidation on failed fuel

In-Pile Particle Failure Statistics



- 24 fuel compacts
- 54,000 particles
- Likely several particle failures

Current estimated particle failure fraction (upper limit @ 95% confidence): ~5 – 40 $\times 10^{-5}$

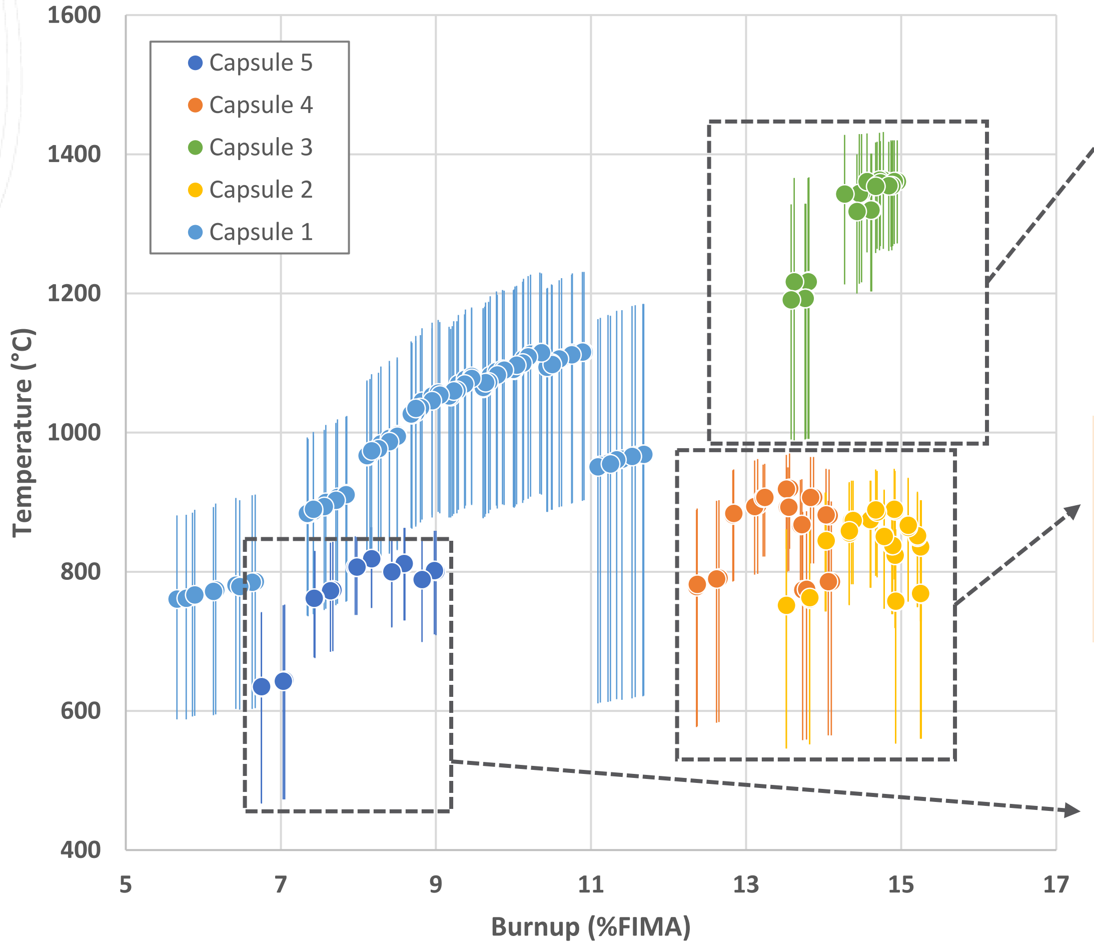
- 80 fuel compacts
- 207,000 particles
- Highest TAVA temperature = 919°C
- Estimated 1 – 4 particle failures in Capsule 2

Current estimated particle failure fraction (upper limit @ 95% confidence): ~2 – 4 $\times 10^{-5}$

- Original experiment specification called for ~500,000 particles irradiated under normal operating conditions (*SPC-1749*)
- If Capsule 1 fuel is eliminated from consideration due to the operational issues, there are still sufficient particle statistics, but irradiation temperatures are much too low
- Obtaining failure statistics over a representative temperature range will require screening out Capsule 1 compacts with external causes for particle failure

J.T. Maki, "AGR 5/6/7 Irradiation Test Specification," SPC-1749, 2015

Post-Irradiation Safety Testing Statistics



- 24 fuel compacts
- 54,000 particles
- Likely several particle failures

- 56 fuel compacts
- 125,000 particles
- Possible small number of failures (Capsule 2)

- 24 fuel compacts
- 81,000 particles
- Ample low-temperature, low-burnup compacts for testing

- Original experiment specification called for ~50,000 particles for 1600°C safety testing and ~20,000 particles for testing at 1700 – 1800°C (*SPC-1749*)
- Capsule 2 – 5 particle numbers are sufficient, but temperature distribution is problematic
- May require salvaging useable compacts from Capsule 1

J.T. Maki, "AGR 5/6/7 Irradiation Test Specification," SPC-1749, 2015

Summary

- AGR-5/6/7 irradiation is complete and PIE is underway
- Reporting is still in progress
- Time-average temperatures: 467 – 1432°C
- Burnup: 5.7 – 15.3% FIMA
- Preliminary estimate of particle failure indicate zero failures in Capsules 4 and 5, 1 – 4 in Capsule 2, and as many as 15 in Capsule 3
- Cause of Capsule 1 particle failures is not yet known

Idaho National Laboratory