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AGR-5/6/7 Capsule 1 Investigation

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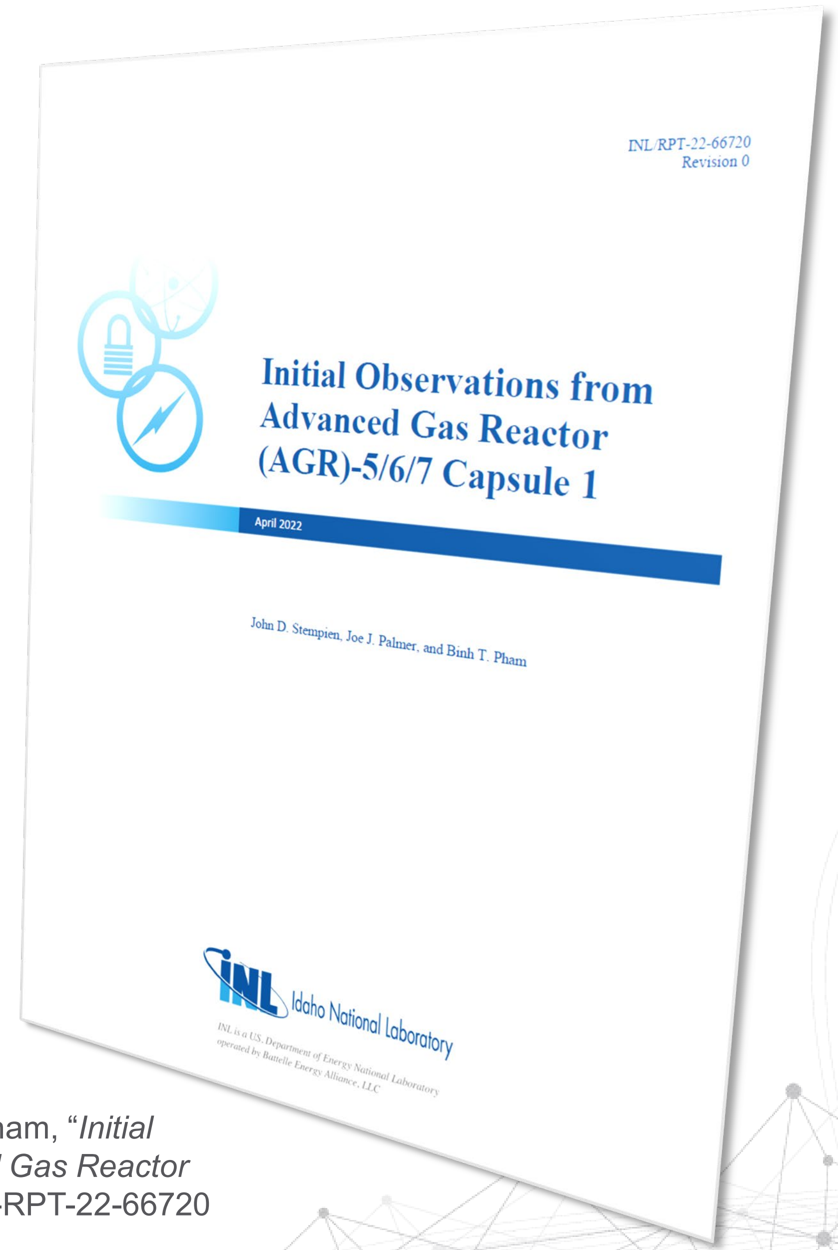
ART Advanced Reactor Technologies
GAS-COOLED REACTORS

Overview

- AGR-5/6/7 Background
- Test train and fuel behavior observations
- PIE observations
- Capsule 1 design issues
- Conclusions and future work



J. Stempien, J. Palmer, B. Pham, "*Initial Observations from Advanced Gas Reactor (AGR)-5/6/7 Capsule 1*," INL-RPT-22-66720

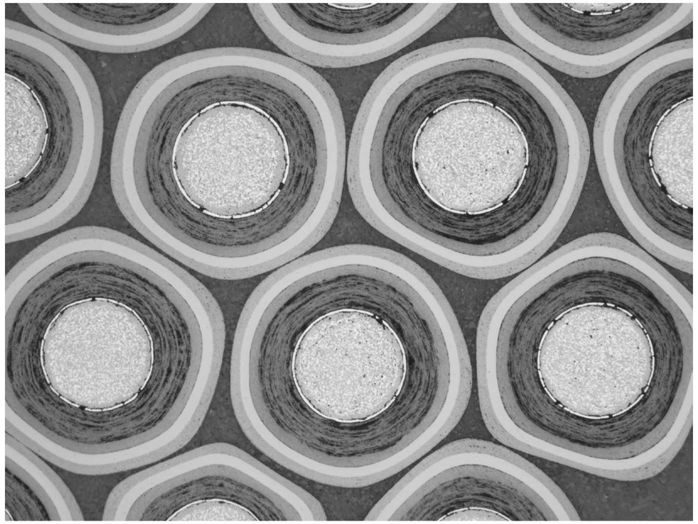
AGR-5/6/7 Fuel

- Fuel fabricated at pilot scale at BWXT
- Coated particles similar to AGR-2
- New matrix fabrication process
  - Novolac phenolic resin instead of resol phenolic resin
  - No organic solvents used
  - Jet milling process
- AGR-5/6/7 is the qualification experiment for LEUCO TRISO fuel fabricated at the pilot scale

Kernels

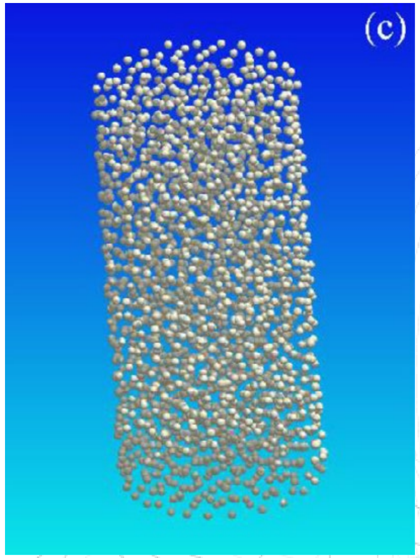
Kernel composition	UCO
Kernel diameter	426 µm
^{235}U enrichment	15.5%

Coated particles



J52R-16-98005 Sample 1501

Compacts



Particle packing fractions	25%	38%
Matrix density	1.75 g/cm^3	1.77 g/cm^3
Mean U loading	0.89 gU	1.36 gU

Defects

PF	DUF 95% confidence (mean)	EKF 95% confidence (mean)
40%	≤5.7×10^{-6} (5.0×10^{-6})	≤8.3×10^{-5} (5.4×10^{-5})
25%	≤5.6×10^{-6} (5.1×10^{-6})	≤3.5×10^{-5} (7.3×10^{-6})

DUF: Dispersed uranium fraction
EKF: Exposed kernel fraction

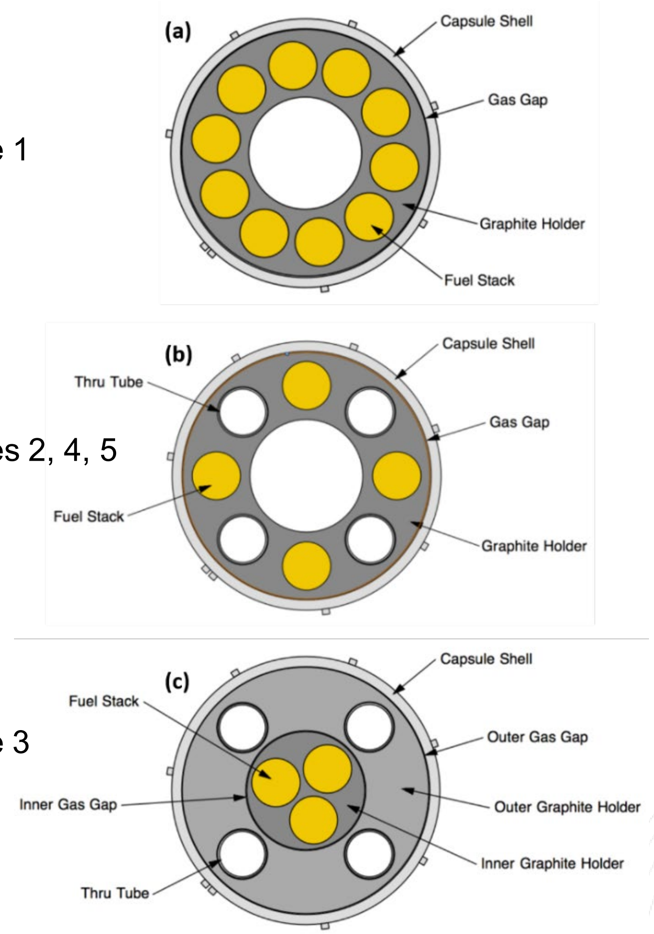
AGR-5/6/7 Irradiation

- Fuel qualification and performance margin test
- 194 fuel compacts (~570,000 particles)
- Irradiated Feb 16, 2018 to July 22, 2020 (361 EFPD)
- Burnup: **5.7 – 15.3% FIMA**
- Fast fluence: **1.6 – 5.6×10^{21} n/cm^2** (E > 0.18 MeV)
- Time-average temperatures: **467 – 1432°C**

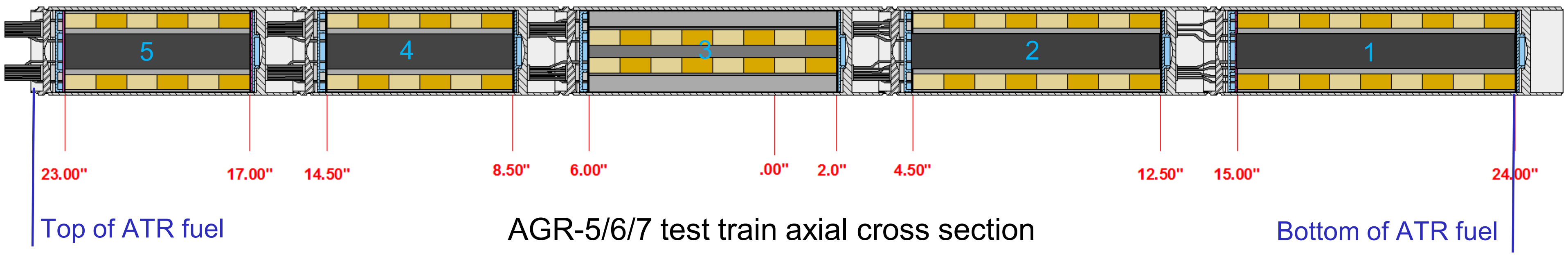
Capsule 1

Capsules 2, 4, 5

Capsule 3



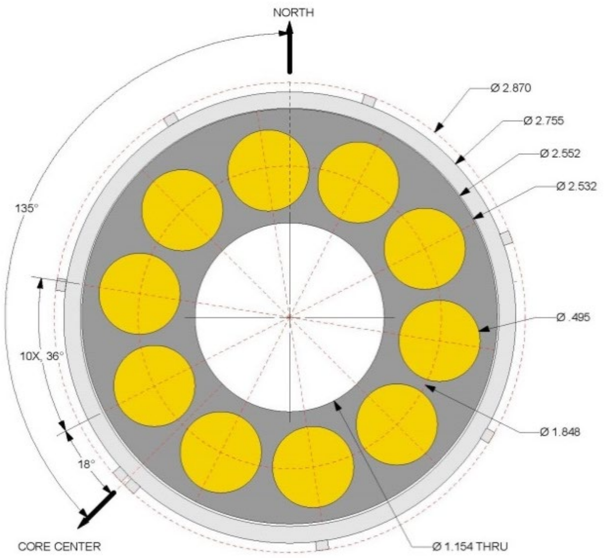
Capsule 5	Capsule 4	Capsule 3 (AGR-7)	Capsule 2	Capsule 1
24 compacts	24 compacts	24 compacts	32 compacts	90 compacts
81,400 particles	52,700 particles	54,400 particles	72,400 particles	309,000 particles

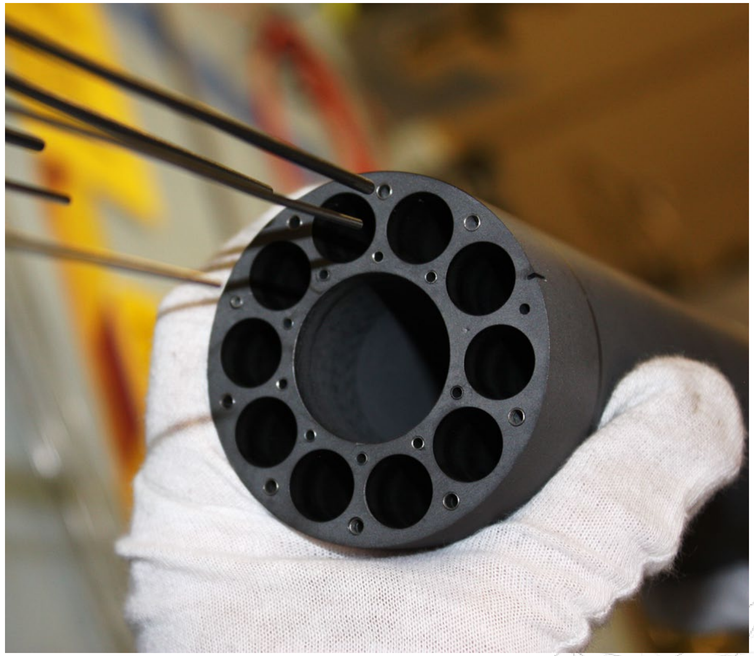


AGR-5/6/7 test train axial cross section

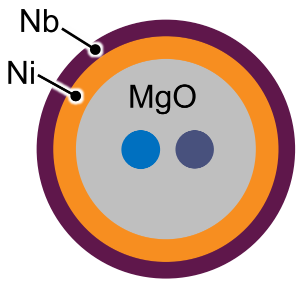
Capsule 1

- Test configuration allowed this capsule to have no through tubes, and therefore a large volume for fuel
- 309,000 particles (~54% of all particles in the experiment)
- All fuel compacts were 38% packing fraction
- Heat flux was particularly high at the top of Capsule 1 due to the large fuel loading

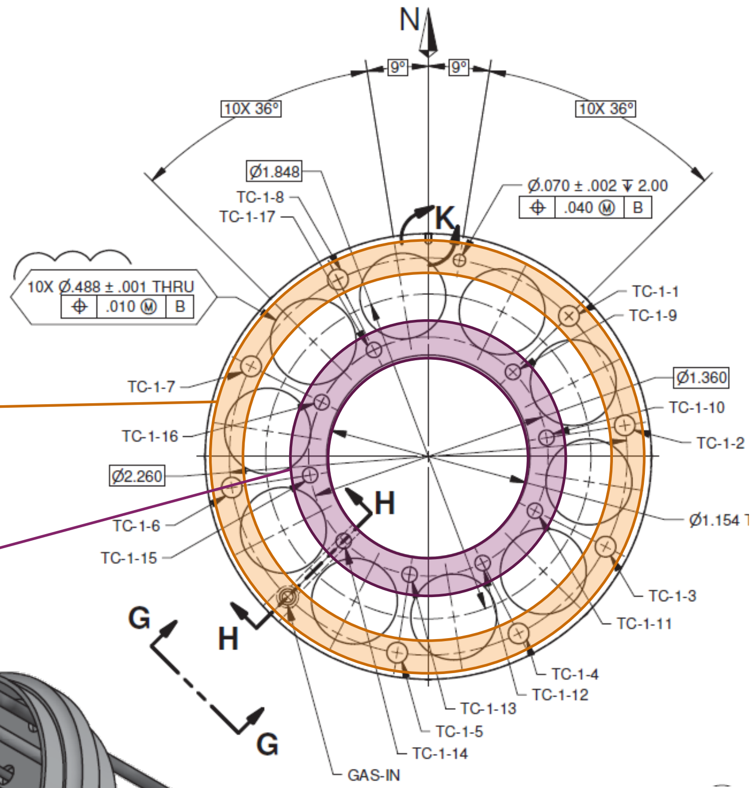


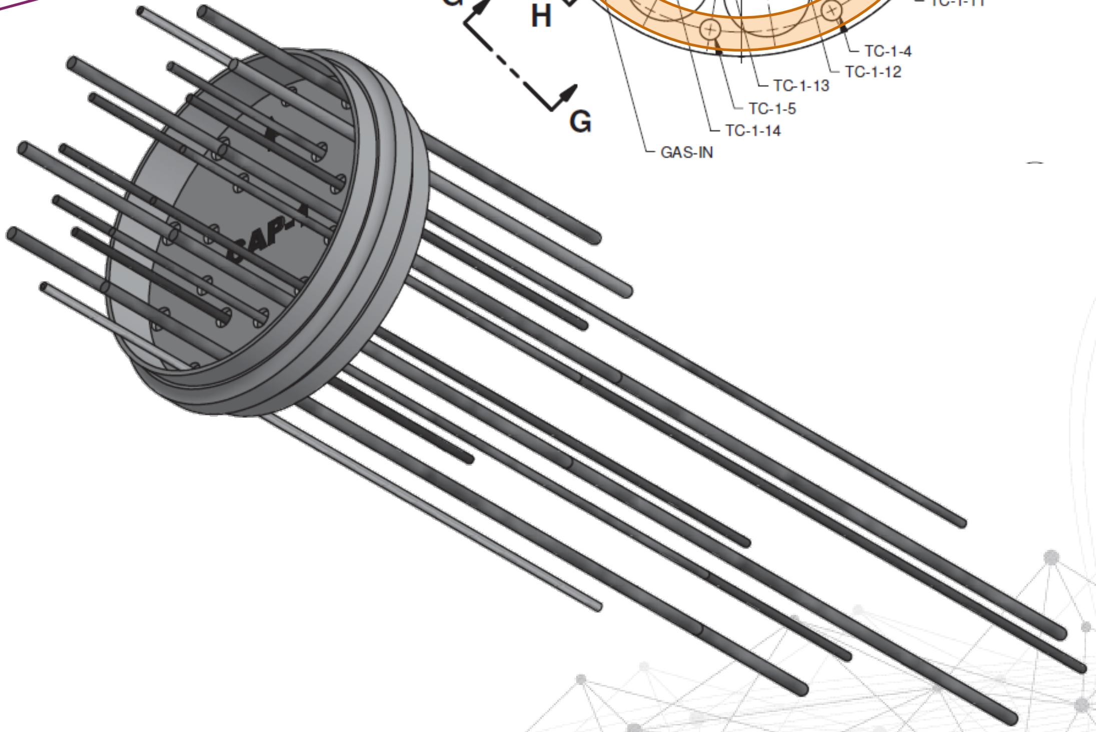


Capsule 1 Thermocouples



- 17 thermocouples
- Cambridge Type N in outer periphery*
  - Ni/Cr/Si/Mg thermoelement wire
  - MgO powder insulation
  - Ni sheath
  - Nb sleeve
- HTIR in inner region
  - Mo/Nb thermoelement wire
  - Al_2O_3 insulation
  - Nb sheath
  - Mo sleeve
- TCs embedded in graphite and varying depths to register temperatures throughout the capsule





* One Type N TC had $MgAl_2O_4$ insulation, Inconel 600 sheath, Nb sleeve

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Capsule 1 Gas Flow Issues

- Gas line plugging starting in Cycle 164B
- Gas line breaks/cracks followed in Cycle 164B
- Low flow for 164B and 165A in an attempt to optimize the operating conditions for the test train
- Intermittent flow in Cycle 166A

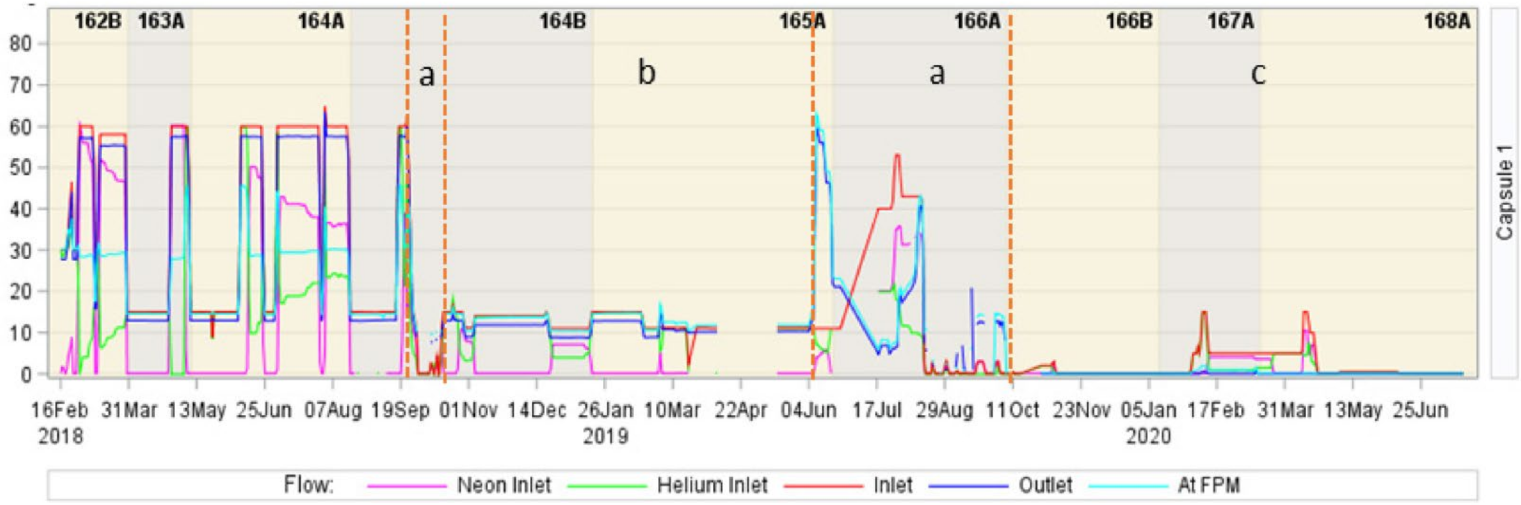

Figure 7. Capsule sweep-gas flow rates (in standard cubic centimeters per minute [SCCM]) with Capsule 1 flow history: (a) intermittent flow, (b) stabilized low flow rate, and (c) mostly isolated gas line with an unsuccessful attempt to reestablish flow during Cycles 167A and 168A.

B. Pham et al., AGR-5/6/7 Irradiation Test Final As-Run Report, INL/EXT-21-64221, Sep 2021

➢ M. Nelson, “AGR-5/6/7 Gas System – Analysis of Various Anomalies Encountered During Irradiation,” ECAR-5114, Sep 2020

Capsule 1 Fission Gas Release: R/B Data

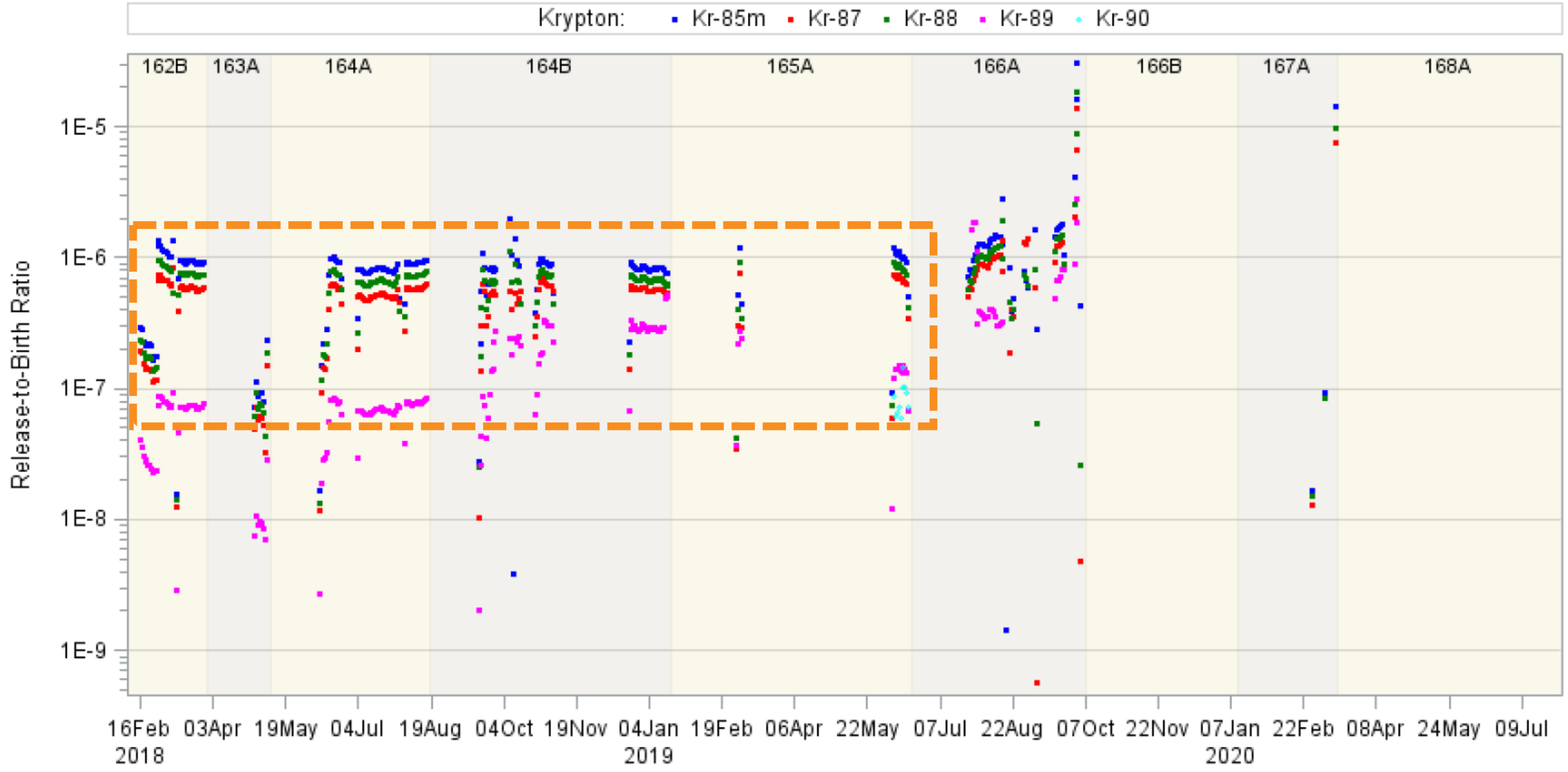

Figure 9. Capsule 1 measured R/B for krypton isotopes.

- Capsule 1 ^{85m}Kr R/B prior to Cycle 166A was consistent with predictions based on known particle defect and dispersed uranium fractions (~9×10^{-7})
- Lack of data during 166B – 168A due to lack of flow in Capsule 1

J. Stempien, J. Palmer, B. Pham, "*Initial Observations from Advanced Gas Reactor (AGR)-5/6/7 Capsule 1*," INL-RPT-22-66720

Capsule 1 Fission Gas Release

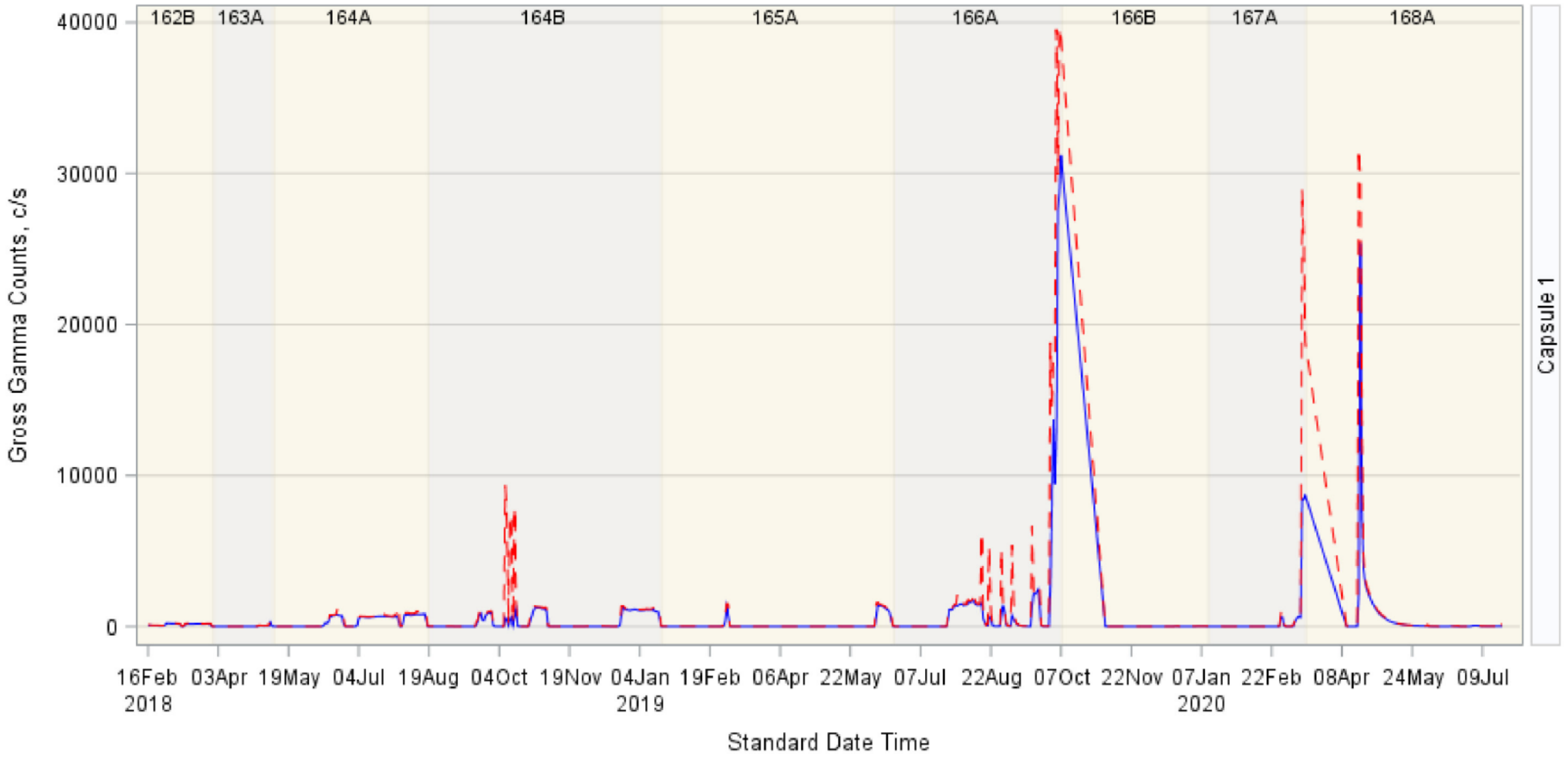

Figure 11. Capsule 1 daily average (blue line) and maximum (red line) GG counts.

- Large increase in fission gas release starting Sep 30, 2019
- Gas flow terminated Oct 6, 2019
- Evidence of hundreds of particle failures prior to the termination of flow and detector saturation

J. Stempien, J. Palmer, B. Pham, "*Initial Observations from Advanced Gas Reactor (AGR)-5/6/7 Capsule 1*," INL-RPT-22-66720

Experiment Approach Following Cycle 166A

- Gas flow in Capsule 1 was terminated at the end of Cycle 166A and the capsule remained isolated for most of the subsequent cycles
- Attempts were made to fill Capsule 1 with 100% He gas during the final cycle (168A) to maintain temperature as low as possible, but gas exchange with the leadout during the last cycle resulted in unknown Capsule 1 gas mix and high calculated fuel temperature uncertainty
- Capsule 1 end-of-irradiation fission gas release is not known and total particle failure count cannot be reliably estimated

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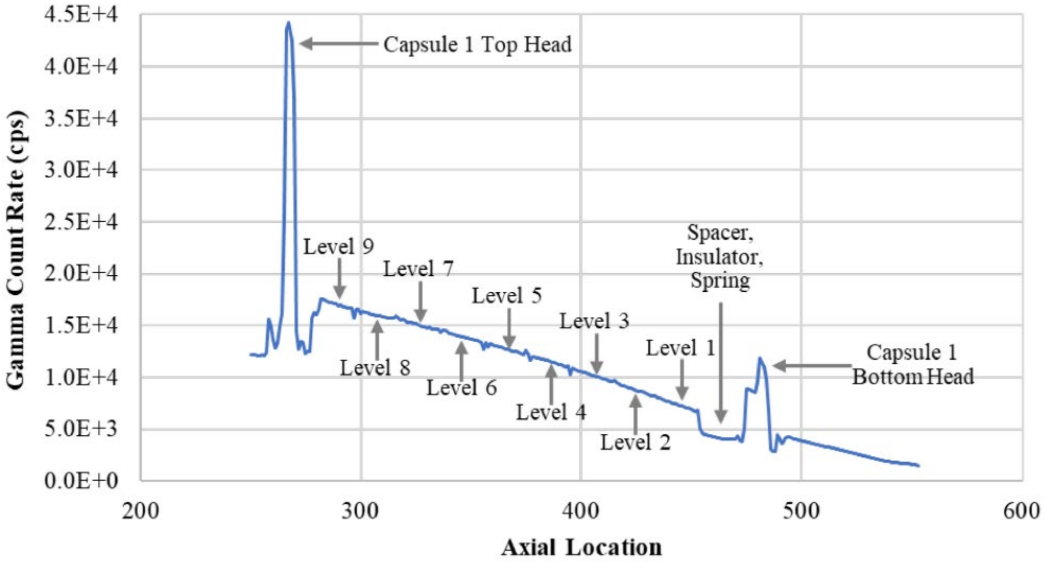
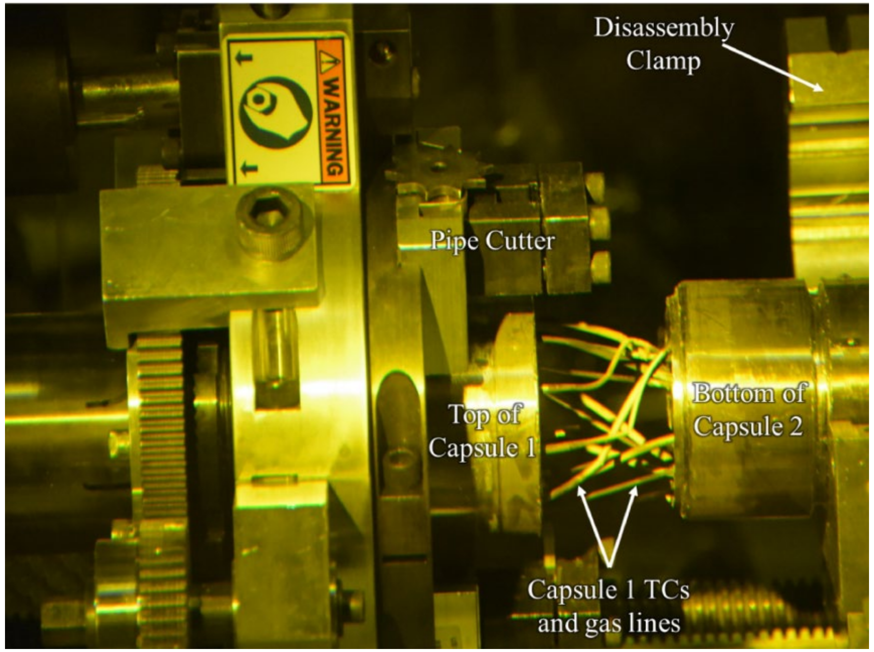
Initial Non-destructive Examination

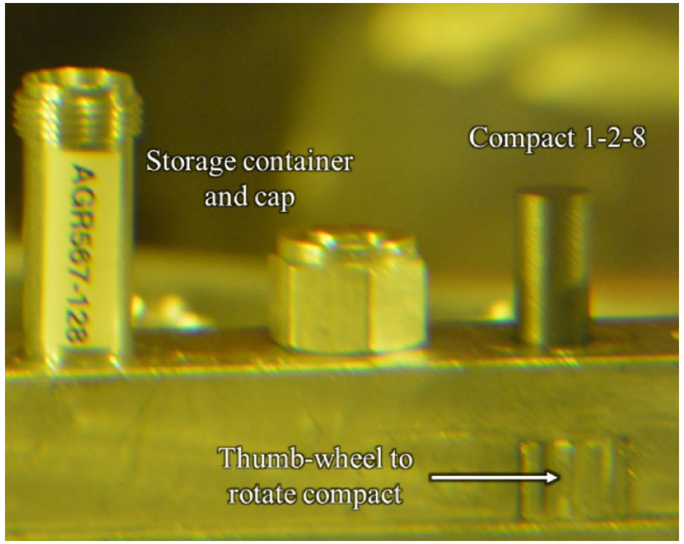
- Test train shipped from ATR to MFC in April 2021
- Nondestructive examination did not reveal discernable damage to Capsule 1 internals
  - Visual examination
  - Neutron radiography
  - Gamma spectrometry

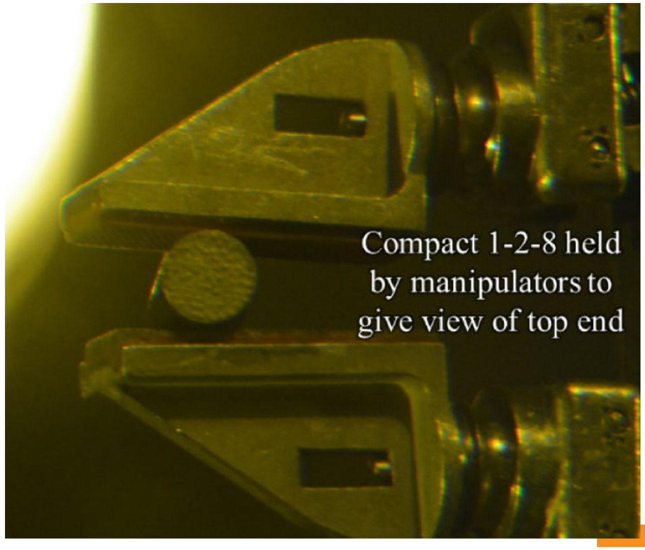


Capsule 1 Disassembly and Component Visual Examination

- Capsules completely disassembled
- All fuel compacts collected and exhibited no observable structural damage
- Inside of Capsule 1 shell appears unremarkable

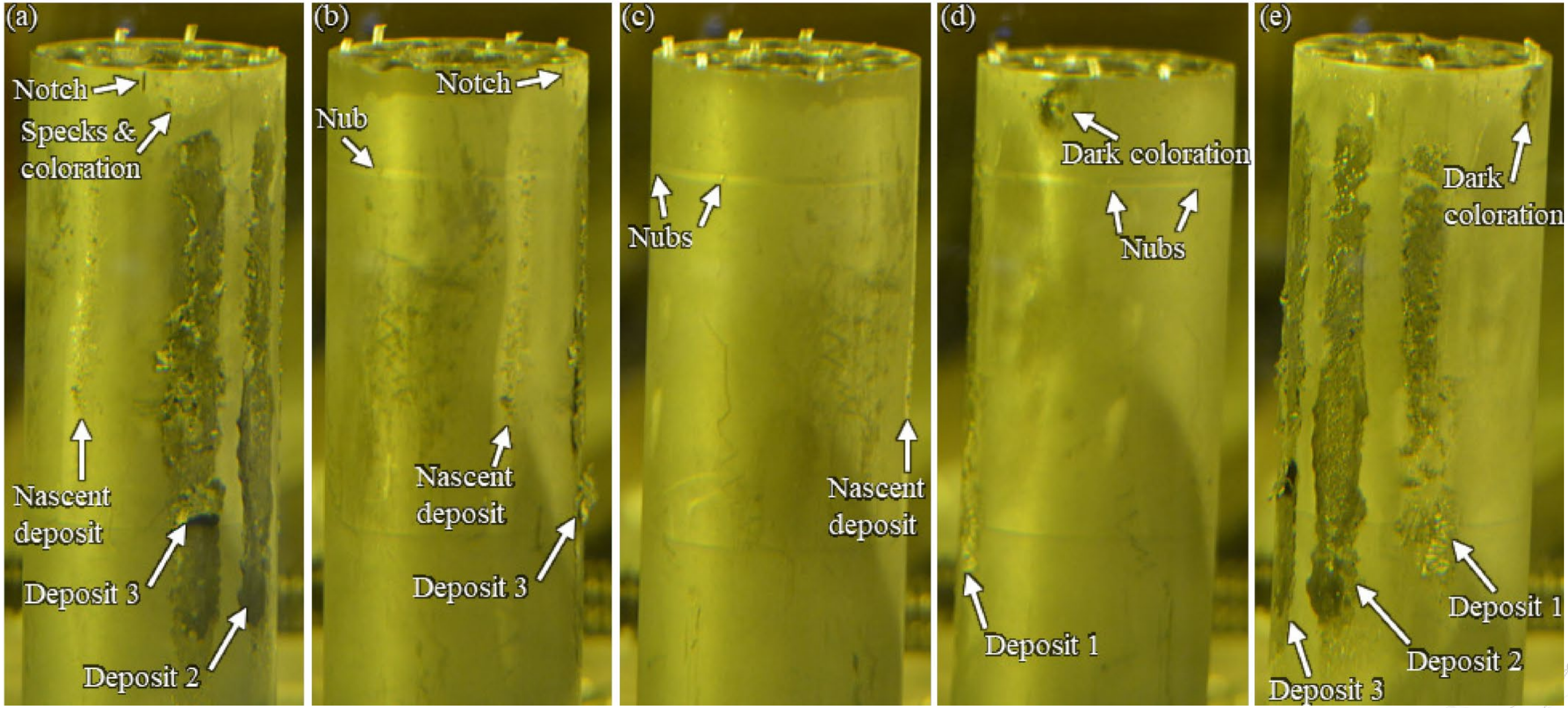






Graphite Fuel Holder 1

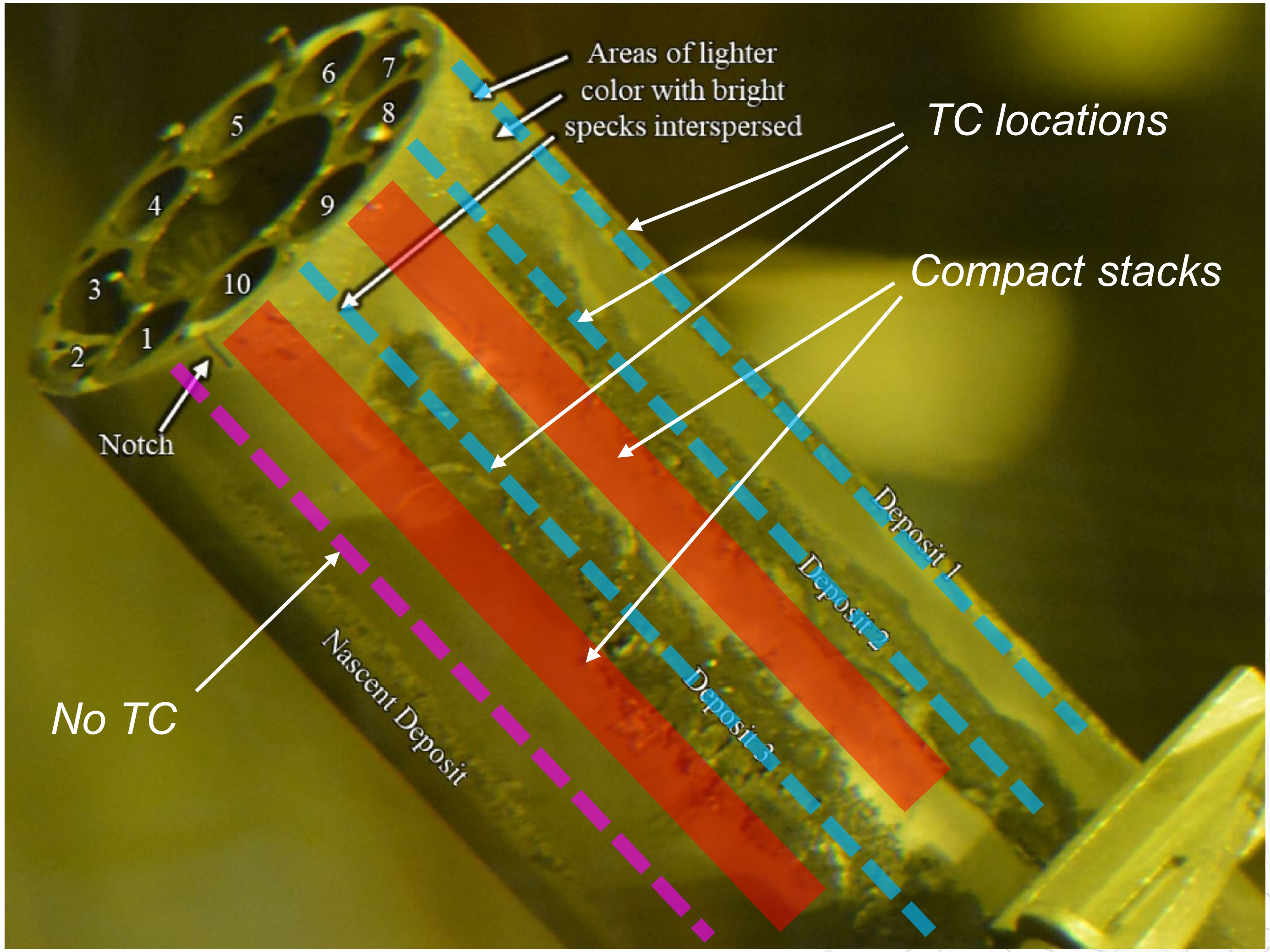
- Foreign material found on the surface of the Capsule 1 fuel holder in vertical strips



J. Stempien, J. Palmer, B. Pham, "*Initial Observations from Advanced Gas Reactor (AGR)-5/6/7 Capsule 1*," INL-RPT-22-66720

Graphite Fuel Holder 1

- Foreign material is aligned with location of TCs, not compacts
- Material is located in the upper ~2/3 of the holder where temperatures were highest



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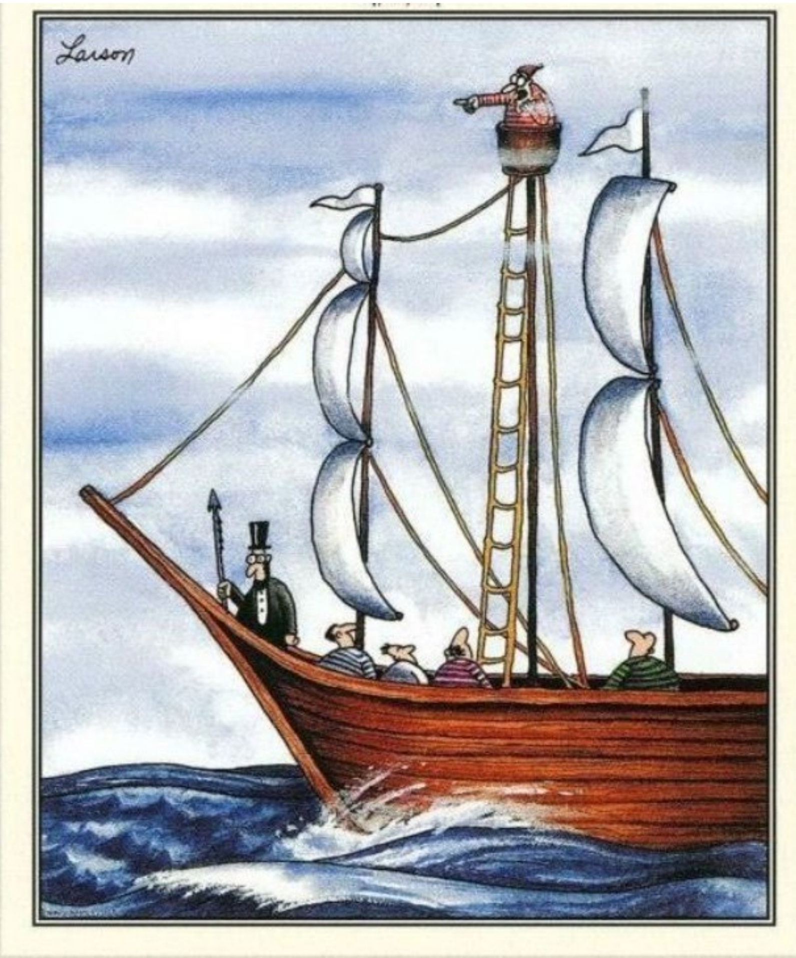
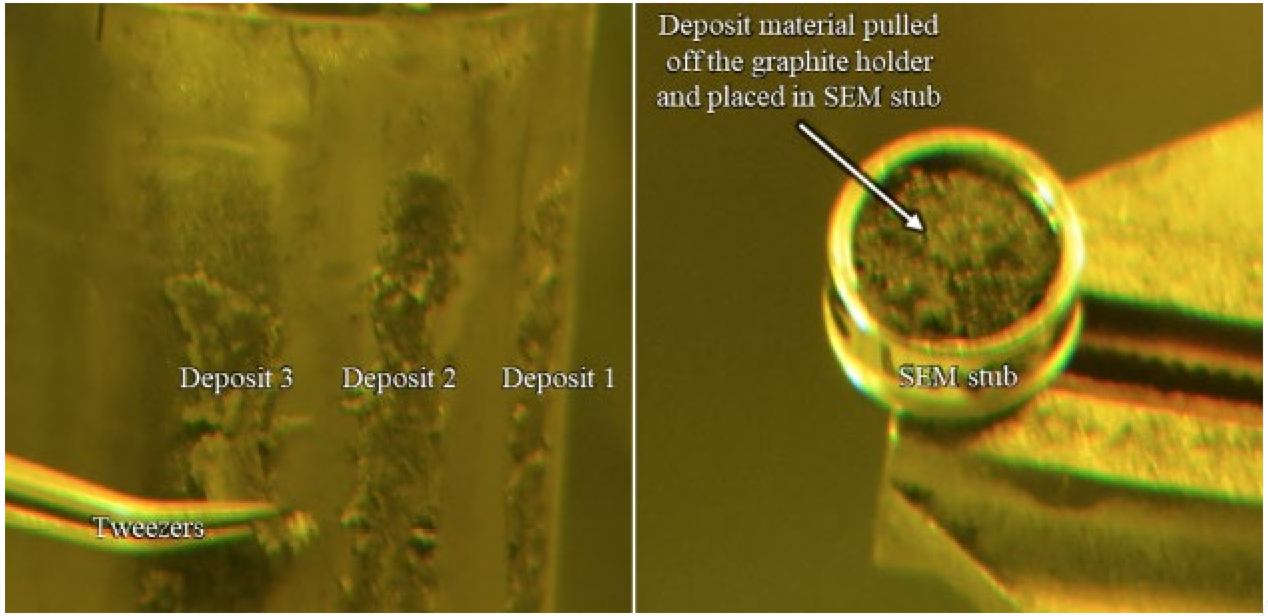


"The white whale! The whiiiiiiite wh ... no, no ... my mistake! ... A black whale! A regular, blaaaaaack whale!"

Surface Material Analysis

- Surface material was sampled and analyzed with gamma spectrometry and EDS
- *Gamma spec*: activity dominated by Co-58 and Co-60 (activation products of stable Ni) and fission products Cs and Eu
- *EDS*: Ni, Cr, MgO
- Confirms TC origin for the surface material



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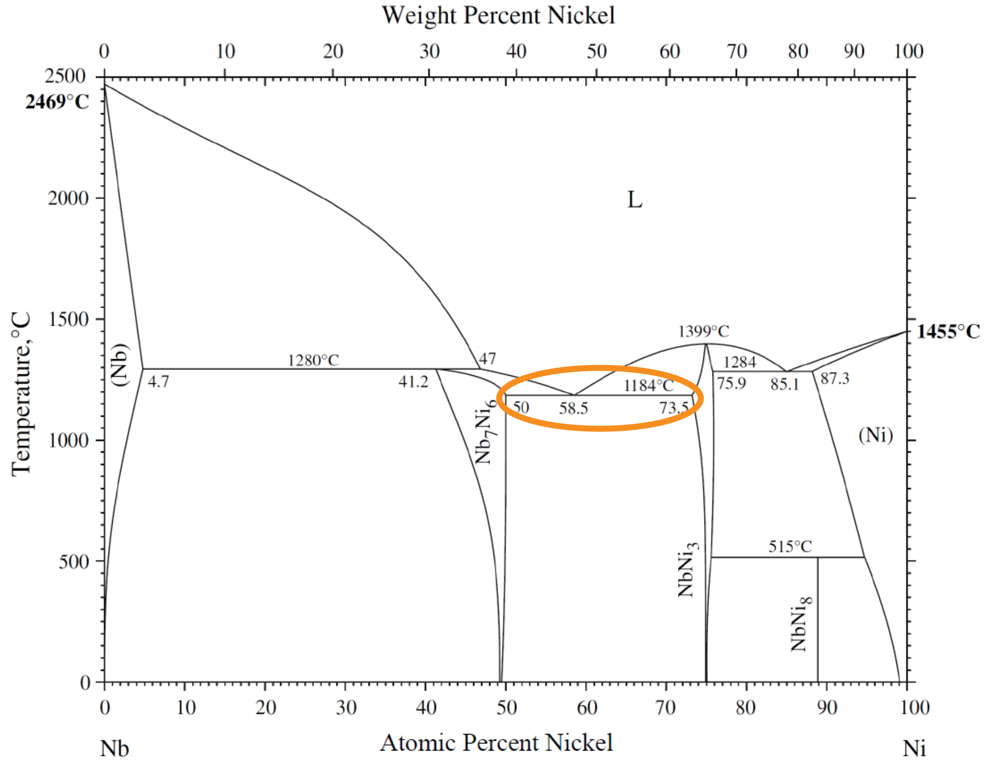
AGR-5/6/7 Thermocouple Requirements

- Previous experience with AGR-2 Capsule 2 demonstrated the potential issue with Ni from surrounding TCs
  - Small number of particles found with SiC failure from external Ni attack
- AGR-5/6/7 Test Requirements included limits on thermocouple construction for T>1050°C
- Pre-irradiation thermal calculations indicated that the Capsule 1 Type N TC locations would not exceed 1050°C
- Early as-run thermal calculations indicated Capsule 1 Type N TC locations could see T>1050°C, but well below the Nb-Ni eutectic



Temperature	Distance from Fuel Compact	Acceptable Materials
>1050°C	>4 mm	Ni surrounded by crack-resistant Mo sleeve, or program-approved high-temperature ceramic sleeve; or Mo, Nb
>1050°C	<4 mm	Ni bearing materials are not permitted; only Mo, Nb, and ceramics (e.g. TC insulation) are permitted
<1050°C	>4 mm	Ni surrounded by Mo or Nb sleeves (it is not necessary to demonstrate crack resistance of Mo sleeve for these lower temperatures); or Mo, Nb
<1050°C	<4 mm	Ni surrounded by crack-resistant Mo sleeve, or Nb sleeve, or program-approved high-temperature ceramic sleeve; or Mo, Nb

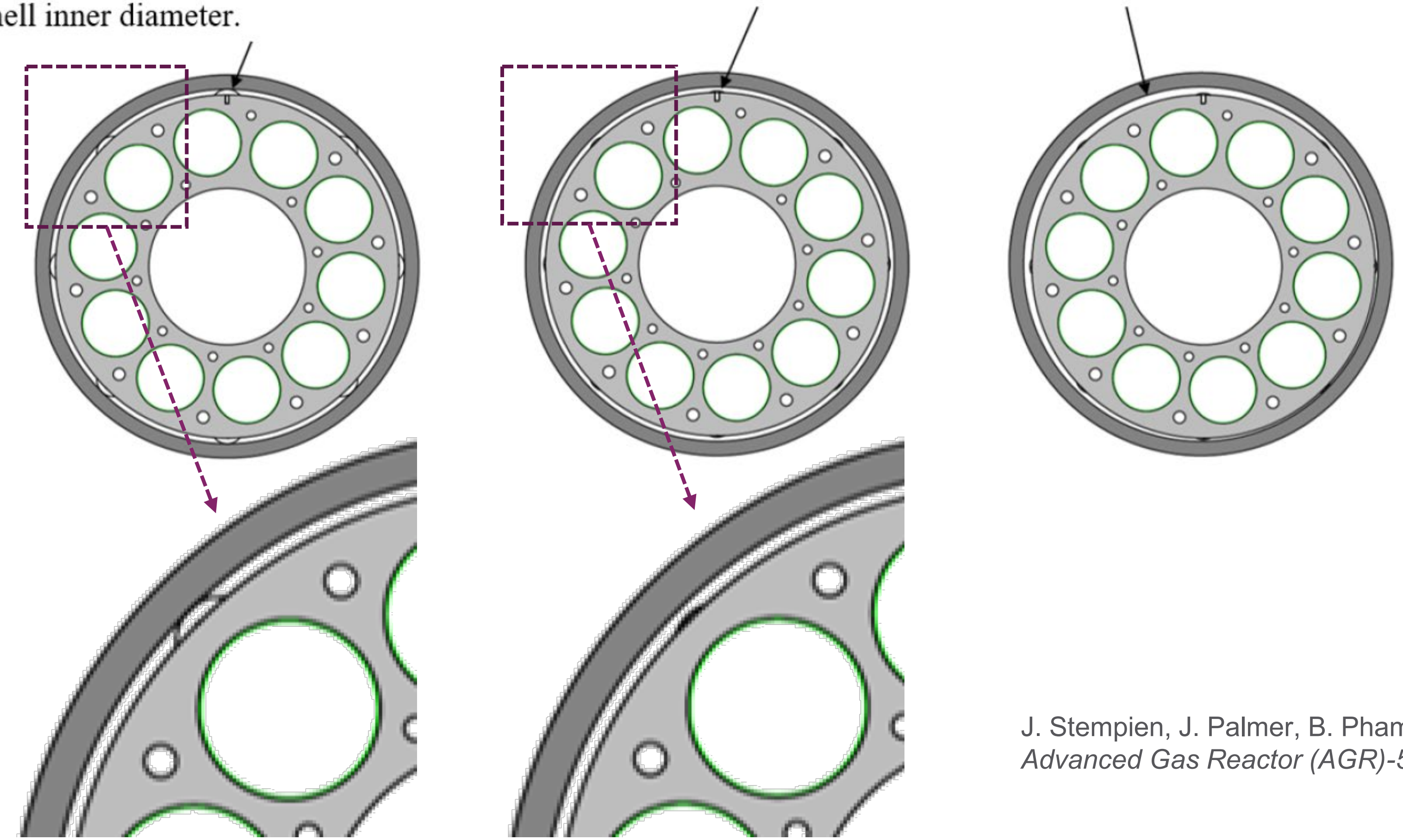
Technical and Functional Requirements, Advanced Gas Reactor AGR-5/6/7 Experiment Test Train, TFR-926, Sep 2016

Graphite Holder Offset

The design was conceptualized as shown here with the nubs essentially touching the capsule shell inner diameter.

Due to failure to verify this aspect of the drawing, the nubs were too small.

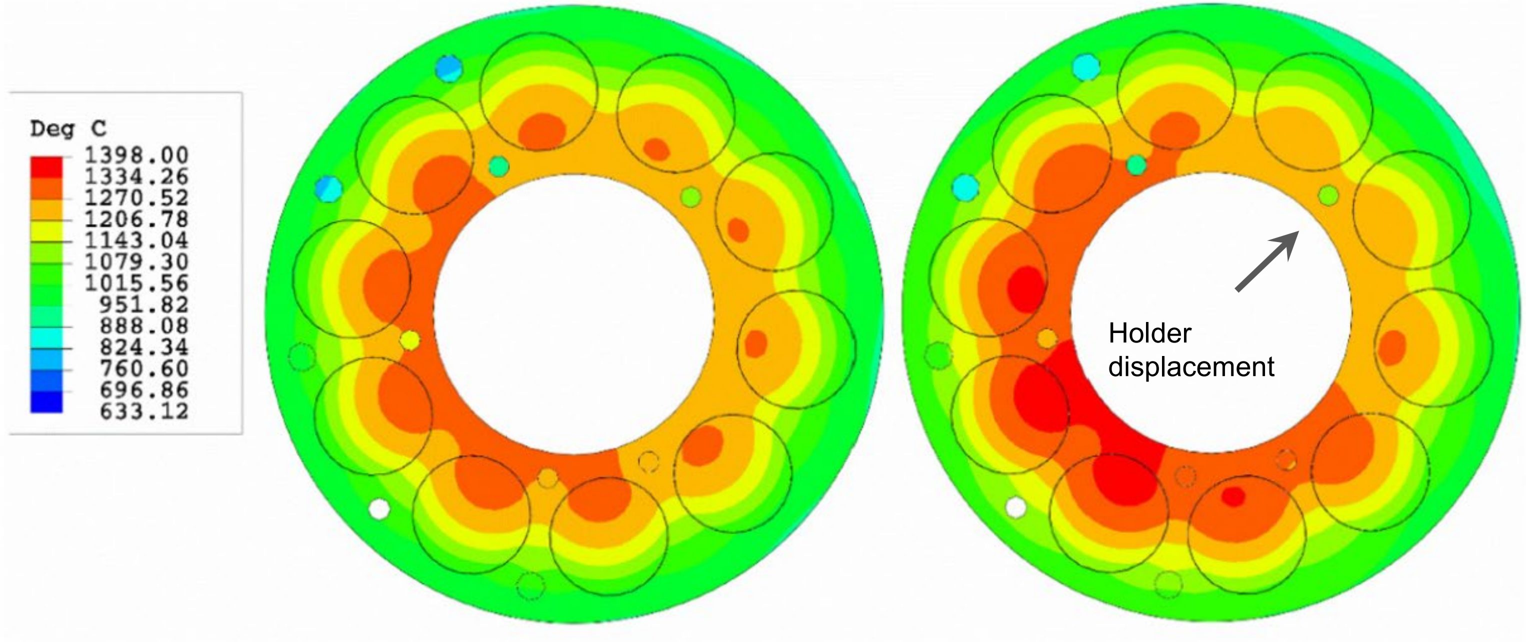
This was the likely offset during irradiation—with the holder offset to the southeast.



- Raised "nubs" are used on the graphite holder outer diameter to provide for a thermal control gap while centering the holder in the shell
- Capsule design error resulted in nub heights that were too small
- This provided excess radial clearance that could allow the holder to be offset within the shell (smaller gap on one side vs. the other)

J. Stempien, J. Palmer, B. Pham, "*Initial Observations from Advanced Gas Reactor (AGR)-5/6/7 Capsule 1*," INL-RPT-22-66720

Impact of Holder Offset on Capsule Temperatures



Holder centered in shell

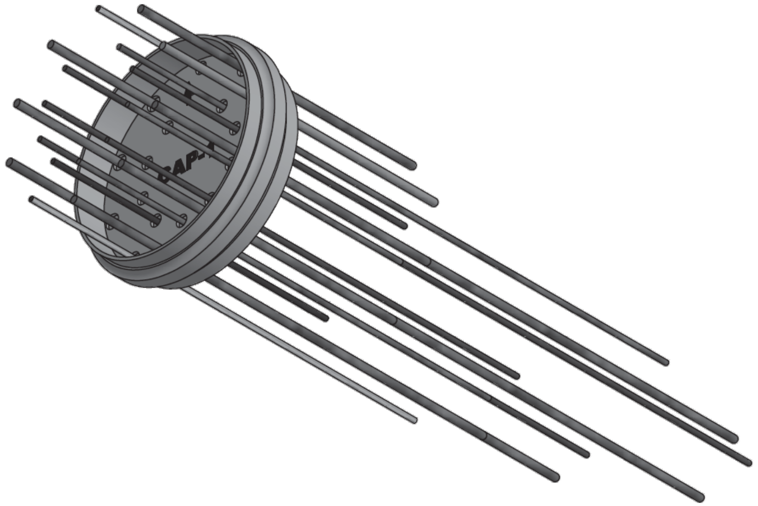
Holder displaced 0.001" in NE direction

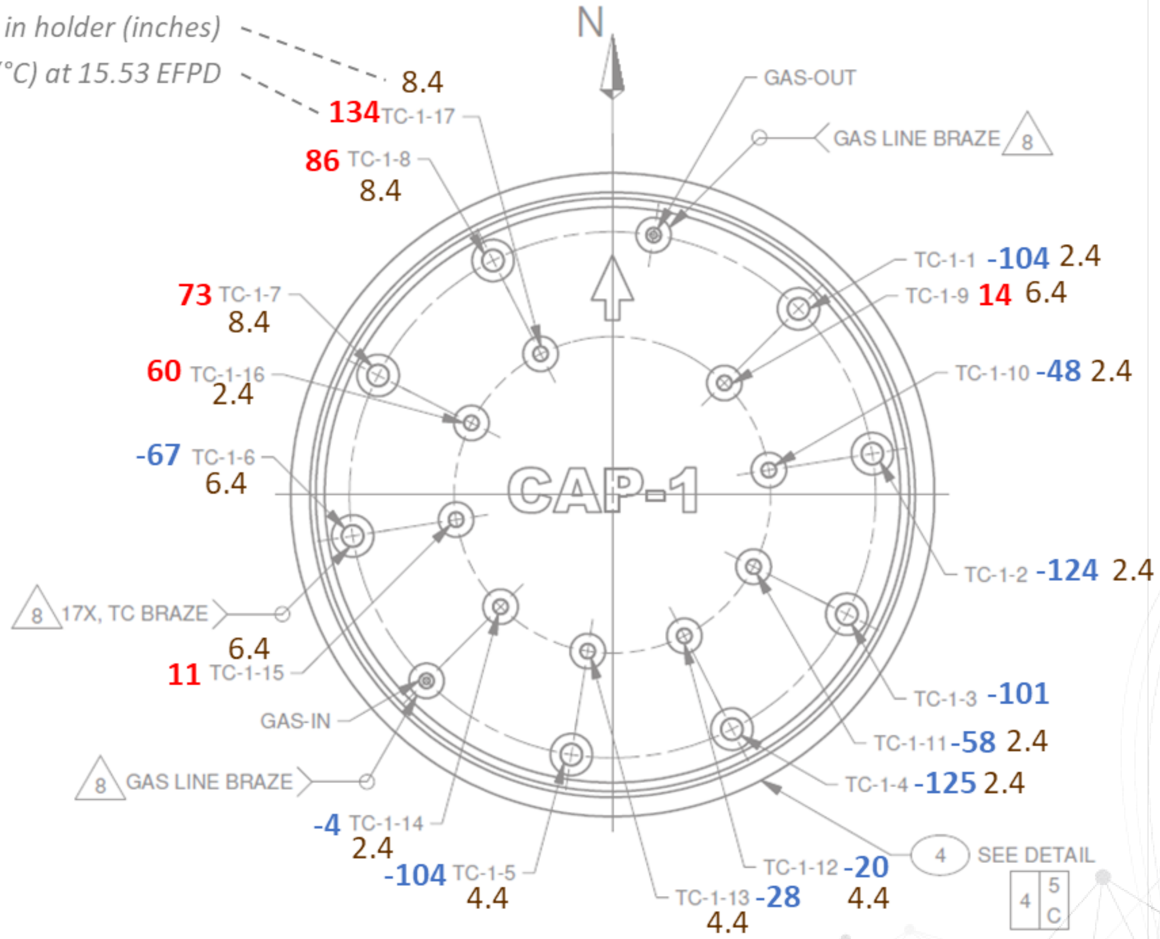
- Previous calculations examined the capsule temperature distribution for a small graphite holder offset
- A 0.001" offset of the holder results in ~50°C temperature increase at the location of the Type N TCs

B. Pham et al., AGR-5/6/7 Irradiation Test Final As-Run Report, INL/EXT-21-64221, Sep 2021
G. Hawkes, IMECE2020-23329, Proceedings of the ASME 2020 International Mechanical Engineering Congress and Exposition (IMECE2020), Nov 2020

Capsule 1 Thermocouple Residuals

- Thermocouples in NW region were mostly hotter than predictions early in the irradiation
  - TC junctions were located mostly in lower half of the holder
- Thermocouples in SE region were mostly colder than predictions
  - TC junctions were located mostly in upper half of the holder



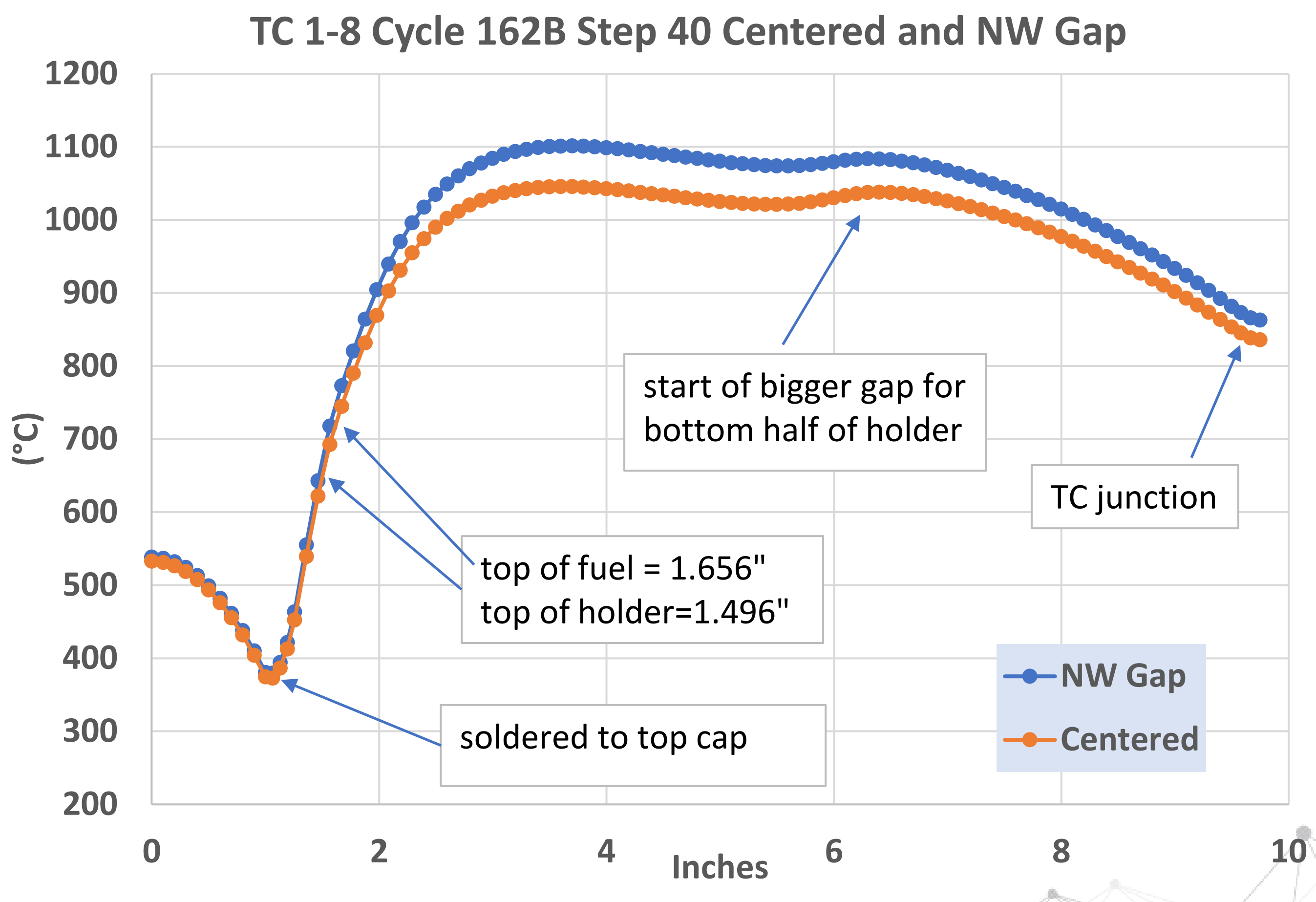


TC residual = $T_{meas} - T_{calc}$

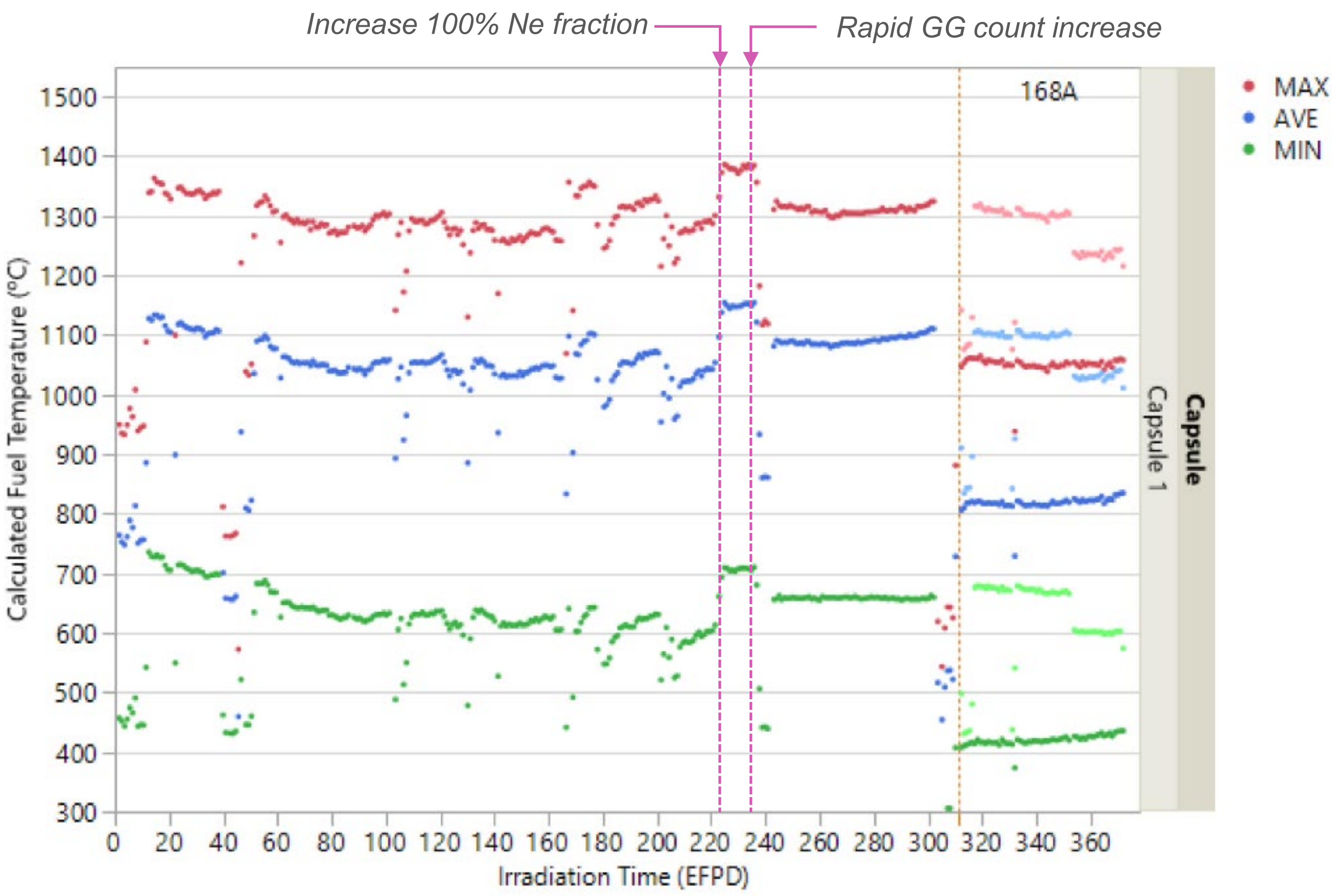
Temperature Variation Along Thermocouples

- For TC 1-8, there was an approximately 200 – 250°C calculated difference in temperature between the TC junction and the highest temperature region ~ 2 inches below the top of the holder
- A shift in the holder by 0.001” to the SE (increased gap width in NW) caused an increase in TC 1-8 junction temperature of ~30°C and peak temperature of ~50°C

Effect of 0.001” holder offset in SE direction on TC 1-8 temperature



Capsule 1 Temperature Adjustments Prior to Particle Failures



- Through Cycle 165A, calculated fuel temperature distribution for AGR-5/6 was still below targets
- Neon fraction in Capsule 1 increased on Sep 18, 2019 to compensate (12 days before rapid gamma count increase)

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Conclusions

Capsule 1 fuel behavior

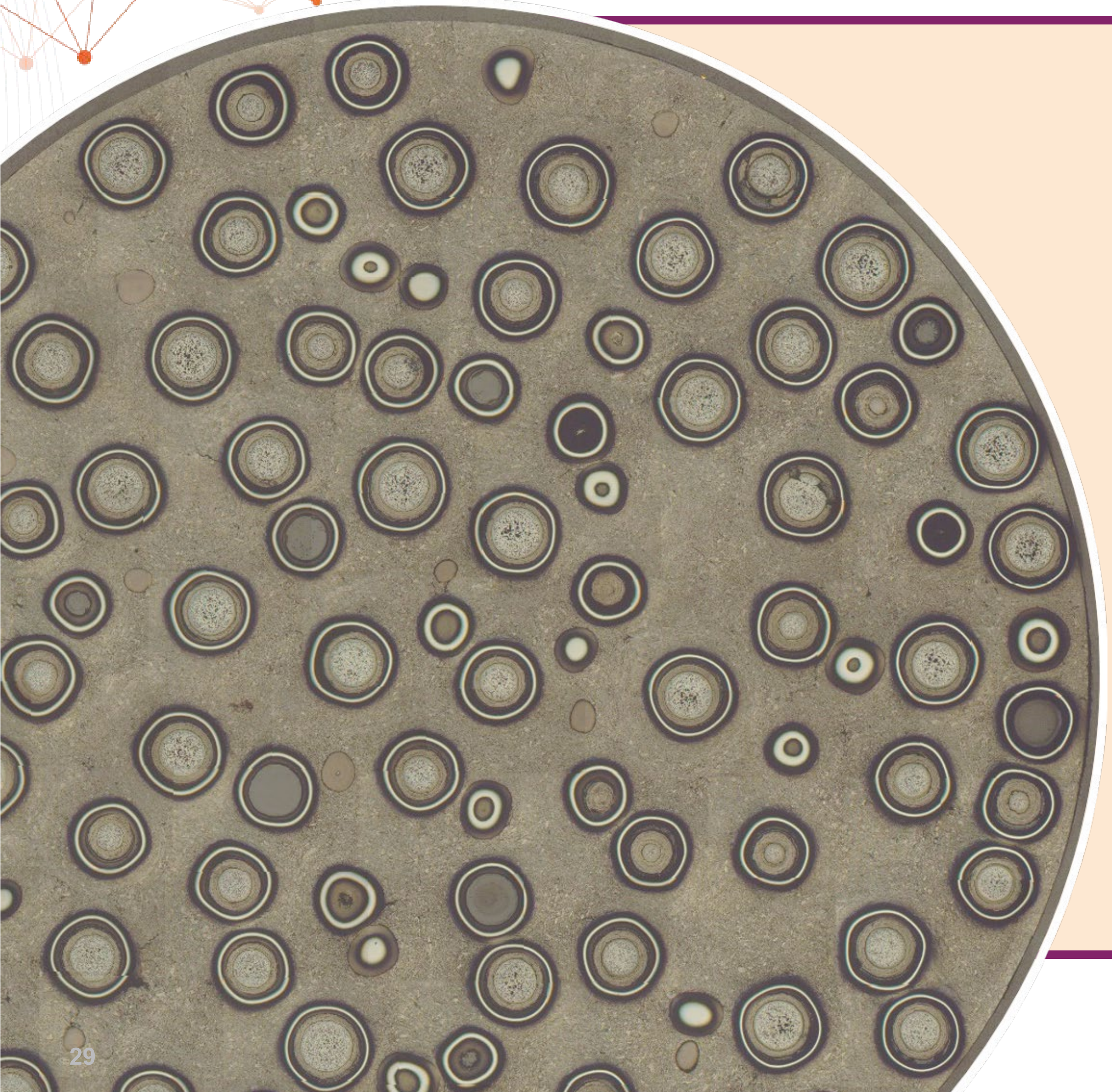
- Cause of particle failures in Capsule 1 appears to be Ni contamination in the graphite holder from TC degradation
- Likely driven by a design flaw that allowed a significant offset of the graphite holder and higher temperatures in one region of the capsule

Most of the work is still ahead of us to obtain AGR-5/6/7 fuel qualification data

- Impact of new matrix formulation on particle performance
- Impact of very low temperature irradiation (T < ~800°C) on particle performance
- Impact of very high temperature irradiation (T > ~1350°C) on particle performance

Future Work – Capsule 1

- Additional detailed destructive PIE on Capsule 1 fuel to confirm the cause of particle failures (*J. Stempien presentation in this session*)
- Salvage “good” Capsule 1 compacts for generating fuel qualification data
  - Capsule 1 contained ~54% of all particles in the test train
  - Capsule 1 contributed the only AGR-5/6/7 fuel in intermediate temperature range (920°C < T_{TAVA} < 1120°C)
  - Possibility that compact damage was localized within Capsule 1
  - Attempt to screen compacts to identify those with no particle failures
- Additional thermal modeling of Capsule 1 incorporating various holder offsets to reproduce observed temperatures



Thank you for your attention

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