INL/CON-23-75484-Revision-0

AGR-5/6/7 CAPSULE 1 THERMAL MODEL WITH OFFSET GAS GAPS

May 2024

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Idaho National Laboratory

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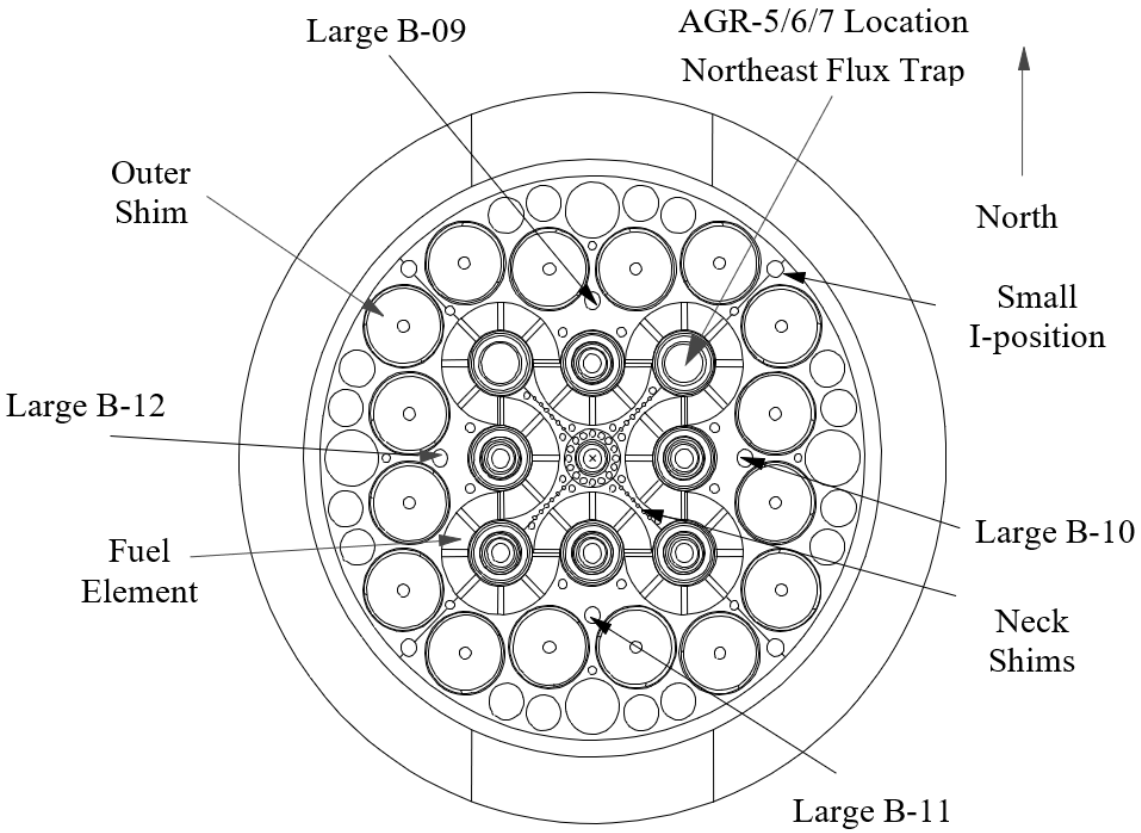
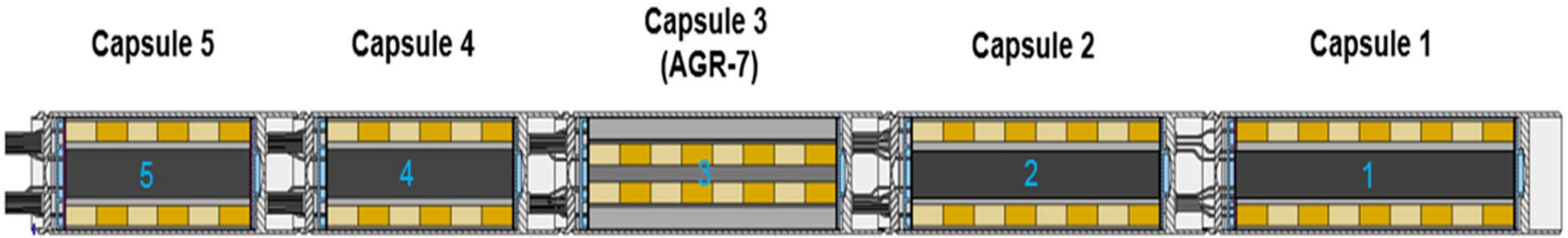
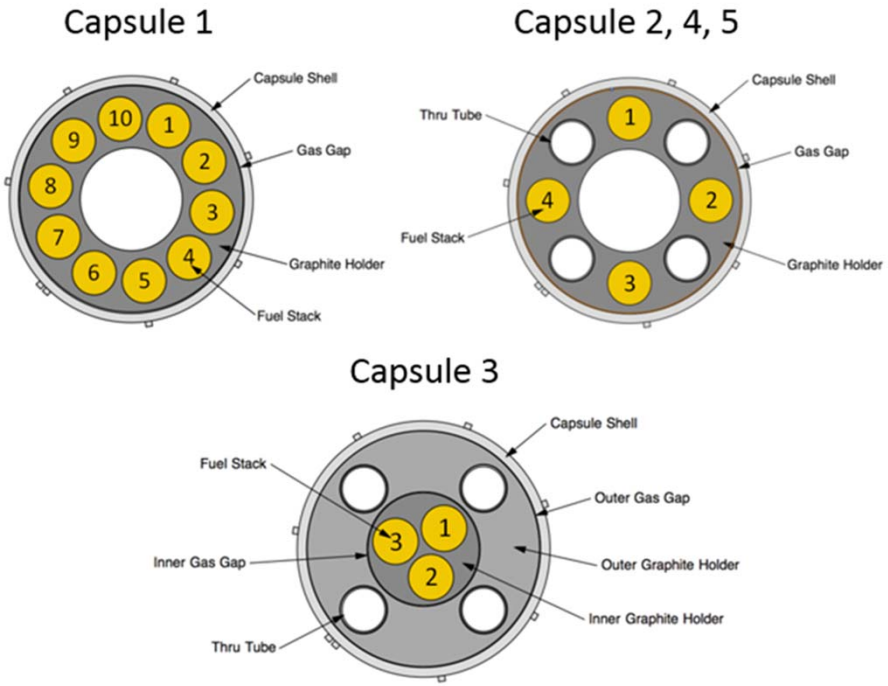
AGR-5 / 6 / 7 in the Advanced Test Reactor (ATR)



Schematic view of the AGR 5 / 6 / 7 test train, rotated 90 degrees from its actual orientation (in which Capsule 1 is at the bottom of the test train).



Cross sections of the AGR-5 / 6 / 7 capsules, showing the compact stacks and through tubes



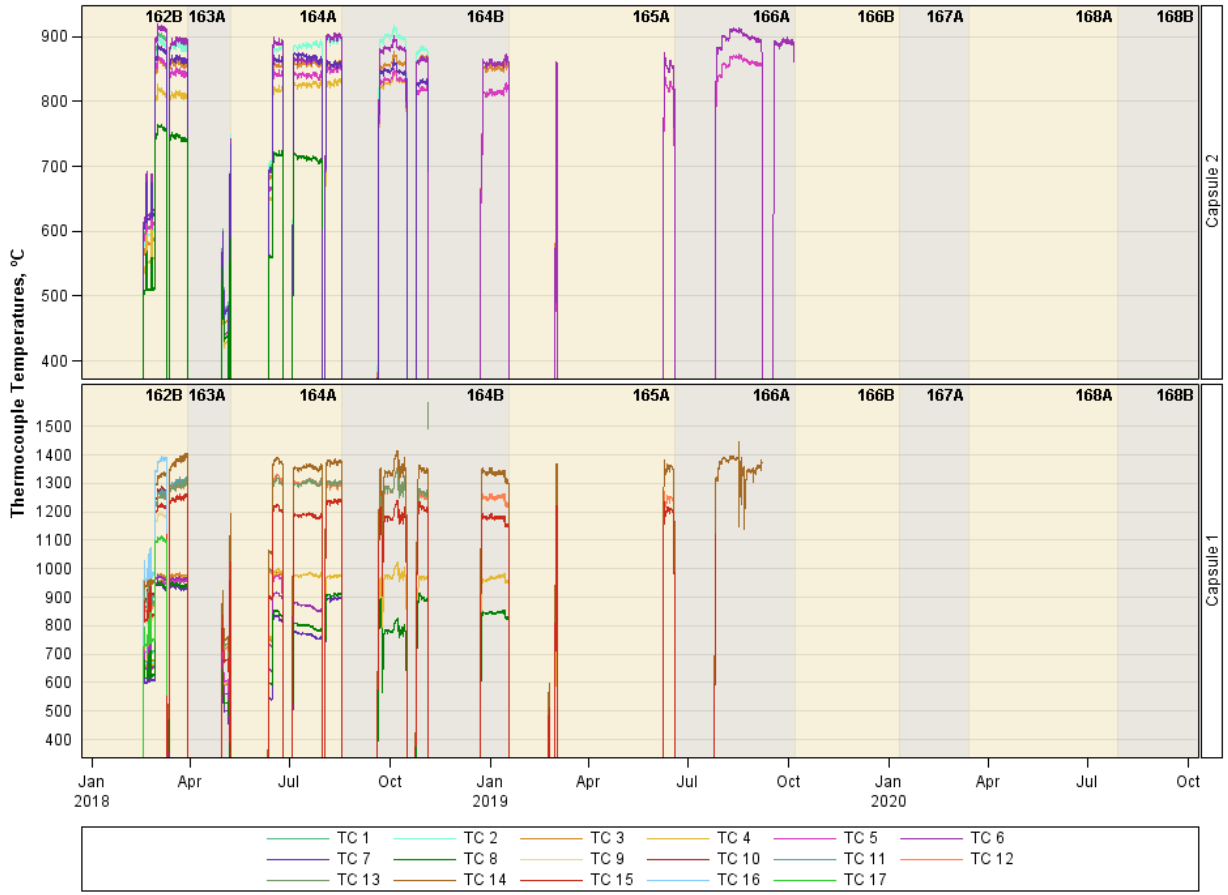
Temperature Control to Maintain Constant Temperature

- Lobe power
  - Started at 13 MW NE lobe power and increased to 20 MW
- Neutron filter
  - Started with stainless steel with hafnium sleeve inside
  - Stainless steel
  - Aluminum
- Helium – Neon gas mixture for each capsule

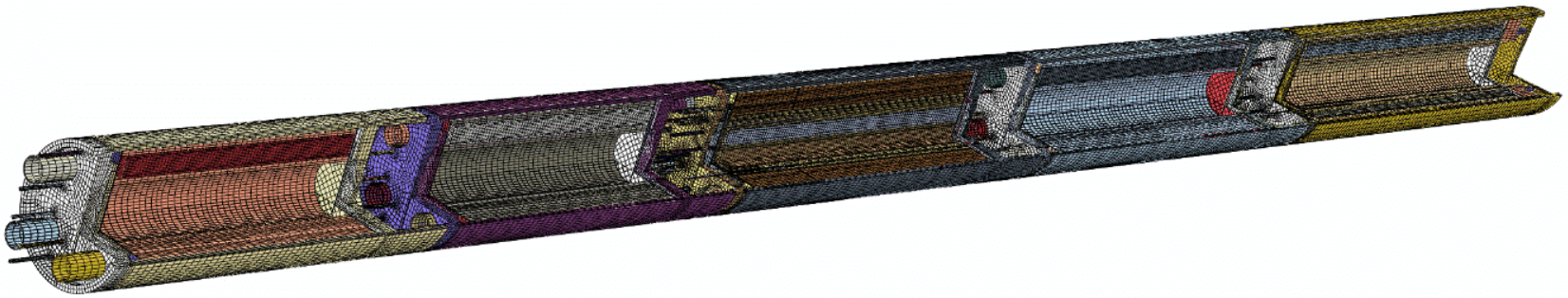
Introduction

- Purpose is to investigate offset through modeling and compare to experimental results
- An ABAQUS finite element model was created for the entire test train (original model created for daily as-run analysis and was centered)
- Capsule 1 was able to be offset due to small nubs and no through-tubes
- Three dates during irradiation were chosen to compare the thermal model with the working thermocouples (TCs)
- Offset distances and direction of offset for the top and bottom of the graphite holder in Capsule 1 were found through a series of computer runs
- The best fit offset and direction was determined by the root mean square error (RMSE) between the TCs and model predictions
- The results indicate that the top of Capsule 1 was fairly stable in one direction, but the bottom wandered

AGR-5 / 6 / 7 daily average measured TC temperatures for Capsules 1 and 2 throughout several ATR cycles



Cutaway view of the finite-element mesh of the entire capsule train

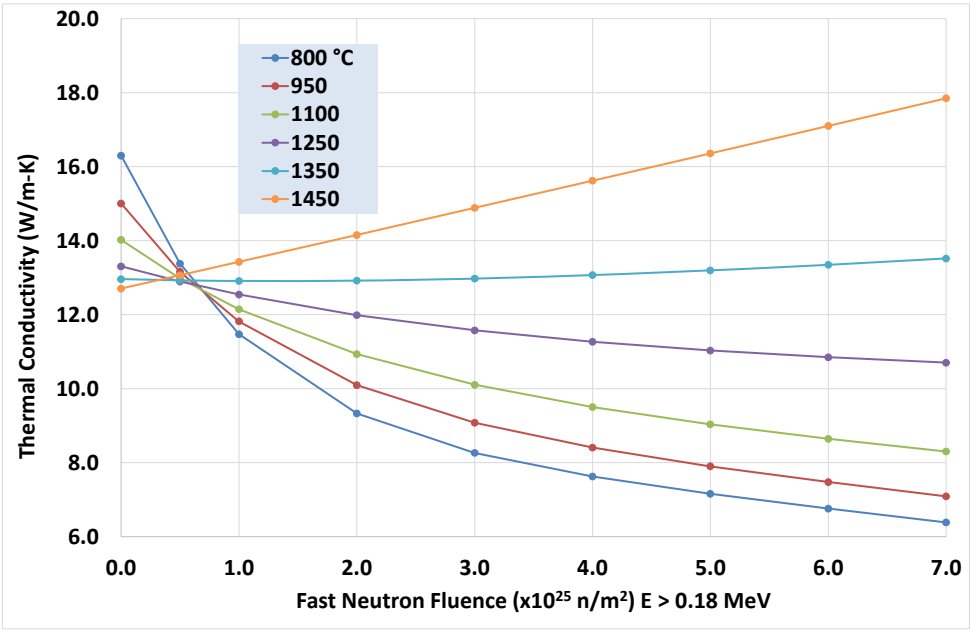


Assumptions

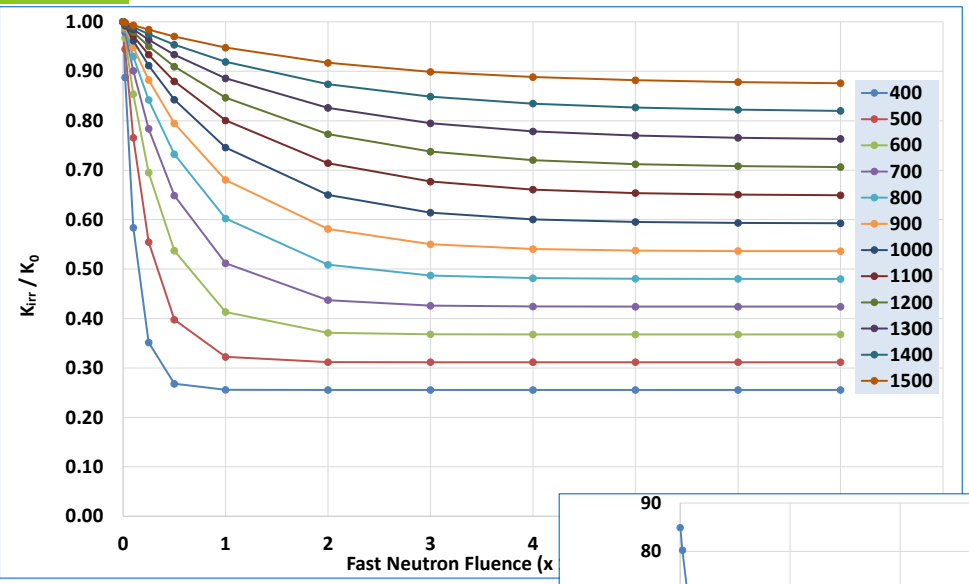
- Daily calculations (steady-state for each day)
- Heat generation rates change each day for the fuel compacts and various materials due to burnup, reactor shim positions and reactor configuration and come from neutronics calculations (MCNP code)
- Gas mixtures
- Thermal properties of graphite and compacts vary with temperature and fast neutron fluence
  - thermal conductivity
  - specific heat
  - density
  - coefficient of thermal expansion
- Post Irradiation Examination (PIE) measured Capsule 1 holder shrinkage was used

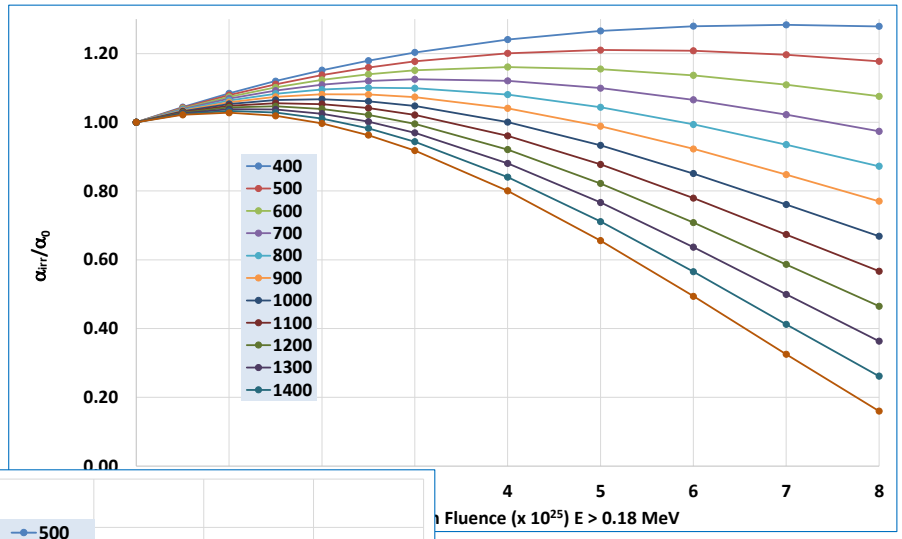
Fuel Compact Thermal Conductivity Capsule 1 Varying with Temperature and Fast Neutron Fluence

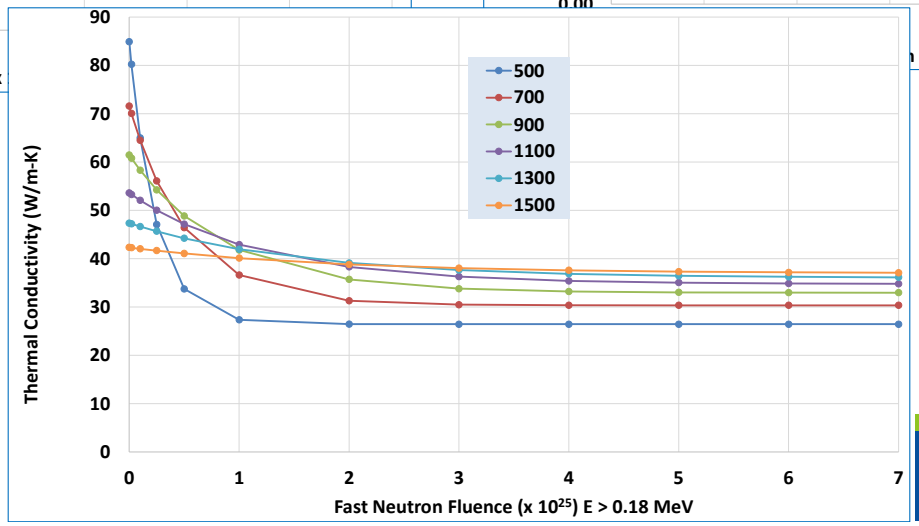
- $\frac{k_e}{k_m} = \frac{1+2\beta\varphi+\left(2\beta^3-0.1\beta\right)\varphi^2+0.05\varphi^3 e^{4.5\beta}}{1-\beta\varphi}$
- $where\ \beta = \frac{\kappa-1}{\kappa+2}\quad and\ \kappa = \frac{k_p}{k_m}$
- Where
  k_e = effective thermal conductivity
  k_m = matrix thermal conductivity (23.6 W / m-K)
  k_p = particle thermal conductivity (4.13 W / m-K)
  ϕ = particle packing fraction
- Chiew and Glandt correlation



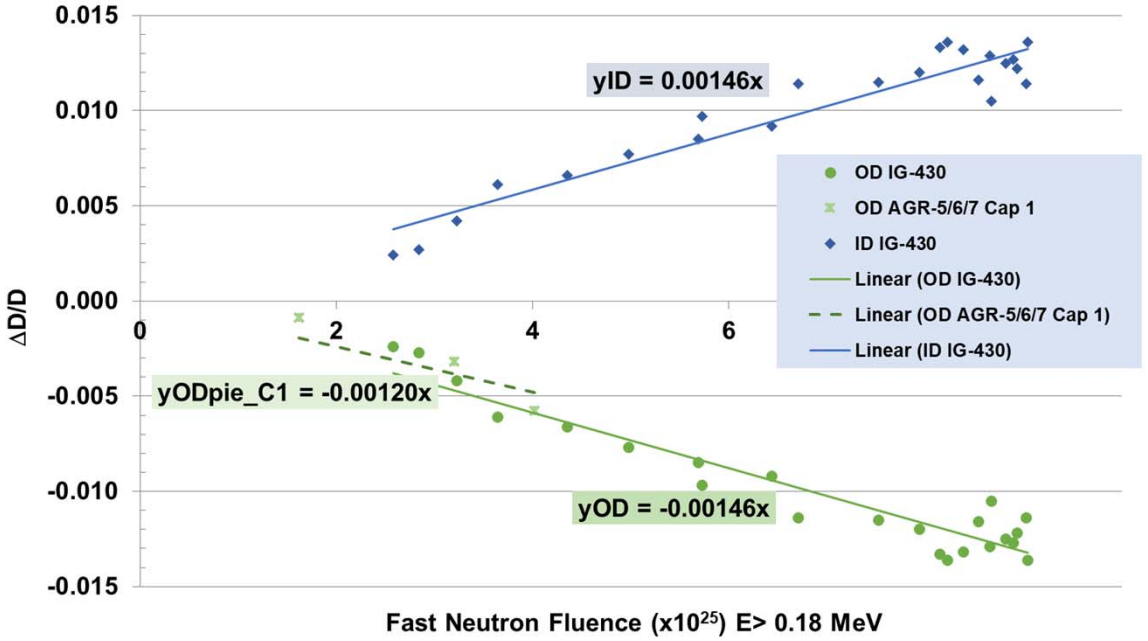
Graphite Holder Thermal Properties







Diametric change of the AGR-5 / 6 / 7 Capsule 1 graphite holder, plotted with IG-430 graphite specimens, as a function of fast neutron fluence with PIE measurements



Offset Gas Gap Calculations

$$gap = \{r_o[\alpha(T_i - T_0) + 1]\}, ss - \left\{r_o\left[1 + \frac{\Delta r}{r}F + \alpha(F,T)(T_i - T_0)\right]\right\}, holder$$

$$gap\ conductance = \frac{kgas(NeF,T)}{gap}, where\ T = \frac{T_{i,ss} + T_{i,holder}}{2}$$

$$where\ T_{i,holder} = \frac{T_{inside,holder} + T_{outside,holder}}{2}$$

$$start\ with\ \ y = \left(\frac{y_i}{x_i}\right) \cdot x_o, \qquad and\ (x_o - h)^2 + (y_o - k)^2 = r_0^2,$$

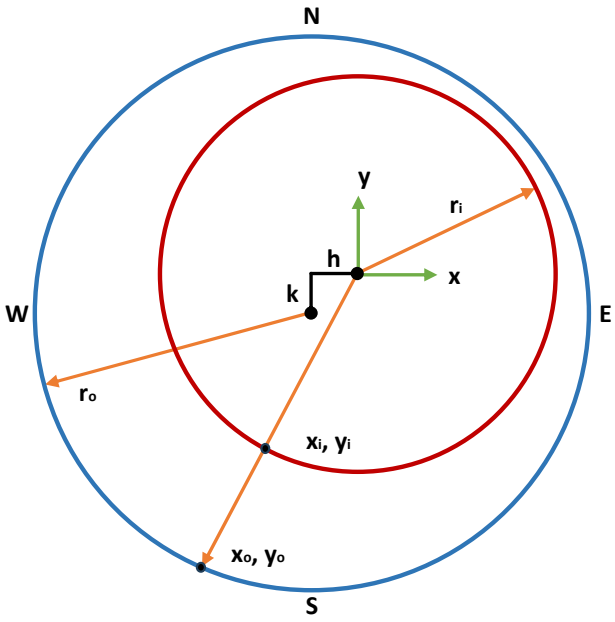
$$solve\ for\ x_o$$

$$a = \left(\frac{y_i}{x_i}\right)^2 + 1, \qquad b = -2\left[\left(\frac{y_i}{x_i}\right) \cdot k + h\right],$$

$$c = k^2 + h^2 - r_o^2$$

$$x_o = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}, y_o = \pm\sqrt{r_o^2 - (x_o - h)^2} + k$$

$$gap = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2}$$



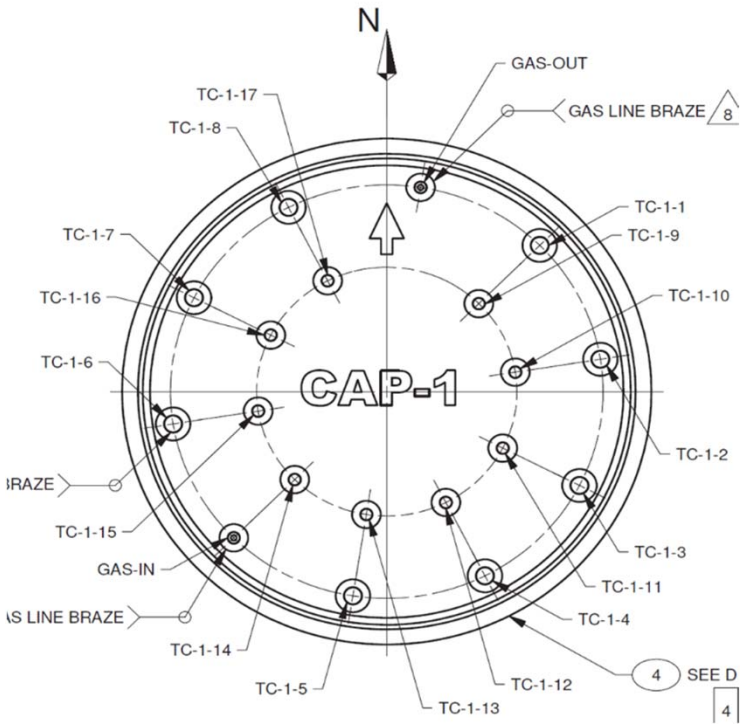
Root Mean Square Error (RMSE) was used to find the best fit for the offset

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(T_{measured} - T_{calculated})^2}{n}}$$

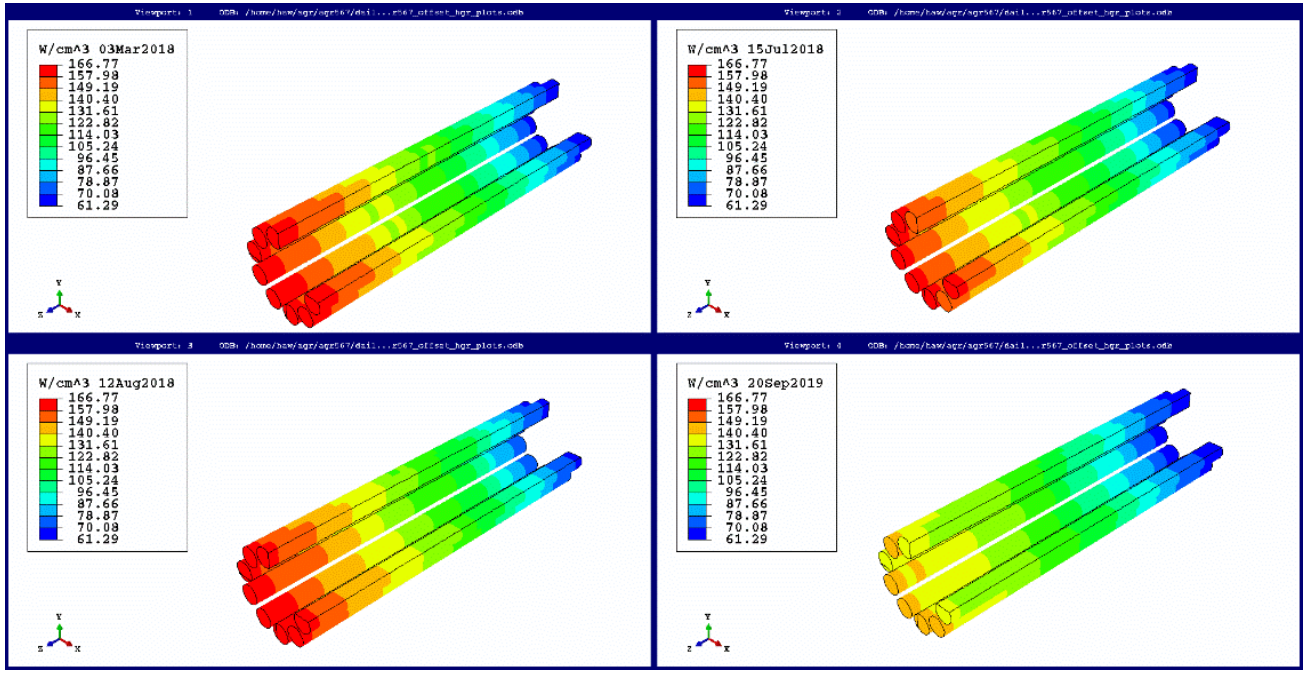
Combinations (65) of the top and bottom offset directions, per computer run

Step	Top Direction	Bottom Direction
1	Center	Center
2–9	E	E, NE, N, NW, W, SW, S, SE
10–17	NE	E, NE, N, NW, W, SW, S, SE
18–25	N	E, NE, N, NW, W, SW, S, SE
26–33	NW	E, NE, N, NW, W, SW, S, SE
34–41	W	E, NE, N, NW, W, SW, S, SE
42–49	SW	E, NE, N, NW, W, SW, S, SE
50–57	S	E, NE, N, NW, W, SW, S, SE
58–65	SE	E, NE, N, NW, W, SW, S, SE

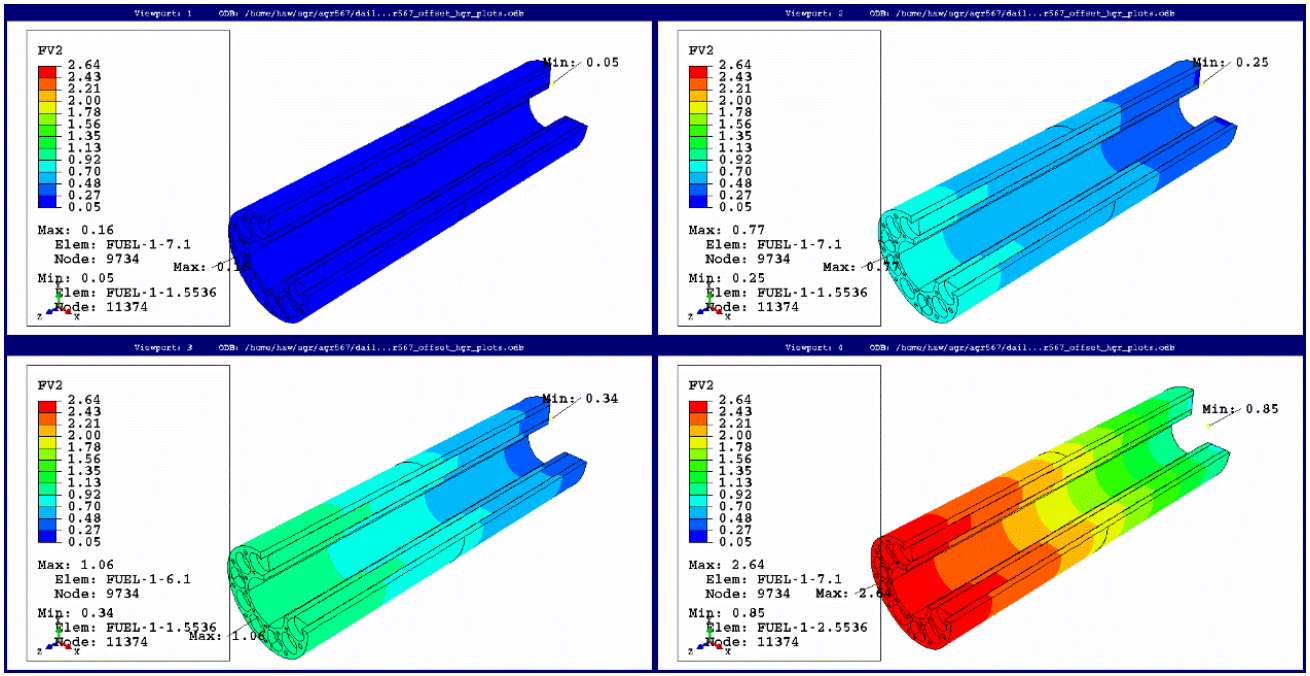
Cross section showing the 17 TCs embedded throughout the Capsule 1 graphite holder



Compact Heat Rates for Four Selected Dates



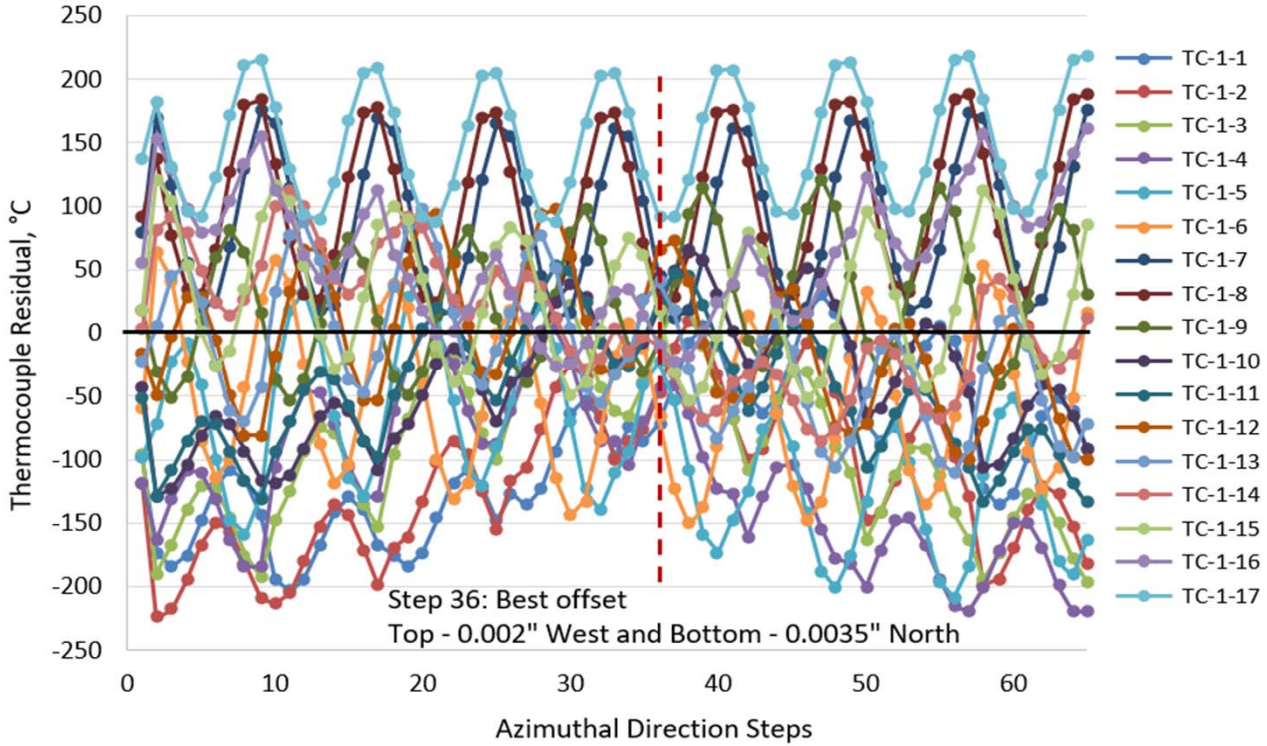
Fast Neutron Fluence (1.0×10^{25} neutrons / m^2 [$E_n > 0.18$ MeV]) for Selected Dates



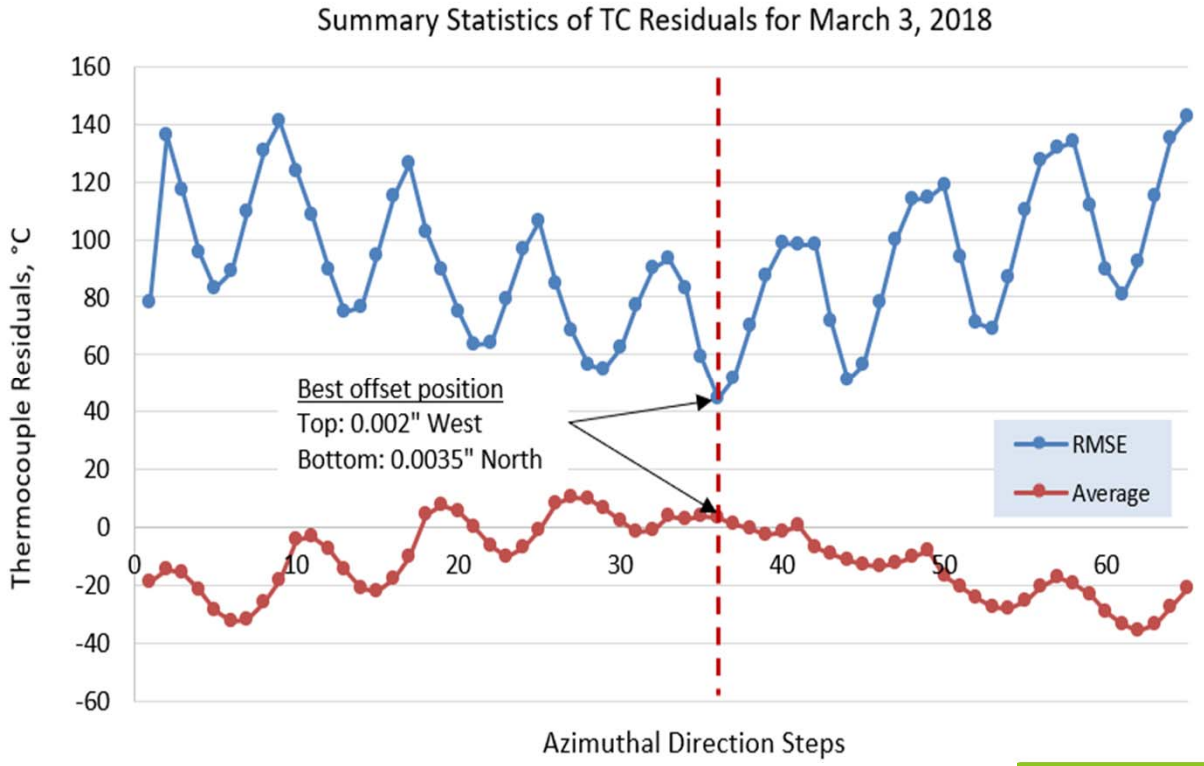
Best-fit options for each of the 16 offset distances, the best-fit direction, and the minimum RMSE for March 3, 2018. The best-fit option is shaded orange

March 3, 2018 (162B)—all 17 TCs remained: Distances / Directions / Minimum RMSE (°C)			
t1b1 / tNWbNW / 59.0	t1b2 / tWbNW / 54.1	t1b3 / tWbNW / 50.8	t1b35 / tWbNW / 50.1
t2b1 / tNWbNW / 53.6	t2b2 / tWbN / 47.9	t2b3 / tWbN / 44.7	t2b35 / tWbN / 44.4
t3b1 / tWbN / 55.3	t3b2 / tWbN / 49.9	t3b3 / tWbN / 47.1	t3b35 / tWbN / 46.8
t35b1 / tNWbN / 59.0	t35b2 / tWbN / 54.4	t35b3 / tWbN / 52.0	t35b35 / tWbN / 51.8

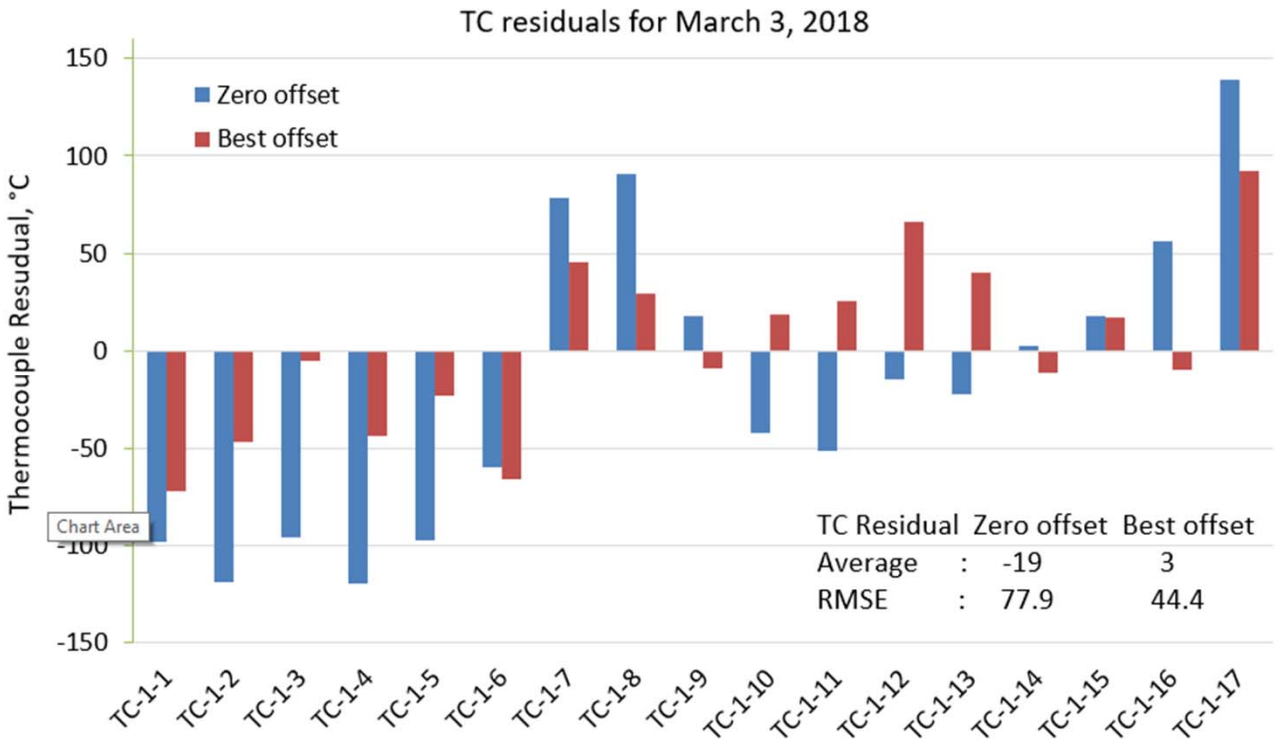
Residuals of the 17 TCs as a function of offset direction (Table 2) for the best-fit offset, showing the smallest TC-residual variation for March 3, 2018, to be at Step 36



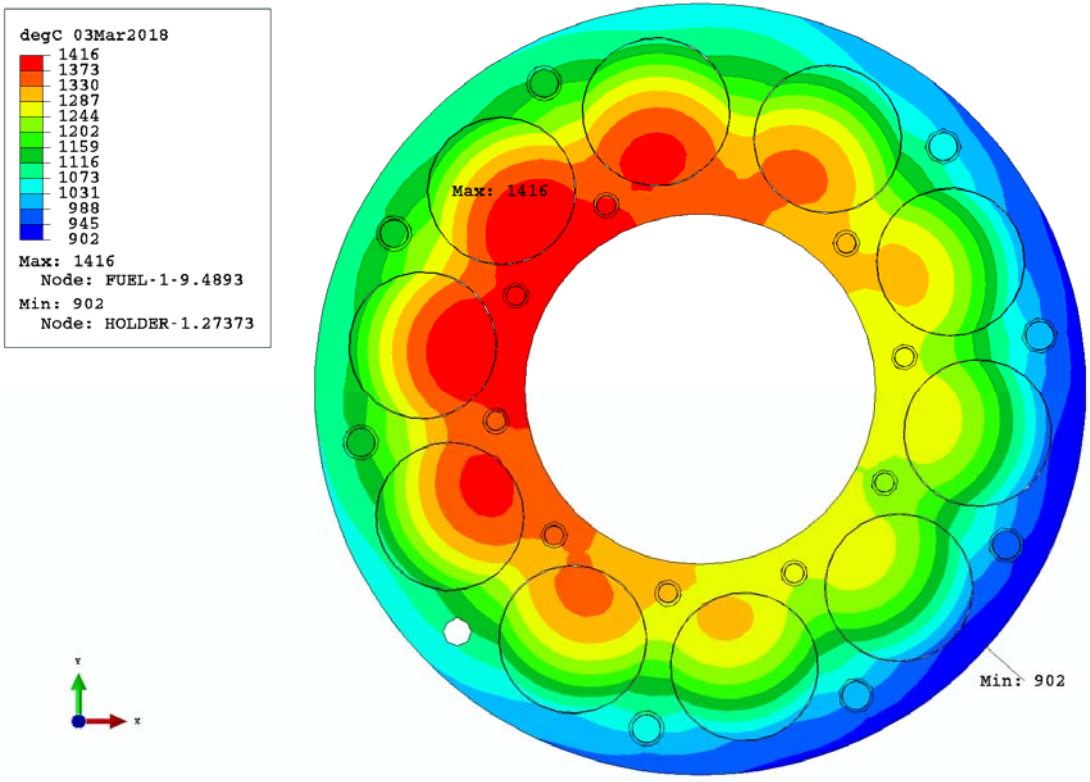
Average and RMSE residuals from the 17 TCs as a function of offset direction step, showing the best offset position for March 3, 2018, to be at Step 36



TC residuals of the zero- and best-fit offsets for March 3, 2018



Temperature (°C) contour plot of the quarter-inch slice (level 7) in which the highest temperature occurs for March 3, 2018—the best-fit offset position being 0.002 in. top west and 0.0035 in. bottom north



Best-fit options for each of the 24 offset distances, the best-fit direction, and the minimum RMSE for July 15, 2018. The best-fit option is shaded orange

July 15, 2018 (164A)—8 TCs remained: Distances / Directions / Minimum RMSE					
t15b15 / tSWbSE / 56.4	—	t15b3 / tWbSE / 56.0	—	t15b45 / tNWbS / 63.8	t15b55 / t0b0 / 65.0
—	t2b2 / tWbSE / 54.8	t2b3 / tWbSE / 54.8	t2b35 / tWbSE / 56.5	—	—
t3b15 / tSWbE / 55.7	t3b2 / tSWbE / 54.7	t3b3 / tWbSE / 53.8	t3b35 / tWbSE / 54.9	t3b45 / tWbSE / 60.4	t3b55 / t0b0 / 65.0
—	t35b2 / tSWbE / 55.1	t35b3 / tWbSE / 54.0	t35b35 / tWbSE / 54.6	—	—
t45b15 / tSWbE / 58.8	—	t45b3 / tWbSE / 55.5	—	t45b45 / tWbE / 58.0	t45b55 / tSWbNE / 61.2
t55b15 / tSWbE / 62.2	—	t55b3 / tWbSE / 58.5	—	t55b45 tSWbNE / 57.9	t55b55 / tSWbNE / 59.5

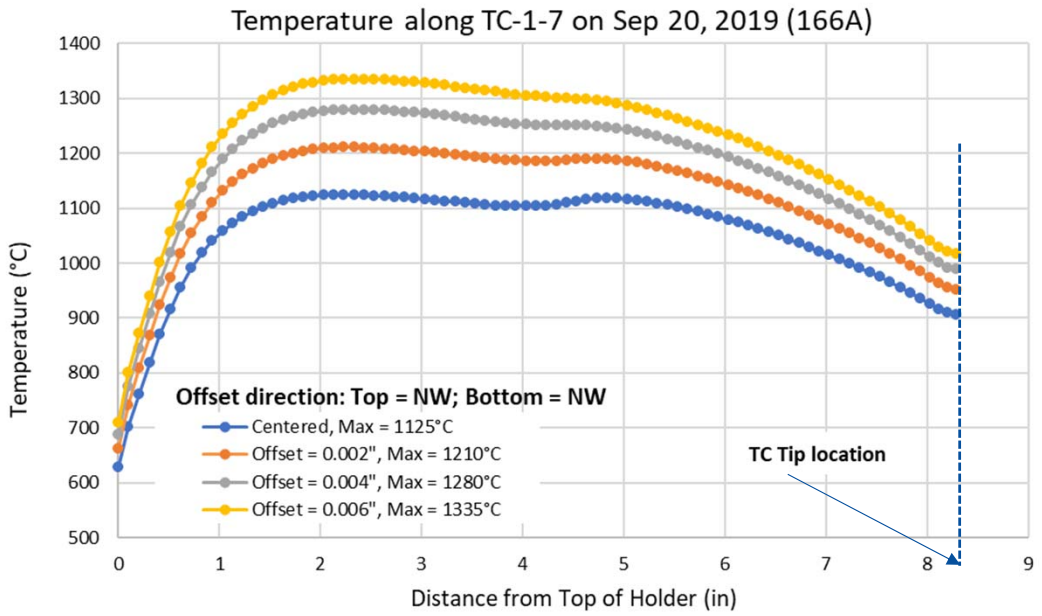
Best-fit options for each of the 16 offset distances, the best-fit direction, and the minimum RMSE for August 12, 2018. The best-fit option is shaded orange

August 12, 2018 (164A)—7 TCs remained: Distances / Directions / Minimum RMSE			
t2b2 / tSWbNW / 54.0	t2b3 / tSWbW / 51.3	t2b35 / tSWbW / 49.9	t2b45 / tSWbW / 48.6
t3b2 / tSWbNW / 52.5	t3b3 / tSWbNW / 49.0	t3b35 / tSWbNW / 48.4	t3b45 / tSWbNW / 49.6
t35b2 / tSWbNW / 52.4	t35b3 / tSWbNW / 48.7	t35b35 / tSWbNW / 47.9	t35b45 / tSWbNW / 48.7
t45b2 / tSWbNW / 53.7	T45b3 / tSWbNW / 49.3	t45b35 / tSWbNW / 48.3	t45b45 / tSWbNW / 48.4

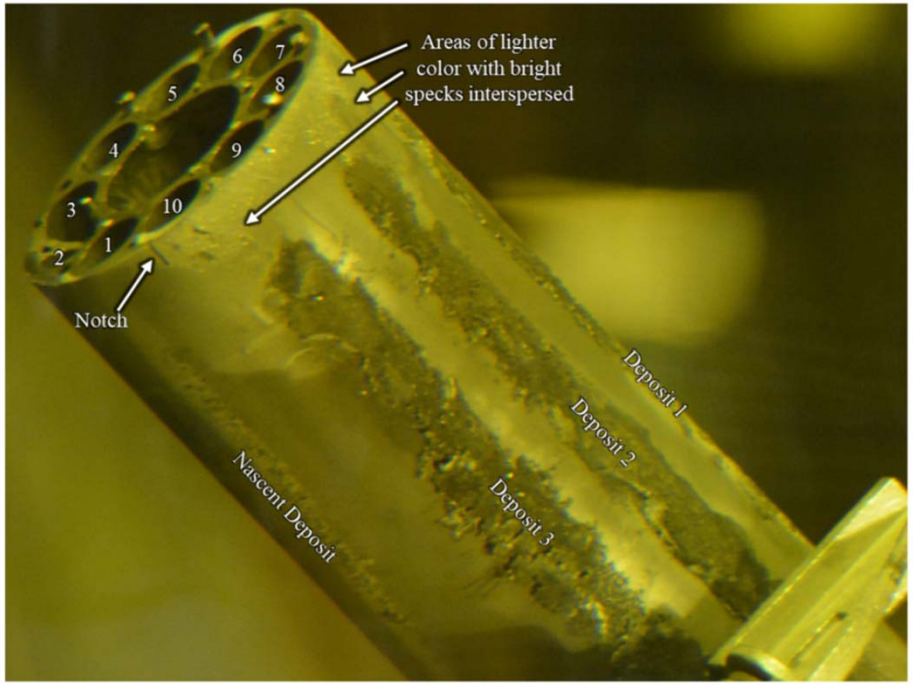
Capsule 1 fuel compact temperatures for the offset options for September 20, 2019 (no TCs remained functioning)

Offset Option	Min Temp ℃	Average Temp ℃	Max Temp ℃	Max Temp Compact
Zero	731	1184	1422	1-8-6
Top: 0.002 in. SW; Bot: 0.002 in. NW	680	1181	1469	1-8-7
Top: 0.004 in. SW; Bot: 0.004 in. NW	614	1173	1512	1-8-7
Top: 0.006 in. SW; Bot: 0.006 in. NW	533	1159	1550	1-8-7
Top: 0.002 in. NW; Bot: 0.002 in. NW	683	1180	1465	1-7-9
Top: 0.004 in. NW; Bot: 0.004 in. NW	609	1166	1516	1-7-9
Top: 0.006 in. NW; Bot: 0.006 in. NW	518	1143	**1557**	1-7-9

The temperature distribution along TC-1-7 from the holder top to tip, for four offset options (zero, 0.002, 0.004, and 0.006 in.) for both the top and bottom, shifted northwest for September 20, 2019



Capsule 1 holder, showing the fuel stacks and major deposits on Northwest (possible Nickel degradation)



Conclusions

- A best-fit offset direction and magnitude for three dates during 2018 was found by minimizing the RMSE calculated temperatures compared to actual TC measurements
- A fourth date, pertaining to when no TCs remained functional, showed the maximum possible temperature along the TC lines and a mechanism for nickel degradation in the fuel particles
- Post irradiation examination photographs revealed deposit stripes along the northwest outer surface of the graphite holder. These photographs justify the in-depth thermal analysis performed in this paper to discover the offset magnitude and direction

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