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AGR-5/6/7 Thermal Model with Non-Uniform Gas Gaps

DOE ART Gas-Cooled Reactor (GCR) Review Meeting
Virtual Meeting
July 25 – 27, 2023

ART
Advanced Reactor Technologies

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

Cutaway view of finite element mesh of the entire capsule train

Capsule 1

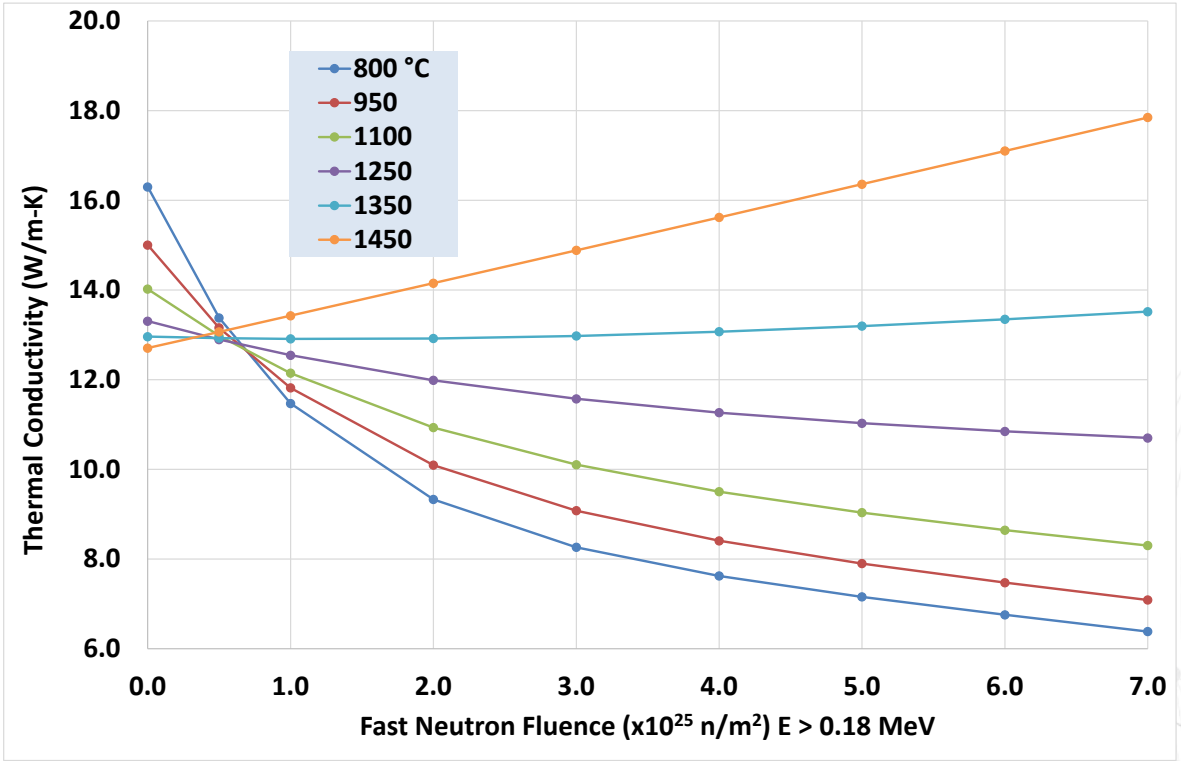
Assumptions

- 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
  - Gas mixtures
  - Thermal properties of graphite and compacts vary with temperature and fast neutron fluence
    - thermal conductivity
    - specific heat
    - density
    - coefficient of thermal expansion
  - PIE measured Capsule 1 holder shrinkage was used
  - Neolube was not considered in this offset model (original model used 0.0015-in.)

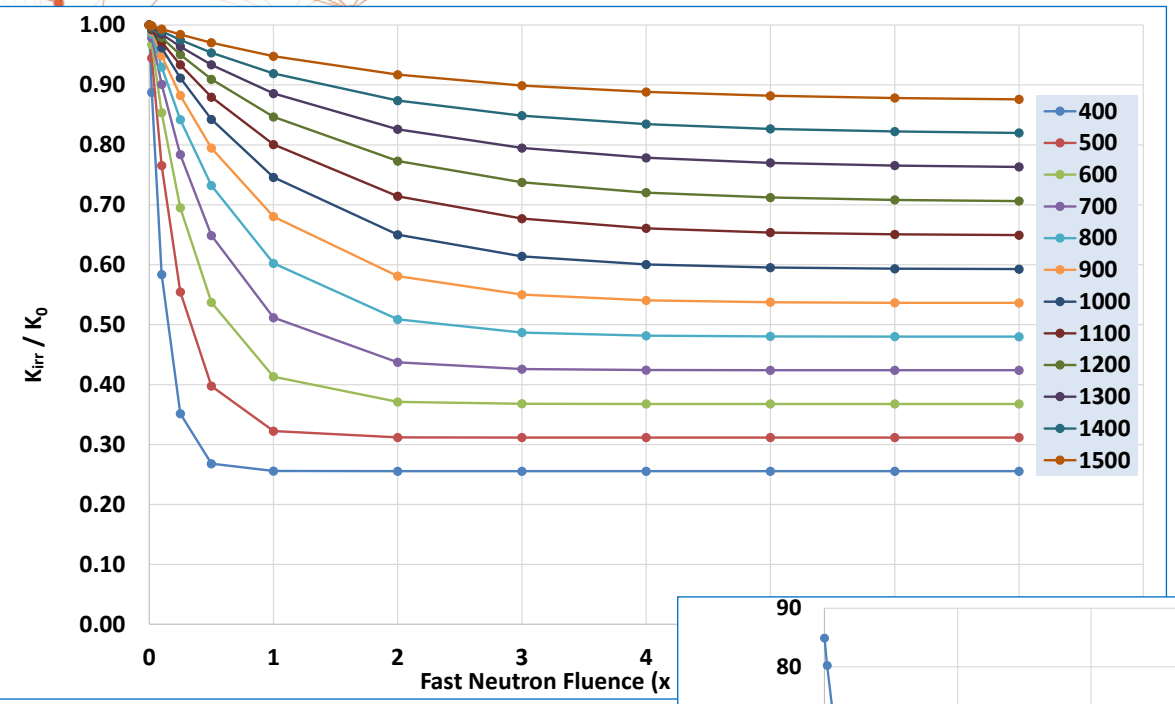
Fuel Compact Thermal Conductivity Capsules 1 and 5 Varying with Temperature and Fast Neutron Fluence

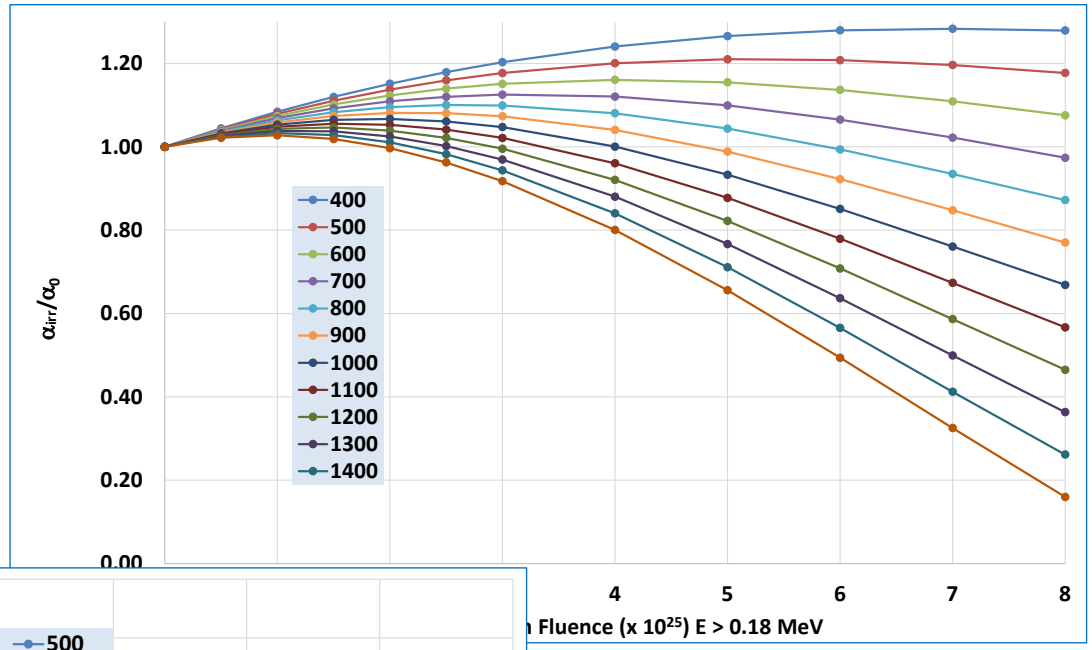
- $\frac{k_e}{k_m} = \frac{1+2\beta\varphi+(2\beta^3-0.1\beta)\varphi^2+0.05\varphi^3 e^{4.5\beta}}{1-\beta\varphi}$
- $where\ \beta = \frac{\kappa-1}{\kappa+2}\quad and\ \kappa = \frac{k_p}{k_m}$
- Where

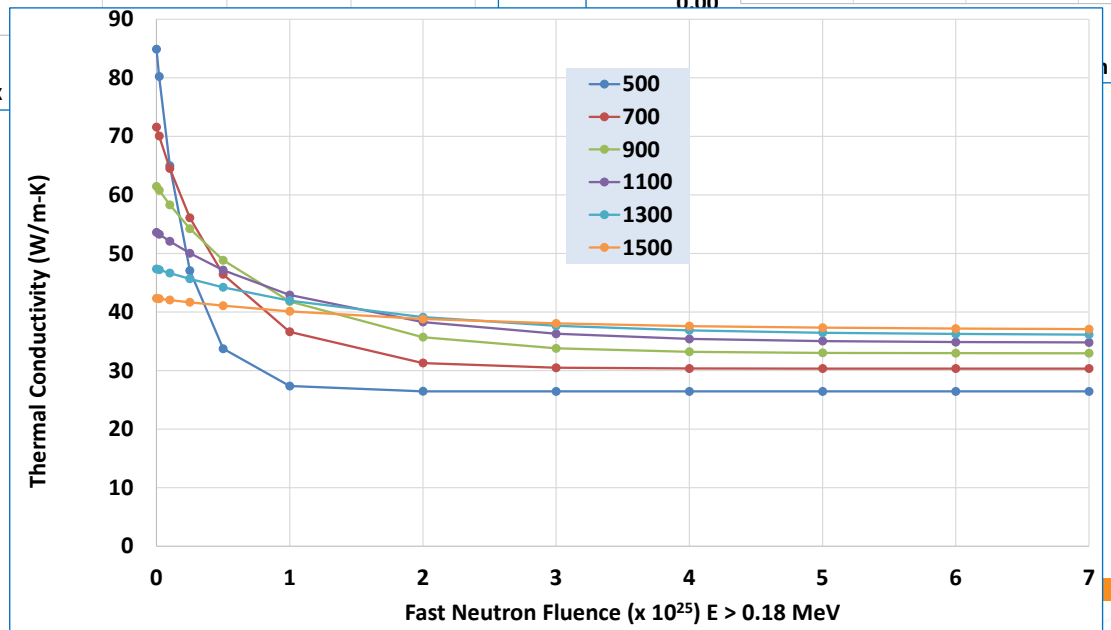
k_e	=	effective thermal conductivity
k_m	=	matrix thermal conductivity (23.6 W/m-K)
k_p	=	particle thermal conductivity (4.13 W/m-K)
ϕ	=	particle packing fraction.



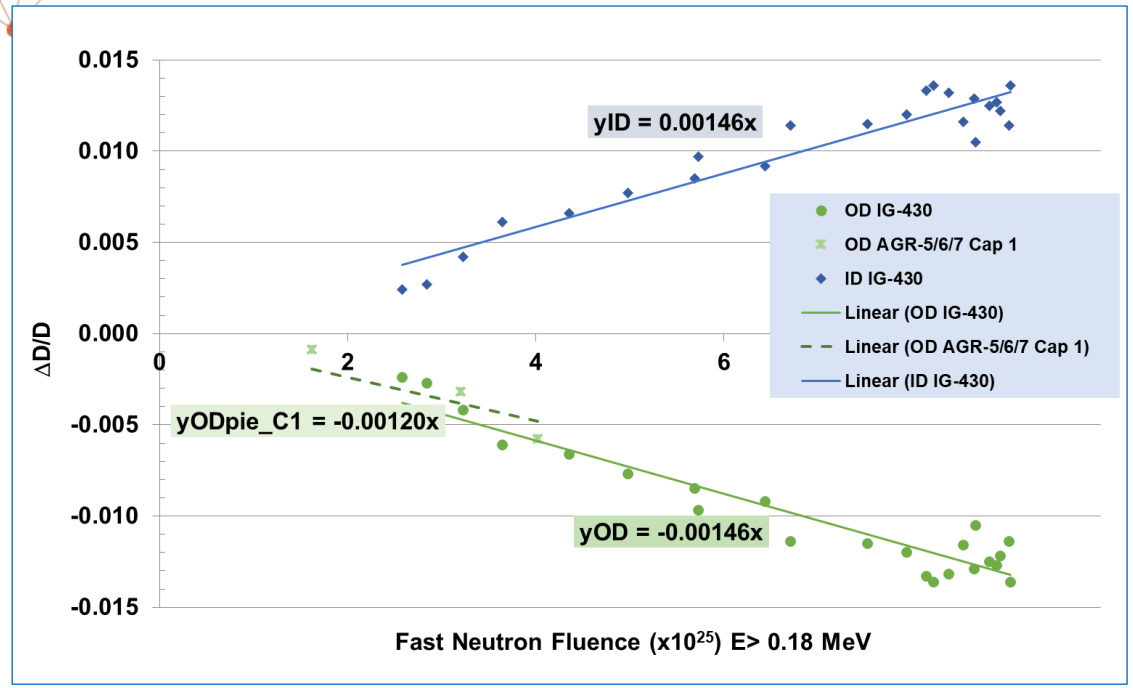
Graphite Holder Thermal Properties

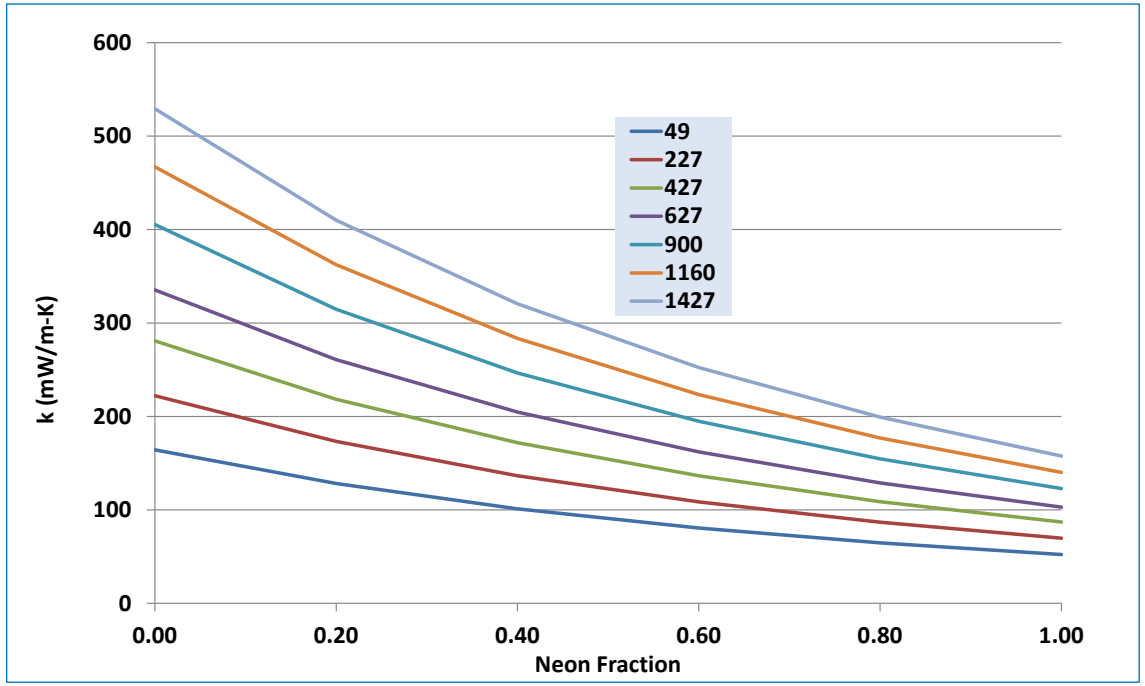






Outer Gaps and Gas Mixture



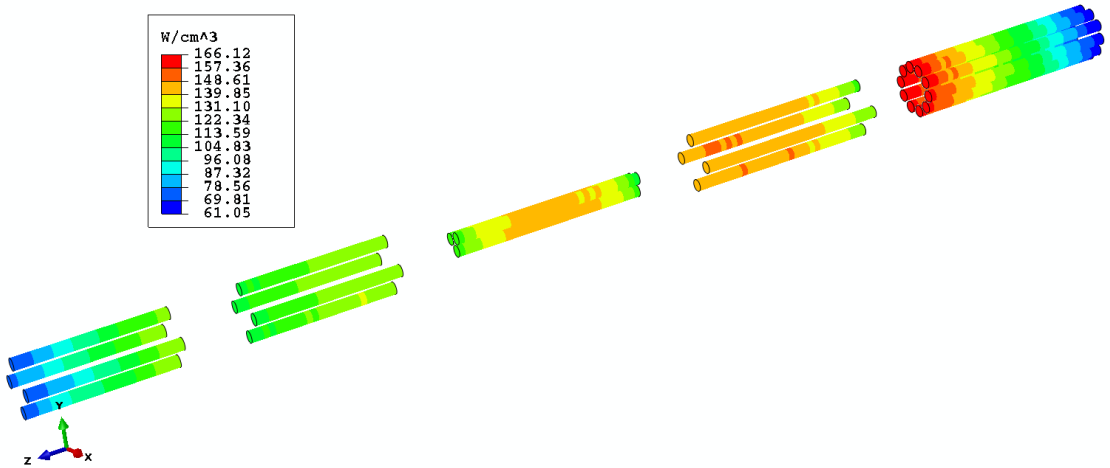


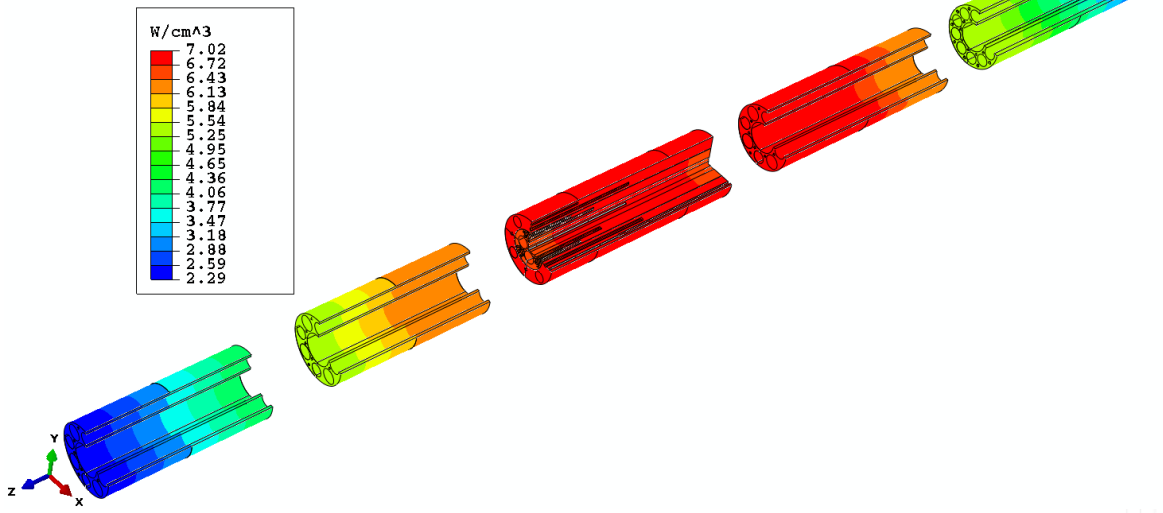
$$gap = \{r_o[\alpha(T_i - T_0) + 1]\}, ss - \left\{r_o\left[1 + \frac{\Delta r}{r}F + \alpha(F,T)(T_i - T_0)\right]\right\}, holder$$

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

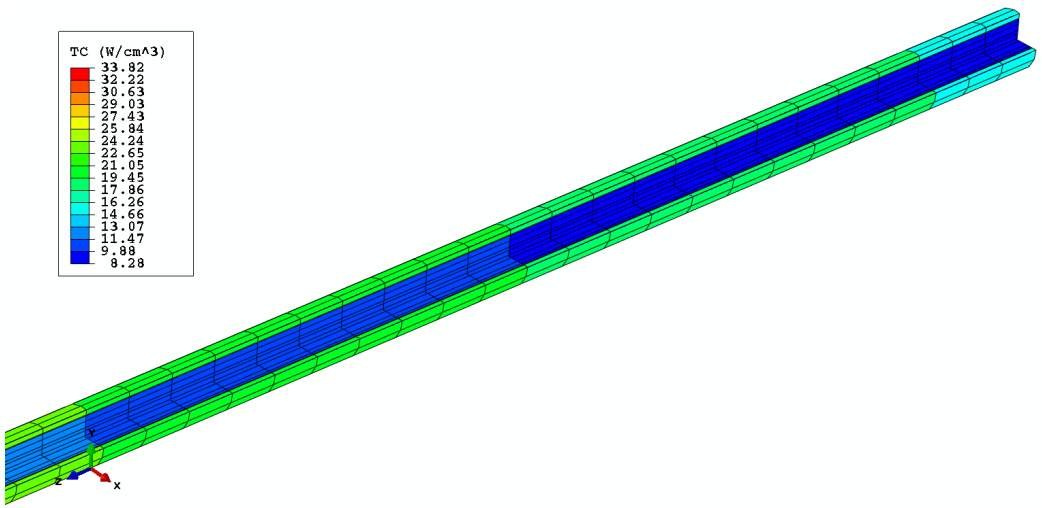
$$where\ T_{i,holder} = \frac{T_{inside,holder} + T_{outside,holder}}{2}$$

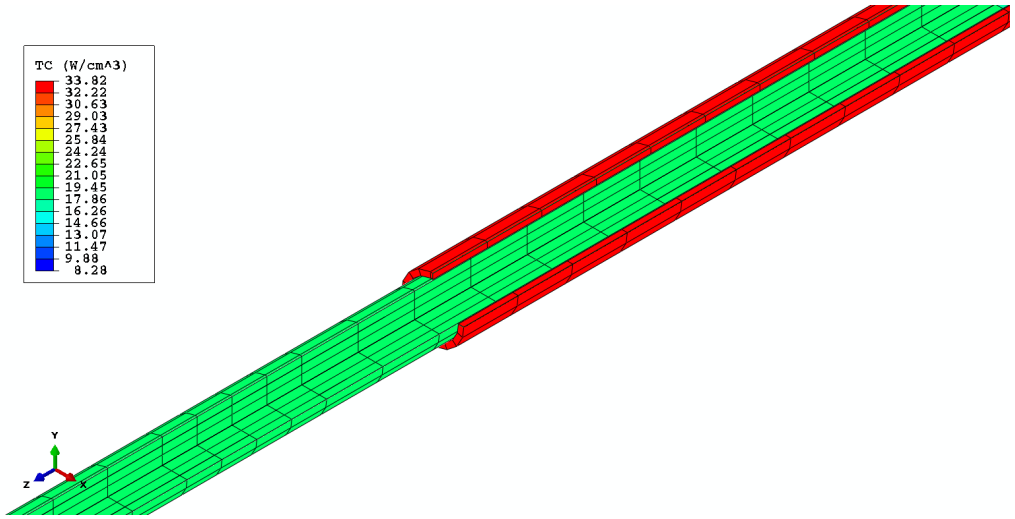
Heat Generation Rates (HGRs) Day 20 of Cycle 162B

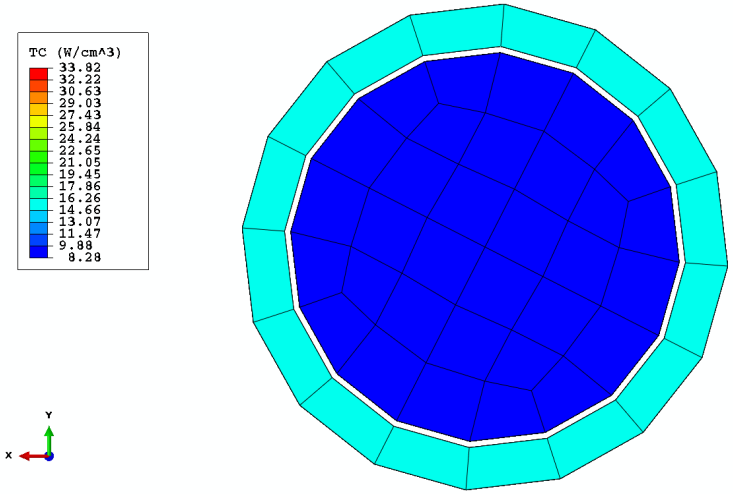




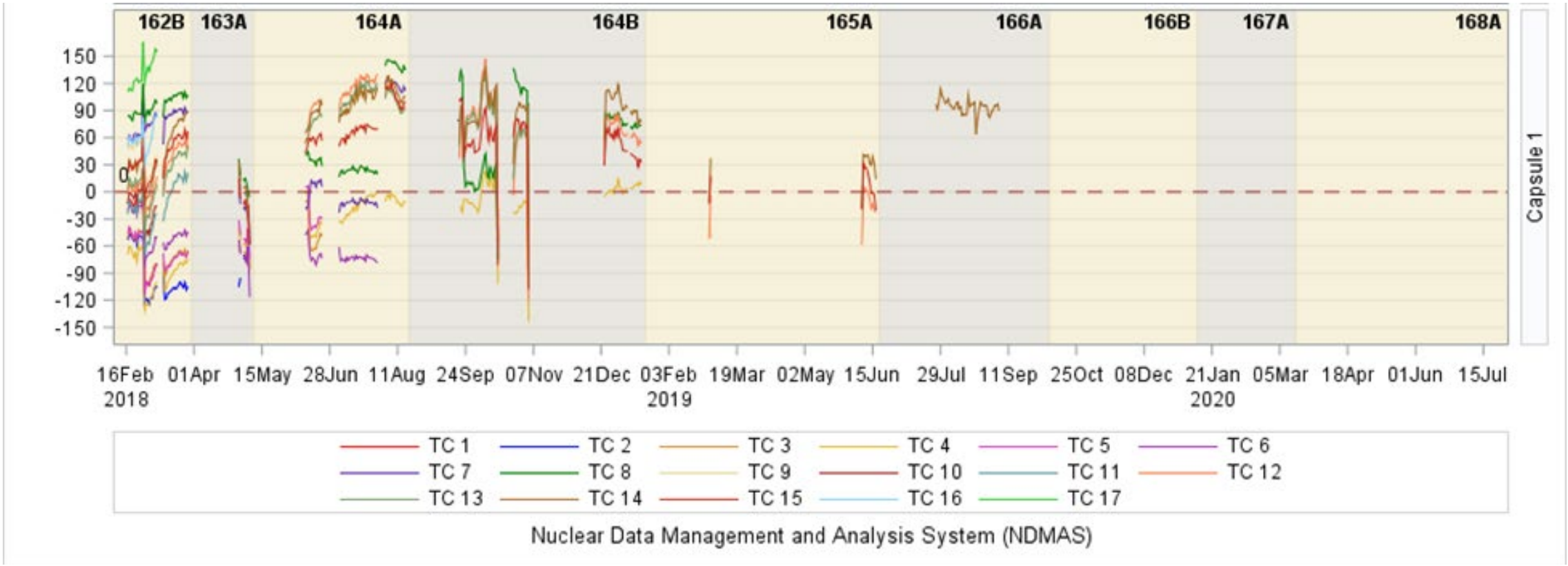
TCs, TC wires, and TC Sleeves Individually Discretized







Original Model (centered) Residuals (measured minus calculated)

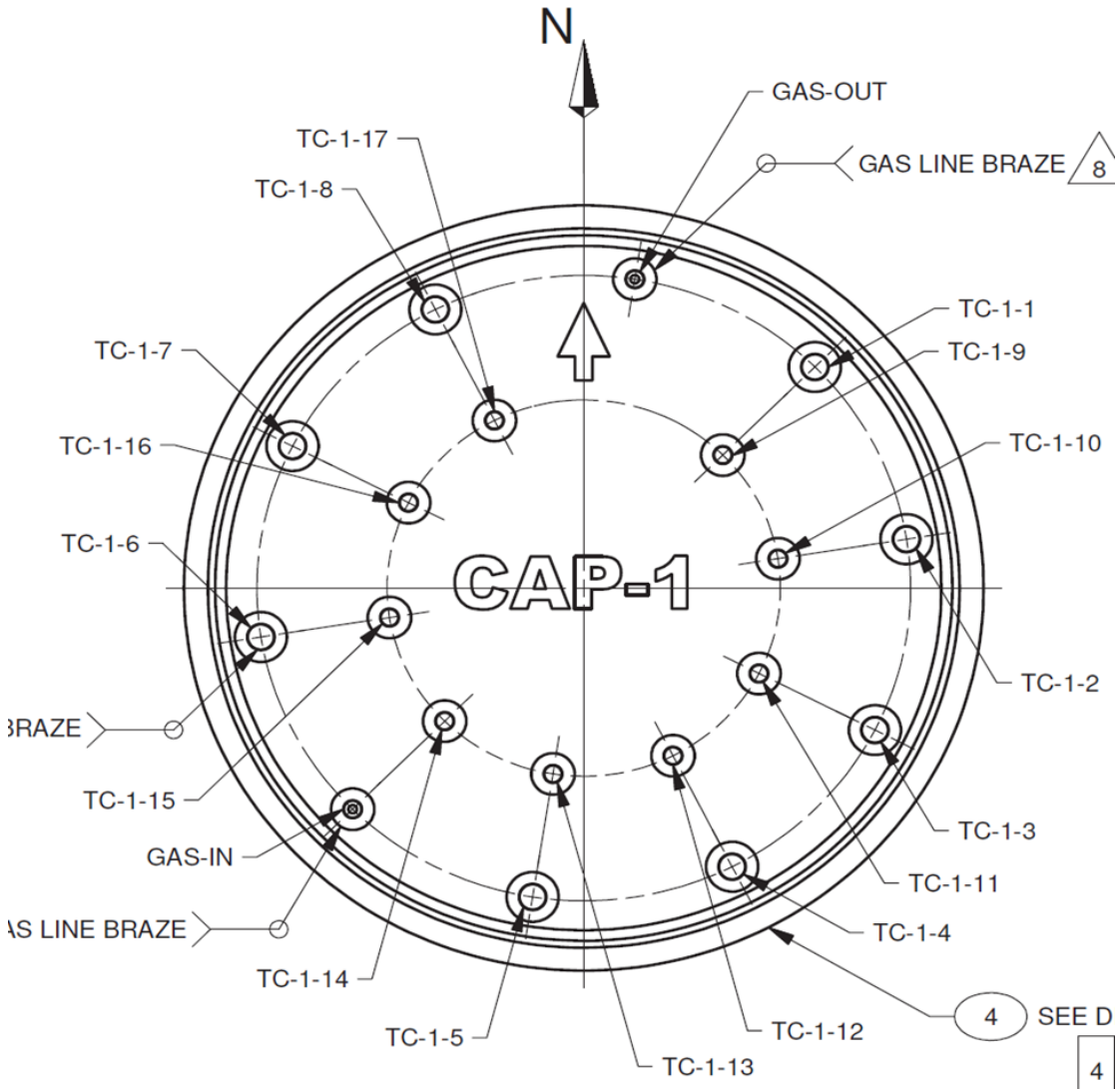


Capsule 1 Offset Examination

- Short nubs lead to holder being able to move with the absence of through tubes
- The basis of this analysis is that the most likely holder shift (offset) should lead to the best match between the measured and calculated temperatures from all operating TC locations in a capsule (with minimum temperature residuals from all TC locations)
- TCs terminate at different depths

TC Number	Penetration, in.	Type or material	Failure during cycle
TC-1-1	2.4	CAMB-N	162B
TC-1-2	2.4	SPINEL-N	163A
TC-1-3	2.4	CAMB-N	164A
TC-1-4	2.4	CAMB-N	165A
TC-1-5	4.4	CAMB-N	164A
TC-1-6	6.4	CAMB-N	164A
TC-1-7	8.4	CAMB-N	164B
TC-1-8	8.4	CAMB-N	164B
TC-1-9	6.4	HTIR-TC	162B
TC-1-10	2.4	HTIR-TC	162B
TC-1-11	2.4	HTIR-TC	162B
TC-1-12	4.4	HTIR-TC	165A
TC-1-13	4.4	HTIR-TC	164B
TC-1-14 – last to fail	2.4	HTIR-TC	166A (middle)
TC-1-15	6.4	HTIR-TC	166A
TC-1-16	2.4	HTIR-TC	162B
TC-1-17	8.4	HTIR-TC	162B

TC Locations

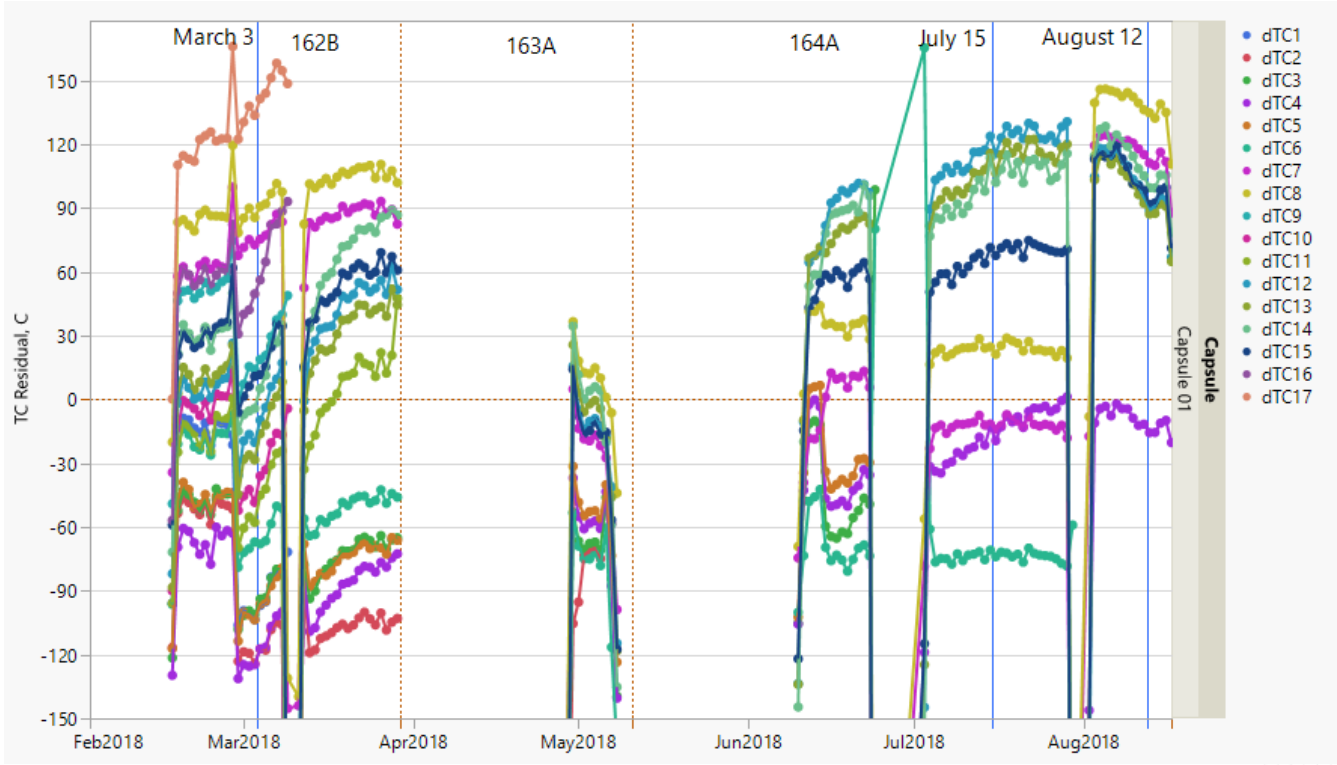


Steps in Examining the Offset Magnitude and Direction

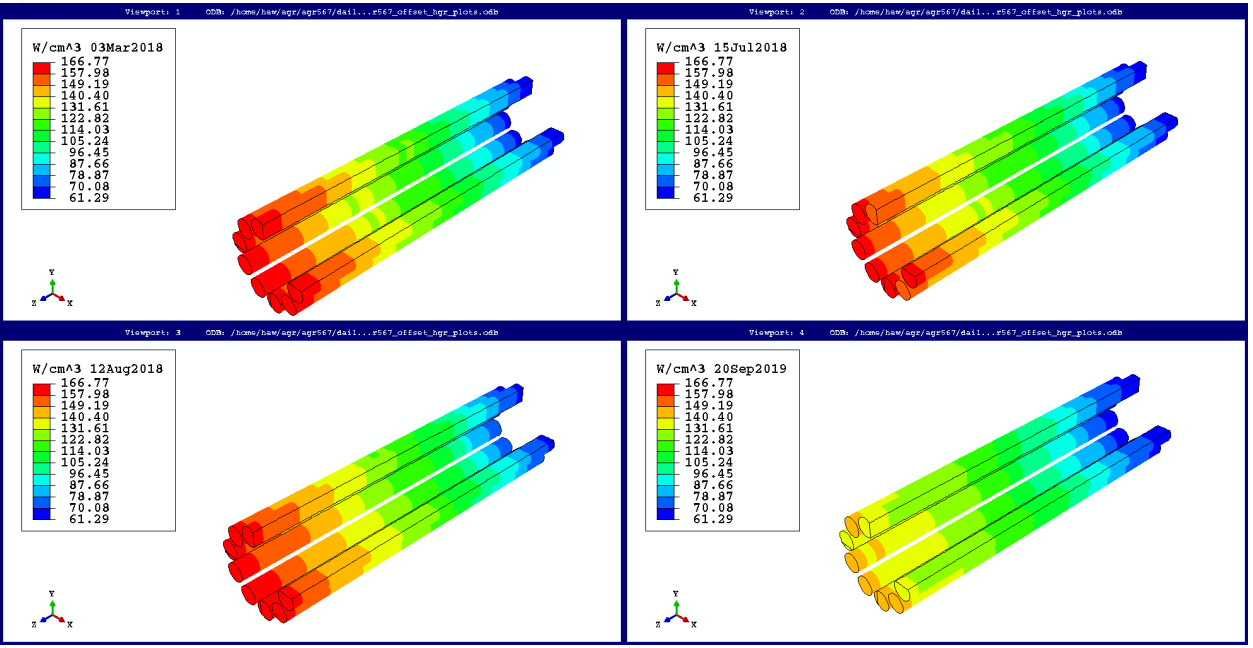
- Select possible options of the offset as combinations of the distances of both the top and /bottom of the holder center from the capsule centerline (i.e., 0.001, 0.002, 0.003, 0.0035 in.) and the top and bottom offset directions (i.e., E, NE, N, NW, W, SW, S, SE).
- Find the best-fit offset combination, when the RMSE of the TC residuals (measured minus thermal simulated TC temperatures) from all the TCs in a capsule is smallest.
- Investigate whether this best-fit offset option is constant over time by repeating Step 1 and Step 2 for several time steps over the AGR-5/6/7 irradiation: March 3, 2018 (Cycle-1 162B); July 15, 2018 (Cycle 3 164A); August 12, 2008 (Cycle 3 164A); September 20, 2019 (Cycle 6 166A). The reasoning behind these selected dates are as follows:

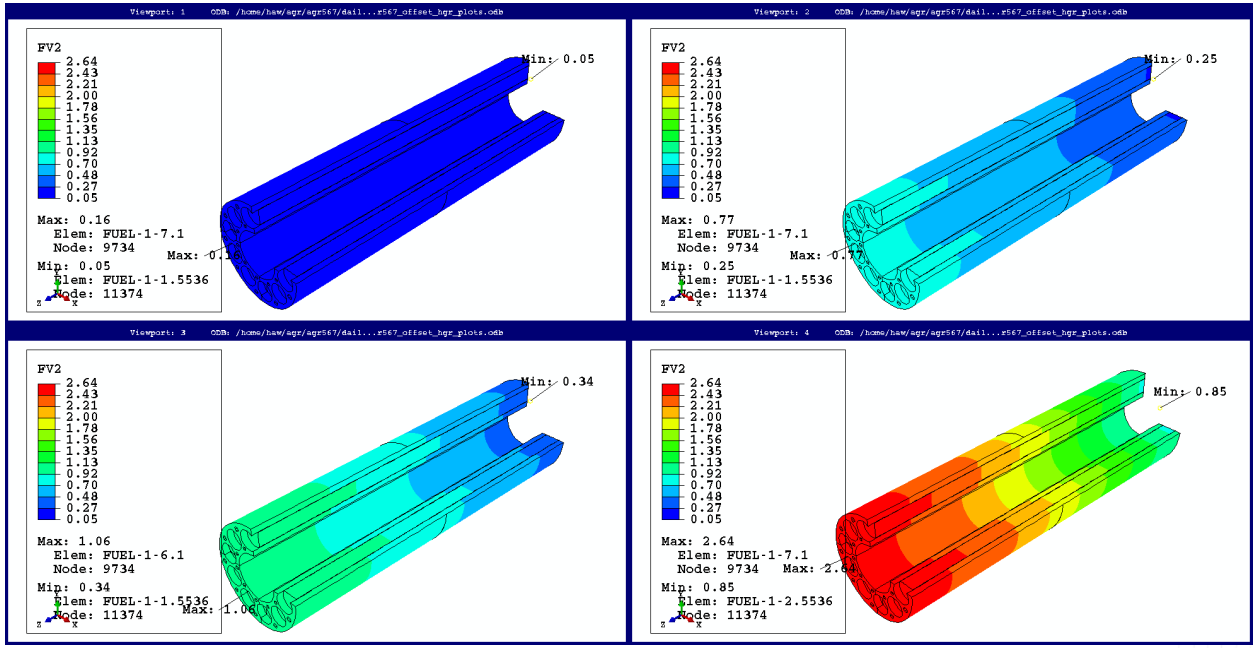
Selected Dates to Examine

- March 3, 2018 (162B): This was near the beginning of irradiation and the temperatures had been raised to the target range. All 17 TCs were still fresh (with minimal drift) and operational, allowing for the best offset optimization.
- July 15, 2018 (164A): This date was selected in order to investigate whether the offset was stable over time, even though only eight of the 17 TCs were still operational (Figure 26).
- August 12, 2018 (164A): This date was selected in order to investigate whether the offset caused a significant increase in TC residuals for several TCs, as shown in Figure 26. For example, the residual for TC-7 (pink) jumped from ~-10℃ to 120℃ and residual for TC-8 (yellow) jumped from ~30℃ to ~140℃ (an increase of more than 100℃).
- September 20, 2019 (166A): All TCs in Capsule 1 failed, so the offset was chosen based on the results from the above three dates in order to investigate the peak capsule temperatures at this time that immediately preceded the start of massive particle failures near the end of this cycle (Pham et al, 2021).

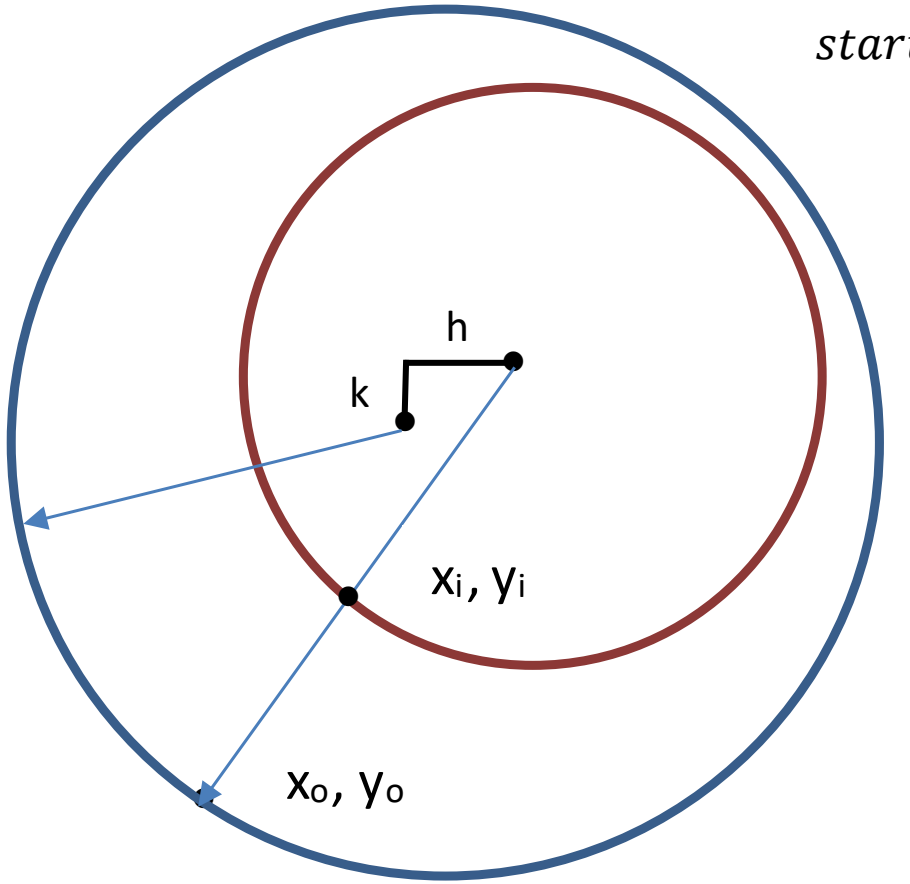


HGRs and Fast Neutron Fluence for Chosen Dates





Offset Theory



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

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

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

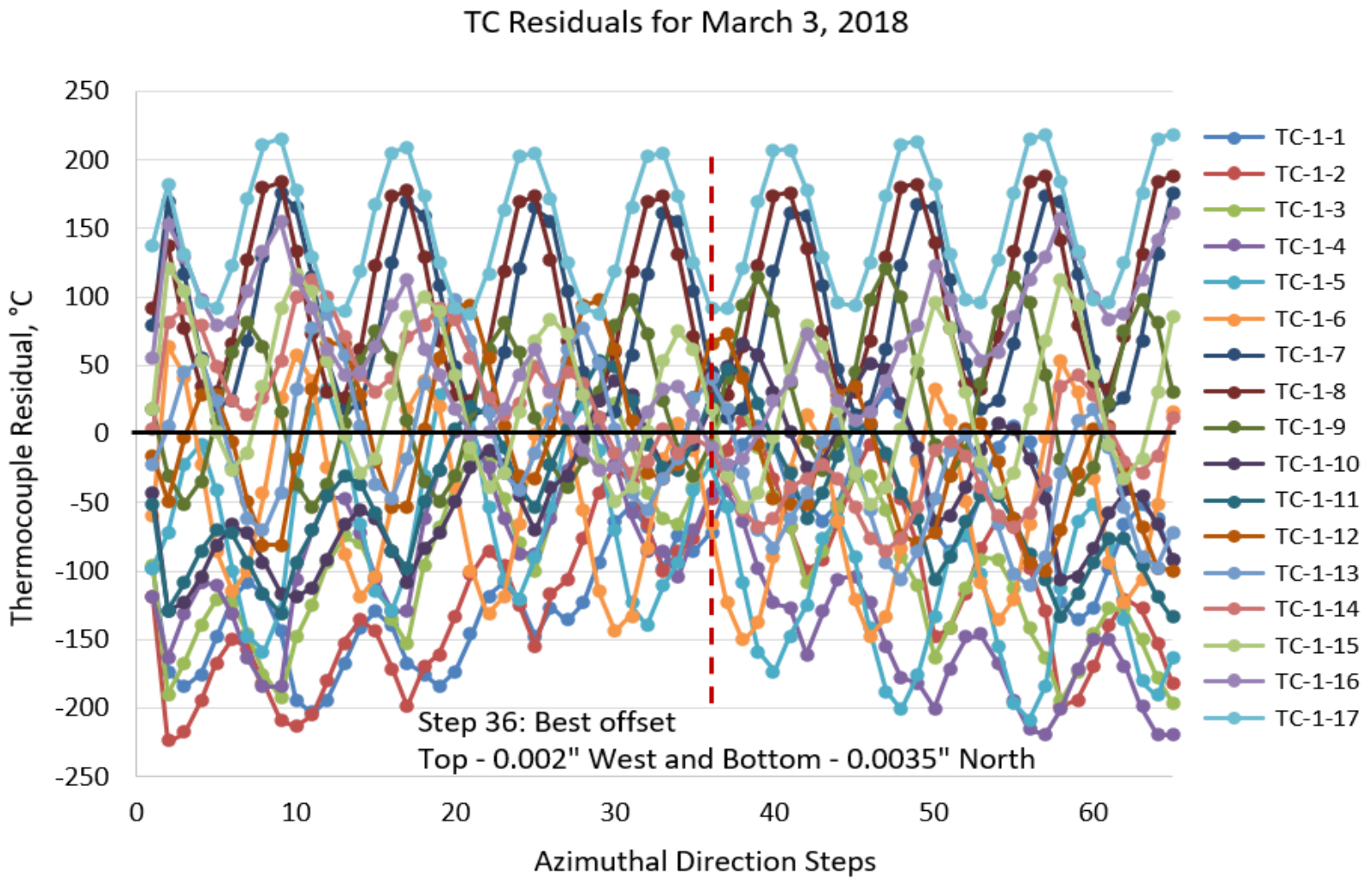
$$gap = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2}$$

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

Sixty-five Combinations of the Top and Bottom Offset Directions per Computer Run

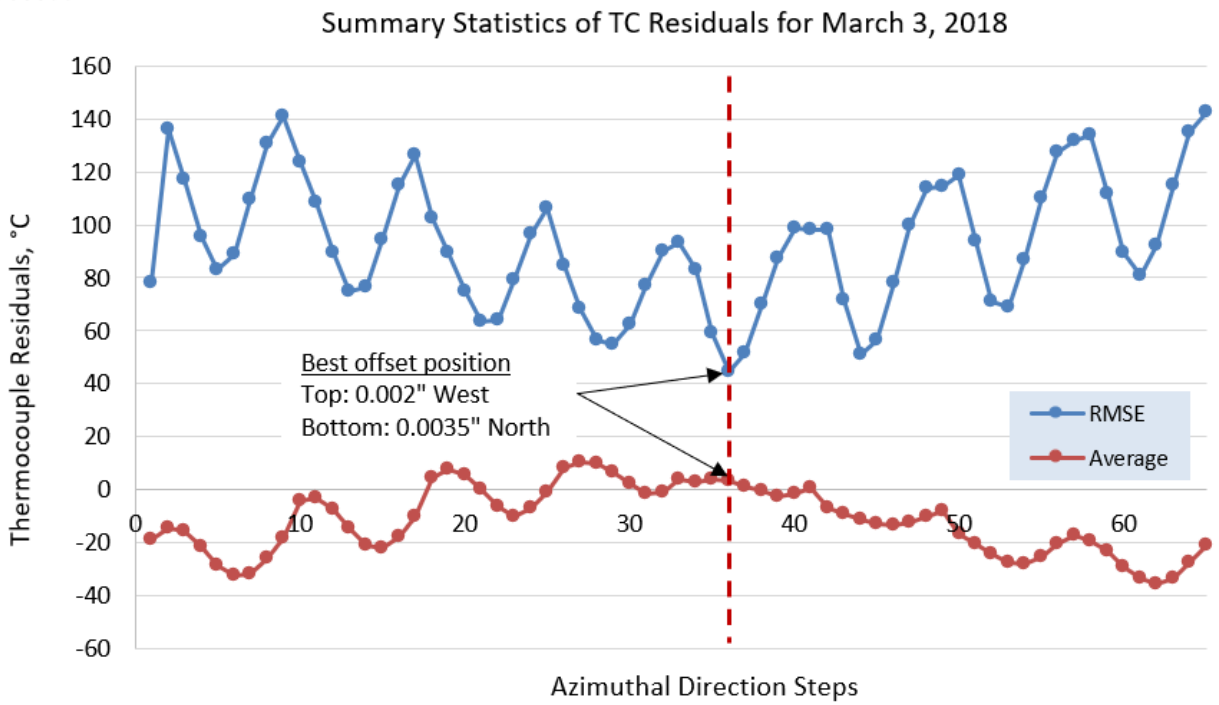
Step	Top direction	Bottom direction
1	Center	Center
2 – 9	E	E, NE, N, NW, W, SW, S, SE
10 – 17	NE	E, NE, N, NW, W, SW, S, SE
18 – 25	N	E, NE, N, NW, W, SW, S, SE
26 – 33	NW	E, NE, N, NW, W, SW, S, SE
34 – 41	W	E, NE, N, NW, W, SW, S, SE
42 – 49	SW	E, NE, N, NW, W, SW, S, SE
50 – 57	S	E, NE, N, NW, W,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

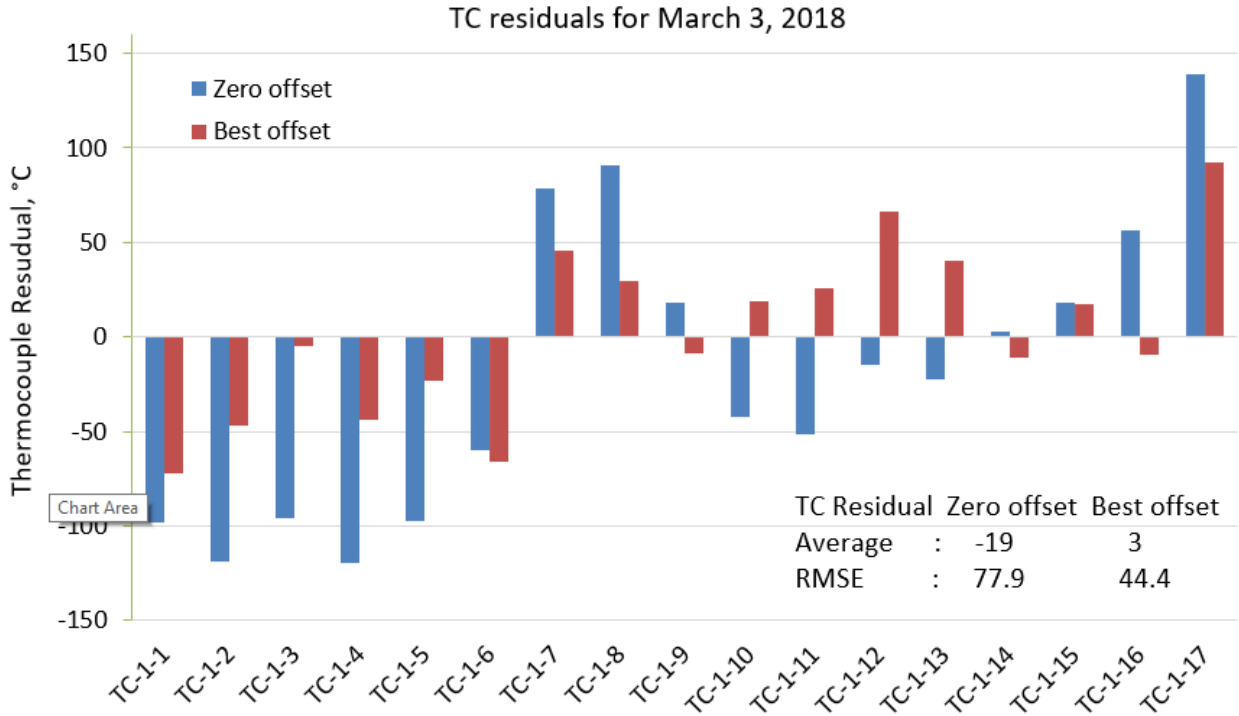
March 3, 2018



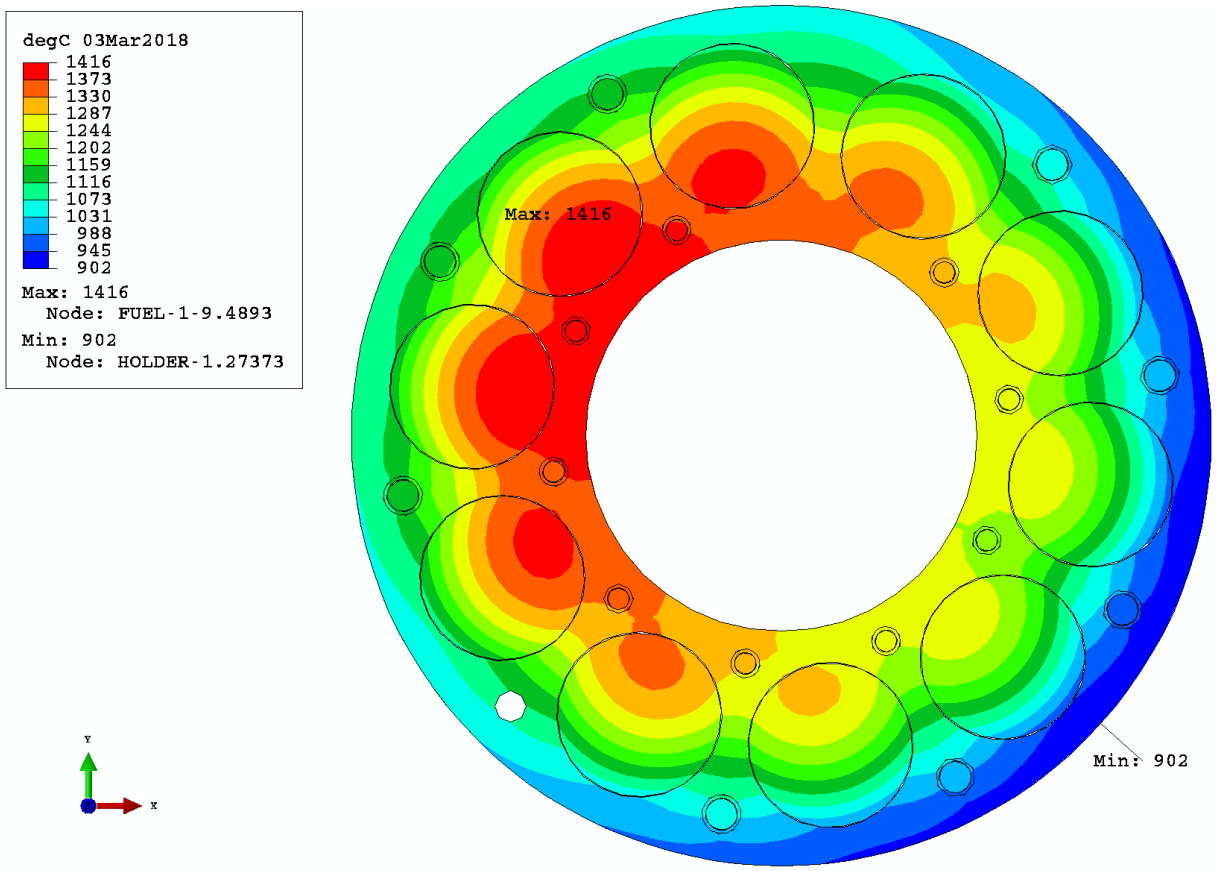
March 3, 2018 (162B) – all 17 TCs remained: Distances / Directions / Minimum RMSE			
t1b1 / tNWbNW / 59.0	t1b2 / tWbNW / 54.1	t1b3 / tWbNW / 50.8	t1b35 / tWbNW / 50.1
t2b1 / tNWbNW / 53.6	t2b2 / tWbN / 47.9	t2b3 / tWbN / 44.7	t2b35 / tWbN / 44.4
t3b1 / tWbN / 55.3	t3b2 / tWbN / 49.9	t3b3 / tWbN / 47.1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

March 3, 2018

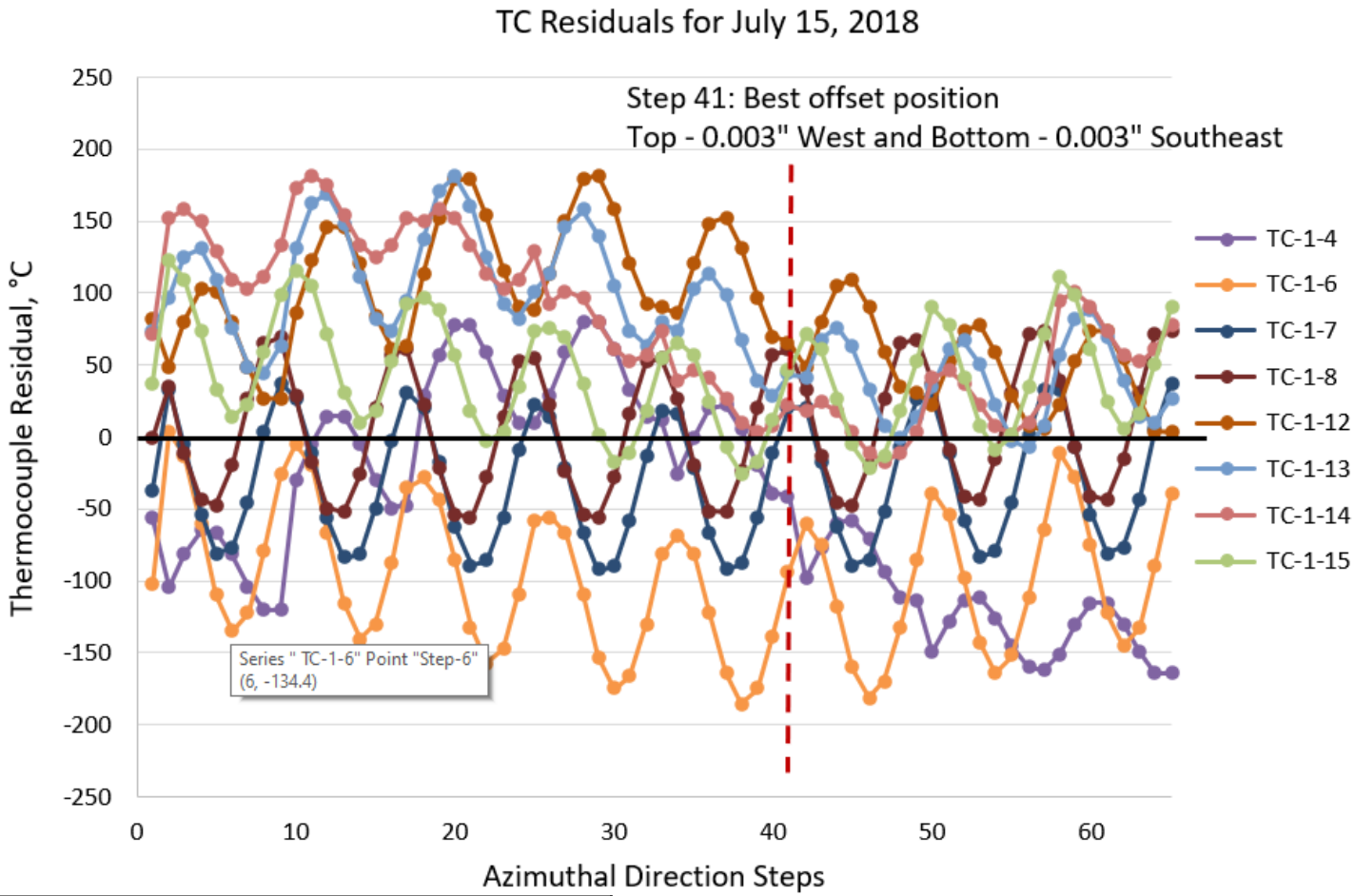

Summary Statistics of TC Residuals for March 3, 2018
Thermocouple Residuals, °C
Azimuthal Direction Steps
Best offset position
Top: 0.002" West
Bottom: 0.0035" North
RMSE
Average


TC residuals for March 3, 2018
Thermocouple Resudual, °C
Zero offset
Best offset
Chart Area
TC Residual Zero offset Best offset
Average : -19 3
RMSE : 77.9 44.4
TC-1-1
TC-1-2
TC-1-3
TC-1-4
TC-1-5
TC-1-6
TC-1-7
TC-1-8
TC-1-9
TC-1-10
TC-1-11
TC-1-12
TC-1-13
TC-1-14
TC-1-15
TC-1-16
TC-1-17

March 3, 2018 temperature (°C) contour plot of the 0.25 in. slice (level 7) in which the highest temperature occurs for the best-fit offset position being 0.002 in. top west and 0.0035 in. bottom north (Step 36)

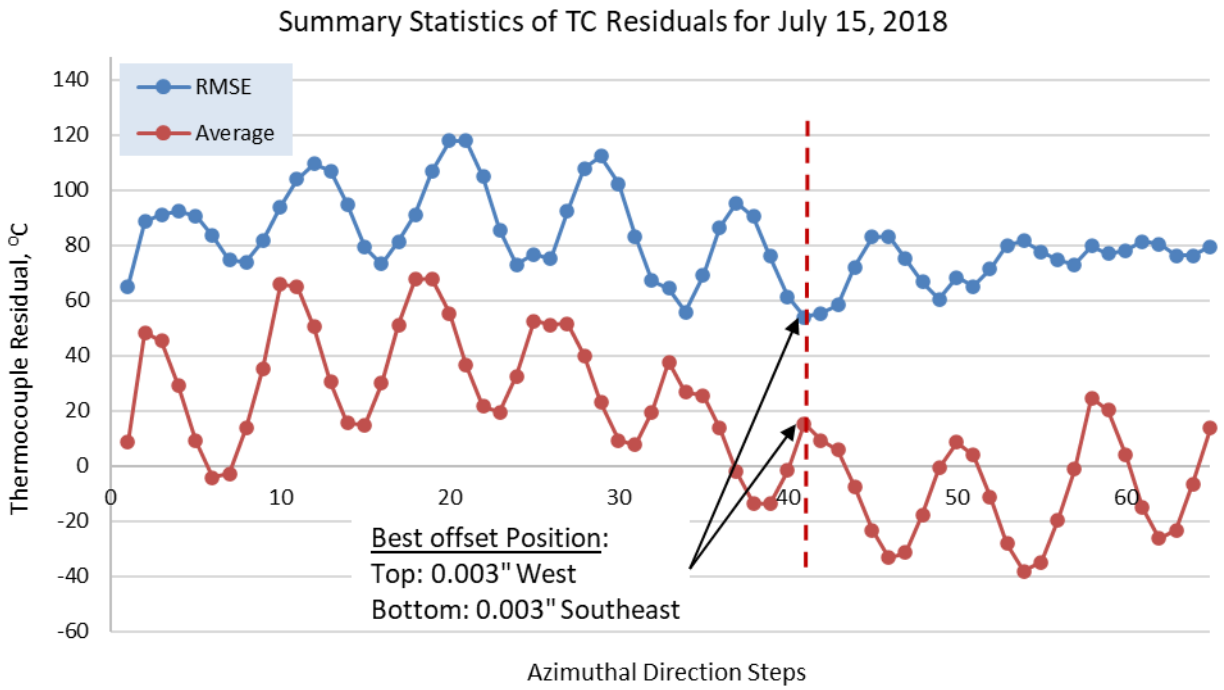


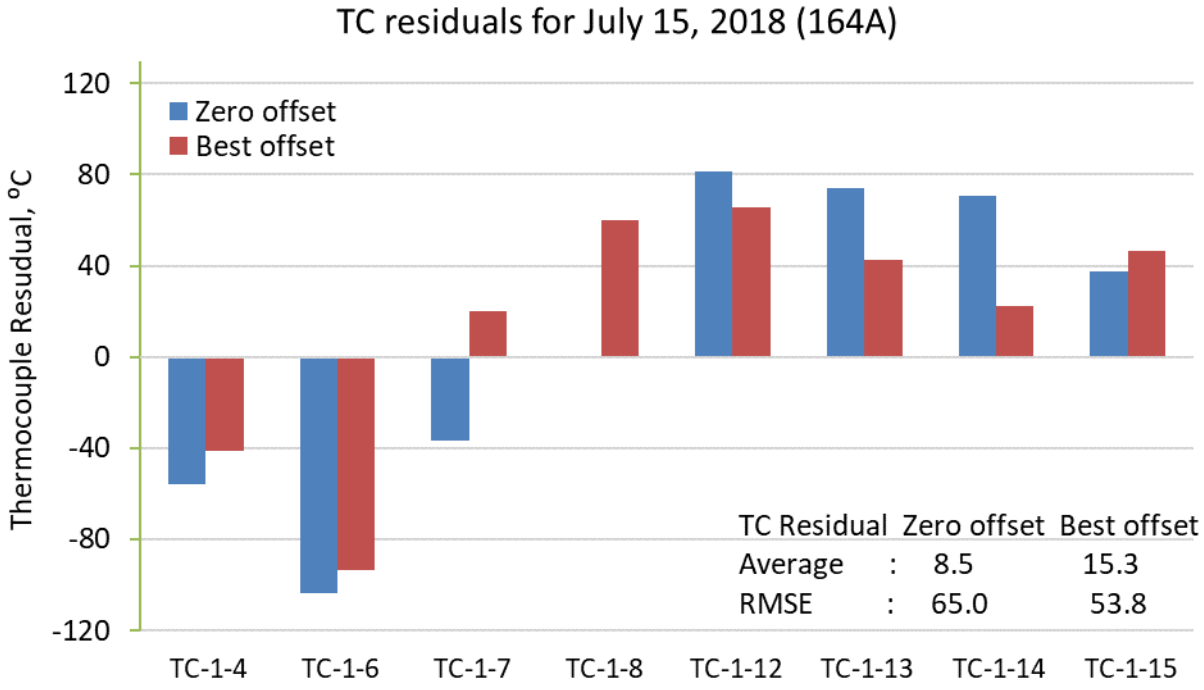
July 15, 2018



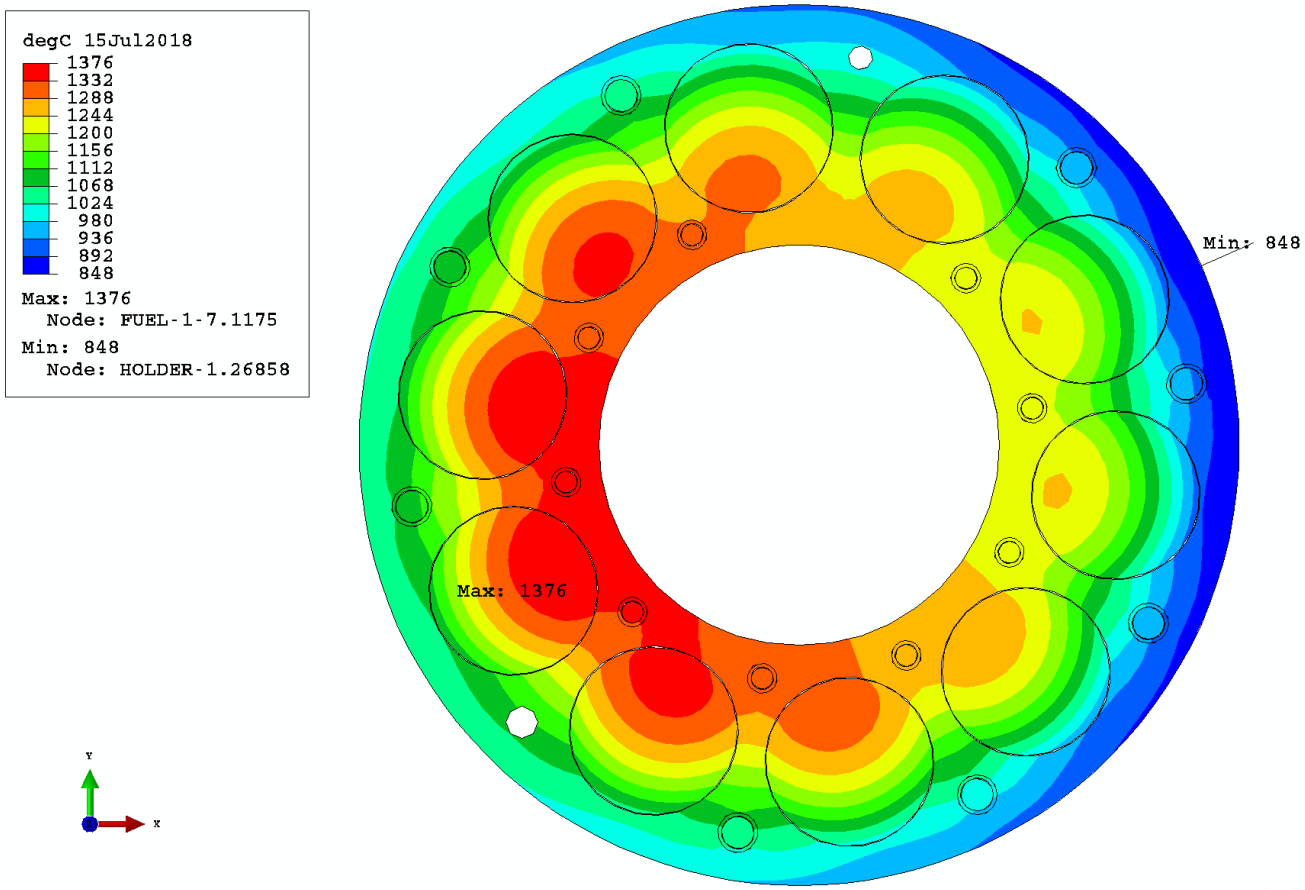
July 15, 2018 (164A) – 8 TCs remained: Distances / Directions / Minimum RMSE					
t15b15 tSWbSE/56.4	–	t15b3 tWbSE/56.0	–	t15b45 tNWbS/63.8	t15b55 t0b0/65.0
–	t2b2 tWbSE/54.8	t2b3 tWbSE/54.8	t2b35 tWbSE/56.5	–	–
t3b15 tSWbE/55.7	t3b2 tSWbE/54.7	t3b3 tWbSE/53.8	t3b35 tWbSE/54.9	t3b45 tWbSE/60.4	t3b55 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

July 15, 2018

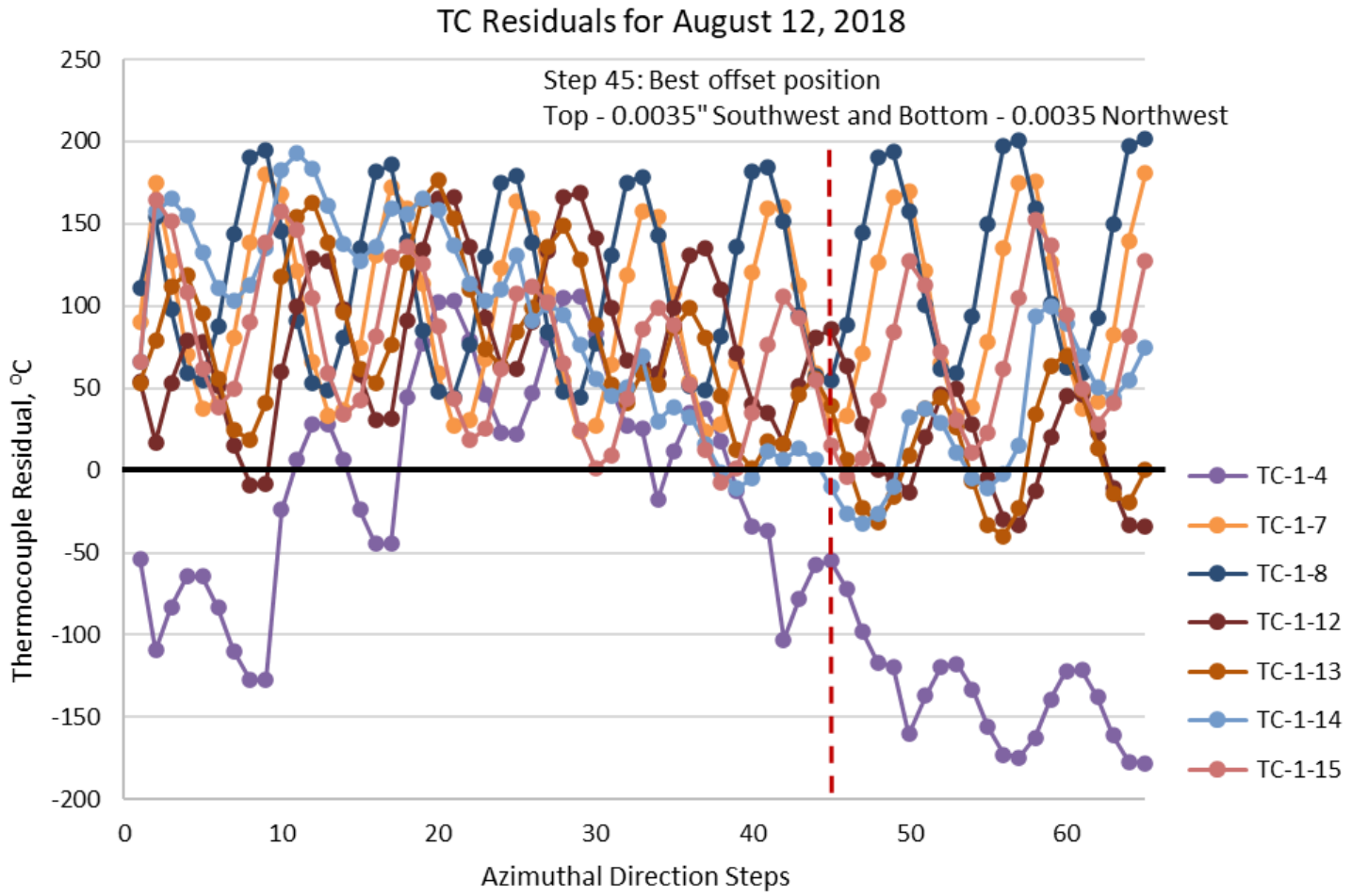

Summary Statistics of TC Residuals for July 15, 2018
RMSE
Average
Thermocouple Residual, °C
140
120
100
80
60
40
20
0
-20
-40
-60
0
10
20
30
40
50
60
Best offset Position:
Top: 0.003" West
Bottom: 0.003" Southeast
Azimuthal Direction Steps


TC residuals for July 15, 2018 (164A)
Zero offset
Best offset
Thermocouple Resudual, °C
120
80
40
0
-40
-80
-120
TC-1-4
TC-1-6
TC-1-7
TC-1-8
TC-1-12
TC-1-13
TC-1-14
TC-1-15
TC Residual Zero offset Best offset
Average : 8.5 15.3
RMSE : 65.0 53.8

July 15, 2018 temperature (°C) contour plot of the 0.25 in. slice (level 8) in which the highest temperature occurs for the best-fit offset position being 0.003 in. top west and 0.003 in. bottom southeast (Step 41).

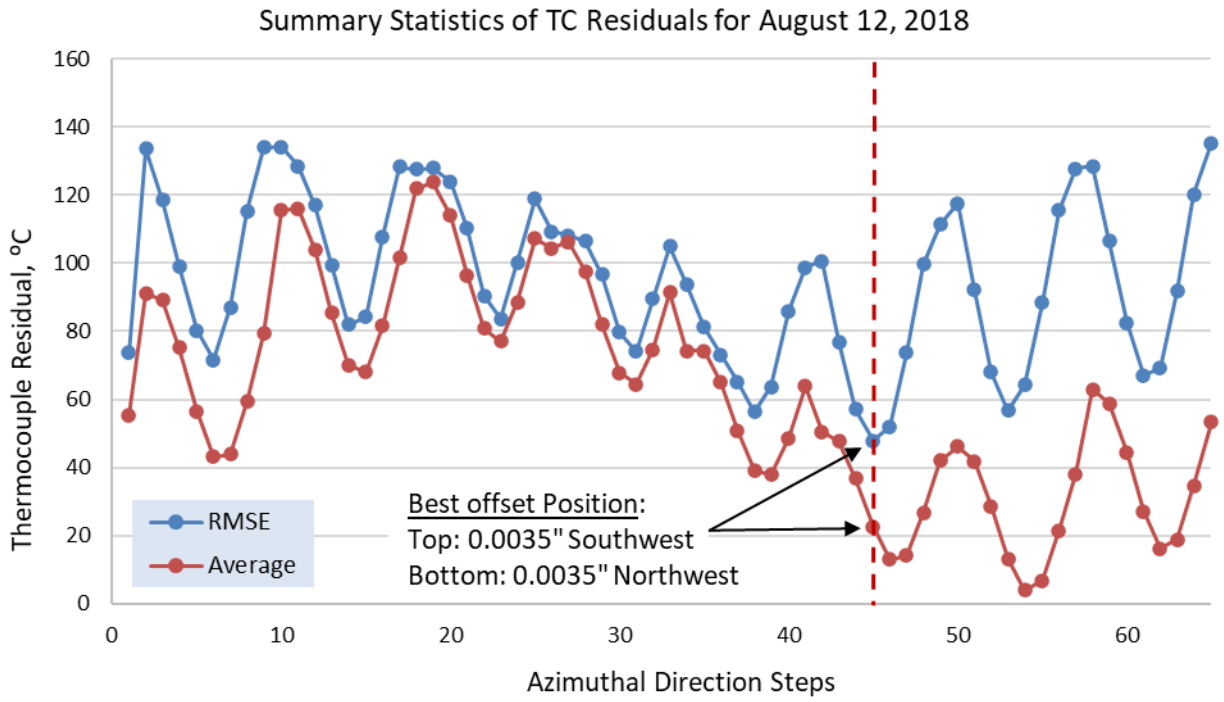


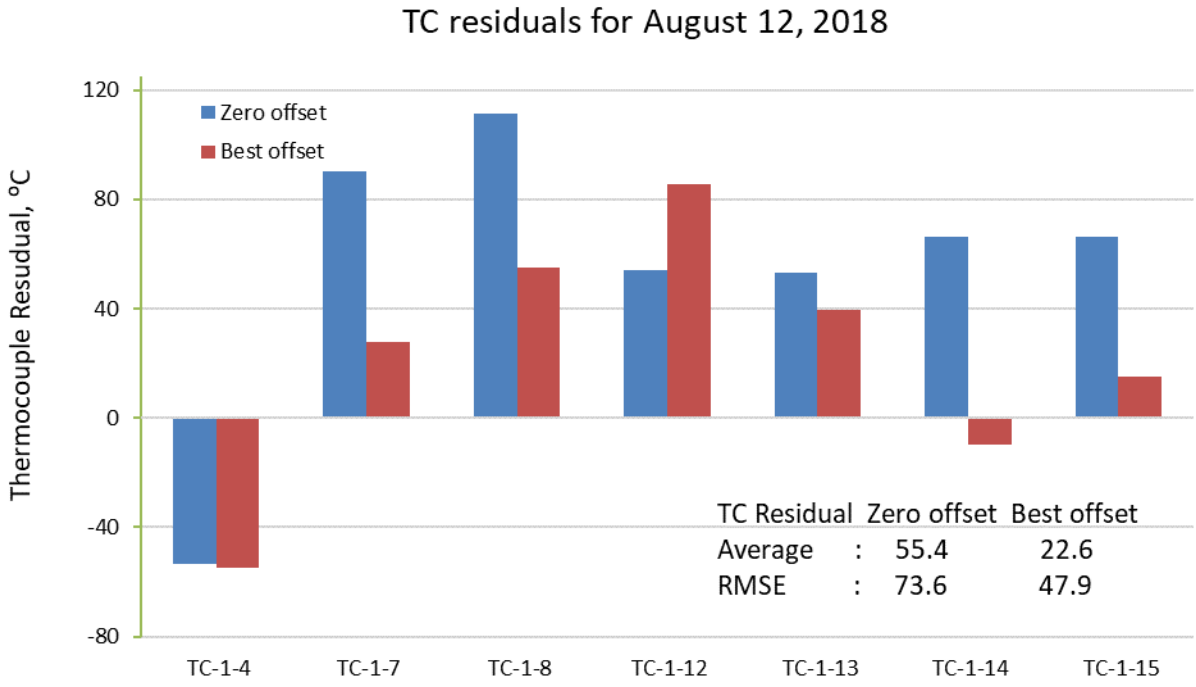
August 12, 2018



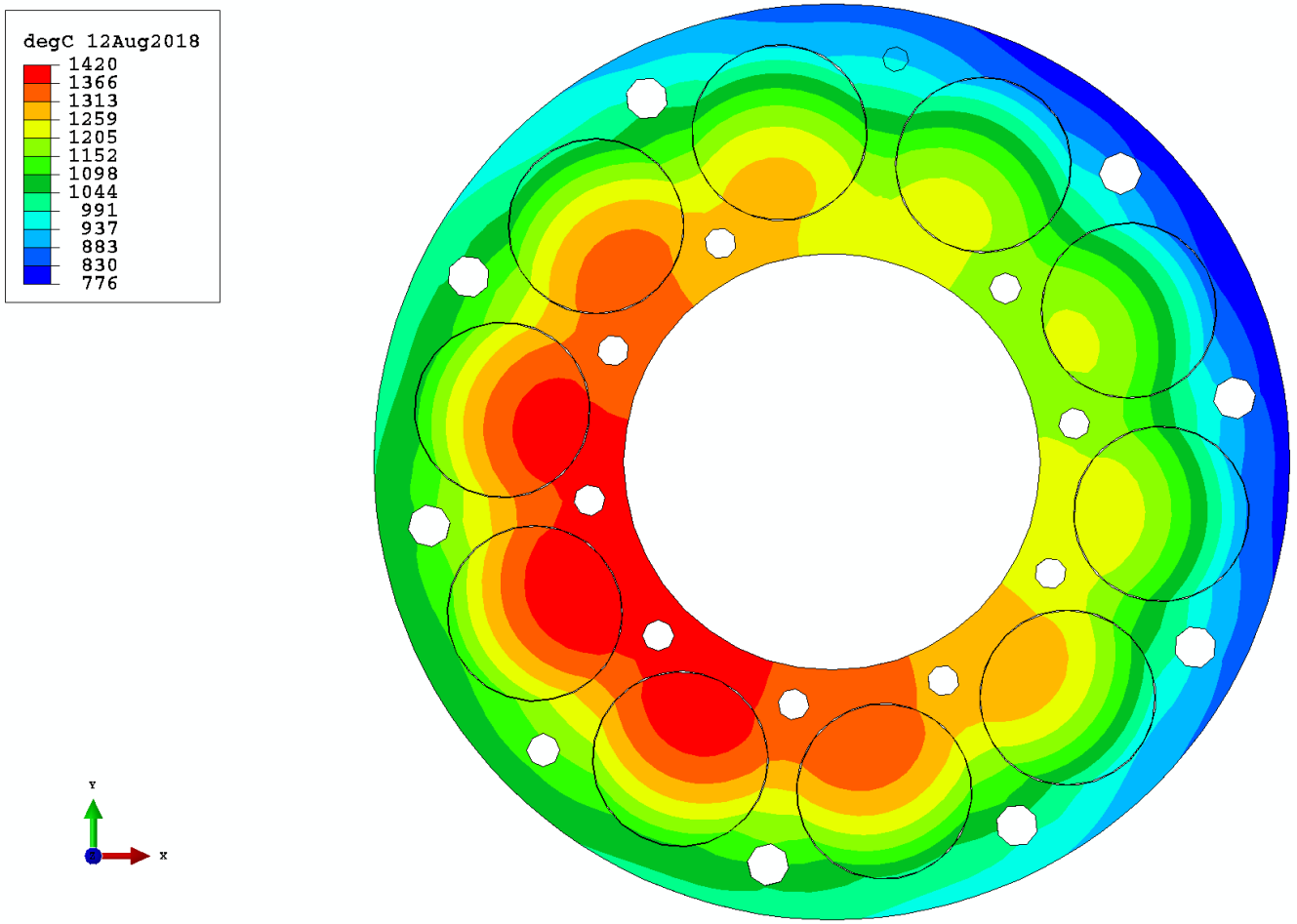
August 12, 2018 (164A) – 7 TCs remained: Distances / Directions / Minimum RMSE			
t2b2 / tSWbNW / 54.0	t2b3 / tSWbW / 51.3	t2b35 / tSWbW / 49.9	t2b45 / tSWbW / 48.6
t3b2 / tSWbNW / 52.5	t3b3 / tSWbNW / 49.0	t3b35 / tSWbNW / 48.4	t3b45 / tSWbNW / 49.6
t35b2 / tSWbNW / 52.4	t35b3 / tSWbNW / 48.7	t35b35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

August 12, 2018

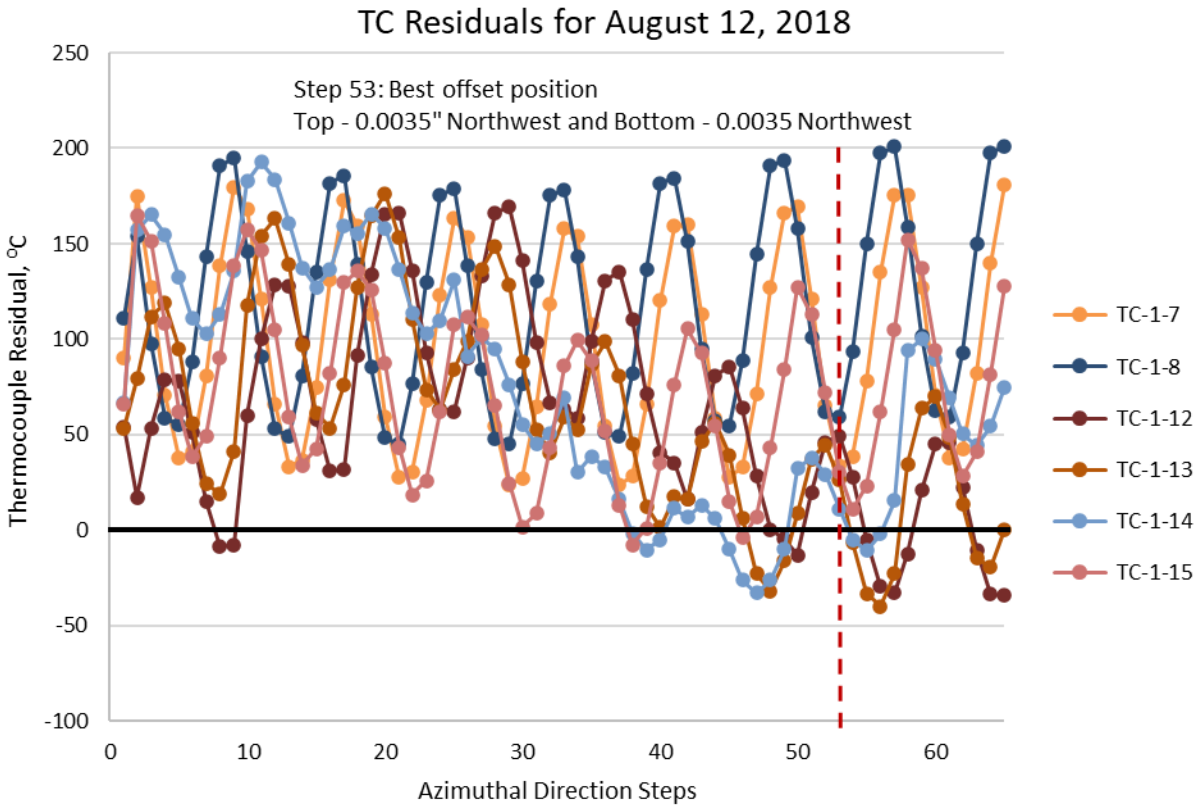


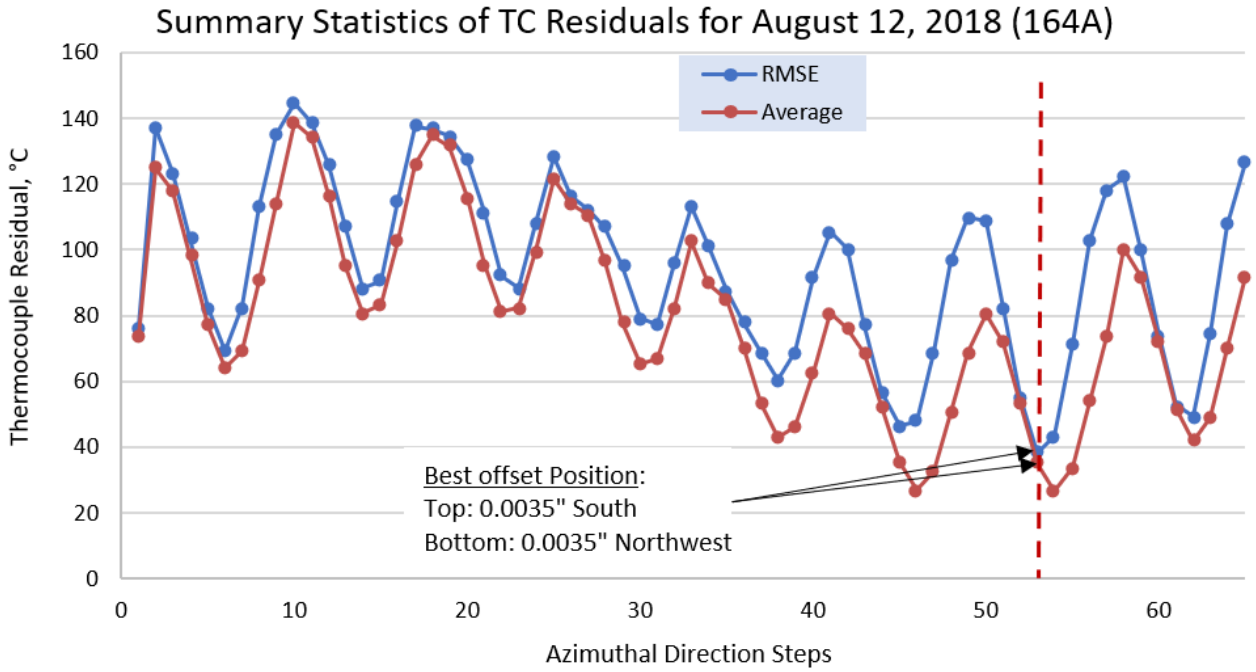


August 12, 2018 temperature (°C) contour plot of the 0.25 in. slice (level 8) in which the highest temperature occurred for the best-fit offset position being 0.0035 in. top south and 0.0035 in. bottom northwest Step 45

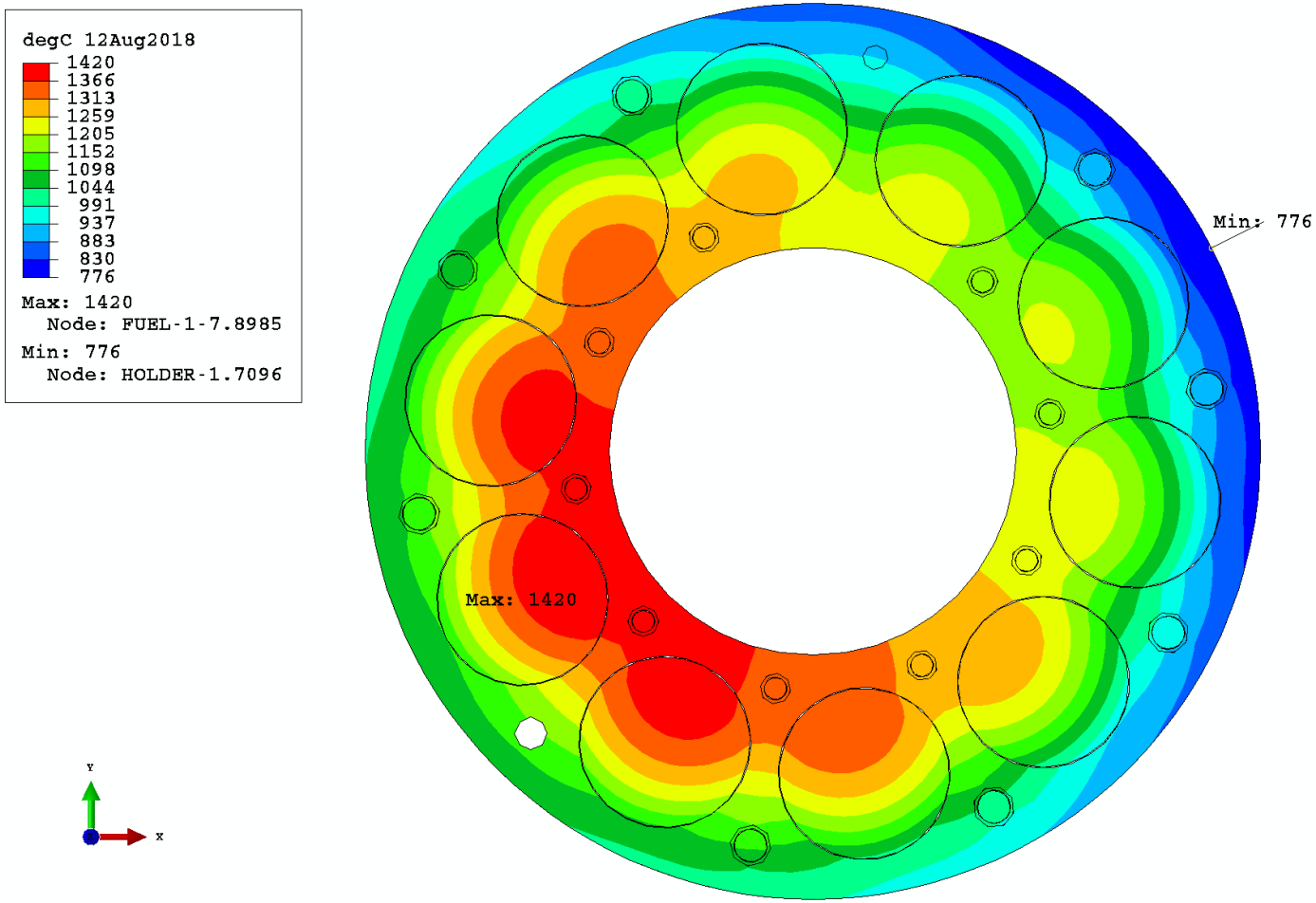


August 12, 2018 Excluding TC 1-4





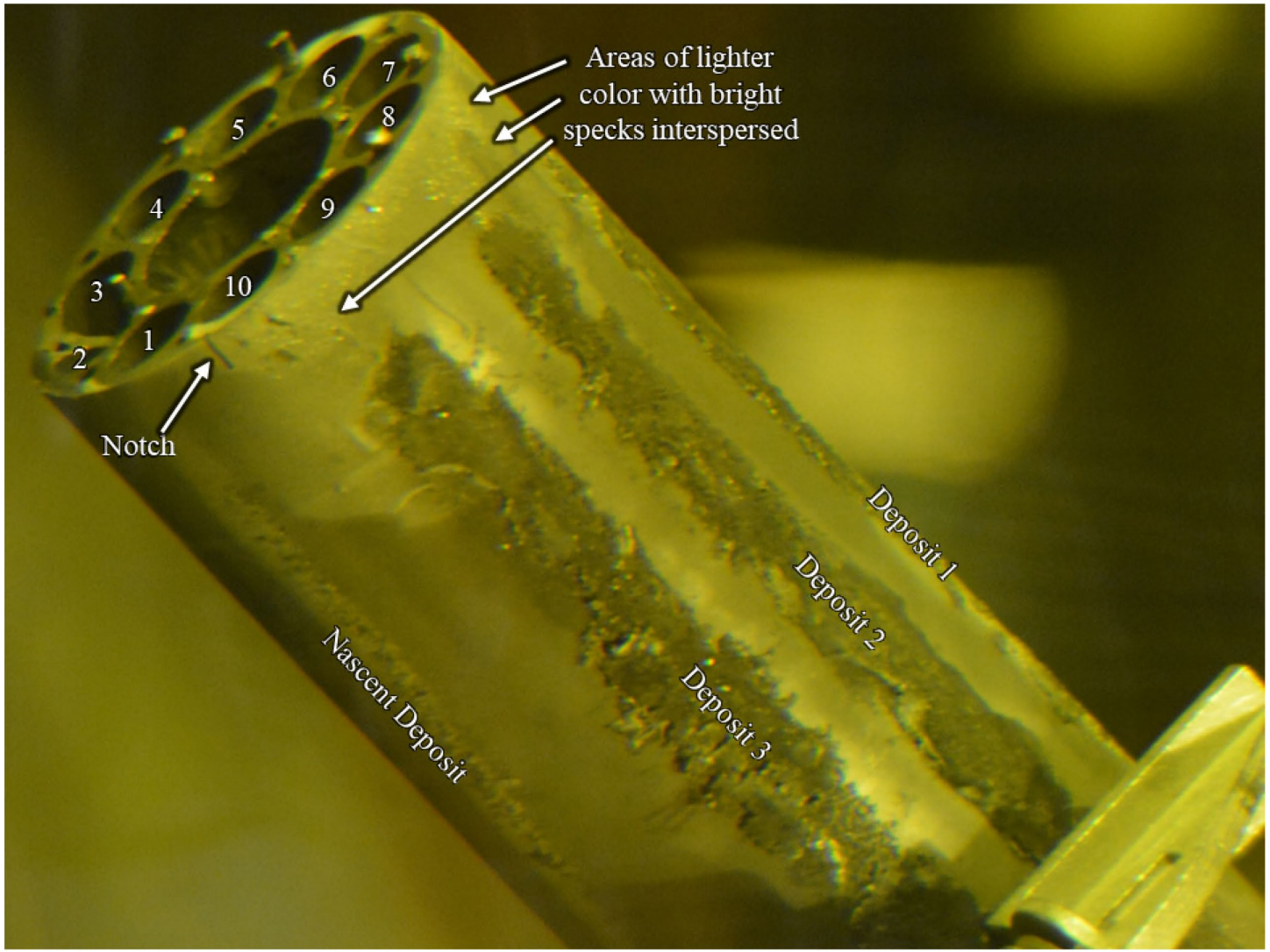
August 12, 2018 temperature (°C) contour plot of the 0.25 in. slice (level 8) in which the highest temperature occurs for, the best-fit offset position being 0.0035 in. top south and 0.0035 in. bottom northwest Step 53 (excludes TC1-4).



Summary of best-fit options for three dates in 2018

Date – Cycle	Distance, in.	Direction	No. of TCs	RMSE reduction, °C	Average residual, °C
March 3 – 162B	T- 0.002 B- 0.0035	T- West B- North	17	77.9 to 44.4	3.0
July 15 – 164A	T- 0.003 B- 0.003	T- West B- Southeast	8	65 to 53.8	15.3
August 12 – 164A	T- 0.0035 B- 0.0035	T- Southwest B- Northwest	7	73.6 to 47.9	22.6

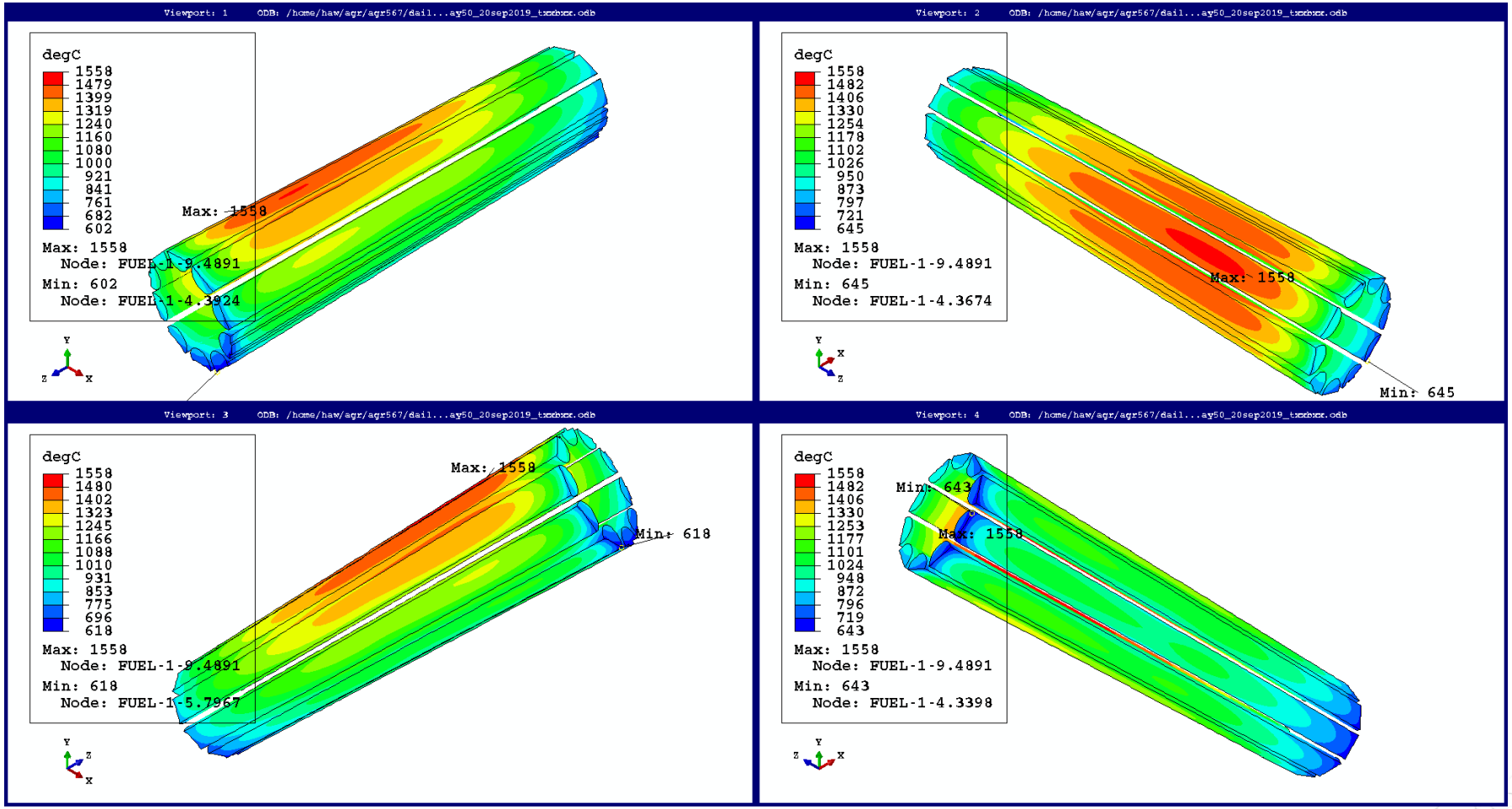
Capsule 1 PIE picture with deposits



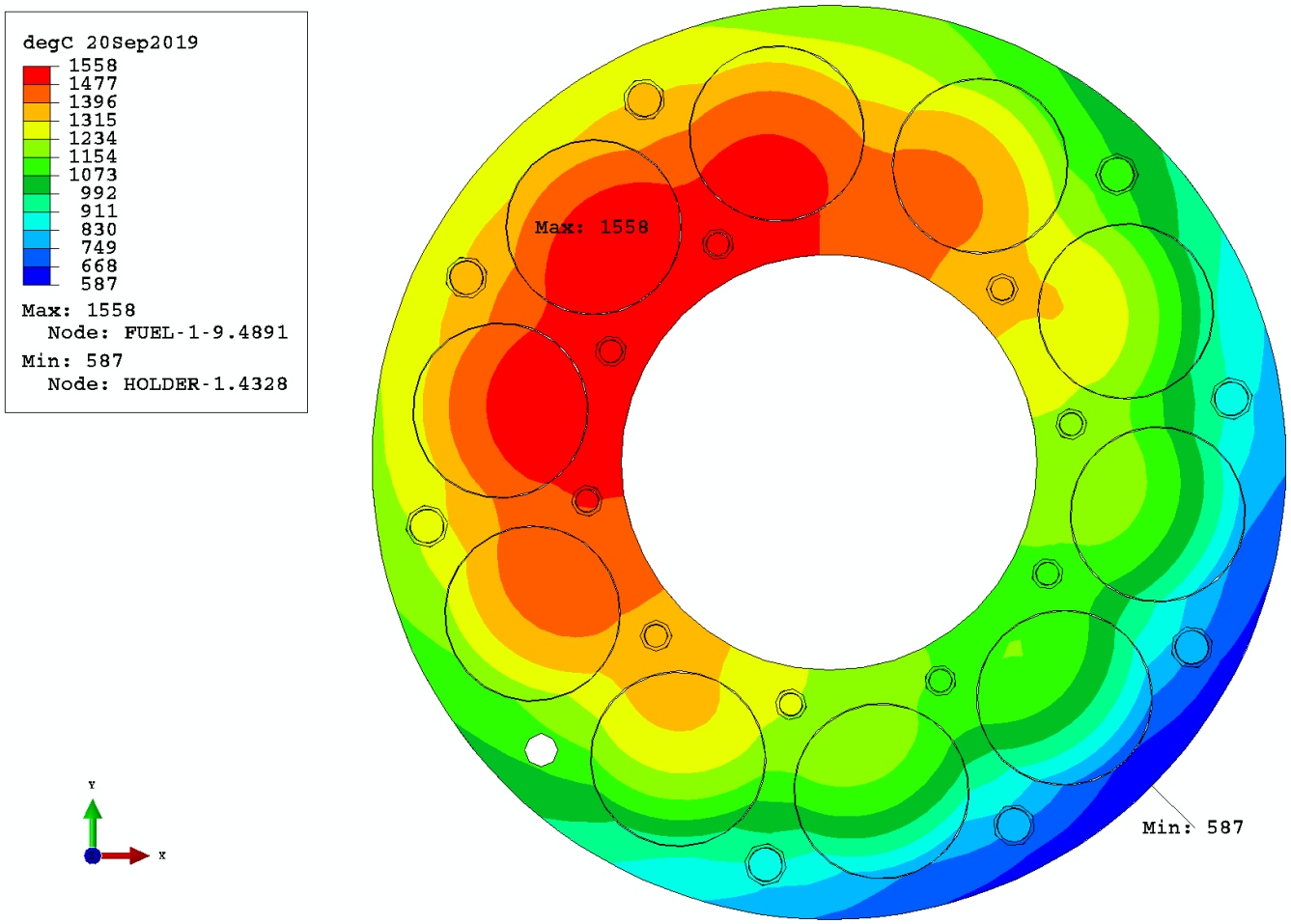
Sep 20, 2019 Capsule 1 fuel compact temperatures for various offset options

Offset Option	Minimum Temperature °C	Average Temperature °C	Maximum Temperature °C	Maximum Temperature Compact
Zero	731	1184	1422	1-8-6
Top: 0.002” Southwest; Bottom: 0.002” Northwest	680	1181	1469	1-8-7
Top: 0.004” Southwest; Bottom: 0.004” Northwest	614	1173	1512	1-8-7
Top: 0.006” Southwest; Bottom: 0.006” Northwest	533	1159	1550	1-8-7
Top: 0.002” Northwest; Bottom: 0.002” Northwest	683	1180	1465	1-7-9
Top: 0.004” Northwest; Bottom: 0.004” Northwest	609	1166	1516	1-7-9
Top: 0.006” Northwest; Bottom: 0.006” Northwest	518	1143	**1557**	1-7-9

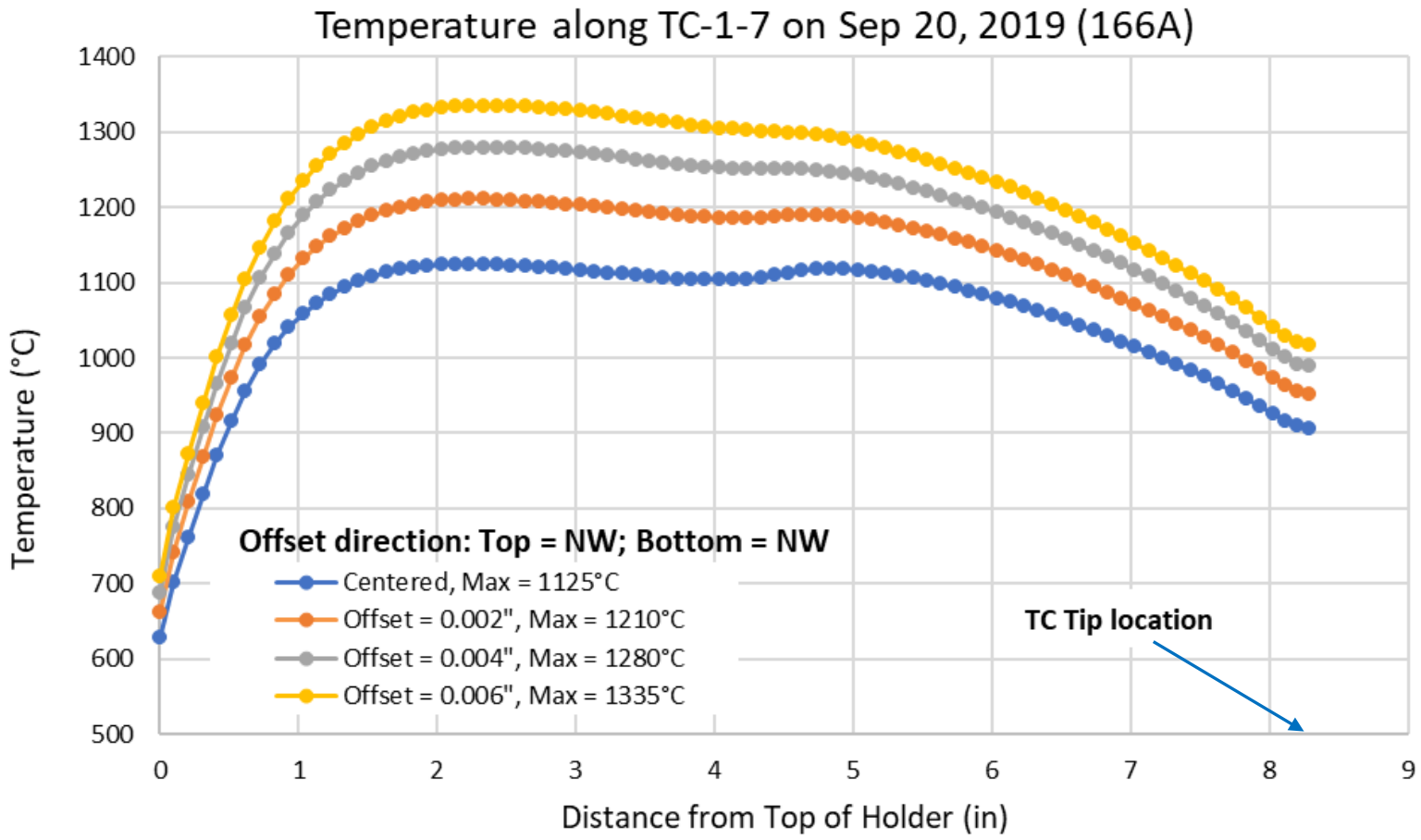
Sep 20, 2019 cutaway view of Capsule 1 fuel temperature (°C) offset 0.006 in. to NW from four different perspective angles



September 20, 2019 temperature (°C) contour plot of the 0.25 in. slice (level 7) in which the highest temperature occurs with the offset position being 0.006 in. top northwest and 0.006 in. bottom northwest



Sep 20, 2019 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



Capsule 1 fuel compact temperatures for zero and best-fit offset for three selected dates in 2018 and maximum offset for Cycle 166A in 2019

	Zero offset			Best-fit offset		
	Minimum	Maximum	Average	Minimum	Maximum	Average
March 3, 2018 (162B): Top: 0.002” West; Bottom: 0.0035” North						
Temperature, C	728	1350	1126	664	1414	1118
Compact name	1-1-1	1-7-7	—	1-1-5	1-7-9	—
July 15, 2018 (164A): Top: 0.003” West; Bottom: 0.003” Southeast						
Temperature, C	662	1319	1082	615	1374	1078
Compact name	1-1-1	1-8-5	—	1-1-9	1-8-7	—
August 12, 2018 (164A): Top: 0.0035” Northwest; Bottom: 0.0035” Northwest						
Temperature, C	652	1336	1086	589	1418	1080
Compact name	1-1-1	1-8-7	—	1-1-9	1-8-7	—
September 20, 2019 (166A): Top: 0.006” Northwest; Bottom: 0.006” Northwest (maximum offset)						
Temperature, C	731	1422	1184	518	1557	1143
Compact name	1-9-2	1-8-6	—	1-9-4	1-7-9	—

Conclusions

- Top offset best-fit was consistently in the W, NW and N direction
- Bottom offset best-fit was in various directions (consistent with Capsule 1 design)
- Any offset magnitude showed lower average fuel temperature, lower low and higher high
- September 20, 2019 (166A) the maximum offset of 0.006 in. to the northwest direction for both the top and bottom yielded a much higher temperature than the original (holder-centered) peak fuel temperature, which increased from 1422℃ to 1557℃ (i.e., a 135℃ increase). This is consistent with the hypothesized cause of massive particle failure near the end of Cycle 165A.
- September 20, 2019 (166A) even though the highest temperature at the tip of TC-1-7 slightly exceeded 1000℃, the temperature along the TC wire reached as high as 1335℃, assuming an offset of 0.006 in. in the northwest. Consequently, at this temperature, nickel from this TC wire could cause particle failure in Capsule 1.

Thank You

- Grant Hawkes - INL