INL/CON-20-59536-Revision-0

Cylindricity Sensitivity Thermal Model of the AGR-5/6/7 Experiment in the Advanced Test Reactor

November 2020

Changing the World's Energy Future

Grant L Hawkes

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

INL/CON-20-59536-Revision-0

Cylindricity Sensitivity Thermal Model of the AGR-5/6/7 Experiment in the Advanced Test Reactor

Grant L Hawkes

November 2020

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Proceedings of the ASME 2020
International Mechanical Engineering Congress and Exposition
IMECE2020
November 16-19, 2020, Portland, OR, USA

IMECE2020-23329

CYLINDRICITY SENSITIVITY THERMAL MODEL OF THE AGR-5/6/7 EXPERIMENT IN THE ADVANCED TEST REACTOR

Grant L. Hawkes[1]
Idaho National Laboratory
Idaho Falls, ID USA

ABSTRACT

The AGR-5/6/7 experiment is currently being irradiated in the Advanced Test Reactor (ATR) at the Idaho National Laboratory and is approximately 70% complete. Several fuel and material irradiation experiments have been planned for the U.S. Department of Energy Advanced Gas Reactor Fuel Development and Qualification Program, which supports the development and qualification of tristructural isotropic (TRISO)-coated particle fuel for use in high-temperature gas-cooled reactors. The goals of these experiments are to provide irradiation performance data to support fuel process development, qualify fuel for normal operating conditions, support development of fuel performance models and codes, and provide irradiated fuel and materials for post-irradiation examination and safety testing. Originally planned and named as separate fuel experiments, but subsequently combined into a single test train, AGR-5/6/7 is testing low-enriched uranium oxycarbide TRISO fuel. The AGR-5/6/7 test train has five capsules with thermocouples and independent gas control mixtures.

Unique to this paper is a sensitivity study concerning the cylindricity of the graphite holders containing the fuel compacts and their eccentricity in relation to the stainless-steel capsule walls. Each capsule has small nubs on the outside used for centering the graphite holder inside the stainless-steel capsule with a small gas gap used to control temperature. Due to machining tolerances of these nubs, and vibration wearing the nubs down when the experiment is running in the reactor, the possibility exists that the holder may move around radially. Each capsule is equipped with several thermocouples placed at various radii and depths within each graphite holder. This paper will show the sensitivity of offsetting the graphite holder for various radii in 45-degree increments around the circle with the objective of minimizing the difference between the measured thermocouples and the modeled thermocouple temperatures. Separate gas mixtures of helium/neon are introduced into this gas gap between the holder and capsule wall and changed as necessary to maintain the desired thermocouple temperatures to keep the fuel compacts at a constant temperature as the nuclear reactor conditions change.

The goal of the sensitivity study is to find a radius and an angle to offset the holder from perfectly centered for each of the five capsules separately. The complex thermal model includes fission heating, gamma heating, radiation heat transfer, and heat transfer via conduction and radiation across the control gaps. Subroutines linked to the thermal model offer an easy method to offset the graphite holder from the capsule walls without remeshing the entire model.

Keywords: TRISO Fuel, AGR

NOMENCLATURE

a,b,c	intermediate steps to simplify equations
gap	distance between graphite holder and capsule
h	offset in x direction
k	offset in y direction
n	number of samples in root mean square calculation
r_o	inside radius of capsule wall
x_i	x location on graphite holder
x_o	x location on capsule wall
y_i	y location on graphite holder
y_o	y location on capsule wall

1. INTRODUCTION

Irradiation experiments of tristructural isotropic (TRISO)-particle fuel are being conducted to support development of the next generation of high-temperature gas reactors in the United States. The Advanced Gas Reactor (AGR) Fuel Development and Qualification Program, which is part of the Advanced

[1] Contact author: Grant.Hawkes@inl.gov

Reactor Technologies (ART) Program, is responsible for these experiments, which demonstrate and qualify new low-enriched uranium (LEU) TRISO-particle fuel for use in high-temperature gas-cooled reactors. The goals of the irradiation experiments are to provide irradiation performance data to support fuel process development, to qualify fuel for normal operating conditions, to support development and validation of fuel performance models, and to provide irradiated fuel and materials for post irradiation examination (PIE) and safety testing. The experiments each consist of multiple separate capsules and are irradiated in an inert sweep-gas atmosphere with individual on-line temperature monitoring and control of each capsule. The sweep gas also has on-line fission product monitoring of its effluent to track performance of the fuel in each individual capsule during irradiation.

Originally seven separate experiments were envisioned to meet various program objectives. The last three tests are being combined into a single irradiation (AGR-5/6/7). These tests serve as the formal fuel qualification irradiations (AGR-5/6) and the margin test (AGR-7). The purpose of the margin test is to demonstrate that there is a margin between the highest fuel temperature in an operating high-temperature gas reactor (HTGR) and the temperature at which fuel particle failure rate becomes unacceptable.

The AGR-5/6/7 experiment is being irradiated at the Idaho National Laboratory (INL) in the Advanced Test Reactor (ATR) northeast flux trap irradiation position. The experiment will consist of five individual capsules each equipped with its own temperature-control system and fission product gas monitoring capability. The different capsules will experience a range of temperatures, fuel burnup, and fast neutron fluence to envelope the range of operational conditions in a future HTGR reactor.

A thermal finite element model has been created for the five capsules comprising the AGR-5/6/7 experiment. Previous thermal models [1], [2], [3] of AGR experiments have been successful in the past. The experiment is composed of five separate stainless-steel capsules all welded together. There are 194 fuel compacts with 170 in the AGR-5/6 portion and 24 in the AGR-7 portion. Each TRISO fuel compact is a right circular cylinder. Heat rates and fast neutron fluence were input from a detailed physics analysis using the Monte Carlo N-Particle (MCNP) code. Individual heat rates for each non-fuel component were input as well. ATR outer-shim control cylinders and neck-shim rods, along with ATR-driver fuel power and fuel depletion were incorporated into the physics heat-rate calculations. Surface-to-surface radiation heat transfer, along with conduction heat transfer through the gas mixture of helium-neon (used for temperature control), was used in the thermal calculations. Graphite shrinkage due to the fast neutron fluence is incorporated into the model. This is a large model with more than 1 million finite element brick elements. More than 150 different parts are modeled in the finite element model and communicate with each other from a heat transfer sense. Fifty-four thermocouples are used in the experiment and calculation results are compared to actual measurements.

2. MODEL DESCRIPTION

The AGR-5/6/7 experiment is irradiated in the northeast flux trap of the ATR as shown in Figure 1. The experiment is comprised of five individual capsules all welded together in a vertical orientation as shown in Figure 2 (top at left, water flowing down). The outside diameter of the stainless-steel capsules is 2.765-in. (0.070231 m), with a total experiment length of approximately 48-in. (1.2192 m). Each capsule contains TRISO compacts that are nominally 0.5-in. (0.0127 m) in diameter with a length of 1.0-in. (0.0254 m). Capsules 1 and 5 have a TRISO fuel particle packing fraction of 40%, while capsules 2–4 have a packing fraction of 25%. The particles are bound together by a carbon matrix material.

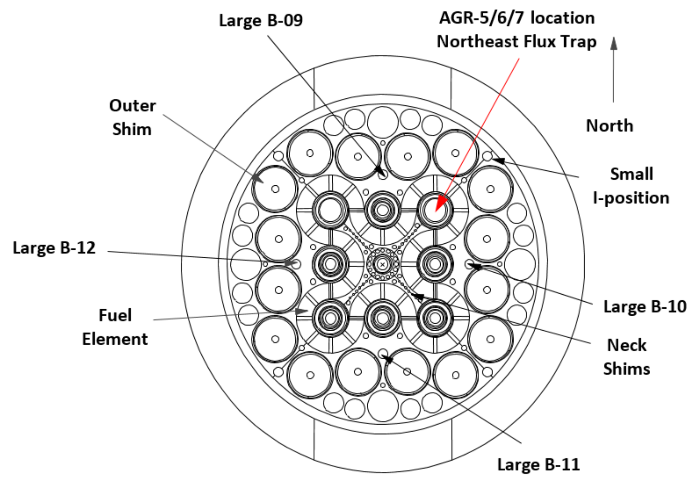

Figure 1. ATR core cross section showing the northeast flux trap position containing the AGR-5/6/7 experiment.

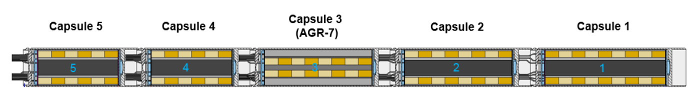

Figure 2. Capsule layout diagram (capsule 5 on top, vertical experiment).

Coolant water flows downward on the outside of the capsules at approximately 12.0 m/s and enters the experiment at 51°C. Program goals for power density, packing fraction, temperature, fluence, and burnup are shown to exceed past German and Japanese TRISO experiments. Capsule cross section views are displayed in Figure 3. Capsule 1 has 10 stacks, while Capsules 2, 4, and 5 have four stacks, Capsule 3 has three stacks arranged in an inner graphite holder to raise the temperature. Thru-tubes are located in Capsules 2–5 to hold the thermocouple wires and gas lines.

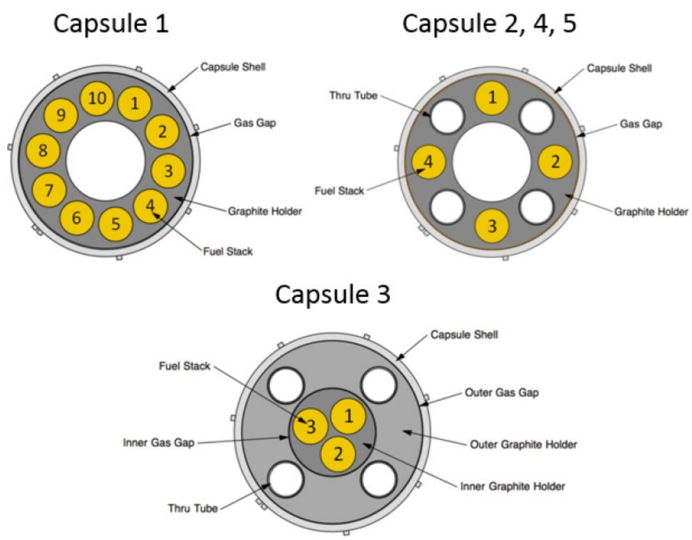

Figure 3. Capsule cross-sectional view for the five capsules.

The finite element heat transfer code ABAQUS [4] was used to model the experiment. Figure 4 shows the cut-away view of the finite element mesh of the entire capsule train. There are approximately 1,200,000 hexahedral finite element bricks in the model.

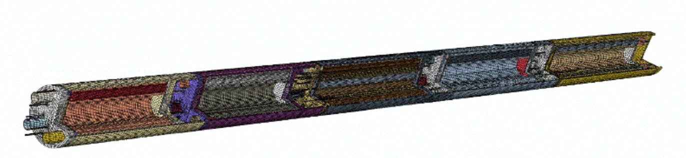

Figure 4. Cut-away view of finite element mesh of entire capsule train.

Figure 5 shows the finite element mesh of Capsule 1. The figure shows the thermocouples and gas lines protruding out of the top. There are no through-tubes in this capsule since it is on the bottom and no gas lines or thermocouple wires need to pass through it to the next capsule. There are 10 stacks of fuel. These capsules are designed to transfer heat in the radial direction as zirconia insulators and gaps are placed on top and bottom of the capsule to insulate it in the axial direction. The top of Capsule 1 is an exception as a ring spring on the bottom pushes up on the graphite holder and fuel, making good contact with the top. This was done since there is a lot of heat generation at the top of the fuel and it can conduct out through the top stainless-steel cap and into the coolant water. The top and bottom caps of all the capsules are tapered in order to remove material and hence gamma heat generation. There are very small gas gaps between the thermocouple and its sheath and between the sheath and the graphite holder.

Shown in Reference [5] is a detailed description of all the material properties varying with temperature and fast neutron fluence. Gas gaps varying with fast neutron fluence are also discussed.

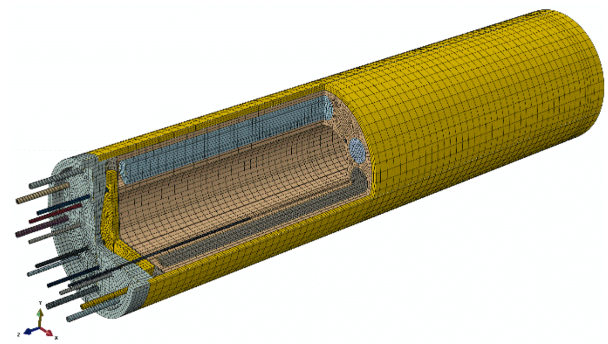

Figure 5. Cut-away view of finite element mesh of Capsule 1.

Offset Holder Calculations

The graphite holders are held off from the capsule wall by small nubs of graphite every 90°. The possibility exists for these nubs to wear down with the vibration in the reactor. The protruding nubs basically fit tightly against the capsule wall. These nubs remain on the holder while still machining the outside diameter to the dimension needed for the gas gap. An offset calculation where the gas gap varies azimuthally is described below. It is possible to move the holder and contents inside the capsule with the ABAQUS CAE model; however, it is not typically prudent to do so since one doesn't know which direction the holder might offset. This offset model is included in the gap conductance subroutine GAPCON. An offset in +/- x and +/-y is available for each capsule individually. This paper shows the calculations performed when moving the capsule wall 0.001-inch in the north, northeast, east, southeast, south, southwest, west, and northwest directions. Figure 6 shows a diagram of the outside (capsule) offset h units in the x direction and k units in the y direction from the graphite holder. Eq. (1) shows the calculations to obtain the x_o, and y_o values since x_i and y_i are given in the subroutine and ultimately the gap distance anywhere around the periphery. Even though the finite element mesh model shows the capsule perfectly centered, this new gap is used for the gap conduction equations.

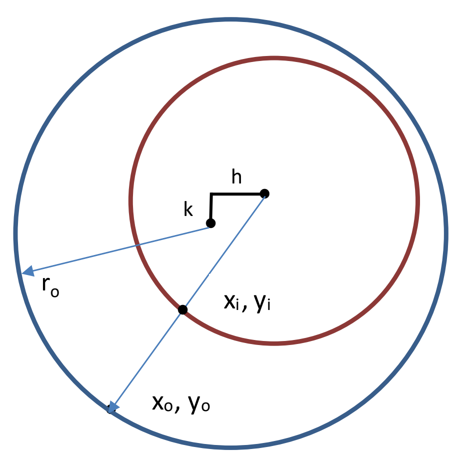

Figure 6. Diagram to calculate gap with capsule center offset h in x direction and k in y direction.

$$a = \left(\frac{y_i}{x_i}\right)^2 + 1$$

$$b = -2k\left(\frac{y_i}{x_i}\right) - 2h$$

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

$$x_o = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$y_o = \pm\sqrt{r_o^2 - (x_o - h)^2} + k$$

$$gap = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2} \quad (1)$$

where x_i and y_i are the actual coordinates on the outer surface of the graphite holder in ABAQUS, x_o and y_o are the corresponding coordinates on the inside of the capsule wall and r_o is the inside radius of the capsule wall. These equations are for an offset of h in the x direction and k in the y direction. The values of a, b, and c are used as intermediate steps to simplify the equations.

Heat Rates

Heat rates are taken from results generated from the MCNP code [6] results specific to the AGR-5/6/7 experiment. Heat rates are calculated and imported into the ABAQUS input file for each compact (fission), and each 1.0-in. (25.4 mm) of the height of the graphite holders (gamma). Gamma heat rates are also implemented from the water, stainless-steel capsules, thru-tubes, thermocouples, and all of the various components on the top and bottom of each capsule. Figure 7 shows volumetric heat generation rates (W/cm^3) of all of the compacts imported from the physics calculations (top at left). The highest heat rates are at the top of Capsule 1 as there is a lot of fissionable material closer to the core center. The gamma heat rates for the graphite holders are in a typical chopped cosine profile.

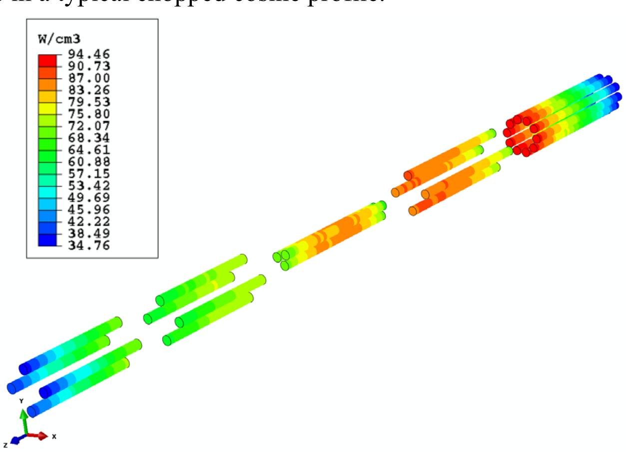

Figure 7. Compact heat generation rates (W/cm^3) imported from physics calculations.

3. RESULTS

Results are displayed in Figure 8 through Figure 12. Figure 8 shows a temperature contour plot of a typical day of irradiation in ATR. The figure is a cut-away view of the entire model with Capsule 5 (the top) on the left. As designed, Capsule 3 and Capsule 1 are the hottest. Capsule 3 has temperatures as high as 1450°C. Capsule 1 has a strong temperature gradient in the axial direction, while Capsules 2, 4, and 5 have temperatures ranging in the 700 to 900°C range. Figure 9 shows a cut-away view of the graphite holder and fuel compacts for Capsule 3. There is a noticeable large temperature drop across the gap between the inner and outer holder. Figure 10 shows a history plot for the initial 42-day ATR irradiation cycle vs. the measured minus calculated temperatures (°C) of the thermocouples (TCs). The first 12 days were run on helium to verify everything was running as expected before increasing to the desired temperature by mixing more neon into the gas mixture. Capsule 5 shows excellent agreement between the measured and calculated TC temperatures. Capsules 4, 3, and 2 show good agreement with the average difference being about 40°C. Capsule 1 has a large variation in predictions compared to actual TCs. The average difference is about 60°C while running cool for the first 12 days of the cycle while it is around 70°C when running hotter for the remaining 30 days of the cycle. All of the TC wires for Capsule 1 go through the thrutubes of all the upper four capsules and thus these wires experience some very high temperatures. The model agrees modestly well with the measured TCs.

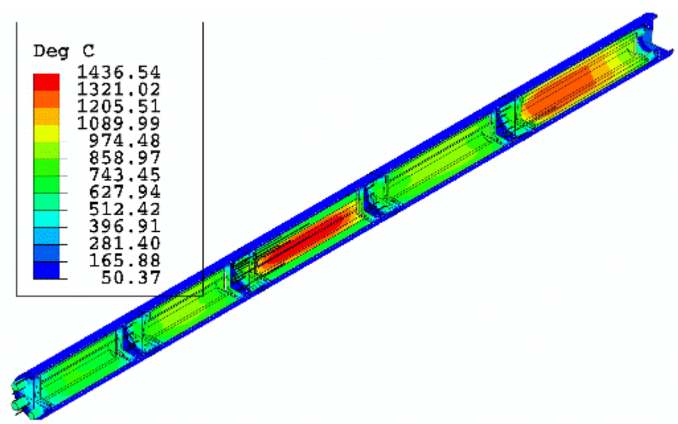

Figure 8. Temperature (°C) contours of cut-away view of entire experiment.

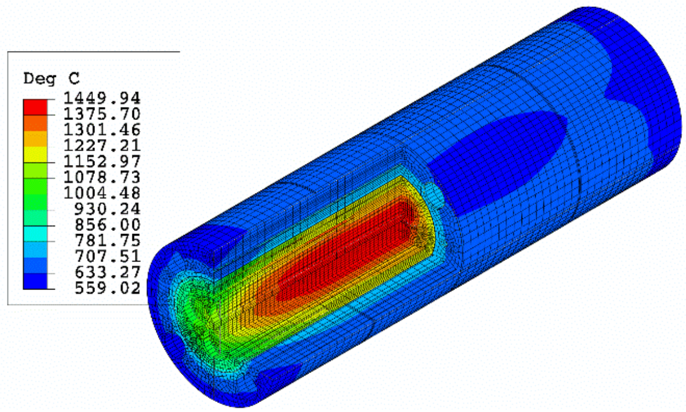

Figure 9. Temperature contours (°C) of cut-away view of Capsule 3 graphite holder and fuel compacts.

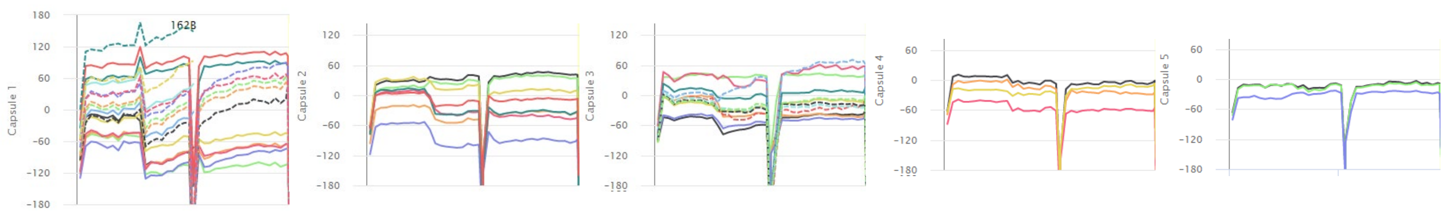

Figure 10. History plot of temperature difference (°C) (measured – calculated) for graphite holder centered for all five capsules for first ATR cycle.

The purpose of this paper is to discover if moving the gap closer to one side or the other results in a better agreement between the model and the measured TCs. We trust the TC readings a lot more during the first ATR cycle than we do toward the end of the irradiation campaign (eighth cycle) due to TC drifting and TC irradiation damage. The root mean square of the temperature difference was calculated with the following equation:

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

where n is the total number of samples (one for each TC for each day), measured is the daily average TC measured temperature, and calculated is the temperature calculated in this study of varying gaps.

Figure 11 shows temperature contour plots at day 41 of the ATR cycle with a cut-away view of Capsule 1 taken at 1.5 in. below the top of the Capsule 1 graphite holder. The base case that has the graphite holder perfectly centered is in the center of the figure. The gas gap for this centered case as this elevation is 0.006 in. The temperatures are slightly hotter on the southwest side since it is closest to the ATR core center as shown in Figure 1 and receives a slightly higher dose of neutrons. The top figure (north) has had the gap increased by 0.001 in. on the north side and shows hotter temperatures since the gas gap is larger and harder to conduct through. Rotating around the figure shows temperatures hottest on the outside where the gas gap is larger.

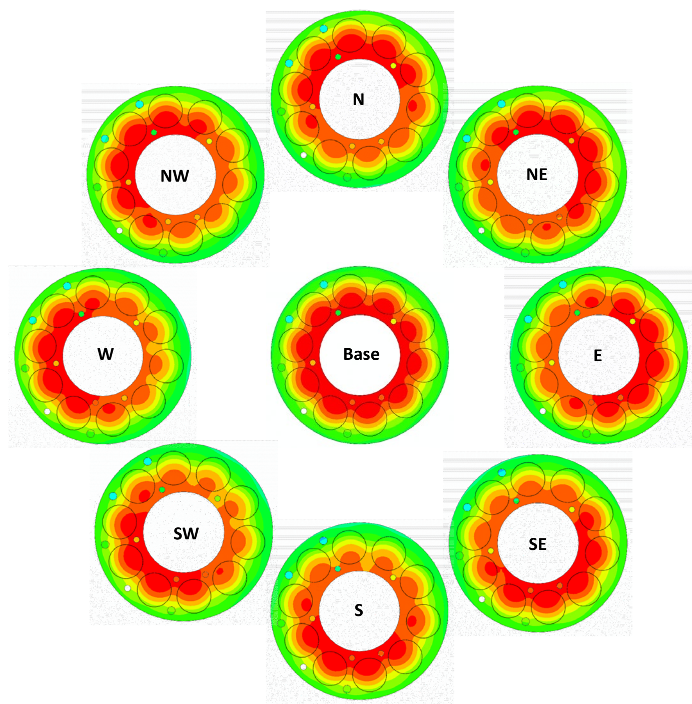

Figure 11. Temperature contour plot showing cut section in Capsule 1 at 1.5 inches from top of capsule varying by gap calculations taken on the second-to-last day of irradiation of the first ATR cycle.

Figure 12 shows the RMS value of the measured minus calculated for the entire first ATR cycle of the AGR-5/6/7 experiment varying with gap orientation in 45-degree increments. The RMS values of the graphite holder being centered are on the left side of the plot for all capsules combined and each individual capsule. Moving from left to right shows the RMS value starting with north and rotating around in a clockwise fashion to northwest. The gold/beige line shows the combination of all capsules. This is heavily weighted toward Capsules 1 and 3 since they each have 17 thermocouples. Capsule 2 has eight thermocouples and Capsules 4 and 5 have six thermocouples each. The gold/beige line representing all capsules has its lowest value of 39°C RMS at northwest. The orange line depicts Capsule 1 and it is also lowest at northwest. Capsule 2 is represented by the purple line and has its lowest value of 35°C at the north. Capsule 3 is shown in gold and has its lowest value of 27°C on the east. Capsule 4 is shown in blue and has its lowest value of 18°C on the east, while Capsule 5 is shown in green and has its lowest value of 15°C in the northeast. There appears to be very good agreement with capsule 5.

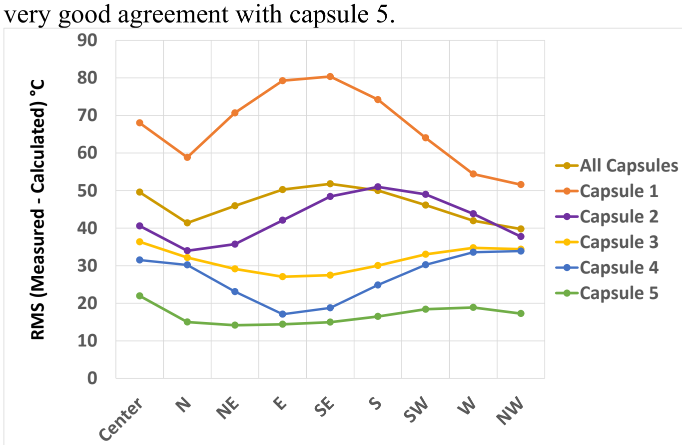

Figure 12. RMS (measured – calculated) °C for first irradiation cycle varying by gap orientation at center and 45 degree increments.

4. CONCLUSION

This work discussed a thermal finite element model of the AGR-5/6/7 experiment, created with ABAQUS software. Heat rates for fissionable TRISO fuel compacts and gamma-heat rates for all other materials were calculated from the MCNP code, then imported into the thermal model. Temperature contours for typical days were shown. Measured minus calculated TC temperatures compare favorably. By varying the offset of the graphite holder in comparison with the capsule wall by 0.001 inch in 45-degree increments, the RMS value of the temperature difference between measured and calculated has been calculated and discussed. A seemingly good improvement can be attained in the thermal model predictions by offsetting the graphite holder in a different direction for each capsule.

ACKNOWLEDGEMENTS

Work supported by the U.S. Department of Energy, NGNP Program, Idaho Operations Office Contract DE AC07 05ID14517.

Work performed on High Performance Computing Center at Idaho National Laboratory

COPYRIGHT STATEMENT

This manuscript has been authored by Battelle Energy Alliance, LLC under Contract No. DE-AC07-05ID14517 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

REFERENCES

[1] G. L. Hawkes, J. W. Sterbentz, J. T. Maki, B. T. Pham, “Thermal Predictions of the AGR-3/4 Experiment with Post Irradiation Examination Measured Time-Varying Gas Gaps,” ASME J of Nuclear Rad Sci 3(4), 041007 (Jul 31, 2017), Paper No: NERS-17-1008; doi: 10.1115/1.4037095

[2] G. L. Hawkes, J. W. Sterbentz, B. T. Pham, “Thermal Predictions of the AGR-2 Experiment with Variable Gas Gaps,” Nuclear Technology / Volume 190 / Number 3 / June 2015 / Pages 245-253, Technical Paper / Thermal Hydraulics / dx.doi.org/10.13182/NT14-73

[3] G. L. Hawkes, J.W. Sterbentz, J. Maki, B. Pham, “Daily Thermal Predictions of the AGR-1 Experiment with Gas Gaps Varying with Time,” paper # 12111, International Congress on the Advances in Nuclear Power Plants (ICAPP 2012), Chicago, IL, Jun 24–28, 2012.

[4] Dassault Systèmes, ABAQUS version 6.14-2, www.simulia.com or www.abaqus.com, Providence, Rhode Island, 2014.

[5] G. L. Hawkes, J. W. Sterbentz, M. Plummer, “Thermal Model Details and Description of the AGR-5/6/7 Experiment,” paper #000142, ICAPP 2019 International Congress on Advances in Nuclear Power Plants, Juan-les-Pins, France, May 12–15, 2019.

[6] The MCNP Code Development Team, MCNP Code Manual, https://mcnp.lanl.gov/references.shtml, Los Alamos National Laboratory, accessed Dec 2017.