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Binh T. Pham
Grant L. Hawkes
Jeffrey J. Einerson

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Improving Thermal Model Prediction through Statistical Analysis of Irradiation and Post-Irradiation Data from AGR Experiments

Binh T. Pham[1], *Grant L. Hawkes*[2] *and Jeffrey J. Einerson*[1]
[1]*Human Factor, Controls and Statistics Department*
[2]*Thermal Science and Safety Analysis Department*
Nuclear Science and Technology
Idaho National Laboratory, Idaho Falls, ID 83415, USA
Phone: 208- 526-8078, Fax: 208-526-2930, Binh.Pham@inl.gov

Abstract – *As part of the High Temperature Reactors (HTR) R&D program, a series of irradiation tests, designated as Advanced Gas-cooled Reactor (AGR), have been defined to support development and qualification of fuel design, fabrication process, and fuel performance under normal operation and accident conditions. The AGR tests employ fuel compacts placed in a graphite cylinder shrouded by a steel capsule and instrumented with thermocouples (TC) embedded in graphite blocks enabling temperature control. While not possible to obtain by direct measurements in the tests, crucial fuel conditions (e.g., temperature, neutron fast fluence, and burnup) are calculated using core physics and thermal modeling codes. This paper is focused on AGR test fuel temperature predicted by the ABAQUS code's finite element-based thermal models. The work follows up on a previous study, in which several statistical analysis methods were adapted, implemented in the NGNP Data Management and Analysis System (NDMAS), and applied for qualification of AGR-1 thermocouple data. Abnormal trends in measured data revealed by the statistical analysis are traced to either measuring instrument deterioration or physical mechanisms in capsules that may have shifted the system thermal response. The main thrust of this work is to exploit the variety of data obtained in irradiation and post-irradiation examination (PIE) for assessment of modeling assumptions. As an example, the uneven reduction of the control gas gap in Capsule 5 found in the capsule metrology measurements in PIE helps identify mechanisms other than TC drift causing the decrease in TC readings. This suggests a more physics-based modification of the thermal model that leads to a better fit with experimental data, thus reducing model uncertainty and increasing confidence in the calculated fuel temperatures of the AGR-1 test.*

I. INTRODUCTION

As part of the Research and Development program for High Temperature Reactors (HTR), a series of irradiation tests, designated as Advanced Gas-cooled Reactor (AGR) experiments, have been defined to support development and qualification of fuel design, fabrication process, and fuel performance under normal operation and accident conditions [1, 2]. The AGR tests employ fuel compacts placed in a graphite cylinder shrouded by a steel capsule and instrumented with thermocouples (TC) embedded in graphite blocks enabling temperature control. The AGR-1 test consisted of six capsules irradiated in the core of the Advanced Test Reactor (ATR) at Idaho National Laboratory and was successfully completed after three years. The crucial test fuel conditions (e.g., temperature, neutron fast fluence, and burnup), while impossible to obtain from direct measurements, are calculated by core physics and thermal modeling codes. Thus, accurate predictions are critical for determination of the test fuel operational condition envelope used in the advanced reactor design optimization and safety analysis. This paper focuses on the uncertainty analysis of the AGR fuel temperatures predicted by the ABAQUS code's finite element-based thermal models.

A daily as-run thermal analysis has been performed separately on six capsules of the AGR-1 experiment for the entire irradiation as discussed in [3, 4]. The thermal model predicts the daily averaged volume-average fuel temperature and volume-peak fuel temperature in each capsule. Model predictions are often affected by uncertainty in input parameters and by incomplete knowledge of the underlying physics leading to making modeling assumptions. Therefore, alongside with the deterministic predictions from a set of input thermal conditions, information about prediction uncertainty is instrumental for the HTR R&D program decision-making. Well defined and reduced uncertainty in model predictions helps increase the quality of and confidence in the AGR technical findings. The predicted fuel temperatures and their uncertainties are also central to qualification and calibration of models for predicting fission product transport and fuel performance models in the next-generation HTR designs. This study discusses two techniques for improving the AGR capsule thermal model prediction, namely: (1) applying statistical analysis methods on TC readings to identify deteriorated data, thus preventing the use of deficient data in the model calibration process; and (2) combining information from multiple sources such as irradiation and post-irradiation examination (PIE) data for a better understanding of physical processes in AGR capsules, thus enabling model improvement and better fit with the experimental data.

The records from TCs terminated in a graphite fuel sample holder provide the only direct temperature data for AGR capsule thermal model calibrations. These TCs were exposed to very high temperatures (from 800 °C to 1000 °C) and high neutron fluence (up to 5×10^{25} n/m^2) for an extended period of time. They also experienced extreme thermal stresses from multiple power-ups and power-downs of the ATR core during its fuel cycles. The harsh irradiation conditions of AGR capsules lead to high probability of TC deterioration and failure (e.g., drift failure and virtual junction formation). A lack of control over these deterioration mechanisms constitutes the main source for uncertainty in interpreting TC readings. High uncertainty in calibrating the TC readings, in turn, complicates assessment of the capsule thermal model. In previous studies [5, 6], several statistical analysis methods were adapted, implemented in the NGNP Data Management and Analysis System (NDMAS), and applied for improving qualification of AGR-1 thermocouple data. The deteriorated data from failed TCs are identified and flagged to prevent the use of deficient data in the model and code calibration. In addition, the consistent trends of measured data relative to calculated results found by the statistical data analysis provide insights on physical mechanisms useful for model improvement.

To further improve the AGR-1 temperature prediction, this study invokes a larger body of temperature dependent (or driven) measurements and observations in the thermal model calibration activity. This includes data from all stages of the AGR campaign such as fabrication, irradiation and PIE. By qualifying and integrating actual observations and data into the AGR dynamic system through a data assimilation framework, the overall model uncertainty can be reduced. This work demonstrates uncertainty reduction of AGR-1 temperature prediction on an example of metrology measurements obtained during PIE. Specifically, the capsule dimensional data suggest that the change in the control gas gap found at the end of irradiation resulted from shrinking and swelling of the graphite sample holder. The graphite shrinkage and swelling are known to be proportional to the reaction rate in the graphite. This forms a basis to formulate a physics-based gas gap model with linear reduction over time. This model is to be contrasted with the constant gas gap assumption in the previous model used in ABAQUS simulations. This linear gap model is justified by significant correlation between fission product Release-to-Birth (R/B) ratios of radionuclides (e.g., Kr-88, Kr-85m, and Xe-135) and fuel temperature profiles. The fission product R/B ratios are well-known to be proportionally dependent on fuel temperature. Even through the complex relationship between R/B and temperature is not available analytically, the improved correlation between R/B and fuel temperature profiles indicates that the capsule thermal model captures governing physical phenomena in the capsules. This helps increase confidence in the simulation results.

II. THERMAL MODEL FOR AGR CAPSULE

Figure 1 depicts the physical sketch representing the thermal model and parameters for each capsule of the AGR-1. The fission power generated in the fuel compact and graphite sample holder is mainly conducted and radiated out through the gas gaps between the graphite holder and the stainless steel shell to the ATR primary cooling water, which serves as the ultimate heat sink for AGR capsules. The neon and helium gas mixture flow through the control gas gap is independently controlled to maintain a temperature set point of the control TC embedded in graphite blocks. This is to ensure the target fuel temperatures follow the test specification defined by the program management [2].

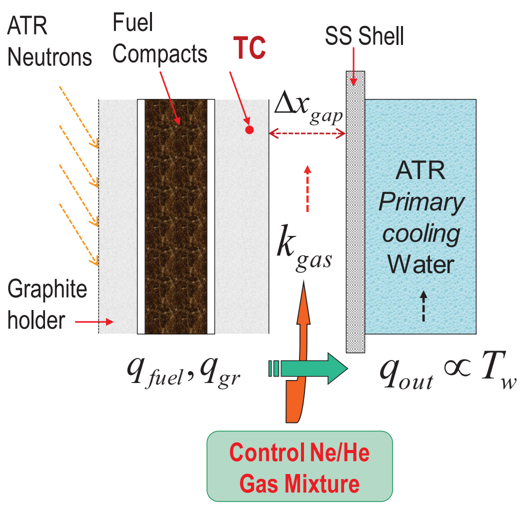

Fig. 1: Physical sketch of the axial cut of a capsule.

II.A. Thermal Model Description

The ABAQUS based finite element thermal models are created for each of six capsules of the AGR-1 test to predict daily averages of fuel compact and TC temperatures for the entire irradiation period when the ATR core is at power. Figure 2 shows the finite element mesh with a cutaway view of the entire model. Approximately 350,000 eight-noded hexahedral brick elements were entirely used in all models. The model details including model validation and verification, calibration, sensitivity analysis, and results are described by the modelers in [3, 4].

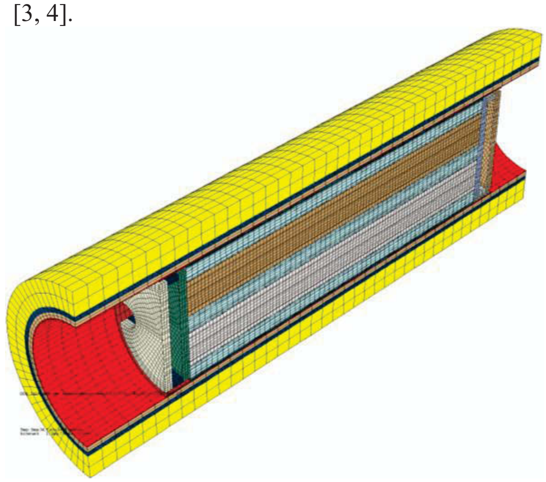

Fig. 2: Sideways cutaway view of mesh with colored entities.

The thermal model for AGR-1 capsules were calibrated by varying the emissivities of surfaces of the graphite holder and stainless-steel retainer to best match temperatures at TC locations with actual TC measurements during earlier cycles, when TC performance is deemed more reliable [4].

II.B. Thermal Model Assumptions

For a system as complex as AGR fuel tests, modeling assumptions are inevitable to enable simulations. Because of insufficient knowledge about and control over details of processes in test capsules, modeling assumptions are the source of model-form and model-parameter uncertainty. Below are the *original* (before PIE) thermal modeling assumptions ordered top-down by the impact on the temperature prediction:

1. The gas gap distance is constant over the entire irradiation for all capsules.
2. Gas mixture thermal conductivity is determined by kinetic theory of gases using pure gas properties of helium and neon to determine mixture properties.
3. Graphite and compact thermal conductivity varying with fluence and temperature is taken from legacy experiment correlations and scaled for AGR-1 material density.
4. Heat rates from components (excluding fuel compacts divided into two nodes) and fluences are spatially constant and vary only with time for each capsule.
5. There is no axial heat conduction from one capsule to the next.
6. Radiation heat transfer only occurs from the graphite holder to the stainless-steel retainer, graphite holder to thru tubes, and thru tubes to stainless-steel retainer.
7. Because the thermal capacitance of the sweep gas is very low (30 cc/min), advection is not considered in the sweep gas, and it is modeled as stationary.

II.C. Thermal Model Sensitivity Analysis

The sensitivity evaluation of the temperature predictions was performed for the AGR-1 fuel experiment on an individual capsule by the modeler and the results are presented in [3]. As an example, the tornado plot in Figure 3 shows the most sensitive input parameters on peak fuel temperature variations sorted from largest to smallest. This example is the sensitivity analysis results for Capsule 4 during the second AGR-1 cycle (139A). According to this study, the biggest effects on calculated temperatures are the heat rate in the fuel, the control gas composition (e.g., neon fraction), and the control gap distance. The next four are heat rate in the graphite, graphite thermal conductivity, fuel conductivity, and gap conductivity between compact and graphite holder.

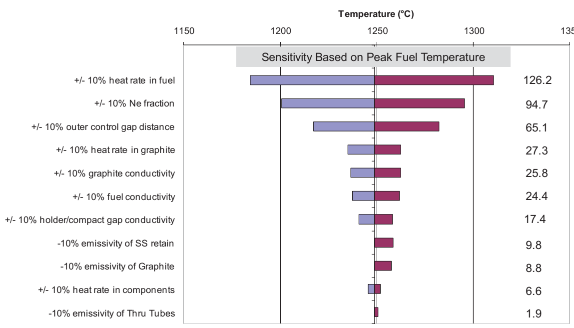

Fig. 3: Input sensitivity for peak fuel temperature.

II.D. Model Uncertainty Analysis

This section focuses on the epistemic uncertainty of the thermal model for AGR-1 test capsules. In contrast to irreducible aleatory uncertainty representing the inherent variation associated with the physical system, the epistemic uncertainty is associated with lack of knowledge (hence, epistemic) in any phase of the modeling process [7]. As such, epistemic uncertainty of the predicted outcome is reducible when new relevant information is identified, incorporated in the model and/or used to improve modeling assumptions. These model uncertainties can be categorized into three groups. The first group belongs to biases and errors in expert assessment of the range of uncertainty associated with input parameters. This includes the parameter range and probability density function (pdf) of the parameter distribution. The second group includes modeling assumptions used to build the ABAQUS model for the AGR-1 test. The third group is associated with numerical treatment (e.g., resulting in discretization errors) needed to implement and operate the ABAQUS simulations. Although the effect of the first and second groups is generally very hard to evaluate, additional information about the capsule thermal property or environment can lead to reduction of the epistemic uncertainties. It is noteworthy that some of these uncertainties may have been cancelling each other (implicitly, "error compensation") in the model calibration effort. Therefore, the use of such simulation models beyond their calibrated domain needs to be done with great caution.

The main sources of the AGR-1 capsule thermal model epistemic uncertainties are listed below:

a. Physical indeterminacy (the quantity of interest is not precisely predictable); e.g., TC readings from TCs with high failure probability used in model calibration.
b. Lack of information (there is not enough information concerning quantity of interest); e.g., gas gap distance (Assumption 1);
c. Information of limited relevance; e.g., thermal conductivities of (i) gas mixture, (ii) graphite holder, and (iii) fuel compacts (Assumption 2 & 3);
d. Intractable models (the real model is too complex); e.g., Assumption 4 to 7;
e. Limits in computational ability; e.g., numerical treatments (e.g., treatment that removes the need for re-meshing when the gas gap distance changes);

The elimination or, in practice, reduction of any of the listed uncertainty sources will improve the model predictive capability. This is usually a constrained optimization process, because the elimination of any model uncertainty source is constrained by available resources (e.g., time and labor) and science and engineering limitations (e.g., limits in computational capacity, modeling capacity, and engineering capacity).

III. STATISTICAL ANALYSIS OF TC DATA

In the ATR core, the TCs employed in AGR tests are subject to rapid deterioration under the harsh irradiation and high temperature environment. Yet, the TC data, including trends and relative differences between TCs, remain the sole and indispensable source of information for assessing nuclear fuel performance models and codes. Confidence in such assessment depends on knowledge about measurement data. For instance, it is important that potentially misleading data, i.e., from partially failed (drifting, conjunct) thermocouples, be accordingly identified.

In-depth analysis and qualification of the thermocouple data were performed in previous work, using statistical methods and their combination with results of thermal simulations from the ABAQUS code [5, 6]. The statistical methods such as control charts, correlation analysis, and regression analysis reveal data trends and anomalies of the experimental data relative to statistics established using data in the past where they are deemed to be reliable. As an example, in the control charting method, a baseline period (a number of "past" cycles) is used to compute the mean value and standard deviation (σ) of a controlled quantity and determine the control bounds [5]. By monitoring variation of the TC pair differences (as a control parameter), the control charting method can identify "out-of-control instances" that indicate subtle changes of one TC relative to the other TC.

It is instructive to note that the abnormal trends of measured data observed from statistical analysis may be caused by either measuring instrument deterioration or physical mechanisms in capsules that may have shifted the system thermal response. Thus, additional evidence obtained from multiple data sources in different stages of the AGR test campaign including fabrication, irradiation, post-irradiation examination, and simulation results will help increase the accuracy and confidence level of the interpretation of the data trends. The present work exercises the idea that – while recognizing uncertainties inherent in physics and thermal simulations of the AGR-1 test – results of the numerical simulations can be used in combination with the statistical analysis methods to further improve qualification of measured data. The simulation results especially help increase the confidence in delineating failures of the measuring instruments (thermocouples) from capsule physical changes that may have shifted the temperature response.

The statistical analysis methods are implemented in NDMAS to scrutinize AGR-1 TC measurements and the thermocouple performance results are reported in [8]. Figure 4 below shows an example of how simulation results used together with statistical methods may help qualification of TC data. In this example, the pair of TC1 and TC5 of Capsule 5 is used and the simulation data is calculated from the *original* thermal model with assumptions listed in Section *II.B*. The control charts of measured (red symbols) and calculated (purple symbols) TC pair differences in the top frame show that the measured out-of-control differences are not supported by simulation data ("Δ" and "x" diverge) indicating that at least one TC may have been drifting relative to other TC.

The differences in measurement and simulation of each TC (or so-called TC residuals) are presented in the bottom panel if Figure 4. They should be randomly and normally distributed around a constant bias (representing a systematic error, ideally zero) when TC is stable relative to simulation. Therefore, the residual plots of this TC pair in the bottom frame lead to following conclusion: (i) TC1's flat residual plot ("o") indicates that TC1 is the stable TC relative to simulation; and (ii) the downward trend of TC3 residuals (+) indicates that TC3 has drifted about 300°C relative to TC3 calculated values.

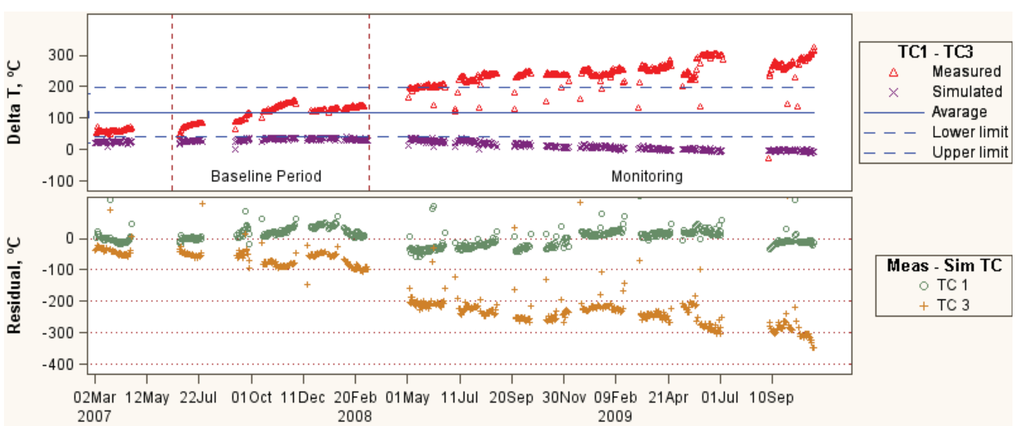

Fig. 4: The drift monitoring for TC 1 and 3 of Capsule 5.

The thermal simulation data provided additional evidence allowing the insight into the difference in the thermal responses of TC1 and TC3 in Capsule 5. There are two possible explanations for this observed data trend: (1) TC3 has drifted meaning the TC3 reading is lower than the actual temperature at its location and (2) the actual gas gap distance near TC3 location might have been decreasing over the time leading to the lower actual temperature at the TC3 location instead of a constant gas gap as assumed in the *original* thermal model (Section *II.B*).

IV. GAS GAP DISTANCE CHANGES

IV.A. PIE data of Gas Gap Distance

As the experiment progresses, the material properties of capsule components change due to high temperature and irradiation neutron fluence. The dimensional measurements of the compacts, graphite holders, and steel capsule shells were performed during PIE and reported in [9]. They show significant changes of geometric dimensions from as-fabrication data. Compact dimensional measurements indicated diametrical shrinkage of 0.9 to 1.4% and length shrinkage of 0.2 to 1.1%. The amount of shrinkage was somewhat dependent on compact location within each capsule and within the test train. Figure 5 summarizes relative changes in outer diameter of graphite holders. The diametrical swelling of the holders in Capsules 2–5 (holders initially contained nominally 7.0% boron carbide as a burnable poison) was 0.7 to 2.1%, and in some cases (particularly in Capsule 3) appear to have expanded sufficiently to contact the steel capsule liner, which complicated extraction from the capsules. By contrast, the graphite holders in Capsules 1 and 6 (containing nominally 5.5% boron carbide) exhibited diametrical shrinkage of 0.4 to 0.9%. The drastic difference in the dimensional change behavior of the two types of graphite is primarily attributed to the difference in boron carbide (B_4C) content and the different location in the test train (outer Capsules 1 and 6 received on average a fast fluence approximately 27% lower than the other capsules). The Capsule 4 graphite holder was damaged in the disassembly process, so no dimensional data were available for Capsule 4. As a result, the control gap shrank for the four middle capsules and expanded for the top and bottom capsules. However, the gap between the graphite body and the fuel compact increases, offsetting somewhat the effect of reduction in the control gap on fuel temperature.

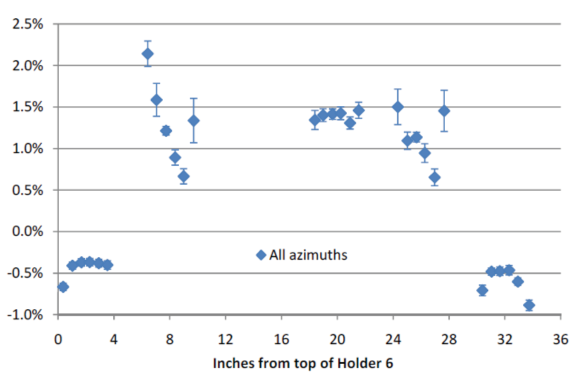

Fig. 5: Relative change in diameter of graphite holder.

IV.B. Update Gas Gap Distance Model

The parameter sensitivity analysis of the AGR-1 thermal model in Section *II.B* listed the control gas gap distance as the most sensitive parameter. The significant gas gap changes revealed during PIE suggests that modeling of phenomena that govern gap thermal resistance is expected to matter the most to the predicted temperature uncertainty. Also, the gap reduction in Capsule 5 is more consistent with the downward trend of TC3 residuals in Figure 4 than the explanation based on TC3 drift failure as suggested by the statistical analysis. Therefore, for a better description of capsule thermal processes, the constant control gas gap over time assumption used in the original thermal model for AGR-1 capsules should be re-evaluated to account for changes of the actual control gap.

This additional evidence prompts enhanced modeling that is more sophisticated than the original thermal model. However, preference is given to the simplest enhancements that reflect key insights and accommodate the new evidences. Over-complicated models necessarily create more "tuning" parameters than granted by the data, thus reducing the model's predictive capability.

Following the above principle, the control gap is still assumed to be axially constant but radially decreasing for the four middle capsules and increasing for the two outer capsules over the whole AGR-1 irradiation. This is from the initial gap width (Δx_s) to the end gap (Δx_e) shown in Figure 6. Further, the end gap width is estimated by using the TC data and fission product R/B ratios data. Note that this approach is preferred over the use of the PIE measurement data because of the large uncertainty in inferring the actual end gap distance from the cold-state time-delayed PIE examination of samples apparently contaminated with an unknown substance (gunk) on the capsule shell surface.

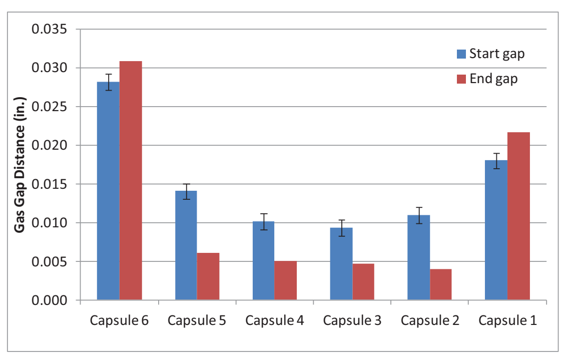

Fig. 6: AGR-1 capsule initial and end gap distances.

Specifically, the end gap width estimation is performed by maximizing the correlation between the predicted temporal profiles of fuel temperature and the measured temporal fission product R/B ratios [10]. As a result, the reduction of the end gap for Capsules 2 and 5 is ~60% of the start gap and for Capsules 3 and 4 is 50% of the start gap. Since the graphite holder of Capsule 4 was broken during disassembly, the Capsule 4 gap reduction is assumed to be equal to the Capsule 3 reduction. The gap distance for a time step (i) is calculated as follows:

$$\Delta x_i = \Delta x_s + (\Delta x_e - \Delta x_s) * \frac{fluence_i}{fluence_{AGR-1}} \qquad \text{(eq. 1)}$$

where Δx_i is the gap distance, $fluence_i$ is the fast fluence at time step (i), and $fluence_{AGR-1}$ is the accumulative fluence at the end of AGR-1 test.

V. UNCERTAINTY REDUCTION OF UPDATED THERMAL MODEL

The uncertainty reduction of AGR-1 temperature predictions gained by the updated gas gap distance model is demonstrated by (1) a better fit with TC data and (2) a significant correlation between fuel temperature and fission product R/B temporal profiles.

V.A. Improved Fit with TC Readings

Figure 7 presents temperature residuals of two peripheral TCs in Capsule 4 (top row) and Capsule 6 (bottom row) for two versions of the AGR thermal model as functions of EFPD (EFPD is Effective Full Power Day representing time span when the ATR core is at full power). The only difference between the two versions of the thermal model is the gas gap distance model: the first version (run 1) assumes constant gas gap over time and the second version (run 2) assumes linear gap change depending on capsule fluence as shown in eq. 1. The peripheral TCs are used for demonstration of improved fit because temperature at these TCs is most sensitive to variation of the gap distance (subsequently, variation in the gap thermal resistance). In other words, the updated gas gap model has the most effect on predicted temperatures at these TC locations. Capsules 4 and 6 are used because of their stark differences of boron carbide concentration (7% vs. 5.5%) and location in the test train (middle vs. outer). These differences lead to different directions of the gap change: the gap in Capsule 4 is decreasing significantly (up to 50% of start gap) because of graphite holder's swelling while the gap in Capsule 6 is slightly increasing (up to ~10%) due to graphite holder's shrinkage as shown in Figure 6.

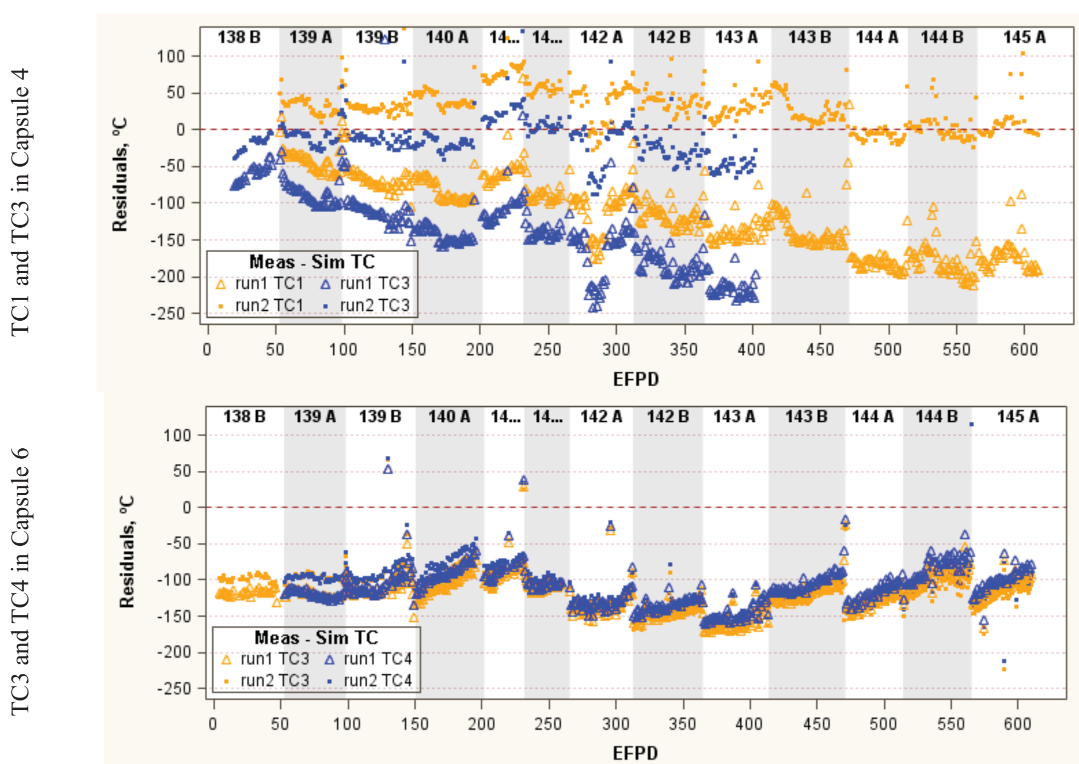

Fig. 7: The TC residuals of the original (run 1) and updated (run 2) thermal models for Capsules 4 and 6.

As a result, TC residuals in Capsule 4 (top row in Figure 7) show big improvement in terms of TC fitting for run 2 results (dot symbols show a random pattern around zero for entire AGR-1) relative to run 1 results (triangle symbols show downward trend over time indicating clear departure of TC readings from simulation as the experiment progresses). Early analysis of thermocouple data indicated that they performed reliably during the beginning cycles of irradiation. Therefore, the thermal models were calibrated to only match the TC readings during this portion of the irradiation. The continued matching of these TC readings over the whole AGR-1 suggests negligible model bias of the run 2 results with updated linear gas model. This leads to reduction of overall temperature prediction uncertainty due to elimination of the model bias. The matching improvement between measured and calculated TCs in Capsule 6 is much smaller (slightly flatter run 2 TC residuals as shown by the dots in the bottom row in Figure 7) due to much smaller gap change over time.

V.B. Significant Correlation between Fuel Temperature and Fission Product R/B

Since there were no fuel particle failures in the six capsules of AGR-1, the fission product R/B ratios are known to be proportionally dependent on fuel temperature. Even though the complex analytical relationship between R/B and temperature is not available, the correlation between R/B and fuel temperature temporal profiles indicates that the capsule thermal model correctly included important physical phenomena occurring in the capsules. Therefore comparison between fuel temperature and R/B will help to demonstrate that the calculated capsule fuel temperatures correctly reflect the capsule thermal condition. For visual correlation comparison, the capsule daily volume average fuel temperature (T_{Nor_i}) and log of R/B for Kr-85m radionuclide ($Log(R/B)_{Nor_i}$) are linearly normalized to the same scale as in following formula for fuel temperatures:

$$T_{Nor_i} = \frac{T_i - \left(T_{ave} - T_{2\sigma}\right)}{2T_{2\sigma}} \qquad \text{(eq. 2)}$$

where T_i is the volume average fuel temperature at time (i), T_{ave} is the time average volume average fuel temperature at the end of irradiation, and $T_{2\sigma}$ is two standard deviations of daily fuel temperatures. Equation 2 is also used to normalize the Log(R/B). To increase accuracy of the comparison, the fuel temperature and Log(R/B) data used for this comparison include only data during the time span when the ATR core is at full power.

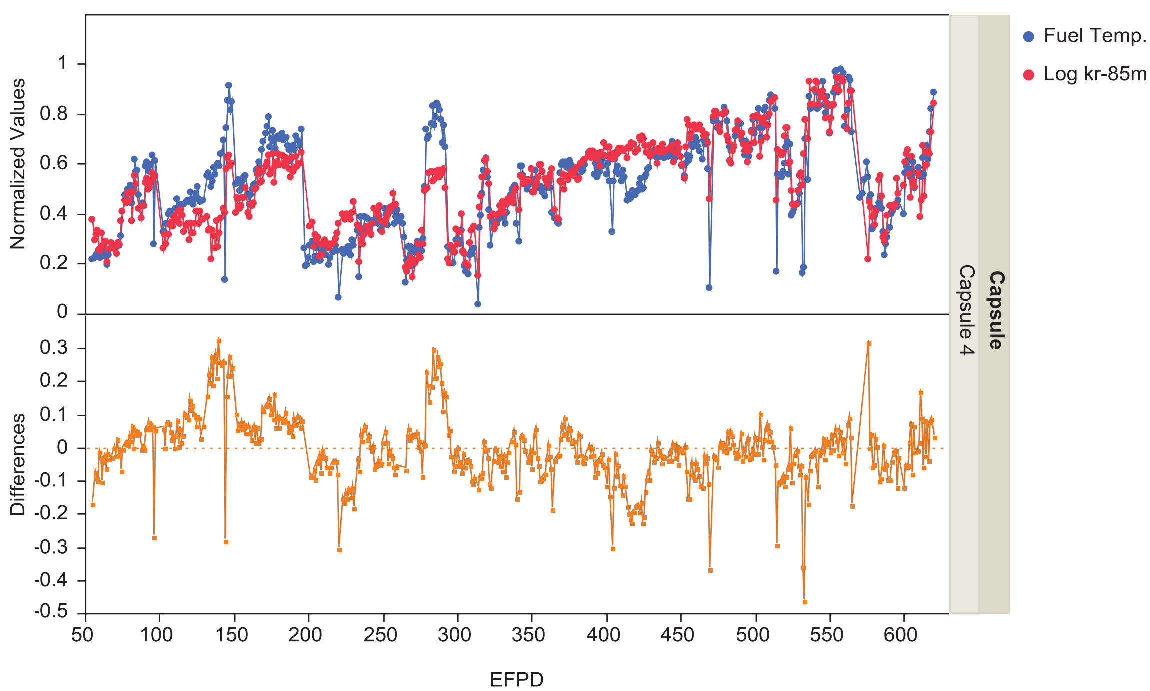

Fig. 8: Capsule 4 normalized volume average fuel temperatures, normalized log(R/B) and their differences.

Figure 8 shows the normalized volume average fuel temperature and normalized fission product log(R/B) on the top frame and their differences on the bottom frame as functions of EFPD for Capsule 4. The normalized values of Log(R/B) (red dots) follow closely the normalized fuel temperatures (blue dots) for entire AGR-1 irradiation. The high pairwise correlation coefficient of 0.86 between normalized fuel temperature and Log(R/B) (Pearson product-moment correlation), which measures the strength of the linear relationship between two variables, also indicates the consistency of predicted and actual fuel temperatures. Additionally, the differences between normalized fuel temperature and Log(R/B) values are scattered around zero as shown on the bottom frame of Figure 8. It is worth mentioning that these plots for the other five capsules are similar to plots for Capsule 4.

Figure 9 shows the predicted instantaneous volume average fuel temperature (Ave FT) and peak fuel temperature (Peak FT) together with their standard deviations of fuel compacts in Capsule 4 as a function of EFPD [11]. Since the TC readings are well-matched with their prediction (Row 1 of Figure 7) indicating negligible model bias, the presented model uncertainty in terms of standard deviation is calculated only by propagation of input parameter uncertainties. The low model fuel temperature uncertainty (e.g., less than 5% (<60 °C) for Peak FT and less than 4% (<45 °C) for Ave FT) confirms the updated linear gap model.

The above evidence of an excellent fit in trend between fuel temperature and Log(R/B) over the whole variation of capsule thermal conditions throughout the AGR-1 irradiation provides assurance that the thermal model has appropriately included all important physical phenomena occurring in the capsule. This increases the confidence that the calculated fuel temperatures reflect the actual fuel temperature with a reduced uncertainty.

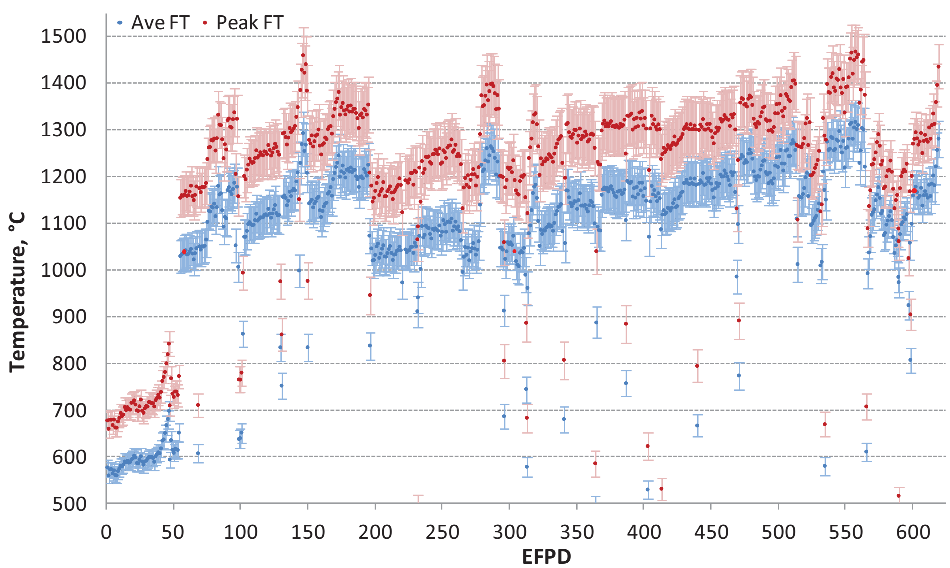

Fig. 9: Model temperature and standard deviation of fuel compacts in Capsule 4.

VI. CONCLUDING REMARKS

Knowledge of the thermal conditions and associated uncertainties of the nuclear fuel in a reactor test is central to the interpretation of the test results. This knowledge is even more important when using the test results for nuclear fuel performance model calibration and code validation, and ultimately for the design and licensing of the new nuclear fuel. The work documented in this paper discusses a novel approach to reducing uncertainty in predicting nuclear fuel temperatures in the AGR-1 test, where it is not practical to obtain direct temperature measurements in the fuel compact domain. The overarching notion is that the model calibration includes not only direct measurements of quantity of interest, but also takes into consideration a variety of other relevant data. Appropriately used, this can increase confidence in the model prediction. While the idea is natural, such assimilation and integration of heterogeneous data and observations has become increasingly practical thanks to the availability and affordability of statistical analysis methods and tools. More importantly, this integrated approach to epistemic uncertainty reduction requires multi-disciplinary collaboration and inputs from a range of experts. In this study, the range includes input from program management; experiment designers and performers; instrumentation, PIE and materials experts and modelers and data analysts.

The above-mentioned collaboration enables a systematic identification of all uncertainty sources, and characterization of the epistemic uncertainties. The collaboration also helps bring together a comprehensive body of insights, and review evidence for their relevance to key modeling assumptions. Then, the parameter sensitivity analysis is performed to focus the effort on areas most effective for uncertainty reduction (e.g., the control gas gap distance uncertainty in this study). Finally, the effort is directed toward maximizing the utility of all available information about the test condition at various stages (e.g., fabrication, irradiation, and PIE) for improving physical models. Another important component in model uncertainty reduction is the quality of data used in the model calibration. Statistical analysis of TC measured and calculated data helps increase confidence of the measured data. Together, these steps result in improved prediction accuracy as demonstrated in this paper.

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