Nuclear Engineering and Design 329 (2018) 110–123

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Impact of gap size uncertainty on calculated temperature uncertainty for the advanced gas reactor experiments

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ARTICLE INFO

Keywords:
Fuel irradiation
Thermal model
Prediction uncertainty
Graphite shrinkage

ABSTRACT

Research being conducted on tristructural-isotropic fuel development and qualification involves seven advanced gas reactor (AGR) experiments that were planned to provide fuel qualification data to support the licensing and operation of the high-temperature gas-cooled reactor. Each AGR test consists of multiple independent capsules containing fuel compacts placed in one or more graphite cylinders shrouded by a stainless-steel shell. These capsules are instrumented with thermocouples embedded in the graphite holder, enabling temperature control. The desired fuel temperature is maintained by variation of the neon/helium gas mixture in response to feedback from thermocouple readings. In the absence of direct measurements, the commercial finite-element heat transfer code ABAQUS was used to predict fuel temperatures. Recognizing inherent uncertainties in the simulation model due to complex physical mechanisms, capsule geometries, and material properties, comprehensive temperature uncertainty quantification was performed. The uncertainty results reveal that the uncertainties in gap sizes are among the most influential factors contributing to calculated temperature uncertainty. The gap size uncertainties originate from a lack of direct experimental data for accurate assessment of dimensional change rates of fuel compacts and graphite components due to complex irradiation-induced material shrinkage or swelling. The study described here focuses on the impact of the gap size uncertainties based on the post-irradiation examination metrology data on calculated temperature uncertainty.

1. Introduction

Research being conducted on tristructural isotropic (TRISO) fuel development and qualification consists of seven advanced gas reactor (AGR) experiments that are assembled, irradiated, and examined to provide fuel qualification data to support the licensing and operation of the Advanced Reactor Technologies' high-temperature gas-cooled reactor (HTGR). Four experiments have been completed to date: AGR-1, AGR-2, and the combined AGR-3/4. Following irradiation in the Advanced Test Reactor (ATR) at Idaho National Laboratory, a post-irradiation examination (PIE) is performed for each capsule of the AGR experiments to determine the irradiation impacts on fuel and graphite materials. These PIE data provide invaluable insights into both fuel performance and graphite properties that are crucial for design and licensing of HTGRs.

Each AGR experiment consists of multiple capsules independently monitored for fission product release and controlled for temperature using a variable neon and helium gas mixture flowing through the gaps within each capsule. These capsules are instrumented with thermocouples (TCs) embedded in the graphite holder, enabling temperature control. There is no direct measurement of fuel temperature because contact between the fuel particles and the TC heads might induce particle failure. Therefore, to support the TRISO fuel performance assessment and to provide data for validation of fuel performance and fission product transport models and codes, a daily as-run thermal analysis was performed on each AGR capsule for the entire irradiation campaign. The commercial finite-element heat transfer code ABAQUS was used for this thermal analysis to predict capsule temperatures (Hawkes et al., 2012, 2015a,b).

The thermal model involves complex physical mechanisms (e.g., dimensional change in graphite) and properties (e.g., conductivity and density), which are not fully understood and accurately quantified due to a lack of relevant data. Therefore, the thermal model predictions are affected by uncertainty in input parameters and by incomplete knowledge of the underlying physics leading to modeling assumptions. Along with the deterministic predictions from a set of input thermal conditions, information about calculated uncertainty is instrumental for decision-making by the Advanced Reactor Technologies Program. Well defined and reduced uncertainty in model predictions increases the quality of and confidence in the AGR technical findings (Pham et al., 2014).

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http://dx.doi.org/10.1016/j.nucengdes.2017.08.009
Received 26 April 2017; Received in revised form 8 August 2017; Accepted 10 August 2017

The uncertainty quantification for AGR temperature predictions is described in detail in Pham et al. (2016). The uncertainty results include not only the uncertainty in calculated temperatures, but also the impact of each input on uncertainty. These results reveal that the uncertainties in gap sizes are among the most influential factors contributing to overall uncertainty of fuel temperature predictions. Gap size uncertainties originate from a lack of direct experimental data for accurate estimation of dimensional change rates of fuel compacts and graphite components due to complex irradiation-induced material shrinkage or swelling. At the end of irradiation, gap sizes and associated uncertainties are estimated using dimensional measurement data obtained during PIE of AGR capsules. The impact of resulting gap size uncertainties on calculated temperature uncertainties is the focus of this study.

2. Thermal model and uncertainty

2.1. Thermal model description

The commercial finite-element heat transfer code ABAQUS was used to build a thermal model for each AGR capsule to predict fuel and graphite temperatures. A basic mesh was created for one capsule in each AGR experiment. This mesh was propagated to all other capsules by varying gas gap conductivity and gap conductance to compensate for individual capsule gap dimensions and changes in the gap size during irradiation (Hawkes et al., 2015b). Fig. 1 shows a cross section of the finite-element mesh with colored entities for one AGR-2 capsule, which is representative of all AGR-1 and AGR-2 capsules. The design of AGR-3/4 capsules is different from that of the AGR-1 and -2 capsules, as shown in Fig. 2. The thermal model was calibrated by varying the graphite emissivity to reasonably match calculated and measured TC temperatures during early cycles, when TC readings were deemed reliable. This is based on the assumption that TC drift was negligible during early cycles, a supposition supported by analysis of TC readings for AGR-1 (Pham and Einerson, 2012, 2013). Model details are provided in Hawkes et al. (2012, 2015a,b), including validation and verification, calibration, sensitivity analysis, and results.

The fission power generated in the fuel stacks and graphite holders (or three rings in AGR-3/4 capsules) is mainly conducted and radiated out through the gas gaps between the surfaces of the fuel stacks, the holder, and the stainless-steel shell to the ATR primary cooling water (dark blue ring in Fig. 1), which serves as the ultimate heat sink for AGR capsules. Governing equations for steady-state conduction and radiation heat transfer are used in the thermal models. The temperature of the ATR primary cooling water was used as an adiabatic boundary condition on the outside of the model's outermost component. Neglecting small temperature variation over time, the inlet temperature is assumed to be 58 °C, with a temperature rise through each capsule of 2 to 3 °C. This assumed inlet temperature is within 0.5 °C of the calculated temperatures, which indicates low uncertainty in the temperature boundary condition.

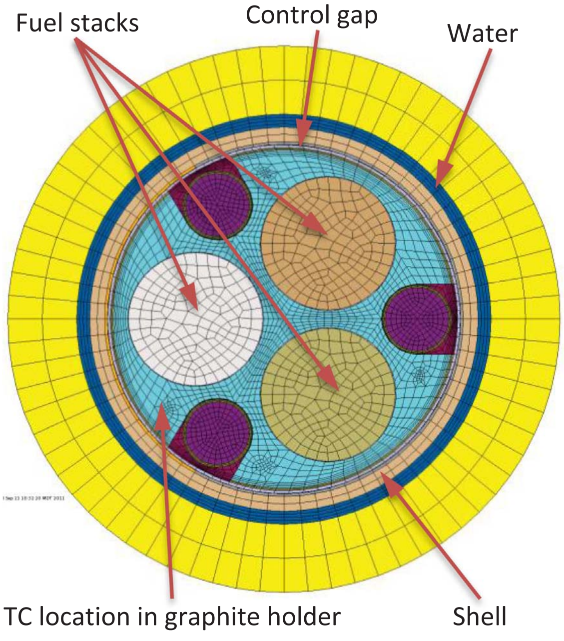

Fig. 1. Finite-element mesh of an AGR-2 capsule.

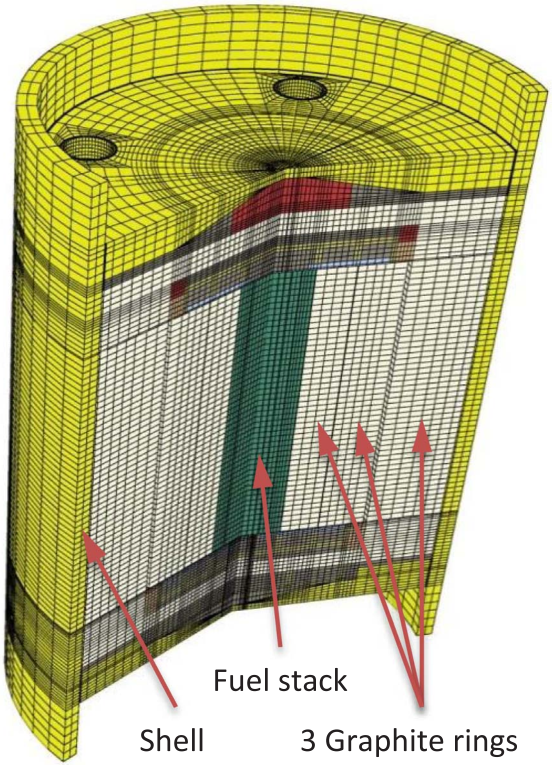

Fig. 2. Finite-element mesh of AGR-3/4 capsule.

2.2. Thermal model input uncertainty

The standard input uncertainty propagation method is used to combine input uncertainties and sensitivities to quantify the overall uncertainty of calculated temperatures (Pham et al., 2016). The first step is the selection of the model inputs of potential importance to calculated temperatures. This selection is based on a thorough analysis of uncertainty sources and model sensitivities. The selected parameters either have high sensitivity to temperature predictions and/or have large input uncertainty, resulting in large impacts on the calculated temperature uncertainty. Details about these input parameters are provided in Hawkes et al. (2012, 2015a,b). Specifically, a detailed explanation of the thermal conductivity of the compacts was presented in Hawkes et al. (2015b), where the impact of particle conductivity and particle packing fraction was discussed.

An accurate estimation of input uncertainties is crucial. Ideally, uncertainties regarding inputs are directly estimated from measurement uncertainties (e.g., the neon fraction of the gas mixture and the gap sizes). When inputs are the results of simulation, their uncertainties are estimated by the modelers, taking into account all uncertainty sources in their codes (e.g., fuel and graphite heat rates taken from the fuel depletion codes). Finally, expert judgment is used as the basis to specify the uncertainty range for those inputs taken from legacy experiments