Informing Transient Testing of Fuel Designs for the Transformational Challenge Reactor*

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INTRODUCTION

The Transformational Challenge Reactor (TCR) is a helium-cooled, yttrium-hydride moderated reactor being designed for the US Department of Energy Office of Nuclear Energy to demonstrate and deploy advanced manufacturing technologies in nuclear design and manufacturing processes [1]. To inform the TCR safety analysis, sample fuel elements will be placed in Idaho National Laboratory's (INL) Transient Reactor Test Facility (TREAT) and exposed to pulses representative of TCR reactivity-insertion accident (RIA) conditions. Using TRACE and RELAP5-3D, we calculated fuel temperatures and average energy deposition in TCR fuel at both hot full power (HFP) and hot zero power (HZP) for both sub-prompt and prompt reactivity insertions. Though RELAP has been used for gas-cooled reactor safety analysis in the past [2], the prompt generation time in TCR is an order of magnitude shorter than for other gas-cooled reactors due to the use of yttrium-hydride instead of graphite as the moderator [3].

The TREAT facility at INL is an air-cooled, graphite-moderated reactor fueled with uranium oxide dispersed into the graphite blocks. It has been used for fuel testing in both fast and thermal reactors, and following its nearly 25-year shutdown, the facility has resumed operation and demonstrated an ability to match historical tests. This provides confidence in the TREAT team's ability to design tests for a wide range of transients including pulses representative of reactivity insertions terminated by either temperature feedback or negative reactivity insertion and pulses providing a power profile representative of a loss of coolant accident in a light-water reactor [4]. The demonstrated capabilities of TREAT for both fast and thermal reactors give us confidence that TREAT can create pulses that mimic anticipated TCR transients.

To gain a better understanding of the impact of our transients on the heterogeneous fuel form, the RELAP boundary conditions were also used to inform a thermomechanical analysis using the fuel performance code BISON. The analysis provides detail of failure on the fuel kernel level and is capable of predicting failure due to stress limits [5].

TCR Fuel and Design Overview

Like many gas-cooled reactors, TCR employs a conventionally manufactured tri-structural isotropic (TRISO) fuel form, but unlike historical TRISO-fueled reactors, TCR fuel meat is composed of uranium mononitride (UN) rather than uranium dioxide or uranium carbides [6]. The TRISO particles, which feature larger fuel kernels than conventional uranium oxy-carbide (UCO) TRISO designs, are embedded into a silicon-carbide matrix to provide an additional barrier to fission product release. The parking fraction of the TRISO particles in the matrix is approximately 50%.

TCR has been designed for an operational power of 3 MW, with an inlet temperature of 623 K. The core height and diameter are just under one meter. The small core size allows for reactivity control via an external shroud. The shroud is divided into eight azimuthal segments, each with a reactivity worth of 0.75$. The analysis conducted here is based on expected design conditions, and the final design may deviate slightly from what has been used in this analysis, but the conservatism employed should provide bounding analysis for the final TCR design.

METHODOLOGY

The systems codes TRACE and RELAP5-3D employ one-dimensional heat transfer models [7, 8], so the fuel element was homogenized into a single smeared material. This method has been shown to cause higher power peaks than a more explicit model of the fuel would produce due to a reduced average Doppler feedback temperature, but energy deposition is comparable to more explicit methods [9]. The RIA was modeled as an insertion of either 0.75$ or 1$ linearly over a period of 0.45 s. We employed two different methods to calculate energy deposition in the fuel kernels to bound the TREAT experiment design conditions: an adiabatic energy deposition in which the power curve is

integrated with respect to time and divided by the fuel mass, and a fuel specific heat method in which the specific heat of UN, as reported by Hayes et. al is integrated with respect to the average fuel temperature over the transient [10]. The adiabatic energy deposition calculation is a very conservative one, because all energy is assumed to be deposited in the fuel and remain there. The specific heat calculation is more representative of TCR response due to the long duration of the transients and the relatively high heat transfer rate out of the fuel. Because the adiabatic method is so conservative, we only present results using the specific heat approach in this summary.

RESULTS

In this section we present RELAP results to demonstrate the system response to the various reactivity insertions. We also show a comparison of our figures of merit between RELAP and TRACE. Finally, we show the results of our thermo-mechanical analysis in BISON using RELAP boundary conditions.

RELAP Results

Our key figures of merit for the RELAP analyses were power, maximum fuel temperature, and energy deposition. As anticipated, larger reactivity insertions led to higher power and faster transients, and for identical reactivity insertions, the HZP transient was slower than the HFP one as seen in Figure 1.

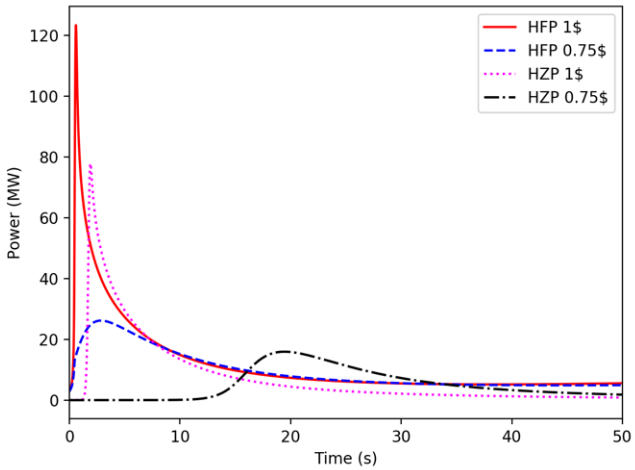

Fig 1. Power profile for each reactivity insertion

Peak fuel temperatures provide a metric by which we can predict fuel failure in the systems-level codes. The slow progression of the HZP accident causes fuel temperatures to peak well after the HFP temperatures and cool down at a significantly slower rate. As seen in Figure 2, both 1$ insertions cause maximum fuel temperatures to reach between 1,900-2000 K. The HFP maximum fuel temperature is 1,928 K, and the HZP maximum fuel temperature is 2,000 K. For the 0.75$ insertion, the HFP peak fuel temperature is 1,647 K, and the HZP peak fuel temperature is 1,697 K. HFP peak fuel temperatures occur within the first 30 seconds of the accident, whereas the HZP peak temperatures occur at a time of approximately 200 seconds.

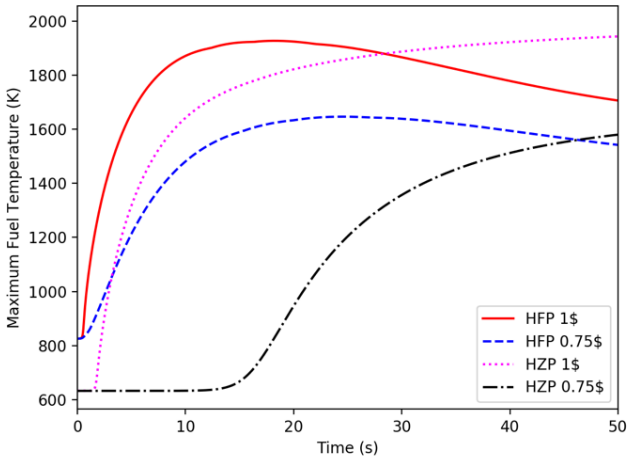

Fig 2. Peak fuel temperature profile for each reactivity insertion

TRACE-to-RELAP Comparison

To provide confidence in our RELAP results, an independent set of simulations was conducted using TRACE, and we compared peak power, both energy deposition calculations, and change in average fuel temperature for the HFP cases, as seen in Table I. The temperature rise shown in the table is the change in average temperature over the duration of the transient.

TABLE I. TRACE-to-RELAP HFP Comparison (1$/0.75$)

Property	RELAP	TRACE
Peak Power (MW)	123/26	83/18
Approximate Fuel Energy Deposition (J/g UN)	163/116	129/91
Rise in Average Fuel Temperature (K)	521/374	389/287

For all figures of merit, RELAP predicts higher values than TRACE due to differences in how the two codes handle reactivity feedback. To confirm the accuracy of our models, we averaged the reactivity coefficients with respect to temperature and found that a 1$ reactivity insertion should cause a temperature rise of 496 K, and a 0.75$ insertion should cause a temperature rise of 373 K. We see that RELAP provides better agreement with simple analytical models as compared to TRACE. We also conducted comparisons between the Nordheim-Fuchs model and the RELAP model for larger reactivity insertions, and saw excellent agreement in the peak power, energy deposition, and pulse width between the analytic predictions and the computer model.

Thermo-Mechanical Analysis with BISON

We performed BISON simulations on single TRISO particles with an external SiC shell to approximate an equivalent volume of matrix for a particle based on the packing fraction. The outer surface of this SiC shell was given the temperature and heat transfer coefficient (HTC) histories from the hottest node in the hot channel calculated in RELAP. The HTC was reduced by a factor of 10 to approximate the additional thermal resistance of transporting the heat through the particle layers, matrix, and to the coolant.

The results showed that the long duration of the expected transients produces small temperature differences (<50 K) in the particles, and kernel melting is not expected. The stress in the SiC layer is driven by the different coefficients of thermal expansion of the kernel (~$10x10^{-6}$ /K) versus the SiC (~$5x10^{-6}$ /K). Thus, the SiC remains in compression until temperatures in excess of the deposition temperature of approximately 1700 K are reached. The hoop stresses experienced during all reactivity insertions are well below SiC failure levels (about 200 MPa), so based on the BISON results, we predict no fuel failure for any reactivity insertion.

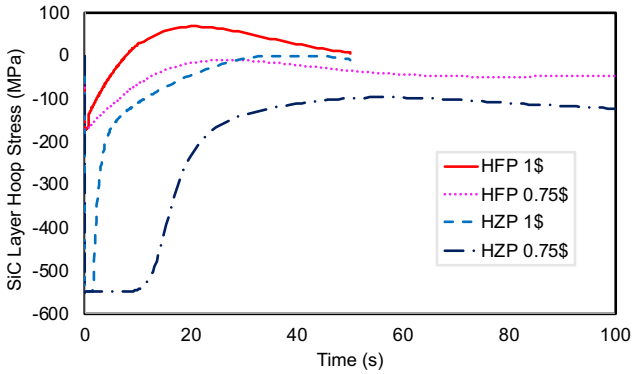

Fig. 3. Plot of the SiC coating layer hoop stress versus time.

CONCLUSIONS

We have performed a series of calculations using systems codes to provide boundary conditions for transient testing of TCR fuel elements in TREAT. When comparing our figures of merit between TRACE and RELAP, we found that RELAP consistently predicted higher energy deposition, power, and asymptotic fuel temperature than TRACE. We also demonstrated that RELAP results are consistent with analytic predictions, providing confidence that the RELAP results are appropriate boundary conditions for TCR fuel testing and thermomechanical simulations. Peak fuel temperatures reach 1,900-2,000 K with 1$ reactivity insertions at HFP and HZP, and BISON models predict no fuel failure.

ACKNOWLEDGEMENTS

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