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TREAT Neutronics Analysis and Design Support, Part II: Multi-SERTTA-CAL

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Abstract. Experiment vehicle design is necessary in preparation for Transient Reactor Test (TREAT) facility restart and the resumption of transient testing to support Accident Tolerant Fuel (ATF) characterization and other future fuels testing requirements. Currently the most mature vehicle design is the Multi-SERTTA (Static Environments Rodlet Transient Test Apparatuses), which can accommodate up to four concurrent rodlet-sized specimens under separate environmental conditions. Robust test vehicle design requires neutronics analyses to support design development, optimization of the power coupling factor (PCF) to efficiently maximize energy generation in the test fuel rodlets, and experiment safety analyses. An integral aspect of prior TREAT transient testing was the incorporation of calibration experiments to experimentally evaluate and validate test conditions in preparation of the actual fuel testing. The calibration experiment package established the test parameter conditions to support fine-tuning of the computational models to deliver the required energy deposition to the fuel samples. The calibration vehicle was designed to be as near neutronically equivalent to the experiment vehicle as possible to minimize errors between the calibration and final tests. The Multi-SERTTA-CAL vehicle was designed to serve as the calibration vehicle supporting Multi-SERTTA experimentation. Models of the Multi-SERTTA-CAL vehicle containing typical PWR-fuel rodlets were prepared and neutronics calculations were performed using MCNP6.1 with ENDF/B-VII.1 nuclear data libraries; these results were then compared against those performed for Multi-SERTTA to determine the similarity and possible design modification necessary prior to construction of these experiment vehicles. The estimated reactivity insertion worth into the TREAT core is very similar between the two vehicle designs, with the primary physical difference being a hollow Inconel tube running down the length of the calibration vehicle. Calculations of PCF indicate that on average there is a reduction of approximately 6 % for PWR fuel rodlets irradiated under both wet and dry conditions. Changes to the primary or secondary vessel structure in the calibration vehicle can be performed to offset this discrepancy and maintain neutronic equivalency. Current possible modifications to the calibration vehicle include reduction of the primary vessel wall thickness, swapping Zircaloy-4 for stainless steel 316 in the secondary containment, or slight modification to the temperature and pressure of the water environment within the primary vessel. Removal of some of the instrumentation within the calibration vehicle can also serve to slightly increase the PCF. Future efforts include further modification and optimization of the Multi-SERTTA and Multi-SERTTA-CAL designs in preparation of actual TREAT transient testing. Experimental results from both test vehicles will be compared against calculational results and methods to provide validation and support additional neutronics analyses.

Keywords: Multi-SERTTA, Multi-SERTTA-CAL, Neutronics, Transient Testing, TREAT.

INTRODUCTION

Ongoing activities at Idaho National Laboratory (INL) include the resumption of transient testing capabilities to support advanced reactor designs and validate computational predictions of fuel and core behavior [1]. Such validation will be instrumental in the review and approval of next generation power reactor design and safety evaluation. The Transient Test Reactor (TREAT) Facility is a thermal-spectrum test reactor designed to evaluate reactor fuels and structural material under simulated nuclear excursion and transient power/cooling mismatch situations that could be encountered in nuclear reactors [2].

Historically, TREAT was operated from 1959 through 1994. Methodologies applied in TREAT utilized very approximate models to establish predicted transient power shapes. Extensive calibration test experiments were required prior to the actual transient test to more accurately estimate the power that would have been deposited into the test experiment during a transient pulse [3]. Much of the expertise supporting the legacy methods, with accompanying computational calculations, has been lost over the past few decades.

With the resumption of transient testing in TREAT, new experiment vehicle designs must be developed to satisfy current and future transient testing needs. The foremost experiment test vehicle to be employed in TREAT's experiment arsenal will be the Multi-SERTTA (Static Environment Rodlet Transient Test Apparatuses) [4,5], which can accommodate up to four concurrent rodlets under separate environmental conditions. Ongoing efforts are necessary in preparation of transient testing support for Accident Tolerant Fuel (ATF) characterization [6] and other future fuels testing requirements. An overview of the Multi-SERTTA experiment test vehicle, which would be placed in the center of the TREAT core, is shown in Figure 1; Unit 1 is the topmost rodlet vessel. In the current design, all four rodlet test vessel are identical.

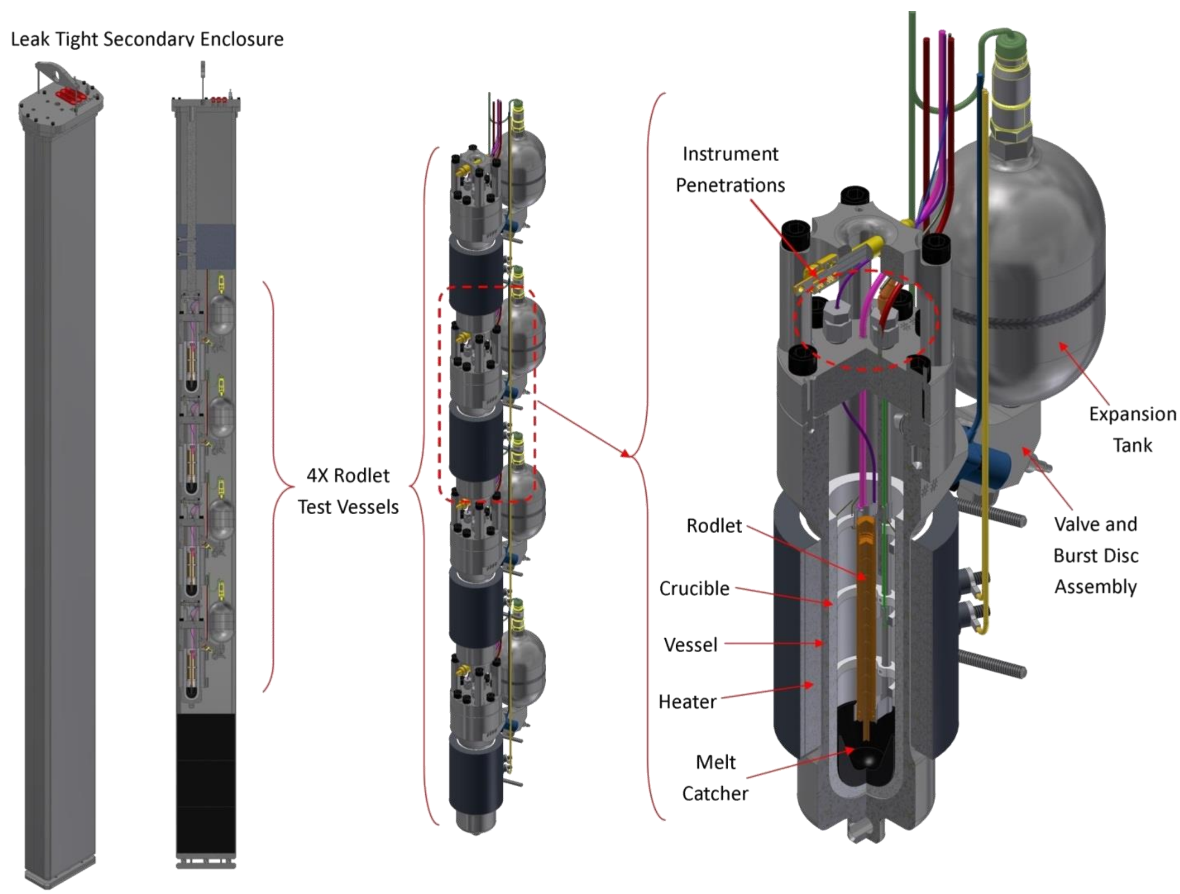

FIGURE 1. Basic Overview of the Multi-SERTTA Experiment Test Vehicle.

There are two key parameters needed when designing and characterizing the performance of a TREAT fuel irradiation experiment: power coupling factor (PCF) and transient correction factor (TCF). The PCF is the effective quantity of fission-generated energy per mass of fuel specimen per total core energy [3], and can be estimated using various reactor physics calculational methods. The TCF accounts for time-dependent effects [7], and traditionally is obtained as part of the experiment calibration procedure [3]. The product of the PCF and TCF is used to estimate the total quantity of energy delivered to a test specimen during a transient test experiment in TREAT. The quantity of energy deposited into a fuel rodlet under various test environments can be utilized to evaluate overall fuel performance, including failure mechanisms and thresholds.

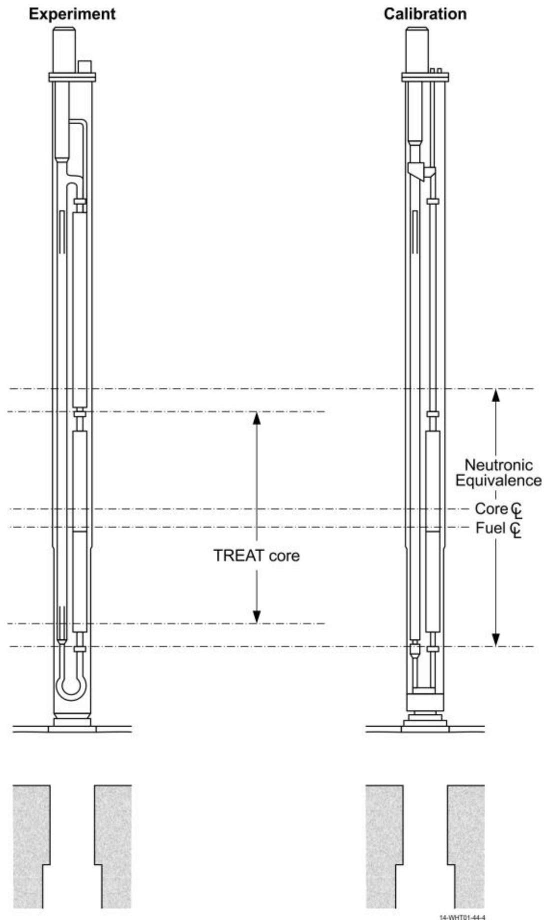

FIGURE 2. Comparison of Experiment and Calibration Vehicles from TREAT Sodium Loop Tests.

The calibration experiment test vehicle package was utilized to perform experiments specifically designed to evaluate and validate test conditions in preparation of actual fuel testing. The calibration experiments established the test parameter conditions necessary to fine-tune computational models of the experiment such that the correct energy deposition is properly introduced into the actual test fuel samples. An example experiment test vehicle and calibration experiment test vehicle from representative of sodium loop tests is provided in Figure 2. The calibration vehicles were specifically manufactured to be very similar in design to the actual test vehicle to be utilized in the transient tests. The portion of the calibration vehicle within the active region of the core needed to be as neutronically equivalent to the actual test vehicle as possible to reduce experimental error introduced into the final transient test experiment.

Often 10 to 20, or more, individual tests were performed using the calibration vehicle to test varying parameters of the core, control rod positions, and calibration test samples. As a minimum, three calibration tests with similar control rod in-core positions would be necessary prior to an actual transient test. The initial test in the calibration vehicle would be to perform a steady-state irradiation of test fuel rodlets very similar to the actual test case samples.

These rodlets would be tested to determine their respective PCF. Next a steady-state irradiation of a test wire would be performed using the calibration vehicle, and then its activation profile characterized. Finally a transient test experiment would be performed using the calibration vehicle and another test wire during a simulation of the actual transient experiment. The second wire would be characterized as well. The steady-state PCF would be multipled by the TCF, which is the ratio of the transient wire irradiation results over the steady-state wire irradiation results. Thus the transient PCF for the actual test fuel rodlets has been experimentally estimated and the actual experiment test vehicle is utilized with the test fuel to perform the full transient test run in TREAT [3].

The Multi-SERTTA-CAL vehicle was designed to serve as the calibration vehicle supporting Multi-SERTTA experimentation. The primary physical difference between the two designs is the incorporation of a long, hollow Inconel tube running down the length of the calibration vehicle (see Figure 3) that has an inner diameter of roughly 1.0 cm and a thickness of between 0.1 and 0.4 cm. The intent of the hollow tube is to minimize the impact on the design of the Multi-SERTTA-CAL test vehicle while significantly increasing accessibility to test materials supported within the tube during calibration experiment tests. The concept is very similar to the M8CAL design [3] where test samples can be irradiated, quickly removed, and sampled, while leaving the complete calibration vehicle in-core for additional transient testing. The four-unit structure of the Multi-SERTTA experiment test vehicle optimizes experiment test space in TREAT for irradiation of concurrent test fuel rodlets. However, disassembly and reassembly of the vessels, especially upon receiving appreciable cumulative neutron activation, would limit the utility and ease of use for this design. A hollow tube running through the calibration mockup of this test vehicle would maintain neutronic similarity to the Multi-SERTTA design while allowing for similar calibration vehicle irradiation testing efficiency as incorporated into the sodium loop calibration experiment designs.

The purpose of this paper is to present ongoing analysis and design support for the Multi-SERTTA-CAL experiment test vehicle via computations of the PCF for varying design perturbations with a baseline PWR fuel-rodlet design [8]. Comparison of Multi-SERTTA-CAL results versus the original Multi-SERTTA test vehicle design are important when developing final experiment campaign measurements and measured corrections for transient testing of test fuel.

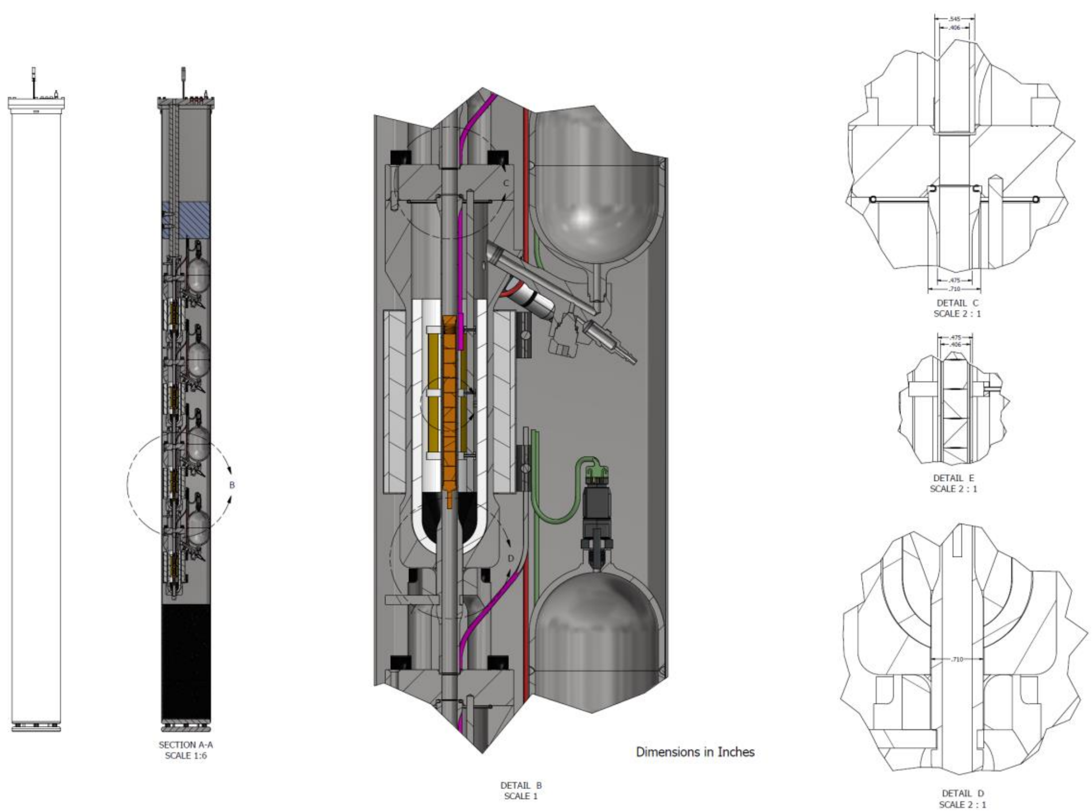

FIGURE 3. Basic Overview of the Multi-SERTTA-CAL Test Vehicle.

ANALYSIS AND DESIGN EFFORTS

Evaluation of PCF

Neutronic calculations were performed with Monte Carlo N-Particle (MCNP) version 6.1 [9] with ENDF/B-VII.1 nuclear data libraries [10]. MCNP is a general-purpose, continuous-energy, generalized geometry, time-dependent, coupled n-particle Monte Carlo transport code. Figure 4 portrays a comparison of the Multi-SERTTA and Multi-SERTTA-CAL model profiles generated for use in MCNP to simulate the baseline reference rodlet design; Figure 5 shows the horizontal profile of the Multi-SERTTA-CAL MCNP model through one of the PWR rodlets. Details regarding the rodlet and encapsulated environment description are provided elsewhere [8].

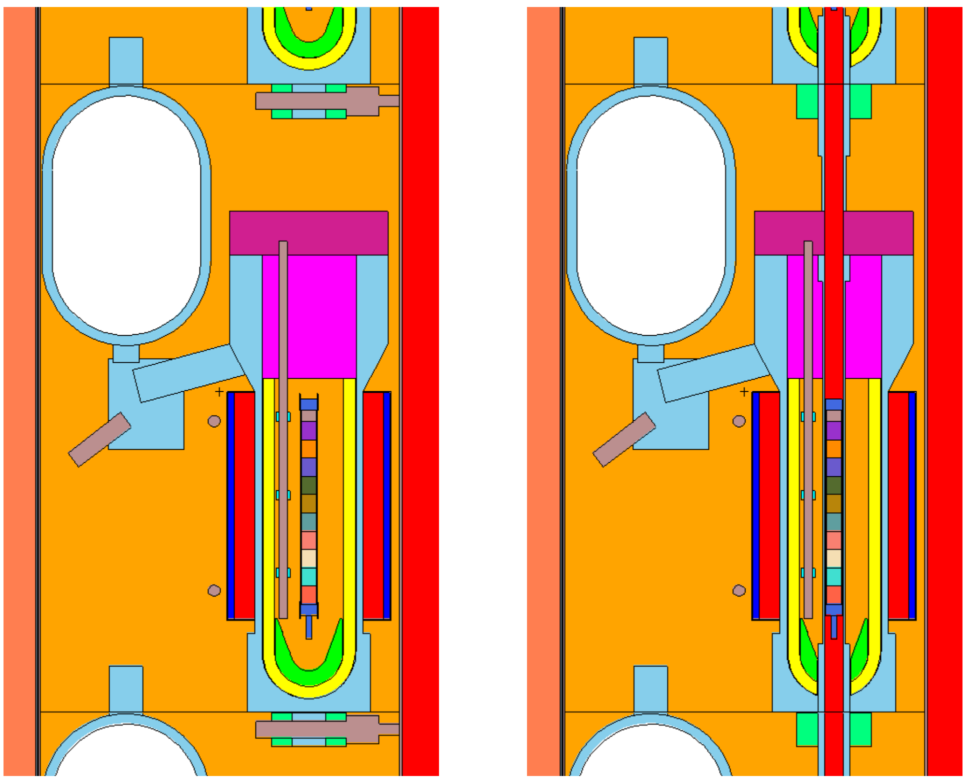

FIGURE 4. Vertical Profiles of the MCNP Multi-SERTTA (Left) and Multi-SERTTA-CAL (Right) Model with PWR Rodlet.

The PCF values are estimated by calculating the total energy deposited in the fuel rodlet pellets divided by the total energy deposited in the TREAT fuel and graphite reflector, which accounts for about 98.9 % of the total core power in the calculations. Both historically performed experiments [3] and modern computational analyses [11,12] have investigated the impact of control rod positioning on PCF with respect to the power-monitoring detectors, including temperature dependence of PCF and core energy during transient testing, that impacts TCF.

The MCNP models are steady-state calculations of the core at room temperature and the experiment at expected operational temperatures to provide a quick baseline analysis similar to simple steady-state calibration runs. Tally calculations for the nuclear heating of the core and fuel pins, to compute PCF, account for energy deposited by fission products, neutrons, prompt gammas, and captured gammas. A heating value of approximately 200 MeV/fission also accounts for deposition from delayed gammas and betas upon completion of the transient. Calculations performed in these analyses are currently not as comprehensive due to the early-stage design and development of the Multi-SERTTA and Multi-SERTTA-CAL test vehicles. As the design becomes more finalized, the impact of transitory and temperature effects upon PCF and TCF can be evaluated more in-depth. The purpose of the current calculations is to investigate design parameters that impact the baseline PCF. These calculations not only support the final design of the Multi-SERTTA experiment and calibration vehicles, but also development of future experimental test vehicles [5] and the development of analyses practices for planned ATF experiments [6] and future fueled experiment designs.

A comparison of the calculated PCF values for PWR environment conditions for both the Multi-SERTTA and Multi-SERTTA-CAL are shown in Table 1; uncertainties reported in the table represent the Monte Carlo calculated statistical uncertainties. Additional calculations for the primary vessels filled with argon covergas at PWR operational conditions is also provided for comparison. Essentially PCF calculations in the Multi-SERTTA-CAL vehicle are approximately 6 % lower than in the original Multi-SERTTA test vehicle design. There is approximately a 13 % drop in PCF when changing the environmental conditions of the test fuel rodlets within the primary vessel containment from a typical PWR environment to a dry argon environment at PWR operational pressure and temperature.

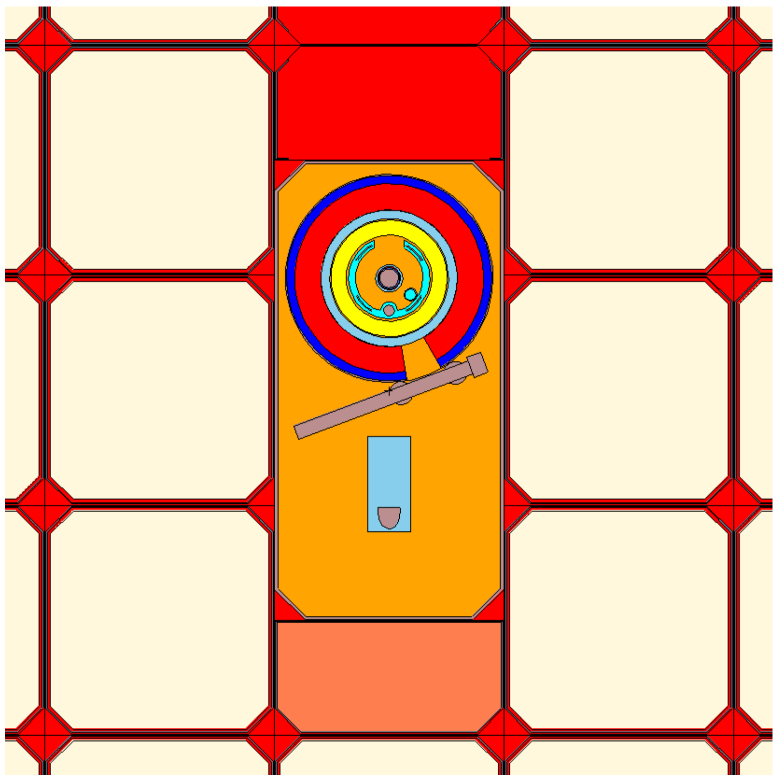

FIGURE 5. Horizontal Profiles of the MCNP Multi-SERTTA-CAL Model with PWR Rodlet.

TABLE 2. Calculation of PCF for PWR Environmental Conditions or Pressurized Argon (Dry) Environment.

Unit	Multi-SERTTA		Multi-SERTTA-CAL	
	Baseline PCF (W/g-MW)	**Argon PCF (W/g-MW)**	**Baseline PCF (W/g-MW)**	**Argon PCF (W/g-MW)**
1 (Top)	0.975 ± 0.005	0.856 ± 0.004	0.918 ± 0.004	0.808 ± 0.004
2	1.479 ± 0.006	1.228 ± 0.005	1.378 ± 0.005	1.167 ± 0.004
3	1.567 ± 0.006	1.298 ± 0.005	1.460 ± 0.006	1.226 ± 0.004
4 (Bottom)	1.170 ± 0.005	1.095 ± 0.004	1.104 ± 0.005	1.024 ± 0.004

Analyses performed and reported herein include calculation of PCF for the reference configuration with comparison against modifications to the experiment environment or test vehicle design. Placement of the four Multi-SERTTA units within the stack impacts the delivered PCF in the simulations. Units at the top and bottom are closer to the axial graphite reflectors instead of the center of the active core region. Units 1 and 2 also exhibit reduced PCF values due to the presence of the four compensation control rods surrounding the experimental region. These control rods are fully withdrawn into the upper axial reflector region. While not used during conventional core operations, these rods serve to provide negative reactivity in the core during the withdrawal of the experiment test vehicles.

The impact of removing instrumentation from the Multi-SERTTA-CAL vehicle was investigated in an effort to identify means to increase the PCF in the calibration vehicle while maintaining the convenience of a vertical tube access. Figures 6 and 7 display the effective increase in PCF due for both dry and wet environment conditions in Multi-SERTTA, respectively, for test fuel rodlets, or pins, in Units 1 through 4. The 1σ uncertainty in the percentages shown in both Figures 6 and 7 is ≤1.5 %. As can be seen in Figure 6, removal of the crucible, heater element, or expansion tank can significantly increase the PCF while many of the other instrumentation components (denoted as "Minor Constituents" in Figure 6) have minimal impact on calculations, and even removed in combination do not significantly impact calculated PCF values. However, for the wet environment conditions in Figure 7, removal of all of these instrumentation components does have an impact on the calculated PCF values. The decision of the experiment design team, however, is to try and retain as much instrumentation as possible between the two designs for consistency, and to avoid the introduction of experimental errors that may have not been readily visible within our computational comparison. Additionally, retention of the instrumentation further facilitates maintenance of neutronic equivalency between the Multi-SERTTA and Multi-SERTTA-CAL test vehicle designs.

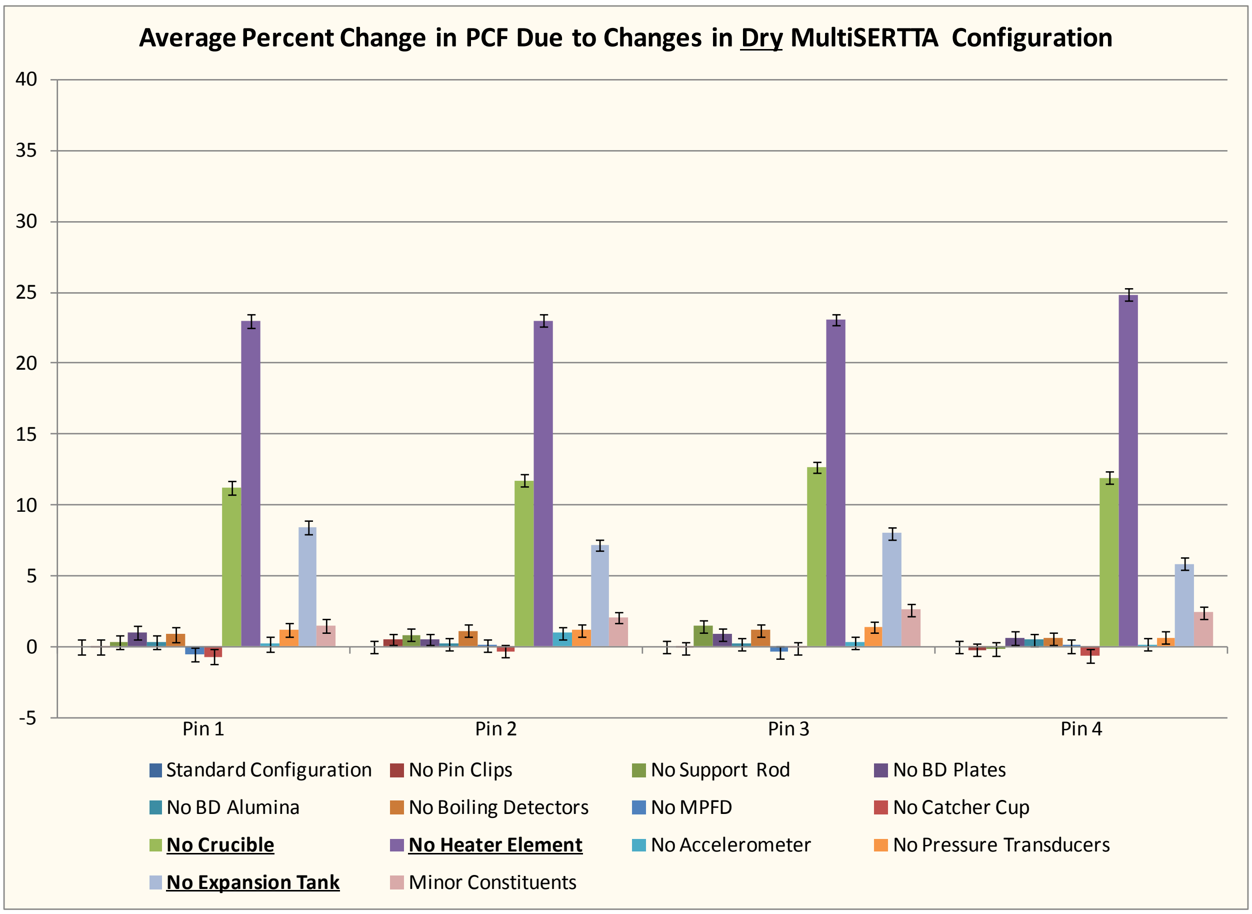

FIGURE 6. Average Percent Change in PCF Due to Changes in Dry Multi-SERTTA.

Calculations using the Multi-SERTTA design show that replacing the secondary enclosure with Zircaloy-4 instead of stainless steel 316 effectively increases PCF values by about 8 %. Replacement of the zirconia crucible (~2 wt.% HfO_2), which is used to prevent melted fuel from contacting with and eroding rodlet containment, in each primary vessel with a nuclear grade version (< 100 ppm Hf in Zr) would increase PCF values on average approximately 13 %. While development of differing grades of purity for crucibles within the different test vehicles could lead to possible confusion and accidently use of incorrect crucible types when micromanaging experimental PCF optimization, the simple replacement of the stainless steel secondary vessel with slightly less neutronically opaque material could be a quick and easy means to more closely correct differences between experiment and calibration test vehicle equivalency.

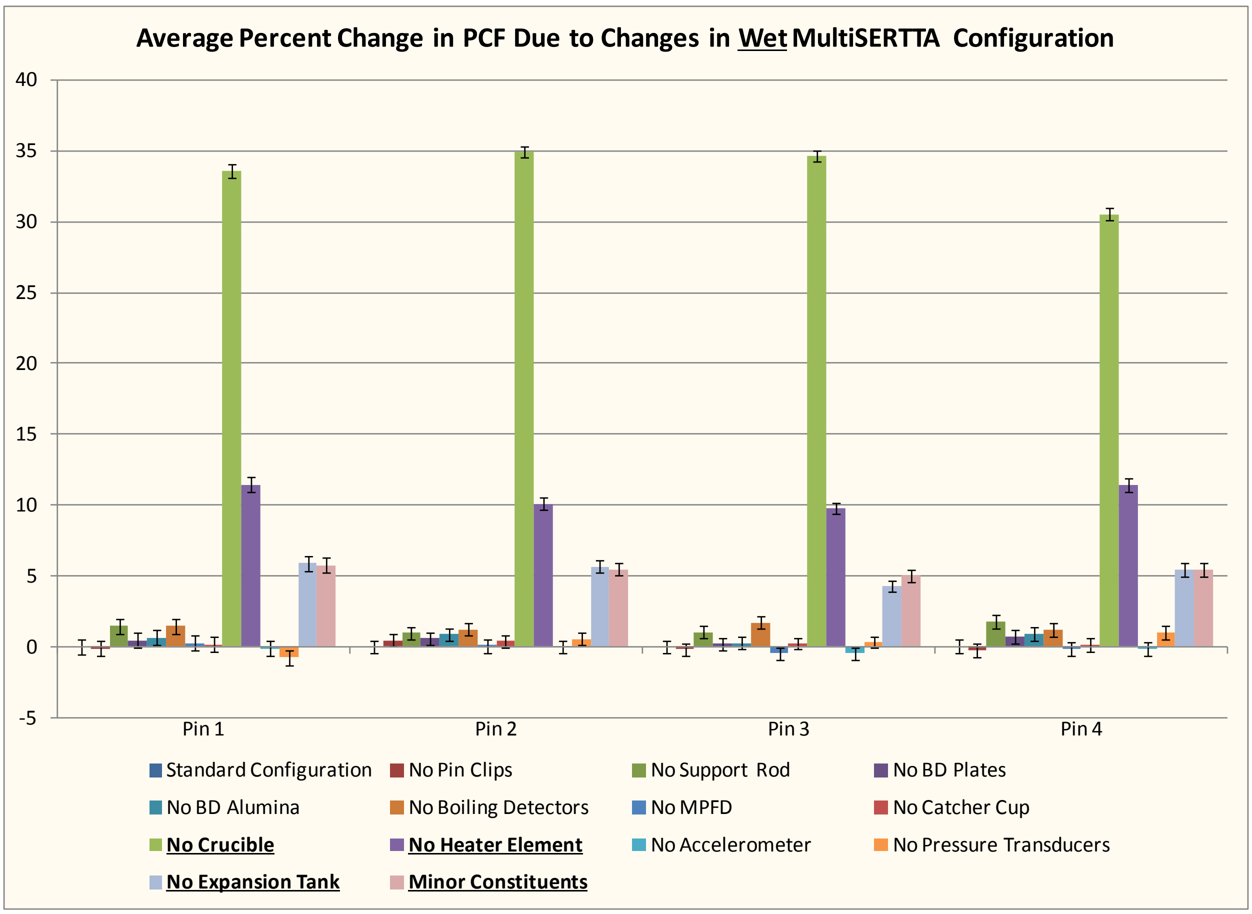

FIGURE 7. Average Percent Change in PCF Due to Changes in Wet Multi-SERTTA.

The intent of the calibration vehicle is to use it for multiple irradiation tests without the need to physically dismantle the constituent units. In that case, the possibility to manufacture thinner primary vessel containments to reduce the quantity of Inconel between the TREAT core and test experiment location has also been investigated. Figure 8 shows that the removal of up to 60 mil (0.1524 cm) could achieve approximately a 6-8 % increase in PCF within the Multi-SERTTA-CAL vehicle. Slight modifications to the environment temperature and/or pressure to adjust the density of the water environment could also help to slightly increase the PCF in the Multi-SERTTA-CAL test vehicle; calculated results for the Multi-SERTTA vehicle are shown in Figure 9 and would also similarly apply to the calibration vehicle. The 1σ uncertainty in the percentages shown in both Figures 8 and 9 is ≤1.5 %.

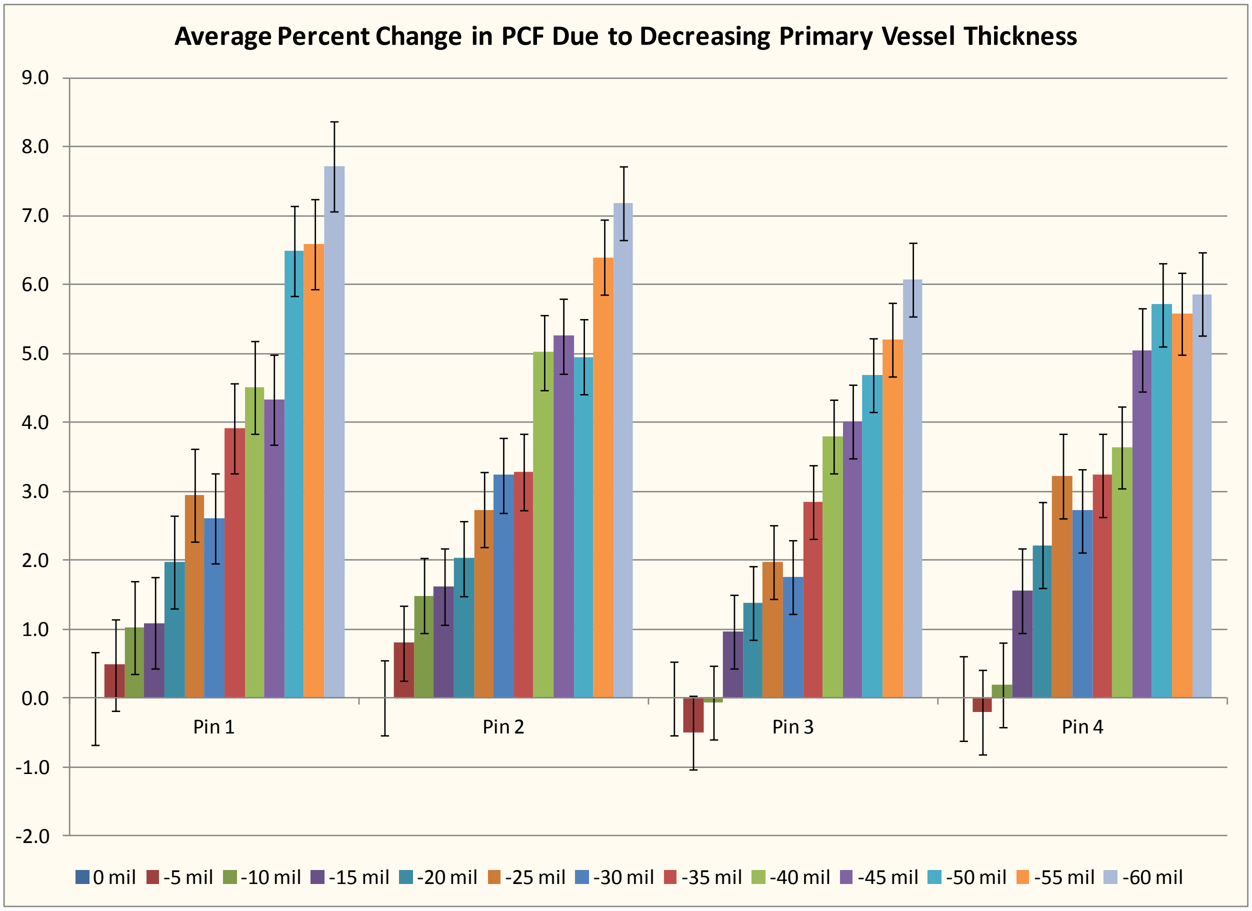

FIGURE 8. Average Percent Change in PCF Due to Decreasing Primary Vessel Thickness.

Future Efforts

Future activities include further evaluation and modification of the Multi-SERTTA [13] and Multi-SERTTA-CAL test vehicles to further optimize their capabilities and create neutronically equivalence within the active region of the core to minimize experimental error during calibration testing. Upon resumption of transient testing, experimental results from both of these vehicles can be compared against the calculated values and utilized to establish benchmark experiment data for further optimization and design strategies, and validation of additional codes and nuclear data.

It is currently unknown whether neutronic equivalence is maintained throughout a transient between experimental and calibration vehicles. Part of the experiment campaign will include use of experimental data to validate modern nuclear simulation tools with multiphysics analysis capabilities to explore transient effects and their impact on TCF and PCF.

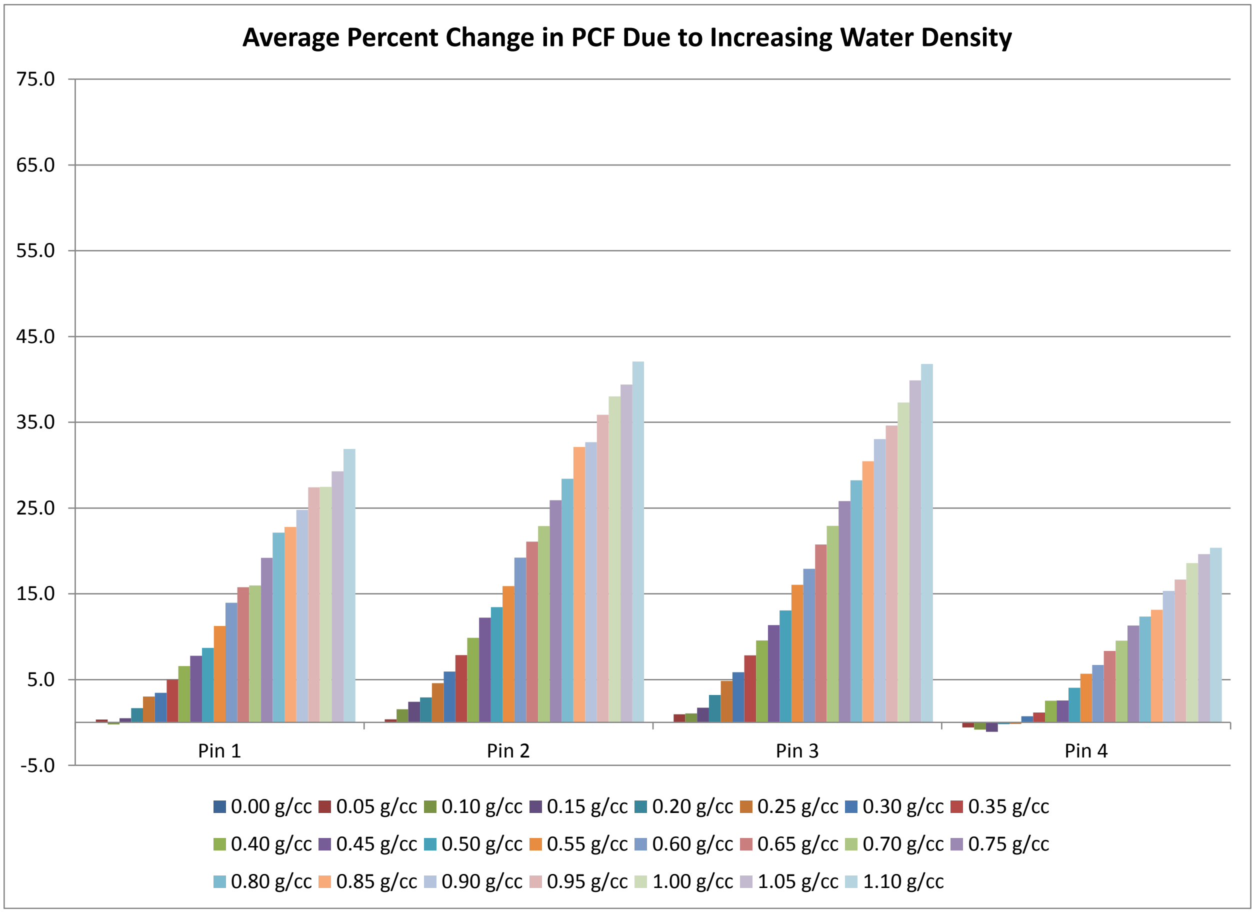

FIGURE 9. Average Percent Change in PCF Due to Increasing Water Density for Baseline PWR Conditions.

CONCLUSION

Models were prepared using MCNP6.1 with ENDF/B-VII.1 nuclear data libraries to calculate the PCF for baseline PWR test fuel rodlets in the Multi-SERTTA-CAL test vehicle for comparison against the Multi-SERTTA experiment test vehicle design to support calibration experiment campaign efforts. Additional calculations were performed to assess means to optimize the design of the Multi-SERTTA-CAL test vehicle, supporting near-final design of the vehicle, the design process for future TREAT calibration test vehicles, and establish analytical practices for comparison of computational results against actual transient test experiments. An optimized balance is necessary between structural integrity, experiment safety, and efficient energy deposition in the experiment to simultaneously maximize programmatic and safety performance. It is currently unknown whether neutronic equivalency between the calibration and test vehicles can be adequately addressed to ensure minimization of the introduction of experimental error during the experimental calibration test campaign for transient testing. Experimental data will be utilized to validate PCF and TCF calculations and experimental predictions.

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