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ABSTRACT

Transient Reactor Test (TREAT) experiment vehicle design is necessary in preparation for TREAT facility restart and the resumption of transient testing to support current Accident Tolerant Fuel (ATF) characterization needs and 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. Development of this robust test vehicle design requires neutronics analyses to support optimization of the Power Coupling Factor (PCF) to efficiently maximize energy generation in the fuel rodlets and to perform essential safety analyses. Current Multi-SERTTA calculations support final design of this vehicle, the design process for other TREAT vehicles, and the development of analyses practices for upcoming transient testing experiments. Models of the preliminary design Multi-SERTTA vehicle with rodlets were prepared and neutronics calculations were performed using MCNP6.1 with ENDF/B-VII.1 nuclear data libraries. Calculations of PCF for both dry and wet operational conditions were performed, with PCF values approximately 28 % greater in a wet environment due to thermalization of neutrons with the experiment medium. Use of neutron absorbing components in the Multi-SERTTA experiment vehicle can significantly reduce PCF values in the experiment. It is estimated that with high-power transients, testing of fuel pins depleted up to 120 GWD/MTU is quite possible in TREAT. It is expected that transient correction factors (TCF) for Multi-SERTTA would be similar to those measured in M8CAL. Actual calibration testing as part of reactor restart and experimental campaign support will be utilized to validate expected PCF and TCF values for Multi-SERTTA experiments.

Key Words: **Accident Tolerant Fuels, Experiment Design, Multi-SERTTA, Neutronics, Power Coupling Factor, TREAT.**

1. INTRODUCTION

The Transient Reactor Test (TREAT) Facility is an air-cooled, thermal-spectrum test facility designed to evaluate reactor fuel and structural material performance under simulated nuclear excursions and transient power/cooling mismatch conditions in a nuclear reactor [1]. The U.S. Department of Energy has authorized resumption of transient testing and the restart of the TREAT facility [2]. Various transient testing campaigns have been previously performed [3] between 1959 and 1995. Prior to being placed in standby, there was significant effort to characterize fuel for the Integral Fast Reactor (IFR) [4], while now there is immediate interest in providing testing support for Accident Tolerant Fuels (ATF) [5].

TREAT experiment vehicle design is needed to provide appropriate environment and cooling conditions (or lack thereof) for fuel specimens and conditions for ATF needs as well as other fuel testing programs. Key considerations include the maintenance of vehicle integrity for specimen containment, including double containment for experiments containing transuranic and fission products. Robust design of the primary containment vessel is required to survive maximum hypothetical unplanned transient conditions. Further discussion of preliminary experiment design considerations has been previously presented [6].

Currently the most mature vehicle design to be implemented upon TREAT restart [7] is the Multi-SERTTA (Static Environments Rodlet Transient Test Apparatuses), shown in Figure 1. The Multi-SERTTA can accommodate up to four concurrent rodlet-sized specimens under environmental conditions such as inert gas, water, and steam ranging from room temperature and pressure up to pressurized water reactor (PWR) conditions of 320 ˚C and 16 MPa, prior to the initiation of a core transient. The robust nature of this vehicle allows for versatility in experiment design; however, the impact of using significant quantities of neutron-absorbing metallic structure needed to be assessed to determine the effective quantity of fission-generated energy per mass of fuel specimen per total core energy, which is also known as the Power Coupling Factor (PCF). The purpose of this work was to provide an investigative neutronic analysis into the impact upon and optimization of PCF for a standard PWR UO_2 fuel pin in Multi-SERTTA as part of the design process.

2. POWER COUPLING FACTOR

The PCF is one of two key parameters utilized in designing and characterizing the performance of a TREAT fuel irradiation experiment. The second key parameter is the Transient Correction Factor (TCF) which accounts for time-dependent effects [8]. Knowledge of these coupling factors is instrumental in assessing the heat generated by the fuel pins during the course of the TREAT experiment, is essential for applying calibration experiment data to actual planned transient tests, is necessary for performing design analysis, and is needed for conducting pretest and posttest analyses [9]. Detailed documentation of PCF analyses are recorded for the IFR [4,9,10] and Heavy-Water Reactor New Production Reactor (HWR-NPR) [11] calibration experiments performed in TREAT.

The numerous tests performed during the IFR experimental campaign demonstrated the variability in PCF axially along the fuel pin. Dysprosium filters were utilized in this series to dampen “end effects”, where neutron streaming axially along the test position could preferentially induce fissions in thick fuel pins but not test wires. Heat generation in the fuel rodlets also depended on the type of fissionable material present, and a minor correction for heating from TREAT fuel gamma rays was also necessary. Some parameters impacting PCF could not be experimentally determined, such as the impact of burnup and changes in fuel density and dimensions; for these studies calculations of the impact on PCF were estimated [4,9,10].

It was also demonstrated that the PCF in TREAT was related more to the ratio of neutron induced fission heating effects in the fuel rodlets to the measurement of power in the power meters located at the edges of the core. Positioning of the control rods impact the resultant PCF and TCF values needed for the various analyses [4]. Modern computational analyses have been performed to further investigate the impact on PCF of control rod positioning with respect to the power-monitoring de-

tectors, as well as temperature dependence of the PCF and core energy during transient testing [12].

Current analyses supporting Multi-SERTTA development are aimed at investigating design parameters that could impact the baseline PCF. The desire is to provide feedback into the design process for estimating experimental capabilities. Calculations support not only the final design of the Multi-SERTTA experiment vehicle assembly, but also development of future experimental vehicles [7] and the development of analyses practices for planned ATF experiments [5].

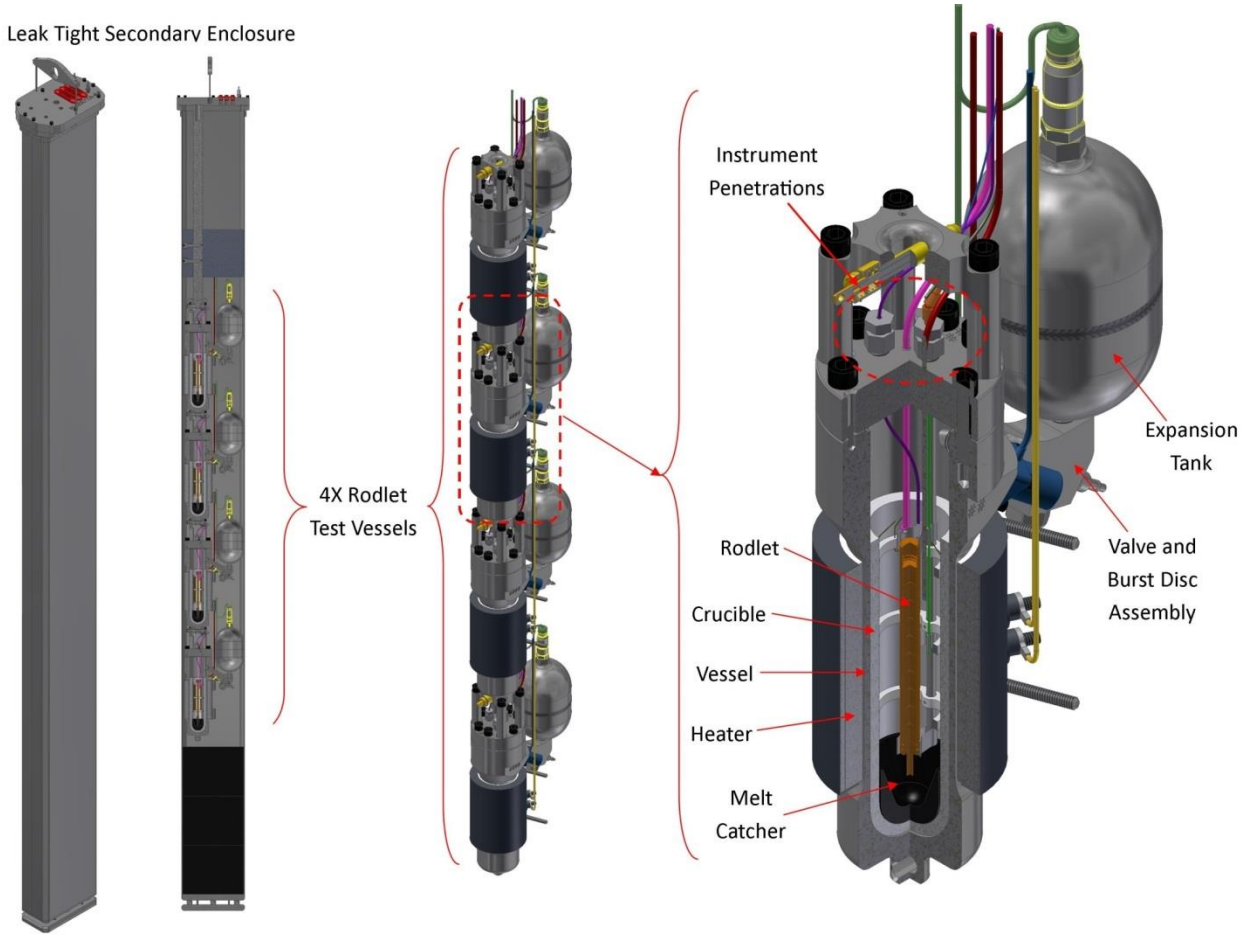

Figure 1. Multi-SERTTA Assembly.

3. NEUTRONICS DESIGN AND ANALYSIS

Variants of highly-enriched-uranium (HEU) TREAT models prepared in the evaluation of low-enriched-uranium (LEU) conversion of TREAT [13,14] were adapted to include preliminary designs of the Multi-SERTTA vehicle. Each of the four primary vessels contained a simulated baseline 6 in (15.24 cm) rodlet of Zircaloy-4-clad, $LEUO_2$ (4.95 wt.% ^{235}U) fuel. Calculations were performed with Monte Carlo N-Particle (MCNP) version 6.1 [15] and ENDF/B-VII.1 nuclear data libraries [16]. Figure 2 presents the Multi-SERTTA model developed for use in MCNP to assess neutronics effects during the design process; it is notably much simpler in design compared to the

final Multi-SERTTA design, with instrumentation, shown in Figure 1. The development of more detailed Multi-SERTTA MCNP design input is ongoing to support final design analyses, support safety assessments, and prepare for actual experimentation activities. The PCF values are determined by calculating the total energy deposited in the fuel pins divided by the total energy deposited in the TREAT fuel and reflector, which accounts for approximately 98.9 % of the core power.

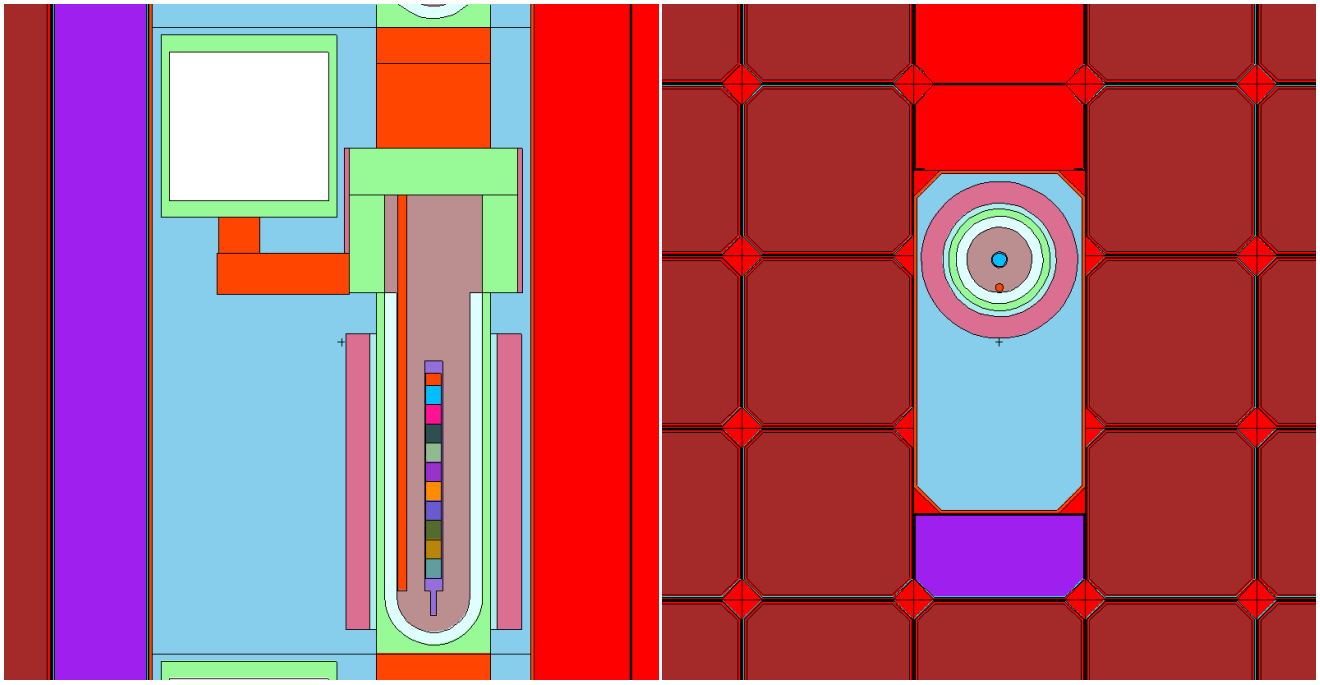

Figure 2. Vertical (Left) and Horizontal (Right) Profile of MCNP Multi-SERTTA Model.

Initial results for the preliminary design provided PCF values of 0.606, 0.875, 0.923, and 0.782 W/g-MW for Units 1 through 4, respectively, under dry conditions. Dry conditions were considered to be Ar gas at 600 K and 2300 psi. The Multi-SERTTA units were ordered with Unit 1 located at the top and Unit 4 at the bottom of the stacked experiment vessels in Figure 1. Wet conditions for this preliminary design included water at 600 K and 2300 psi filled to the top of the crucible with Ar covergas. The addition of water, which thermalizes incoming neutrons from the reactor and reflected neutrons from the irradiated fuel specimen, increased the calculated PCF values to 0.955, 1.416, 1.527, and 1.175 W/g-MW, respectively. Unit 3 and then Unit 2 have the highest PCF values because they are near the center of the active core region. Units 1 and 4 are situated near the axial graphite reflector regions of the core. Units 1 and 2 are also impacted by the compensation/shutdown control rods located around the experiment region of the TREAT core. While these rods are fully withdrawn from the active region of the core, there is still poison material present in the upper axial graphite reflector region.

The neutron spectra for the preliminary design were further investigated to assess means to increase the PCF values. Replacing the secondary enclosure vessel, which provides structural support and additional in-core containment, with Zr-4 instead of stainless steel 316 alloy increases the PCF by

approximately 14 % for dry conditions. Use of nuclear-grade zirconia or a quartz crucible in place of a zirconia crucible containing approximately 2 % hafnia is estimated to increase the PCF by an additional 9 % for dry conditions. The simulated heater tape planned for use to heat the primary vessels included a B_2O_3 content of almost 4 %; use of boron-free heater tape increased the calculated PCF by approximately 70 % for dry conditions and 37 % for wet conditions. The flux per unit lethargy for different vessel mediums in the configuration with nuclear-grade heater tape is shown in Figure 3. In-vessel mediums compared include dry Ar conditions and wet operational conditions as described above. Additional mediums include water and heavy water at room temperature/pressure. There is a noticeable epithermal component of the neutron flux present in the fuel pin for dry and heavy water conditions that is thermalized in experiments containing water.

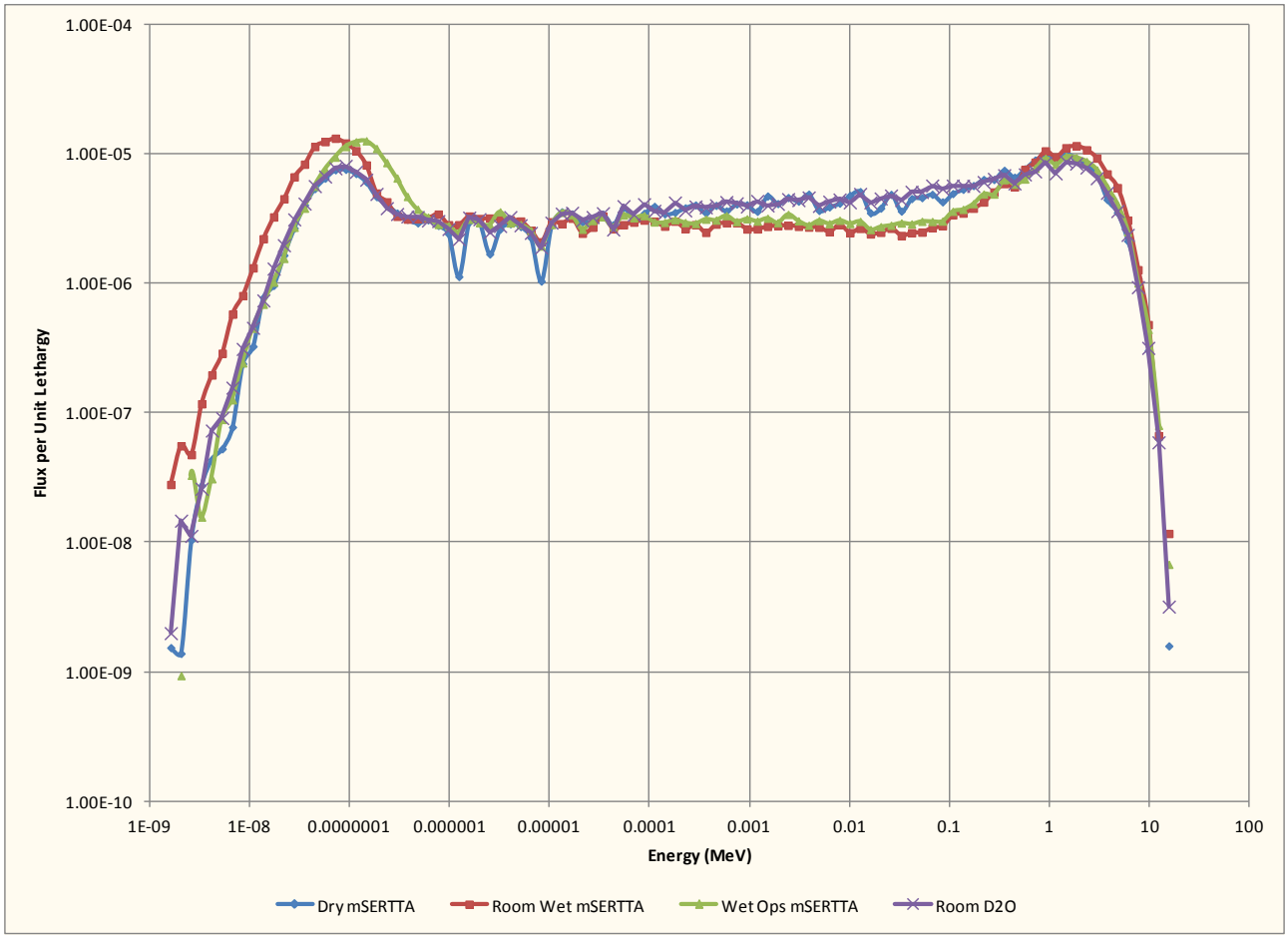

Figure 3. Flux per Unit Lethargy Comparing In-Vessel Medium.

Monte Carlo PCF calculations were performed for $LEUO_2$ fuel pins depleted by 10, 30, 50, and 70 GWD/MTU to estimate the effective capability of Multi-SERTTA to perform transient experiments of heavily irradiated fuel pins under wet operational conditions. As expected, as the fissile content of the fuel pins is reduced, so is the effective PCF. The decreasing trend is approximately linear in each unit, with an effective PCF reduction of approximately 6.5, 19.1, 31.8, and 44.4 %, respectively. Assuming the trend maintains linearity to 120 GWD/MTU depletion, the effective PCF is estimated

to be reduced by approximately 76.0 %, indicating that with high-power transients, testing of significantly depleted fuel pins in TREAT remains quite possible.

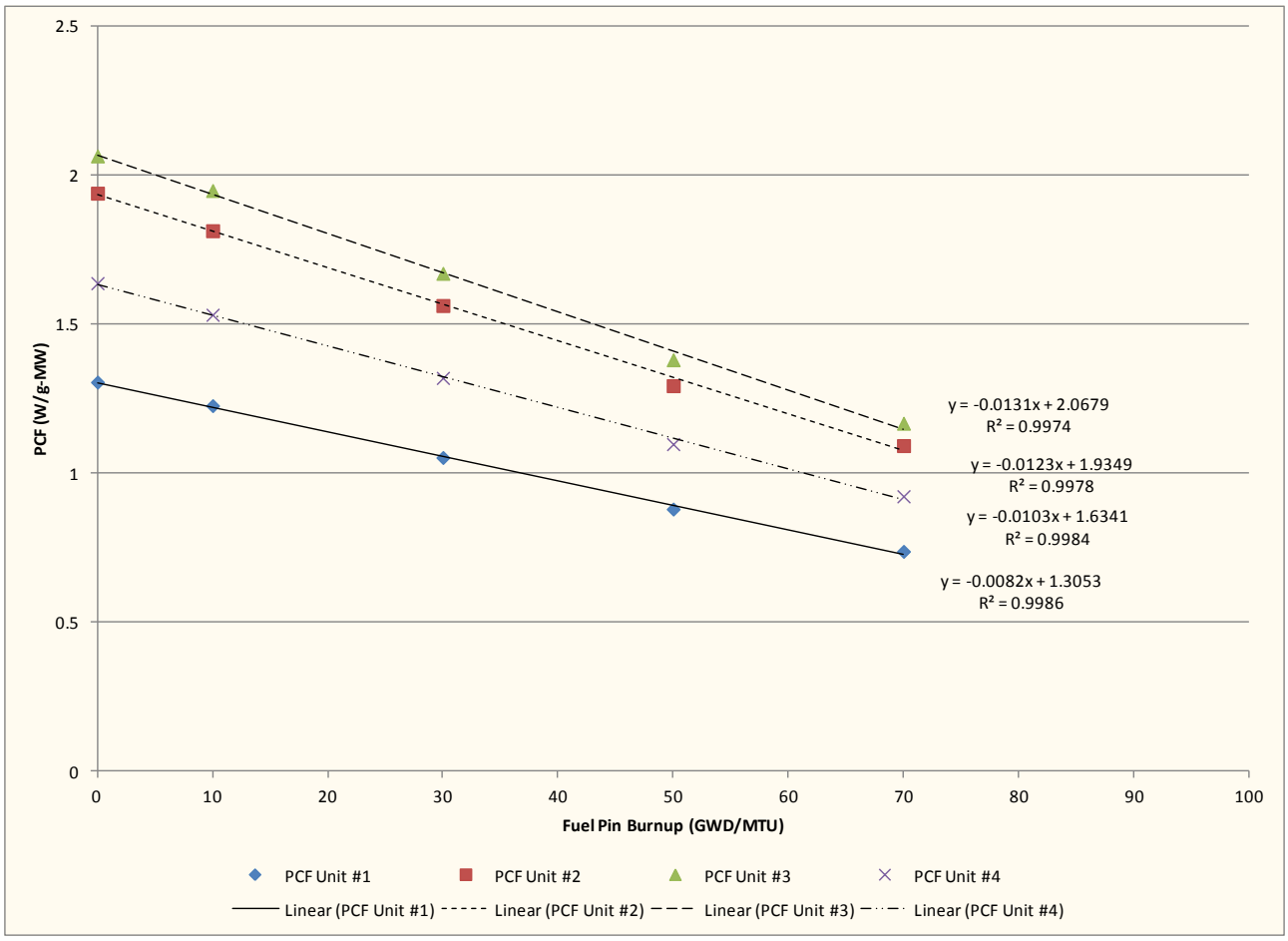

Figure 4. MCNP Calculations of PCF vs. Fuel Pin Depletion.

At the moment, transient Monte Carlo computations in MCNP to support direct calculation of the TCF are not possible. Actual core operations, especially transients, are not isothermal. However, to investigate the feedback effect on PCF due to increased core temperature, isothermal calculations were performed for the entire TREAT core, including the Multi-SERTTA experiment, at 300, 400, and 600 K. The effective TCF of 1.0 at reference conditions of 300 K increases to 1.1 and 1.3 for the higher respective temperature. Based on isothermal transient calculations and actual core operating temperatures, a TCF of less than 1.3 would be expected.

As core heating occurs during an actual transient, peak assemblies (see Figure 5) will achieve higher temperatures sooner, reducing core reactivity, and terminating core power increase. This effect will propagate as a wave from the peak assemblies through the adjacent core assemblies and eventually the experiment. Without performing actual transient studies, a best estimate of the TCF can also be obtained by looking at prior experimental measurements using the nearly identical core layout of the

M8CAL core configuration [4]. Over the M8CAL series of transient experiments, TCF values ranged from 0.95 to 1.27. However, generally a TCF of 0.95 to 1.0 was determined for the full-slotted core configuration and 1.1 to 1.2 for the half-slotted core configuration, the latter of which applies to planned Multi-SERTTA experiments.

	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	R	S	T	U
1	0.014	0.023	0.701	0.702	0.708	0.709	0.704	0.699	0.700	0.007	0.698	0.694	0.696	0.696	0.689	0.681	0.689	0.023	0.014
2	0.024	0.727	0.720	0.727	0.726	0.714	0.692	0.672	0.702	0.009	0.701	0.670	0.687	0.707	0.718	0.721	0.721	0.736	0.024
3	0.760	0.757	0.779	0.794	0.774	0.735	0.714	0.541	0.738	0.011	0.738	0.540	0.713	0.734	0.776	0.798	0.789	0.776	0.793
4	0.801	0.819	0.862	0.886	0.851	0.621	0.817	0.831	0.844	0.012	0.844	0.831	0.819	0.624	0.858	0.897	0.879	0.846	0.846
5	0.870	0.897	0.953	0.994	0.998	0.978	0.994	0.994	0.958	0.013	0.959	0.996	1.000	0.985	1.008	1.009	0.975	0.926	0.915
6	0.945	0.977	1.044	0.819	1.143	1.160	1.155	1.121	1.048	0.015	1.050	1.125	1.161	1.170	1.156	0.832	1.065	1.005	0.982
7	1.012	1.049	1.125	1.203	1.261	1.285	1.271	1.214	1.105	0.016	1.107	1.217	1.278	1.295	1.276	1.221	1.147	1.075	1.045
8	1.066	1.108	0.887	1.285	1.352	1.016	1.352	1.272	1.120	0.018	1.122	1.276	1.359	1.025	1.367	1.304	0.902	1.131	1.094
9	1.106	1.155	1.252	1.352	1.422	1.444	1.414	1.309	1.085	0.013	1.087	1.313	1.423	1.456	1.436	1.370	1.271	1.177	1.132
10	1.128	1.181	1.285	1.391	1.465	1.495	1.466	1.352	1.082	mS	1.083	1.356	1.475	1.508	1.482	1.409	1.307	1.204	1.153
11	1.131	1.183	1.286	1.395	1.476	1.514	1.503	1.422	1.223	0.061	1.226	1.428	1.513	1.528	1.493	1.414	1.306	1.205	1.155
12	1.116	1.162	0.935	1.368	1.453	1.109	1.515	1.487	1.415	1.368	1.419	1.495	1.526	1.121	1.472	1.387	0.951	1.185	1.140
13	1.084	1.129	1.218	1.315	1.399	1.455	1.490	1.501	1.491	1.483	1.494	1.509	1.503	1.472	1.418	1.335	1.241	1.151	1.108
14	1.039	1.077	1.156	0.916	1.301	1.356	1.403	1.441	1.461	1.467	1.464	1.448	1.416	1.373	1.321	0.932	1.178	1.098	1.063
15	0.982	1.010	1.077	1.135	1.160	1.170	1.240	1.306	1.351	1.368	1.354	1.314	1.252	1.186	1.180	1.157	1.100	1.032	1.007
16	0.922	0.936	0.987	1.025	1.004	0.753	1.034	1.101	1.179	1.218	1.183	1.111	1.046	0.767	1.025	1.049	1.012	0.959	0.947
17	0.875	0.870	0.899	0.926	0.922	0.900	0.906	0.710	1.007	1.066	1.012	0.717	0.920	0.920	0.947	0.955	0.927	0.896	0.903
18	0.027	0.835	0.831	0.846	0.862	0.872	0.872	0.875	0.931	0.964	0.936	0.886	0.890	0.898	0.895	0.882	0.865	0.867	0.028
19	0.016	0.026	0.802	0.806	0.832	0.859	0.879	0.898	0.921	0.933	0.927	0.913	0.902	0.892	0.877	0.859	0.848	0.027	0.017

0	Minimum
0.153	10%
0.306	20%
0.458	30%
0.611	40%
0.764	50%
0.917	60%
1.069	70%
1.222	80%
1.375	90%
1.528	Maximum

Figure 5. Peak to Average Power per TREAT Assembly.

The calculations performed as part of this study are preliminary in nature to support the neutronics design aspect of the Multi-SERTTA experiment vehicles for deployment in TREAT. Feedback from these calculations support further vehicle design refinement, safety analysis, experiment design, and development of calibration vehicle packages prior to actual experimentation in the TREAT facility. Actual calibration testing performed upon reactor restart can be used to validate expected PCF and TCF values for the Multi-SERTTA experiments.

4. CONCLUSIONS

Computational models have been developed to simulate the impact of Multi-SERTTA experiment vehicle design upon PCF to predict transient experiment capabilities and perform safety analyses. These neutronics assessments provided the necessary feedback to finalize Multi-SERTTA development for upcoming experimental needs. Calculations of PCF for both dry and wet operational conditions were performed, indicating wet PCF values approximately 28 % greater due to neutron thermalization. Reduction of the quantity of neutron-absorbing materials within the experiment vehicle design can significantly increase PCF values for the fuel pins. Testing of fuel pins depleted by up to 120 GWD/MTU is quite possible using high-power transients in TREAT. The TCF values for Multi-SERTTA are expected to be similar to those measured in M8CAL. Calibration testing performed as part of experimental campaigns in TREAT will be utilized to validate Multi-SERTTA PCF and TCF values.

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