Calculation of TREAT Minimum Critical and M8CAL Core Benchmarks with SERPENT

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Abstract – *The Monte Carlo code SERPENT was used to model and analyze the TREAT reactor steady state benchmark problems. Three different core loadings were modeled and criticality, temperature coefficient, rod worth and power profiles were calculated. The results were compared to measured data and good agreement was observed.*

I. INTRODUCTION

The Transient Reactor Test Facility (TREAT) is located at the Idaho National Laboratory (INL) and is a small, air-cooled test facility designed to assess the behavior of reactor fuels and structural materials during reactor operation. Transient testing is performed by subjecting the reactor materials to short pulses of high-power radiation. The main design objective of TREAT is to simulate and monitor conditions which lead to fuel damage. This requires the rapid movement of control rods, easy access to the center of the core, and an inherent temperature-dependent shutdown mechanism. A schematic of the TREAT facility is shown in Fig. 1.

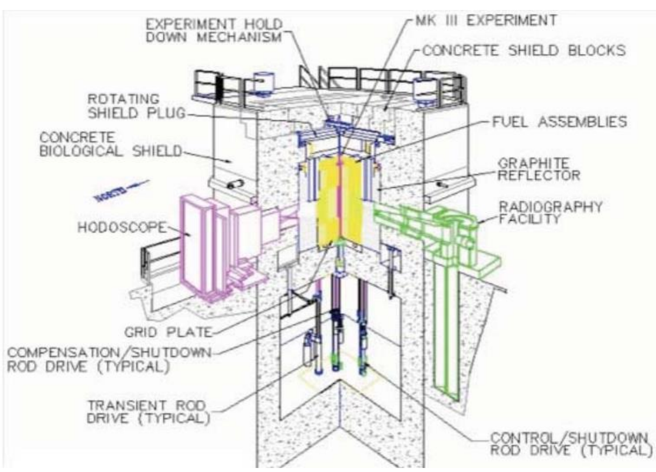

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Figure 1. TREAT Facility.

A benchmark problem was designed to serve as a basis to validate advanced modeling and simulation of computer codes as a part of the NEUP-IRP project. The paper here presents the modeling and results of the steady-state part of the benchmark problem and the analysis performed using the continuous energy Monte Carlo code SERPENT.

II. DESCRIPTION OF THE ACTUAL WORK

1. Description of the TREAT Benchmark

The benchmark consists of three steady-state core configurations of the TREAT reactor. The first two were taken from the original sequence of ñMinimum Critical Coresò when the reactor began operation and the third core is the M8CAL core which was the final core design before operation was suspended in 1994 and will be the first core used for the TREAT restart. Three core configurations were chosen for the benchmark to span the range of reactor measurements and core complexity necessary to model the current TREAT core configuration. The basis for much of the reactor specifications were obtained from the recently published reactor specifications in the INL report, ñBaseline Assessment of TREAT for Modeling and Analysis Needs,ò [1]. Additional documentation of the operating conditions for the initial minimum critical core was obtained from [2] and the operating conditions for the M8CAL core was obtained from [3]. The specification of the fuel used for the benchmark analysis is shown in Table 1.

Table 1. Treat Fuel specifications

TREAT FUEL	
Boron impurity (ppm)	7.53 (±1.16)
Iron impurity (ppm)	267
Vanadium impurity (ppm)	30
Uranium Content	93.24% U-235 5.43% U-238 0.91% U-234 0.41% U-236
Graphitization (%)	59

The Monte Carlo code SERPENT [4] was used to model all three TREAT core loadings. The details of the models are given in the following sections. All SERPENT calculations were performed using the ENDF/B VII.1 library.

2. Minimum Critical Mass Core Loading

The initial TREAT core loading went critical in February 1959, with 146 fuel elements and a neutron source element at the core center. This source was replaced and the core was reconfigured into the Minimum Critical Mass (MCM) core as shown in Fig. 2, consisting of 133 standard fuel elements, eight control rod elements, and 16 Zircaloy-clad dummy fuel assemblies placed inside a 19 × 19 square lattice. The control rods were withdrawn completely from the core in this configuration, which will serve as the basis for the first of the 3 cores discussed here.

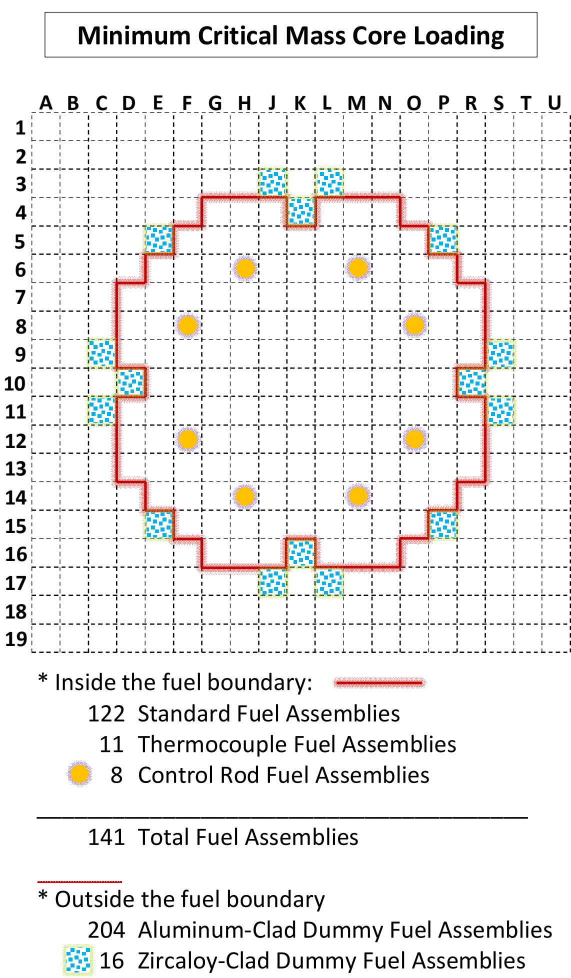

Figure 2. MCM core loading

A special set of ñshortò control rods were used in the MCM core to achieve a cleaner core. The bottom 18in of 60in long B_4C section of the control rods was replaced with graphite which takes the poison section out of the upper reflector when the rods are all the way out. Figure 3 shows the control rod positioning for the MCM cores. The details of the control rods can be found in Ref 1.

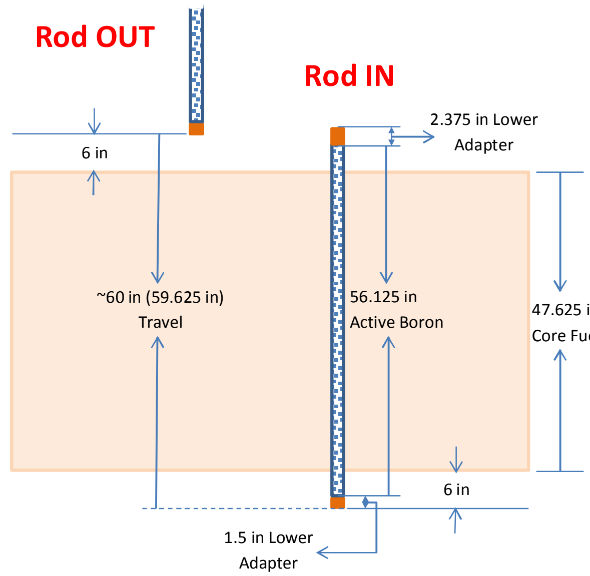

Figure 3. MCM control rod positioning

The MCM core with the loading configuration shown in Fig. 2 was about 160 pcm supercritical [5]. The exact location of the 11 thermocouple fuel assemblies was not documented and introduce some uncertainty since the vertical holes drilled to place the thermocouples slightly reduced the fuel mass in these assemblies.

3. MCM Core SERPENT Model

The SERPENT model extends to the outer surface of permanent reflector in the radial direction and to the outer surfaces of the top and bottom reflectors in the axial direction. The radial model is a square with a side length of 325.12 cm. The bottom reflector is 59.25 cm and top reflector is 63.58 cm in height and the total core height is 120.97 cm. The radial and axial cross sectional views of the MCM core model is shown in Fig. 4 and 5.

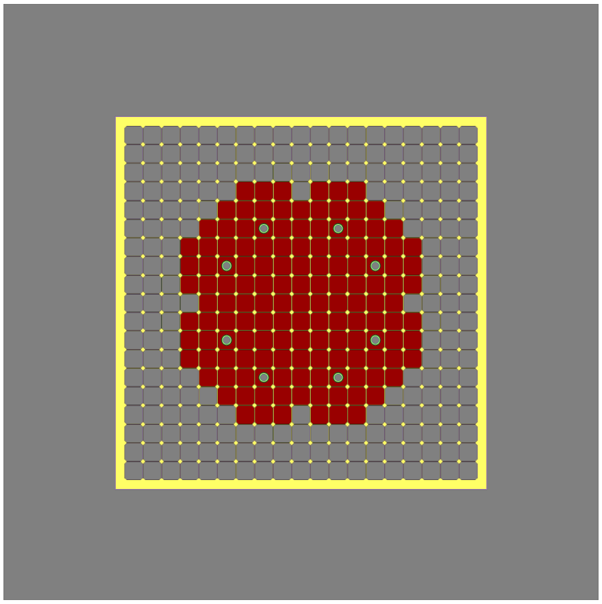

Figure 4. Radial Layout of the MCM SERPENT Model

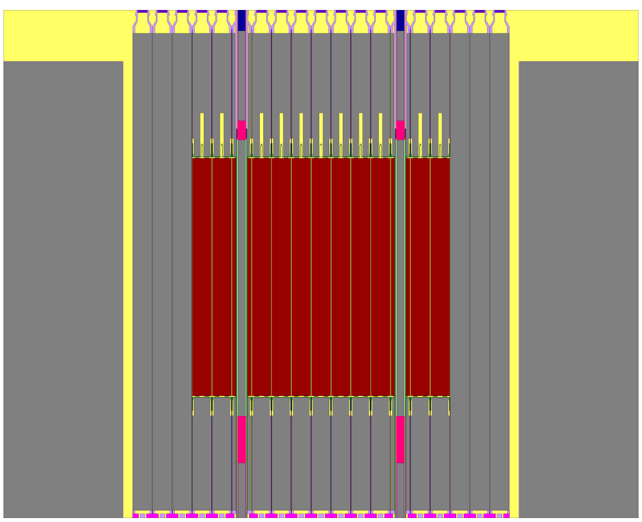

Figure 5. Axial layout of the MCM SERPENT Model

After the MCM experiment was completed several different experiments and measurements were conducted with slight different core loadings. Control rod worths, fuel element worths, the worth of half and full slots, neutron flux and temperature distributions are some of the measurements that were performed. The neutron flux distribution experiment is one of the problems included in this benchmark and core laoding used for this experiment is called MCM+.

4. MCM+ Core Loading

The MCM+ core model was based off the MCM model, but replaces two Zircaloy-clad dummy assemblies with two standard fuel assemblies for a total of 135 fuel assemblies, 16 Zircaloy-clad dummy assemblies, 8 control rod assemblies. The short control rods of the MCM model were also replaced by the standard long control rods. Unlike the MCM model, one control rod bank (#1 in Fig..6) is partially inserted to a position between 47.5 and 49.5 inches to account for the two extra fuel assemblies in the core. Fig. 6 shows the MCM+ core layout.

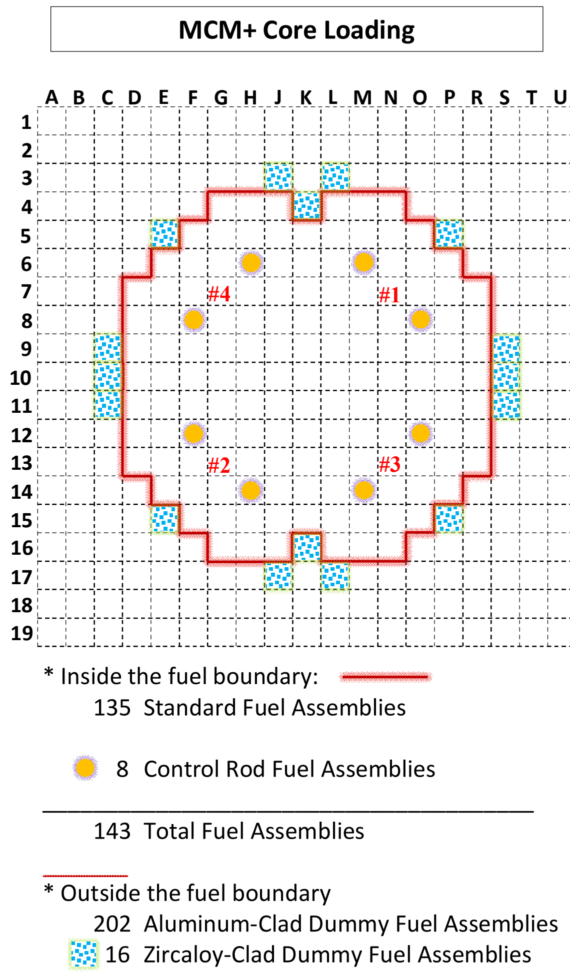

Figure 6 MCM+ core loading

The flux measurements were performed by fission counters and foils of U235, Pu239, Pu-Al Alloy and gold. In the study presented here only U235 foils measurement were simulated. The uranium foils were 1cm square by 1 mil thickness and placed vertically in the upper left coolant channel of the K-10 assembly.

5. MCM+ Core SERPENT Model

The radial and axial model boundary conditions of the MCM+ core were the same as the MCM core. Fig. 7 shows the axial layout of the MCM+ SEPRENT model with the rod bank 1 partially inserted.

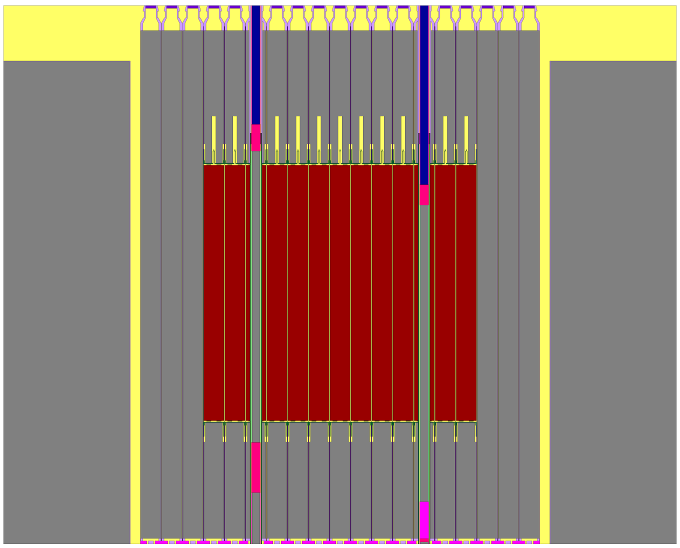

Figure 7. Side view of MCM+ core SERPENT model

6. M8CAL Core Loading

The M8CAL half-slotted core is composed of 318 fuel assemblies (15 with thermocouples), 20 control rod assemblies (8 shutdown, 8 transient and 4 compensation), 12 Zr-cladded dummy fuel assemblies, 8 slotted dummy assemblies, 1 slotted half assembly, 1 Zr-cladded half dummy assembly and M8 test train in the center of the core. This core loading was used to perform 23 different irradiations experiments with monitor wires and test fuels. Fig. 8 shows the core loading for M8CAL experiments. A distinctive feature of the M8CAL core is hodoscope region shown as the gray x assemblies in the Figure.

The control rod positioning for the M8CAL core is shown in Figure 9. During the wire irradiation experiments the compensation and transient rods were all the way out while the control/shutdown rods were 22in inserted.

	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	R	S	T	U
1	Z	Z	F	F	F	F	F	F	F	X	F	F	F	F	F	F	F	Z	S
2	Z	F	F	F	F	F	F	F	F	X	F	F	F	F	F	F	F	F	Z
3	T3	F	F	F	F	F	F	CS	F	X	F	CS	F	F	F	F	F	F	F
4	F	F	F	F	F	CS	F	F	F	X	F	F	F	CS	F	F	F	F	F
5	F	F	F	F	F	F	F	F	F	X	F	F	F	F	F	F	F	F	F
6	F	F	F	CT	F	F	F	F	F	X	F	F	F	F	F	CT	F	F	F
7	F	F	F	F	F	F	F	F	F	X	F	F	F	F	F	F	F	F	F
8	F	F	CT	F	F	CC	F	F	F	X	F	F	F	CC	F	F	CT	F	F
9	F	F	F	F	F	F	F	F	F	X2	F	F	F	F	F	F	F	F	F
10	F	F	F	F	F	F	F	T3	F	MK	F	T3	T3	T3	F	F	F	F	F
11	F	F	F	F	F	F	F	T1	F	Z2	F	T1	F	F	F	F	F	F	F
12	F	F	CT	F	F	CC	F	T3	F	F	F	T3	F	CC	F	F	CT	F	F
13	F	F	F	F	F	F	F	T3	F	T3	F	T1	F	F	F	F	F	F	F
14	F	F	F	CT	F	F	F	F	T1	T3	F	F	F	F	F	CT	F	F	F
15	F	F	F	F	F	F	F	F	F	T3	F	F	F	F	F	F	F	F	F
16	F	F	F	F	F	CS	F	F	F	F	F	F	F	CS	F	F	F	F	F
17	F	F	F	F	F	F	F	CS	F	F	F	CS	F	F	F	F	F	F	F
18	Z	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	Z
19	Z	Z	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	Z	Z

Figure 8. M8CAL Core Loading [6]

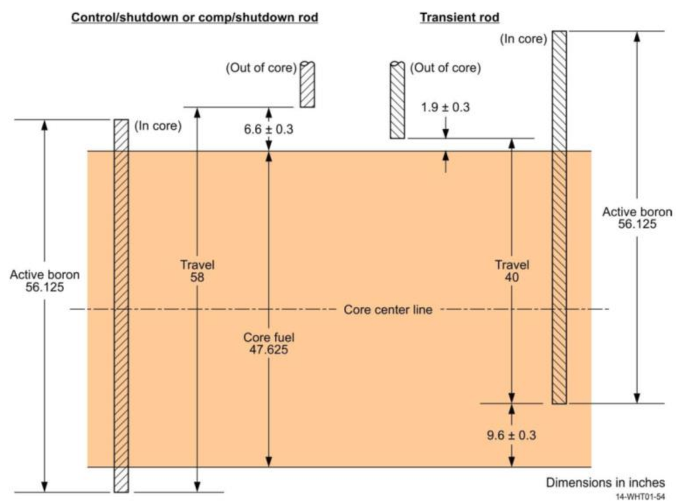

Figure 9. M8CAL Control Rod Positioning

6. M8CAL Core Serpent Model

The axial and radial model boundaries were same as MCM core models. Fig. 10 shows the M8CAL core radial cross sectional view.

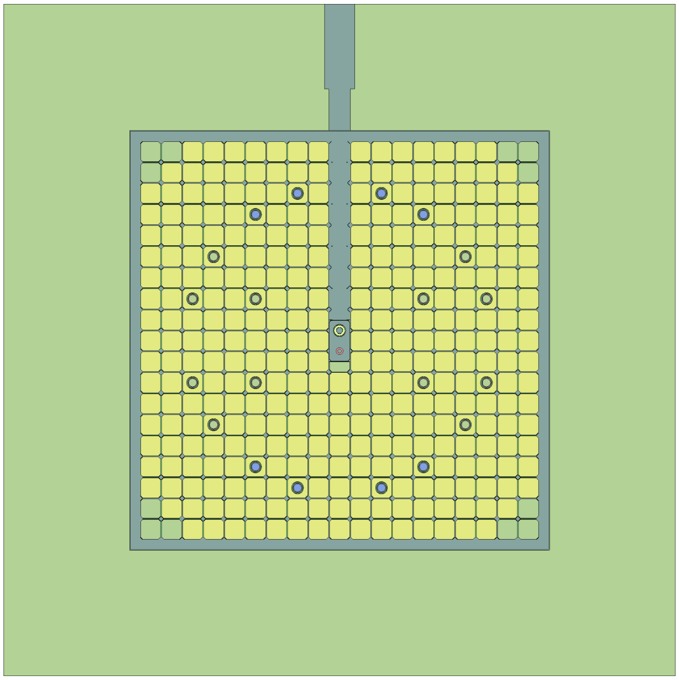

Figure 10. Top down M8CAL core SERPENT model.

III. RESULTS

1. MCM Core Measurements

Table 2 shows SEPRENT k-effective result for the MCM core. Two different MCM results were show in the Table 2. First result is from the model where all 133 fuel assemblies are considered standard while the second model accounts for the 11 thermocouple assemblies. Since the exact location of the thermocouple assemblies are not known, the average fuel density is reduced to preserve the total mass of 122 standard and 11 thermocouple fuel assemblies. The SERPENT result is 136 pcm higher than the measurement. When the thermocouple assemblies are accounted for, the SERPENT result is only 67 pcm off of the measurement. The short rods were only used during the MCM experiment. All subsequent measurements used the long standard rods. The k_{eff} result with long rods were also shown in Table 2. Each case was run in SERPENT at a temperature of 300 K using 200000 neutrons per cycle, 200 inactive cycles, and 500 active cycles.

Table 2. SERPENT MCM Results

	k_{eff}	Δk (pcm)
Experiment	1.00160	-
133 Standard Fuel Assemblies	1.00296 (±6 pcm)	136
122 Stadard Fuel + 11 Thermocouple Fuel Assemblies	1.00227 (±7 pcm)	67
MCM with Long Rods	1.00020 (±7 pcm)	-

Another measurement performed with the MCM core was the isothermal temperature coefficient. For this measurement the k_{eff} was determined after the reactor had been cooled overnight by circulating cold outside air through the reactor and building, and then again after the reactor had been heated by circulating warm inside air through the reactor. During the cold measurements the permanent reflector was 4^{o}C warmer than the core and 8^{o}C colder than the core during the hot measurements. The SERPENT results for the isothermal temperature coefficient are shown in Table 3.

Table 3. Isothermal Temperature coefficient results

	Hot T (K)	Cold T (K)	Δk/T (pcm/K)
Measurement	310.65	295.15	$1.8\pm0.2 \times 10^{-4}$
Serpent	310.65	295.15	1.7×10^{-4}

2. MCM+ Core Measurements

The foil counting rates were normalized to the counting rate of central foil. The SERPENT results were obtained by tallying fission rates of the U-235 foils. The results shown in the Figure 11 compares well with the measurement data.

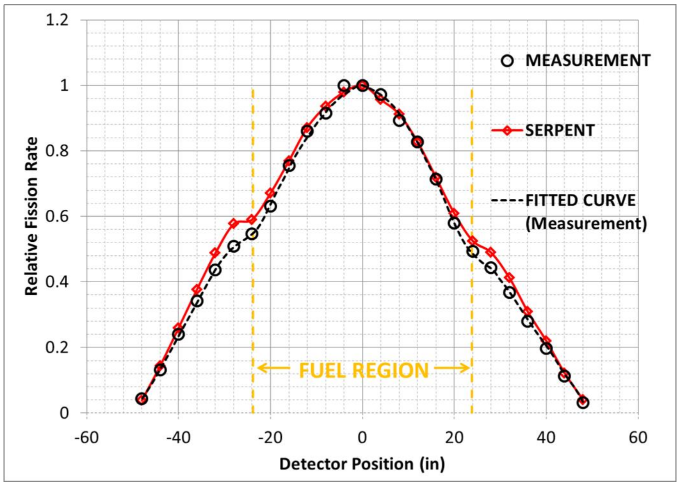

Figure 11. Relative fission rates in the center fuel assembly.

3. M8CAL Core Measurements

The k_{eff} of the M8CAL SERPENT model was 1.00023 ± 12 pcm which is very close to criticality. The worth of the shutdown and transient control rods were calculated with SERPENT and compared to the measurement data in Figures 12 and 13. Overall rod worth data compares very well. However there is slight discrepancy between the SERPENT results and measurement data when the rods are close to the full inserted position.

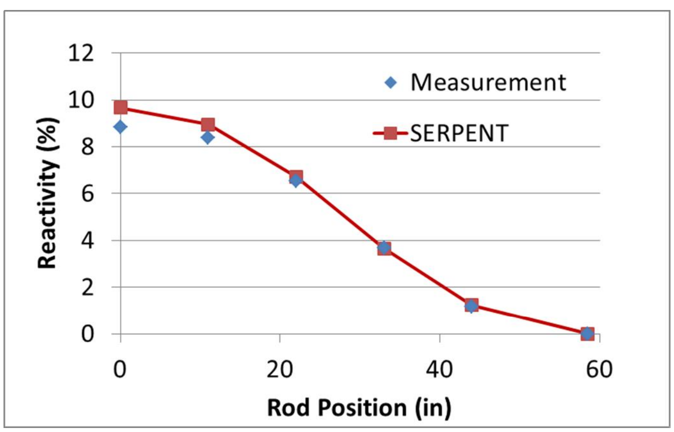

Figure 12. Control/Shutdown Rod Worth

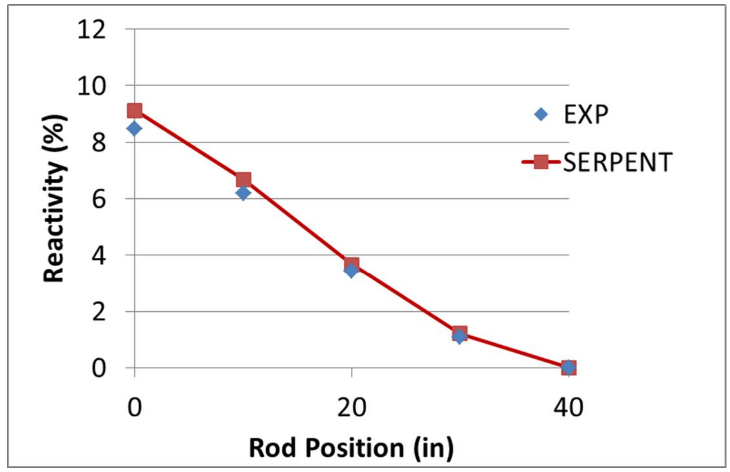

Figure 13.Transient Rod Worth

The monitor wire irradiation experiment were also simulated with SERPENT where the 60 in low enriched uranium wire was used. As shown in Figure 14 the SERPENT result compares very well to the measurement data.

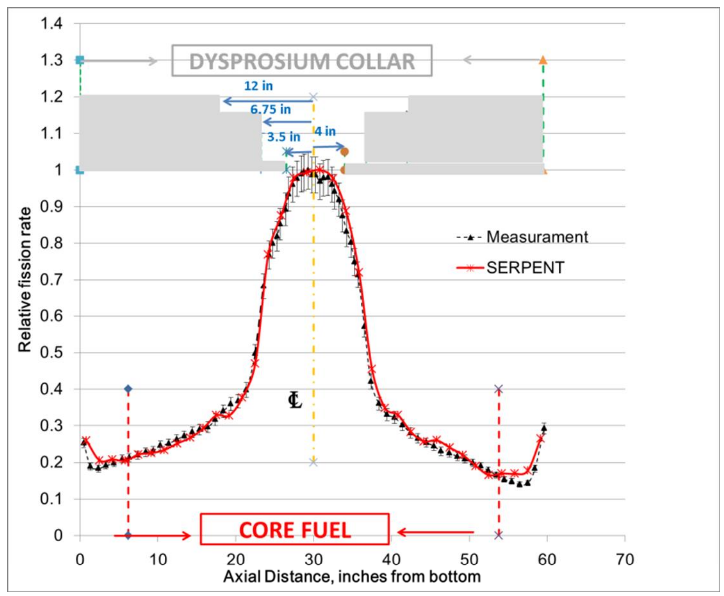

Figure 14.60in wire axial power profile

IV. SUMMARY AND CONCLUSIONS

A sequence of steady-state benchmark problems was designed for the TREAT core to serve as a basis to validate advanced modeling and simulation of the reactor. This paper described the modeling and the results using the continuous energy Monte Carlo code SERPENT. Results were shown to be in good agreement with measured data.

The benchmarks have been submitted for publication as an IRPhEP benchmark and the specifications will provide a basis for evaluating the ability of advanced deterministic codes to model the steady-state condition of the TREAT reactor. Work is ongoing to develop a similar benchmark for selected transients performed with the M8CAL core.

ACKNOWLEDGMENTS

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