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Benchmark Evaluation of the Initial Isothermal Physics Measurements at the Fast Flux Test Facility

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BENCHMARK EVALUATION OF THE INITIAL ISOTHERMAL PHYSICS MEASUREMENTS AT THE FAST FLUX TEST FACILITY

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ABSTRACT

The benchmark evaluation of the initial isothermal physics tests performed at the Fast Flux Test Facility, in support of Fuel Cycle Research and Development and Generation-IV activities at the Idaho National Laboratory, has been completed. The evaluation was performed using MCNP5 with ENDF/B-VII.0 nuclear data libraries and according to guidelines provided for inclusion in the International Reactor Physics Experiment Evaluation Project Handbook. Results provided include evaluation of the initial fully-loaded core critical, two neutron spectra measurements near the axial core center, 32 reactivity effects measurements (21 control rod worths, two control rod bank worths, six differential control rod worths, two shutdown margins, and one excess reactivity), isothermal temperature coefficient, and low-energy electron and gamma spectra measurements at the core center. All measurements were performed at 400 ºF. There was good agreement between the calculated and benchmark values for the fully-loaded core critical eigenvalue, reactivity effects measurements, and isothermal temperature coefficient. General agreement between benchmark experiment measurements and calculated spectra for neutrons and low-energy gammas at the core midplane exists, but calculations of the neutron spectra below the core and the low-energy gamma spectra at core midplane did not agree well. Homogenization of core components may have had a significant impact upon computational assessment of these effects. Future work includes development of a fully-heterogeneous model for comprehensive evaluation. The reactor physics measurement data can be used in nuclear data adjustment and validation of computational methods for advanced fuel cycle and nuclear reactor systems using Liquid Metal Fast Reactor technology.

Key Words: benchmark, fast reactor, liquid sodium, MOX fuel, partial homogenization

1. INTRODUCTION

As the intended integration and implementation of advanced nuclear fuel cycles with advanced nuclear reactor designs progresses, there exist concerns regarding the impact of current nuclear data uncertainties on design parameters of major Fuel Cycle Research and Development (FCR&D) and Generation-IV (GEN-IV) systems. Experimental data from tests and operations with the Fast Test Reactor (FTR) at the Fast Flux Test Facility (FFTF) can provide useful information for nuclear data adjustment for liquid metal fast reactor (LMFR) systems [1-2]. Recent activities at the Idaho National Laboratory (INL) included the use of Monte Carlo N-Particle version 5 (MCNP5) [3] with ENDF/B-VII.0 data libraries [4] to develop a comprehensive benchmark evaluation of the initial isothermal physics measurements of the FFTF for inclusion in the International Reactor Physics Experiment Evaluation Project (IRPhEP) Handbook [5]. Available information was consolidated and assessed such that the experimental data and evaluated results could be made available for future applications requiring the use of liquid metal fast breeder reactor (LMFBR) experience, such as integral data for nuclear materials in fast neutron flux environments, improvement of nuclear data libraries, and means for analytical methods development and validation.

2. BENCHMARK MODEL DEVELOPMENT

The FTR was a 400 MWt, sodium cooled, high temperature, fast flux nuclear reactor designed for the irradiation testing of nuclear fuels and materials for the development of LMFBRs. It was fueled with mixed uranium-plutonium oxide (MOX) and reflected by Inconel 600. Preliminary to an extensive Reactor Characterization Program (RCP) and conventional operation, a series of isothermal physics measurements were performed; this acceptance testing program consisted of a series of measurements with sufficient analysis to establish that the FTR nuclear characteristics were within the design specifications for safe operation. While a summary of the main experimental measurement data is available [6], a collection of data from various reports has been compiled into a single benchmark report [7].

The FTR reactor core is comprised of a vertical array of 199 replaceable hexagonal assemblies with two types of MOX driver fuel assemblies, nine boron carbide control rod assemblies, and two types of radial reflector assemblies. The reactor was maintained at an isothermal temperature of 400 ºF during the initial physics tests. A HEX-Z partially-homogenized benchmark model was developed to represent the fully-loaded core critical configuration of the FTR utilized during these initial tests. Data regarding additional reactor physics experiments performed during this series of experiments that were also evaluated during the benchmarking process include the following:

- Two neutron spectra measurements near the axial center of the core,
- Twenty-one control rod worth measurements,
- Two control rod bank worth measurements,
- Six differential control rod worth measurements,
- Two shutdown margin measurements,
- A measurement of excess reactivity,
- Measurement of an isothermal temperature coefficient, and
- Low-energy gamma and electron spectra measurements at the core center.

The initial criticality of the FTR achieved with a partially-loaded core during fuel loading and various subcritical configurations of the FTR fully-loaded core were not evaluated.

Key heterogeneous features of the benchmark FTR model include retention of the pin-lattice structure for the fuel pins in the driver fuel assemblies (Figure 1) and the absorber pins in the control rod assemblies. Remaining portions of the core were then homogenized according to vertical positioning within the hexagonal core lattice (Figure 2).

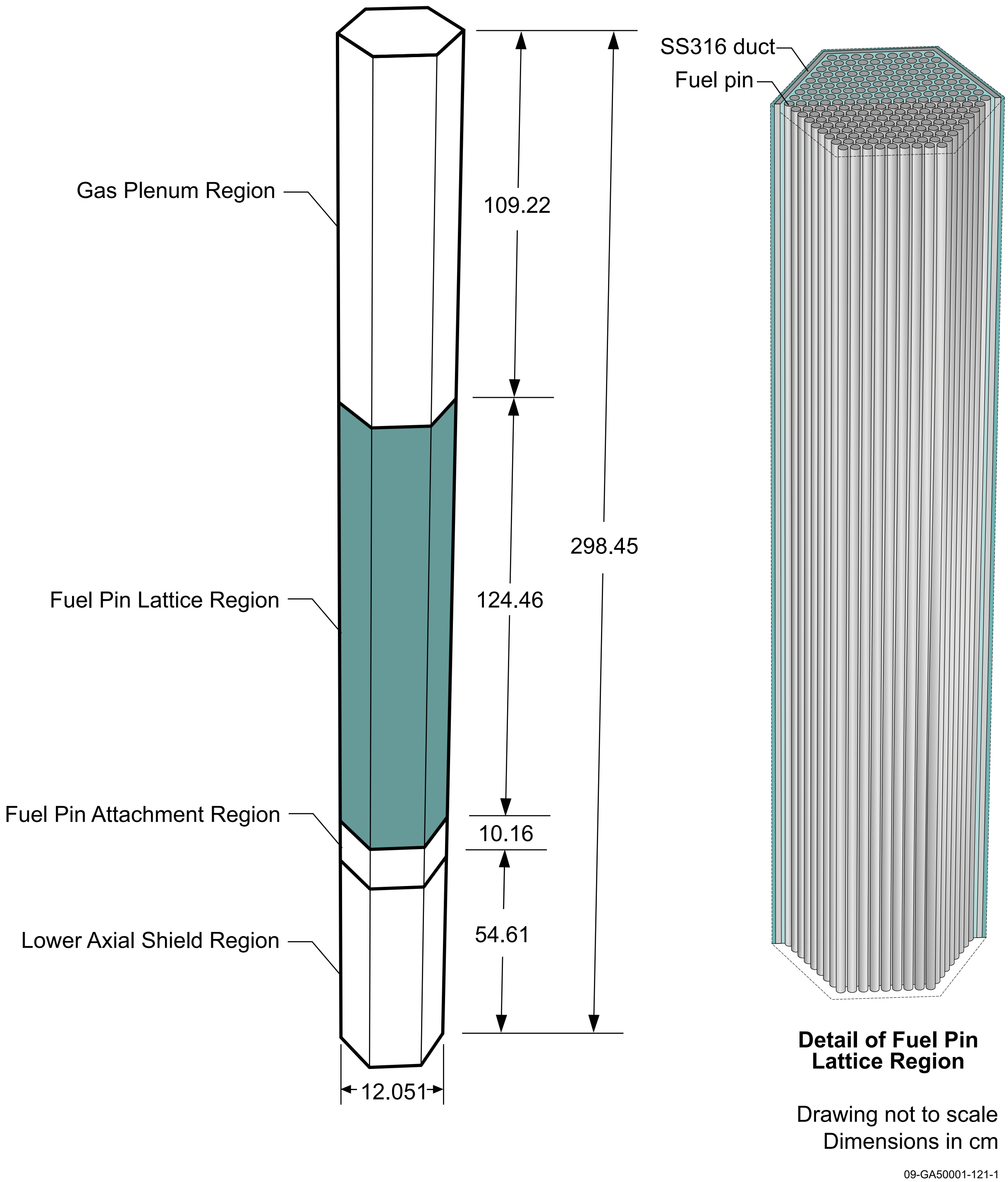

Figure 1. Diagram of Partially-Homogenized Driver Fuel Assembly.

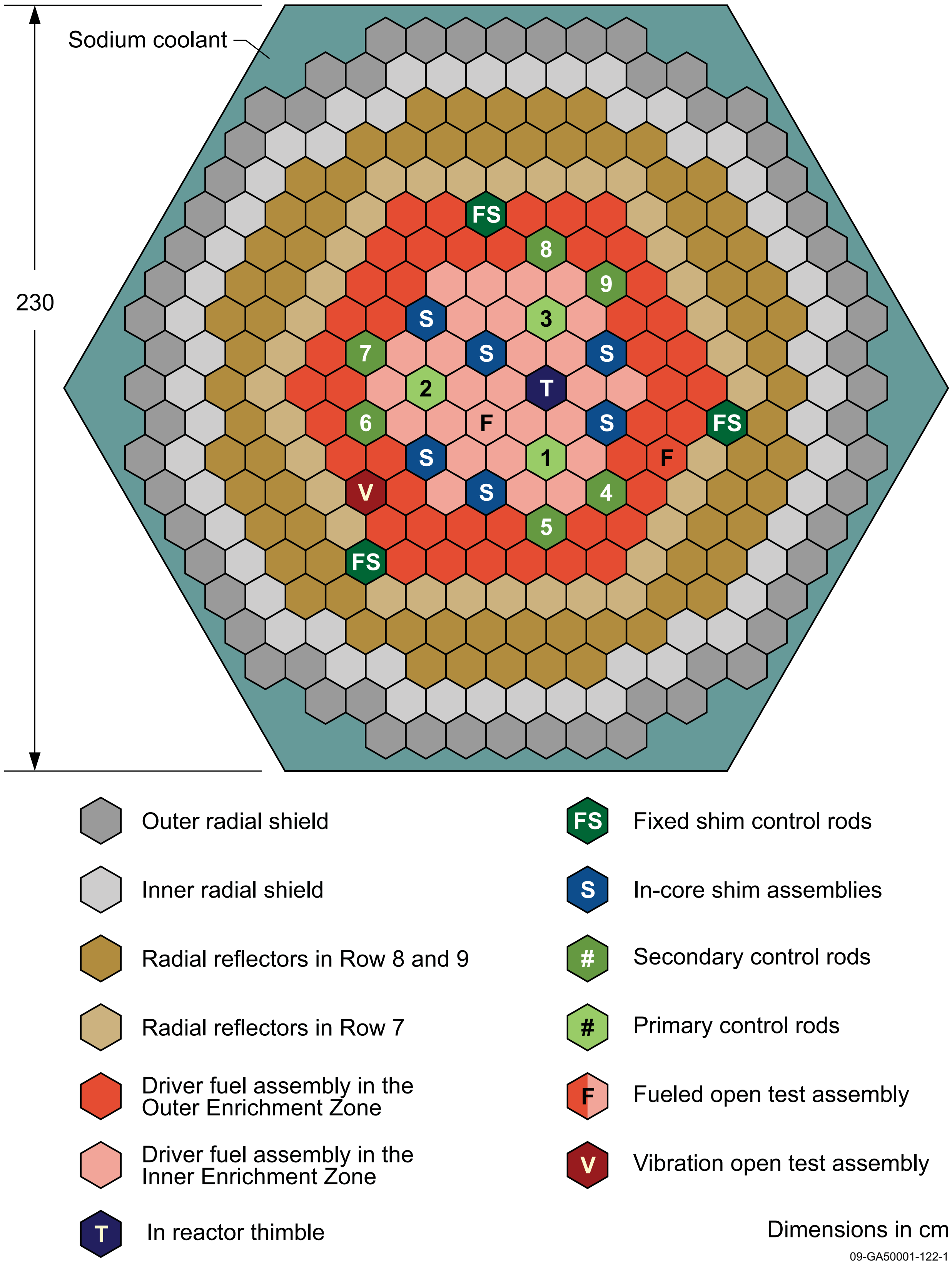

Figure 2. Diagram of FTR Fully-Loaded Core Configuration.

3. RESULTS AND DISCUSSION

3.1. Evaluation of Fully-Loaded Core Criticality

The criticality benchmark eigenvalue, k_B, for the fully-loaded core configurations of the FTR is provided in Table I. The uncertainty in the benchmark model eigenvalue is provided, as is the calculated eigenvalue, k_C. The benchmark eigenvalue represent the experimental eigenvalue (k_{eff} = 1.0000) that have been adjusted for the removal of impurities in various reactor components. The computed eigenvalue is within a two-sigma uncertainty of the benchmark value.

Table I. Comparison of Eigenvalues for the Fully-Loaded FTR Core.

Calculated			Benchmark			$\frac{k_C - k_B}{k_B}(\%)$
k_C	±	1σ	k_B	±	1σ	
1.0031	±	0.0001	0.9993	±	0.0021	0.38

3.2. Evaluation of Neutron Spectrum Measurements

Two neutron spectra measurements were performed in the In Reactor Thimble (IRT) of the FTR (see Figure 2) at core midplane and 80 cm below core midplane. A comparison of the benchmark experiment and calculated normalized neutron spectra values are shown in Figures 3 and 4, respectively. The calculated and benchmark spectrum share the same general trend for measurements at the core midplane but the trending in the below-midplane measurements appears to have only slight agreement for energies less than 150 keV. The calculated spectrum deviates significantly from the benchmark spectrum for higher energies. Homogenization of the IRT and the core components below the fuel pin region most likely have a significant impact upon the neutron spectra analysis using the benchmark model of the FTR.

3.3. Evaluation of Reactivity Effects Measurements

The benchmark reactivity worths, ρ_B, for the various reactivity effects measurements are in Table II. The uncertainties in the benchmark experiment values are provided, as are the calculated worths, ρ_C. The calculated values for the control rod worths are approximately 2-6% lower than their benchmark worths; most are within 1σ of the benchmark values. The difference between the calculated and benchmark rod bank worths is less than 1% and within 1σ of the benchmark values. The differential control rod worths calculate approximately 3-8% lower than the expected benchmark values and within 2σ of the benchmark values. The calculated shutdown margin values are approximately 1% from the benchmark values and within 1σ. The excess reactivity is calculated ~7% lower than the benchmark reactivity and is within 2σ. Whereas most of the reactivity calculations are lower than the reported experimental values, it is quite possible that the originally reported β_{eff} coefficient used to convert the measured reactivities into dollars, which was determined using ENDF/B-V data, may have been slightly high.

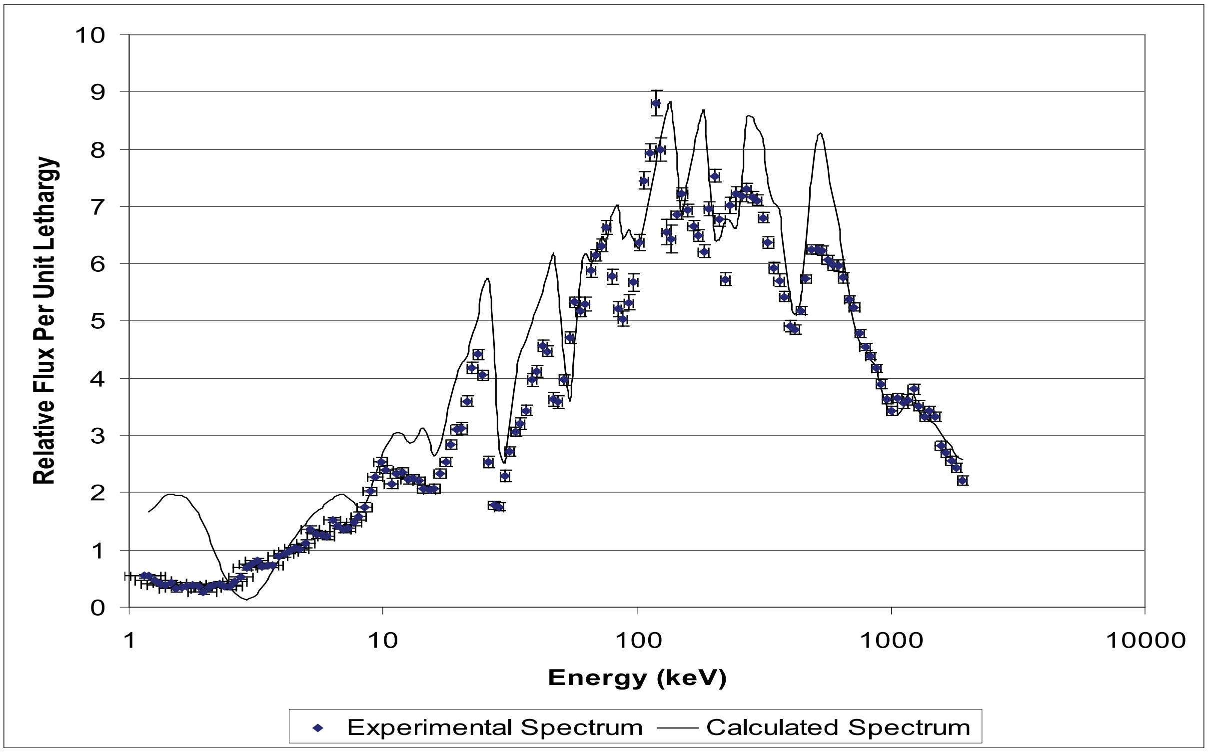

Figure 3. Neutron Spectrum in the FTR Core Center (at Midplane).

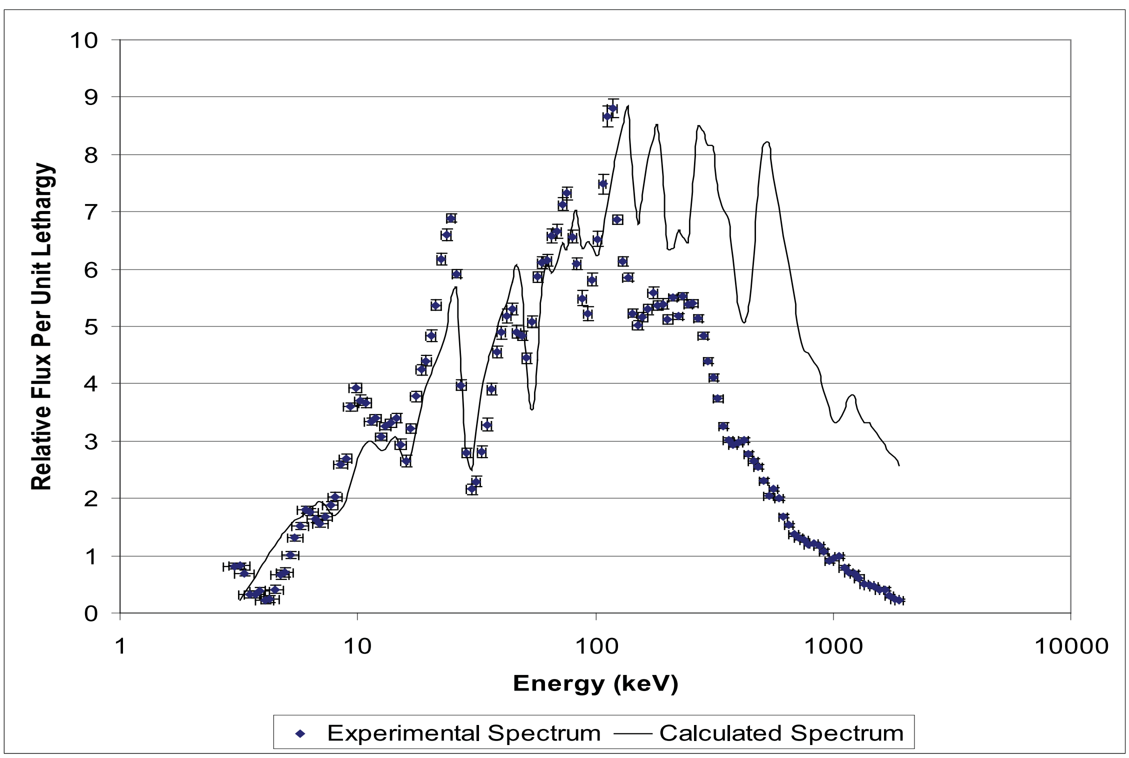

Figure 4. Neutron Spectrum in the FTR Core Center (80 cm Below Midplane).

Table II. Comparison of Reactivity Effects Measurements.

	Case	Rod(s) Dropped	Calculated			Benchmark			ρ_C/ρ_B
			ρ$	±	1σ	ρ$	±	1σ	
Rod Worths	1	1	5.92	±	0.02	6.04	±	0.32	0.98
	2	2	5.65	±	0.02	5.89	±	0.31	0.96
	3	3	4.36	±	0.02	4.65	±	0.25	0.94
	4	5	3.63	±	0.02	3.84	±	0.20	0.85
	5	7	2.85	±	0.02	2.90	±	0.15	0.98
	6	1+2	12.08	±	0.02	12.45	±	0.69	0.97
	7	1+3	10.57	±	0.03	11.01	±	0.60	0.96
	8	1+5	8.61	±	0.02	9.00	±	0.48	0.96
	9	3+5	8.47	±	0.02	8.8	±	0.46	0.96
	10	1+2+5	15.07	±	0.03	15.84	±	0.87	0.95
	11	2+3+5	14.94	±	0.02	15.22	±	0.86	0.98
	12	1	5.64	±	0.02	5.81	±	0.33	0.97
	13	2	5.36	±	0.02	5.51	±	0.29	0.97
	14	3	5.18	±	0.02	5.40	±	0.29	0.96
	15	4	3.97	±	0.02	4.06	±	0.21	0.98
	16	5	3.97	±	0.03	4.09	±	0.21	0.97
	17	6	3.48	±	0.02	3.57	±	0.18	0.97
	18	7	3.76	±	0.02	3.86	±	0.20	0.97
	19	8	3.01	±	0.02	3.19	±	0.19	0.94
	20	9	3.62	±	0.02	3.83	±	0.19	0.95
	21	2+3	10.89	±	0.03	11.22	±	0.58	0.97
	Case	**Rod(s) Dropped**	**Calculated**			**Benchmark**			ρ_C/ρ_B
			ρ$	**±**	**1σ**	**ρ$**	**±**	**1σ**	
Bank Worths	22	1+2+3	16.76	±	0.03	16.34	±	0.83	1.03
	23	4+5+6+7+8+9	20.04	±	0.03	19.9	±	1.00	1.01
	Case	**Rod Movement**	**Calculated**			**Benchmark**			ρ_C/ρ_B
			ρ¢/cm	**±**	**1σ**	**ρ¢/cm**	**±**	**1σ**	
Differential Worths	24	4	5.9	±	0.2	6.1	±	0.3	0.97
	25	5	5.7	±	0.2	6.2	±	0.3	0.82
	26	6	5.0	±	0.2	5.4	±	0.3	0.93
	27	7	5.3	±	0.2	5.7	±	0.3	0.94
	28	8	4.5	±	0.3	4.8	±	0.3	0.95
	29	9	5.5	±	0.2	5.6	±	0.3	0.97
	Case	**Rods Dropped**	**Calculated**			**Benchmark**			ρ_C/ρ_B
			ρ$	**±**	**1σ**	**ρ$**	**±**	**1σ**	
Shutdown Margin	30	All	23.67	±	0.02	24.0	±	1.40	0.99
	31	All	23.76	±	0.03	23.7	±	1.27	1.00
	Case	**Rods Withdrawn**	**Calculated**			**Benchmark**			ρ_C/ρ_B
			ρ$	**±**	**1σ**	**ρ$**	**±**	**1σ**	
Excess Reactivity	32	All	13.66	±	0.03	14.66	±	0.85	0.93

3.4. Evaluation of the Isothermal Temperature Coefficient

A comparison of the calculated, ρ_C, and expected benchmark, ρ_B, values for the isothermal temperature coefficient at 400 ºF (204 ºC) is shown in Table III. The assessment was performed with a temperature variation of ±25 ºC, which included model adjustments in temperature, sodium coolant density, and neutron cross-section libraries. Density effects in core structural material would be negligible as much of the core was homogenized. A correlation between the core temperature and core assembly pitch was unavailable; therefore the effect of the pitch was estimated, with uncertainty, and included in an evaluation of the isothermal temperature coefficient. The calculated value is 8.7% lower than the benchmark coefficient and within 1σ.

Table III. Comparison of Isothermal Temperature Coefficient.

Calculated			Benchmark			ρ_C/ρ_B
ρ_C (ρ¢/K)	±	1σ	ρ_B (ρ¢/K)	±	1σ	
-1.15	±	0.18	-1.26	±	0.19	0.91

3.5. Evaluation of Low-Energy Gamma and Electron Spectrum Measurements

Low-energy electron and gamma spectra measurements were performed at core midplane in the IRT (see Figure 2). A comparison of the benchmark experiment and calculated normalized spectra values are shown in Figures 5 and 6, respectively. There is not a good agreement between the calculated and benchmark spectra values. There is in general good trend correlation between the calculated and measured values for the normalized photon energy spectrum. On average, however, the calculated normalized flux is ~37% greater than the benchmark experiment values. Homogenization of the IRT would have had a significant impact upon these calculations, as the model does not accurately account for scatter and streaming effects in the IRT.

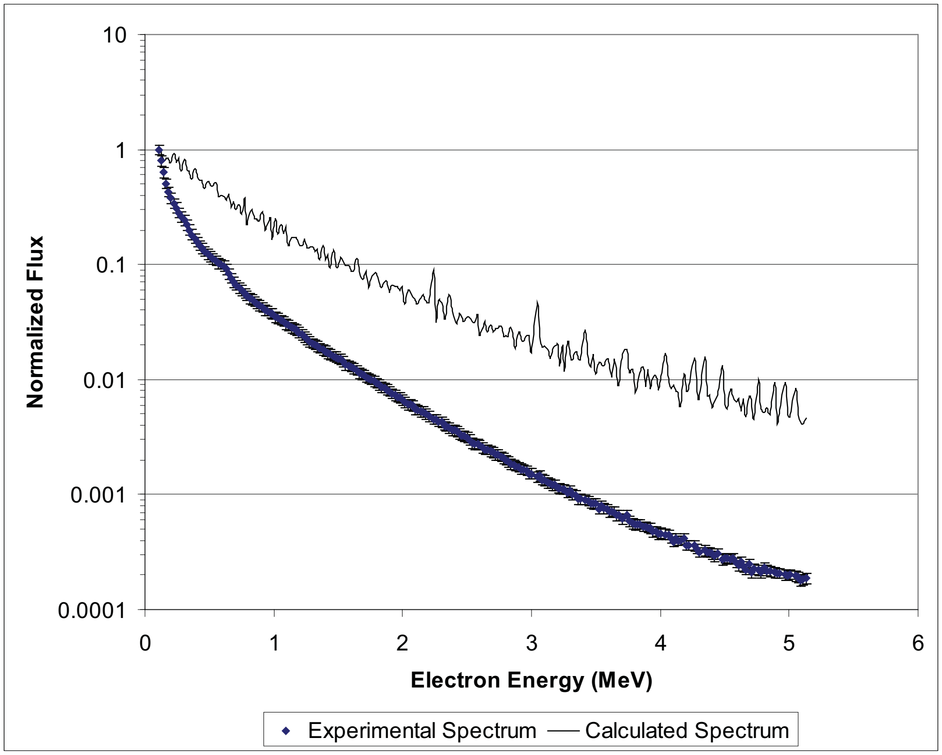

Figure 5. Low-Energy Electron Spectrum in the FTR Core Center.

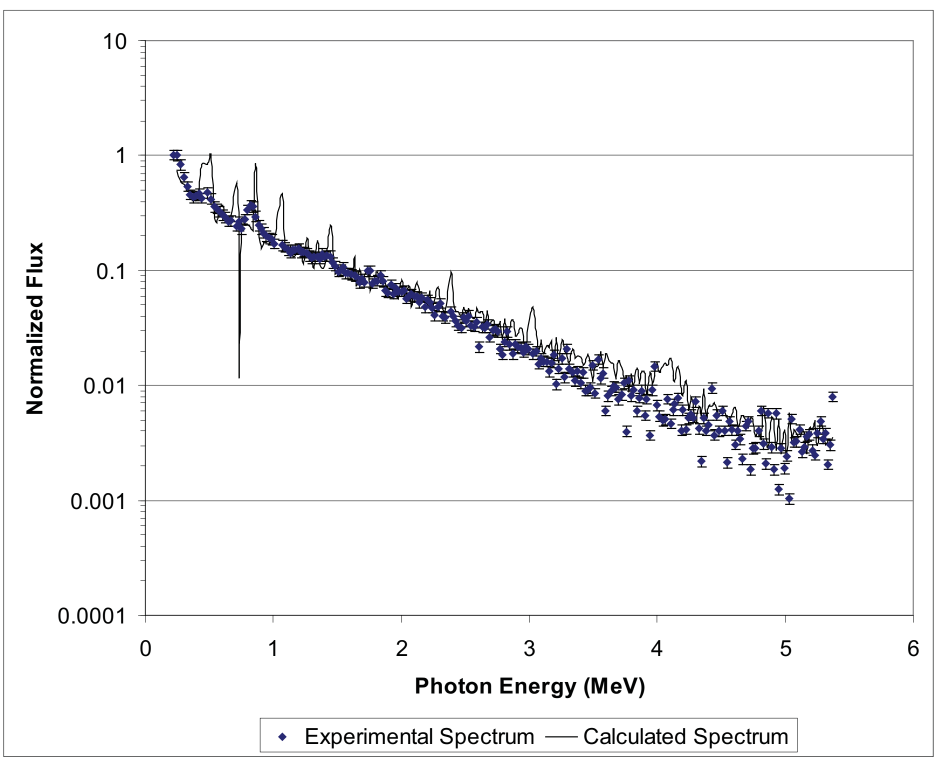

Figure 6. Low-Energy Gamma-Ray Spectrum in the FTR Core Center.

4. CONCLUSIONS

Benchmark assessment of the initial isothermal physics tests performed at the FFTF, in support of FCR&D and GEN-IV activities at the INL, have been completed using MCNP5 with ENDF/B-VII.0. The results have been documented in an IRPhEP report. Evaluated measurements at 400 ºF include criticality of the fully-loaded core, two neutron spectra, 32 reactivity effects (21 control rod worths, two control rod bank worths, six differential control rod worths, two shutdown margins, and one excess reactivity), isothermal temperature coefficient, and low-energy gamma and electron spectra at the core center.

There was good agreement between the calculated and benchmark k_{eff} eigenvalues for the fully-loaded-core critical configuration. There is very good agreement between calculated and benchmark values for the fully-loaded core critical eigenvalue, reactivity effects measurements, and isothermal temperature coefficient. While the comparison of calculated and experimental values for the neutron and low-energy gamma spectra agree well at the core midplane, the below-core measurement of the neutron spectra and the low-energy electron spectra at the core center do not agree well over the entire energy range evaluated. It is believed that homogenization of many of the core components, including the IRT, where the measurements were performed, had a large impact upon computational assessment of these effects.

Future work includes development of a fully heterogeneous model for comprehensive evaluation of measurements performed during the FFTF RCP. Utility of this new model will allow for reassessment of spectral measurements performed during the isothermal physics measurements to evaluate the impact of homogenization. Modification of this model will allow for further assessment of data from other tests performed in the FTR over the course of its ten years of operation.

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