CRITICAL BENCHMARKS AT THE RENSSELAER ZERO-POWER REACTOR FACILITY

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Abstract

A benchmarking project was performed at the Walthousen Critical Reactor Laboratory [1] at Rensselaer Polytechnic Institute in Schenectady, NY, with the goal of submitting a benchmark to the International Criticality Safety Benchmark Evaluation Project [2]. A detailed model of the reactor was created using MCNP4C2 [3] using precise data for the reactor component compositions and dimensions. The model was then tested by using it to calculate k_{eff} at the experimentally-determined critical rod bank height and critical water height. The model was found to accurately predict k_{eff} for these conditions.

KEYWORDS: Benchmark, Research Reactor, MCNP, Critical Experiments.

1. Introduction

The L. David Walthousen Critical Reactor Laboratory at Rensselaer Polytechnic Institute is a zero-power experimental reactor which is ideal for many experiments that would be very difficult at high-power facilities. The negligible fuel depletion and corresponding low decay product gamma activity of the fuel permits direct access to the core. This allows experimenters to rapidly change perturbation conditions by adding void, poisons, or fuel. This paper presents two experiments that were performed for the International Criticality Safety Benchmark Evaluation Project. The objective of these experiments was to demonstrate that the Walthousen reactor could be used to benchmark new criticality codes by using a given set of material compositions and component dimensions to model the reactor in the code, and then to compare the simulated reactor behavior to the experimentally-observed behavior. Specifically, we showed that our benchmark data resulted in an accurate prediction of the critical water height and critical control rod position when modeled in MCNP4C2.

2. Description of the Facility

The L. David Walthousen Laboratory is a light-water moderated critical reactor laboratory located along the Mohawk River in Schenectady, NY. It was first commissioned by the American Locomotive Company in 1956 to provide research to aid in the design of the Army Packaged Power Reactor [APPR]. Initially loaded with high-enriched annular plate fuel, the core was modified in 1985 to use low-enriched SPERT F-1 fuel pins.

The open-pool reactor core consists of an octagonal 1.63 cm square-pitch lattice of fuel pins. Each pin is 104.8 cm long, with a 91.5 cm long fuel region containing 4.82% enriched uranium fuel pellets. The pellets have a radius of 0.533 cm. The fuel pin is steel clad, and has an outer radius of 0.592 cm. The octagonal lattice contains 329 pins, with three to four additional pins added to the perimeter of the octagon for a total core loading of 332 to 333 pins. Control is provided by four flux-trap control rods, which consist of a rectangular stainless steel basket containing boron-impregnated iron plates. The control rods are located at the perimeter of the core near the thermal neutron flux peak. Figure 1 shows an illustration of the reactor core and control rods, and their size relative to the reactor tank.

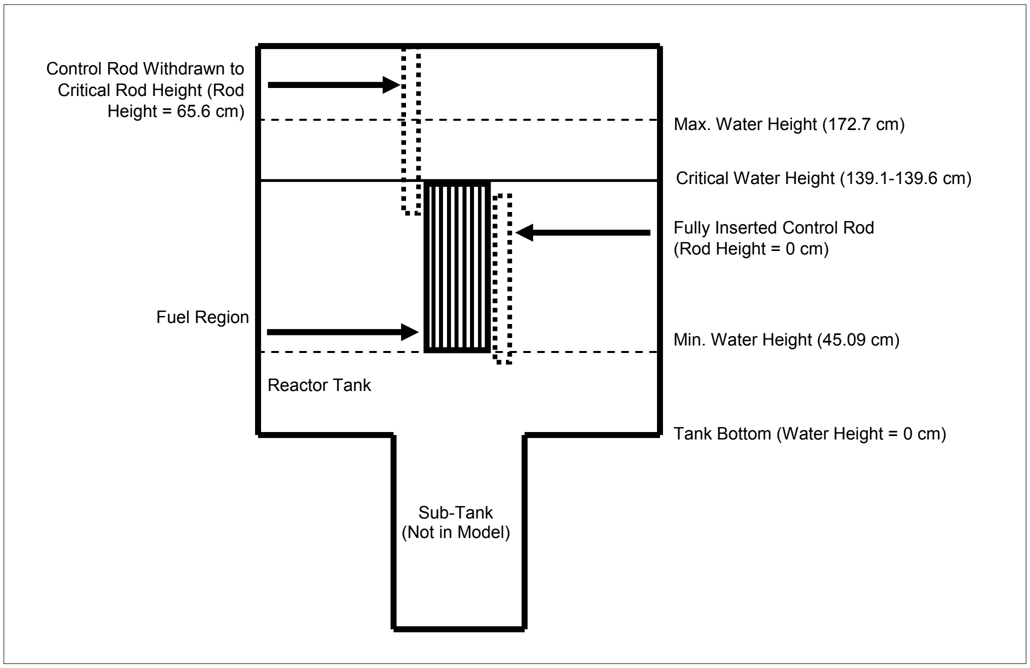

Figure 1: Side view of reactor core and control rods in reactor tank [to scale].

The Walthousen Lab is used primarily as a teaching tool, and is the location of a senior-level laboratory class in which undergraduates are permitted to operate the reactor and perform simple experiments under the supervision of the reactor staff. The ICSBEP project was performed as part of an ongoing attempt to showcase the abilities of the reactor that lie beyond its teaching mission.

The reactor is administratively limited to operation below 15 W indicated total power, and so it cannot be used for neutron imaging or neutron activation analysis experiments. The advantage of the reactor is the convenient access to the core and rapid start-up and shut-down speed. The control rods can be raised to their critical bank height in approximately ten minutes from a fully-inserted state. After the reactor is shut down, the reactor room is safe to enter within a few minutes and fuel pins can then be safely removed from the core. (Typical operation results in deck-area dose levels of less than 5 mrem per hour, and dose levels of less than 100 mrem per hour on-contact with a fuel pin). This allows us to perform a variety of experiments, such as foil activation and gamma scanning of active fuel pins for flux mapping, void reactivity worth and other reactivity perturbation measurements.

This ability to rapidly cycle the reactor makes it possible to perform a wide variety of criticality experiments in addition to those described in this report. For example, the approach to critical mass is a trivial task performed as an undergraduate lab experiment in approximately 3.5 hours. Another important advantage of the reactor is the simplicity of the open-pool design and low cost of operation.

3. Experimental Method and Results

The critical control rod bank position was found after filling the tank with water until the fuel pins were submerged by 25.4 cm. The core configuration used in the experiment was a full 329 pin octagon with four extra pins at the perimeter, for a total of 333 pins, as shown in Figure 2. The control rod bank was withdrawn until the neutron population was seen to increase at an exponential rate, indication a supercritical condition. At this point, the rods were lowered slightly until criticality was achieved. The critical control rod bank position was found to be 65.6 cm from the rods-bottomed position.

The critical water height experiment was found by filling the tank to the lowest moderator position known to be supercritical, which was 145 cm from the bottom of the main tank. The reactor was brought to critical by withdrawing the control rods. Next, a small amount of water was withdrawn, and the rods were withdrawn again to the new critical position. This process was repeated until, at a water height of 139.7 cm, the reactor was found to be slightly supercritical with the rod bank fully withdrawn. In the next iteration, the water was drained to 139.1 cm, causing the reactor to become slight subcritical. Therefore, the critical moderator height was known to be between 139.1 and 139.7 cm.

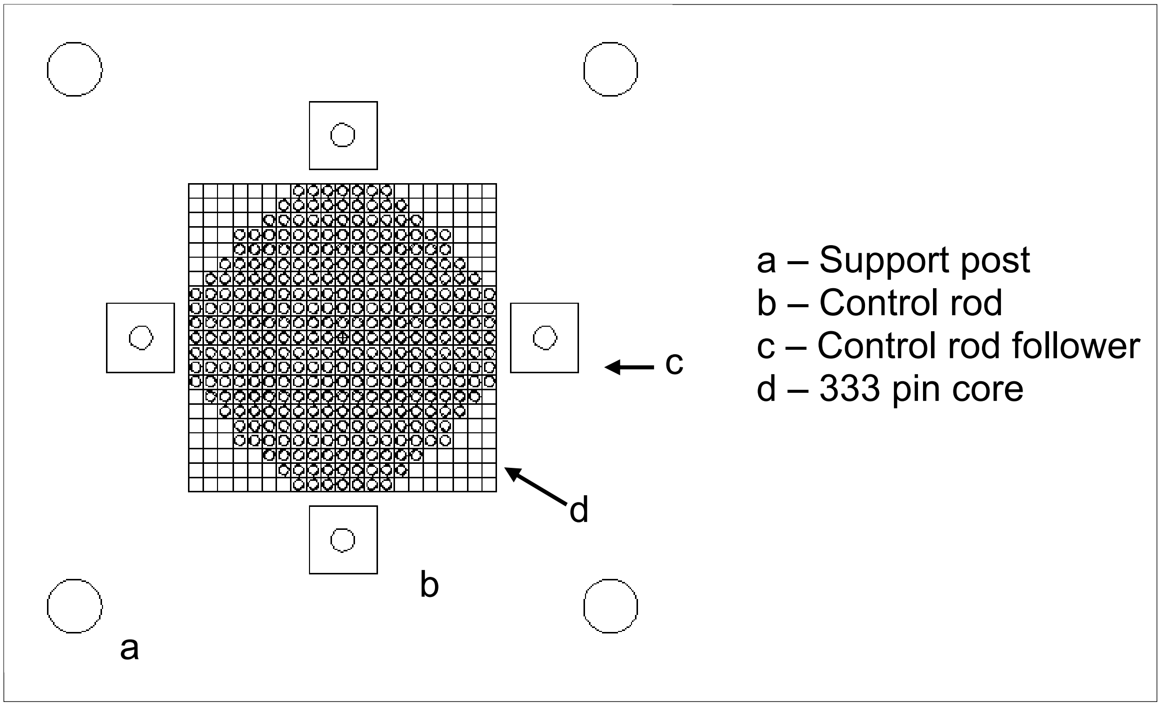

Figure 2: Fuel Lattice Illustration, 333 Pin Core

4. MCNP Model

As part of the benchmarking project, a model of the reactor was created in MCNP4C2 using the component dimension and material composition data included in the benchmark dataset. The model allowed for the adjustment of the water level by altering the z-plane defining its upper boundary. The control rod height could be adjusted with a linear transformation card. The model included each fuel pin and control rod in detail, as well as the core support structure.

Several small simplifications were made to the model.

- The gas and spring in the gas plenum region of each fuel pin was modeled as a homogenized mixture of steel and gas.
- The hydraulic brake at the base of each control rod was modeled as a homogenized mixture of steel and water.
- The reactor tank and the water in the reactor sub-tank region were not included in the model, nor were the channels for neutron detection instruments. Each of these components is far from the core.
- The hole in the top of each fuel pin (to allow for a hook to attach to the pin for core loading and unloading) was modeled as homogenized mixture of water and steel.
- Several unused control rod orifices in the bottom support plate were not modeled explicitly. Instead, the bottom support plate was modeled as a homogenous mixture of water and steel in the appropriate ratio.
- The instrument housings containing the neutron detection equipment for the reactor were not modeled in the benchmark These regions are all at least several thermal neutron mean free paths from the core.
- The boron in the control rods was modeled as ^{10}B instead of natural boron, which is likely to be the real composition of the boron. This model was not sensitive to this simplification for critical control rod height measurements. This is discussed below in the Results section.
- Finally, the void region between the fuel pellets was not modeled explicitly. The fuel region in each pin was modeled as a cylinder of a homogenous mix of fuel and void.

The effects of these changes were judged to be minor do not impact the accuracy of the model.

The nuclear data used in the model were obtained from the libraries listed in Table 1.

Table 1: Nuclear data libriaries used for each isotope in the reactor benchmark model.

Isotope	Cross Section Library Used in Model
^{1}H	ENDF-VI.1
^{4}He	ENDF-VI
^{10}B	ENDF-VI.1
^{11}B	ENDF-VI
^{16}O	ENDF/B-VI
^{27}Al	ENDF/B-VI
^{52}Cr	ENDF/B-VI.1
^{55}Mn	ENDF/B-VI
^{56}Fe	ENDF/B-VI.1
^{58}Ni	ENDF/B-VI.1
^{233}U	ENDF-VI
^{234}U	ENDF-VI
^{235}U	ENDF-VI.2
^{236}U	ENDF-VI
^{238}U	ENDF-VI.2

The calculation was performed using the *kcode* feature of MCNP, with 550 total batches of 10000 histories per batch. The first 50 batches were discarded to allow source convergence, for a total of 5E6 histories per calculation.

5. Results

The MCNP4C2 model used to test the benchmark data showed excellent agreement with the experiments, as shown in Table 2.

Table 2: k_{eff} Calculated by MCNP4C2 for Experimentally-Measured Critical Conditions

Measured Quantity	Measured Critical Position	MCNP4C2-Calculated k_{eff} at Experimentally-Measured Critical Position
Critical Rod Bank Height	65.6 cm from rods-bottomed position	$k_{eff} = 0.99848 \pm 0.00035$
Critical Moderator Height	139.1 - 139.7 cm from tank bottom	$k_{eff} = 0.99996 \pm 0.00018$ (139.4 cm)

The critical moderator height calculation exactly matched the expected k_{eff} value of 1.00000 at 139.4 cm. For the critical bank height calculation, the MCNP model yielded an estimate of k_{eff} that was further than two sigma from the expected value of $k_{eff} = 1.00000$. However, the result was still within 200 PCM of exact critical. The actual boron content of the control rods was not known. Therefore, we tested the model at several values of boron concentration, including that of natural boron (19.8% ^{10}B), which was thought likely to be the actual composition of the control rods. Due to self-shielding, and the low worth of the control rods inserted in the core at the critical position, the model was found to be insensitive to the boron content in the control rods. Specifically, at 65.6 cm from rods-bottomed, the natural boron model yielded $k_{eff} = 0.99849 \pm 0.00035$, which is identical (considering standard error) to the value obtained for rods consisting of fully-enriched ^{10}B. The shutdown margin for the core model was slightly sensitive to changes in the boron composition in the control rods, due to the greater insertion of control rod worth into the core. At rods-bottomed position, the natural boron model yielded $k_{eff} = 0.98971 \pm 0.00033$, versus 0.98761 ± 0.00071 for the case of 100% ^{10}B.

The k_{eff} calculation at the measured critical water height was within two standard deviations of the expected value. This is especially encouraging, since the worth of the water in the core is much greater than the worth of the control rods (see Figure 3).

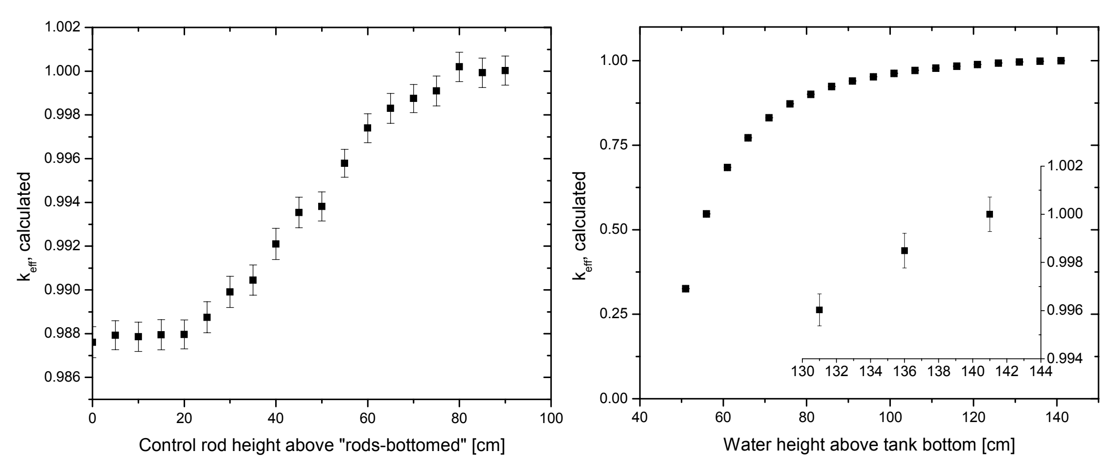

Figure 3 : Effect of control rod height and water height on effective multiplication factor. [Note: The fuel region of the core is located between 46.0 cm and 137.8 cm from the bottom of the tank].

Due to the low differential control rod worth for the core of the Walthousen reactor, the benchmark should be used to test k_{eff} at a known data point (e.g., $k_{eff} = 1.00000$ at 65.6 cm from rods-bottomed), instead of trying to predict the critical control rod height. When such a test was performed with our model, it over-predicted the critical rod bank height by 15 cm, but the calculated value of the multiplication factor was within 500 PCM of the experimentally-determined value for a range of 25 cm.

6. Conclusion

Rensselaer's critical reactor facility was shown to be useful for benchmarking criticality codes. We used our benchmark data for the material compositions and component dimensions for the reactor to create a model in MCNP4C2. The experimentally determined control rod bank height yielded an estimate of $k_{eff} = 0.99848 \pm 0.00035$ (two standard deviations) in our model, and the experimentally determined critical water height of 139.4 cm yielded an estimate of $k_{eff} = 0.99996 \pm 0.00018$ in our model. While the model's estimate of k_{eff} was close to the known value at the critical rod bank height, further refinement of the control rod model is necessary before the MCNP model can be used to predict the critical control rod height for the reactor.

The unique design of the critical facility allows for many similar experiments to be performed, including critical core loading, void coefficient of reactivity, and poison worth. The accuracy of the benchmark model in MCNP allows its use in conjunction with experiments to thoroughly characterize the behavior of the core.

References

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