Neutronics Benchmark Studies on the Hallam Nuclear Power Facility (HNPF) First Core Loading

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INTRODUCTION

Sodium Graphite Reactors (SGRs) are an appealing design [1] as they are capable of high operational temperatures at or near atmospheric pressure due to their use of a liquid sodium coolant. This increases the thermal efficiency of the plant while also allowing SGRs to be used to produce process heat. The lack of pressure requirement reduces the cost of the reactor vessel and piping as the forces expected on them are greatly reduced. While high operational temperatures and lack of pressurization are both quite appealing, these traits are shared by the Sodium Fast Reactor (SFR) family, the only difference being that SGRs have graphite moderators to thermalize neutrons while SFRs have no moderator and operate using fast neutrons.

The Hallam Nuclear Power Facility (HNPF) was a unique reactor designed and developed based on the SGR concept. HNPF was a 75 MWe liquid metal (sodium) cooled, graphite moderated nuclear reactor, built and operated in the 1960s. It was the site of one of only two sodium cooled graphite moderated reactors to have ever been in operation in the world. The HNPF reactor was intended as a commercial power reactor, scaled up from the design of the Sodium Reactor Experiment (SRE) [2]. What makes HNPF further intriguing and advantageous is that it can operate using fuel of low enrichment, or even natural uranium.

While there has not been an SGR in operation since the retirement of the HNPF in 1966, there has been renewed interest in the nearly forgotten family of reactors. Due to the extensive cost of building and operating a small-scale SGR to collect data not available from the SRE, not to mention the expense of a commercial scale nuclear power facility to gather data not available from the HNPF, a computational reactor physics benchmark (the HNPF benchmark) can be developed and evaluated in a short time to provide valuable reactor physics insights to this unique reactor type. This forms the primary research motivation of this study.

Based on the geometry and materials description of the HNPF first core (i.e., initial core) configuration [3], a computational reactor physics model based on Monte-Carlo N-Particle (MCNP) code [4] for HNPF was created and continually improved upon to increase its accuracy in matching historical data recorded during the operation of the HNPF. It is hoped that with a high-fidelity neutronics benchmark developed to match or closely approach the recorded behavior of the HNPF, one can be used to determine the expected behavior of the HNPF to conditions it may not have been subjected to.

An experimental data validated reactor benchmark can similarly be used to determine what changes may result from small modifications made to the reactor design, such as adding additional support material for the graphite moderating elements, the failure of which caused the plant's final shutdown. While these moderator elements could have been repaired, it would be at great expense and no customers were lining up to purchase a new reactor design, and as such the facility was retired. Should SGRs once again be built, knowing how they will react to certain situations and over long periods of time beforehand is essential.

HNPF OVERVIEW AND MCNP MODEL

HNPF belongs to an unusual type of reactor composed of a graphite moderated core with liquid sodium coolant. HNPF had two planned fuel loadings, forming the first and second cores, respectively. The first core loading, which is the focus of this benchmark study, utilized uranium molybdenum metallic fuel (3.6 wt.% U-235 enriched uranium alloyed with 10 wt.% molybdenum, i.e., U-10Mo). Due to the utilization of sodium as the coolant fluid, the reactor did not require pressurization, although a helium atmosphere was maintained to limit corrosion and chemical reactions within the reactor vessel and its outlying systems. Within the reactor core, hexagonal prisms of graphite canned in stainless-steel moderate fission neutrons to thermal energies. The prisms were scalloped at their corners, and when placed together three such corners form a circular column of sodium, in which various types of rods could be loaded. Dummy and reflector rods are loaded into unused rod positions at the outer extent of the core to provide additional moderation and are simply canned cylinders of graphite. In the first core loading, fuel assemblies consist of a central stainless-steel tube of helium, on which spacers were mounted, while 18 stainless steel tubes were radially arranged in groups of 6 and 12 each containing a sodium annulus around the U-10Mo fuel slugs. The void and fuel pins sit within a Zircaloy-4 process tube, openings at both ends allowing coolant to flow within the process tube. In addition, coolant flows between the various rods and the moderating elements, as well as the narrow channels between the faces of each moderator block. A thermal shock liner just outside of the core separates the circulating sodium from a generally stagnant sodium body.

To develop a precise MCNP model, the geometric parameters of the HNPF first core were extracted from the report. The materials specified in the original HNPF program's documentation were used along with their natural abundances to generate the initial nuclide composition of each material in the reactor model. Density and temperature information from steady state operation were obtained for usage in the reactor model. The HNPF first core lattice was divided into hexagonal unit cells, each being centered either on a graphite moderating element, or a rod position in which a fuel assembly rod, a shim-safety control rod, a graphite reflector rod or some form of instrumentation could be loaded through the reactor face plate. Modeling of the core surroundings includes the region from above the core face plate to extend through several feet of concrete below the reactor, and radially extends through several feet of concrete outside the reactor vessel cavity. The top-down view of the reactor core region is shown overall in Fig. 1.

A top-down view of the reactor core region (specifically, the top right quadrant) is shown in greater detail in Fig. 2, with the various regions numbered 1-9. Region 1 represents the concrete surroundings of the reactor. Region 2 corresponds to the various steels used in the reactor structures. Region 3 represents the helium gaps between these components. A white region encircles the reactor vessel, representing the insulation of the reactor (not modeled). Regions 4 and 7 represent the sodium coolant outside and inside (respectively) of the individual fuel assemblies. Region 5 represents graphite moderating material. Region 6 represents U-10Mo fuel in the fuel rods of each assembly, while region 8 represents the helium gas in the void rods. Region 9 is a helium void within the control rod thimbles, as MCNP modeling was performed with all rods withdrawn.

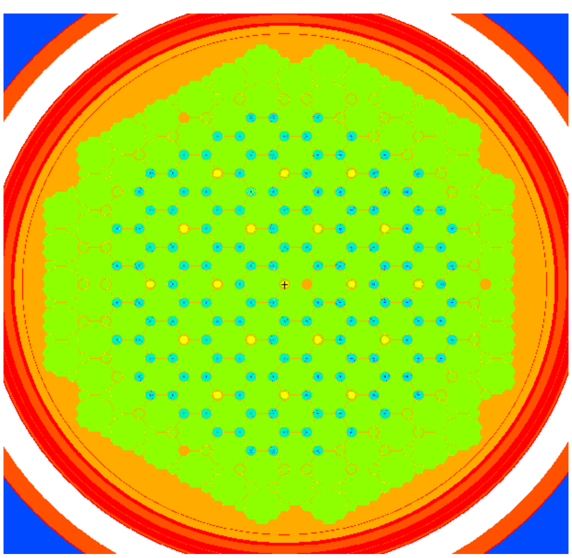

Fig. 1. Cross sectional top-down view of the HNPF reactor.

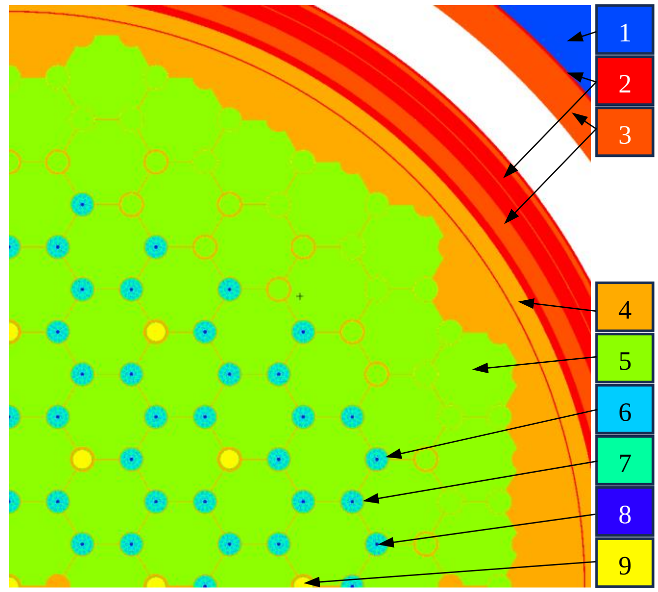

Fig. 2. Detailed view of quarter core of the HNPF reactor.

RESULTS

As part of the preliminary evaluations of the HNPF benchmark model, a couple of calculations were performed in this study. To validate the effectiveness of the MCNP model, the fuel enrichment of the reactor benchmark was modified to allow the model to be compared to a series of predicted effective multiplication factors at varying fuel enrichments. In particular, as the HNPF benchmark proceeded with a 3.6% enrichment of the fuel (by weight), a measured effective multiplication factor was available in the report and indicated in the study. The calculations were performed by adjusting the weight percent of both U-234 and U-235 to linearly increase while reducing the balance of U-238. These results are shown in Fig. 3. Despite differences between the benchmark results and the values expected by engineers prior to the reactor's operation, the benchmark results are just slightly above the value measured during reactor operation. Specifically, the benchmark model gives a k_{eff} of 1.08163 with a standard deviation of 0.00067, compared to the measured legacy value of 1.08.

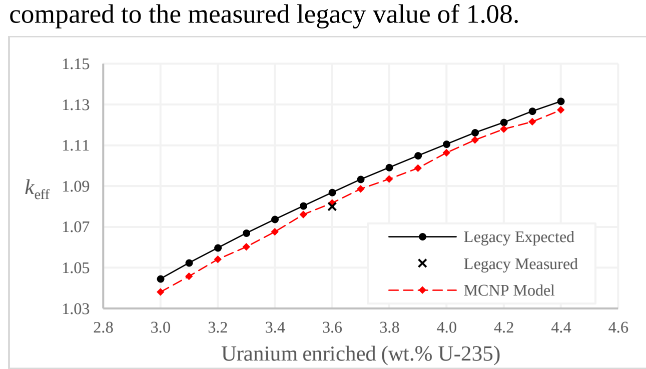

Fig. 3. Effective multiplication factor (k_{eff}) versus fuel enrichment [3].

Another evaluation we performed is on the effect of the fuel rod loading to the reactor. Based on the isothermal (~177°C) reactor core model enriched to 3.6 wt.% U-235, fuel rods were loaded into the reactor core at low power in small groups, their reactivity have been measured. Results from the MCNP benchmark model were obtained and compared alongside these legacy measurements as shown in Fig. 4. Here the fuel rod loading pattern strictly followed the same schedule as designed by the HNPF reactor, with unloaded positions containing sodium columns. As indicated in the figure, the k_{eff} results indeed follow the general shape of both the corrected and analytically measured values of the effective multiplication factor. However, a noticeably larger magnitude difference remains for further investigations.

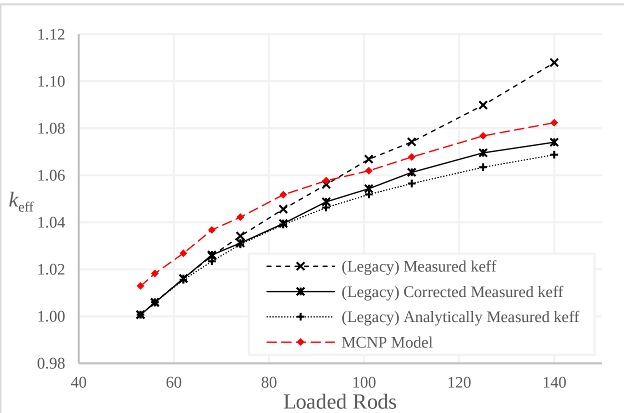

Fig. 4. Effective multiplication factor (k_{eff}) versus fuel rod loading [5].

CONCLUSIONS AND FUTURE WORK

In conclusion, the current HNPF benchmark is not sufficiently accurate to reproduce known legacy measurement data for now. This is partly due to a lack of clear documentation combined with sometimes contradictory details between documents, which makes it difficult to ascertain exactly what assumptions the HNPF reactor experiments were performed under. In addition, the accuracy and modeling extent of the analytical models used to predict or correct legacy data is unclear. As a result, the current benchmark has few inaccuracies when compared to known reactor geometry and fails to account for things such as fuel expansion at higher temperatures.

To best compare the HNPF benchmark to scenarios tested on the HNPF reactor, further points of comparison are needed. Not only will this provide a more definitive verification of the completed HNPF benchmark, but also it will help steer the benchmark's development by showing what criteria it fails to meet, as this may help locate any inadequacies in the benchmark model. In addition, uncertainty quantification (UQ) modules are available in MCNP and will be used as part of the benchmark refinement and verification stages, however no UQ has been performed at the time of this paper.

There are numerous potential additional points of comparison between the HNPF benchmark and the reactor, which have yet to be fully explored. While the predicted and measured effective multiplication factors of the HNPF reactor at varying enrichments and rod loadings were easy to compare, work is ongoing in determining the thermal reactivity feedback coefficients of the reactor. Additionally, numerous flux profiles are documented which could be compared to the reactor benchmark, and control rod worth should be calculated in the future.

Currently, the model is unable to effectively measure each of these, as control rod positions within the reactor core are instead replaced with vertical sodium columns. Control rod positions are not well documented for individual legacy data points, although the effective multiplication factors of all legacy data points were determined by the control rod worth necessary to cause in-core fission chambers to read a constant flux. Control rods have been modeled in the current MCNP benchmark, continuing the thermal reactivity coefficient calculations by calculating the effective multiplication factor at "all rods out".

Xenon worth may be investigated along with burnup, although using MCNP burnup calculation CINDER is resource intensive, and has yet to be performed due to inaccuracies in the current model. Due to the time required for these calculations, they are planned as a final verification stage for the HNPF benchmark.

The current neglect of the presence of fission products in the HNPF core (despite the fuel being at relatively low burnup during all experiments) is a source of variance between legacy and measured data. Potential faults in the fission chamber detectors or improper control rod worth calculation may have skewed legacy data from its true value, and as such future comparison should be done by matching recorded control rod positions at each data point to the MCNP modeled control rods. In addition, thermal reactivity feedback coefficients, xenon worth and control rod worth should all be performed to further guide and refine the HNPF neutronics benchmark.

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