INTRODUCTION

The purpose of this work is to perform a neutronic and fuel cycle analysis of the single-fluid Oak Ridge National Laboratory (ORNL) Molten Salt Breeder Reactor (MSBR) as described in ORNL-4541 [1]. Expected design requirements and system outputs were published in this referenced report; the work described herein is focused on building a model of the core, determining the best strategy for modeling the reactor core, and ultimately implementing this modeling/analysis strategy for future research in liquid fueled reactors. Similar analyses for the MSBR using unit cell and full-core models performed using MCNP [2] showed that multiregion models can accurately represent the spectral properties of the multizone MSBR [3,4].

REACTOR DESIGN

The MSBR was designed to use low-cost liquid fuel instead of enriched ceramic uranium oxide [1] used in conventional light water reactors. The fissile material is dissolved into a FLiBe carrier salt. The use of a single-fuel salt in the MSBR is an alternative to using a two-fluid system with separate salt mixtures for fertile and fissile materials. Using a single-fuel salt also allows for improved fuel processing, limited replacement of moderator graphite materials. Using a single-fuel salt also allows for improved fuel processing, limited replacement of moderator graphite versus replacement of the entire core assembly, and more comprehensive modeling/simulation with the simplicity of one fuel salt.

A traditional breeder reactor contains separate core regions: a central area comprised of fissile material surrounded by a ring or blanket consisting of fertile isotopes that absorb neutrons from fissions in the central core and transmute them into fertile isotopes. The MSBR does not have separate core salts, but the fuel-to-moderator ratio is increased in the outer regions of the core, increasing the amount of fertile-to-fissile conversion (breeding) [1].

The MSBR is a thermal/epithermal breeder reactor. It is fed with fertile $^{232}$Th dissolved into the MSR primary fluid. The thorium absorbs neutrons, and through a series of decays, it eventually converts to $^{233}$U, which is the fissile isotope used to drive fissions in the reactor. The reactor uses chemical processing to remove specific fission product poisons, as well as protactinium. The protactinium decays to $^{233}$U and is then fed back into the core to power the reactor.

COMPUTATIONAL METHODS AND MODELS

The primary computational tool for this work is ChemTriton [5], a modeling and simulation tool developed for molten salt reactor (MSR) analysis in which SCALE [6] is used to perform the neutron transport and depletion calculations with the SCALE/TRITON [7] module. This tool builds upon previous ORNL efforts in MSR modeling and simulation tool development [8] and applications to thorium-fueled systems [9–12]. Additional development of this tool has led to implementation of the Shift [13] Monte Carlo tool for transport and depletion simulations.

Three approaches were used to model the MSBR core. The first approach modeled the core as an infinite lattice of identical average cell units, all with the same ratio of liquid fuel to moderator graphite. The ratio of salt volume to graphite volume for the base unit was determined from the ratio of salt to graphite present in the core. Each unit was a rectangular prism 396.24 cm tall with a square face (10.16 cm $\times$ 10.16 cm). It consisted of graphite with a centered salt-filled cylindrical channel through the square face (Fig. 1). The salt volume of the unit is adjusted by changing the fuel salt channel radius.

The second more detailed approach distinguishes between the fuel salt regions in the core that were comprised of units with different fuel salt channel radii. The core is comprised of three different graphite base units, each with the same dimensions except for the fuel salt channel radii. These regions are referred to as I-A, I-B, and II-A. Each unit was modeled in Shift in a manner similar to that used for the average unit cell. Power values were distributed to units proportionally based on the ratio of units present in the core and the expected core power profile. The power in zones I-A, I-B, and II-A constitutes only 94% of total core power, with the remaining 6% provided by salt flowing through graphite ribs in region II-B and a surrounding fuel salt annulus. Thus, the power in the

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three zones was renormalized to 2,250 MW to be consistent with the other approaches.

The third and final approach used a model of the full core of the MSBR. This allows for the most detail; the core reflector, annulus, control rods, and region II-B were modeled, along with the units for I-A, I-B, and II-A. The three unit-based regions defined earlier were modeled in a lattice based on their defined geometric dimensions. The outer salt for each unit was modeled uniformly around the unit’s graphite to approximate the unit cell geometry. A specific unit was also used to approximate region II-B; the graphite ribs were modeled to be two inches thick and maintain the salt volume fraction defined in the design parameters. The lattice of unit cells was then enclosed with a fuel salt annulus ring surrounded by a graphite reflector placed on the top, bottom, and outer edges of the core model (Figs. 2–3).

RESULTS AND ANALYSIS

The full core model delivers a $k_{\text{eff}}$ of 0.99460, which is slightly lower than critical, but it is sufficient for fuel cycle simulation. Each of the three modeling approaches delivers a very different conversion ratio: the single-unit, three-unit, and full core models deliver average conversion ratios of 1.03, 1.09, and 1.14 over the first 500 days of operation. The expected conversion ratio of this system is 1.06, with an annual fissile yield of ∼3%. Additionally, the conversion ratio continuously decreased during operation due to the build-up of fission products. These fission products compete with the fertile material, and as the rate of $^{233}$U production decreases over time, the conversion ratio decreases accordingly. It is unclear whether the expected conversion ratio of 1.06 is an average during operation or if it is instantaneous at equilibrium. Changes in the conversion ratio occur over weeks and months; short time scale transients are not tracked with these computational tools.

As expected, the conversion ratio for the single-unit model is the lowest; this model does not simulate the heterogeneities in the core, and a single spectrum is unable to capture the conversion ratio of the full-core model. The multiregion model also has some difficulties due to the lack of interaction between the three unit cell models and an assumed power distribution. An appropriate full-core power distribution is used for the full-core simulations, as this distribution is effectively calculated during the transport.

Flux maps show the behavior of neutrons at different energies in the MSBR (Figs. 4–6). The highest thermal fluxes are at the center of the reactor in the driver zone. The increase of fissionable material (fuel salt) along the graphite core outer edges increases the fast-to-total flux ratio to breed more fissile material. Fast energy neutrons are responsible for most of the flux through the plenum and annulus regions.

Adjusting the geometry of the full core model in the reflector regions (using approximate models for the graphite ribs) had little impact on the fuel cycle simulation. The
addition of a plenum region above and below the graphite core units increases fissions in these reflector regions.

SUMMARY AND CONCLUSIONS

Comparisons of the use of reduced-fidelity and full-core models in fuel cycle simulations for the MSBR were presented. Using coarser unit cell representations greatly reduce computational burdens with respect to full-core models. The conversion ratio varies significantly depending on the fidelity of the model, and single unit cells are unable to capture the breeding rate within the core. Multiple-cell models may be more representative, but they must have appropriate definition and distribution of power. Full-core analysis of the MSBR is achieved through the use of Shift by the ChemTriton tool.

Additional efforts will focus on providing power feedback information between the full-core and reduced-fidelity models to determine the effect of this parameter on the fuel cycle simulation. This effort will also quantify the importance of modeling the interaction between the different core zones.

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