Neutronics Benchmark Development of the ALFRED Alike Reactor Using MCNP Code

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INTRODUCTION

A lead-cooled fast reactor (LFR) is a liquid metal cooled reactor that operates within the fast neutron spectrum (often referred to as more than 0.1 MeV neutron energy). LFR is an advanced reactor type that is within the generation-IV classification having "goals of improved safety, sustainability, efficiency, and cost in contrast to earlier reactor generations" [1]. The Advanced LFR European Demonstrator (ALFRED) is a LFR design currently fostered by various European organizations [2]. ALFRED is rated 300 MWth and is cooled by pure lead and operates in the temperature range 400 °C (core inlet) – 520 °C (average core outlet). Fig. 1 illustrates the major components in the primary system of ALFRED.

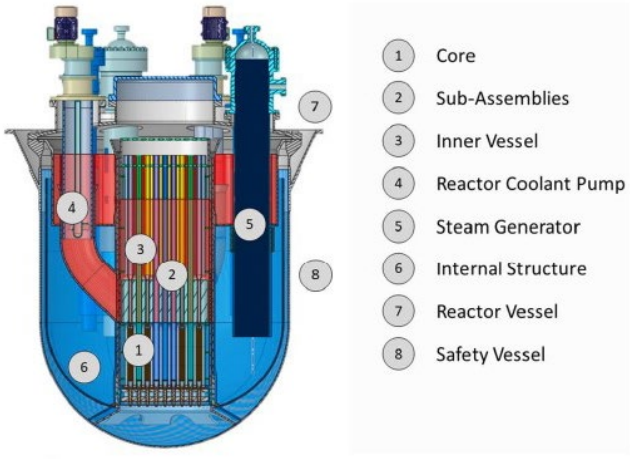

Fig. 1. ALFRED Primary System Layout [2].

This paper presents a status update on neutronics benchmark and evaluation of a LFR model derived from the ALFRED design through computational simulation and modeling. This is achieved by using the Monte Carlo Nuclear Particle (MCNP) code [4] to model the LFR and perform these calculations by tracking of the neutron behaviors in the core. This study has emphasis on eigenvalues for different configurations of the reactor, flux experienced within elements of the reactor, and the burnup within the fuel. This is to place importance on physics, neutronics, and the capability of the LFR core.

MCNP MODEL

For simplicity and thoroughness, the computational modeling process consists of three steps that break the whole core into three distinct levels that count for pin, subassembly, and full core configurations, respectively. The first step was on the pin level, which was done on the focus of solidifying material and geometry specifications. The following step was on the subassembly level, which was focused on creating the "building blocks" of the core in a hexagonal lattice. This step also included the creation of control rods, shielding assembly, and safety rods that would be used to assemble the full core. This step also included a sub-step of creating super-assembly cases (i.e., supercell models) that included a group of assemblies surrounding either control rods or shielding assemblies. The final step was on the full core level that required the user to assemble the reactor using the components built in the previous steps to form the full reactor. Fig. 2 illustrates the pin-level, subassembly-level, and supercell models of the LFR using the MCNP Visual Editor, and Fig. 3 shows the whole core model.

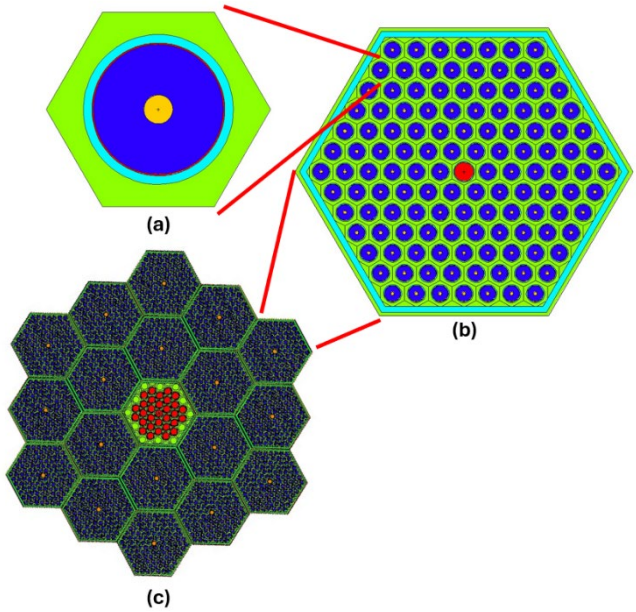

Fig. 2. The LFR (a) pin-level (a), (b) subassembly-level, and (c) supercell models by MCNP.

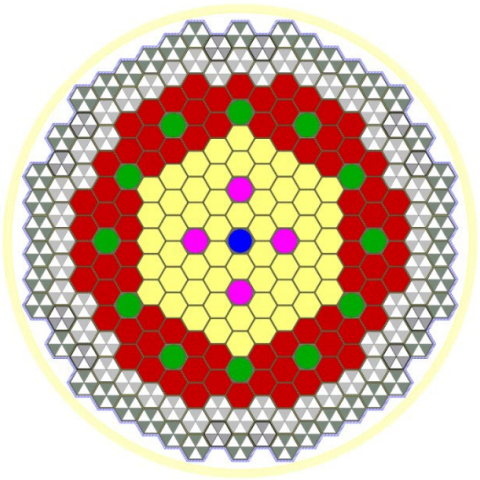

Fig. 3. The whole LFR core model, where yellow portion represents the driving fuel, red portion is the breeder fuel, and grey portion is reflector [2].

One approach that is worthy of noting during the modeling is the method adopted to construct material cross sections at different temperatures. Though the material temperature treatment has been significantly improved in many recently developed Monte Carlo neutronics analysis codes including Serpent [3] and RMC [4] using the so-called TMS (target motion sampling) 'on-the-fly' method [5], MCNP 6.2 is built to use cross section data that have been created by different physics experiments and these data are set at very specific temperatures. Assessment with the LFR was performed with the 80 series data within MCNP 6.2 under the data set ENDF/B-VII.1x [6]. With the available data set for specific cross sections, one would confront a problem that there was not a data set at the desired 700 K for most of the materials used in the LFR benchmark model. We employed the stochastic mixing method [7] to overcome this limitation. The underscoring idea of this method is using the data sets that bracket the value demanded in specific proportions to achieve the value needed. For example, in order to achieve cross section data at 700 K, the user would mix the 600 K and the 900 K data sets using interpolation to achieve the desired temperature. This was demonstrated by trying to get the most accurate results from the testing as shown in Fig. 4.

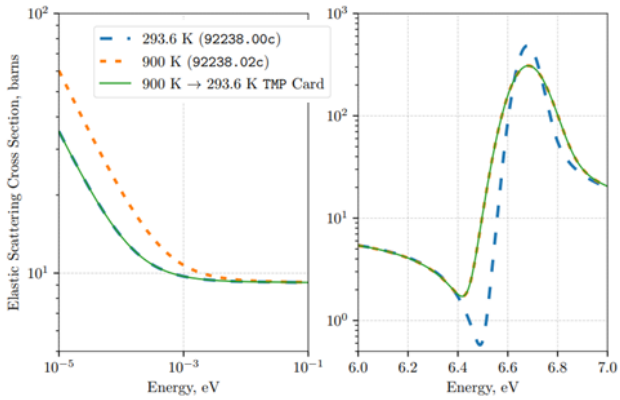

Fig. 4. Temperature effects on cross sections [7].

MODEL VERIFICATION

As part of the verification efforts of the LFR benchmark development, results from the simplest level (the pin level) were compared to another independent working group's data. Results from the ININ (Instituto Nacional de Investigaciones Nucleares) were used for this comparison as their results were obtained using a different Monte Carlo based neutronics code – Serpent [3]. Table I summarizes these comparisons, and an overall good agreement is received between the results of both parties.

Table I. Pin Level Model Results Comparison.

Results from Inner Fuel Pin				
VCU		ININ		Difference
k_{eff}	Std Dev	k_{eff}	Std Dev	k_{eff}
1.34412	0.00005	1.34394	0.00002	0.00018
Results from Outer Fuel Pin				
VCU		ININ		Difference
k_{eff}	Std Dev	k_{eff}	Std Dev	k_{eff}
1.53004	0.00006	1.53025	0.00002	0.00021

RESULTS

For simplicity and smooth organization, the LFR result section is split up into three different subsections pertaining to the calculations that they hold. These subsections cover eigenvalue calculations, flux spectrum calculations, and burnup calculations, respectively.

Eigenvalue Calculation

The reactor eigenvalue calculations can be performed on the level of pin, subassembly, super-assemblies, and full core calculations. For concise purposes, the pin, subassembly and

super-assemblies level eigenvalue calculation results were not reported in this summary. The full core level calculations consisted of following three considerations: full core with rods all out, including CR (control rods) and SD (safety devices), full core with CR and without SD, and full core with both CR and SD inserted. For simplicity, only the beginning of life (BOL) materials are considered for all the three conditions. The full core level eigenvalue results were summarized in Table II. These results are in an acceptable agreement with ININ results at this preliminary analysis stage.

Table II. Results of k_{eff} for the LFR Full Core at BOL.

Condition	k_{eff} (VCU)	k_{eff} (ININ)
Rod all out	1.00851±0.00009	1.00273±0.00002
CR inserted	0.96844±0.00009	0.95685±0.00002
Rod all in	0.95292±0.00011	-

Flux Spectrum Calculation

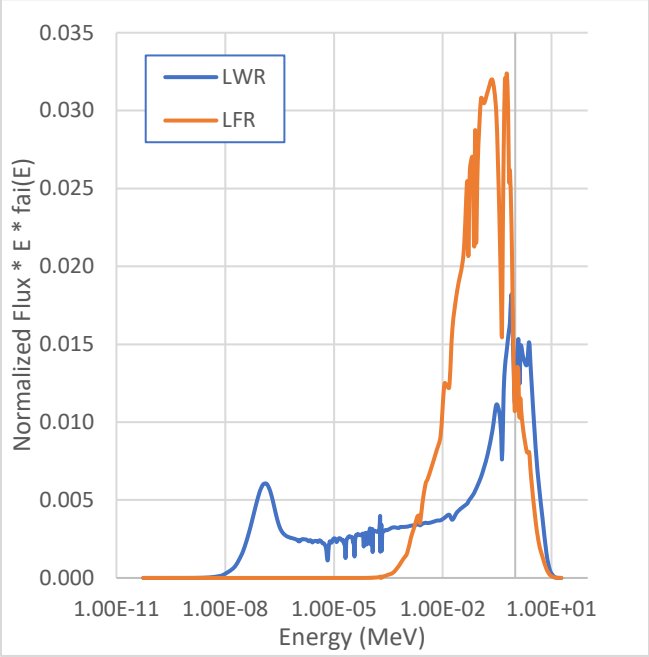

Fig. 5. Flux spectrum comparison between a typical LWR and the LFR reactor.

Flux spectrum indicates important physics characteristic of a fission reactor. In this work, the reactor spectrum is generated by MCNP using the flux tally capability based on the standard SCALE 252 group structure [6]. To show the distinct feature of the LFR in this regards, we compared the LFR spectrum to a typical thermal light water reactor (LWR) as this reactor is assumed to operate mainly on the fast energy region. This was done to make sure that the LFR is differing from the LWR and in fact operating within the fast region. The flux energy spectra of the LFR comparing to a typical PWR is shown in Fig. 5.

Burnup Calculation

The fuel burnup calculation was to inspect how the fuel changes throughout reactor operation lifetime. It is enabled by the BURN card in MCNP 6.2. In this work, the burnup calculations are performed only in the subassembly level. The specific power (W/kg) used for the burnup calculation was estimated by dividing the total power of the reactor (300 MWth) by the total amount of fissionable materials. Uranium and plutonium mixed oxide (MOX) fuel is used at the beginning state. The burnup calculations were performed with the aim of investigating the immediate and long-term effects of burnup, therefore nonuniform burnup steps are purposely defined, varying from minutes, hours, to tens and hundreds of days.

Fig. 6 reports the result of k_{eff} changing along with the burnup times, with statistical errors shown as error bars for each eigenvalue. Fig. 7 and Fig. 8 illustrate the mass change trends of the two major actinides (^{238}U and ^{239}Pu) change along with the burnup, respectively.

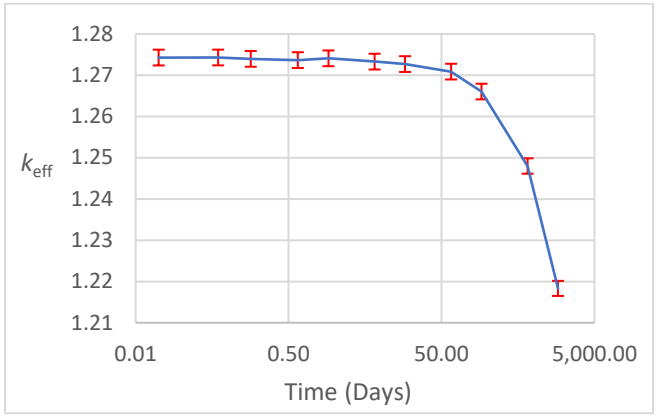

Fig. 6. Subassembly k_{eff} as a function of burnup.

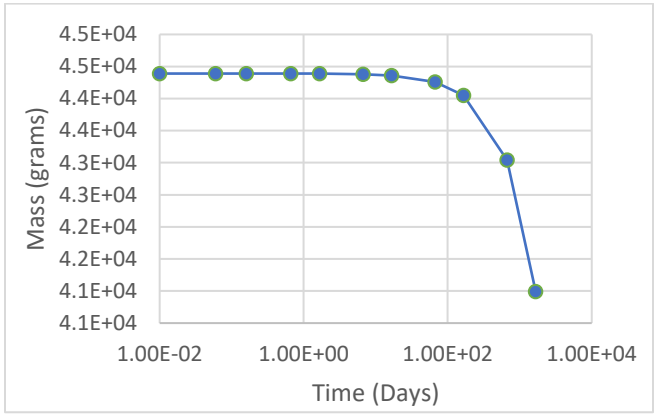

Fig. 7. Subassembly ^{238}U mass as a function of burnup.

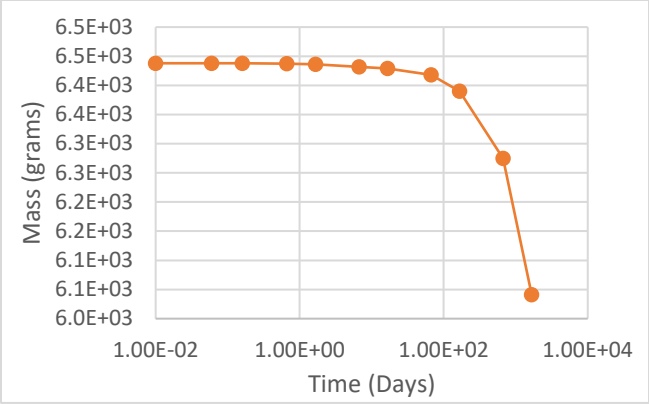

Fig. 8. Subassembly ^{239}Pu mass as a function of burnup.

CONCLUSIONS AND FUTURE WORK

A lead fast reactor neutronics benchmark model has been established successfully at Virginia Commonwealth University using MCNP for the LFR type of reactor analysis based on the ALFRED design. This reactor benchmark can be specifically used for assessment and outlining certain properties of this reactor and its advantages. These advantages include but are not limited to the burning of nuclear waste, effective shutdown and safety mechanisms, and the creation of new fissile fuel to be used in the future.

There are a few more tasks that can be performed in the future work, continuing the current benchmark model development. First, there is a need to understand the reactivity coefficients of the reactor as this was not examined yet with current calculations. Investigation into the coefficients and their effects on reactor operation would be important as it would greatly affect the reactor transient behavior. This includes the effects of the coolant and fuel reactivity coefficients.

The other task that can be further investigated is other fuel options that are viable for the reactor. While uranium and plutonium are good to use in LFR, there are other fuel combinations that could work and should be tested. One of these combinations that should be noted is the combination of uranium and thorium. This is because within this reactor benchmark there is a large content of ^{238}U acting as fertile fuel to be turned into fissile fuel (in the form of ^{239}Pu). It is worth testing if the plutonium could be replaced with ^{232}Th, which is convertible to fissile ^{233}U. In this scenario, the fuel would be a MOX fuel with most likely HALEU (high assay low enriched uranium) fuel to replace the ^{239}Pu and ^{241}Pu within this benchmark. This is beneficial as it prevents the creation of plutonium, an element with great nuclear proliferation concerns

ACKNOWLEDGEMENTS

This study was performed in accordance with the LFR benchmark working group led by the Organization for Economic Co-operation and Development (OECD) and under the guidance of the Expert Group on Physics of Reactor Systems (EGPRS).

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