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ABSTRACT

The Systems for Nuclear Auxiliary Power (SNAP) program accumulated extensive experimental measurements over a span of 15 years. This work builds upon previous studies which validated Serpent against experimental data for various criticality configurations of the SNAP 8 Experimental Reactor (S8ER). A 2-stage sequence is applied here with Serpent used for the generation of few-group cross sections and Griffin as the transport eigenvalue solver. This paper provides the procedure adopted for the pre-generation of few group parameters, generation of unstructured mesh geometry, and selection of transport solver parameters. The preliminary results from Griffin are compared against the reference Serpent. In future studies this work will be expanded to create a generalized methodology for the Serpent-Griffin 2-stage approach particularly suited for microreactor applications.

KEYWORDS: SNAP, SERPENT, GRIFFIN, MOOSE, MICROREACTOR

1. INTRODUCTION

The S8ER was part of a fleet of reactors built during the Systems for Nuclear Auxiliary Power (SNAP) program [1]. These reactors were designed to be used in space as auxiliary power for components such as satellites as well as for nuclear electric propulsion such as the S8ER itself. These systems were the first to explore novel microreactor technology and share many similar characteristics to modern designs that include comparable power output, compact core design, representative reactor-physics phenomena, alkali metal working fluids and high temperature solid moderators. They also share similar challenges, such as hydrogen migration.

This work is part of an ongoing joint effort between Georgia Tech, University of Wisconsin-Madison, BWXT, and INL that leverages extensive experimental data from the SNAP program to validate the performance of specific NEAMS tools in modeling effects that are unique to microreactor technology [2] [2] [3] [4]. The activities reported here were partially sponsored by the National Reactor Innovation Center (NRIC) Virtual Test Bed (VTB) project (https://mooseframework.inl.gov/virtual_test_bed) [5].

2. REACTOR DESCRIPTION

2.1 System Characteristics

The S8ER was designed to operate for a total of 10,000 hours at a power level of 600 kWth. In the interest of reducing size, weight, and performance, the system used HEU in the form of Uranium-Zirconium Hydride (UZrH), with eutectic Sodium-Potassium Alloy (NaK) coolant in a tight hexagonal lattice arrangement. The main system characteristics are presented in Table I. The system uses a mix of burnable poisons as well as stationary and moveable reflectors for reactivity control. The core contains 211 elements arranged in a hexagonal lattice. Each element/rod contains the homogenous UZrH mix as the fuel base, a hydrogen diffusion barrier consisting of the ceramic AI-8763D infused with burnable poison Sm_2O_3, an internal atmosphere consisting of Helium as a gap, and a layer of Hastelloy N cladding. The fuel pins contain upper and lower endcaps for containment as well as indexing [6].

Table I. System characteristics of the S8ER.

Parameter	**Value**
Thermal power (kw_{th})	600
Inlet coolant temperature (k)	1100
Outlet coolant temperature (k)	1300
Heavy metal loading (kg U 93.15 weight %)	6.56
Fuel material	UZrH
Coolant material	NaK
Core vessel outer diameter (m)	0.2372
Control drum thickness (m)	0.0560
Number of fuel elements	211
Element pitch (m)	0.01448
Element outer radius (m)	0.01352
Element height (m)	0.3556

2.2 Critical Configuration Experiment

This work focuses on the C3 Criticality Configuration Experiment, where the criticality configuration experiments include a set of measured total system excess reactivities for a variety of material and geometry configurations [6]. The C3 configuration is characterized by having no control shims installed with control drums fully closed in and no Lucite rod loading. C3 configuration is known as a dry experiment meaning the system had no active coolant running and was operating a cold zero power, where the coolant channels are filled with ambient air. Due to the lack of coolant and the very low power there is no need to account for any coupled feedback mechanisms. Therefore, only neutronic studies are included here. The ambient air channels are representative of void and hence there are high gradients in the neutron flux introduced between fuel and channel interfaces. This is relevant to the discussion in Section 3.2. A schematic of the C3 Configuration is shown in Fig. 1 (Shim A & B not included in C3 Configuration).

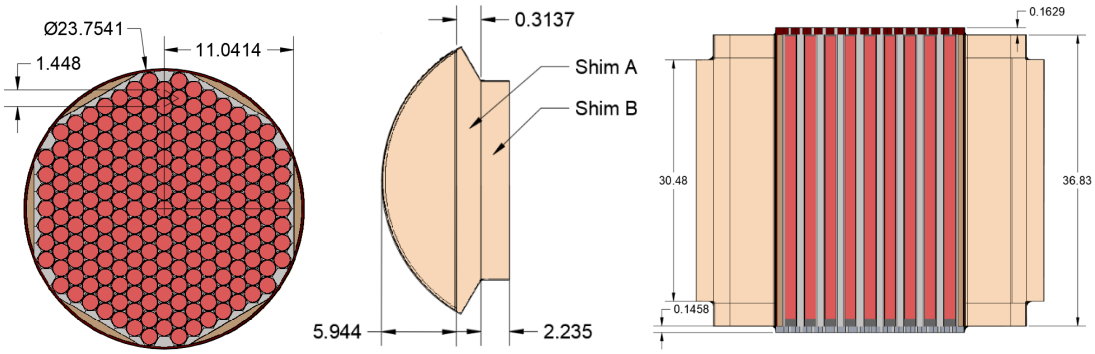

Figure 1. Serpent Model Radial and Axial Diagram.

3. MODELING

As previously mentioned, the end objective is to assess the capabilities of different MOOSE-based computational tools in the context of microreactor applications. MOOSE is a finite element-based Multiphysics Object Oriented Simulation Environment, where several MOOSE based applications exist for simulating different physics such as heat transfer, thermo-mechanics, and neutronics for example [7]. Griffin is the MOOSE-based neutronics solver in the NEAMS suite [8]. The S8ER experiment serves as an ideal candidate to test Griffin due to its small size and high neutron leakage and intricate coupled multiphysics. The latter together with the material heterogeneity introduces computational challenges associated to the generation of few-group parameters and the overall 2 stage neutronics approach. Complexities and considerations that are key to the fidelity of the solution will be partially discussed but will need to be addressed in more detail in future work.

3.1 Computational Environment

The two stage neutronics workflow consist of a pre-generation stage where parameters to be used in a reduced order solver are deduced from a reference high-fidelity solution. The parameters from the pre-generation stage are tailored to be able to reproduce the high-fidelity solution within the reduced order framework. Assuming the pre-generation stage is done correctly, and the reduced order solver parameters are adequate, perturbations and sensitivity studies would be performed in the reduced order framework saving time and computational work. This is essential for multiphysics simulations where several physics are involved, and computational complexity is increased significantly. However, this work only investigates the neutronics solution obtained with Griffin.

The generation of few group parameters as part of the pre-generation stage will be discussed as well as the generation of the unstructured mesh required for the finite element MOOSE environment. The Discontinuous Finite Element Discrete Ordinate (DFEM-SN) Transport scheme in Griffin rather than the Continuous Finite Element Diffusion (CFEM-Diffusion) scheme is used to obtain the neutronics solution. While most Griffin applications have chosen to go with lower order methods such as CFEM-Diffusion, this allows to have a more direct workflow from generation of the few-group parameters to establishing our Griffin model. This approach avoids the need to generate equivalence parameters such as super homogenization (SPH) correction factors usually required for reasonable agreement between Griffin and reference solutions when using CFEM-Diffusion [9]. DFEM-SN is also heavily optimized for parallel computation and thus very suited for relatively large problems such as the one reported in the current study [10]. Future work will provide comparisons between the DFEM-SN and CFEM-Diffusion schemes with equivalence methods.

The continuous energy Monte Carlo code Serpent [11] is used for the generation of homogenized few-gro up data and the finite element MOOSE based DFEM-SN neutronic solver in Griffin is used as the transpo rt eigenvalue solver [8]. All simulations were conducted on the SAWTOOTH INL HPC Cluster using Ser pent 2.1.32 with the ENDF8 cross section library and the latest compiled version of Griffin/2023-04-30. F or the generation of the unstructured mesh Coreform Cubit is used [12].

3.2 Generation of Few-Group Parameters

For generation of the reference solution and neutronic data, Serpent is used for its versatile few-group cro ss section generation features. Various sensitivity studies were conducted to find the ideal parameters that ensured good agreement between Griffin and Serpent. The main focus was to capture the required few-gr oup energy structure and spatial resolution to be used in the generation of the few-group parameters [13]

Due to the small size of system, the S8ER experiences high leakage (~30%). The high concentration of U -235 in the UZrH fuel makes the fast fission factor nearly 50% greater than that of a Pressurized Water Re actor (PWR). The traditional Hansen-Roach 16 few-group structure is adopted [13] in our study. However , a slight modification to the Hansen-Roach structure is made by inserting more groups specifically at the low end and high end to ensure the structure spans the entirety of the spectrum Table 3.

Table 3. Modified Hansen-Roach 18 Few-Group Structure.

	Modified Hansen-Roach	**Original Hansen-Roach**
Group Number	Lower Energy Limit (MeV)	Lower Energy Limit (MeV)
1 (fast)	2.00E+01	1.00E+01
2	1.00E+01	3.00E+00
3	3.00E+00	1.40E+00
4	1.40E+00	9.00E-01
5	9.00E-01	4.00E-01
6	4.00E-01	1.00E-01
7	1.00E-01	1.70E-02
8	1.70E-02	3.00E-03
9	3.00E-03	5.50E-04
10	5.50E-04	1.00E-04
11	9.70E-05	3.00E-05
12	3.00E-05	1.00E-05
13	1.00E-05	3.00E-06
14	3.00E-06	1.00E-06
15	1.00E-06	4.00E-07
16	4.00E-07	1.00E-07
17	1.00E-07	2.50E-08
18	1.00E-08	----------
19	5.00E-09	----------

The ENDF8 cross section library is used for the addition of 0 Kelvin cross sections which is important since the experiment is conducted at ambient temperature (294 K) [15]. The ENDF8 library also featured improvements in thermal scattering data for UZrH and new thermal scattering for several materials that are present in the S8ER. Previous work determined this to be essential for good agreement with experimental data [4].

For the spatial homogenization scheme, concentric rings inside the active core region are layered for a total of 8 active fuel ring regions. The fuel, ceramic, gap, cladding, and air regions are homogenized over the hexagonal lattice element as seen in Fig. 4. The outer ring of peripheral air does not contain any fissile material and thus separated in its own region. The internal reflector, barrel and external reflector regions only contain one material hence no error is introduced by homogenization. The homogenization effects of ring regions were shown to not introduce significant error and were sufficient in this study. It must be noted that the spatial homogenization scheme must be recreated exactly in the unstructured mesh geometry to enforce preservation of mass and reaction rates in individual regions.

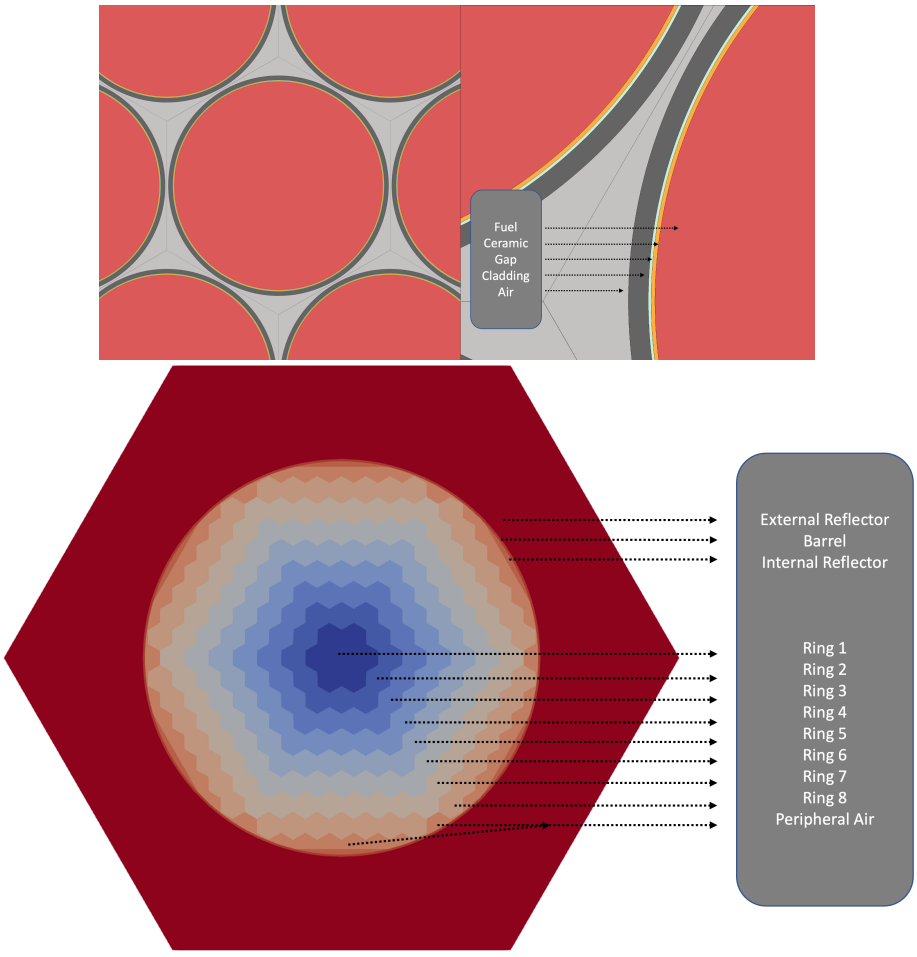

Figure 3. Serpent Model with Homogenized Universe Mapping.

3.3 Generation of Unstructured Mesh

As stated previously the unstructured mesh geometry must follow exactly the spatial homogenization scheme for proper preservation of reaction rates and mass. Due to complexity of the reactor geometry, Coreform Cubit is used with its python interface which allows easy integration into scripting workflows and exodus format support [12]. The ability to export meshes with tailored parameters directly into the exodus format is key for working in the MOOSE environment. The mesh seen in Fig. 4 is composed of only trishell3 elements because these are the most capable of reproducing irregular geometry without severely increasing the element count. The triangular scheme is tailored for each region such as to not introduce any sharp gradients in element size between regions. The current mesh consists of 3000 elements and 6000 nodes which is relatively coarse for a 2D core. Although the unstructured mesh follows the homogenization scheme exactly there is still slight error in the volumes determined by the reference serpent model and griffin model. Volume correction factors are included however, the effect is very minimal being the factors are near unity; still, they are included for completeness.

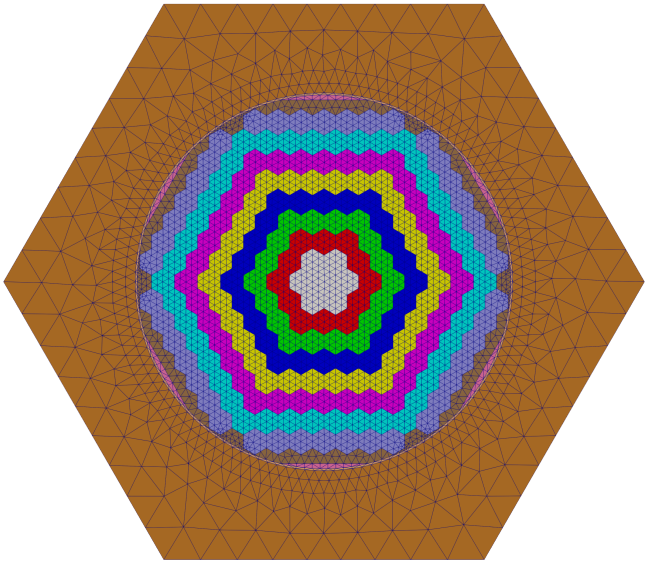

Figure 4. Cubit Unstructured Mesh Geometry.

3.4 Griffin DFEM-SN Transport Solver Parameters

The DFEM-SN solver is a discontinuous finite element based discrete ordinates transport solver. The quadrature scheme used in the problem is Level-Symmetric (LS) as opposed to Gauss-Chebyshev (GC), while Gauss-Chebyshev has advantages such as being able to independently set the number of polar and azimuthal angles, this feature is best employed in 3D geometries where the neutronic behavior can be peaked in either axis for efficient angular discretization. Since the problem is 2-dimensional, Level-symmetric is suitable with the quadrature order being S-30 implying ((AQ *(AQ+2))/2) or 480 discrete directions, AQ being quadrature order. The order of anisotropy is set at 1 implying linearly anisotropic scattering, results show that the contribution of the 1st order scattering moments are only significant in a couple of the higher energy groups and overall have very little effect such that order of anisotropy can be reduced to zero. Th

e solver is set as an eigenvalue problem using the modified Hansen Roach 18 few-group structure with va cuum boundary conditions at the outer edge of the external reflector as in the reference serpent model.

Table 4. Griffin DFEM-SN Transport Parameters.

Parameter	Value
Quadrature Order	30
Degree of Anisotropy	1
Quadrature Scheme	LS
Geometry	2D
Boundary Conditions	Vacuum
Problem Type	Eigenvalue
Number of Groups	18
Inner & Outer Iteration Sweep Tolerance	1E-06

4. RESULTS

The DFEM-SN solver in conjunction with the asynchronous parallel sweeper implemented in Griffin for the inversion of the streaming operator allows to efficiently perform neutron transport calculations in a parallel fashion on an unstructured mesh [11]. Various few-group spatial flux distributions are illustrated in Fig. 5 where 2 representative thermal and fast groups are mapped on the mesh. The typical thermal reflector bump is best seen in group 16 and the expected very center peaked flux is best observed in group 2.

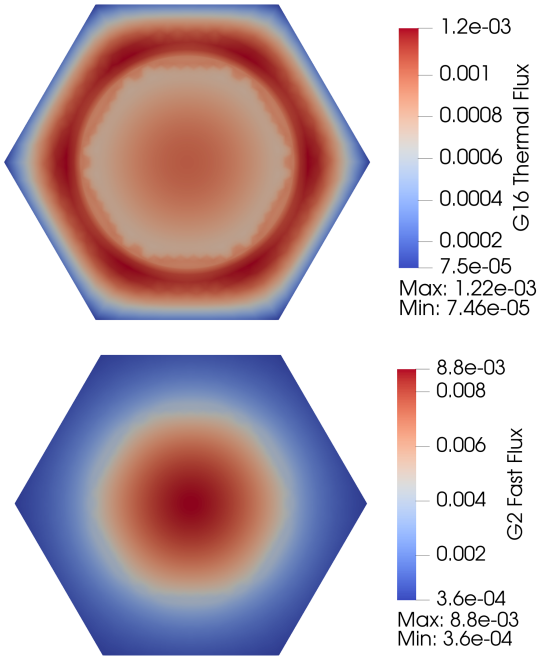

Figure 5. Griffin Few-Group Spatial Flux Distributions.

Results indicate agreement within ±3σ between the Serpent reference and Griffin effective multiplication factor in Table 5. The system effective multiplication factor is the one of the measures that will be used to quantify the fidelity of agreement between Serpent and Griffin. The few-group spectrum will also be compared where they are overlayed in Fig. 6. There are some discrepancies specifically in the lower end thermal region and in the fast resonance region. Comparing the L2 norm of each respective spectrum, the difference is 2.653% which requires further investigation in the future but is deemded acceptable for this preliminary stage.

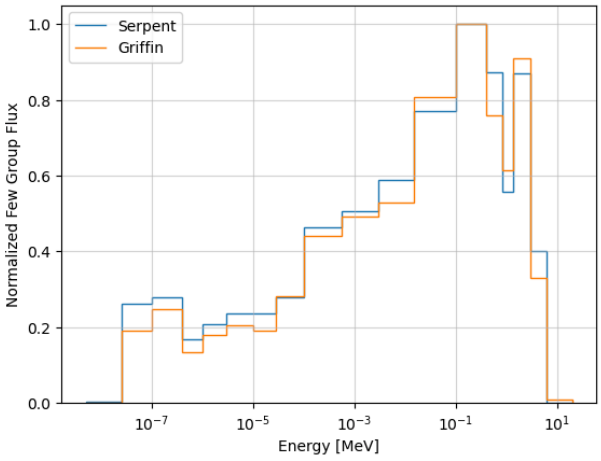

Figure 6. Griffin Radial Power Distribution.

Table 5. Serpent-Griffin S8ER Results

Parameter	**Value**
Serpent Effective Multiplication Factor	1.14195
Serpent Effective Multiplication Factor Uncertainty (PCM)	7
Griffin Effective Multiplication Factor	1.14171
Reactivity Difference (PCM)	18.30
L2 Norm Difference (%)	2.653

5. CONCLUSION & FUTURE WORK

Current work has developed a 2D model for the S8ER C3 Criticality Configuration using the 2-stage Serpent-Griffin approach with results showing good agreement with the reference Serpent model. The models presented in this paper are hosted on the open source snapReactors database [3] [16] and the Virtual Test Bed [5]. This paper is an initial assessment, which will then be followed by 3D modeling to be compared against the S8ER criticality experiments for various configurations with varying fuel element pattern loading, control drum orientation, and control element worth. These models will then be used to validate the full 2-stage Serpent-Griffin model and develop a generalized methodology for

microreactor applications.

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