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Introduction

Argonne National Laboratory (ANL) and INL have developed a GRIFFIN steady state neutronics model for the multiphysics simulations of the Kilopower Reactor Using Sterling TechnologY (KRUSTY) microreactor in the Multiphysics Object Oriented Simulation Environment (MOOSE). The reliability of such deterministic neutronics models can be validated by comparing with computations from Monte Carlo codes (e.g. MCNP, SERPENT, OpenMC, Shift, etc). Furthermore, potential modeling/design improvements can be identified by incorporating uncertainty quantification (UQ), which can be performed by MOOSE's Stochastic Tools Module (STM).

KRUSTY is a prototype for a 5-kW thermal nuclear-powered space reactor [1]. Its primary components consist of nuclear fuel, heat pipes, a control rod, a reflector, and the shielding (see figure 1) [1]. The fuel consists of 3 stacked U-7.65Mo cylinders with a hole in the center for the control rod [2]. 8 liquid sodium heat pipes transfer fission energy from the solid fuel block to the Sterling power conversion system where the energy is extracted, and the cooled sodium flows back to the core via capillary action [1]. The movable Boron Carbide control rod regulates the neutron population during startup or when a reactor temperature boost is needed [2]. The beryllium oxide reflector is in 3 places in the reactor; it surrounds the core axially, it lies beneath the core on a platen, and it is present in the shim [2]. The axial and lower reflectors rest on an adjustable stainless-steel platen that moves upward to cover the fuel and help the reactor reach criticality [2]. Lastly, radial stainless steel surrounds the core offering protection from radiation exposure [1].

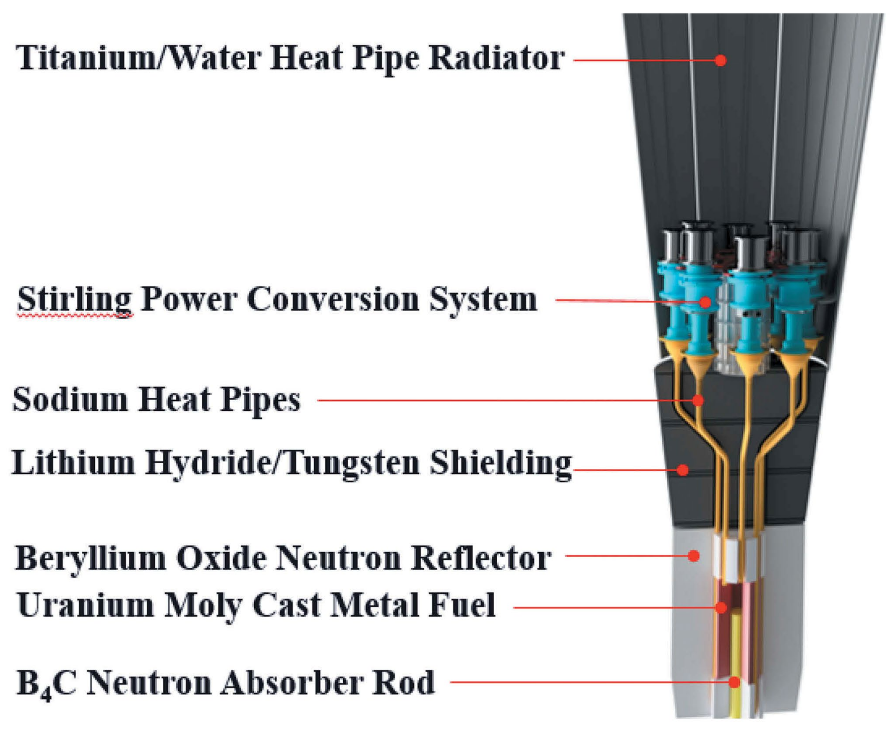

Figure 1: Breakdown of the KRUSTY reactor Design [1]

Methods

GRIFFIN is a multiphysics module in MOOSE that performs neutronics calculations in steady-state or transient environments by leveraging other moose-based applications such as BISON (Fuel Performance), Relap-7 (Nuclear Systems Safety), and Sockeye (Heat Pipe Simulator) [3]. GRIFFIN performs these computations using the linearized 3D Boltzmann Transport Equation. To do this, GRIFFIN requires a cross sections library of all relevant materials for multiple temperatures within the range of interest [3]. GRIFFIN can then interpolate those cross sections as necessary. The cross-section library was generated using SERPENT and MC^2-3.

A GRIFFIN single physics neutronics model was utilized in this work. Neutronics computations were performed on the KRUSTY reactor design at varying structural and fuel temperatures. Fuel temperatures ranged from 300K to 1200K while structural temperatures ranged from 300K to 1000K. To validate the model, eigenvalue (k-eff) outputs were compared with SERPENT output data for comparison. The goal is to capture similar behavior in the eigenvalues as the fuel temperature increases. Next, Uncertainty Quantification was conducted using MOOSE's Stochastic Tools Module by sampling 100 sets for the fuel temperature and the surrounding structural temperature by means of Gaussian and Uniform Distributions. For the Gaussian Distribution, the fuel temperature average was set to 700K, while the structural average temperature being 350K. Both contained a 5% standard deviation. For the uniform distribution, the bounds for the fuel were set between 300K and 1200K while the structural bounds were set between 300K and 1000K. 100 samples from the Gaussian Distribution set were collected to form 100 input cycles to measure their impact on the power density of the outer fuel ring. This was repeated for the Uniform Distribution. The UQ setup is also described for each case in table 1. The fuel mesh is divided into 7 rings for radial measurements and the outer (7th) fuel ring is the last layer that borders the cladding (structural materials). Figure 2 illustrates the radial fuel subdivisions.

Run	Parameters	Distribution	Features
	Fuel Temperature	Uniform	Range: 300K-1200K
1	Structural temperature	Uniform	Range: 300K-1000K
	Fuel Temperature	Gaussian	Mean: 800K, St Dev: 5%
2	Structural temperature	Gaussian	Mean: 350K, St Dev: 5%

Table 1: Summary of UQ setups for Uniform and Gaussian Distributions

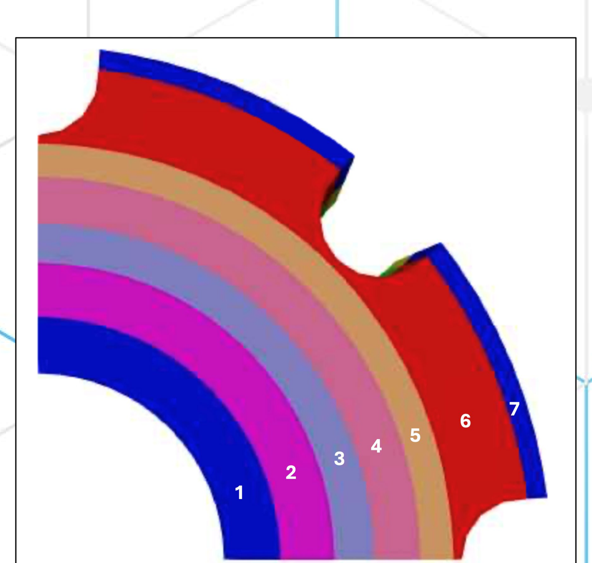

Figure 2: Quarter image of KRUSTY fuel with the fuel discretized into 7 radial layers for UQ Assessment.

Results

Figure 3 shows the results for the eigenvalues calculated at various fuel and structural temperatures. Overall, the data points between the SERPENT model and GRIFFIN model are consistently within 1% of their respective counterpart, suggesting strong agreement between the models.

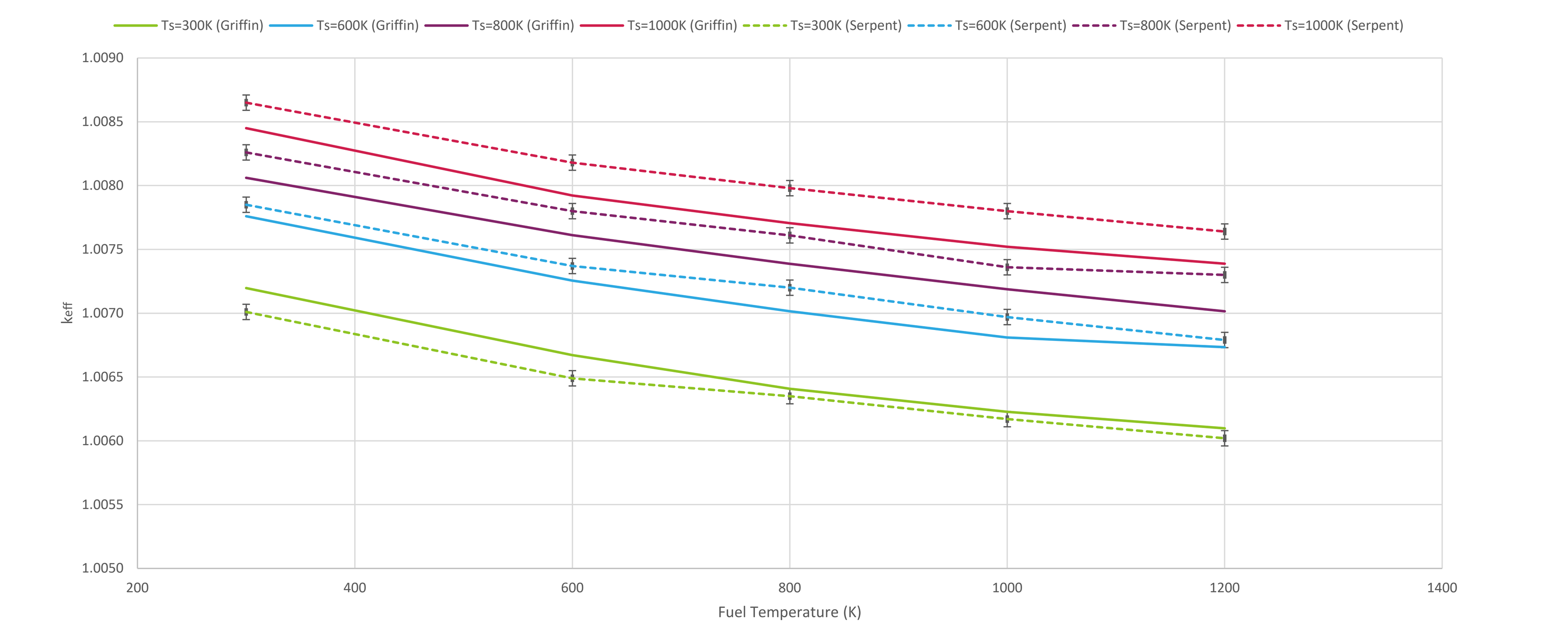

Figure 3: Graphical comparison of eigenvalues (keff). across varying fuel and structural temperatures between GRIFFIN and Serpent programs.

For UQ, figure 4 illustrates the mean values as well as the 99% confidence range for the Uniform and the Gaussian Distribution data. The confidence range is scaled up by a factor of 100 for visualization purposes. The results exhibit significantly larger power uncertainties in the two outer layers of fuel compared with the inner layers, indicating that large temperature variations in the KRUSTY reactor may cause unstable power in the outer fuel layers, which may also impact on the radial reflector integrity.

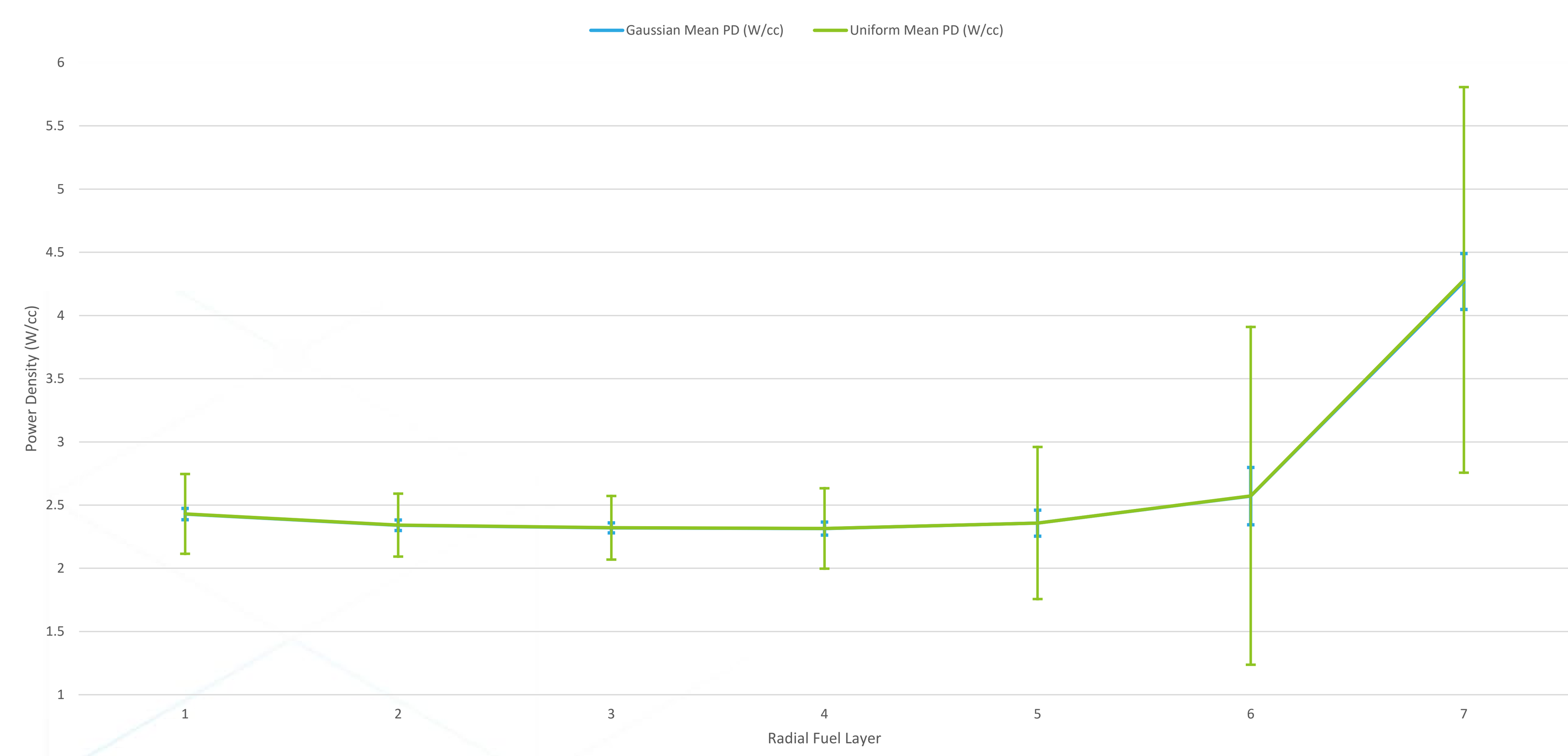

Figure 4: Average power density distributions across fuel layers with 99% confidence interval for uniform and gaussian fuel and structural temperature distributions. The confidence interval is scaled up by a factor of 100.

Conclusions

Neutronics analysis was performed on the KRUSTY microreactor model in the GRIFFIN neutron transport solver. Eigenvalue comparisons to the Serpent model across varying temperatures suggested high agreement between the two. UQ was utilized to investigate how reactor fuel/structural temperature variations impact on the core power distributions. The higher uncertainties on powers in the outer radial layers indicate unstable powers in these zones with the large temperature variations, which may also impact on the radial reflector integrity.

Future Work

With validation complete on the neutronics model and parameter studies complete using MOOSE's Stochastic Tools Module, work can now be aimed at incorporating more complex physics into the model. Such physics will begin with assessing material plasticity in steady state and transient environments by making use of the BISON fuel performance module in MOOSE. This can then be further improved upon by modeling thermal behavior in KRUSTY's heat pipes by incorporating Sockeye into the now multi-physics KRUSTY reactor model. Each implemented step, of course, will also need to make use of uncertainty quantification and sensitivity analysis to improve model confidence and further provide a framework for future optimization.

References

[1] Poston, David I, et al. KRUSTY Reactor Design, 31 Jan. 2020.

[2] KRUSTY Multiphysics Model Description.

[3] DeHart, Mark, et al. Griffin: Reactor Multiphysics Application Available from INL Software. Idaho National Laboratory, https://inlsoftware.inl.gov/product/griffin.

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