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A Comprehensive Uncertainty Quantification Methodology for High Fidelity Multi-Physics Simulation of Sodium-cooled Fast Reactors

PI: Dr. Xu Wu, North Carolina State University (NCSU)

Collaborators:
Dr. Maria Avramova (NCSU)
Dr. Yang Liu (Texas A&M University)
Dr. Ling Zou (Argonne National Laboratory)
Dr. Som Dhulipala (Idaho National Laboratory)

Advisors:
Dr. Joshua Kaizer (US Nuclear Regulatory Commission)
Dr. SuJong Yoon (TerraPower)

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ABSTRACT:

The objective of this proposal is to develop a comprehensive uncertainty quantification (UQ) methodology for high fidelity multi-physics simulations. This methodology integrates prior knowledge, inverse UQ results from the calibration domain, and quantitative validation results from the validation domain, to improve results in the prediction domain where there is little experimental data available. This method is comprehensive in the sense that it simultaneously accounts for all major sources of quantifiable uncertainties in modeling & simulation (M&S), i.e., uncertainties from parameters, experiment, model, and code. It combines M&S, experimentation, and scientific machine learning (SciML) into a unified approach to improve the predictive capabilities of computational models, with robustly established uncertainty estimations for safety parameters of interest thus enabling trustworthy regulatory licensing calculations. By bridging the gap between model and data, this method can reduce the reliance on expensive measurement data for validation, which is especially important for advanced nuclear reactor M&S development.

The proposed methodology is general and applicable to any type of computational tools. In this project, we will demonstrate it for both single physics and high-fidelity multi-physics simulations of sodium-cooled fast reactors (SFRs) using the SAM code. We will focus on SFR case studies with the aim to predict the complex behavior of SFRs during accident transients with uncertainty. These applications can support the development and deployment of new SFR designs such as the Natrium reactor by TerraPower. The proposed work will complement the existing NEAMS efforts by providing a rigorous technical basis to bridge the gap between models and data. Successful completion of the project will enhance the predictive capability of the high-fidelity multi-physics simulation tools developed within NEAMS and beyond. The collaboration with the senior advisors from US NRC and TerraPower will ensure practical applications of the developed methodology from regulatory and industrial perspectives.

The outcomes of the proposed work can be summarized as: (1) a comprehensive UQ methodology that integrates prior knowledge, inverse UQ and quantitative validation to improve M&S predictive capability with established uncertainties; (2) more complete theories for Bayesian inverse UQ and quantitative validation metrics; (3) generally applicable methodologies for UQ of ML models when they are extrapolated outside of the training domain; (4) demonstration of the develop methods on high-fidelity single and multi-physics simulations with a focus on NEAMS code SAM, for licensing calculations of SFRs, under the guidance of advisors from US NRC and TerraPower; (5) demonstration of the MOOSE STM capabilities for the calibration, validation, and model selection given complex high-fidelity multi-physics simulations; (6) three graduate students trained with relevant topics supervised by the university co-PIs at NCSU and TAMU, and (7) publications in conference proceedings and journals.