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Development and Application of a Data-Driven Methodology for Validation of Risk-Informed Safety Margin Characterization Models

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ABSTRACT

The proposed project aims to develop and demonstrate a data-driven methodology for validation of advanced computer models used in nuclear power plant safety analysis. Specifically, the advanced computer models are those in the toolkit developed to support risk-informed safety margin characterization (RISMC), an integrated deterministic/probabilistic safety analysis methodology developed in the Department of Energy's Light Water Reactor Sustainability (LWR-S) program.

The project envisions that the new validation methodology for safety analysis codes will build upon the U.S. Nuclear Regulatory Commission's Code Scaling, Applicability and Uncertainty (CSAU) methodology, and its subsequent regulatory guide NRC 1.203 on "Transient and Accident Analysis Methods", also known as Evaluation Model Development and Assessment Process (EMDAP). The resulting methodology, called Risk-informed EMDAP, should meet requirements of the RISMC methodology. The proposed project will bring to bear advanced methods and tools in verification and validation (V&V), sensitivity, and uncertainty analysis to facilitate the implementation of already demanding EMDAP in a risk-informed application.

One major challenge in validation is a lack of relevant data, including lack of confidence in the applicability of models and their supporting data in prototypical reactor conditions. In addition to this, the computational and methodological limitations of previous eras led to a reliance on human judgment that can now be reduced. It is not that we no longer need data: rather, nowadays, it is possible to improve the use that we make of data we have (or can obtain). In particular, a new physics-guided validation strategy based on first principles will rigorously map and bound simulation errors in the domain of intended model use. To our knowledge, this represents a first-of-a-kind approach in the determination of the validation domain in the nuclear engineering community, and one that presents a significant shift from the current one based on expert-determined scale distortion uncertainties. This is what we mean by "data-driven."

In addition, in order to bridge the remaining gap in data, the project will investigate and advance (i) a decision-theoretic framework for predictive capability maturity quantification; (b) techniques for simulation-based scaling for evaluation of applicability of experiments and determination of the validation domain; (c) reduced order modeling techniques to enable uncertainty quantification; (d) data-driven multi-scale integration that enables effective use of "big data" generated by advanced experiments and validated computational simulations; (e) a validation data plan as a dynamic risk-informed instrument to guide the design of experiments and simulation, and (f) a validation data management system that makes use of the Nuclear Energy Knowledge-base for Advanced Modelling and Simulation (NE-KAMS) infrastructure.

The project team will apply the developed validation methodology to guide the validation of computer models for flooding hazard analysis and system thermal-hydraulics analysis. Respectively, the RISMC tools are (1) a Smoothed Particle Hydrodynamics computer code NEUTRINO used in the LWR-S program for flooding simulation, and (2) the RELAP-7 reactor system simulation code developed at the Idaho National Laboratory. The RISMC application scenarios are (1) storm-surge–induced flooding and (2) a flooding-induced extended station black-out accident. In both cases, the RISMC models are applied to study a selected class of accident scenarios, for which sources of errors and uncertainties and predictive capability gaps are identified. Methods and tools of sensitivity, uncertainty, and scaling analysis are applied to guide the development of a verification and validation plan, including the validation data plan. The latter identifies and characterizes existing and available data and databases, and defines requirements for data to be obtained experimentally and computationally. Validation experiments (e.g., fluid dynamics, and fluid-structure interactions, turbulent mixing, and thermal stratification) and high-fidelity computer simulation ("numerical experiments") will be formulated, designed, built, and operated to produce data for validation of the respective RISMC tools. Lessons learned by means of the two applications will serve as useful feedback for refining the proposed methodology and associated techniques.

Broadly, the proposed methodology will enable the RISMC models to provide a prediction of plant safety characteristics with associated uncertainty, which are crucial in the RISMC decision-making process. It will also serve as an instrument to coordinate the R&D program for validation of RISMC models, supporting the continued safe operation of existing nuclear plants, and to guide much needed efforts to modernize reactor safety research. The proposed research is an opportunity to provide valuable input for guiding the development of the RISMC methodology and the RISMC toolkit, with the recognition that V&V should not be an afterthought. The information-guided decision-theoretic based approach proposed in this project can actually assist by ranking the relevance of data for a particular RISMC scenario and thereby guiding management of resources for future experimental and computational studies, and progressively using advanced numerical simulations to greatly increase the value of experiments.

The project will bring together a team of university, industry, and national laboratory researchers with an established track record of cross-institutional and multi-disciplinary collaboration. The project will leverage the strong presence of team members in the relevant DOE R&D programs, including the Nuclear Energy Knowledge and Validation Center (NEKVaC), and their connections to standards, methods and guidelines committees, and the community of practice. Through a comprehensive educational plan, the project will contribute to nurturing a science-based safety analysis paradigm.