



**UNITED STATES
NUCLEAR REGULATORY COMMISSION**
WASHINGTON, D.C. 20555-0001

Grant # 31310021M0044

Grantee: Kansas State University

Title of Grant: Statistical Learning Based Multiscale Safety Analysis Framework for Advanced Reactors

Period of Performance: 9/27/2021-9/26/2024 (FY2021 Notice of Funding Opportunity NOFO)

Executive Summary

The main objective of this proposed work is to provide an experimentally validated multiscale approach for safety analysis of advanced reactors, that will be valuable in licensing and regulation. Current techniques for system analysis lack capabilities in resolving detailed 3D thermal hydraulic behavior that are critical for the design and performance evaluation of advanced reactor candidates. The risk evaluation and uncertainty envelop of safety features in advanced reactors are highly dependent on complex physics in contrast to probabilistic failure rates of engineered safety features in existing reactors. Therefore, accurate physical depiction in system analysis tools is essential for risk quantification. This project will result in a statistical learning-based coupling mechanism between multiscale models – one-dimensional (1D) system level models and detailed 3D Computational Fluid Dynamics (CFD) simulations of advanced reactor systems for safety analysis. This coupled framework will be implemented with System Analysis Module (SAM) and Nek5000, which are part of NRC's Comprehensive Reactor Analysis Bundle (BlueCRAB). It will be demonstrated on two test cases relevant to advanced reactors such as liquid metal (sodium fast reactors - SFRs) and high temperature gas-cooled reactors (HTGRs). The existing experimental capabilities at KSU will be used for validating 1D/3D coupled models. KSU will develop closure relations for multiscale coupling and obtain validation grade experimental data, while VCU team will lead the CFD simulations and SAM development scope.

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Presentations and Publications

The list of publications was submitted with the final report after grant expiration.

1. *Journal article:* Ross, Molly, Ling Zou, and Hitesh Bindra. Numerical Simulation and Experimental Comparison of System Analysis Module 1D Mixing Model for Cold Shock Transients in the Gallium Thermal-Hydraulic Mixing Facility. *Nuclear Technology* (2024): 1-14.
2. *Journal article:* Gomez, Andres, Molly Ross, and Hitesh Bindra. "Network Graph Laplacian-Based Sensor Projection in System-Level Modeling of Liquid-Metal Loop." *Nuclear Technology* (2024): 1-16.

3. *Journal article: Sieh, Broderick, and Hitesh Bindra* Effect of geometry on the evolution of DLOFC transients in high temperature helium loop. *Progress in Nuclear Energy* 169 (2024): 105042.
4. *Journal article: Matulis, John and Hitesh Bindra* Thermal field reconstruction and compressive sensing using proper orthogonal decomposition. *Frontiers in Energy Research* 12 (2024): 1336540.
5. *Journal article: Molly Ross, Hitesh Bindra*, Development of a subgrid-scale model for Burgers turbulence using statistical mechanics-based methods. *Physics of Fluids* 35.12 (2023).
6. *Journal article: Brendan Ward, Hitesh Bindra*, Characterization of thermal stratification using validated liquid metal pool mixing models, *Accepted for publication in International Journal of Heat and Mass Transfer* (2023)
7. *Conference Proceeding: T. Chu, T. Franklin, and L. Carasik*, "LES at Low Richardson Number to investigate Thermal Stratification in SFRs Upper Plenums", Advanced Reactor Safety Embedded Topical Meetings in the 2024 ANS Annual Meeting
8. *Conference Proceeding: T. Chu, T. Franklin and L. B. Carasik*, "LES at Low Richardson Number to Investigate Thermal Stratification in SFRs Upper Plenums," ANS student conference April 2024, State College, PA – Awarded Best Presentation Award in Thermal Hydraulics (G)
9. *Conference proceeding: Andres Gomez, Molly Ross, Hitesh Bindra*, Discrete Element Simulation of Thermal-Fluidic Transport in a Packed Spherical Particle Bed, Transactions of American Nuclear Society, November 2023
10. *Conference Proceeding: Molly Ross, Ling Zou, Hitesh Bindra* Validation of System Analysis Module axial mixing model for thermal stratification and mixing application in the upper plenum of a liquid metal reactor, Accepted for NURETH 2023 (Invited for special issue journal article on SAM validation)
11. *Conference Proceeding: Molly Ross, Xu Chu, Hitesh Bindra* Early Prediction and Classification of Heat Transfer Degradation in Coolant Channels using Kramers-Moyal Coefficients, *Accepted for PSA 2023 meeting (Molly Ross invited for student award competition)*
12. *Conference Proceeding: ANS student conference, T. Chu and L. B. Carasik*, "Large Eddy Simulations of Channel Flow with one Heated Wall for Liquid Metals and High Temperature Gasses," April 2023, Knoxville, TN
13. *Conference Proceeding: ASME international Conference of Nuclear Engineering, Molly Ross, John Matulis, Hitesh Bindra*, A Statistical Approach to Quantify Taylor Microscale for Turbulent Flow Surrogate Model, 2022 (Molly Ross received best paper award)
14. *Conference Proceeding: ANS student conference, Molly Ross, Hitesh Bindra*, Statistical surrogate for high-fidelity turbulent channel flow, April 2022, Urbana, IL (Molly Ross received best paper award)
15. *T. Chu, Molly Ross, Hitesh Bindra, L. B. Carasik*, "Large Eddy Simulations of Low Prandtl Channel Flow with One Heated Wall for Developing Data-Driven Stochastic Emulators," *Transactions of the American Nuclear Society*, November 2022

16. *T. Chu and L. B. Carasik, "Large Eddy Simulations of Channel Flow with one Heated Wall for Liquid Metals and High Temperature Gasses," Accepted for NURETH 2023 Lightning Talk*

Patents

N/A