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Development of an Advanced Computational Fluid Dynamics Technology for the Next-Generation Nuclear Reactor System Analysis and Safety Margin Characterization Code

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ABSTRACT

The objective of the proposed research effort is to develop, apply, and implement an advanced computational fluid dynamics (CFD) technology that can be used in a next-generation computer code for design and safety analysis of advanced nuclear energy systems. The proposed work will directly support the development, implementation, verification, and validation of a modern nuclear reactor system safety analysis project termed R7 that is currently under development at Idaho National Laboratory (INL). Current reactor safety simulation tools like TRAC, RELAP5, CATHARE, TRACE, etc., have served the role of reactor safety simulation effectively for the last thirty years. They fit well with the types of reactors they were designed to work on and the way that those reactors were licensed. However, for new reactors, new licensing approaches, risk mitigation procedures, and simulation tools will need to be developed to address these new requirements. Unlike the old-generation safety simulation codes, R7 extends beyond what is normally thought of as thermal hydraulic, includes much more of the physics of a nuclear reactor coupled into a single solution algorithm, and incorporates the most advanced algorithmic developments. The R7 is designed to be the best at providing a complete system simulation with the required level of accuracy (reduction in uncertainty) to make an important decision about a nuclear reactor's safety. The advanced CFD capability is a central feature in R7, enabling high-quality engineering analysis of Next Generation Nuclear Plant reactor designs in a timely manner with the potential for improved safety margin characterization.

The research work will further develop, improve, implement, verify, and validate a reconstruction-based, discontinuous Galerkin method in a complex configuration environment that will be used and incorporated as the CFD component of R7. This higher-order spatial-temporal fully implicit RDG method will provide significant improvements in both accuracy and efficiency, compared to today's state-of-the-art second-order methods, and is well aligned with the philosophy of the multi-fidelity simulations. To accomplish this objective, the following goals will need to be achieved: (1) develop an efficient scheme for discretizing diffusion terms, (2) develop efficient time integration algorithms for unsteady problems, and (3) develop an efficient numerical method for the solution of the nonlinear system of equations as a result of a higher-order implicit temporal discretization in the Jacobian-Free Newton-Krylov (JFNK) framework. This higher-order RDG-JFNK method will be able to perform accurate simulations for high fidelity simulations where higher-order solutions are deemed to be absolutely necessary, (such as Direct Numerical Simulation, Large-Eddy Simulation, Detached-Eddy Simulation) and for simulations where the classical second-order methods are doomed to fail due to too much inherited numerical dissipation. It will offer significant improvements in performance over its finite-volume or finite-element counterparts in low-fidelity simulations, such as Euler or Reynolds-Averaged Navier-Stokes simulations, where a second-order method has proven sufficient and accurate. The successful development, implementation, and integration of this higher-order (>2nd) RDG

method in R7 will open previously unimaginable opportunities to tackle a variety of complex flow problems in nuclear engineering. This ultimately enables the three-dimensional predictions of the key components of system thermal-hydraulics in the next generation computational engine for nuclear reactor system analysis and safety margin quantification to be computationally efficient and physically adequate.