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Integrating Thermal Hydraulic Simulation and Experimentation with Data-Driven Methods to Support Molten Salt Reactors Development

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ABSTRACT:

The nuclear engineering community is now focusing on developing advanced nuclear reactors to fight climate change and reduce carbon emission. Among multiple concepts, the molten salt reactors (MSRs), including fluoride salt-cooled high-temperature reactor and liquid-fueled molten salt reactor, are promising candidates. To support the development and deployment of MSRs, nuclear thermal hydraulics (T-H) faces both challenges and opportunities. These opportunities stem from advancements in algorithms and technologies that enable nuclear T-H to produce comprehensive data through both experimentation and simulation. A primary challenge, however, remains: the data generated are not fully harnessed due to existing gaps between the coarse-grained nuclear code, experiments, and high-fidelity simulations. As a result, the coarse-grained codes such as SAM and Pronghorn still have unsatisfactory fidelity with unquantified uncertainty when applied to the design and licensing of MSRs.

This proposal aims to address these challenges with a transformative analysis framework for T-H research. This framework employs various data-driven methods, ensuring the integration of experimentation and modeling and simulation (M&S) to support MSR development. The proposed framework includes three core thrusts:

> Thrust 1: Efficient Multiscale Modeling and Simulation (M&S) capability: coarse-grained T-H tools informed by high-fidelity simulations.
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> Thrust 2: Digital twin augmented experimentation: integrating a physical facility with its digital model to obtain whole system status including unmeasurable quantities of interest.
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> Thrust 3: Two-way integration between T-H M&S tools and experiments: experimental measurements inform simulations to reduce model discrepancies, and simulation results guide experiments to generate high-value data.

Leveraging the framework, applications will be developed to 1).enhance efficiency via heat exchanger optimization, 2). reduce excessive safety margins through accurate transient analysis, and 3). support licensing and regulatory development through risk-informed analysis. Each of these topics is crucial for the development and deployment of MSRs.

The framework promises a transformative paradigm shift in T-H studies by integrating experimentation with simulation. It accelerates data generation by leveraging methods such as deep neural networks, Gaussian processes, Bayesian optimization, and inverse Bayesian inference. A distinct advantage of this framework is that it avoids the typical "black-box" usage of data-driven models. Instead, data is derived directly from M&S and experimentation, ensuring that the underlying physics is preserved throughout the process. Consequently, this approach promises to expedite the development and deployment of MSRs by delivering reliable data more swiftly. Following a proven track record with MSR applications, this pioneering framework can be expanded to benefit other advanced nuclear reactor designs, including sodium fast reactors and high-temperature gas reactors.