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## Digital Twins for 4D Spatiotemporal Prediction of Advanced Reactors

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### ABSTRACT:

The goal of this project is to develop digital twins for 4D spatiotemporal prediction of key operational parameters and structural health conditions of advanced reactors, with a focus on early detection of anomalous strain and temperature in metallic piping and vessels, which are indicators of microcracks, thermal fatigue, and other degradation mechanisms. The digital twin will fuse information from thermal hydraulic and structural health monitoring sensors, as well as physics-based models. This will be achieved by strategically combining the power of direct robotic 3D conformal sensor printing for real-time on-demand data acquisition and a novel "data+physics"-based deep learning framework for rapid predictive simulation and live model-data fusion. The digital-twin model aims to significantly enhance the design and predictive capabilities, operational efficiency, and safety measures of advanced reactors. The proposed project offers several significant advantages over current approaches, including (1) Enhanced Sensing Accuracy through Conforming Printing Features; (2) Superior Spatial and Temporal Measurement Resolution; (3) Direct Printing and Integration of Multiple Sensor Materials for Multimodal Sensing; (4) Novel Physics-Integrated Neural Differentiable Modeling Framework; (5) Uncertainty Quantification (UQ) and Active Learning for Optimal Sensor Placement. To achieve our goal, we will perform three major tasks: Task 1: Autonomous robotic printing of self-powered wireless multimodal sensors; Task 2: Development of digital twin models via physics-integrated machine learning; Task 3: Demonstration, testing and validation of the digital twin model.

The success of this project will lead to a paradigm shift to create innovative methods and capabilities for real-time data acquisition and assimilation, modeling and simulation, advanced sensor manufacturing, monitoring and control for advanced nuclear reactors. The adaptive direct sensor printing and intelligent placement presents a unique approach to acquire the most informative real-time data in places where real-time data is difficult to obtain via conventional sensing technology. The novel physics-integrated neural differentiable model proposed here is capable of seamlessly integrating the physics-based PDE solvers and deep learning models via differentiable programming to significantly improve the efficiency over conventional numerical modeling while reducing the amount of required data for machine learning.

The proposed digital twin technology has crosscutting impacts on a broad range of DOE-NE programs. The predictive digital twin model will provide fundamental understanding of the fluidic flow dynamics, structural mechanics and the complex interplay between the fluid and structures, which will facilitate design innovations and optimizations of both existing plants and accelerate the development of a range of advanced reactor concepts. The digital twin model will further enable real-time diagnosis, prognosis, and predictive maintenance of critical and costly components, extending the operational period and reducing the overall operational cost of nuclear power plants. The project will provide opportunities for workforce training to graduate and undergraduate students on advanced sensor and instrumentation, advanced manufacturing, and digital twin technologies for nuclear science and engineering.