EXPECTED REAL VALUE PROVIDED BY A DIGITAL TWIN IN THE DEVELOPMENT OF THE eVINCI™ MICROREACTOR


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INTRODUCTION

The eVinci microreactor utilizes heat pipes for cooling and can produce up to 5MWe with a 15MWt core design. The fuel utilized in the eVinci microreactor is TRISO fuel. The TRISO-fueled reactor core is designed to run for eight or more full-power years before refueling, and the factory-built and assembled reactor can be shipped in a container to provide versatile, scalable energy for a variety of applications. See Figure 1 for a schematic of the reactor design. Unlike most current reactor designs, the eVinci fuel is contained within a graphite core block and is designed for inherent, passive safety as well as the capability to support microgrid integration. However, being contained in a solid graphite core block creates some additional issues such as accessibility of in-core sensors. A digital twin initially based on simulation results allows for a clearer picture of the physics in the core since in-core sensors are challenging to insert into the design.

Figure 1. Conceptual design of the eVinci microreactor.

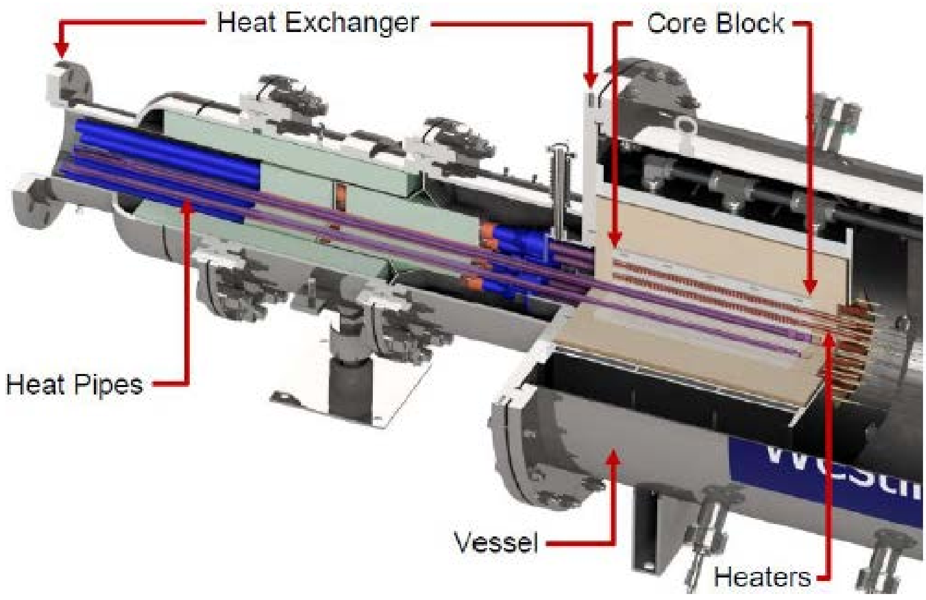

Figure 2. eVinci microreactor Electrical Demonstration Unit (EDU).

To support the development of this design, integral effects testing (experimental facilities) has been identified as necessary. The Westinghouse Electrical Demonstration Unit (EDU), shown in Figure 2, was constructed and is currently being operated as a demonstration and testing environment to validate various assumptions of the eVinci microreactor thermal system. The facility uses a single unit cell core block with 24 electrical heaters, 7 heat pipes and 31 temperature sensors. An air-cooled heat exchanger removes heat from the heat pipes in a manner similar to the eVinci microreactor design. Outside the core block, there are multiple other sensors related to the heat exchanger and other supporting equipment.

A digital twin of the EDU has been developed to demonstrate real-time predictive and analytic functionality when synchronized with data during its operation. The EDU was built and tested prior to the twin's development, so the twin has been developed using existing simulation and test data. Initial reduced-order models (ROMs) that correlate predicted measurements at sensor locations with key operational parameters (independently controlled test conditions such as heater power and heat exchanger flow rate) were solely based on full-physics simulations using the DireWolf suite of codes. DireWolf, which combines Nuclear Computational Resource Center (NCRC) applications like Bison (nuclear fuel performance), Griffin (neutronics calculations), and Sockeye (heat pipe modeling), is based on the MOOSE platform developed by Idaho National Laboratory. It includes sub-models for reactor physics, thermal behavior, fuel, and heat pipes.

The implementation of a digital twin for the EDU has several immediate techno-economic benefits as well as several potential long-term techno-economic benefits. The benefits listed below will be discussed in more detail in the following sections.

Immediate techno-economic benefits:

- Methodology to develop a digital twin to optimize the cost of future digital twin development.
- Reduction in the number of sensors required in future test facilities and/or reactors.

Potential long-term techno-economic benefits

- Reduction in the required number of personnel on site.
- Improved condition monitoring (reduction in maintenance costs).
- Improvement of fuel utilization.
- Capability for continuous operational improvement.

DEVELOPMENT AND APPLICATION OF DIGITAL TWINS FOR THE eVINCI MICROREACTOR

Broadly speaking, a digital twin integrates sensor data with pre-computed analyses to better understand, control, and predict the reactor's behavior in near real-time. This technology creates a virtual replica of the physical system, allowing for continuous monitoring and optimization. By simulating various scenarios and conditions, digital twins can provide valuable insights into performance, maintenance needs, and potential issues before they occur.

To achieve this, one key component is the ROM, a simplified version of a complex model that captures the essential behavior of a system using fewer variables and/or equations. To build a ROM for a digital twin application, either historical data or simulation data is needed. For these new reactor designs, there is no historical data available, so simulation is used as a starting point. One can pre-compute many simulations and then extract input data associated with sensor locations (heat pipe temperature, electrical heater power, heat exchanger flow rates, etc.) and the output data (temperature at select locations within the core block), and then develop a ROM which defines a correlation between them.

Digital twins are often comprised of many sensors placed on many different physical components, each simulated by

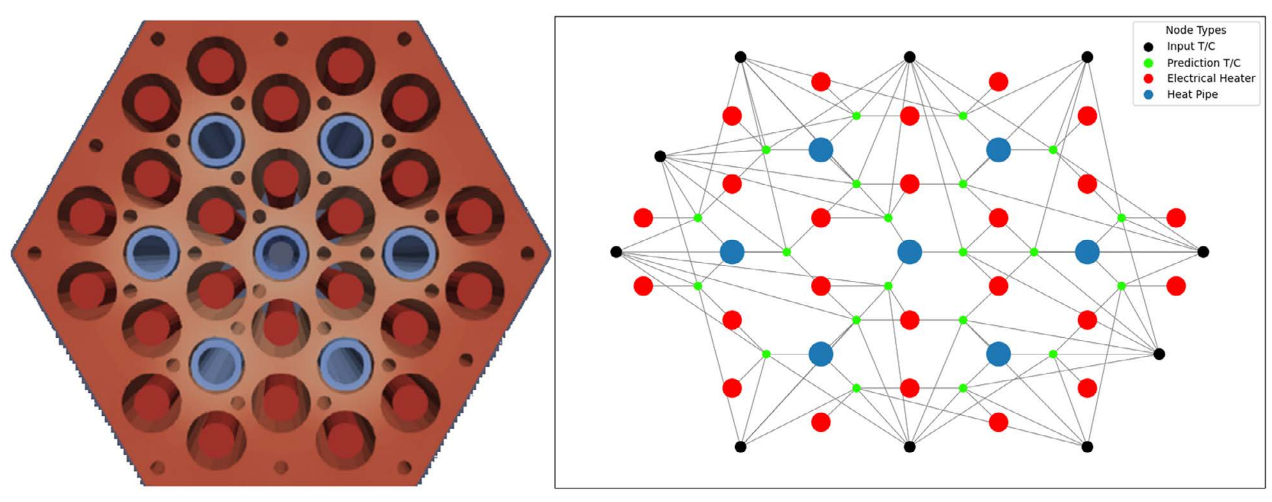

Figure 3. Representation of the EDU full-physics predictions (left) and graph neural network (right).

one or more computational models. In theory, all components can be set up to communicate with and inform one another as part of the digital twin framework. Since this work is focusing on an experimental facility, the number of components is somewhat limited. However, for full reactor systems, the number of components can be quite large, so it was desirable to simplify the approach/methodology of this proof-of-concept twin. Accordingly, the initial twin for the EDU was defined to be made up of a single machine learning (ML)-based ROM, to be utilized for prediction of a pseudo-steady-state (i.e., at any given snapshot in time) two-dimensional temperature distribution on a plane within the EDU single unit cell core block. For the initial twin, the collection of 31 unique core block thermocouple (T/C) locations were divided into a set of prediction versus input locations, representing locations for which the model would predict temperature and locations for which a measured T/C temperature would be provided as input to the model, respectively. This methodology allowed for an explicit evaluation of ROM performance according to both simulation results and empirically measured data and provided a framework to demonstrate potential cost savings associated with a ROM which required fewer physical sensors but maintained appropriate fidelity in core block temperature predictions. Additionally, it also allowed investigation into how predictions could be calibrated according to incoming sensor data using a hybrid ROM approach which leveraged both simulation and measurement data.

Figure 3 shows a representation of the temperature distribution predicted in a full-physics simulation and the relative locations of the thermocouples, heat pipes and electric heaters on a plane of the single unit cell core block along with some of the connections between these elements in the graph neural network (GNN) utilized for the ROM of the EDU. The heaters and heat pipes (heat removal) can potentially affect the response of each of the thermocouples, although the localized response tends to be dominated by the nearest heat pipe due to the very high axial conductivity. For this reason, a heat pipe opposite from a point on the unit cell has limited influence, allowing for a relatively simple GNN.

The initial form of the EDU ROM relied exclusively on full physics DireWolf simulations to form the training database. As shown in Figure 4, the ROM predicts the experimental data with accuracy equivalent to the simulations; this demonstrates that the ROM has successfully been trained with the data and forms an adequate representation of the full-physics simulation. Known modeling simplifications, such as the use of nominal geometries and the assumption of full symmetry, lead to the expected differences between both the ROM and DireWolf simulation, and the real-world experiment test data.

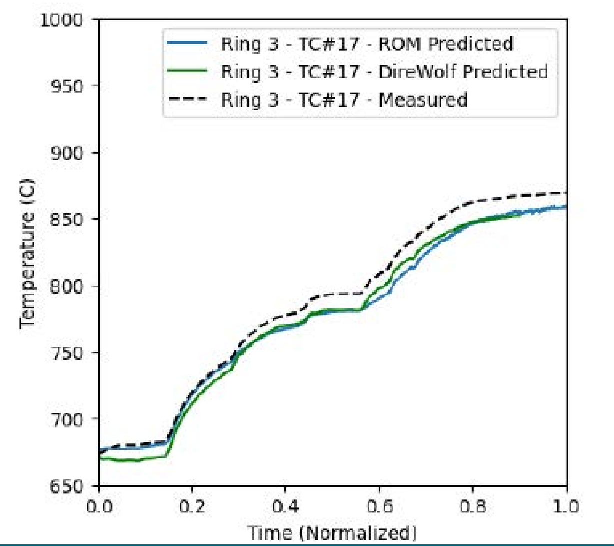

Figure 4. Comparison of simulation-based ROM, simulations, and measurements.

This work provides an evaluation of potential tools that could be utilized to construct a digital twin, as well as an assessment of the economic benefits associated with twin development.

Immediate Economic Benefits

Building a digital twin from 'scratch' is a costly and time-intensive effort if adequate guidelines are not available. Decisions on what platform to use, what is the best software, how to create the Reduced Order Models (ROM), and how to couple the streaming data to the digital twin are just some of the issues that need to be addressed in order to create a functional digital twin. This ARPA-E sponsored work has identified an appropriate platform, the best software options, evaluated a ROM creation process, and methods to couple the streamed (live) data into the digital twin. It is expected that following the best practices that were developed as part of this project, the cost for building an equivalent digital twin would be offset by the expected financial benefits. Even assuming only a 50% reduction in effort to build a future digital twin based on these best practices would imply a more significant cost savings for every twin developed/applied.

During the development of the ROM for the EDU digital twin, it was discovered that about 2/3 of available core block thermocouples were not needed to develop enough fidelity in the ROM to accurately predict thermal response of the EDU. For the design of the eVinci microreactor, it is expected that each heat pipe in each hexagonal unit cell will have a separate sensor. The hexagon will have either six or seven heat pipes and there are hundreds of hexagons. By using a digital twin, the number of sensors for each hexagon could be reduced. Assuming one less sensor per hexagon, this amounts to a large savings in design, installation, maintenance, and monitoring.

Potential Long-Term Economic Benefits

A digital tool allows condition monitoring which involves the comparison of the sensor signal with the expected value considering the output of an algorithm (trained with historical values) using the current value of the rest of the sensors. The deviation (if higher than a given margin) can be a consequence of an early stage degradation in a component. A process subject matter expert analyzes the deviation identifying potential actions in order to prevent failures that cause unavailability of the plant. A mature condition monitoring program allows for a predictive maintenance strategy, optimizing the maintenance costs while increasing the plant availability and reliability.

The envisioned application of the technology to the eVinci microreactor is shown in Figure 5, in which the digital twin with both reactor and supporting system ROM capabilities is used for real-time simulation of the operating facility conditions. Available instrumentation in the physical facility is used as input to the digital twin, including sparsely located core thermocouples, neutron flux sensors typically used for protection systems, and status feedback from the reactor control drums. Supporting power system parameters involving the reactor calorimetric heat balance, turbomachinery conditions, and grid interface information are used to inform reactor operating conditions.

With this information, the digital twin is utilized to create a surrogate representation of the detailed conditions within the reactor, providing far more information than is available from the physical measurements. Conditions within the block can be inferred, detailed fuel utilization history can be calculated, and anomalies with respect to equipment performance such as those which could arise in the heat pipes can be detected. Furthermore, digital twin capabilities can be tuned to as-built geometries and operating environments of individual reactors, and data can be collected and analyzed across an entire fleet. Two main outcomes become possible from this insight; (1) identification of operational improvements which could involve proactive maintenance or changes to the operating strategy, and (2) more granular information available to operators (on-site and remote) for improved understanding of current conditions as well as detailed capability for forecasting the reactor's response to anticipated operating changes.

A digital twin allows an operator or subject matter expert to monitor the behavior of a reactor facility. It is conceivable that if a site has multiple eVinci microreactors, it is

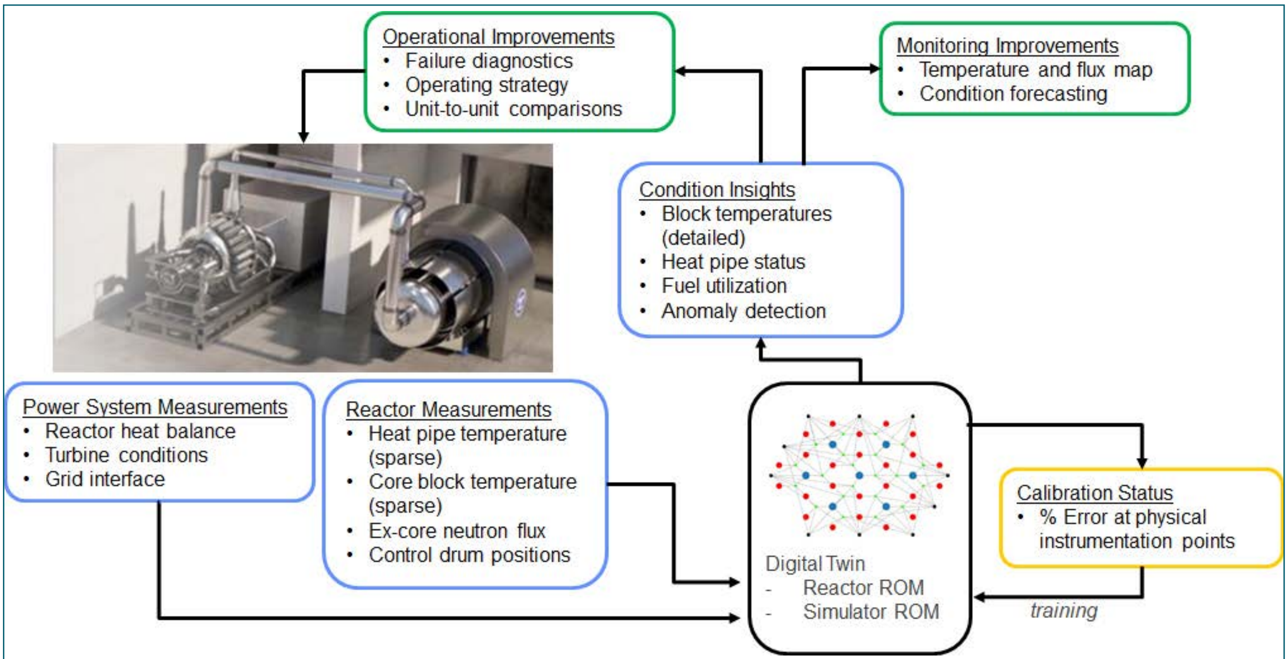

Figure 5: Digital twin technology as applied to the eVinci microreactor.

possible that one operator could monitor multiple reactors (through the digital twins). Reducing the number of operators staffing a site has a significant impact on the techno-economic benefits associated with a digital twin.

As with most reactors, a significant long-term cost is the fuel. While reactor physics is not yet currently incorporated in the digital twin being developed for the EDU test facility, it is envisioned that a digital twin with reactor physics could conceivably improve the utilization of fuel through optimized grid integration and more efficient control drum (reactivity) and temperature operating condition choices. A major advantage of the eVinci microreactor design is its ability to operate at a site without refueling for 8 to 10 years. Significant value is achieved by extending the core life through such optimization by better utilizing the fuel and thus reducing the net transportation and waste costs.

Figure 5 shows the vision for a deployed digital twin for the eVinci microreactor. Continuous adaptation of the twin will support operational and monitoring improvements by giving insights on various conditions within the reactor not otherwise directly measurable. The current work will be expanded to larger test facilities and eventually the eVinci microreactor itself. The future work will also attempt to incorporate additional capabilities such as fuel depletion and material degradation to further increase the value of a digital twin.

CONCLUSION

A digital twin provides several potential value streams, both near-term economic benefits and potential long-term economic benefits. The near-term benefits involve the development of a methodology to cost-effectively create a digital twin and the reduction in the number of sensors needed. Potential long-term benefits may involve the reduction in the number of personnel on site, improved condition monitoring, improved fuel utilization, and the capability for continuous operational improvement. This work sponsored by the ARPA-E MEITNER program has helped establish some approximate valuations for these value streams and has successfully demonstrated a proof-of-concept thermal digital twin at a test facility representative of the eVinci heat pipe microreactor. A conservative estimate from all the value streams mentioned above indicate that application of a digital twin (similar to the one in this work) to one or two new or similar units would immediately provide a positive net return on investment. ■