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Changing the World's Energy Future

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Modeling for a Digital Twin-Based Remote Operation System Framework

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INTRODUCTION

New reactor designs and technologies are being developed to grow and advance the nuclear industry, and microreactors are one of the many new concepts. Microreactors are very small reactors generally designed to have an operating power of 20 MWth or less. They are ideal for many applications in which it would not be feasible to have a large-scale reactor, such as powering remote communities, military bases, and mining sites. Many of these remote sites currently rely on diesel generators for power, and replacing those generators with the carbon-free energy of a microreactor is a major driving factor for microreactor development.

However, most of these use cases for microreactors are in isolated locations where construction and labor costs are high. Microreactors will need to be financially comparable to other energy production methods for their deployment to be successful. Remotely operating these microreactors has a great potential to benefit the economics and make it more cost competitive. With remote operations, the operation facility location could be strategically chosen based on factors such as construction costs and workforce size.

The benefits of remote operations could be leveraged even more if the remote operation system is semi-autonomous, allowing more microreactors to be operated and monitored from one remote operation facility. Additionally, with the system handling some tasks for the human operator, it could reduce the number of operating staff necessary for the microreactor. Digital twins can be used to introduce a level of automation to the remote operation system. Digital twins are capable of component monitoring, system operation and control, and predictive performance [1]. All these features are important for a successful semi-autonomous remote operation system.

Many other industries such as wind, oil and gas, and mining have already incorporated forms of remote monitoring and operation to reduce operating and maintenance costs [2–4]. However, the nuclear industry has heightened safety concerns and does not have any remote operation experience. The potential consequences of any failure in remote operations for a microreactor are higher than they are for other industries. A higher level of security and assurance in the integrity of the transmitted data is critical for the remote operation system of nuclear systems. The proposed framework mentioned in this summary uses digital twins in a novel way to add an additional level of security and assurance to a secure communication infrastructure.

DIGITAL TWIN-BASED CERTIFICATION SYSTEM

A major concern with remote operations in the nuclear industry is trusting that the information sent between the reactor and remote operations facility is accurate and secure. The digital twin-based certification system (DTCS) is a proposed system framework designed to address these concerns since it can be used in conjunction with a secure communications network infrastructure. The DTCS will use a novel implementation of two separate digital twins to provide an additional level of security and assurance that the information being distributed over the communications network is secure, accurate, and maintains integrity. Figure 1 shows the general architecture for the DTCS.

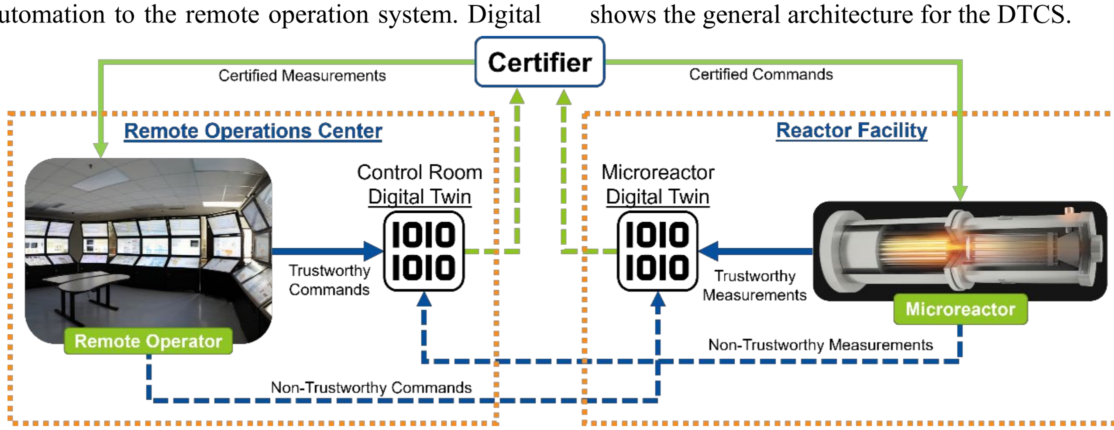

Fig. 1. General architecture of the DTCS [5].

For additional security and resiliency, the two digital twins are not identical models. The digital twin located in the control room (DT-CR) is a generic, fleetwide model of the microreactor and is intended to recreate the average behavior of the reactor in question. The DT-CR has a direct, local connection to the commands being sent from the remote operations center and receives sensor data transmitted over the communications network. The digital twin located in the reactor facility (DT-MR) is created to be representative of the specific microreactor housed within the facility and accounts for the uniqueness of the reactor such as specific manufacturing tolerances or maintenance differences. The DT-MR has a direct, local connection to the microreactor's supervisory control and data acquisition system and receives commands transmitted over the communications network. In Figure 1, there are "trustworthy" and "non-trustworthy" labels on the command and measurement connections. A direct, local connection is labeled as "trustworthy" because there is minimal opportunity for that signal to be altered or dropped during transmission. The information is labeled as "non-trustworthy" if it is sent over a communication network between the reactor and remote control facilities. This is because there is a chance it could have been altered, delayed, or dropped, and it has not gone through the certification process yet. With each digital twin having a more secure connection to one piece of the separated system, their results can be compared and used to assess the integrity of the information being transmitted over the communications network.

This paper focuses on the modeling done for the digital twins and how they will fit in with the rest of the framework for implementation of the system. More details of the DTCS and its operation are discussed by Kaeley Stevens, et al. [5]. Since the DTCS is a novel remote operations concept, it needs to be tested to demonstrate its functionality under normal and adverse scenarios.

TEST FACILITY

The DTCS is planned to undergo thorough simulated testing for normal as well as adverse operating conditions to prove its capability to add security to the remote operations process. Table I shows some of the simulated test scenarios.

TABLE I. Testing Scenarios.

Test Type	Testing Scenario
Abnormal physical conditions	A degraded/failed sensor input
Cyber-threat conditions	Man-in-the-middle attack
Unauthorized user	An unauthenticated command is sent

These tests will demonstrate the system's capabilities in scenarios that are possible concerns when working with a remote operation system. Additionally, the capabilities of the DTCS will be demonstrated in a physical test facility. Physical testing and demonstration can lead to insights beyond what can be learned from simulated testing. So, the DTCS is being developed for the non-nuclear Single Primary Heat Extraction and Removal Emulator (SPHERE) facility at Idaho National Laboratory (INL).

SPHERE is a test facility that studies the operation of a single heat pipe. The setup of the facility is as follows: there are six cartridge heaters placed within a hexagonal stainless steel core block surrounding the evaporator end of the heat pipe, a cross-sectional view of the core block is shown in Figure 2. The core block and adiabatic region of the heat pipe are surrounded with insulation, and a water-cooled gas-gap calorimeter is over the condenser region for heat removal. This is a simpler test facility, which is beneficial for remote operations proof of concept. It is a relatively safe system, therefore, there are no concerns with using a novel remote operations concept to control the system.

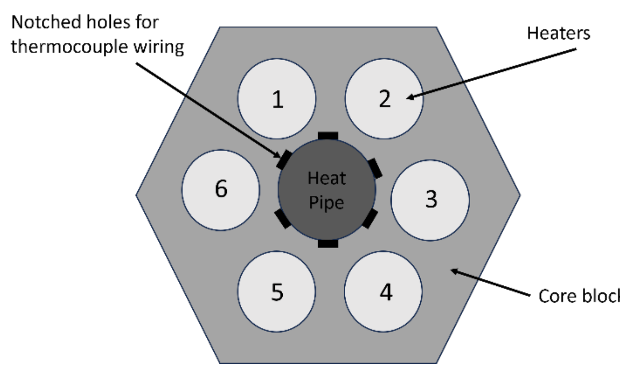

Fig. 2. Cross-sectional view of SPHERE

Transient scenarios are more ideal for testing the capabilities of the DTCS framework. This is because a remote operation and monitoring system is most useful during transient times, such as right after a command is implemented to change the state of the system. A sufficient body of transient data for SPHERE did not exist, so a set of tests was done specifically to guide the system through multiple temperature set points to collect transient data. Figure 3 shows the temperature set point profile that was used for testing.

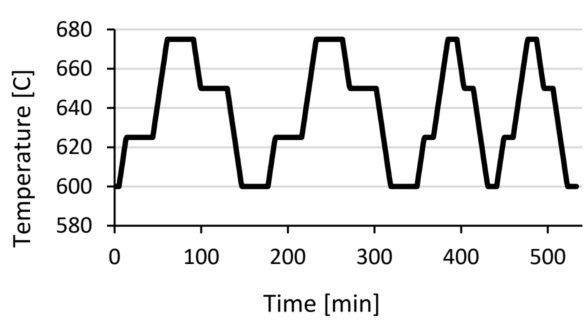

Fig. 3. Temperature profile for SPHERE transient data.

Modeling for the digital twins will be validated against data that were collected from these tests with SPHERE. The validated models will be incorporated with the rest of the system framework and then SPHERE will be brought through the temperature set points once more, but it will be controlled by the DTCS.

PHYSICS-BASED MODELING

INL's finite element framework, MOOSE (Multiphysics Object-Oriented Simulation Environment), is being used for the development of the physics-based modeling for SPHERE. Sockeye is a MOOSE-based application specifically for modeling heat pipes [6]. Sockeye's current capabilities for heat pipe modeling are transient one-dimensional (1-D), two-phase compressible flow or transient 2-D, axisymmetric heat conduction modeling. The 2-D axisymmetric heat conduction modeling method is being coupled with a 3-D model of the core block to simulate the behavior of a SPHERE test facility. The coupling of the 2-D heat pipe model with the 3-D core block is to model the power input conditions more accurately. This coupling is especially useful for properly modeling a scenario in which the heaters are applying an asymmetric heating profile around the heat pipe (e.g., one or more heaters losing power).

The heat conduction model approximates the heat pipe as a solid rod with a very high thermal conductivity. This method solves the governing transient heat conduction equation (eq. 1) everywhere (vapor core, wick, and cladding).

$$\rho c \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = q''' \quad (1)$$

Where T is the temperature, ρ is the assumed constant density, c is the assumed constant specific heat capacity, k is the temperature dependent thermal conductivity, and q''' is the volumetric heat source. Within Sockeye, the definition of thermal properties and boundary conditions are done in ways that attempt to incorporate thermal-hydraulic phenomena since they are not directly simulated.

The model takes the heater power as its input for the system and outputs the temperature along the length of the heat pipe.

Sockeye Model Verification

To verify the Sockeye model, a grid convergence index (GCI) study was performed to ensure that the results are independent of the mesh size. Three mesh sizes (coarse, medium, fine) were generated for this study. The coarse mesh had 70 elements, the medium mesh had 119 elements, and the fine mesh had 202 elements. The meshes need a grid refinement factor of 1.3 or greater to be considered acceptably different from one another [7]. The refinement factors for the coarse to medium grids and medium to fine grids were 1.304 and 1.302, respectively.

Temperature is the parameter of most interest for the Sockeye model, so the temperature results were used for the GCI study. The results of the GCI study can be seen in Table II.

TABLE II. GCI Study Results

Section	Grid	T [C]	Section Cells	GCI
Evaporator	Coarse	600.3	15	0.01%
	Medium	600.4	25	0.03%
	Fine	601.2	45	
Adiabatic	Coarse	211.5	29	3.73%
	Medium	215.7	50	2.23%
	Fine	218.2	75	
Condenser	Coarse	177.9	15	0.17%
	Medium	178.1	25	0.08%
	Fine	178.3	45	

The results show that the GCI between the medium and fine mesh is 0.03%, 2.23%, and 0.08% within the evaporator, adiabatic, and condenser regions, respectively. Generally, a GCI of 5% or less is accepted for the results to be considered mesh independent. Since the GCI for each section of the heat pipe is less than 5%, the medium mesh size can be used for the simulations moving forward.

For further model verification, the Sockeye model monitors for linear and nonlinear convergence. The nonlinear convergence is defined by absolute and relative tolerances, both of which are defined as 1e-8. The linear convergence criterion is defined as 1e-3. Monitoring these features ensures that the simulation has properly converged.

INITIAL SOCKEYE MODEL RESULTS

The Sockeye modeling is still under development but has already shown promising results within the evaporator region with steady-state input data from the SPHERE setup. Table III shows the plotted comparison of the simulated evaporator temperatures to the experimental data. Thermocouple location 1 is closest to the endcap of the evaporator and 4 is closest to the adiabatic region.

TABLE III. Evaporator Result Comparison

Thermocouple Location	Avg. Simulated T [C]	Avg. Experimental T [C]	Percent Error
1	547.50	522.87	4.71
2	545.20	562.76	3.12
3	541.89	579.08	6.42
4	537.52	583.43	7.87

The largest percent error between the simulated and experimental results within the evaporator region is roughly 8%. This is promising for a model that is still undergoing improvements. Limitations in Sockeye's current modeling capabilities contribute to this error, but ongoing work includes adjustments to better represent realistic system conditions (e.g., system heat losses).

The adiabatic and condenser sections rely more heavily on boundary conditions to match the temperature profiles and therefore are more difficult to accurately model. This is partially because the gas-gap calorimeter over the condenser cannot be explicitly modeled, and therefore boundary conditions need to be tuned to replicate the realistic heat extraction process as closely as possible.

DATA-BASED MODELING

In addition to the physics-based Sockeye modeling, there will be data-based models incorporated with the DTCS digital twin architecture. These data-based models are intended to be used for predictions and to confirm that the data transferred over the communications network are representative of the actual state of the physical system.

Regression analysis will be used for the data-based modeling. Regression analysis can predict dependent variable values based on known independent variable values. Regression is a common analysis method and is useful for predicting continuous processes.

Within the DTCS, the regression models will use a sparse set of data to predict the full system state. The predicted results will be compared to the full set of raw data from the physical system. This comparison will be used to assess whether the system is behaving as expected. If the predictions and raw data do not match, then the remote operator will be notified of the need to execute diagnostic procedures.

USE OF MODELS IN THE REMOTE OPERATIONS SYSTEM

The combination of both physics-based models and data-based models will be used to create the digital twins for the DTCS. The Sockeye models will be used to simulate the effects of a desired command and assess whether that command is safe for the system to implement. The regression models will be used to confirm that the data seen by the remote operator are an accurate representation of the physical system's current state.

The models and the comparison of their results to each other and to the raw data are crucial for providing additional assurance in the integrity of the information being transmitted over the communications network. The novel implementation of two separate digital twins allows for the digital twins to work as an additional tool for identifying system anomalies. Each digital twin will have a physics-based and data-based modeling component. These models will interact with the raw system data, the operator commands, and the human machine interface.

ENDNOTES

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