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Changing the World's Energy Future

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DEVELOPMENT AND DEMONSTRATION TESTBED FOR THE REMOTE OPERATIONS AND MONITORING OF MICROREACTORS

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ABSTRACT

The nuclear industry is rapidly developing many advanced-reactor concepts for near-term deployment in both traditional and non-traditional nuclear-powered applications. One such category of advanced reactor is the microreactor, a class of reactor with less than 20MWth power output, intended for applications where the economics or logistics of traditional power sources are difficult. This includes applications such as remote communities, mining sites, defense installations, or humanitarian and disaster-relief missions. One key enabling feature for the successful deployment of microreactors is a remote operations capability. Remote operations provide monitoring and control capabilities which can significantly reduce staffing costs by eliminating the need for licensed operators at each reactor facility and improve the economic viability for microreactor deployment. A remote concept of operations is not currently an established capability in the nuclear industry. In addition, no demonstration microreactor is expected to complete construction or go critical until at least 2026. This leaves two major capability gaps: the successful demonstration of a remote concept of operations for microreactors and a test bed suitable for said demonstration. Both gaps must be addressed in order to advance the remote concepts of nuclear operation and, more broadly, microreactors themselves from paper to reality. This paper aims to fill these gaps and describes a test bed that would support development and deployment of a remote concept of nuclear operations, initial experimental results from that test bed, and the application of the test bed and experimental results for a digital-twin-based remote concept of operations under development at Idaho National Laboratory (INL). The platform chosen as a remote concept of nuclear operations test bed is the Single Primary Heat Extraction and Removal Emulator, known as SPHERE, located at INL. SPHERE is a small-scale non-nuclear test bed that emulates thermal behavior of a microreactor. The small-scale and non-nuclear nature of SHPERE limit safety concerns associated with remote operations while still providing the physical response representative of a microreactor. A network connection was added to SPHERE that enables remote-monitoring capability. This allows for real-time data streaming to networked workstations, data historians, and human-machine interfaces (HMIs). These are all critical components in a remote concept of operations, thus providing a robust development and demonstration platform. An initial experiment was performed using the SPHERE remote operations testbed. This included running a comprehensively instrumented SPHERE through a series of steady-state and transient operating scenarios in both normal and abnormal operating conditions, all while streaming live test data to a remote HMI and data warehouse. This initial experiment served three purposes: (1) characterizing the response of SPHERE, (2) demonstrating the remote connection to SPHERE, and (3) providing a baseline data set for development of a digital-twin-based remote concept of operations that is under development at INL.

Keywords: Microreactor, Remote Operations and Monitoring, Digital Twin

1. INTRODUCTION

1.1 Motivation for Microreactors

Microreactors are a class of advanced reactors that are designed to operate with a power output of 20 MWth or less [1]. The small size of the reactors will allow for them to be more-easily transported to the operating site. The concept of microreactors stemmed from the desire to provide stable, carbon-free power to applications in which current large-scale plants are not feasible—for example, providing power to remote communities, mining sites, and military bases. Many of the potential use cases for microreactors currently rely on diesel generators for power—e.g., most of the rural communities in Alaska [2]. Remote communities around the world are burdened with the high fuel costs and negative environmental impacts of relying on diesel generators for power. Replacing those generators with a microreactor, or a microreactor solar/wind hybrid plant, is a key benefit of microreactors and a driving force in their ongoing development.

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1.2 Remote Operation Motivation

Microreactors are faced with a unique set of challenges for operation because most ideal applications are in remote locations. There is significant uncertainty with development costs for these regions [3] and a smaller workforce to support operations. Thus, it is anticipated that building, staffing, and operating a microreactor facility in these isolated communities will be more expensive. Remotely operating the microreactor has the potential to provide significant economic benefits to its deployment. Remote operation would provide the capability to strategically choose the site for a remote operations facility based on different factors: such as construction costs and workforce size for a given area. Remote operation would also reduce the construction that is needed at the reactor site because a full onsite operating facility would not be necessary. Having the remote operation system be semi-autonomous provides even more economic benefit to microreactor deployment. With some of the actions being performed by the machine instead of a human operator, it is possible to increase the number of microreactors being monitored and operated from one remote operations facility. A semi-autonomous remote operations system could further reduce the staffing that is necessary for operation. These many capabilities of remote operation make a very important contribution toward microreactors' cost competitiveness, especially during their early deployment.

1.3 Remote Operations Digital-Twin Certification System

Other industries currently use remote monitoring and operation systems to reduce operating costs and system downtime [4–6], but the nuclear industry has heightened safety needs that have prevented the implementation of remote operation systems. The Digital Twin-based Certification System (DTCS) is a remote-operation framework developed at INL that is designed to work with a secure communication infrastructure to provide an additional layer of security and assurance for information transferred between the reactor site and remote-operation facility. Full detail of the DTCS can be found in [7], but a summary is provided below. The general architecture for the DTCS is shown in Figure 1.

The DTCS has two separate digital twins that are not identical models. The digital twin located in the remote operations center, referred to as the control room digital twin (DT-CR), is a general, fleet-wide model of a given microreactor and is constructed based on the microreactor design's nominal parameters. The DT-CR receives the commands implemented by the operator directly over a local connection, and receives its sensor data via transmissions over the communication network. The digital twin in the reactor facility, referred to as the microreactor digital twin (DT-MR), is made to be representative of the specific microreactor that is on site, and the model will incorporate the features unique to that reactor—e.g., where precisely the dimensions fall within the manufacturing tolerances. The DT-MR directly receives sensor data from a local connection to the supervisory control and data acquisition system, and receives operator commands over the communication network. With each digital twin having a hardwired, trustworthy connection to one piece of the separated system, comparison of their results can be used to verify and validate the information being transferred between facilities. The certifiers, one located in the control room facility and one located at the microreactor, are used to assess the outputs from each digital twin and the microreactor sensor data to determine whether these outputs meet a set of certification criteria. Meeting the criteria indicates that the information exchanged between the facilities is authentic, safe, and accurate.

For the DTCS, implementing an operator-issued command at the microreactor begins by sending the command to both DT-CR and DT-MR. Upon reception of the desired command, both digital twins simulate the effect of the intended command. Once both digital twins have simulated the future state of the microreactor based on the command, the outputs will be sent to the microreactor certifier for comparison. The microreactor certifier will use criteria, such as trend detection and parameter tolerances, to determine whether the simulation results match. Passing this stage of certification shows that the digital twins were simulating the same command; i.e., the command was securely transmitted over the communication network without any interference. The microreactor certifier will check to ensure the predicted state is within safe operational bounds for the reactor. After meeting all of the criteria, the command action is considered to be certified and can begin to be implemented by the microreactor.

Additionally, the digital twins and control room certifier are used to ensure that the sensor data being viewed by the remote operator is authentic and accurate. Each digital twin will receive separate sparse sets of the data as inputs to predict the expected full state of the reactor. The control room certifier will assess the digital twin-simulated results and the full set of sensor data against a set of criteria for comparison. If the results and raw data match, it can be concluded that the transmitted data are trustworthy and accurate. The certified data will be displayed on the human machine interface (HMI) in the remote-operation center for consumption by the operator. In the case of failed certification, the operator is alerted and diagnostic started to identify the cause of the issue and wheter it is a problem with the reactor, the digital twins, or the communication infrastructure.

The novel use of two separate digital twins allows for the DTCS to provide more security, resilience, and assurance to the information being transmitted over the communication network.

1.4 Remote Operations Testbed

Because it was desired to evaluate the DTCS through physical testing of the system, a physical test bed was required, and INL's Single Primary Heat Extraction and Removal Emulator (SPHERE) [8] was chosen as the evaluation platform. SPHERE is a small-scale non-nuclear test bed that emulates thermal behavior of a microreactor. The small scale and non-nuclear nature of SHPERE limit safety concerns associated with remote operations while still providing certain physical behaviors representative of a microreactor. Because of the very limited safety risks of SPHERE, it serves as an excellent test bed for proof of concept testing for remote operation, a concept of operations new to the nuclear industry. The first step to build SPHERE into a remote operations test bed for the DTCS is to characterize the test bed in order to validate the models that reside within the DTCS digital twins as well the sensors installed in SPHERE. In addition, a remote operations system should be able to identify and respond to abnormal operating conditions. Therefore, abnormal operations

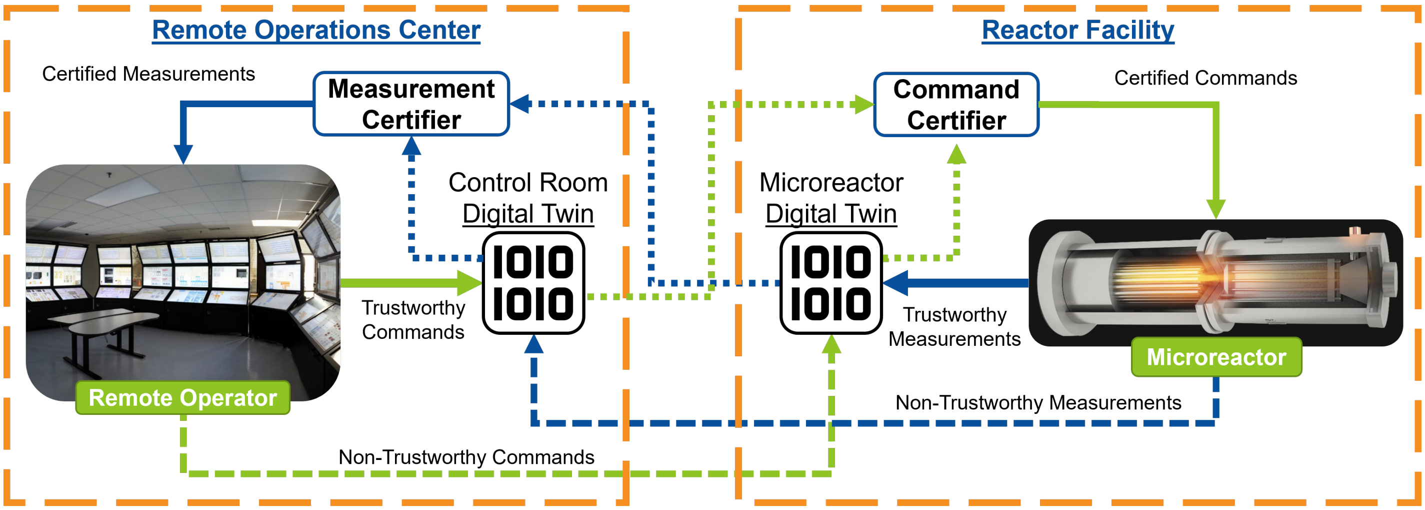

FIGURE 1: Digital Twin Certification System Architecture [7]

of SPHERE must be characterized. Finally, a remote connection and data-storage infrastructure need to be added to SPHERE. This paper summarizes an initial remote operations experiment of SPHERE that (1) characterized the response of SPHERE in normal and abnormal operating conditions, (2) demonstrated the remote connection to SPHERE, and (3) provided a baseline data set for development of a digital-twin-based remote concept of operations that is under development at Idaho National Laboratory.

The remainder of the paper is organized as follows: Section 2 details the SPHERE test bed and the remote-monitoring capabilities added to SPHERE for this test. Section 3 covers the testing plan for the experiment. Section 4 reports the test results from the experiment. Section 5 explains the applications for the test results for the development of the remote operations system. Finally, section 6 discusses the planned future activities for the DTCS development and the remote operations test bed.

2. REMOTE OPERATIONS TESTBED

2.1 SPHERE Overview

SPHERE is an INL facility that tests the operation of a single heat pipe that is heated via a core block containing embedded heaters. The general system layout is shown in Figure 2. The evaporator region of the sodium-filled heat pipe is surrounded by a stainless steel, hexagonal core block. The core block also houses six cartridge heaters; the layout of the heaters is shown in Figure 4. A water-cooled gas-gap calorimeter is installed over the condenser end of the heat pipe for heat removal. All of these components are enclosed within a stainless steel tube, which is either filled with an inert gas or made into a vacuum. For this project, a vacuum was created within the capsule.

2.2 SPHERE Instrumentation Plan

The temperature instrumentation package consisted of 43 type-k thermocouples (TCs) within various locations in SPHERE. Sixteen TCs were mounted on four faces of the core block — Faces A, B, C, and D as shown in Fig. 4 — , with four TCs per face located axially at Locations 1, 2, 3, and 4 as shown in Fig. 3. The second set of 16 TCs consisted of four Type

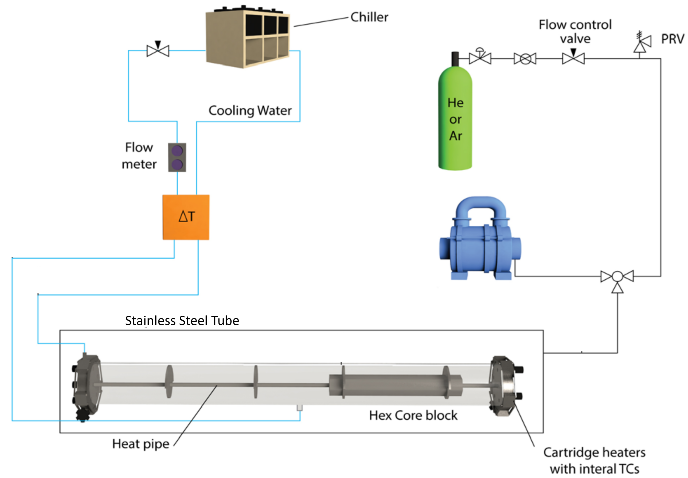

FIGURE 2: SPHERE system layout.

K multipoint thermocouples, each with four axial measurement locations at Points 1–4, given in Fig. 3, that were inserted into notched Holes E, F, G, and H surrounding the heat pipe, as shown in Fig. 4. A group of four TCs were used to monitor the outer-wall temperature of the adiabatic section of the heat pipe. These are referred to as the Group J TCs and were mounted axially along the heat pipe at Locations 5–8, as shown in Fig. 3. Six TCs monitor heater temperature, with one TC embedded in each heater (I–VI). Finally, a single TC was placed in the ambient space within the SPHERE chamber to record the ambient temperature of the nitrogen surrounding the SPHERE core block and heat pipe.

In addition to the temperature-instrumentation package, a strain-measurement package was included in the test setup. A strain gauge was installed on both remaining faces without TCs, as shown in Fig. 4. Strain Gauge 1 has an operating temperature range of up to 500°C while Strain Gauge 2 has an operating temperature range of up to 750°C. It should be noted that the expected operating temperatures of SPHERE exceed that of Strain Gauge 1. This is an intentional decision in order to introduce a

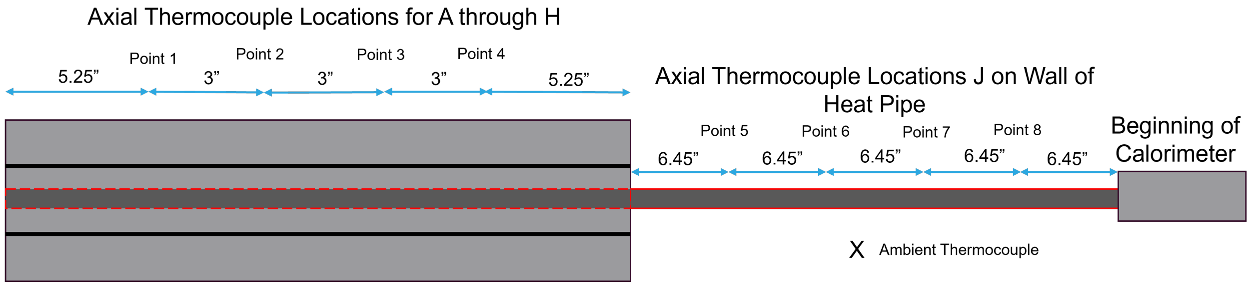

FIGURE 3: SPHERE instrumentation layout: front view

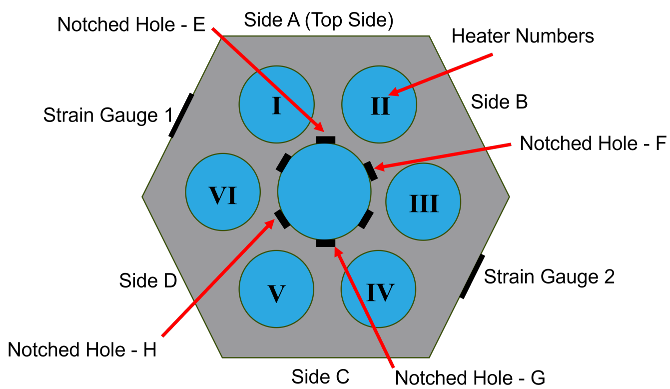

FIGURE 4: SPHERE instrumentation layout: Front View

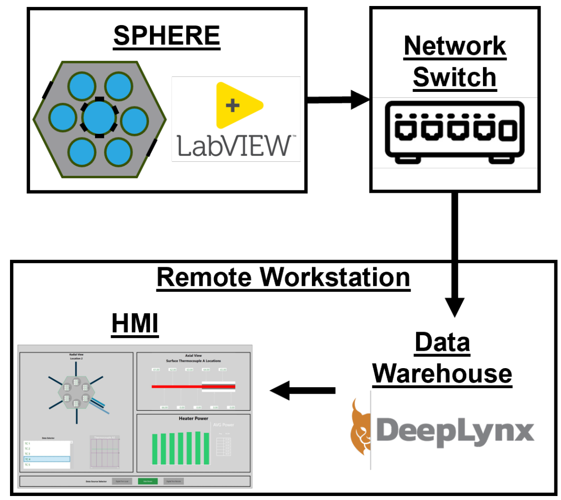

FIGURE 5: Network architecture.

"failed" or improperly installed sensor into the recorded data set. The purpose of this is that, in a remote operations setting, a sensor may fail or be improperly installed, and the remote operations system will need to identify this anomaly. Adding this sensor to the instrumentation package provides a data representative of a failed or improperly installed sensor to be used in DTCS development.

2.2.1 Network Architecture. An 8-port Power over Ethernet (Gen1) Ubiquity switch was used to support a local area wired network between the LabVIEW control system computer and the experimental remote operations computer that ran a docker-based DeepLynx instance and the prototype HMI. The network was minimal for this initial proof-of-concept testing and simply enabled User Datagram Protocol (UDP) communication between the SPHERE LabVIEW controller computer and the experimental computer. The data were transmitted based on the polling rate of the LabVIEW controller computer, which resulted in a 1 second sampling rate for the system transmitted over the local network. A basic diagram of the network architecture is provided in 5.

2.3 SPHERE Remote Operations Architecture

2.3.1 Data Warehouse. DeepLynx, an open-source data warehouse technology that has been proven in previous digital twin testing [9], was used to store, view, and move data from the Labview control system computer to the HMI. DeepLynx provides storage capabilities for both structured and unstructured data. Data was continuously received via UDP and appended to a PostgreSQL table within DeepLynx that contained the time series data generated by SPHERE. Users could view live plots of the data as it was stored over time, and the DeepLynx application programming interface (API) was used by the HMI to pull the latest SPHERE data on regular intervals.

2.3.2 Human-Machine Interface. An HMI was developed to support remote monitoring and control of the SPHERE experimental system. The design inherently reflects the physical characteristics of the SPHERE test article by necessity, but the design of visual specific visual elements was system agnostic and focused on developing conceptual visual representations suitable for multiple data sources associated with the digital-twin system. These are the instrumentation and control (I&C) data stream, remote operations center digital twin and the local digital twin. The system was designed to provide flexibility to support rapid comparisons between different data sources while also synthesizing different data sources into aggregated data source views. For example, the radial display contains spars, with each spar akin to a bar chart representing TC temperature values. When each data source provides corresponding values, the spar collapsed into single element representing the synthesized value. The spar splits into three separate spars to represent each data-source value sent when a discrepancy between the values exceeds a configurable threshold. This provides rapid identification and diagnosis as to how the values differ across data source and allows operators to

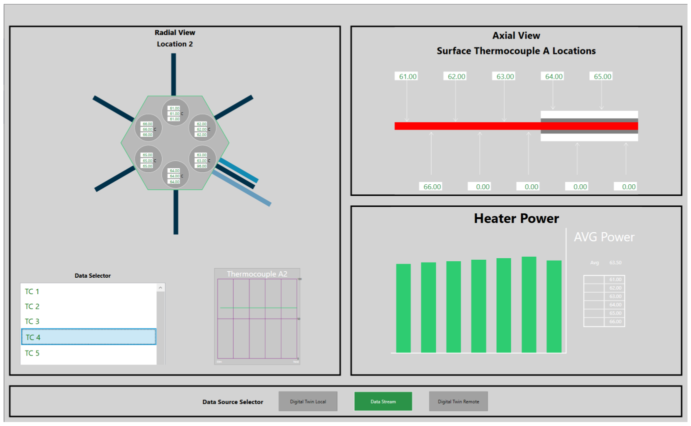

FIGURE 6: HMI with radial (upper left) and axial (upper right) views of the sphere instruments. A global data-source selector (bottom) allows the operator toggle the data source for specific elements, such as heater power (bottom right). Individual instruments can be selected for trending (bottom left).

view sensor sets to identify and attribute the cause of the data sources' discrepancy to a physical system error, sensor error, digital-twin modeling error, corrupt signal transmission, etc. In this experiment, the HMI presented only I&C data because the other systems are still under development, but the concepts for providing comparative views of the different data sources can be seen in Figure 6.

3. TESTING PLAN

Table 1 provides the heater-temperature set points that SPHERE was brought to for each cycle of testing. Each testing cycle consisted of moving through each set point four times. The first two times through, the set-point was held for a target of 30 minutes. The third and fourth time through, the set point was held for a target of 15 minutes. The ramp rate followed between temperature set points was 60°C per hour. Figure 7 shows an example of one cycle through the set points.

TABLE 1: Temperature Set Points

Set Point	1	2	3	4
T [°C]	625	675	650	600

3.1 Normal Operations

The normal operations test plan consisted of navigating through one set-point cycle, Fig. 7, with all six heaters set to temperature-control mode. This control mode is designed to track the heater set-point temperature for all six heaters. While running the normal operations test, all measurements were simultaneously sent over the remote connection to the DeepLynx instance and, from there, forwarded to the HMI.

3.2 Abnormal Operations

One intended outcome of this testing was to produce physical anomalies within the system. Generating these anomalies provides a reference case for the DTCS development because the

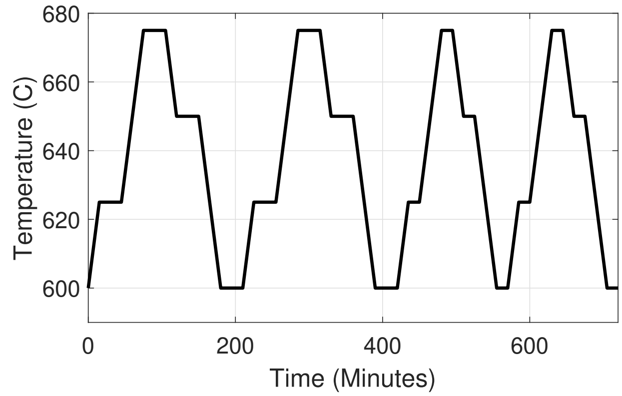

FIGURE 7: Heater set-points and hold duration for one test cycle.

DTCS needs to be validated to detect such anomalies. It is expected that, within the lifetime of a microreactor, some physical anomaly would occur within the reactor system, and the DTCS needs to be designed to identify such anomalies in order to provide the remote operator with an accurate diagnosis. The anomaly planned in this test is a reduction in power applied to two of the six heaters present in SPHERE. Heaters I, II, V, and VI were left on temperature tracking control as was used in normal testing while Heaters III and IV were set to a reduced power level in abnormal operations. The reduced power level was selected as a percentage reduction of the power output of Heaters III and IV, logged during normal testing for each heater temperature set point in the cycle. During the first cycle of abnormal testing, a 30% reduction in power from the logged normal-cycle power level was used while a 70% reduction was used for the second cycle of abnormal testing. Justification for testing both power reductions is given in section 4.2. Heater number location is shown in Fig. 4. The resulting abnormal system state from the modified input conditions should be most evident in the radial plane. This was expected to result in lower temperatures at TC Locations B and C relative to A and D, as well as lower temperatures at Locations F and G relative to E and H.

4. TEST RESULTS

This section provides an overview of the testing results collected during both normal and abnormal testing. An overview of the system state during normal operations is provided and is followed by a presentation of the abnormal-operations system state and an analysis of the difference between normal and abnormal operations. How these results will be used in the development of the DTCS remote operations system will be detailed in section 5.

4.1 Normal Operations

Normal-operations testing consisted of running the SPHERE through one set-point cycle with all six heaters operating normally with respect to the power supplied, based on each temperature set-point controller. Figure 8 shows the temperature of all six heaters relative to the heater temperature set point and is provided in order to demonstrate that the system is indeed tracking the intended set points. For figure clarity and ease of display, this plot and all plots in the remainder of the article show results

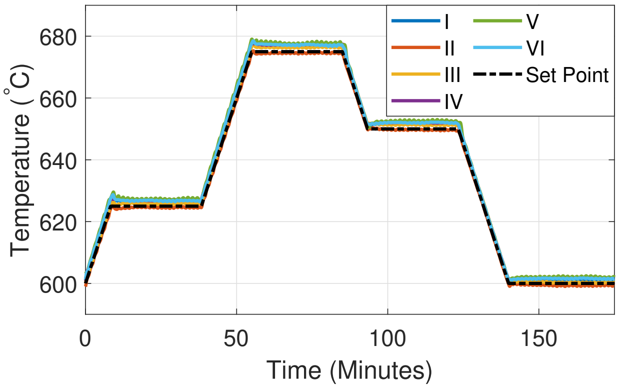

FIGURE 8: Heater temperatures relative to heater set-point temperature.

from the second set-point cycle using 30-minute hold time at the set point (time 200–400 minutes in Fig. 7). In addition to the heater temperatures presented in Fig. 8, Fig. 9 gives the temperature profiles from the surface-mounted TCs at Location 2. For simplicity, this measurement location will be used as the point of comparison for quantifying system-response differences during abnormal operations in Section 4.2.

One critical system characteristic to note is the slight variation in temperatures measured by TCs A–D. Theoretically, A–D should read the same temperature given the radial symmetry of SPHERE (see Fig. 4), but small offsets appear among the readings of TCs A–D. Potential explanations include imperfections in the core block or mounting of the heater that led to subtle asymmetric system heat distributions and imperfection in the mounting of the TCs or in the accuracy of the TCs themselves which, in the case of Type-K TCs, is ±2.2C or ± .75% of the measured temperature, whichever is greater. At 600°C, the accuracy is ±4.5°C. Table 2 and Fig. 10 provide the average difference in TC temperature for TCs B–D relative to TC A during the steady-state hold portions of the normal cycle test. This comes to the forefront in the subsequent section describing the analysis of abnormal-operations test condition.

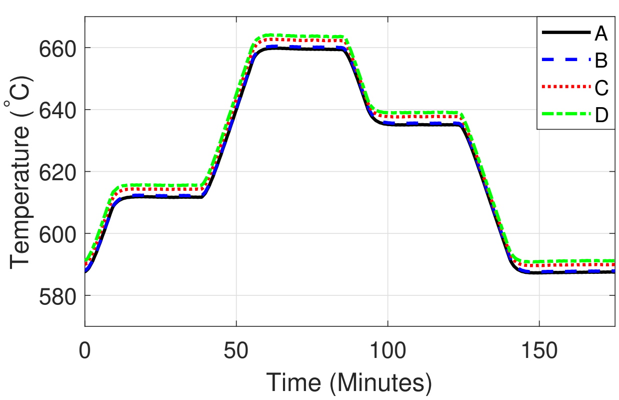

FIGURE 9: Normal operations temperature measured by TCs A-D at Surface Location 2.

TABLE 2: Average TC temperature difference relative to TC A_2

Thermocouple	B_2	C_2	D_2
Normal Operations [ΔT °C]	0.5	2.7	4.0
30% Power Reduction [ΔT °C]	-2.2	0.4	4.4
70% Power Reduction [ΔT °C]	-5.5	-2.2	4.9

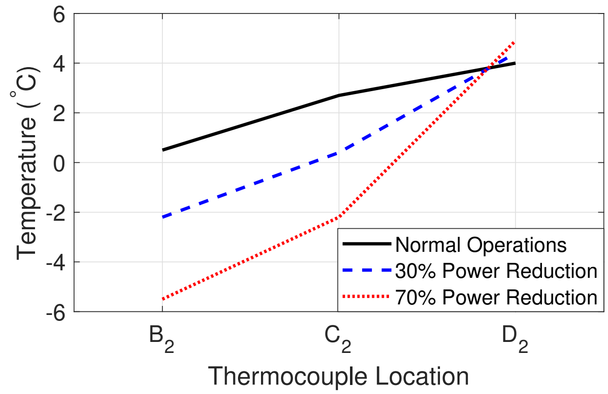

FIGURE 10: Average TC temperature difference relative to TC A_2.

4.2 Abnormal Operations

The first cycle of abnormal testing was conducted by reducing the power output of Heaters III and IV by 30%, with the expectation of seeing a significant reduction in the temperatures at Surface Locations B and C relative to A and D. However, the reductions seen were smaller than expected. The surface temperatures at Surface Location 2 are given in Fig. 11. Table 2 and Fig. 10 provide the reduction in temperature relative to TC A, while Table 3 and Fig. 13 provide the temperature change total temperature change relative to normal operations. For all cases, the relative reduction in temperature was less than 3°C. This was an issue as the accuracy of Type-K TCs is ±2.2C or ± .75% of the measured temperature, whichever is greater. At 600°C, the accuracy is 4.5°C—meaning the reduction in temperature for Locations B and C—fall within the accuracy limits of Type-K TCs and leads to a situation where an operator, either local or remote, may not know if a true temperature change occurred, or if the change observed is a sensor accuracy issue. Therefore, it was decided to repeat the abnormal cycle testing with a 70% reduction in power for Heaters III and IV relative to the normal case with the hopes of introducing a temperature gradient greater than the accuracy limits of the TCs.

The second cycle of abnormal testing was conducted by reducing power to Heaters III and IV by 70% in order to induce a larger temperature reduction at TC Locations B and C relative to A and D. This second round of abnormal testing ended up being a success; in all cases the temperature reduction induced was greater than the accuracy limit of the TCs. In both cases, the gradient introduced was 5°C or greater. The surface temperatures at Surface Location 2 are given in Fig. 12. Results for surface TC B–D change relative to TC A are given in Table 2 and Fig. 10, while Table 3 and Fig. 13 provide the temperature change total temperature change relative to normal operations..

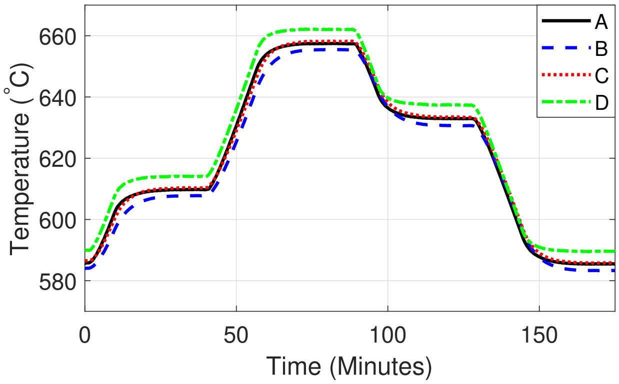

FIGURE 11: Abnormal operations (30% power reduction) temperature at Surface Location 2.

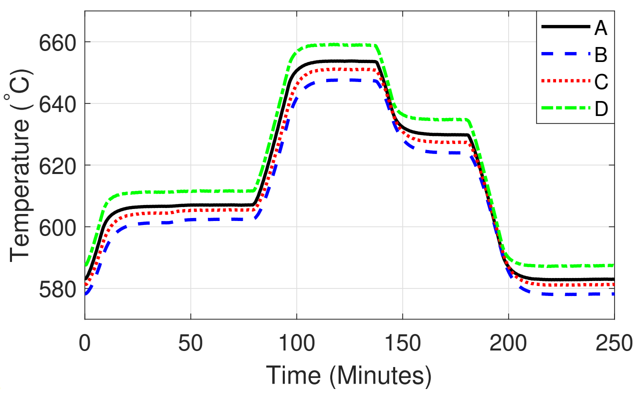

FIGURE 12: Abnormal operations (70% power reduction) temperature at Surface Location 2.

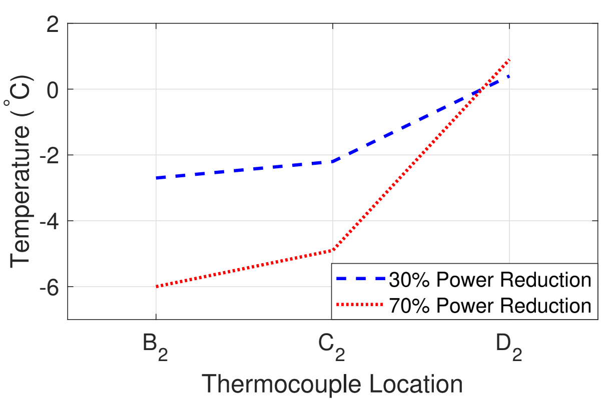

FIGURE 13: Abnormal operations average steady-state hold temperature difference relative to normal operations relative to TC A_2.

TABLE 3: Abnormal operations average steady-state hold temperature difference relative to normal operations relative to TC A_2.

Thermocouple	B_2	C_2	D_2
30% Power Reduction [ΔT °C]	-2.7	-2.2	0.4
70% Power Reduction [ΔT °C]	-6.0	-4.9	0.9

5. REMOTE OPERATIONS APPLICATIONS FOR TEST RESULTS

This testing was conducted to aid in the development of a remote operations system for microreactors. The three goals were to (1) characterize the response of SPHERE, (2) demonstrate the remote connection to SPHERE, and (3) provide a baseline data set to support system analysis and future model construction. This section describes how the collected data and their analysis will be used in the development of the digital-twin-based remote concept of operations that is under development at INL. The analysis used to evaluate the TC data for TC A–D at Location 2 illustrates the value of using experimental platforms such as SPHERE to capture realistic system behaviors that serve as meaningful use cases for digital-twin-based I&C systems.

5.1 Normal Operations

The normal-operations data served as a baseline of system behavior that has two primary uses. First, these data can be used to inform a physics-based or to train a machine-learning-based system model. These models will serve as the basis for the digital twins in the DTCS system as described in section 1.3. Second, the baseline is a critical element for anomaly detection. As can be seen in Table 2, the measured temperatures for each TC demonstrated small discrepancies. These inherent discrepancies will also be present during abnormal-operation conditions. To systematically account for each sensor's discrepancies, a reference set point is used to calculate a difference or contrast value. Characterising this contrast value during normal operations is important because it can then be used to determine whether the actual measured value corresponds to the expected relative contrast to identify abnormal system behavior indicative of sensor or component failure. Finally, the purpose of the DTCS is to certify any data being sent from the microreactor to the remote operations center as well as any commands sent from the remote operations center to the microreactor. This baseline normal-operations data set can be used to validate the functionality of the DTCS under nominal operating conditions.

5.2 Abnormal Operations

The intention of the abnormal-operations testing was to induce a physical anomaly as a use case to develop detection methods suitable for the proposed digital-twin system. As noted in a previous section, the planned 30% power reduction from the baseline power resulted in smaller-than-expected temperature reductions. As such, a 2.2 and 0.4 degree temperature difference relative to A_2 was observed for B_2 and C_2 respectively. After adjusting for the baseline temperature discrepancies, the gradient for the 30% power reduction remains within the accuracy range of the TCs. As such, this use case represents one of the more-challenging system states for a digital-twin system to classify as a potential physical anomaly. Furthermore, this use case also captures an additional complexity to the classification process. TCs A_2 and D_2 demonstrated agreement while TCs B_2 and C_2 also demonstrated agreement, which illustrates the need for additional strategies to resolve competing consensuses. This analysis was restricted to this specific location, but the solution to solving these lies in using larger sets of sensor groups from other system locations and leveraging sensor-group relationships as one potential mechanism for competing and counter-indicating sensors. The 70% power-reduction condition serves as a representative case for a larger-magnitude physical anomaly in which the observed temperature differences for TCs B_2 and C_2 exceed and marginally exceed the sensor accuracy, respectively. A digital-twin based system can more-easily flag the -6.0 degree difference observed for surface B_2 TC as outside of the expected difference value associated with normal operating conditions. The ambiguity can be resolved between the A_2–D_2 and B_2–C_2 sensor groups because C_2 has a value that corresponds with the flagged B_2 TC, and D_2 corresponds with the reference value that is also within expected normal-operating range. Additional use cases are needed to cover the gamut of use cases envisioned for digital-twin systems to accommodate. However, these two small examples illustrate the approach to gathering applicable data sets from physical test environments that can be used to develop system models. Specifically, these two use cases demonstrate how use cases can serve to support developing methods to detect anomalous behavior of a system after first establishing baseline characteristics.

6. FUTURE WORK

The testing performed for this paper is one step toward a larger program aimed at developing a DTCS system that enables the resilient remote operation of a microreactor. The completion of this testing is a key milestone for the program and enables the remaining development and testing of the DTCS. Provided in this section is a discussion on the remaining tasks in the program and how the testing discussed in this paper enables the completion of those tasks.

6.1 DTCS Development

The first follow-on task is the completion of models that reside at the core of digital twins in the DTCS. Two models for SPHERE have been developed, both a a data-based model and a physics-based heat-pipe model developed in Sockeye, the MOOSE-based heat-pipe simulation code. The results collected in this testing will be used as a verification and validation data set for these two models. This will ensure that the models are suitable for use in a digital twin of SPHERE. In addition, as outlined in Section 5, a capability to flag and identify abnormal operating conditions such as physical anomalies or sensor failure will be built into the DTCS and validated using the testing data. Part of DTCS will include the evaluation of different communication protocols, adding encryption and authentication features, and consideration of communication mediums that may be needed to support remote deployments of microreactors.

6.2 DTCS Simulation Testing

Follow the completion of the development of the DTCS, a two-step evaluation process is planned. The first step involves real-time simulation of the DTCS while the second step is a true remote operations test of SPHERE with a fully functional DTCS. In the simulation testing phase, the DTCS will be deployed to all relevant nodes in the system. Both the microreactor digital twin and the control-room digital twin will be deployed to their respective locations and connected via a secure network. The HMI will be deployed to INL's Human System Simulation Lab (HSSL) and connected to the control-room digital twin. However, in place of an operational SPHERE, the data collected in the initial testing of SPHERE will be streamed throughout the system in order provide real-time simulation to test the response of the entire DTCS in normal and abnormal operations before moving to more-expensive and time-consuming physical tests.

6.3 DTCS Physical Testing with SPHERE

The final piece in the development of the DTCS is a full remote operations test where the DTCS resiliently controls and monitors SPHERE from a remote operations center. Commands will be sent to SPHERE from the remote operations center over a secure communications network, and all commands will have to clear the DTCS system before being issued to SPHERE. In addition, all measurements will be provided to the HSSL-based remote operations center via the secure communication network and also need to be certified by the DTCS before being provided to the remote operator. In this final test, the scenarios conducted in the first round of testing—normal operations and physical anomaly abnormal operation—will be repeated and the performance of the DTCS evaluated in a live test scenario.

7. CONCLUSION

The microreactor concept is innovative and has great potential in providing reliable and carbon-free energy to remote areas of the world, and remotely operating microreactors can aid in their successful deployment. However, remote operation has never been done within the nuclear industry and therefore needs thorough investigation into the reliability and resilience of a remote operations system. Therefore, the novel DTCS remote operations concept needs to be thoroughly researched and tested, and the SPHERE test facility was chosen for proof of concept testing for this remote operation system. Initial testing with SPHERE was conducted to characterize the system's response, demonstrate the remote connection, and collect a baseline data set for supporting digital-twin model development. Cycling through various temperature set points was done to collect a large set of transient data under normal operating conditions as well as with a physical anomaly in the system. This testing is a key step in the development and demonstration of the DTCS remote operations concept. First, it provides the testing data that enables the continued development of the DTCS. Second, the testing serves as a baseline from which simulation testing of the DTCS can be evaluated against. Finally, this testing provides operational experience with the SPHERE test bed where full remote operations using the DTCS will be demonstrated as fart of future work.

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