AGN-201 Digital Twin Concept of Operations

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NA-241 Concepts and Approaches

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Ryan Stewart,
Emerald Ryan, and
Ashley Shields

Idaho National Laboratory

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Ryan Stewart,
Emerald Ryan, and
Ashley Shields
Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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SUMMARY

The AGN-201 is a nuclear reactor at Idaho State University (ISU) and is currently being used in the development of a digital twin (DT) with Idaho National Laboratory (INL). The goal is to create a DT (called the AGN-201 DT) which can monitor an operating nuclear reactor to determine when the reactor is being operated normally; normal operations are any operations that is declared by the ISU staff. To accomplish this, researchers at INL developed a DT ecosystem which can ingest data from the AGN-201 reactor. This data is fed into a series of machine learning (ML) and reactor physics models. The ML and reactor physics models assess the data and determine if the reactor is operating normally. Event(s) that are flagged as anomalies are investigated by the INL staff to determine if any undeclared experiments were conducted. The AGN-201 DT was verified in July/August 2023, when the ISU staff performed undeclared experiments and the INL staff were able to assess the anomalous events and determine what likely caused each event. This project was a steppingstone to promote the use of DTs for international safeguards and marks the first time a DT was able to monitor a nuclear reactor for this purpose.

This document provides the concept of operations (CONOPS) for the AGN-201 digital twin (DT). The CONOPS describes how the AGN-201 and AGN-201 DT are expected to operate and details how each are established.

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ACRONYMS

AGN	Aerojet General Nucleonics
AI	artificial intelligence
AO	authorized operator
CONOPS	concept of operations
DAS	data acquisition system
DT	digital twin
GUI	graphical user interface
HPC	high-performance computing
IEEE	Institute of Electrical and Electronics Engineers
IFML	Isolation Forest machine learning
INL	Idaho National Laboratory
ISU	Idaho State University
NRC	Nuclear Regulatory Commission
ML	machine learning
RNN	recurrent neural network
SAR	safety analysis report
SM	surrogate model
SOP	standard operating procedure

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AGN-201 Digital Twin Concept of Operations

1. SCOPE

1.1 Identification

This concept of operations (CONOPS) document applies to the Aerojet General Nucleonics (AGN-201) digital twin (DT) to support remote monitoring of the AGN-201 reactor at Idaho State University (ISU). The AGN-201 has been used as a test bed for creating a DT to remotely monitor a nuclear reactor to detect anomalies within the reactor for initial support of nuclear safeguards.

1.2 Document Overview

The AGN-201 DT CONOPS describes the operational states, capabilities, benefits, and limitations of the AGN-201 DT, including how the AGN-201 DT can:

- Transmit live data from the AGN-201 data acquisition system (DAS) to Azure Government Cloud, a remote server accessible to Idaho National Laboratory (INL)
- Integrate data from the AGN-201 DAS into the data warehouse DeepLynx
- Integrate machine learning (ML) and reactor physics surrogate models (SMs) with DeepLynx
- Perform near real-time assessment of anomaly detection during reactor operations.

This CONOPS provides general information on operational processes and procedures required to utilize the AGN-201 DT along with a set of expected benefits from the system. This document follows the Institute of Electrical and Electronics Engineers (IEEE) CONOPS format for organization, which details scope in Section 1, references in Section 2, current state of system and context to the situation in Section 3, justification for deviating from the current system in Section 4, details on the AGN-201 solution in Section 5, and the analysis of the AGN-201 DT system in Section 6.

1.3 System Overview

The AGN-201 DT is a digital engineering concept that seeks to integrate an operating nuclear reactor with a DT for monitoring the reactor during operations. Monitoring the AGN-201 reactor allows a third-party observer to determine if the reactor is operating in a normal or declared manner. Detected anomalies are shared with ISU staff members to verify if anomalies are intentional or indicate off-normal operation. Figure 1 shows the architecture for the AGN-201 DT, where each component will be described briefly.

- DeepLynx: central data warehouse for storing data obtained from the DAS, ML, and SM
- Jester: transmits data from AGN-201 DAS to DeepLynx
- ML: scripts that use live DAS data from DeepLynx and returns ML predictions of operational conditions and anomaly detection
- SM: models with DAS data from DeepLynx and returns anomaly detections based on a physical modeling of the system
- Graphical User Interface (GUI): displays relevant predictions, operational data for comparison, and three-dimensional visualization of the AGN-201 facility

The AGN-201 DT comprises all components once data has been transferred from the AGN-201 reactor DAS system (i.e., LabView). This provides a framework that can monitor the AGN-201 and make predictions about its behaviors based on an ML interpretation of the data and physics simulations.

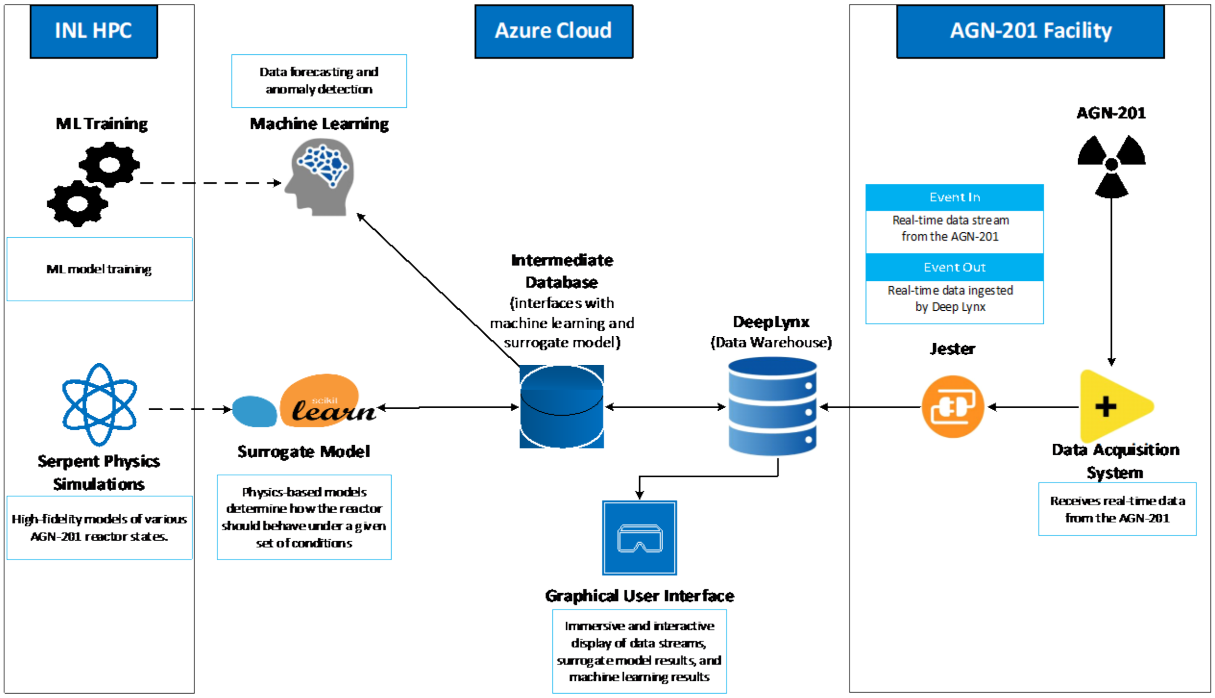

Figure 1. AGN-201 DT architecture for interfacings with the AGN-201.

2. REFERENCED DOCUMENTS

The references, standards, and guidelines used in preparation of this document are listed below.

- Software Engineering Standards Committee of the IEEE Computer Society. IEEE Std 1362, IEEE Guide for Information Technology-System Definitions-Concept of Operations (ConOps) Document, March 19, 1998

This document can be found on the IEEE website.[a]

3. CURRENT SYSTEM

This section details the current system for AGN-201.

3.1 Operational Policies and Constraints

The AGN-201 reactor shall be operated in accordance with the technical specifications, standard operating procedures (SOPs), and safety analysis report (SAR) for the facility. The technical specifications provide an overview of how the reactor can be operated (how the control rods can be inserted, what power level the reactor can be operated at, etc.). The SOPs provide an overview of how to perform day-to-day operations and maintenance. The SAR provides the bounding justification for the technical specifications and the SOPs. The technical specifications, SOPs, and SAR can be requested from the ISU operational staff. The current method for monitoring the system has been approved by and complies with the U.S. Nuclear Regulatory Commission (NRC).

[a] http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=761853&contentType=Standards&queryText%3D1362

3.2 Description of the Current Situation

Data is obtained via the reactor console, transferred to the DAS, and stored on a separate hard drive. The DAS system is not required to operate the AGN-201, due to this, basic reactor operations data are stored in a logbook. Logbook additions require an authorized user to document various reactor quantities (i.e., reactor power) every 15 minutes. This limits the ability to monitor the system in an automated fashion and requires manual data entry and analysis.

3.2.1 Reactor Console

The AGN-201 reactor console was updated in 2020 and converted from vacuum tube relays to solid-state relays to provide a more robust system. Figure 2 shows a picture of the reactor console. The reactor console is only energized when the reactor is being operated.

Figure 2. AGN-201 reactor console.

3.2.2 Data Acquisition System

The DAS pulls operational data (i.e. power, temperature) from the reactor console and sends these data to a LabView program. Data generated by the DAS and LabView system are stored locally and can be viewed through the LabView user interface. The DAS and LabView system was developed by the reactor operations team and INL.

3.3 Operational Scenarios for Current Situation

The following scenarios represent the current anticipated scenarios to be experienced for the AGN-201 reactor:

- Startup
- Normal operations
- Maintenance procedures
- Unintended scram event
- Emergency.

3.3.1 Startup

To start the AGN-201, a series of preoperational checks must be completed by the authorized operator (AO) to ensure the reactor is operational. This includes ensuring all lines of communication between the reactor's sensors and control console are functioning properly. The DAS system can be turned on before, during, or after the preoperational checks.

Once the preoperational checks have been concluded and the reactor deemed operational, a reactor startup can begin and control rods are inserted into the core to bring the reactor to a critical state at roughly 10 mW. Normal operations then ensue.

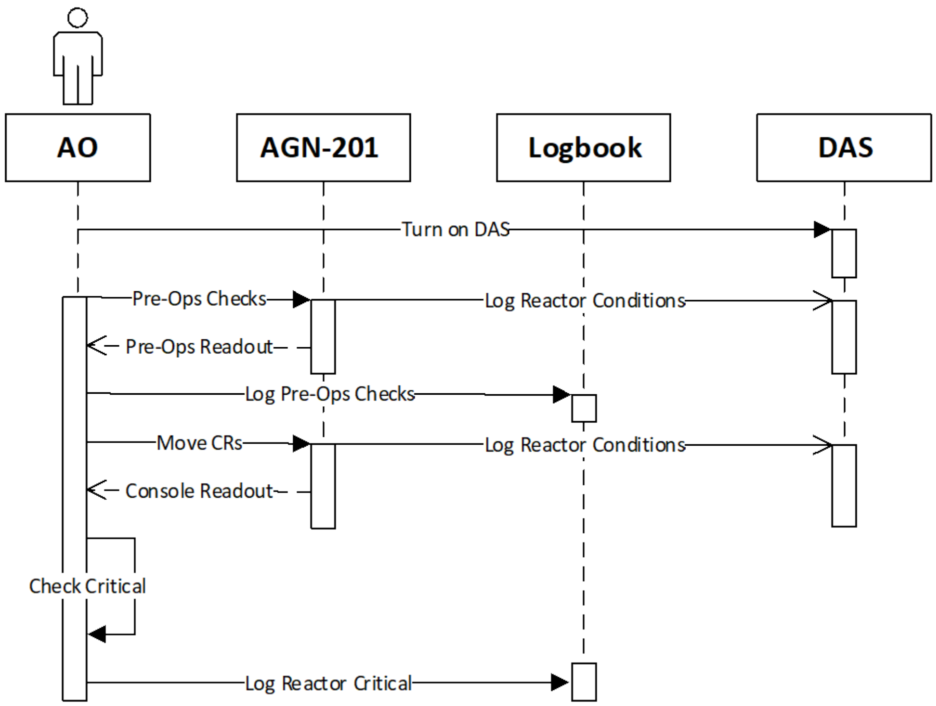

Figure 3. Sequence diagram for the AGN-201 startup.

3.3.2 Normal Operations

The normal operation scenario includes the reactor operating in steady-state and transient conditions. Steady state occurs when the reactor is critical at a desired power level and remains at this power level for a period of time. The steady-state scenario can range in power from <0.1 mW to 5 W. After initial criticality during startup, a transient scenario is required to change the power of the reactor. A transient occurs when the reactor deviates from its critical condition in the steady-state scenario. This means the reactor is either increasing or decreasing in power. The transient scenario can be initiated by multiple events including control rod movement or experimental insertion and removal.

Normal operations would also cover the reactor being shut down due to a scram (a near immediate shutdown of the reactor) and the reactor console being deenergized. A scram provides a near-instantaneous shutdown of the reactor, where the safety control rods, and coarse control rod are dropped out of the core. A scram can either occur on purpose or be caused by a reactor sensor being in an unauthorized or unsafe state. A list of scram conditions are:

- Manual—depression of the manual scram button
- Channel 1 Lower Power—channel drops below 0.5 counts/second

- Channel 2 Low Power—power drops below 3.0×10^{-13} amps
- Channel 2 High Power—power exceeds 6 W
- Channel 3 Lower Power—power drops below 5% of full scale
- Channel 3 High Power—power exceeds 6 W
- Period—reactor period less than 3 seconds
- Seismic—lateral force of 0.6 g acceleration
- Power—loss of power to the console
- Water temperature—temperature falls below 15°C
- Water level—water level falls 10 inches below the highest point.

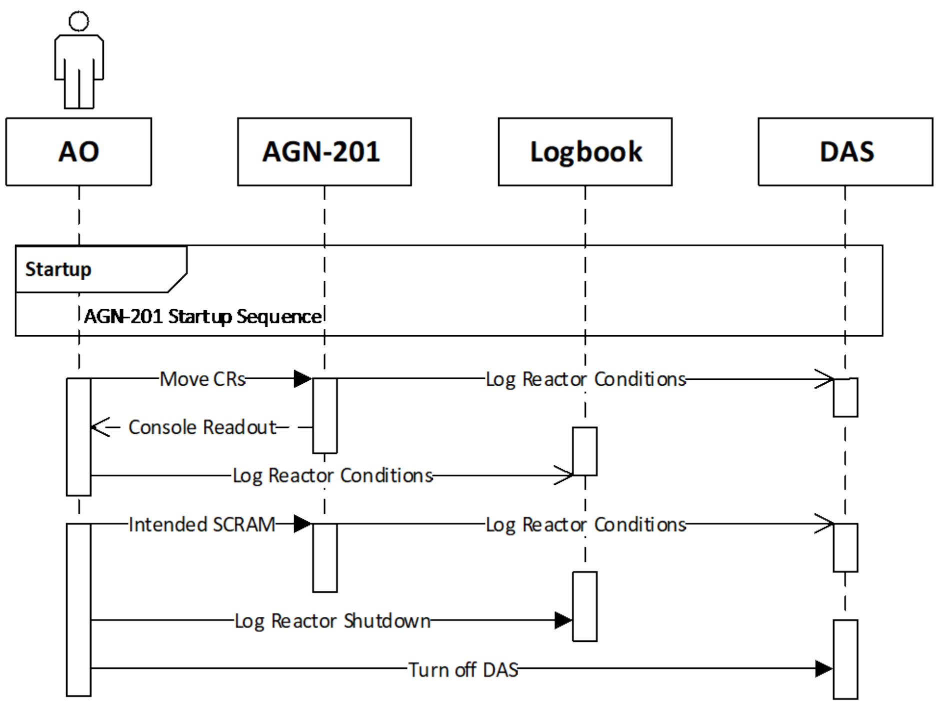

Figure 4. Sequence diagram for normal operations of the AGN-201.

3.3.3 Maintenance

Maintenance is performed on various components of the AGN-201. The procedures for performing maintenance are outlined in the SOPs. Some maintenance examples include control rod drop testing, control rod maintenance, etc.

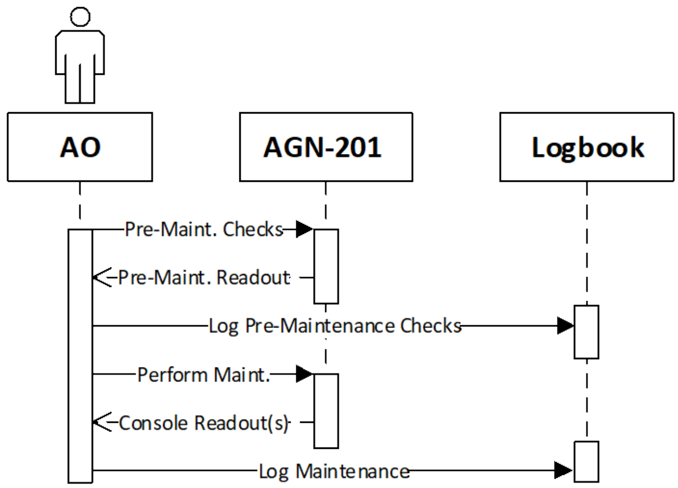

Figure 5. Sequence diagram for maintenance on the AGN-201.

3.3.4 Unintended Scram

Unintended scram events cause an immediate scram of the reactor due to unknown reactor operations or other events that would cause the reactor operations team to cease operations until the event was documented and diagnosed. Currently, unintended scrams are documented in the logbook. This provides information on the date, time, and diagnosis of the anomaly. Startup requires a senior reactor operator to sign off on the anomaly diagnoses.

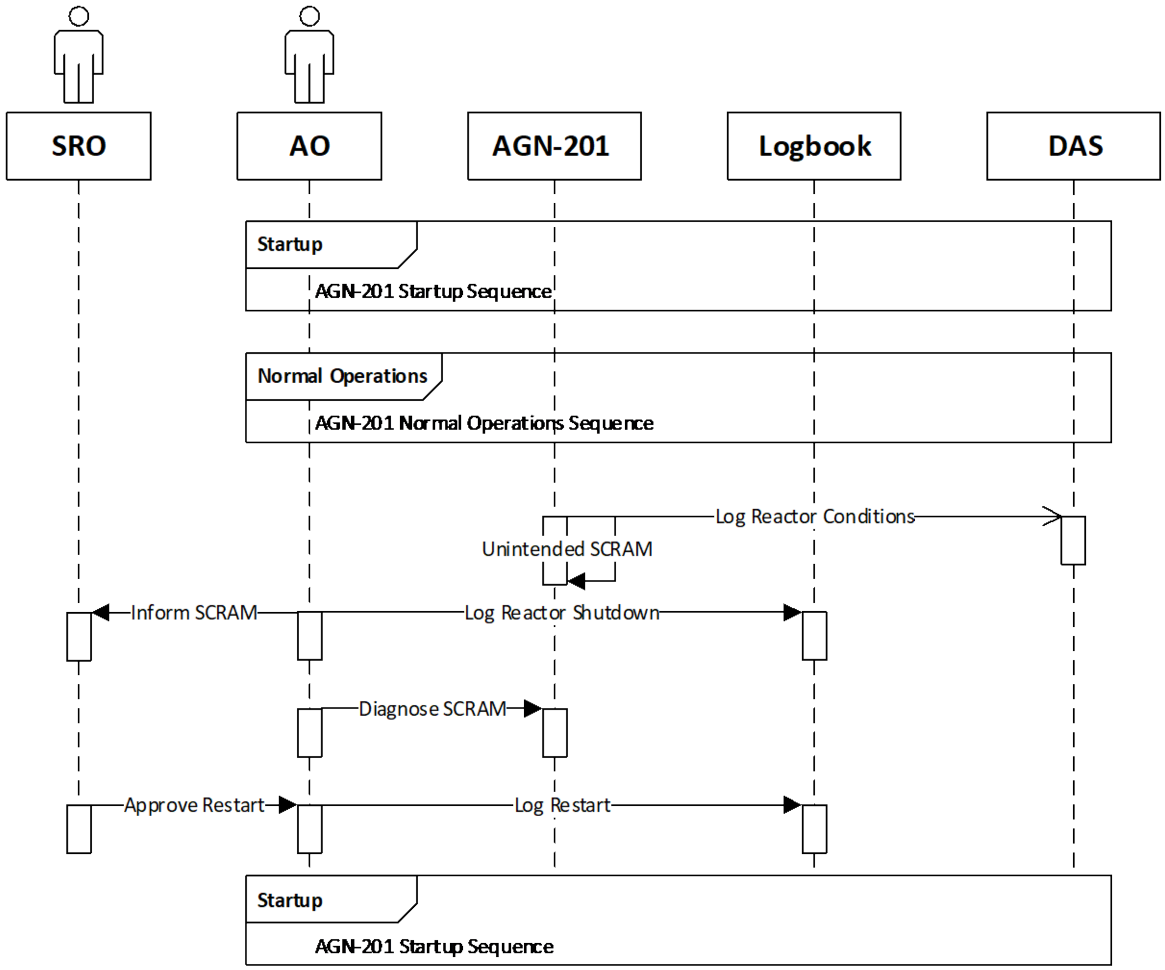

Figure 6. Sequence diagram for unintended scram event.

3.3.5 Emergency

The emergency scenario occurs when the reactor or its associated facility undergoes some type of accident such as a fire, radiation exposure, etc. This scenario would likely involve the inclusion of offsite personnel to assist in returning the facility to normal operating conditions. Since an emergency scenario could involve the reactor or its associated facility, a generic sequence diagram could not be created as actions would be emergency depended

3.4 User Classes and Other Involved Personnel

The ISU AGN-201 reactor is an NRC license research reactor, which involves a stringent organization structure to ensure safe operations.

Key roles at the AGN-201 include:

- Reactor safety committee—responsible for the safe operations of the AGN-201, determines if the reactor can be placed in an operable state after an incident
- ISU administration—this includes individuals who have responsibilities to the AGN-201 reactor within ISU that are not involved in the day-to-day operations

- Authorized/reactor operator—AOs are allowed to manipulate the controls of the AGN-201 reactor; reactor operators are licensed to operate the AGN-201 reactor
- Reactor administrator—responsible for the operation of the AGN-201 reactor facility, this individual may be an AO
- Reactor supervisor—oversees day-to-day operations of the AGN-201, ensures facility maintains all necessary maintenance and checks in accordance to its license, this individual may be an AO
- Senior reactor operator—allowed to perform maintenance, responsible for operating the reactor, this individual is an AO
- Certified observer—responsible for ensuring the reactor can be placed in a safe state if the reactor AO is incapacitated
- NRC—provides operating license to ISU to allow for AGN-201 operation under the current technical specifications
- First responders—provide medical, fire, or police assistance in the event of an emergency scenario

3.5 Interactions Among Classes

Table 1. Interaction map for current AGN-201 operations.

4. JUSTIFICATION FOR AND NATURE OF CHANGES

4.1 Justification of Changes

4.1.1 High-Level Justification

Automated monitoring of nuclear facilities can have lasting impacts for reactor operators by helping them determine the health of the plant and for international safeguards analysis to help determine if the reactor is operating as declared. The AGN-201 DT was developed to detect and identify anomalies during AGN-201 operation. Changes to the declared operation of the AGN-201 are meant to be caught by the AGN-201 DT remotely, such that an individual would not need to be present at the facility to understand what was happening.

Previous work involved monitoring and controlling a non-nuclear test bed and monitor a virtual nuclear reactor. The Microreactor Agile Non-Nuclear Experimental Test Bed (MAGNET) DT was a non-nuclear DT that was able to successfully demonstrate autonomous operations based on ML and predictive capabilities. The safeguards DT (SG-DT) was a virtual DT of a sodium fast reactor that could be used for safeguards be design work. To advance the use of DTs in nuclear applications, the AGN-201 was selected as a test bed for deploying a DT to monitor an operating nuclear reactor. It is difficult to determine what deficiencies are prominent when moving from a non-nuclear or virtual system to a nuclear reactor. As such, the AGN-201 DT was envisioned to bridge the gap between non-nuclear and virtual test beds and full-scale reactors. This CONOPS is meant to provide the necessary documentation for the AGN-201 DT as it stands at the end of the project.

4.1.2 Data Access

Data generated from the AGN-201 can be obtained by examining the logbook or associated DAS computer. The DAS computer has historical operations dating back to January 2023, containing data from each of the seven data streams. The logbook contains at least 10 years of historical operations data, including reactor power at specified time steps, anomalous events (scrams, oddities in startup, etc.), and experiments. The logbook also contains information about the AO operating the AGN-201. The DAS does not contain this information, but cross-referencing with the logbook would reveal AO data.

4.1.3 Deficiencies in Current System

The initial set up at the AGN-201 only provides the data from the reactor console to a DAS to be stored for later use. Moving this data to a central data repository would require a manual effort each time new data were generated. If the AGN-201 were to utilize any form of real-time monitoring, a process for collecting reactor operations data would be necessary.

Anomaly detection is not required for AGN-201 operations; however, the AGN-201 DT does provide a unique opportunity to learn how a DT can be used for anomaly detection in a real-world nuclear reactor. The AGN-201 DT could also be used in the future to help diagnose anomalies that are not easy to discern without a significant amount of data.

5. CONCEPTS FOR THE PROPOSED SYSTEM

The following subsections provide a description of the proposed AGN-201 DT system, including the background, objectives, scope, constraints, process and workflow, user classes, personnel, and required support environment. Some introductory material from Section 1.3 is repeated in this section for the convenience of the reader.

5.1 Background, Objectives, and Scope

Nuclear reactors currently rely on human monitoring and experience to determine if a reactor is operating in a known realm of operations. Monitoring a nuclear reactor requires visually examining readouts, responding to auditory alarms, etc. for normal operations. Any unintentional alarms or shutdowns are recorded in the reactor logbook to allow for a history of operations to be maintained. This CONOPS is meant as a primer for an end user who would monitor the AGN-201 using the AGN-201 DT. It is expected that a user would have a fundamental understanding of a nuclear reactor to determine the context for the various data streams.

Current reactor operations require a human to constantly monitor all systems (and subsystems) to ensure they are operating within the designed parameters. Future reactors deployed domestically or internationally will likely be operated or monitored remotely to reduce operations and maintenance costs. Remote operations allow for the control and monitoring facility to be located away from the reactor facility, enabling reactor deployment in very rural or hard-to-reach locations if needed.

To detect off-normal conditions, the DT would ingest live data combined with a series of ML and reactor physics data to determine if the reactor was operating within the original bounds classified by the reactor operator. If anomalies were detected, the DT would provide the monitoring agency information on areas of interest for a future inspection of the facility.

To this extent, the AGN-201 DT acts as a bridge between a virtual DT and an operational power reactor. The AGN-201 DT provides a test bed for determining how to best implement a DT into a nuclear reactor facility. INL personnel (INL monitors) are the main users of the AGN-201 DT. The AGN-210 DT will be used to determine requirements for the remote monitoring of a nuclear reactor.

The objectives for the AGN-201 DT are:

- Provide a monitoring system that can ingest near real-time data from a nuclear reactor and a determination if anomalous operations are observed
- Determine what constraints are placed on DT development for a nuclear facility based on operational data
- Assess which methodologies and approaches are appropriate for capturing the underlying physics in ML and SMs

To the extent possible, the AGN-201 DT has been developed in accordance with tailored IEEE CertifAIEd requirements.

5.2 Operational Policies and Constraints

The AGN-201 DT was developed to assist in monitoring the AGN-201 nuclear reactor by detecting anomalous events in the system. This system was codeveloped between ISU and INL. The AGN-201 DT system is separate from the AGN-201 reactor, meaning the AGN-201 does not require the AGN-201 DT to operate. The AGN-201 DT can be initiated by an ISU AO by initializing the Jester software on the DAS computer. To perform this, the AO would need to turn on the DAS computer and double click on the Jester executable on the main screen.

A user of the AGN-201 DT who wanted to examine a new dataset would need to make a request to the AGN-201 operations team. This process would require an email to the reactor supervisor to ensure that the AGN-201 operations staff would be available.

The AGN-201 DT was built with a predefined dataset based on operations from January 2023 to March 2023. These data encompass a small window of operations; however, it was deemed appropriate for initial deployment. It is recommended that the AGN-201 DT is updated semiregularly to ensure all reactor physics and ML models are kept up to date. This is especially true over the various seasons (and temperatures) that are common in Pocatello, where the AGN-201 is housed. Seasonal changes may also have an effect on hardware, which could affect the various reactor physics and ML algorithms and their accuracy.

The AGN-201 DT should also be reviewed periodically by a set of subject matter experts in reactor physics and ML. These experts will be able to assess, quantify, and determine potential biases that may arise from changes and updates in the models. Biases and deviations from normal operations should be detailed, and if necessary, updates to the reactor physics and ML models should be made to bring them into compliance. All parties involved should be made aware of these deviations should they occur. Current operating conditions require the constraints placed in Section 5.3.1 to be met. If the AGN-201 DT should deviate from these conditions, the models need to be retrained to ensure compliance with these constraints.

The AGN-201 DT is currently being released as open-source software (https://github.com/IdahoLabUnsupported/agn201_Digital_Twin). The AGN-201 DT software will include the framework, reactor physics SM, ML models, and visualization tools. Not included in this are the specific reactor physics models; although, they may be made available upon request. Utilization of the AGN-201 DT requires a specific login for anyone with access to the AGN-201 DT DeepLynx page (https://deeplynx.de.inl.gov/#/, Container ISU Digital Twin) will be able to access the AGN-201 DT. To access the AGN-201 DT page, previous authorization must be granted by a delegated authority.

Data obtained from the AGN-201 DT will be housed in the government Azure cloud. Access to this data is restricted by INL personnel, and only individuals involved in the project will be allowed to access it. If others seek to utilize this data, written consent from the ISU AGN-201 reactor operations team will be required. No other sharing of AGN-201 data to third parties will be allowed.

5.3 Description of the Proposed System

The AGN-201 DT is a digital engineering concept that seeks to integrate an operating nuclear reactor with a DT to allow for monitoring the reactor during operations. Monitoring the AGN-201 reactor allows a third-party observer to determine if the reactor is operating in a normal or declared manner. Anomalies that are detected can then be shared with ISU staff members to identify if these anomalies were intended or if there is something truly off-normal about the reactor operations. Figure 1 shows the architecture for the AGN-201 DT, including:

- DeepLynx: central data warehouse for storing data obtained from the DAS, ML, and SM
- Jester: transmits data from AGN-201 DAS to DeepLynx
- ML: scripts that use live DAS data from DeepLynx and returns ML predictions of operational conditions and anomaly detection
- SM: models with DAS data from DeepLynx and returns anomaly detection based on a physical modeling of the system
- GUI: displays relevant predictions, operational data for comparison, and three-dimensional visualization of the AGN-201 facility.

These elements provide the architecture for the AGN-201 DT. For this document, the AGN-201 DT is comprised of all components once data has been transferred from the AGN-201 reactor DAS system (i.e., LabView). This provides a framework that can monitor the AGN-201 and make predictions about its behaviors based on an ML interpretation of the data and physics simulations.

5.3.1 Major System Components

- Software: The software component provides the interfaces with DeepLynx, the ML/SM adapters, and ability to ingest data from the AGN-201 DAS system.
- Users: Users provide insight into the data ingested and produced by the AGN-201 DT.
- Hardware: The AGN-201 facility provides the raw data and nuclear reactor (i.e. the physical asset) of the DT, including the physical reactor, reactor console, and DAS.

- The INL high-performance computing (HPC): This provides a resource for high-fidelity reactor physics calculations to be performed. The high-fidelity simulations provide the background required to create a reactor physics SM for anomaly detection. The INL HPC also provided an avenue to train the ML models.

The four elements—software, users, hardware, and the INL HPC—provide the resources necessary to populate and utilize the AGN-201 DT during normal and anomalous operations.

5.3.1.1 Software

To use the AGN-201 DT, a computer with access to the DeepLynx user interface page (https://deeplynx.de.inl.gov/#/, Container ISU Digital Twin) is required. Access to the ISU Digital Twin can be obtained by emailing Ryan Stewart (ryan.stewart@inl.gov) or another member of the DeepLynx team (found here: https://github.com/idaholab/Deep-Lynx). This will allow a user to load the GUI for DeepLynx. With the GUI, a user can monitor the current operations of the AGN-201 facility or examine historical operations.

To modify the AGN-201 DT, four major software components are required for the AGN-201 DT: DeepLynx, LabView, Python, and Serpent. DeepLynx is the central data repository from which the DT is created; this ensures a common mapping between all of the other software pieces and components. Data transferred to DeepLynx can be stored indefinitely. LabView is installed at the AGN-201 facility and is used as the DAS, where data from the AGN-201 are pulled into LabView and passed to DeepLynx. The Python language is used to model the reactor physics SM, ML prediction, and ML anomaly detection models. Scikit-learn is used for the ML anomaly detection and reactor physics SM; TensorFlow is used for the ML prediction. Serpent is a reactor physics code that uses a Monte Carlo method for solving the neutron transport equation. This allows us to create a physical representation of the AGN-201 core during operations.

DeepLynx

DeepLynx is an ontological data warehouse specializing in storing data for DTs. Not only can we store a graph representing the actual reactor, its requirements, and other data, but we can also store the raw data flowing in from various sensors and collectors in the same space. This combination of metadata and tabular sensor data is stored securely in the cloud using a DeepLynx instance running in Azure Government. The data are available in near real time from the reactor and can be returned via simple queries or more complex requests for data, such as the ML software. DeepLynx provides the means for identifying and analyzing past data to track its behavior patterns. This process is currently manual, and expanding this framework to a larger system would require some type of automated process to ensure cooperation between the current DT and previous data.

Machine Learning Adapters

Two ML models are present in the AGN-201 DT. The first is used to predict reactor operations based on current conditions. The second is used to detect anomalies in the system.

The initial ML model for predicting reactor operations was a multilayer perceptron model, which originally sought to use five parameters from the DAS to predict the sixth parameter. Original results were promising; however, significant bias was found due to temporally correlated or seasonal data. Temporally correlated data were derived from the fact that the power of a nuclear reactor is not simply a function of the current five parameters at a point in time but is dependent on the parameters of previous time steps to determine the current time step. A basic example of this is, if power was being predicted, the same control rod heights could correspond to multiple power values. For seasonal discrepancies, the original training data only had operations from winter. When the trained models were used for predicting operations in summer, they failed to capture the temperature effects adequately. The seasonal changes could be fixed by including additional training data; however, the failures due to temporally correlated data deemed the multilayer perceptron model a failure.

The final model used to make predictions about reactor operations was a recurrent neural network (RNN) with long short term memory. This model uses five parameters from the DAS to predict the sixth parameter. The parameters present are Channel 1 power, Channel 2 power, Channel 3 power, fine control rod height, coarse control rod height, and temperature. One important aspect of the RNN is the ability to capture time in the model. This is essential as a low-power reactor can have multiple end states (i.e., power) with the same inputs (i.e., control rod positions). Incorporating time ensures that the ML algorithm can learn how to move from state to state based on previous data.

For the anomaly detection model, an Isolation Forest ML (IFML) model was used. The IFML model assumes that anomalies are “few and different,” resulting in an unsupervised learning method that can distinguish anomalies with a high degree of accuracy. Despite this, there are known biases relating to the startup and shutdown of the reactor. The anomaly detection algorithm flags these events as off-normal due to the large shifts in power, control rod heights, etc. during this time. This bias is currently known, and a remediation technique is currently underway. The IFML method does not require a training set and thus should help minimize biases in anomaly detection. If anomalies are detected that are not actually present, the IFML method may need to be reconsidered as an appropriate algorithm. Quantifiably, this means anomalies are found to be present less than 5% of the time. A value of 5% accounts for unique operational states that, while not anomalous, deviate from regular operations.

Surrogate Model Adapter

The SM utilizes the coarse and fine control rod data along with the reactor temperature to determine the k_{eff} of the reactor. When the reactor is first determined to be critical, this k_{eff} value is obtained and used as the expected critical eigenvalue for the operation. Data are obtained for every 0.1 second of operation, and a new k_{eff} value is determined as the operations continues. If reactor power is not changing, the k_{eff} value is compared with the expected k_{eff} value. If the new value is within a predefined uncertainty on k_{eff}, the reactor is assumed to be operating in normal conditions. If the new value of k_{eff} is larger than the uncertainty, this period is determined as off-normal.

The SM relies on reactor physics models that were derived from an equivalent high-fidelity physics model, which incorporated known design details. The SM would naturally incorporate biases associated with the reactor physics solver and assumptions used to create the model. For the SM, 196 reactor physics models were generated to calculate k_{eff} as a function of the various control rod heights and operational temperatures. Comparing the SM with the Serpent data, the SM had an R^2 of 0.999 and a mean absolute error of 1.04%. The largest errors occur when both control rods are fully withdrawn, which is not a feasible state for the reactor to be in while it is critical. If the SM were to be trained with new data, the mean absolute error should be improved or maintained. If the mean absolute error were to get worse, the SM would need to show that it can perform to a level equal to its state before the new data was added.

Known biases in the reactor physics simulations include the coarse control rod worth, fine control rod worth, and critical eigenvalue bias. The critical eigenvalue bias likely stems from uncertainties within the material composition. This is addressed by using a relative k_{eff} value upon startup for the reactor. Along with this, we create an uncertainty about k_{eff} based on historical critical eigenvalue data from normal operations. If the reactor is declared critical and k_{eff} is outside this uncertainty range, off-normal conditions are suspected.

Both the coarse and fine control rod worths are overpredicted compared with the SAR, despite this, the experimental uncertainty in the known coarse and fine control rod worths are comparable. These biases are accounted for by incorporating the uncertainty around k_{eff} for expected deviations around the expected k_{eff}. Current work is being performed to generate a correction factor that relates operations data to SM data.

Graphical User Interface

The GUI provides users with the ability to either watch the core in real time or "play back" a previous operation using the historical mode of the AGN-201 DT. It is envisioned that monitoring the reactor in real time would be unnecessary as the ML and SM adapter would be sufficient to determine if or when an anomaly occurs. Once an anomaly occurs, a user would be able to examine current data to determine if the anomaly was still occurring or could use the data stored in DeepLynx to play back the event to help determine the source of the anomaly.

5.3.1.2 Users

The main users of the AGN-201 DT are the INL monitors. The INL monitors examine live and historical data to determine if anomalous reactor operations took place. Currently, this entails emailing or calling the reactor supervisor to inform them of the anomalous operations. Users of the system will be able to provide feedback to the development team regarding biases, errors, or general feedback that may need to be incorporated in the system. This is currently be performed manually via email.

During operations, the ML and SM adapters can flag the operations as off-normal, indicating that the reactor is not being operated as it was originally declared. Once an off-normal operation has been declared, the INL monitors would have the responsibility to determine if the off-normal operation is justified or in itself an anomaly. If an anomaly occurs, it would need to be investigated to determine if the root cause of this was an actual anomaly, systemic bias, or something less malicious, such as a spurious reading.

5.3.1.3 Hardware

The major hardware component is the AGN-201 reactor, reactor console, DAS, and the AGN-201 DT. While the AGN-201 DT is in the cloud, it is still considered an integral hardware component. The AGN-201 reactor is the nuclear chain reaction that provides sensor data to the reactor console and DAS system. From the monitoring side, additional hardware would be the use of a holo-lens to view the augmented reality feed.

5.3.1.4 INL HPC

The INL HPC is used to run high-fidelity physics simulations of the AGN-201 reactor. These simulations are run in Serpent. Data from these simulations are used to train the SM to provide a real-time assessment of the reactor physics.

The INL HPC is also used to train the ML models, or more specifically the RNN model.

5.3.2 Use of the Proposed System

The AGN-201 DT is not required for normal operations of the AGN-201. Along with this, the AGN-201 does not interfere with any safety system requirements and does not require special permissions to operate. The AGN-201 DT may be disconnected or removed at any time, and the reactor facility must opt-in each time the AGN-201 DT is operated.

The AGN-201 DT serves as a mechanism to test how DTs can be utilized for remote monitoring of a reactor facility. Remote monitoring consists of predicting how a reactor should be operating based on its current state and determining if an anomalous event has occurred during operation. These two components are intended to reflect how the AGN-201 DT could be expanded to a larger reactor system and used to monitor the system for international nuclear safeguards.

To perform this mission, the AGN-201 DT ingests data from the DAS during operations and feeds these data to the ML and reactor physics adapters. The ML and reactor physics adapters use these data to make predictions about the state of the reactor. For ML, we compare previous predicted operational parameters (power for Channel 2, power for Channel 3, coarse control rod height, etc.) with the live data to determine if they match. The IFML monitors the data for anomalies. The reactor physics SM pulls in the data and determine if the reactor is in an expected critical state.

The AO is tasked with turning on the AGN-201 DT. This involves turning on the DAS system, turning on the computer which houses the Jester software, and starting Jester. Upon completion of an operational run, the AO will then shutdown Jester and turn off the computer. All other class members do not have formal interactions with the AGN-201 DT during operations.

The AGN-201 DT will periodically be updated with new reactor physics models and ML models and may have updates to the overarching DeepLynx system. This is currently communicated verbally and via written communication with the ISU reactor operations team. Currently, the AGN-201 DT does not provide this feedback within the system.

5.4 User Classes and Other Involved Personnel

5.4.1 Organizational Structure

The ISU AGN-201 reactor is an NRC license research reactor, which involves a stringent organization structure to ensure safe operations. With the inclusion of the AGN-201 DT, additional INL personnel are added to the structure in a non-safety related monitoring role. To help distinguish roles and responsibilities surrounding the AGN-201 DT, three classes of users were deemed necessary:

- Primary user: directly interacts with the AGN-201 DT via the GUI, raw data, etc.
- Secondary user: indirectly interacts with the AGN-201 DT, which could include obtaining results form a primary user based on the AGN-201 DT.
- Tertiary user: a broad stakeholder in the AGN-201 reactor or AGN-201 DT.

Key roles at the AGN-201 include:

- Reactor safety committee—responsible for the safe operations of the AGN-201, determines if reactor can be placed in an operable state after an incident. The reactor safety committee would be a secondary user since they can determine the safety of the reactor but are not responsible for operating the reactor or the DT.
- University officer—administrative office responsible for the university and in whose name the application for the licensing is made. The university officer would be considered a tertiary user since they would know about the AGN-201 DT and can make decisions about the operations and licensing, but they do not actually interact with the reactor or DT themselves.
- Dean, College of Engineering—administrative officer responsible for the operation for the college of engineering. The Dean would be considered a tertiary user since they about the AGN-201 DT and can make decisions about the use of the DT for the College of Engineering, but they do not actually interact with the DT themselves.
- AO—allowed to manipulate the controls of the AGN-201 reactor. An AO would be considered a secondary user since they operate and control the reactor but do not interact with the DT.
- Reactor administrator—responsible for the operation of the AGN-201 reactor facility, this individual may be an AO. The reactor administrator would be considered a secondary user since they are responsible for the operation of the reactor but do not interact with the DT.
- Reactor supervisor—oversees day-to-day operations of the AGN-201 and ensures the facility maintains all necessary maintenance and checks in accordance to its license; this individual may be an AO. The reactor supervisor would be considered a secondary user since they oversee the day-to-day operations of the reactor but do not interact with the DT.

- Senior reactor operator—allowed to perform maintenance and responsible for operating the reactor; this individual is an AO. The senior reactor operator would be considered a secondary user since they can operate and maintain the reactor but do not interact with the DT.
- Reactor operator—responsible for operating the reactor, this individual is an AO. The reactor operator would be considered a secondary user since they can operate the reactor but do not interact with the DT.
- Certified observer—responsible for ensuring the reactor can be placed in a safe state if the individual operating the reactor is incapacitated. The certified observer would be considered a secondary user since they ensure the reactor can be placed in a safe state but are not specifically controlling the reactor.
- NRC—provides an operating license to ISU to allow for the operation of the AGN-201 under the current technical specifications. The NRC would be a tertiary user since they allow ISU to operate the reactor but do not interact with the reactor or DT themselves.
- First responders—provide medical, fire, or police assistance in the event of an emergency scenario. First responders would be a tertiary user since they may be aware of the reactor but do not interact with it or the DT.

  Additional AGN-201 DT roles include:

- INL monitor—assess the data coming from the AGN-201 DT to determine if anomalous behavior has been detected and needs to be reported. The INL monitor would be a primary user since they interact with the DT.

Table 2. Interaction map for the AGN-201 DT.

AGN-201	AGN System Data from the following systems (ASD): fine and coarse control rod heights; Temp of reactor pool; Channel 1 (count rate); Channel 2 (log power output); Channel 3 (linear power output); Inverse period (reactor power rate of change)	Full ASD data set									
	Digital Twin			Real time (5s) full ASD; historic data; DT model outputs (5s); informs of anomoly via web interface							
Startup; Manipulates power; Shutdown	Initiates data flow to cloud (i.e., DAS and adapter); Stops data flow to cloud.	Authorized Operator / Reactor Operator		Inform AO of anomaly			Informs failure	Informs failure		Informs emergency	Indident reporting
			Certified Observer				Informs failure	Informs failure		Informs emergency	
	Ensures proper start up and data flow; Analyzes data	Current: Inform of anomaly via standard communication methods (e.g., email, teams, or phone). Historic data		INL Monitor							
License; operation of facility; recovery after accident	Approves use				ISU Administration		Informs failure	Informs failure	Informs license violation	Informs emergency	
						Reactor Administrator	Informs failure	Informs failure		Informs emergency	
Directs operation; directs maintenance		Directs operations			Informs failure		Reactor Supervisor	Informs failure	Incident reporting	Informs emergency	Informs failure
								Senior Reactor Operator		Informs emergency	Indident reporting
Provides license and regulations, Inspection and oversight, Emergency preparedness, Safety Assessments, and Decommissioning		Operator License, regulatory compliance, training and certification, Ongoing Oversight, Incident reporting, enforcement			Provides license		Licensing, regulatory compliance, training and certification, professional development, ongoing oversight, enforcement	Operator License, regulatory compliance, training and certification, Ongoing Oversight, Incident reporting, enforcement	NRC	Emergency preparedness planning, training and excersises, information sharing, regulatory oversight, Radiological monitoring and assessment, mutual aid agreements	Regulatory compliance, inspections and audits, radiation monitoring and reporting, training, licensing
		Provide assistance	Provide assistance		Provide assistance	Provide assistance	Provide assistance	Provide assistance	Emergency preparedness planning, training and excersises, information sharing, mutual aid agreements	First Responders	Training and education, information exchange, joint drills and excerises, collaborative response planning, on-site support, radiation monitoring and assessment, post-incident evaluation
Approves state of reactor		Collaborative safety oversight, trainings and certification, compliance, joint emergency response, must maintain open lines of communication and collaboration			Approves state of reactor		Approves state of reactor	Collaborative safety oversight, trainings and certification, compliance, joint emergency response, must maintain open lines of communication and collaboration	License applications, radiation safety protocols, training programs, incident reports, radiation motitering data, inspection and audit reports, any changes in the facility	Information sharing, joint trainings and drills, notification and alerts	Radiation Safety Committee

5.5 Modes of Use

The following modes represent the anticipated scenarios to be experienced by the AGN-201 DT:

- Startup
- Normal operation
- Maintenance
- Anomaly detection
- Historian
- Emergency.

Currently, the AGN-201 DT only has a function with five of the six modes; the emergency mode has no interaction with the AGN-201 DT. The remaining scenarios are distinguished in the various ML and SM adapters found within the AGN-201 DT, but the general framework does not state what scenario the system is in.

5.5.1 Startup

To start the AGN-201, a series of preoperational checks must be completed to ensure the reactor is in an operational condition to proceed. This includes ensuring all lines of communication between the reactors sensors and the control console are functioning properly. The DAS system and computer housing Jester can be turned on to ensure communication with the AGN-201 DT is established before, during, or after the preoperational checks.

Once the initial checklist has been concluded and the reactor is deemed operational, a reactor startup can be performed. This involved inserting control rods into the core to bring the reactor to a critical state at roughly 10 mW. Normal operations then ensue. During the startup period, reactor data are continuously being uploaded to DeepLynx in the standard 5 second interval. This interval was selected as it allows for near real-time monitoring.

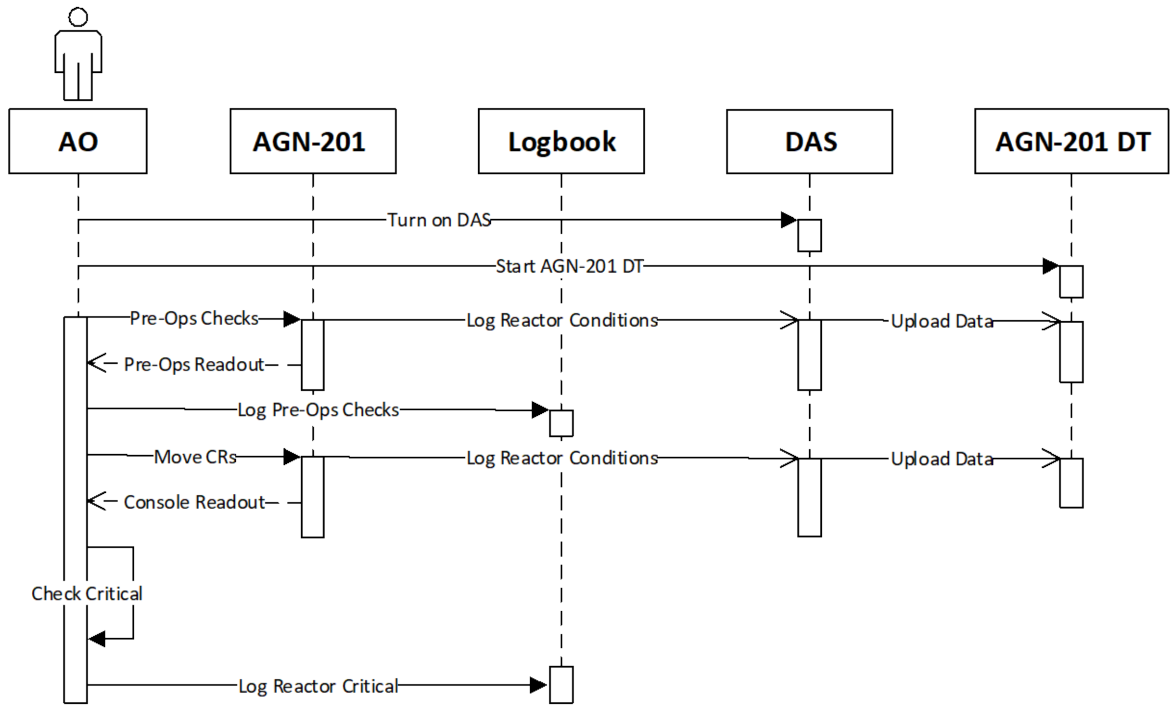

Figure 7. Sequence diagram for startup when the AGN-210 DT is included.

5.5.2 Normal Operations

The normal operations scenario includes the reactor operating in steady-state and transient conditions. Steady state occurs when the reactor is critical at a desired power level and remains at this power level for a period of time. The steady-state scenario can range in power from < 0.1 mW up to 5 W. After initial critical during startup, a transient scenario is required to change the power of the reactor. A transient occurs when the reactor deviates from its critical condition in the steady-state scenario. This means the reactor is either increasing or decreasing in power. The transient scenario can be initiated by multiple events, including control rod movement or experimental insertion and removal.

Normal operations would also cover the reactor being shut down due to a scram and the reactor console being deenergized. A scram can either occur on purpose or be caused by a reactor sensor being in an unauthorized or unsafe state. A list of scram conditions are:

- Manual—depression of the manual scram button
- Channel 1 Lower Power—channel drops below 0.5 counts/second
- Channel 2 Low Power—power drops below 3.0×10^{-13} amps
- Channel 2 High Power—power exceeds 6 W
- Channel 3 Lower Power—power drops below 5% of full scale
- Channel 3 High Power—power exceeds 6 W
- Period—reactor period less than 3 seconds
- Seismic—lateral force of 0.6 g acceleration

- Power—loss of power to the console
- Water temperature—temperature falls below 15°C
- Water level—water level falls below 10 inches of the highest point.

During steady-state operations, data from the DAS are sent to DeepLynx in 5 second intervals, where the various adaptors continuously run to determine if the operational state that the reactor is currently in matches the predicted states obtained by the ML and SM. The reactor condition (steady state, transient, and shutdown) affects how the DT interacts and makes predictions on the data, as this fundamentally affects the physics occurring. The DT utilizes a Python script to determine when the reactor is critical, which initiates the SM/ML adapters. Once the same Python script detects when the reactor is shutdown, it ceases to transmit data to the DT

Once the reactor has been shut down, the AO will turn off both the DAS and computer housing the AGN-201 DT. During operations, the INL monitor may use the AGN-201 DT to examine the operational status of the reactor. If an anomaly occurs, the state of the AGN-201 DT will transition to "anomaly detection" mode.

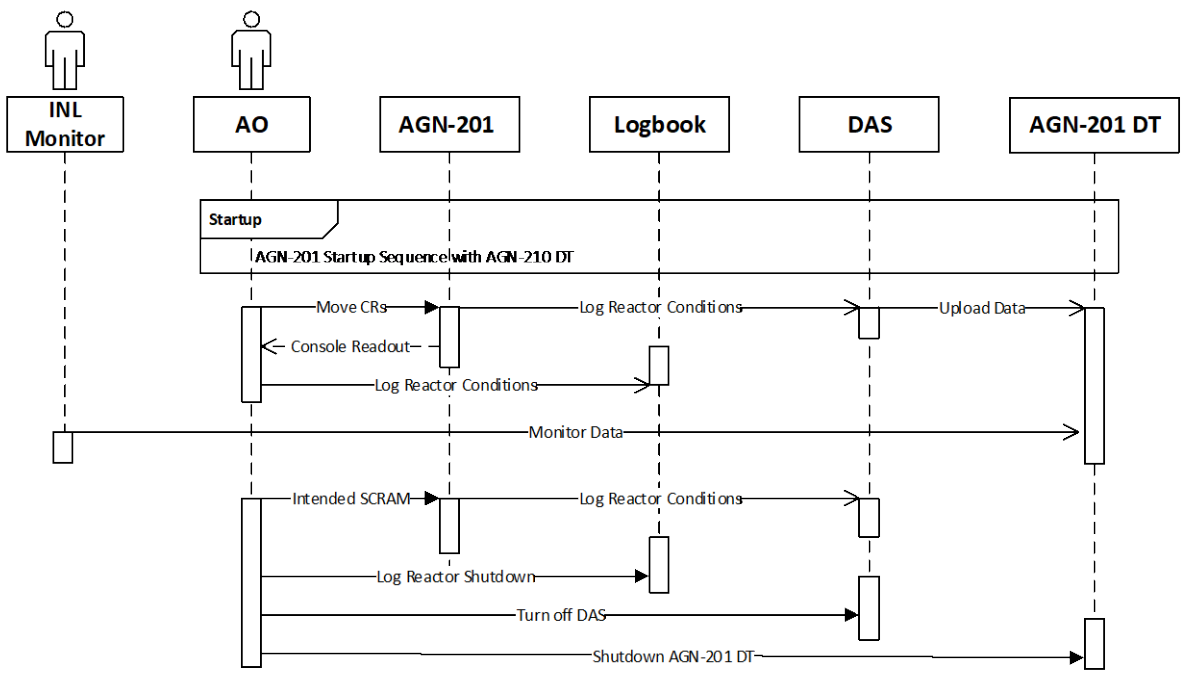

Figure 8. Sequence diagram for normal operations with the AGN-201 DT.

5.5.3 Anomaly Detection

The reactor will normally operate within the "normal operations" mode. There may be times when an anomaly is initiated either on purpose or accident. These events can trigger the "anomaly detection" mode of operation. An outline of the sequence for how the AGN-201 triggers an anomaly can be seen in Figure 9.

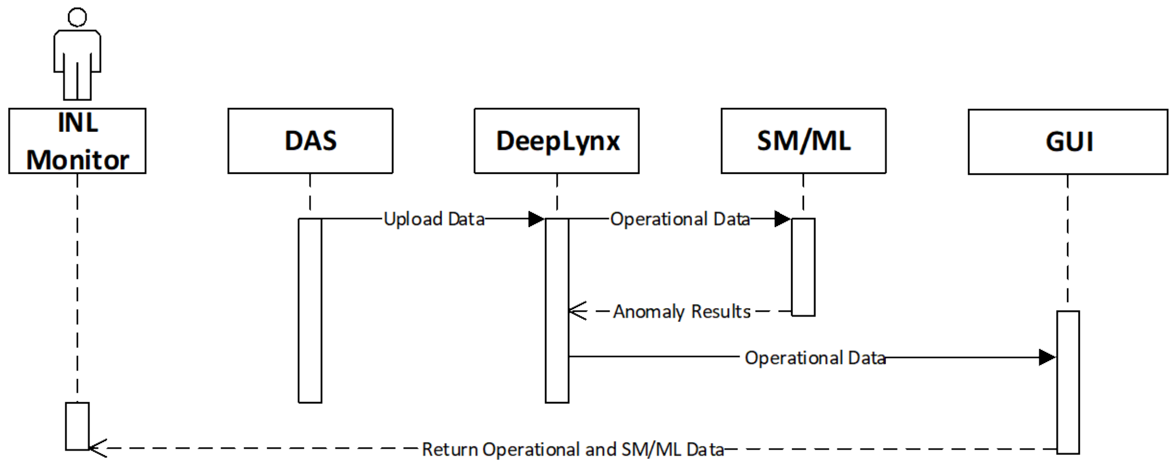

Figure 9. Sequence diagram for AGN-201 DT anomaly detection.

Anomalous events are tracked by the reactor physics SM and the IFML. The reactor physics SM examines the criticality of the reactor and determines if the reactor has deviated from the expected critical eigenvalue (k_{eff}). The critical eigenvalue is examined once the reactor is critical to determine if it is within a 2-sigma uncertainty (the 1-sigma uncertainty is 0.00018) of the historically derived critical eigenvalue (k_{eff} = 1.00164). If the critical eigenvalue is within the standard deviation, the start of the operation is declared normal.

During operations, the critical eigenvalue is continuously updated by the reactor physics SM based on the control rod heights and the temperature. If an experiment were placed in the core, this could likely cause the reactor operator to change the control rod heights, which would cause a perturbation in the critical eigenvalue. The reactor physics SM would not see the experiment being inserted, and this could cause the critical eigenvalue to deviate from the expected critical eigenvalue. If the critical eigenvalue deviates by more than 2-sigma, an anomalous event is declared.

For the IFML, reactor operations data are recursively partitioned, a process that iteratively divides the data space. A distinctive feature of this partitioning process is its randomness; given a dataset, at each node, an attribute and a split value are selected randomly. This randomness is critical, as it ensures that anomalies, which are few and differ significantly from the majority, are isolated early, thus requiring fewer splits. If an anomaly is detected, it is flagged for the operational parameter that the IFML is examining.

If any INL monitor is using the AGN-201 DT and an anomalous event is flagged by the ML and reactor physics adapters, these anomalies would be presented to the user. This would likely be highlighted by a different color in the line or a prompt that would show up on the GUI. This aspect currently has not been fully formed within the AGN-201 DT, and thus anomalous events are not automatically flagged. This currently requires manually pulling data from the AGN-201 DT, performing the anomaly detection, and providing the results to the ISU AO.

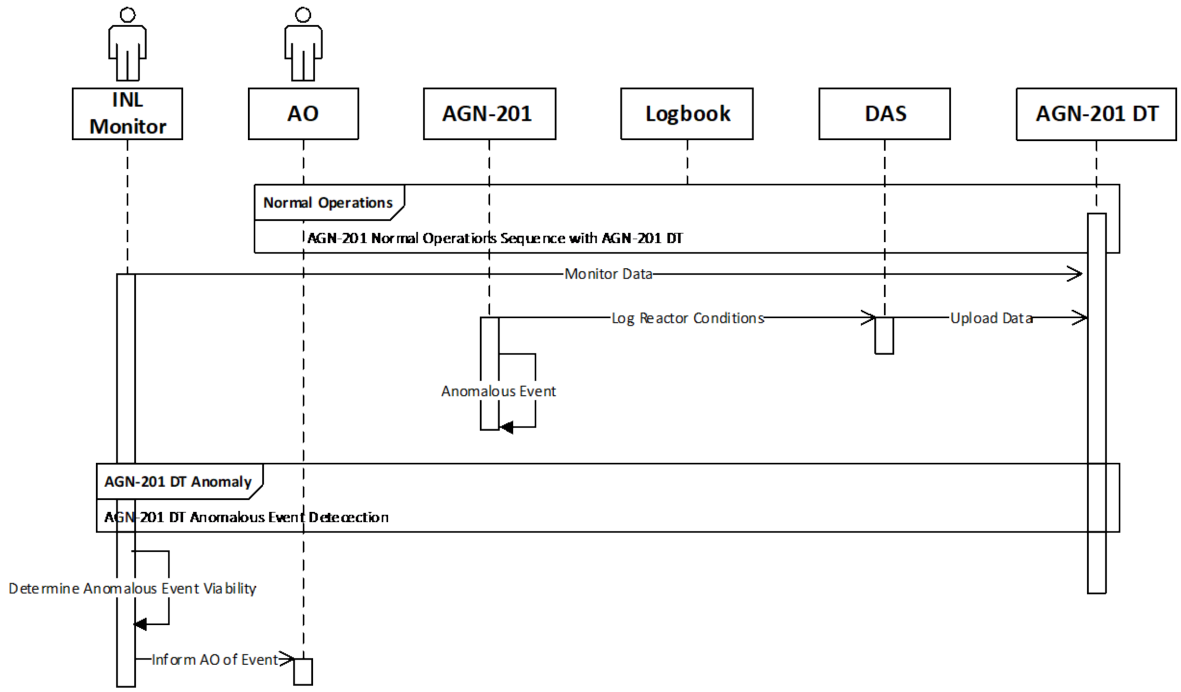

Figure 10. Sequence diagram for an anomaly detection event.

5.5.4 Historian

The historian scenario occurs when an INL monitor accesses the AGN-201 DeepLynx repository to view previous operations of the AGN-201 that were captured by the AGN-201 DT. This scenario allows for the ability to replay reactor operations, pull data from previous operations, and provide a basic graphical representation of the data ingested.

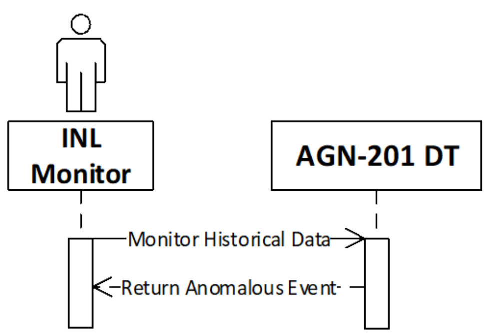

Figure 11. Sequence diagram for historian mode.

5.5.5 Emergency

The emergency scenario occurs when the reactor or its associated facility undergoes some type of accident such as a fire, radiation exposure, etc. This scenario would likely involve the inclusion of offsite personnel to assist in returning the facility to normal operating conditions. The AGN-201 DT is not meant to operate during emergency scenarios.

6. ANALYSIS OF THE PROPOSED SYSTEM

6.1 Summary of Improvements

The use of the AGN-201 DT provides a system that can monitor the AGN-201 reactor and detect anomalies. This project goal was to collect data and understand how DTs can be used for monitoring a real nuclear asset. Most of the AGN-201 DT development was built with this in mind.

The development of the AGN-201 DT kept international nuclear safeguards in mind. The project was able to show that a reactor physics model and ML models could be generated with enough fidelity to monitor the AGN-201 reactor in near real time. This culminated in a red-blue team test of the AGN-201 DT. The red team was the ISU AOs who performed a series of experiments with the reactor without informing the blue team (the INL monitors). The INL monitors took the data obtained from the test and were able to discern areas of potential off-normal operations within 15 minutes of the operations concluding.

Given the success of the project, this work could be extended to larger reactors to determine scalability for a DT in international nuclear safeguards. Along with this, the framework could be used to examine how DTs can be used in other areas of nuclear operations. If DTs are expanded into normal reactor operations, they could be used for monitoring a nuclear facility, predicting maintenance schedules, and potentially supporting autonomous operations.

The CONOPS has focused on the technical usage of the AGN-201 DT, however extending DTs to international safeguards or other areas of deployment has a major implication on the benefits and drawbacks for the system and human user.

Deploying a DT for international nuclear safeguards could have major implications in the interaction between the Internation Atomic Energy Agency (IAEA) and the state being monitored. There are likely four major pillars DT deployment would need to consider: biases, transparency, privacy, and accountability. DTs for a nuclear reactor would require detailed design information that would likely contain proprietary data and need to be controlled accordingly. If ML or a reactor physics model were to be used in assessing anomalies, care and consideration would need to be utilized to ensure trust in these models and ensure biases against a country, individual, etc. are not propagated into the DT. Along with this, some level of transparency will be required to provide a level of trust in the DT (and its subsequent components), but the IAEA must maintain a degree of separation to ensure it can perform its job independently.

Despite the aspects that would need to be addressed, the inclusion of a DT into the workflow of an IAEA inspector could help reduce their overall workload. This would be especially true if hundreds of new reactors were added worldwide and the funding for the IAEA remained nearly constant. Care would need to be taken to ensure a DT would be used appropriately. It would ideally be a tool to investigate and assess an anomaly in reactor operations and would not replace the inspector or their subject matter expertise.

To help address these concerns, the AGN-201 DT is undergoing an assessment according to the IEEE CerifAIed program to assess the four pillars. Much of the work being performed in the CerifAIed program could also be extended to other agencies as well such as the NRC. The process of evaluating the DT for bias, transparency, privacy, and accountability will foster an environment where the AGN-201 DT can be expanded to new assets with relative ease, as many of the evaluations will likely be comparable across different use cases.

6.2 Disadvantages and Limitations

The AGN-201 DT could be improved through the automatic detection of data flow failure, and methods to remediate these failures, and an automatic response to ISU operating staff when an anomaly is detected.

For future use of the AGN-201 DT, the user should be aware that they will need to make a DeepLynx account and request access to the AGN-201 data.