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DIGITAL TWINS FOR NUCLEAR SAFEGUARDS AND SECURITY: ASSESSMENT OF CHALLENGES, OPPORTUNITIES, AND CURRENT STATE-OF-PRACTICE

September 2023

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EXECUTIVE SUMMARY

This report explores the application of digital twin (DT) technologies for safeguards and security (S&S) at nuclear power plants and fuel cycle facilities. Digital twins and DT-enabling technologies are expected to integrate with future nuclear reactor designs and also have the potential to impact currently operating nuclear facilities. Expanded and advanced digital integration, instrumentation and control systems, data analytics, modeling and simulation, and operations and maintenance practices are all associated with DT-enabling technologies. This report identifies and discusses the considerations and opportunities, and potential challenges and gaps related to the application of DTs and DT-enabling technologies for nuclear S&S activities. The following are some key considerations, opportunities, challenges, and gaps discussed in this report:

Considerations and opportunities for DT application in S&S:

- **Physical inventory**: tracking historical inventory, reconciling records with physical inventory, digitally tracking special nuclear material, simulating what-if scenarios of missing or defective items, and ensuring that physical inventories meet regulatory acceptance criteria.
- **Perimeter intrusion detection system (PIDAS)**: automated classifying of nuisance alarms across different sensor modalities, leveraging sensor self-diagnostics to meet regulatory requirements for periodic testing, detecting anomalies and predicting sensor failures.
- **Security-by-design**: identifying gaps in addressing design basis threats, incorporating security-by-design into the facility, planning and preparing for changes in design basis threat and upcoming security scenarios.

Challenges and gaps related to DT for S&S:

- **Increasing realism in modeling and simulation**: developing technology and approaches for increased understanding and knowledge of S&S scenarios, understanding, and analyzing attack vectors and real-time changes in S&S for a facility, identifying quantities and parameters that best represent integrated S&S postures and performance.

- **Verification and validation of S&S DT**: producing high-quality and high-fidelity test data for integrated models especially for future facilities, developing integrated testing methodologies for complex model interactions, validating performance testing over the lifecycle of facility, developing training datasets and integrated models and simulations that usefully represent important S&S features.
- **Integrating advanced sensors for S&S DT**: supporting data heterogeneity when integrating existing sensors with S&S DT, identifying gaps in sensor deployment and sensitivity from adversary testing, integrating cybersecurity into advanced sensors and communication technology.

Digital twins in complex industrial and engineering applications have proven benefits that include increased operational efficiencies, enhanced safety and reliability, reduced errors, faster information sharing, and better predictions. The interest in DT technologies continues to grow, and the technology is expected to experience rapid and wide industry adoption in the next decade. Additional effort is needed from interested stakeholders to meet the challenges and bridge the gaps in implementing DTs for S&S at currently operating and future nuclear facilities.

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ACRONYMS

AI	Artificial intelligence
ANSI	American National Standards Institute
AR	Advanced reactor
CAS	Central alarm station
DBT	Design Basis Threat
DMA	Deliberate motion analytics
DT	Digital twins
FoF	Force-on-force
HALEU	High-Assay Low-Enriched Uranium
ICA	Item control area
ID	Inventory difference
IDS	Intrusion detection system
INL	Idaho National Laboratory
JCAS	Joint or integrated Central Alarm Station
LWR	Light-water reactor
M&S	Modeling and simulation
MC&A	Material Control and Accounting
ML	Machine learning
NPP	Nuclear power plants
NRC	Nuclear Regulatory Commission
O&M	Operations and maintenance
ORIGEN	Oak Ridge Isotope GENeration
ORNL	Oak Ridge National Laboratory
PIDAS	Perimeter intrusion detection and assessment system
PPS	Physical protection system
PRA	Probabilistic risk assessment
S&S	Safeguards and security
SAS	Secondary alarm station
SEID	Standard error of inventory difference
SNM	Special nuclear material
SME	Subject matter expert
SSC	Systems, Structures, and Components
TRISO	TRi-structural ISOtropic
UQ	Uncertainty quantification
V&V	Verification and validation

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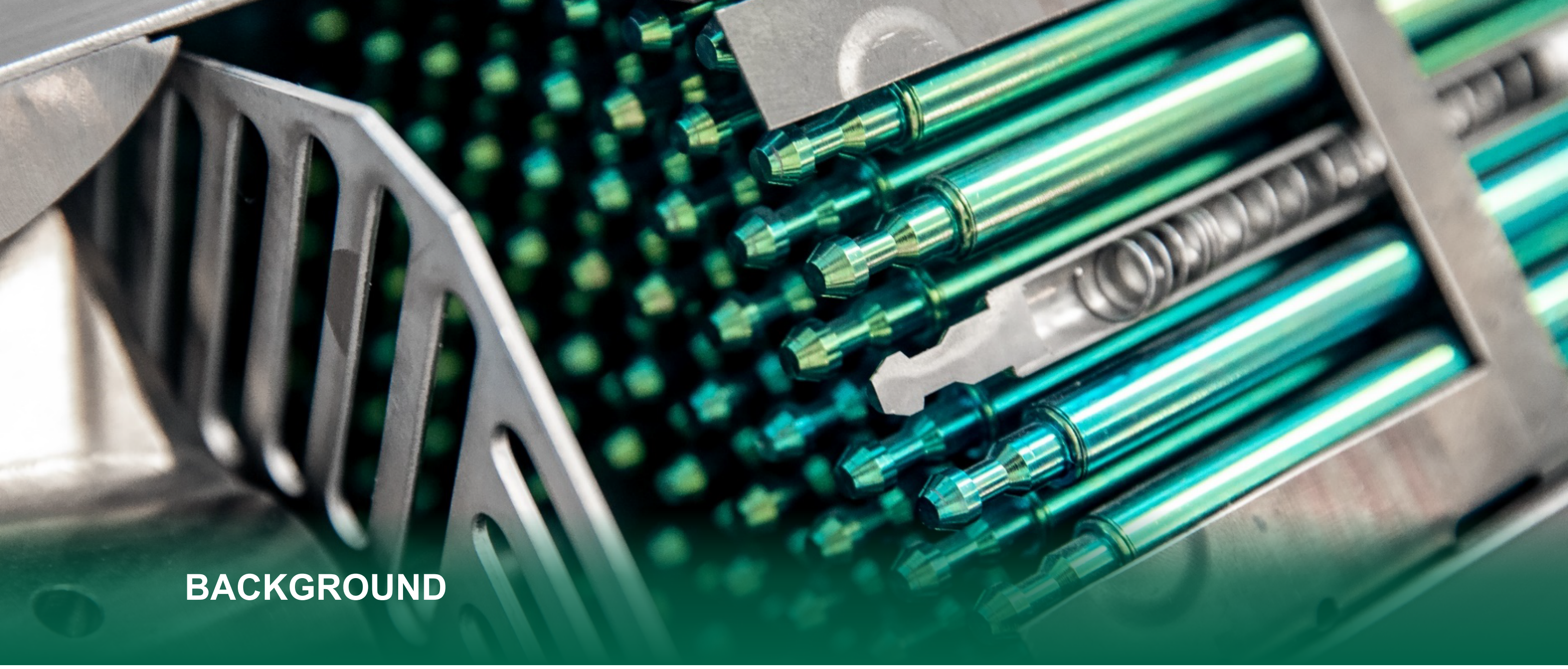
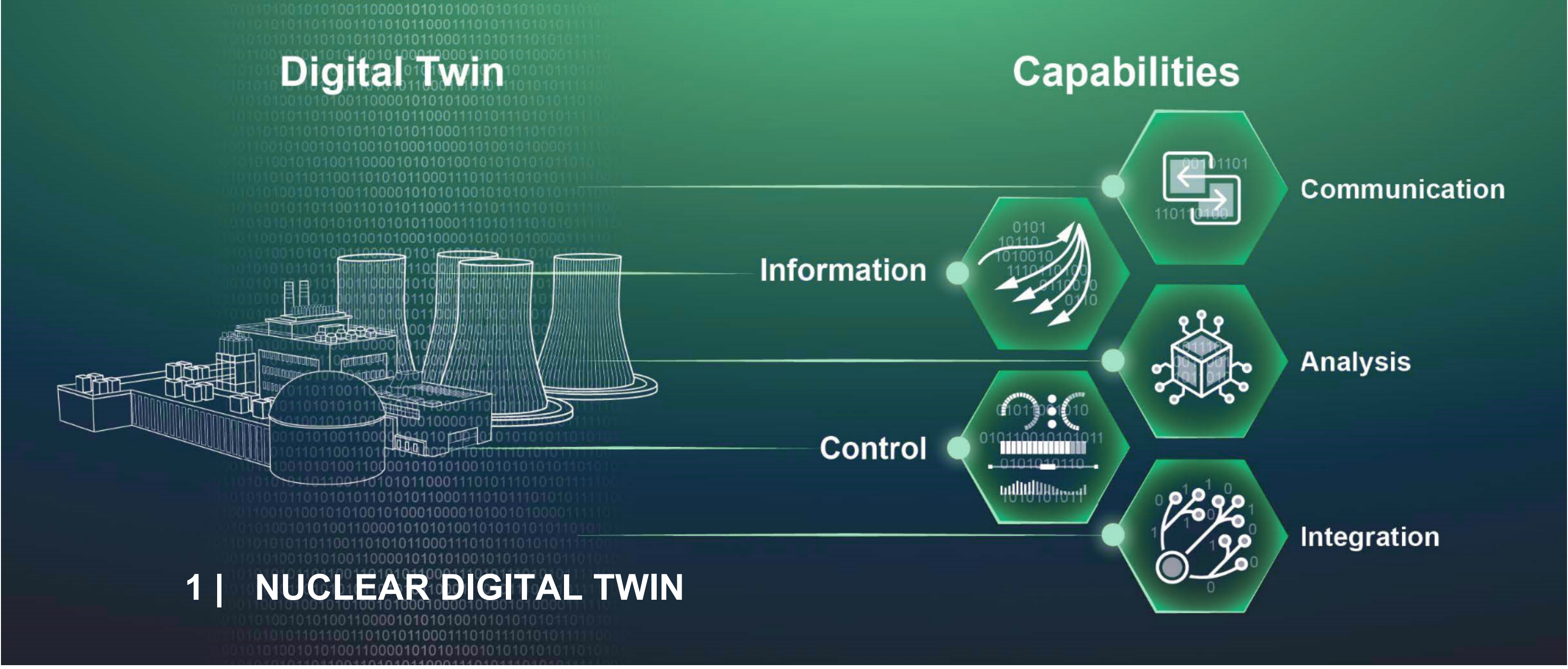


BACKGROUND

Staff in the Office of Nuclear Regulatory Research at the United States Nuclear Regulatory Commission (NRC) recently completed a future-focused research project aimed at assessing the regulatory viability of digital twins (DTs) for nuclear power plants (NPPs). Idaho National Laboratory (INL) led this project in collaboration with Oak Ridge National Laboratory (ORNL). The project and subsequent follow-on activities included conducting a comprehensive state-of-technology assessment of DT-enabling technologies [1], engaging stakeholders in the form of workshops and public meetings [2, 3, 4], identifying challenges and gaps in the application of DT-enabling technologies [5], developing a DT problem space for nuclear energy applications [5], identifying areas that may benefit from future regulatory focus [6], and assessing the challenges and gaps associated with integrating advanced sensors, instrumentation, and communication technology with DTs in nuclear energy applications [6]. The NRC continues to assess the regulatory viability of DTs for NPPs and fuel cycle facilities by identifying and evaluating technical and regulatory challenges associated with implementing DTs in nuclear energy applications.

The focus of this report is to discuss the considerations and opportunities and identify potential challenges and gaps related to applying DTs and enabling technologies in safeguards and security (S&S) activities at nuclear facilities. The NRC's domestic safeguards program is aimed at ensuring that special nuclear material (SNM) within the United States is not stolen or otherwise diverted from civilian facilities for possible use in clandestine fissile explosives and does not pose an unreasonable risk owing to radiological sabotage [7]. The users of the SNM and certain quantities of byproduct material apply safeguards to protect against sabotage, theft, and diversion, including the physical protection of facilities and/or SNM, and material control and accounting (MC&A) for SNM. Section 1 presents a brief overview of the DT-NPP problem space and DT-enabling technologies, Section 2 provides a brief discussion on S&S activities at nuclear facilities, Sections 3 and 4 present a detailed discussion on opportunities and considerations of DT for safeguards and security, respectively, and Section 5 presents a discussion on potential challenges and gaps associated with DT application for S&S.



1 | NUCLEAR DIGITAL TWIN

A unified definition of a DT does not exist yet in literature because various interpretations of a DT may exist based on different technologies, applications, or other criteria. However, it is possible to define some main characteristics of a DT. A recent report published by the NRC [6] identifies the following four characteristics of a nuclear DT system (Figure 1):

1. **Exists in Digital Form:** The technologies and information that form part of a DT must exist in a digital form that can be managed, processed, communicated, and executed using digital technology. It is important that this characteristic be explicitly defined for applications in the nuclear industry, which has a legacy of information sharing via nondigital formats (e.g., paper).

2. **Maintains State Concurrence:** The DT must be able to update dynamically to represent the current state of a physical entity or phenomenon, and it must be able to maintain that state. This vital condition differentiates a DT from an existing modeling or simulation capabilities that can run in digital form but do not maintain concurrence with the actual system in real time.

3. **Ensures State Cognizance:** The DT must be able to provide new and integrated sets of insights, information, relationships, and outcomes—all pertaining to the physical entity being twinned, and all made possible, feasible, or efficient with DT technology. State cognizance is an important characteristic that ensures DTs do not simply recreate preexisting capabilities but add a unique and novel value to the selected application.

4. **Serves an Underlying Purpose:** The technology must have an underlying purpose related to an NPP life cycle activity, and that purpose should inform decisions about the system or component represented.

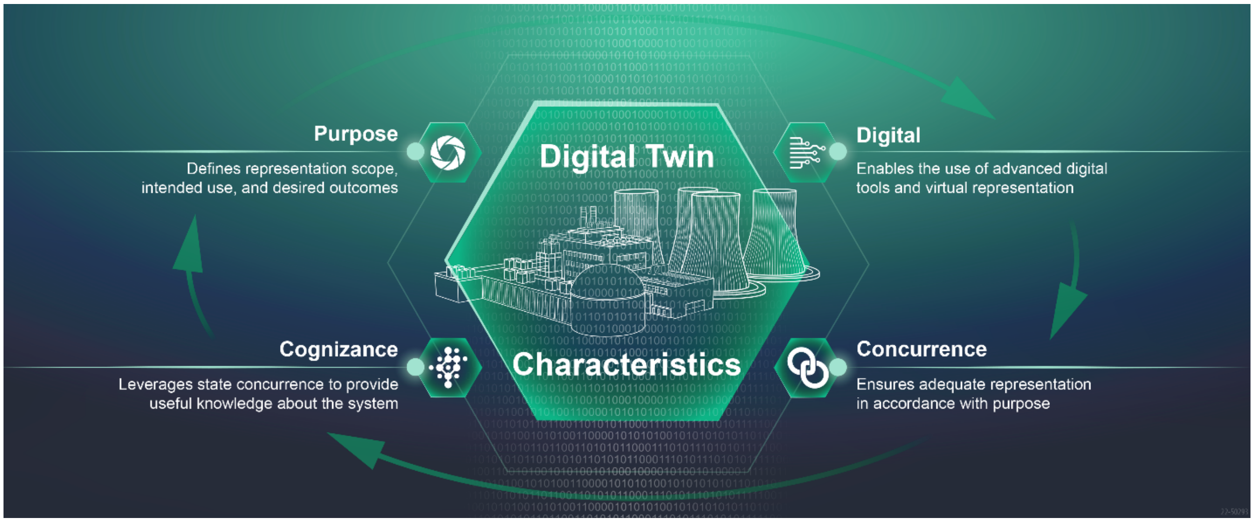


Figure 1. The four characteristics of a nuclear digital twin system. [6]

A DT system for NPP as illustrated in Figure 2 is described in [6] to comprise four broad elements detailed below.

The Nuclear Power Plant: NPPs contain complex physical entities that can be categorized in numerous ways, depending on their objective and purpose. From a DT system perspective, these entities can be categorized into the five broad technical areas: (1) physical assets: these are commonly known as systems, structures, and components (SSCs) which include structures such as reactor and plant buildings, systems (e.g., cooling, feedwater, power generation, and electrical systems), and thousands of mechanical, electrical, and other types of components, including pumps, motors, valves, chillers, circuit breakers, compressors, fans, and batteries; (2) physical phenomena: natural processes such as reactor thermal hydraulics, corrosion, and concrete degradation that influence both plant performance and changes to plant states; (3) advanced sensors and instrumentation including powering requirements and communication or data transfer infrastructure (e.g., cable or wireless technologies) [6]; advanced sensors and instruments may provide a means for novel and efficient NPP control including potential future DT capabilities to autonomously influence NPP operational states; (4) computing and networking systems including both hardware and software for enabling regular plant operation and maintenance (O&M) and ranges from complex computing clusters to simple handheld devices; and (5) procedures and human actions which includes normal reactor operations, refueling, engineering, maintenance, safe shutdown, chemical control, etc., as well as include control actions. These actions can be continuous (e.g., procedural operator actions to control power) or periodic (e.g., scheduled testing, maintenance, and upgrades).

Among the five broad entities in an NPP, the physical assets, physical phenomena, and procedures and human actions can be considered as those that can be potentially represented in digital form resulting in their respective DTs. The other two entities, advanced sensors and instrumentation and computing and networking systems, would be required not only for plant operations but also to enable and support the DTs of NPP assets, phenomena, and procedures.

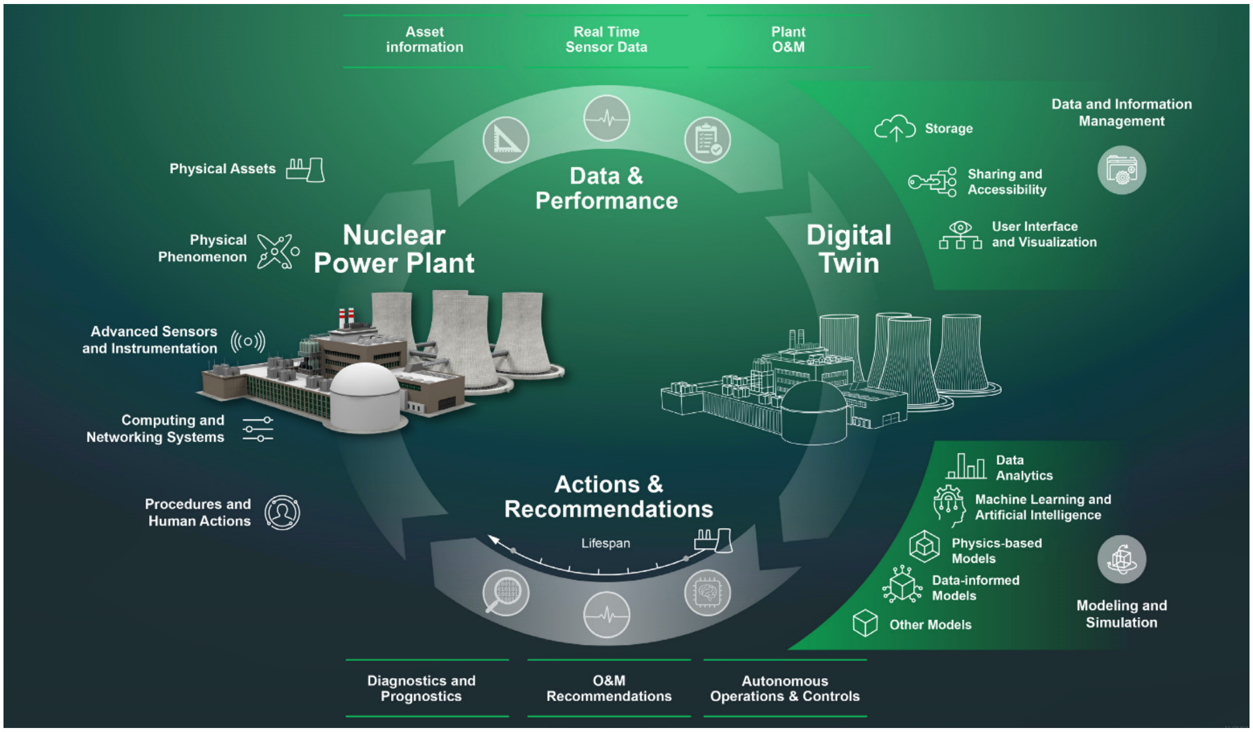


Figure 2. Description of digital twin for nuclear power plant applications [6].

Digital Twin: A DT is a representation of one or a collection of entities in NPP that meet the DT characteristics described earlier. For a DT to exist, especially in an NPP, certain technologies are required which are classified by [6] into two broad technological categories, modeling and simulation (M&S), and data and information management. M&S is described in [6] as consisting of one or more of the following: data analytics, machine learning (ML), artificial intelligence (AI), physics-based models, data-informed models, and other types of models, such as probabilistic risk assessment models. Data and information management encompasses infrastructure for gathering, processing, and disseminating information in a logical, organized manner that complies with all applicable requirements and presents information to users and computer interfaces in a manner that can be clearly visualized, absorbed, and verified for integrity and correctness. This includes data storage systems, such as local plant servers, fleet-wide data infrastructure, and cloud-based storage systems; software solutions to ensure seamless integration of the heterogeneous plant data, uninterrupted data availability, and real-time interaction across DT models and data storage; and user interfaces beyond main control room, such as a plant monitoring and diagnostic center, a M&S interface, and even handheld digital devices.

Data and Performance: Information on the plant, its SSCs, physical phenomena, procedures, actions, and sensor/instrumentation data is vital for enabling sustained, accurate, reliable, and efficient DT operation. Asset information includes dimensions, geometries, topologies, materials, chemical makeups, etc., all depending on factors such as SSC type/function and the requirements of the digital representation. Real-time data acquisition in NPPs is intended to primarily support NPP control room information (e.g., reactor power level and pressurizer level/pressure), and for the rest of the plant, it is aimed at ensuring safe, reliable operation of SSCs and is mostly performed both manually and periodically. Advanced digital sensors that foster wireless capabilities, high bandwidths, and quick installation enable real-time data acquisition and a large number of sensor modalities (e.g., vibration, temperature, pressure, flow rate, voltage, and current) on a much larger and more diverse subset of plant SSCs. Data about plant O&M activities include corrective and preventive work order logs, outage logs, and licensee event reports that provide comprehensive details on O&M activities—details that can be valuable to DT applications.

Actions and Recommendations: The objective in implementing a DT system is to provide actions and recommendations for safe, reliable, and efficient operation. To this end, [6] classifies DT actions and recommendations into diagnostics and prognostics, O&M recommendations, and autonomous operations and controls. Diagnostics and prognostics, such as anomaly detection, identification of sensor malfunctions, differentiation between true anomalies and sensor malfunctions, failure prediction, and critical event prediction, can be enabled in real time by DTs and thus provide plant staff with real-time notification and recommendations regarding emergent or future conditions. Predictive algorithms in DTs can go beyond diagnostics and prognostics to generate recommendations for efficient O&M practices.

2 | SAFEGUARDS AND SECURITY ACTIVITIES AT NUCLEAR FACILITIES

1.1 Safeguards

The term “safeguards” has various domain-dependent meanings. This section will discuss some of the meanings and clarify how the term “safeguards” will be used within this report especially in reference to common NRC definitions. The U.S. NRC defines *safeguards* as (1) the use of MC&A programs to verify that all SNM is properly controlled and accounted for, as well as (2) the physical protection (or physical security) equipment and security forces; safeguards information is (3) a special category of sensitive unclassified information that must be protected [8]. Safeguards information concerns the physical protection of operating power reactors, spent fuel shipments, strategic SNM, or other radioactive material. The NRC further defines materials control as the use of control and monitoring measures to prevent or detect SNM loss when it occurs or soon afterward [9]. Material accounting is the use of statistical and accounting measures to maintain knowledge of the quantities of SNM present in each area of a facility. It includes the use of physical inventories and material balances to verify the presence of material or to detect the loss of material after it occurs; in particular, through theft by one or more insiders [9]. The term safeguards when used in the rest of this report will refer to the first NRC definition of safeguards focused on the use of MC&A programs to verify that all SNM is properly controlled and accounted for, unless specifically noted otherwise [10].

The NRC uses a graded approach for the safeguards of SNM [11], based on the type and quantity of material, using the following material categories: Category I: strategic SNM, Category II: SNM of moderate strategic significance, and Category III: SNM of low strategic significance [11]. In practice, this categorization is applied to fuel cycle facilities or other licensees that handle large quantities of SNM in bulk form. Nuclear reactors licensed under 10 CFR Part 50 are excluded by rule from the more rigorous MC&A requirements due to the nature of the SNM in fresh and spent nuclear fuel. Control and accounting for SNM at nuclear facilities could be straightforward when the material is maintained in the form of readily identifiable fuel assemblies that can be managed on a per-item basis. However, challenges in MC&A can arise when SNM is not managed in the form of identifiable fuel assemblies, such as SNM at fuel cycle facilities or in case fuel rods become separated from the parent assembly at NPP. The NRC

Regulatory Guide 5.29, “Special Nuclear Material Control and Accounting Systems for Nuclear Power Plants," provides the American National Standards Institute (ANSI) standard ANSI N15.8-2009 as an acceptable approach for MC&A system at NPPs to meet the NRC MC&A performance requirements [31]. The ANSI N15.8-2009 provides guidance on the control and accounting of (1) fuel rods that are separated from their parent assemblies and (2) pieces of irradiated material that are separated as a result of fuel damage [24]. The nuclear fuel in light-water reactors (LWRs) and research and test reactors is typically contained in discrete assemblies that can be treated as items for MC&A purposes, in contrast to the bulk material processed in fuel cycle facilities and some proposed advanced reactor (AR) designs.

An NRC-approved MC&A system at a licensee has three general performance objectives: (1) confirm the presence of SNM, (2) resolve indications of missing SNM, and (3) aid in investigation and recovery of missing SNM [8]. The following is a list of MC&A activities that are typically performed by a licensee toward meeting the general performance objectives:

- Maintain a reliable SNM measurements system
- Maintain a SNM measurement control system
- Maintain an effective statistical program
- Perform periodic physical inventories
- Maintain an item control system
- Conduct and document shipper-receiver comparisons for SNM
- Perform independent assessment of the MC&A program
- Maintain and follow tamper-safing procedures for SNM storage
- Appropriate designation of MC&A boundaries and areas
- Resolving indications of SNM loss
- Investigation and recovery of missing SNM
- MC&A recordkeeping
- Alarms and reporting

These MC&A activities are performed across various nuclear facilities such as commercial NPPs and fuel cycle facilities. On the interaction with MC&A experts, it is recognized that some of these activities are more relevant than others for nuclear reactor facilities. The MC&A activities discussed in this report were identified to ascertain potential opportunities DTs may provide for effectiveness and efficiency gains.

1.2 Security

The 10 CFR 73.55 [13] prescribes requirements for the establishment and maintenance of a physical protection system (PPS) that will have capabilities for the protection of SNM, whether in transit or at fixed sites including NPPs. The NRC regulation requires each nuclear power reactor licensee to implement the requirements of 10 CFR 73.55 [13] through its NRC-approved physical security plan, training and qualification plan, NRC safeguards contingency plan, and cybersecurity plan referred to collectively hereafter as “security plans.” These regulatory requirements are intended to establish and maintain a physical protection program that protects the facility against the design basis threat of radiological sabotage, i.e., significant core damage and spent fuel sabotage in 10 CFR 73.1(a)1 [13] and theft or diversion of SNM in 10 CFR 73.67 and 73.46 [13].

The physical protection program is implemented through a security organization; using security equipment and technology, such as an intrusion detection system with sensors and barriers; training and qualification of security personnel; administrative controls; implementing predetermined response plans and strategies; and protecting digital computer and communication systems and networks [14]. The nuclear power reactor licensee is responsible for maintaining the on-site physical protection program in accordance with NRC regulations through implementing security plans and written security implementing procedures. The design of the physical protection program is focused on a series of target sets that require protection.

The nuclear industry approach to maintaining effective security at a nuclear facility includes various security programs [14], each with their own individual objectives that when combined provide a holistic approach to maintaining the effective security of the plant. The facility’s protected area is encompassed by physical barriers, such as one or more chain-link fences and is restricted to authorized personnel. The area is primarily protected by the perimeter intrusion detection and assessment system (PIDAS), a sophisticated and complex system along the border of an NPP that consists of a dual fence line forming an isolation zone, intrusion sensors, an alarm system, communication system, video cameras, video display, and alarm station personnel. The objective of a PIDAS is fast detection and assessment of movement through the isolation zone, where assessment is the accurate resolution of a sensed condition from the intrusion detection system [14]. The resolution will be one of three conditions: (1) an intrusion, (2) a false alarm, or (3) nuisance alarm (e.g., tumble weeds impacting a taut-wire system).

Assessing the effectiveness of a licensee’s physical protection program is vital for that licensee to ensure their security is capable of preventing adversarial attempts of causing radiological sabotage. Licensees use several techniques for assessing physical security effectiveness, such as force-on-force (FoF) drills and exercises, tabletop exercises, and M&S. The current landscape of available M&S tools consists of several different levels of functionality and analysis capabilities from spreadsheet-based tools that only analyze adversary pathways to next generation tabletop creation tools to 3D-capable tools, where analysts can model an entire facility in 3D, characterize the model with real-world values for detection, delay, and response, and run highly detailed combat simulations [15,16,17]. Tools use common algorithms to compute likely adversary pathways using factors such as fastest traversal, least probability of detection or neutralization, and most vulnerable or minimum probability of interruption, which is usually based on speed and probability of detections along a given pathway. Some tools automatically compute the critical detection point, which is the last point of detection along a given adversary pathway where the calculated guard response time will be sufficient to interdict the adversary before they can complete their objective of SNM theft, radiological sabotage (i.e., destruction of a target set), or both [18].

Tools that simulate complex combat engagements offer a wide variety of settings the analyst can use to simulate opposing force engagements. These tools can model adversary pathways, guard response tactics, rudimentary human behaviors, vehicle movement, multiple barrier breaches, and different adversary capabilities either within or beyond the design basis threat (DBT) which describes the type, composition, and capabilities of an adversary (e.g., equipment, training, and weapons) against which a licensee must protect its systems. This class of tools normally creates very large data sets by running thousands of attack scenarios, and comparing and contrasting the common data in each [15]. Threat modeling allows operators to explore scenarios and pathways that may be challenging to test using exercises due to safety considerations as well as supporting a security-by-design approach by modeling the effects of security requirements on the safety operations within a plant. M&S capabilities could be extremely impactful in testing a variety of what-if scenarios virtually before implementing physical changes in a security posture.

Modeling and Simulation Tools for NPP Security Applications

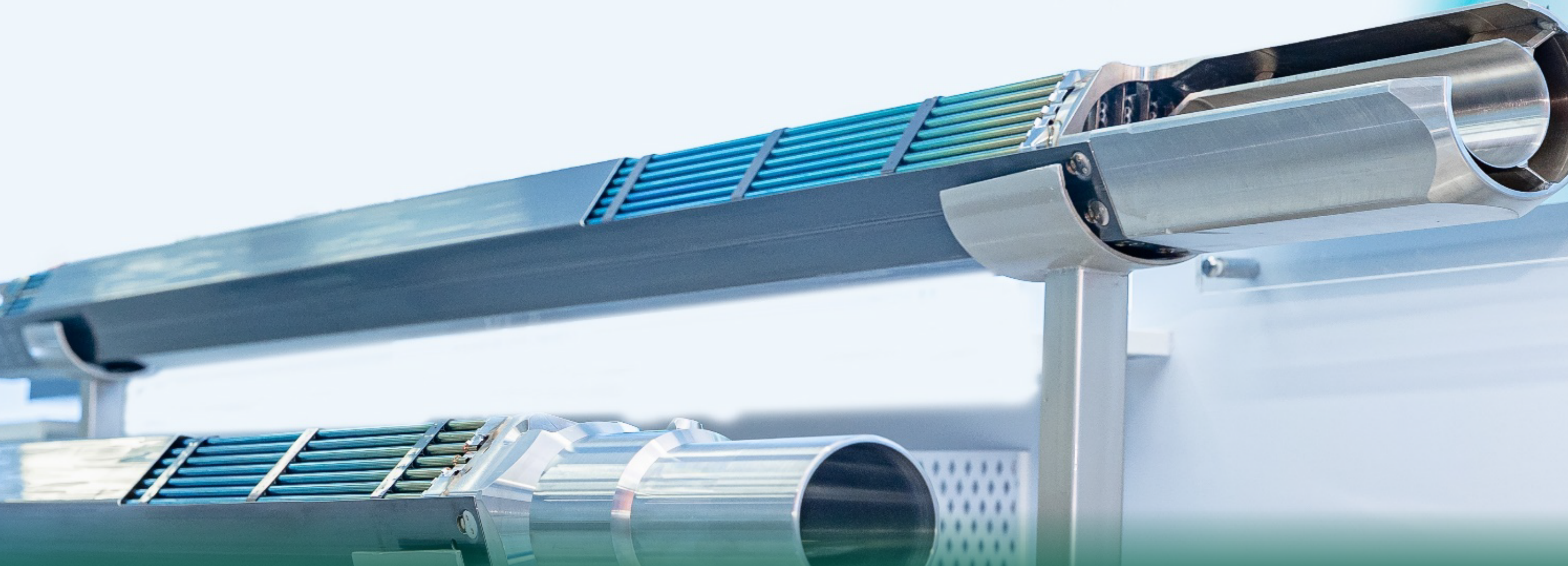
AVERT and Simajin: These tools are two of the most widely used M&S software tools across the commercial NPPs in the United States. Both the tools are quite similar in capabilities and utilize 3D models of any nuclear facility to model FoF engagements and analyze the performance of the site's physical security configurations and response tactics against a variety of threats that are unique and specific to the site [20,21]. The software simulates various types of threats, attack scenarios, adversarial timelines, and plant security posture to enable the quantitative and qualitative assessment of security systems. In addition to FoF modeling, these tools can perform vulnerability assessment, training simulation, biological incident modeling and response, radiological incident and event modeling, insider-analysis, and combined cyber-physical security events.

Scribe3D: This tool conducts next generation tabletop training exercises developed using modern game engine technology. It runs tabletops on actual or notional facilities complete with a range of personnel, weapons, props, security system components, and vehicles and enables a user to visualize the exercise in real time, tracking all personnel actions and events to convey time, events, personnel actions, and realistic consequences [19].

EMRALD: Event Modeling Risk Assessment using Linked Diagrams (EMRALD) is a dynamic risk analysis tool developed at INL which has been implemented for use cases such as seismic analysis, pipe rupture, flooding, and FoF analysis of current plant security posture [22]. The operator's actions in mitigating the adverse effects of the sabotage attack are also modeled in EMRALD, and the mitigating actions, as well as their timing information, are fed to the reactor's safety analysis codes to determine the end state of the reactor and for performing scenario timing evaluation of existing NPP protection strategies to be able to incorporate plant thermal-hydraulics models, operational behavior, and mitigating actions.

PathTrace: This path analysis tool uses established algorithms to help facility operators identify site security risks and vulnerabilities. It enables the user to upload floorplans or images of real-world, hypothetical or mock facilities and define site security components, detection areas, response force times, and targets [18]. The user then specifies the adversary, including the adversary's skills and tools. Using this information, it analyzes potential entry paths the adversary might use to successfully breach facility defenses and provides the user with outputs and insights, such as adversary task time, probability of detection, critical detection point, probability of interruption, and the delay and defeat time of barriers.

Dante: It models adversary attacks and the security response according to policy and includes models of delay elements, sensors, communications, and command-and-control behaviors of responders. It internally conducts dynamic path analysis and lethality effects [23]. Results can be used to compare the effects of potential changes in site security.



3 | DT FOR SAFEGUARDS AS RELATED TO MATERIAL CONTROL AND ACCOUNTING

The MC&A activities discussed in Section 2 can potentially benefit from the use of DTs. For example, a DT may compliment physical periodic measurements by virtual measurements, provide real-time and more reliable techniques for statistical tests and analysis of SNM, streamline the physical inventory process, aid in training and qualifications, and more. This section identifies and discusses potential DT effects on MC&A activities that merit consideration and present novel opportunities for change within that activity.

Periodic Measurement:

Measurement processes include mass and volume determination of SNM to confirm material attributes, verify material quantity, or adjust inventory accountability values. Licensees may utilize engineering estimates when material cannot be measured. Three categories of measurements used for SNM are: confirmation measurements, such as gamma-spectroscopy, which are generally qualitative measurements that are made to validate the integrity of an item; verification measurements, which are quantitative remeasurements of the amount of SNM in an item; and accountability measurements, which are quantitative measurements of the amount of SNM in an item or location made to establish initial book values for the material or replace the existing book value. A licensee's measurement procedures could require the operator to ensure current calibration of measurement instruments prior to their use. All scales and balances are checked for accuracy and linearity on each day that periodic measurements are performed.

DTs, when used as part of periodic measurement activity, can be applied for verifying material quantity or adjusting inventory accountability values. Licensees conduct verification measurements or remeasurements of SNM to verify the quantity of material present. DTs that keep historical records with measurement quantities and associated metadata, such as time and location, can support and inform verification measurements by recommending remeasurement timing and location. When remeasurements result in adjusting the accountability records, DTs for measurements can keep track of and record historical records and adjusted records.

There could be instances when a licensee's MC&A plan specifies material that are deemed "not amenable to measurement" for various reasons such as high radiation levels, large critical assemblies, storage configurations with restricted access, or assemblies that cannot be separated or measured. In such cases, licensees could estimate the SNM quantities utilizing alternate methodologies such as analyzing historical measurement data, modeling, or engineering estimates. A DT for SNM measurements could communicate with real-time analytics or physics models to provide estimates of measurement quantities. Physics-based models, such as the Oak Ridge Isotope GENeration (ORIGEN) [25] developed by ORNL, provide the M&S capability for depletion, decay, activation, and emission calculation of nuclear material. An MC&A DT in communication with such M&S tools could run real-time simulations based on historical and current data and provide real-time estimates of the calculated quantities.

Scales used for SNM measurements are a form of sensor technology and can undergo degradation and failure, such as sensor drift and electrical or mechanical damage. An MC&A scale DT could be a digital representation of scales that provides real-time performance monitoring, failure prediction, sensor drift assessment of the scale, and makes recommendations for actions, such as scale calibration or maintenance scheduling [7]. Such an MC&A scale DT could also support real-time continuous virtual measurements based on historical data and analytics that can be utilized in verification of physical measurements and analyzing trends.

Statistical Test:

Statistical evaluations of the measurement system ensure the quality of SNM measurements and measurement control data and provide estimates of uncertainty for inventory control statements and provide assurance that all SNM items are present during periodic inventories. Statistical methods are used in developing sampling plans for inventory verifications; evaluating shipper/receiver differences; quantifying random and systematic uncertainties in measurement; and determining control limits, rejection limits, and outlier criteria. The statistical analysis of SNM measurements evaluates the quality of periodic measurements to ensure that the uncertainty in measurement data meets the regulatory requirements.

Conducting real-time analysis to not just analyze current and past states but also predict future states is one of the powerful capabilities of DTs [6]. An MC&A DT could provide advanced capabilities for a variety of statistical tests, analysis, sampling, and uncertainty quantification (UQ) with high reliability and accuracy in results. Statistical sampling for SNM measurement is an efficient alternative to conducting a hundred-percent inventory and is based on technical and statistical principles and accounts for material type, measurement requirements, and/or operational considerations. Analytics within an MC&A DT could analyze such complex considerations to determine the optimum sampling plan for SNM and keep a digital record of historical sampling plans that may inform determining future sampling plans. An MC&A DT could conduct real-time statistical tests that meet the regulatory requirements for detecting a SNM loss. Choosing an appropriate methodology could depend on factors such as the statistical distribution, limited data, process variations, and sampling quantity. An MC&A DT could be equipped with libraries of a wide range of statistical analysis and UQ methodologies and could recommend the appropriate methods for specific applications.

DT usage could enhance the currently used statistical approaches by determining the distribution of historical measurement data using advanced techniques, such as Bayesian methods, conduct real-time updates in distribution parameters, and incorporate repeated simulation of virtual measurements when needed. Such capabilities will enhance the statistical analysis of the SNM from the current method of merely determining percent power to obtain deeper insights such as probability distributions, parameter evolution, tail probabilities, graphical interface, and trend analysis.

Licensees conduct an assessment of inventory difference (ID) by closely monitoring errors, biases, and trends in SNM measurements. An MC&A DT could offer advanced statistical models, data analytics, and ML models of SNM measurements and associated quantities to estimate accurate and reliable ID trends over time, provide confidence intervals, determine if trend limits were exceeded, and provide graphical interface and real-time statistical insights in trends such as errors, biases, and outliers.

Physical Inventory:

This section presents the NRC regulations that apply to MC&A physical inventories at NPPs and fuel cycle facilities. In addition, the specific activities that are included in a physical inventory for NPPs and fuel cycle facilities are described. Also, potential DT applications for both NPP physical inventory and fuel cycle physical inventories are discussed. With respect to NPP, physical inventories of fuel assemblies and fuel component containers, in conjunction with other MC&A elements, ensure that (1) SNM is in authorized locations, and (2) discrepancies between the physical inventory and the accounting records are detected and resolved. The NRC regulation 74.19 requires licensees to perform periodic physical inventories at reactor facilities [10].

The typical physical inventory at an NPP consists of an item count of SNM in each item control area (ICA) [23]. The ICA is a defined area within the owner-controlled area for which the SNM, such as fuel assemblies, fuel components, or non-fuel SNM, is maintained in such a way that, at any time, an item count and related SNM quantities can be obtained from the records for the SNM located within the area. The ANSI Standard N15.8-2009 provides guidance that a licensee shall conduct physical inventory of all SNM possessed under license and in all ICAs, including new fuel storage areas, irradiated fuel storage areas, reactor vessels, spent fuel pools, dry interim storage areas of spent nuclear fuel, and non-fuel SNM storage areas [24].

With respect to fuel cycle facilities, physical inventories of material containers and material processes in conjunction with other MC&A elements (i.e., application of measurement technologies), ensures that (1) SNM is in authorized locations, and (2) discrepancies between the physical inventory and the accounting records are detected and resolved. The NRC regulations for Categories I, II and III are, respectively 74.959(f), 74.43(c) and 74.31(c)(5), which require licensees to perform periodic physical inventories at fuel cycle facilities [10].

MC&A DTs dedicated to physical inventory could support a wide range of activities within the physical inventory processes of (1) planning and preparation, (2) conduct, and (3) reconciliation [9]. The planning and preparation process involves preparing the facility as per the licensees MC&A plan and documenting the physical inventory procedures. A DT for MC&A physical inventory could support digital documentation, creating or recommending physical inventory procedures based on historical inventory, validation with book inventory, and real-time communication of procedures across all ICA stakeholders. Such DTs would enable fast, accurate, and real-time communication across all stakeholders of information regarding the facilities being inventoried, procedures for preparing bulk SNM to be placed in its required form and configuration, and the SNM movement in and out of the designated areas for inventory. A physical inventory DT could ensure that an inventory is conducted in accordance with the established procedure by conducting independent checks of the inventory procedure such as ensuring material is not inventoried more than once during an inventory and ensuring that all SNM is inventoried.

While conducting the physical inventory, a DT could provide a digital and visual representation of historical book inventory and help identify material that is not reflected in the book inventory. A typical physical inventory team consists of more than one individual. An inventory DT within handheld devices across the team members could facilitate real-time communication and information exchange across the team. Conducting physical inventory involves the verification of material information such as location, identification numbers, or serial numbers; an inventory DT could enhance efficiency of verification activities by readily providing digital and visual representation of such SNM metadata and information.

In some cases, in lieu of a hundred-percent inventory a licensee might conduct physical inventory using an approved statistical sampling plan with required confidence level and detection capability. An inventory DT with statistical methods, data analysis, and ML models could provide recommendations for an optimum sampling plan for conducing physical inventory with the right balance of efficiency and accuracy. Inventory DTs with data analytics and M&S capabilities could offer benefits of integrating and analyzing a variety of inventory data and inputs such as historical book inventory, SNM transfers, past detections and findings, likelihood of detection, and virtual what-if scenarios. Such an inventory DT could make recommendations beyond current statistical sampling plans to provide enhanced inventory procedures that are optimized for efficiency and effectiveness, recommend special inventories such as non-routine or emergency inventories, and novel walkthrough paths and teams. A DT could also make a determination if the sampling plan will not be acceptable in case there are indications of any significant change in SNM concentration or distribution within an item due to external factors, such as oxidation or moisture.

A licensee's physical inventory reconciliation process provides assurance that all SNM has been accounted for, and facility's record system reflects the physical inventory. An MC&A DT with historical inventory data in digital form could go beyond the existing digital recordkeeping by performing periodic maintenance and documentation of SNM transfers, receipts, and inventory findings as well as ensure accurate and efficient digital verification and reconciliation of physical and book inventory. The regulation requires a licensee to calculate the ID, estimate the standard error of ID (SEID), and investigate and report any ID values or SEID estimate that exceed the limits specified in [10]. The magnitude of an ID reflects both the loss detection capability of the MC&A system and the degree of assurance that SNM is in the authorized location. Existing commercial NPPs handle discrete quantities of SNM for which ID is based on a count and not measurement and, therefore, is invariably zero.

A DT with data analytics and ML algorithms could support in calculating ID values, estimating ID uncertainties, performing ID trend analysis for cumulative IDs across multiple inventory periods, determining if trends exceeded limits, and detecting protracted diversions. A DT could enable licensees to accurately establish ID control limits which could be based on plant-specific information, such as operating conditions for the material balance period of inventory, past inventory data, uncertainty and variance in past inventories, and SNM transfer rates. If calculated ID values exceed control limits, diagnostics capabilities in an MC&A DT could help licensees in conducting root cause analysis of discrepancies, appropriately keep and maintain digital records of the discrepancy, facilitate communication and reporting of the incident to meet the regulatory requirement, and recalibrate ID control limits.

Item Control:

The NRC regulations requires a licensee to establish, document, and maintain an item control system to protect against unauthorized and unrecorded removal of items, or of SNM from items and enable the timely location of items. The regulatory definition of the term item as it applies to MC&A is as follows [9]: any discrete quantity or container of SNM or source material, not undergoing processing, having a unique identity and also having an assigned element and isotope quantity. To meet the item control requirements, the records of SNM as part of a licensee's MC&A program provide current knowledge of the location, identity, and quantity of all SNM contained in all items.

A DT for item control could be implemented to conduct analytics for verifying that items shown in MC&A records are stored and identified in the manner indicated in the records. The MC&A plan and records consist of item identity information such as unique item ID, and storage information such as storage areas, SNM values, any past violations, administrative controls such as custodian assignments, and physical controls such as access and authorizations. An item control DT could periodically run autonomous digital verifications to ensure that the MC&A records and updates are consistent with the physical changes in SNM, and the physical changes in items and item locations are appropriately recorded in MC&A record system. Employing a DT-based MC&A record system could also reduce the inefficiencies and challenges associated with paper-based record system of SNM handling.

Resolving:

A licensee is required to promptly investigate and resolve any indications of a possible loss, theft, diversion, or misuse of SNM. The resolution program in a licensee's MC&A plan addresses the possible indicators of missing SNM. An investigation of SNM provides an estimate of the involved SNM quantity, material type or physical form of the material, the type of unauthorized activity or event detected, the time frame within which the loss or activity could have occurred, the most probable causes, and recommendations for precluding reoccurrence. A licensee's resolution process could include (1) thoroughly checking the accountability records and source information, (2) locating the source of the problem, (3) isolating the exact reason for the problem within the area or processing unit, (4) determining the amounts of SNM involved, and (5) making a determination that the indication is or is not resolved.

An MC&A DT could aid a licensee and the regulators in investigating missing SNM by combining information from MC&A records, physical inventory, and other activities focused on providing insights on loss or theft, such as estimates of lost SNM quantity, time frame, and probable causes. Such an investigative DT could consist of anomaly detection ML algorithms trained to combine the MC&A records data with other inventory and activities information. Such an investigative and recovery DT could also result in providing additional insights and generating novel information for resolving indications of missing SNM such as detecting unauthorized activity and identifying personnel responsible. The resolving DT could also have integration and communication capabilities to work with the information and inputs from a security DT or other models, such as process models, and security information, such as unauthorized personnel in an access-controlled area identified by a security DT.

Recovery

A licensee is required to provide the regulators with all information in a timely manner that is relevant to the recovery of SNM involved in a loss or theft. The type of information that could aid the investigation and recovery efforts are: data and information that led to detection of the loss or theft; data and assessments related to resolving the missing SNM; and the time period and means by which SNM may have left the facility.

A recovery DT could investigate potential causes of loss or theft by backtracking the MC&A records, inventory records, to provide a wide range of information such as the type of unauthorized activity detected, the interval during which the loss may have occurred, and the amount of material and form of the material involved in the loss, and provide this data to investigators for resolution of missing SNM, potentially through a resolution DT. To determine the probable causes of SNM loss, a recovery DT could also integrate various outcomes, such as results of measures to validate indicators, results of extended measures to resolve indicators, results from inventories and tests performed, audit results of SNM accountability source data, assessments of measurement data and measurement controls, results from reviews of the MC&A program, and reports on the MC&A program status. These status reports can cover different elements of the MC&A activities including corrective actions, history of indicator investigation and resolution activities, anomaly investigation and resolution procedures, and conclusions. Similar to a resolving DT, the recovery DT could communicate with other DTs and models such as radiation detectors real-time data and security DT's personnel access and entry information.

Recordkeeping:

NRC regulations require a licensee to establish and maintain records that include the documentation of (1) receipt, shipment, disposal, and current inventory of SNM, (2) quantities of SNM added to and removed from a process, and (3) shipper-receiver evaluations associated with SNM receipts.

A DT implemented for MC&A recordkeeping could keep digital records safe and secure as well as conducting autonomous and periodic auditing and verifying analysis to ensure correctness and completeness of records. Additionally, a recordkeeping DT could have anomaly detection capabilities for detecting missing or erroneous, falsified, or spoofed data and records. Such a DT can be run either autonomously, periodically, or manually in case of an event. Several data analysis and ML techniques exist for estimating missing data or information in a database, such capabilities in a recordkeeping DT could be implemented for potentially reconstructing lost or destroyed SNM records.

Alarms and Reporting:

Licensees establish a surveillance program at facilities for monitoring SNM, including detecting unauthorized activities or anomalous conditions, that would trigger and report automated alarms. The surveillance program includes visual surveillance, direct observation, assess SNM movements and inventory status, and process inventory records or other information to indicate anomalies. Alarms as part of an MC&A program could be triggered by three broad events: (1) unauthorized access or activities involving SNM, (2) anomalous conditions, and (3) ID value exceeding alarm limits during physical inventory.

An MC&A DT for surveillance and alarms could take form of an advanced digital portal for surveillance, monitoring, alarms, communication, and response. The surveillance DT would communicate in real time with the digital surveillance system with access control, intrusion detection, cameras, motion sensors, wired and/or wireless communication, and other sensors and technologies. Such DTs could facilitate real-time communication and reporting and resolution of alarms across stakeholders and regulators. Post an alarm event, such DTs in conjunction with data analytics and ML algorithms, could help in detecting false alarms and their causes, recalibrating alarm limits in ID statistical models, and updating MC&A procedures.

Table 1. Summary of considerations and opportunities in DT for MC&A.

Considerations	Opportunities
Periodic measurements	- Verify material quantity or adjust inventory accountability values - Determine engineering estimates when material cannot be directly measured - Scale DT for detecting drift in scales and informing scale calibration - DT for virtual measurement - DT for *continuous* virtual measurement
Statistical test and analysis	- DT for real-time calculations, updates, and tracking of ID values - DT for determining distribution of historical measurement data, real-time update of distributions, and repeated simulation of virtual measurements - DT of expected measurements to compare with real measurement and determine errors and anomalies - Digital measurement chart and interface with real-time statistical insights, such as errors, biases, outliers, and trends in SNM measurements - Develop real-time DT with fuel burnup models to assign expected accounting values of spent fuel
Physical inventory	- Inventory DT for tracking historical inventory, record reconciliation during physical inventory - Inventory DT to track and highlight SNM transfers - Recommend physical inventory frequency

Table 1. (continued).

	- DT for recommending stratified sampling of physical inventory to achieve highest likelihood of detecting missing or defective items - DT for simulating what-if scenarios of missing or defective items - DT to recommend special inventories, such as non-routine or emergency - Measure and estimate residual holdup - Minimize remeasurements of previously measured and recorded SNM - Infer SNM content estimates from indirect measurements - Ensure that the plan physical inventory meets the regulatory acceptance criteria
Alarms and reporting	- DT for establishing alarm and action limits - DT for real-time communication and reporting of alarms across stakeholders and regulator
Item control	- DT to verify that items shown in MC&A records are stored and identified in the manner indicated in the records - DT to conduct autonomous and periodic checks to ensure that generated items and changes in item locations are appropriately recorded in MC&A record system
Resolving	- DT for investigating loss or theft by combining information from MC&A records, physical inventory, and other activities - DT for providing insights on loss or theft such as estimates of lost SNM quantity, time frame, and probable causes - DT for providing insights and generating novel information for resolving indications of missing SNM (e.g., detecting unauthorized activity, anomaly investigation, and personnel responsible) - Safeguards DT working in integration with security DT or other models, such as process models (e.g., unauthorized personnel in access-controlled area identified by security DT)
Recovery	- Recovery DT that communicates with resolution DT that investigates potential causes of loss or theft by backtracking the MC&A records, inventory records, and others - DT specially designed for recovery to keep track of all relevant information that can aid in recovery of SNM (e.g., radiation detectors, real-time data, security DT's personnel access/entry-exit information)
Recordkeeping	- DT for autonomous and periodic auditing and verifying the correctness and completeness of records - Anomaly detection DT for detecting missing or erroneous, falsified, or spoofed data and records - DT for potentially reconstructing lost or destroyed SNM records

Unique Considerations for Advanced Reactor MC&A:

Current MC&A processes of using statistical and accounting measures to maintain the knowledge of the quantities of SNM present in each area of a facility are mostly established for LWR fuel. ARs are expected to use a variety of fuel types that can be distinct from LWR fuel (e.g., fuel mixed with molten salt or in pebble form), thereby impacting the MC&A processes. For instance, tri-structural isotropic (TRISO) particle fuel to be used in pebble bed reactors have low-SNM content per pebble and constantly feed pebbles through the reactor with a possible loss or disintegration of fuel pebbles within the reactor. Reactors using TRISO fuel use fuel shipments, which can be accounted for in terms of number of containers, batches of material, or number of pebbles. Such unique characteristics of AR fuels may require novel approaches in MC&A practices which can be supported by an MC&A DT. An AR MC&A DT could be implemented to develop generic MC&A practices that use online monitoring data, such as reactor performance, fuel consumption, and fuel inventory, integrated with real-time M&S of physics-based models of reactor operation and ML algorithms for detecting material diversion, resulting in material accounting processes that could be independent of fuel type.

4 | DT FOR PHYSICAL SECURITY

Meeting Regulatory Requirements:

The 10 CFR 73.55 (b)(3)(i) requires the licensee to ensure that the capabilities to detect, assess, interdict, and neutralize threats up to and including the DBT of radiological sabotage, as stated in § 73.1, are maintained at all times [13]. Currently, efforts to ensure this compliance are mostly manual through periodic inspections. A DT for security could be utilized to establish online monitoring of the intrusion detection system (IDS) availability, which includes sensors and barriers. Smart intrusion sensors connected to a network could be utilized to monitor a sensor's condition, connectivity, and status. Some barriers, such as doors and gates, could be assessed through a combination of sensors and CCTV monitoring system equipped with computer vision capabilities. Responders' shift schedules and availability may be digitized in the DT module to ensure that a sufficient response capability is available at all times.

Article (b)(3)(ii) of the regulation requires the licensee to provide defense-in-depth through the integration of systems, technologies, programs, equipment, supporting processes, and implementing procedures as needed to ensure the effectiveness of the physical protection program [13]. Tools to evaluate the effectiveness of a physical security posture can be implemented in a security effectiveness DT, such that any change in the physical security component (e.g., a sensor or barrier is unavailable due to maintenance, or a post is unavailable because of personnel illness) can be reflected and evaluated in real time. Recommendations can be provided for compensatory measures when it happens and ensure that the overall security posture effectiveness remains comparable to the initial.

In article (b)(4) of the regulation, the licensee shall analyze and identify site-specific conditions, including dynamic target sets, that may affect the specific measures needed to implement the requirements of the section and shall account for these conditions in the design of the physical protection program [13]. A DT can communicate data on equipment unavailability due to various events, such as random failures and scheduled plant maintenance activities to the security module, to identify equipment within target sets that are unavailable due to maintenance. It will be easier for adversaries to sabotage a plant when target sets are reduced due to periodic maintenance. A DT could anticipate this vulnerability in advance and recommend temporary modifications in the security posture during the maintenance period.

DT for Perimeter Intrusion Detection and Assessment System

A PIDAS DT could be a digital representation of the intrusion sensors, alarm system, alarm communication system, video cameras, and other technologies that is part of PIDAS at a facility. Such a PIDAS DT could integrate real-time data from PIDAS sensors with data analytics and ML algorithms designed to provide real-time information such as sensor conditions as healthy vs. degraded, power levels, sensor reliability, etc. A PIDAS DT can help the security operators in real-time identification of degraded or failed sensors and recommend maintenance actions, identify spatial gaps in intrusion detection, and recommend optimum placement of PIDAS sensors.

One major challenge in current PIDAS at nuclear facilities could be high rates of nuisance alarms, which could be attributed to the high level of detection sensitivity of the PIDAS sensors. A security DT could address this challenge by recommending the optimum level of sensitivity and nuisance alarm rates for a given PIDAS sensor. Data processing, data analytics, and ML algorithms within a security DT can combine multiple sensor data to provide a more confident detection on security intrusions. An example is the use of deliberate motion analytics (DMA) on fused data from complementary sensors to reduce nuisance alarms within the PIDAS and potentially extend intrusion detection to beyond the site's perimeter [26]. This technology could detect intruders attempting to approach the outer fence of a traditional perimeter, separating them from noise data due to foliage moving in the wind, wildlife movements, and jitter in camera mountings. A PIDAS DT equipped with a DMA algorithm could be implemented to filter the raw sensor alarms and yield lower nuisance alarm rates.

Mobile surveillance units and their flexibility to incorporate additional sensing or processing modules may be beneficial to resolve the issue of data-flooding. One way to solve this issue is by deploying edge computing, where data are processed to be useful information at the sensor node where the data are generated. Mobile surveillance units with their dedicated power source allows the mounting of a data processor module to process sensor data and only transmit the processed information to the DT module. In addition, this capability may also address one of the regulatory requirements for an IDS, which is the requirement to test each intrusion alarm at least once every seven days [13]. Currently, this test is done manually. However, future intrusion detection sensors equipped with edge computing may have a periodic self-testing capability, process the test data locally, and send the results to a central alarm station (CAS). Data from these advanced technologies can be used to implement a DT model for the PPS of an NPP.

It could be possible that the DT in combination with subject matter expert (SME) expertise and/or M&S tools may be able to predict an adversary's attack path based on their number, entry point, movement speed, and other information gathered from the intrusion detection sensors. Such capabilities could also make recommendations on intervention, neutralization, and fallback strategies to the response force.

Security-by-Design:

In its early stages of development, security M&S can be run on attack scenarios such as on a test data set to evaluate and assess performance effectiveness of proposed designs before final commitment [27,28,29]. Integrating a security DT with other DTs, such as safeguards and safety DTs, could allow designers to evaluate effectiveness, efficiency, and robustness of S&S systems including the identification of gaps in addressing design basis threats during the design phase. This includes assessing the impact of sensor losses either due to operational failure modes or as a consequence of an adversary attack. Incorporating DTs in this way may result in a highly efficient and cost-effective design process which minimizes the need for future retrofits to address shortcomings.

Integrated Safeguards and Security Digital Twin

Safeguards and security DTs could mutually benefit from integrating with each other. To maximize the potential benefits of the S&S DTs, they need to be integrated into a single functioning system that supports the facility as a whole. For instance, analyzing the facility by the security DT might indicate a target location, such as an operational nuclear material vault. As this information is communicated to the safeguards DT, it would then determine the preferred counter safeguards measures such as securing the vault door while at the same time the security DT determines the preferred security counter measures such as an armed response to protect the material access doors. Similarly, a safeguards DT can identify missing SNM and communicate that information to a security DT to interdict those involved.

In an event triggered by a safeguards sensor, such as the detection of a nuclear material safe opening without the proper authorization, it could be the security DT that determines the potential pathways an adversary might use to exit the facility. With integrated communication between the safeguards and the security DT and their analyses, the integrated S&S DT can dispatch security teams to the potential exit points. Such an integrated S&S DT that provides recommendations for a coordinated response can result in maximum effectiveness and efficiency of S&S at a nuclear facility.

The integrated S&S DT could help in considering and implementing the concept of integrating safeguards, security, and safety (3S), for currently operating facilities and early in the design process of future facilities, so that the design and operation of the facility will have a rapid, effective, and efficient joint response capability across the three disciplines [29]. Historically, information sharing and communication between the each of the 3S personnel may not have been transparent, continuous, or real time. One critical portion of the technical capability is a joint or integrated central alarm station (JCAS) where all the necessary DT-enabling technologies, such as sensors, models, algorithms and others, can be available to all parties in a real-time fashion in order to respond to events. An integrated approach during conceptual design phase could enable operational safeguards, safety, and security-by-design. This can be followed on the operational side by developing coordinated operations and training and response to emergencies through the direction from a JCAS with analytical tools, such as a DT with AI to ensure the most efficient and effective response to alarms/events.

Insider Threat Assessment and Mitigation:

Insider security can be described as a combination of preventive and protective measures such as compartmentalization and access controls. Preventive measures minimize both the number of potential insider threats before and during employment and the number of opportunities for insiders to perform malicious actions [30]. In contrast, protective measures fulfill the traditional detect, delay, and response physical security roles. A DT has the possibility of being able to assess real-time human behavior and patterns that fall outside of a standard range of acceptable values (e.g., anomalous, or unexpected access to a vital or material access area by personnel). This in turn could alert the appropriate facility staff of the anomaly and make recommendations so they may assess the situation and take preventive and protective actions if warranted.

Data analytics or ML algorithms implemented within DTs could also assist with differentiating between malicious intent and natural organizational evolution to explain observed anomalies in operational workplace patterns, suggesting benefits from evaluating collective behaviors observed in the facilities to improve insider threat detection and mitigation. Recent advances in ML algorithms provide more robust pathways for capturing, analyzing, and collating disparate data signals into quantitative descriptions of operational workplace patterns.

DT for CAS and SAS:

Similar to a virtual control room, a CAS, and secondary alarm station (SAS), a DT could enable assessing CAS and SAS operator performance including human factors assessments. A CAS-SAS DT could enable the collection of quantitative and qualitative data on security scenarios evolved in the CAS or SAS and various operator actions. Key quantitative data would include the time it takes for an operator to recognize an alarm, make an assessment, and accurately communicate the need to respond along with the variability associated with day, night, diversion scenarios, and various weather conditions. Such data could in turn be used to optimize CAS-SAS operator performance and provide additional inputs for security M&S.

Table 2. Summary of considerations and opportunities in DTs for security.

Considerations	Opportunities
Meeting regulatory requirements	- DT to establish online monitoring of IDS availability and responders' availability - DT can be used to predict and monitor unavailability of PPS components, and recommend a defense-in-depth measure either using a personnel or alternative assessment means - DT to create and track dynamic target sets, which include updating the availability/unavailability of baseline target sets due to various events such as random failures and scheduled maintenance
DT for PIDAS	- Edge computing in PIDAS sensors - Automated classification of nuisance alarms across different sensor modalities - Potential detection outside the protected area within owner-controlled area - PIDAS of the future: optimized single fence, virtual fence - Robots and drones for intrusion detection - Self-diagnostics of sensors to meet regulatory requirements - Eliminate or reduce periodic testing and maintenance based on the assessment of sensor health and degradation - Anomaly detection and sensor failure prediction, sensor drift - Predict adversary attack path and recommendation of response strategies
Integration of S&S	- DT can provide a bird's eye view of protection/vulnerability within a facility by creating a heatmap of detection, neutralization, and/or vulnerability - DT to update dynamic target sets including significant quantities of radioactive materials; AI/ML can be used to simulate potential pathways of adversaries
Security-by-design	- Identify gaps in addressing design basis threats - Incorporate security-by-design elements into the facility - Preplan for changes in DBT - Preplan for upcoming FoF scenarios
Insider threat assessment and mitigation	- Leverage advanced AI/ML algorithms for an insider threat assessment - Dynamic models to capture real-time deviations from expected plant behavior - Generate recommendations for insider threat mitigation
DT for CAS and SAS	- Conduct CAS and SAS operator performance assessment and human factors assessment in the DT - Obtain qualitative and quantitative data on various assessments - Perform design iterations of CAS and SAS layout based on data and SME feedback

5 | CHALLENGES AND GAPS RELATED TO DIGITAL TWINS FOR SAFEGUARDS AND SECURITY

Increasing Realism in M&S:

Existing M&S for S&S effectiveness may have limitations such as incorporating human factors, operator actions, realistic data, and effects of environmental and weather conditions. Addressing these limitations could result in benefits, such as more accurate M&S results, higher reliability, reduced uncertainty, and faster decision-making. Enhancing the M&S capabilities to address limitations in S&S could be a complex task owing to limited information and historical data and not understanding a certain physical phenomenon. One of the gaps to increase realism in M&S lies in developing DT-enabling technologies, such as sensors and instrumentation, real-time data acquisition systems, and communication technologies specific to S&S. Information and data from such DT-enabling technologies could be applied toward increased qualitative and quantitative insights in S&S models, such as accurate measure of SNM quantities for MC&A, field data on adversary and guard performance, or component performance and reliability data.

One of the current gaps in incorporating facility data and experience in S&S models is a lack of a structured information sharing and communication platform dedicated to safeguards events. Commercial licensees have been sharing operational experience and events information in the form of licensee events report or reactor operational experience database. Existing models, such as probabilistic risk assessment (PRA), leverage shared industry component performance and failure data to conduct periodic updates of quantitative measures, such as failure rates and probabilities in plant-specific PRA models. Establishing a DT-based information sharing mechanism for S&S events at facilities will enable regular updates and increased realism and M&S capabilities for S&S.

Outcomes of security DT when integrated with physics-based models and simulation could provide real-time predictive modeling for scenario progression. For instance, by connecting a security DT to thermodynamic modeling of a facility through software, such as MELCOR, scenario progression of a power plant can be modeled to safety criteria such as external release. Additional software, such as MACCS, can model the effects of that release using the historical data of the region. MACCS uses weather data to model the plume release and can leverage internal economic modeling to yield a cost of such a release. Using modeling software, such as the MELCOR and MACCS combination, allows the DT to seek out scenario progression to determine if trends will yield a release and what the consequences of that release are in terms of public safety and environmental and economic impact. However, there currently exists a challenge in integrating these different M&S tools in a DT.

Verification and Validation of S&S DT

The verification and validation (V&V) of a nuclear DT generally presents challenges in at least two areas. The first area is the lack of high-quality and high-fidelity data with which to validate the model, and the second challenge is the lack of integrated testing methodologies for complex model interactions. These challenges could be even bigger for an S&S DT for which high-fidelity data and model interactions information is already lacking. One of the biggest challenges in conducting V&V of an S&S DT would be the lack of sufficient and reliable data on security and safeguards operations and events at a nuclear facility. To overcome this challenge, there is a need to develop realistic testing scenarios and conduct performance testing over the life cycle of a facility. Developing and conducting such testing could be an extensive endeavor that requires a wide range of considerations which are not limited to security considerations such as target sets, DBT, or attack scenarios but also factors such as reactor performance, plant location, geography, and topology, external hazards, operator actions, and human factors. There exists a further gap in integrating such a wide variety of data in existing M&S for S&S DT and developing a methodology for conducting the V&V using the testing data.

Integrating Advanced Sensors for S&S DT

The security posture at nuclear facilities of the future may consist of sensors and intrusion detection technology that could be significantly different and advanced compared to existing PIDAS or MC&A sensors. A S&S DT developed today must be capable of integrating the evolving technologies of the future. Such a DT must be adaptable to changes in data acquisition systems, as well as manage data heterogeneity, and temporal resolution in integrating existing and advanced sensors with S&S DT. An S&S DT could also be utilized to identify gaps in existing posture and make recommendations for additional indicators or sensor modalities required to address the gaps. One of the long-standing challenges for any advanced sensor and instrumentation technology developed for nuclear is the extensive effort required in collecting data on performance and reliability for qualification. For digital and wireless sensors, ensuring cybersecurity and secure transmission is already one of the gaps that needs to be addressed. For S&S DT application, the cybersecurity and data security concerns must be considered from a security scenario perspective such as data spoofing as an adversarial tactic during an attack scenario.

If a DT is designed to collect and process data from various sensors in a centralized manner, it will create a virtual flood of raw data going to a centralized data storage and processing unit. Most existing NPPs are not designed to establish new hardwired or wireless data connections easily. Moreover, the data flow is limited by technical constraints, such as bandwidth, latency issues, and unpredictable network disruptions.

Digital Representation of MC&A Practices:

While certain elements of MC&A practices such as recordkeeping might exist in digital form at an NPP, others might not. To develop a DT for all MC&A activities at a plant, it is critical to be able to represent all current MC&A practices in some digital form. Developing digital representations of all MC&A practices could be a challenge if the current practices exist in nondigital-digital form. The MC&A practices that currently exist in nondigital form would require adequate digital technology and infrastructure to enable the development and continuous support of a MC&A DT. Some MC&A activities may not be currently integrated, such as statistical tests operating separately from item controls. Developing a holistic MC&A DT would require identifying and developing appropriate mechanisms for real-time integration between different MC&A activities.

Table 3. Summary of challenges and gaps in DT for safeguards and security.

Challenges	Gaps
Increasing realism in modeling and simulation	- Developing technology and approaches for increased understanding and knowledge of S&S scenarios - Establishing communication and sharing of information specific to S&S events at nuclear facilities - Analysis will require a full understanding of the attack vectors and dynamic changes in S&S for a specific facility - Identifying quantities and parameters that best represent performance of an integrated posture for S&S - Developing novel parameters, quantities, and metrics specific to S&S
V&V of S&S DT	- High-quality and high-fidelity integrated test data for integrated models - Integrated testing methodologies for complex model interactions - Performance testing over the life cycle of facility - Developing training data sets and challenge points and integrating in M&S
Integrating advanced sensors for S&S DT	- Addressing technological challenges such as data heterogeneity and temporal resolution in integrating existing sensors with S&S DT - Depending on the identified sensor need from adversary testing, gaps in available sensors and/or their sensitivity may be identified. - DT may identify new indicators for which there is no existing sensor. - Cybersecurity in smart sensors such as edge computing enabled sensors - Secure data transmission from sensors to data collection system
Digital representation of MC&A practices	- Few elements of MC&A process exist in digital form, such as recordkeeping; developing an MC&A DT would require developing digital representation of a wide range of MC&A practices - Develop digital infrastructure for existing MC&A program to support an MC&A DT - Some MC&A activities may not be currently integrated, such as the statistical test may be separate from item controls; developing an integrated MC&A DT would require identifying and developing integration "threads" between different MC&A activities

SUMMARY

This report presents some key considerations and opportunities, and identifies potential challenges and gaps related to application of DTs and DT-enabling technologies for S&S activities at nuclear facilities. The gaps identified in this report suggest the need for additional efforts by research institutions, national laboratories, reactor systems designers, vendors, and licensees to address challenges in M&S, V&V, and integration of advanced sensors and instrumentation related to DT for S&S at nuclear facilities.

Implementing DTs and associated DT-enabling technologies for S&S applications would require collaboration and cooperation among different subject matter experts, facility personnel, and strategic governmental and commercial partners. An incremental approach to creating a DT may be necessary because the functionality, systems affected, features and processes of a DT are yet to be completely defined. It is expected that standards, guidance, and best practices for a DT will continue to evolve as new pilot programs are created, tested, and refined.

Several U.S. NPPs already have 3D models of their facilities with varying levels of granularity and fidelity created by commercial M&S tools. Combination of these models with plant sensors and data feeds may usefully comprise elements of a nascent DT for S&S, and enable adversary pathway analysis, detection probability testing, response force tactics, and security-by-design methodology for existing facilities. Such DT for S&S technologies may also inform planning and designs for future AR designs and lead to more fully developed and integrated DT for S&S applications.

The NRC continues to assess the regulatory viability of DT for nuclear energy applications by identifying and evaluating technical challenges associated with key technologies and their application to DT in nuclear energy with the goal of ensuring a regulatory infrastructure appropriate for the use of DT.

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