Letter Report
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REGULATORY CONSIDERATIONS FOR NUCLEAR ENERGY APPLICATIONS OF DIGITAL TWIN TECHNOLOGIES

August 2022

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CONTENTS

FIGURES

ACRONYMS

AI	artificial intelligence
ALARA	as low as reasonably achievable
CIP	construction inspection program
D&D	dismantling and decommissioning
DT	digital twins
ERDS	Emergency Response Data System
INL	Idaho National Laboratory
IST	in-service testing
ITAAC	inspection, tests, analyses, and acceptance criteria
ML	machine learning
NPP	nuclear power plants
NRC	Nuclear Regulatory Commission
NROD	NRC Reactor Operating Experience Data
O&M	Operations and Maintenance
OpE	operating experience
ORNL	Oak Ridge National Laboratory
PRA	probabilistic risk assessment
QA	quality assurance
SSC	structures, systems, and components

EXECUTIVE SUMMARY

Digital twins (DTs) in complex industrial and engineering applications have potential benefits that include increased operational efficiencies, enhanced safety and reliability, improved security engineering, reduced errors, faster information sharing, and better predictions. The interest in DT technologies continues to grow, and many of these advanced technologies are expected to experience rapid and wide industry adoption in the near future. Some of the potential application areas for DTs in the nuclear industry are design, licensing, plant construction, training simulators, predictive operations and maintenance, autonomous operation and control, failure and degradation prediction, physical protection modeling and simulation, and safety and reliability analyses. The Office of Nuclear Regulatory Research at the U.S. Nuclear Regulatory Commission (NRC) has initiated a future-focused research project to assess the regulatory viability of DTs for nuclear power plants and other NRC-regulated activities, such as fuel cycle facilities and operations.

This report explores the potential impact of DT technologies in nuclear applications on NRC-regulated activities of interest. This report describes a nuclear DT system and its capabilities for nuclear power plant applications, followed by identification and discussion of some regulated activities that merit special consideration and present opportunities in implementing DT-enabling technologies and capabilities. The table below presents a list of these NRC-regulated activities.

PROJECT OBJECTIVES

1. *Understand the current state of DT technology and potential applications for the nuclear industry*
2. *Identify and evaluate technical issues that could benefit from regulatory guidance*
3. *Identify and investigate potential regulatory methodologies, infrastructures, and guidance for DTs in nuclear applications*

Regulated Activities that Merit Special Consideration

1. Regulations and Guidance

- New Standards and Guidance Development
- Information Reporting

2. Licensing, Decommissioning and Certification

- Safety Analysis of Design and Safety-Case of Design
- Operator Licensing
- Change Management and License Amendment Request
- Inspections, Tests, Analyses, and Acceptance Criteria
- Construction Inspection Program
- Quality Assurance
- Waste Volumes
- Radiation Dose Estimation
- Decommissioning Funds

3. Oversight

- In-Service Testing Programs and Technical Specifications Surveillance
- Operability Determination
- Facility Inspections and Audits
- Radiation Dose Prediction
- Environmental Impact and Public Health Dose Limits
- Monitoring Performance or Condition of Structures, Systems, and Components
- Preventive Maintenance
- Maintenance Risk Management
- Theft Detection
- Intrusion Detection
- Physical Security Design
- Emergency Response

4. Operational Experience

- Plant Operational Data
- Event Assessment

5. Support for Decisions

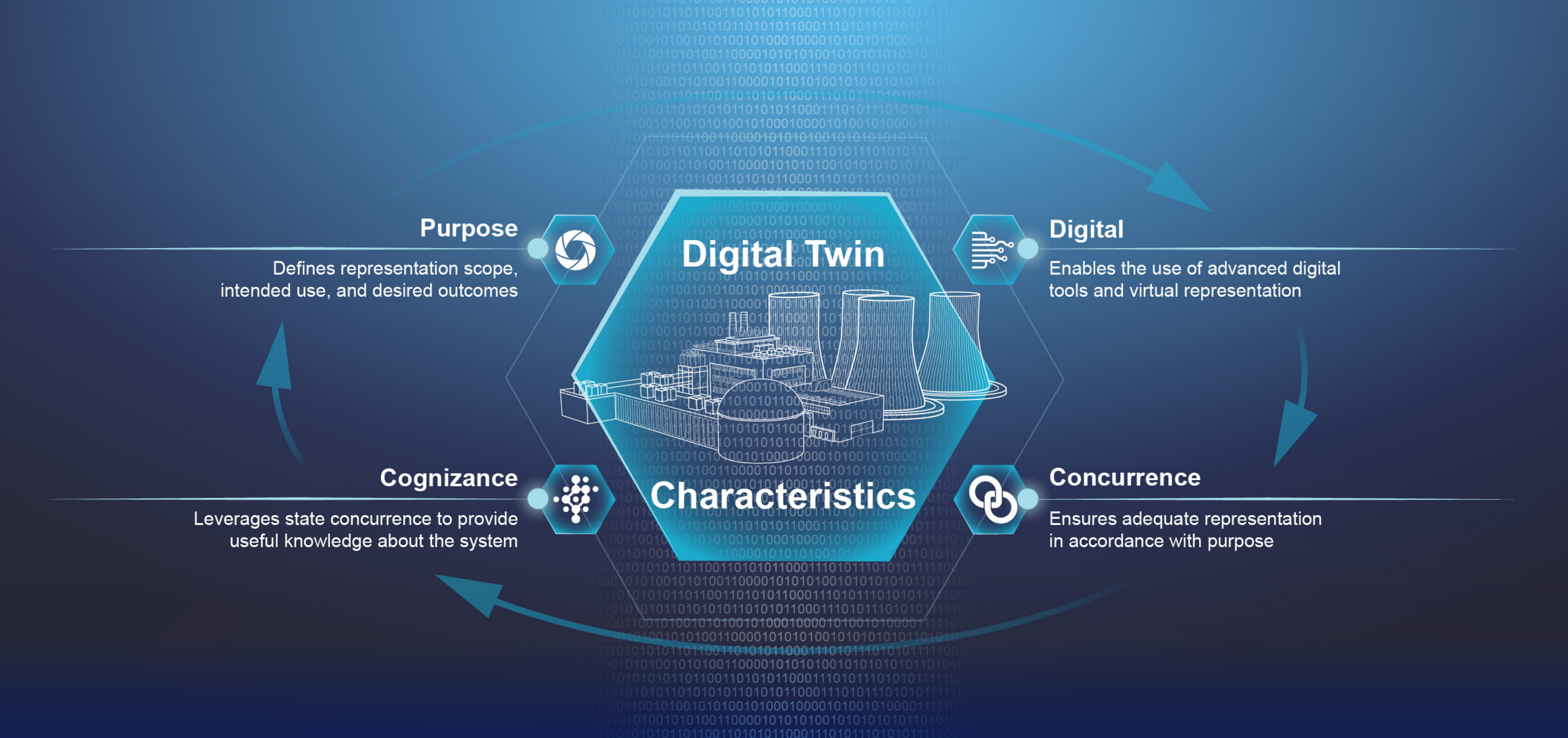
- Modeling and Simulation to Inform Safety Analyses
- Integration of DTs with Probabilistic Risk Assessment

BACKGROUND

The Office of Nuclear Regulatory Research at the U.S. Nuclear Regulatory Commission (NRC) has initiated an effort to assess the regulatory viability of digital twins (DTs) for nuclear power plants (NPPs). This effort is led by Idaho National Laboratory (INL) in collaboration with Oak Ridge National Laboratory (ORNL). The objective of the NRC's DT project is the identification and evaluation of technical challenges associated with the application of DTs in reactors that would impact the regulatory outcomes to prepare the NRC for licensee applications of DT technologies. As part of this effort, the NRC sponsored the Virtual Workshop on Digital Twin Application for Advanced Nuclear Technologies in December 2020 [1] and the second Virtual Workshop on Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization in September 2021 [2]. These workshops were meant to assess the current understanding of DTs and identify their potential benefits, opportunities, and challenges for applications to nuclear reactors. Two technical reports have been published so far in this project, the first of which disseminates the findings of a state-of-the-art review of DT technologies and their applications in non-nuclear and nuclear industries [3]. The second report describes the potential DT NPP problem space (e.g., the nuclear DT system) and provides a detailed discussion of technical challenges and gaps associated with DT-enabling technologies within the problem space [4]. Additionally, in preparation for this report, the NRC held a public meeting in March 2022 to solicit input from the industry and the public on DT regulatory considerations and opportunities [5].

> ***This report identifies and discusses NRC-regulated activities that may be impacted by digital twin technologies.***

The main focus of this report is to discuss potential applications of DT capabilities within regulated activities related to NPP facilities, fuel cycle facilities, and other related facilities. The ongoing and planned near-term efforts for DTs in nuclear reactor applications are mostly focused on non-safety systems and processes [3]. An increasing industry application of DT technology may result in greater benefit and confidence in the application of these technologies. Such applications may have direct and indirect impacts on NRC-regulated activities. Section 1 identifies four foundational characteristics of a nuclear DT system and presents a brief overview of the DT NPP problem space [4]. Section 2 introduces and discusses five overarching capabilities that a nuclear DT system can provide. Section 3 describes regulatory processes, followed by a detailed discussion on potential regulatory considerations and opportunities for DT applications among NRC-regulated activities considered within those processes. The discussion presents specific areas in which DTs may impact regulated activities and compiles the opportunities for further technical and regulatory efforts needed for DT implementation. Use cases and examples of ongoing DT research, development, and implementation are cited to provide context and clarification when needed.



1 NUCLEAR DIGITAL TWIN CHARACTERISTICS

The evolution and definition of DTs for industrial applications have been discussed in a recent NRC report on “Technical Challenges and Gaps in Digital-Twin-Enabling Technologies for Nuclear Reactor Applications” [4]. Various interpretations of a DT exist based on different technologies, applications, or other criteria. This project adds to work in [4] and identifies four characteristics of a nuclear DT system:

1. **Serves an Underlying Purpose:** The technology must have an underlying purpose related to an NPP lifecycle activity, and that purpose should inform decisions about the system or component represented, including what should be represented, how the representation will be used, and what outcomes are desired. That is, a nuclear DT must be part of a DT system, coupled in terms of both state and purpose with the physical NPP. For instance, if the DT’s purpose is to enable condition-based maintenance, performance data from a pump might be used to train a machine learning (ML) model of pump performance and then update the model frequently enough to reflect the current pump state. The purpose of a DT also dictates the scope, elements, relationships, granularity of representation, and the enabling technologies needed to form the DT. For instance, for the same pump, a DT aimed at condition-based maintenance and a DT aimed at informing operations and controls could have different types and forms of inputs, representation, analytics, and outputs.
2. **Exists in Digital Form:** The technologies and information needed to accomplish the underlying purpose must exist in a digital form that can be managed, processed, communicated, and executed using digital technology. This condition seems obvious but needs to be explicitly defined for the nuclear industry because some nuclear plant data and information have traditionally been handled in a non-digital form. For instance, historical information at an NPP, such as maintenance records, may exist as paper or microfiche. Information of this type must first be transformed into a digital format with the appropriate level of fidelity (e.g., via machine-readable scans and context-aware processing) before it can be used within a DT.
3. **Maintains State Concurrence:** Enabled by digital technology, the DT must be capable of updating dynamically to represent the current state of a physical entity or physical phenomenon and must maintain that state concurrence to achieve the underlying purpose of the DT. For example, a physics-based model of a reactor core can be referred to as a DT if it represents, using real-time data, the current conditions of the reactor, such as fuel temperature, reactor fluid temperature, neutronics, etc. The update frequency needed to maintain

state concurrence is dependent upon the rate of change of the represented physical system. For instance, representation of highly dynamic systems such as a reactor core may require state updates on the order of a fractional second, while systems with less dynamic change such as concrete structures may only require state updates on the order of weeks or months. Note: the term “real time” implies update frequencies dictated by the purpose of the DT and the dynamics of the underlying physical system.

4. **Ensures State Cognizance:** A DT has the capability to leverage state concurrence to provide new and integrated sets of insights, information, relationships, and outcomes related to the physical entity that were not possible, feasible, or efficient prior to implementing the DT. For example, a DT of a reactor core could employ not only traditional physics-based models but also enhanced capabilities such as integration with real-time reactor data and ML/artificial intelligence (AI) models to provide new insights about current and future reactor performance and accomplish the underlying purpose of the DT.

Figure 1 illustrates the DT problem space for the nuclear power industry that is described in detail in [4]. The DT problem space for NPPs is broadly composed of four elements: the NPP, the DT, the data and response from the NPP to the DT, and actions and recommendations from the DT to the NPP. The formative pieces and functioning of each of these four elements are discussed extensively in [4].

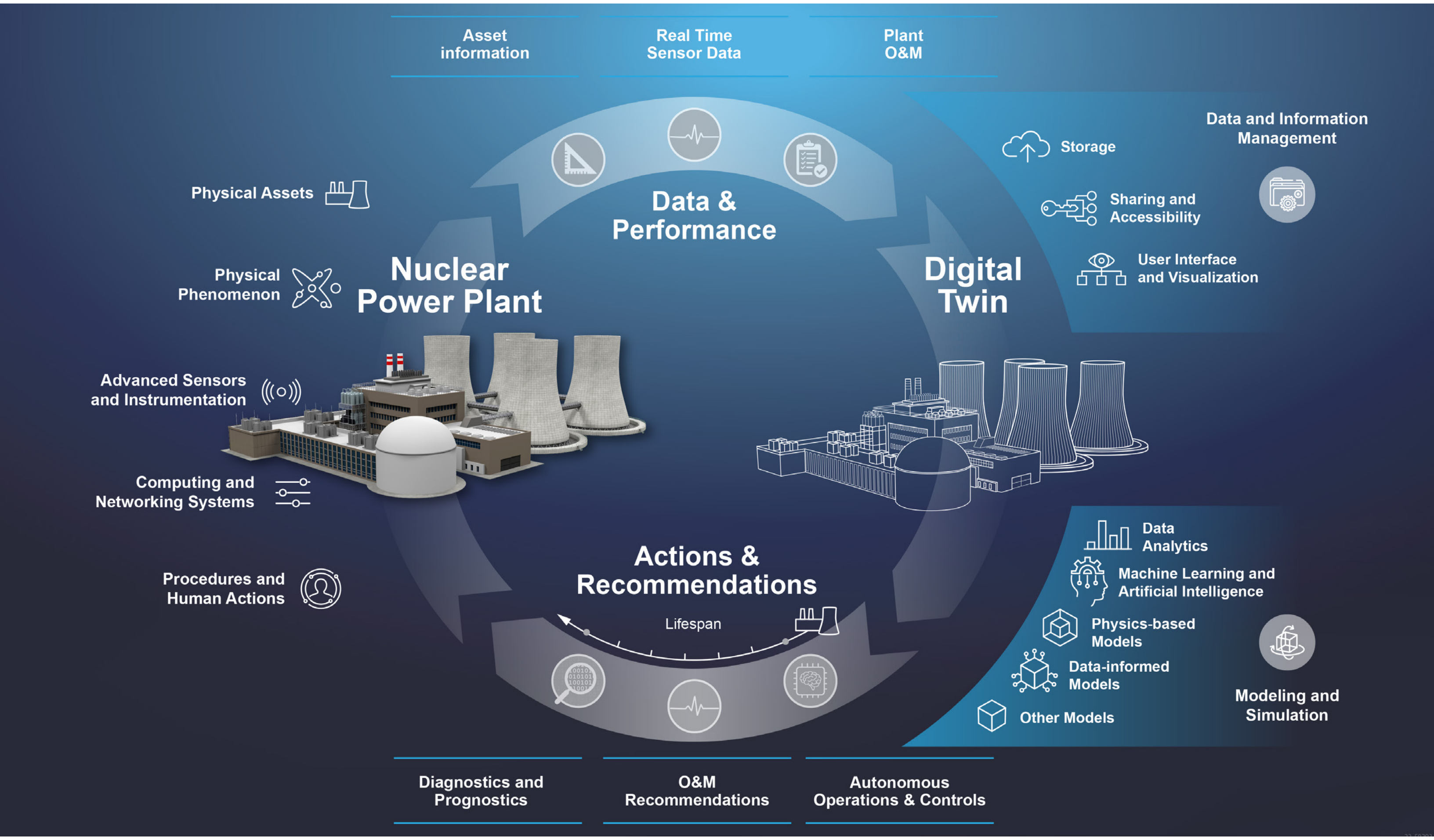
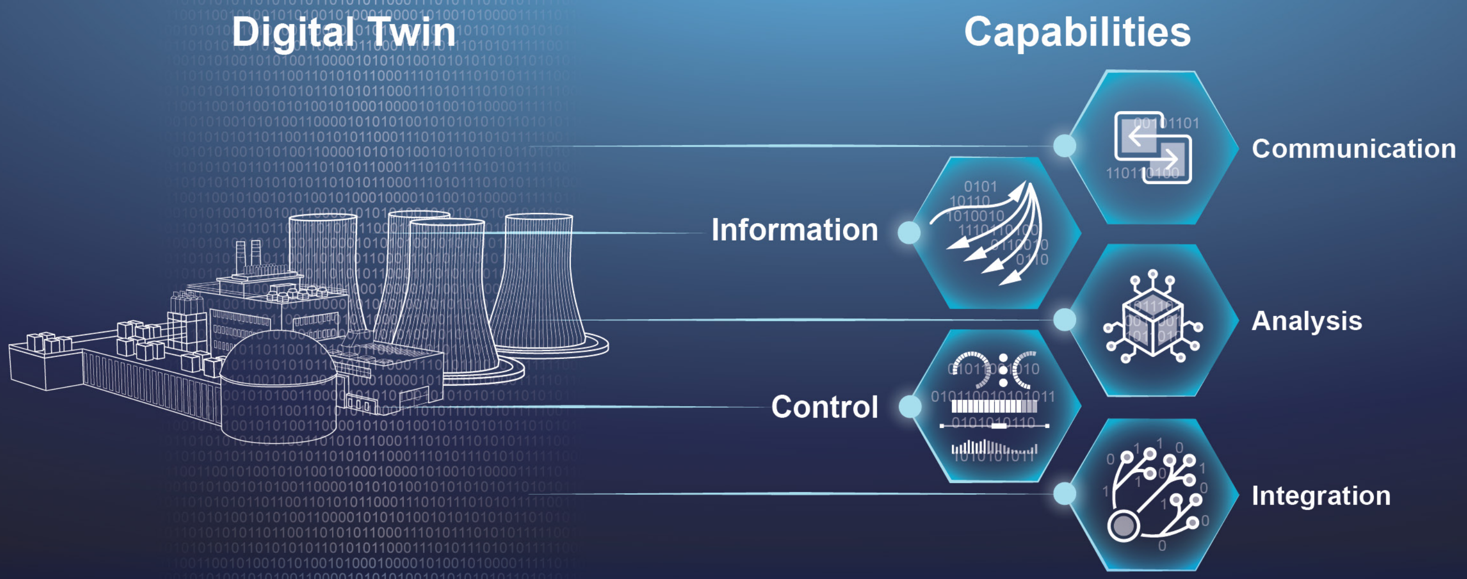


Figure 1. *Overview of DT system in an NPP application [4].*



2 CAPABILITIES OF DIGITAL TWIN

Across various industrial applications DT technology holds promise for significant enhancement in several capabilities. Five capabilities are emphasized based on their potential for significant impact on regulated activities. For this report's purpose, these capabilities are broadly classified.

2.1 INFORMATION

Information forms the backbone of all other DT capabilities. A DT has the potential to provide new and significantly improved plant information that is trusted, timely, on-demand, correct, and complete. This capability is enabled by state concurrence and state cognizance. In addition to merely receiving and transferring information, a DT should be capable of storing, retrieving, sharing, and managing it in such a way that the information is able to support and enhance other capabilities, such as communication, analysis, and control.

DTs provide a single source of trusted information that is timely, on-demand, correct, and complete.

As discussed in the DT description, data and performance in an NPP are formative elements of a nuclear DT and are broadly categorized as real-time sensor data, asset information, and plant operations and maintenance (O&M) information [4]. An NPP DT would demonstrate automatic, continuous, and real-time data acquisition from plant structures, systems, and components (SSCs), manage the heterogeneity of plant information, and enable the shared information flow, within and outside DT elements.

2.2 COMMUNICATION

Communication is an overarching capability that propagates information not only among the various DT-enabling technologies, such as advanced sensors, information management, and modeling and simulation (Figure 1), but also among nuclear DT stakeholders, such as plant staff, regulators, and the public. While data and information flows facilitate various plant operations and controls, a DT may significantly enhance existing activities and help implement new activities with efficient, on-demand, and user-need-tailored communication. Such communication has the potential to facilitate deeper insights and new

DTs have the potential to convey deeper insights and state cognizance in user-need-tailored communication.

cognizance of plant states. For example, during plant events, a DT may organize and present information to operators to ensure they can understand and react to the most relevant and important information first. Also, a DT may communicate different views of the plant based on individual user needs. For example, a grid operator may need to view plant states only in terms of electrical output, a maintenance technician may need to view the states of individual valves, switches, flows, and vibrations, and a member of the public may need to only see information related to regulatory performance measures.

A DT may also significantly improve stakeholder communication by facilitating direct communication among multiple parties and increasing message clarity, conciseness, and understandability. Timely, efficient, clear, and continuous communication is key to efficiency, and the use of DT technology may prove beneficial by enabling the continuous sharing of plant information such as designs, safety analyses, and current plant performance.

2.3 INTEGRATION

A DT serves as a centralized hub and enabler for the integration of a variety of data, information, models, and analytics to address the underlying purpose in a reliable and accurate manner. A DT implemented for most industrial applications in general, and NPP applications in particular, would require a capability to integrate heterogeneous data, information, models, and analytics. Some examples of plant data and response heterogeneity are [4]: digital and non-digital form; historical and real time; different time resolutions ranging from milliseconds to DT lifetime; different sensor modalities; manually collected or automated acquisition; and numerical, text, categorical, or other formats.

DTs integrate a wide-ranging heterogeneity of data, information, models, and analytics to carry out their designated purpose.

The process of integrating such complex data and information continuously or on-demand, with variable granularity and over the long term poses unique operational challenges for a DT. A DT should be capable of complex integration across not merely the incoming and outgoing dataset of the same kind, but also across different datasets and various analytics, outputs, controls, applications, and users. For instance, an O&M DT for a plant component such as a coolant pump would comprise several elements such as fluid-dynamics, data analytics, and ML models as well as real-time sensor data, historical performance data, maintenance logs, and pump O&M procedures. All of these heterogeneous elements must be integrated within the coolant pump DT.

2.4 ANALYSIS

A significant capability of DT is analysis, which supports numerous activities affecting an NPP. A DT can provide both new and significantly improved analytical products and tools to produce, process, and represent information about a plant. DTs offer great potential to not just analyze current and past states but also to predict future states, as well as provide insights to support decision-making and risk assessments. Additional features include the DT's use for performing diagnostics and making corrections to operate safely and efficiently. From design iterations and safety analysis during construction to process optimization and real-time feedback while operating, DT analytic capabilities are applicable throughout the plant lifecycle.

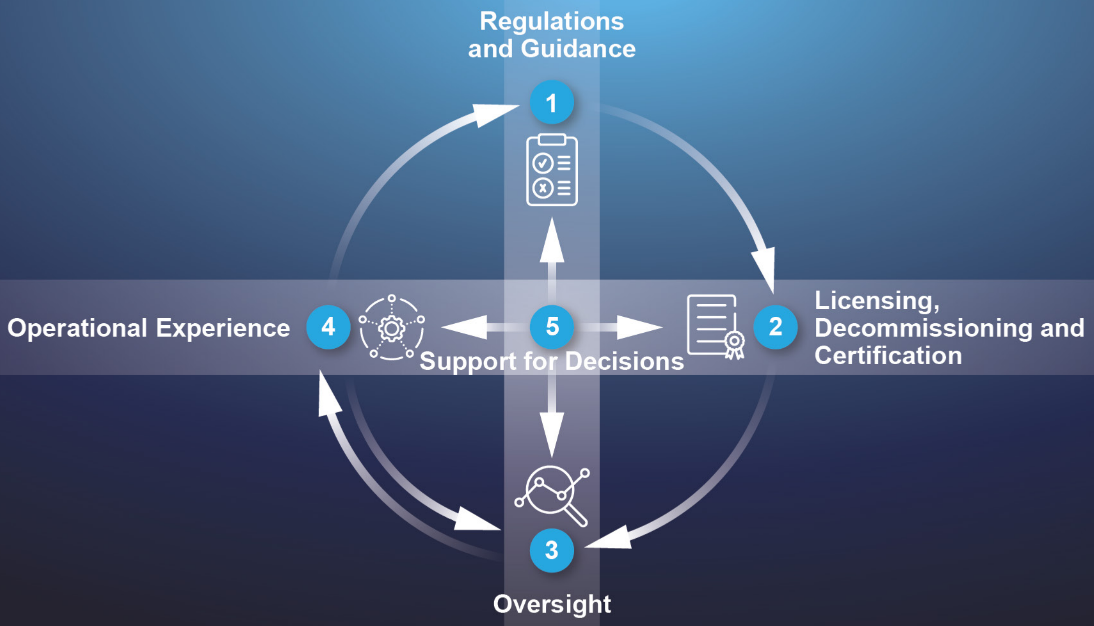
DTs support decision making and risk assessments through analysis of current and past states, and prediction of future states.

2.5 CONTROL

Traditional control systems follow three fundamental steps: determine the current measured value of a control variable, calculate the desired value of the control variable to achieve the desired system performance, and calculate the deviation magnitude of system performance as the difference between measured and desired system performance parameters. A control system enabled by or integrated with a DT can combine classical controls with novel ML/AI-driven control, predictive controls, and virtual sensors measurements as well as leveraging multiple real-time input and output systems. Such DT-enabled control systems can result in operations that are adaptive, using the real-time process identification or controller modification to adapt the controller; optimal, solving a real-time optimization problem to identify optimal control actions based on multidimensional criteria; robust, addressing uncertainty in the control process from measurement noises to modeling uncertainties; and autonomous, requiring less operator supervision.

DTs have the potential to enable enhanced and novel control schemes that are adaptive, optimal, robust, and autonomous.

The main goal of control systems in NPPs is to enable and support safe and reliable power generation, and NPPs have traditionally relied on set-point-based controls that issue corrective actuation commands driven by the deviation of system performance parameter from a design set-point. Currently, automated controls are used at NPPs to ensure plant safety and prevent unsafe conditions, some with limited to no operator interference [5]. DT-enabled controls in NPPs could leverage plant state cognizance to achieve more reliable, accurate, consistent, rapid, and risk-informed autonomous or semiautonomous controls with optimal human supervision and inputs.



3 REGULATORY CONSIDERATIONS AND OPPORTUNITIES FOR DIGITAL TWINS

This work focuses on regulated activities within scope of the following five main components of NRC's regulatory process [6]: (1) regulations and guidance, (2) licensing, decommissioning, and certification, (3) oversight, (4) operational experience, and (5) support for decisions.

1. **Regulations and Guidance:** NRC regulations provide licensees with requirements that, if met, will result in the adequate protection of workers, the public, and the environment. Guidance and standards provide information and acceptable ways to meet the regulations. The process of developing regulations, called rulemaking, or developing guidance and standards involves several steps of communicating to and receiving inputs from nuclear stakeholders.
2. **Licensing, Decommissioning, and Certification:** Through the process of issuing a new license or by amending, renewing, or transferring an existing license, the NRC authorizes an applicant to conduct any or all of the following activities:
    - Construct, operate, and decommission commercial reactors and fuel cycle facilities
    - Possess, use, process, export, and import nuclear materials and waste, and handle certain aspects of its transportation
    - Site, design, construct, operate, and close waste disposal sites.

    For new reactors, the NRC can issue one or more of the following to an applicant: design certification that approves an NPP design, early site permit that approves sites for a new nuclear power facility, or combined license that authorizes the licensee to construct and operate a new NPP at a specific site. In reviewing the above applications, the NRC addresses the various safety issues associated with the proposed NPP design, site safety issues, environmental protection issues, plans for coping with emergencies, applicant qualifications, operational programs, and verification of construction with the NRC's inspection, tests, analyses, and acceptance criteria (ITAAC).

    The NRC's decommissioning program activities include reviewing and approving decommissioning plans and license termination plans and reviewing and approving license amendment requests for decommissioning facilities.

3. **Oversight:** Oversight is one of the major NRC regulatory processes and is aimed at ensuring that the licensees meet the NRC's regulatory requirements. Oversight processes include:
    - Inspections to verify that licensees' activities are conducted in accordance with the NRC's regulations
    - Assessments of facility performance based on inspection findings to determine appropriate agency actions
    - Enforcement of appropriate agency actions to licensees who violate NRC regulation
    - Adjudication of concerns associated with NRC requirements and wrongdoings by licensees
    - Investigations into alleged wrongdoings by licensees
    - Incident response to events involving licensee when public health and safety could be affected.
4. **Operational Experience:** This NRC process gathers and analyzes information about regulated activities and uses it to inform regulations and guidance. Elements within this process include:
    - Event assessment in which NRC reviews certain events required to be reported by a licensee
    - Identification and tracking of the resolution of generic issues involving public health and safety, common defense and security, or the environment.
5. **Support for Decisions:** These processes develop technical and scientific bases to inform and support decision-making related to all other regulatory processes. For example, the NRC regulatory research program supports NRC decision-making by improving the agency's knowledge in the areas of nuclear reactors, nuclear materials, and radioactive waste.

Activities within the scope of NRC regulatory processes can potentially be significantly impacted by DTs. For example, a DT may facilitate new or changed plant information; alternative ways to meet regulatory requirements; licensee processes, such as maintenance, operations, testing, engineering, design and training; licensee analysis methods; licensee communications with the NRC and others; safety and security insights and outcomes; and plant controls and control systems. The following section identifies and discusses potential DT effects on regulated activities that merit consideration and present novel or unique opportunities for change within that activity.

3.1 REGULATIONS AND GUIDANCE

Industry efforts to develop DT standards and guidance will likely inform future NRC regulatory frameworks and guidance. One area of potential consideration is the applicability of existing standards to DT technologies, and where gaps exist, there is an opportunity for industry to develop new standards to address those gaps. Another area of consideration is the potential impact that the DT's capability of gathering and communicating new and improved information will have on NRC stakeholder information reporting activities.

3.2 PLANT LICENSING, DECOMMISSIONING, AND CERTIFICATION

Licensing and Certification

The development of an overall plant design coupled with the design analysis and safety analysis requires continuous iteration and involves multi-disciplinary teams. Typically, there will be a design analysis team and a safety analysis team. These teams will interface with each other as the design and analyses progress. Regulatory interests overlay these tasks. Ensuring continuity between the teams as well as with the regulatory authorities is very challenging and can be quite inefficient.

Engagement with regulatory authorities is essential for a successful design certification or licensing because numerous decision points are encountered throughout the process. DTs have the potential to streamline the overall plant design process, particularly the design analysis and safety analysis process, by ensuring all parties involved are always in possession of the most up to date design, plans, and strategies. Furthermore, from a regulatory perspective, the use

APPLICATION

Several advanced reactor developers, such as Kairos Power and X-energy, envision using DTs in prototype development, enabling quick iteration through successive developmental prototypes of key reactor plant subsystems, reducing uncertainties, and increasing efficiencies in the design, licensing, and construction processes [3] which may affect associated regulatory processes. Research efforts at INL and ORNL are leveraging DT capabilities for material characterization, virtual testing, microstructure prediction, and other applications in additively manufactured components for nuclear reactor applications [7].

of a DT can complement and support the NRC's safety evaluation of topical reports. For example, a licensee could provide the NRC with access to a DT or a specified portion of the DT for staff review of data, information, and analyses including selected safety measures, instead of a lengthy paper report. A similar approach could be taken in using a DT for the 10 CFR 50.69 safety classification review process [7] as well as reviewing in-service testing (IST) and inspection results. This DT-enabled approach could potentially result in an order-of-magnitude improvement in the information and communication needed for these processes. Thus, a DT may provide increased efficiency in the review of design and safety analyses. A DT could be employed in the early integration of a safety assessment into the design process and design iteration process for safety-based design concepts aimed at assessing the effectiveness of safety measures in design and operation, identifying design-specific risk surrogates, and classifying the safety of SSCs as high or low safety significance.

DTs, when used as part of the design process, can support novel concepts, such as design-to-license that defines the licensing process as one of the design criteria, and the DT maintains state cognizance to ensure the design meets licensing requirements. Similarly, a DT has the capability of supporting the regulatory review of design-specific or technology-inclusive risks in addition to traditional risk metrics, such as core damage frequency.

Simulation facilities and plant-referenced simulators are already widely used across nuclear stakeholders for the administration of operating tests and to meet experience requirements for applicants for operator and senior operator licenses [9]. Plant-referenced simulators can be characterized as "limited simulation and modeling" plant representation. That is, fidelity to the physical plant is maintained through not only modifications to the physical panels or digital displays but also the periodic mapping of plant response and design data onto the plant models through an update of the simulator model code and variables and validation of the response as required by 10 CFR 55.46 and associated regulations [9]. Leveraging state concurrence, a DT has the potential to significantly improve plant representation compared to current plant-referenced simulators. However, any potential use of DTs for operator licensing would require that the NRC evaluate the suitability of a DT for operator qualification, especially in new and advanced reactors that are likely to feature all-digital control rooms.

APPLICATION

In September 2020, the 4-year digital reactor restructuring project, "le Project Structurant Pour la Compétitivité" [10], was launched to create a DT of every nuclear power unit in France. This collaborative project involves the EDF Group, Framatome, French Alternative Energies and Atomic Energy Commission, and six additional organizations from academia and the French nuclear industry. The project goal is to develop DTs that will serve as training simulators for operators and provide simulation environments for engineering studies.

Certain types of changes in a licensed facility may require a licensee to obtain prior NRC review and approval in accordance with 10 CFR 50.54 for change management [11] or 10 CFR 50.90 for a license amendment request [12]. A DT could support several aspects of these extensive processes, such as enabling real-time communication of the change between the licensee and the NRC as well as using analytics in identification, evaluation, and presentation of precedent-setting licensing actions. Such use of a DT can potentially improve the quality of the license amendment request, provide useful input for the NRC safety evaluation, and reduce the potential for a request of additional information [13].

Construction

An area during the construction phase where a nuclear DT could have impact on regulated activities is the ITAAC. A combined license enables the licensee to construct an NPP and operate it upon completion if certain criteria, the ITAAC, are satisfied [14]. Throughout the construction process, the NRC performs inspections at the site to confirm that the licensee has successfully met the ITAAC. A DT could significantly enhance the efficiency of ITAAC inspections by maintaining state concurrence with the physical facility during construction and directly informing NRC inspection activities.

Another consideration of DT application for ITAAC is the potential reduction of risk associated with failed or inadequate tests or analyses. A nuclear DT could maintain and update completed ITAAC records to ensure those test results are consistent with the current plant state. After an ITAAC is completed, the licensee is required to report new information materially altering the basis for a prescribed inspection, test, or analysis. A DT could integrate and analyze new information and identify the need for additional or updated tests and analyses to demonstrate compliance with ITAAC requirements.

Conducted in parallel with ITAAC inspections, the NRC implements a construction inspection program (CIP) during the period between licensing and initial operation. The CIP inspects licensee construction programs, preoperational testing activities, and the readiness of programs required during operations. This is to ensure that facilities are constructed correctly, and the licensee will have the appropriate programs in place to operate safely. A DT could be utilized to enhance CIP activities to verify the as-built facility conforms to the combined license.

Reviews and inspections of quality assurance (QA) programs and their implementation would benefit from DT applications. The NRC's objective is to determine whether licensee and their service suppliers are meeting the agency's requirements. A DT could be utilized as part of QA inspections. For example, as part of the CIP, the NRC conducts vendor QA inspections to ensure that products and services furnished to reactors meet and maintain the established regulatory requirements for quality and other safety factors. Through its information management and enhanced communication, a DT could support QA by maintaining easily accessible metadata for a plant component over the lifetime of the plant, including acquisition, test, and maintenance data, to ensure compliance.

APPLICATION

A collaborative effort between INL and North Carolina State University is developing a demonstration DT aimed at improving the management of NPP construction projects and could be utilized in NRC's QA inspection activities. Unmanned aerial vehicles or drones are deployed to efficiently capture regular imagery of a facility under construction, providing continuously updated as-built construction data for a construction digital twin of the facility. This construction digital twin will then be used to check component fits, building schedule, construction inventory management, and consistency with design [15].

Decommissioning

The use of a DT within the decommissioning activities offers some advantages that may have not been previously considered. Utilizing data analytics capabilities in a DT, more rigorous and accurate waste volume estimates, dose estimates, and economic estimates can be obtained. These estimates could then allow the licensee to ensure regulatory compliance with areas such as the as low as reasonably achievable (ALARA) requirement [16] as well as financial assurance from a regulatory perspective. The total cost of decommissioning a reactor facility depends on many factors, including the timing and sequence of the various stages of the program, type of reactor or facility, location of the facility, radioactive waste burial costs, and plans for spent fuel storage [17]. An NPP DT equipped with economic analytics could address the requirements of the NRC for licensees to report and demonstrate the status of their decommissioning funds at least once every 2 years, annually within 5 years of the planned shutdown, and annually once the plant ceases operation [17].

Summary of Plant Licensing, Decommissioning, and Certification

Licensing and Certification

Considerations	Opportunities
Safety analysis of the design and safety-case of design	Assess effectiveness of safety measures in design and operation Integrate safety assessment early in the design process and in the design iteration process for safety-based design concepts Support the design-to-license concept Provide a design-specific and technology-inclusive risk surrogate (e.g., alternative to core damage frequency for advanced reactors) Safety classification such as 10 CFR 50.69 classification Design SSCs for IST programs and technical specifications
Operator licensing	Provide high-fidelity simulator in operator training and licensing Update simulator model code and variables, and validate response
Support change management and license amendment request	Identify and evaluate precedent-setting licensing actions Demonstrate how amendments meet regulatory requirements

Construction Activities

Considerations	Opportunities
Inspections, Tests, Analyses, and Acceptance Criterion (ITAAC) survey	Maintain state concurrence between facility and DT during construction Reduce the risk of failed or inadequate tests (e.g., maintaining and updating ITAACS list)
Construction Inspection Program (CIP)	Verify the as-built facility conforms to the Combined Construction and Operation License
Quality Assurance (QA)	Enable data and information sharing across stakeholders to ensure compliance with quality requirements (e.g., support inspection across vendors, fabricators, designers, and construction team)

Decommissioning

Considerations	Opportunities
Potential waste volumes	Project and estimate volumes of future waste by category Understand and project future waste disposal needs and facility permitting
Radiation dose estimation	Overlay radiation dose map with facility map to allow for evolutions to estimate and track task times and potential exposures during dismantling and decommissioning (D&D) activities
Decommissioning financial reporting requirement	Provide forward cost and resource projections for D&D costs based upon above activities

3.3 OVERSIGHT

Operations

Perhaps one of the most significant uses of a DT centers on its ability to provide real-time information related to compliance with technical specifications. When licensees enter technical specification action statements, the DT could immediately provide the key information to stakeholders, enhancing and complementing notifications through traditional channels. Additionally, development or modification of IST programs and technical specifications could be informed by DT lessons learned.

APPLICATION

Many utilities have established monitoring and diagnostic (M&D) centers that monitor plant equipment and provide early warning to the station for equipment anomalies and, in some cases, information related to compliance with technical specifications. Utilities that have implemented an M&D center include Duke Energy, Tennessee Valley Authority, Public Service Enterprise Group, Florida Power and Light, Arizona Public Service, Xcel Energy, Exelon, and EDF Energy [3], [18]. Playing the role of a M&D center, but with a much greater information gathering, communication and analysis capabilities, a DT could support verification of compliance with technical specifications.

A major opportunity for DT technology is support for operability determinations. Operability determinations rely on a variety of plant information, including past history, current performance, and technical judgements to continuously assess the capability of SSCs to perform their specified safety functions. A DT could support such assessments leveraging capabilities for information gathering, integration, and analysis for tracking and trending current SSC health and performance and enable all users to easily share the same plant information, including analysis results, to make the process of determining SSC operability more predictable, transparent, and efficient. A licensee's assessment of operability and resultant actions, such as reducing reactor power output due to ultimate heat sink or decay heat removal system conditions, would be immediately available to stakeholders through the DT for independent review. Also, the consequences of operability determinations (e.g., technical specification actions) could be informed in real time by a DT. There is even a potential opportunity to develop plant-state informed technical specifications. While this approach would need evaluation and approval, technical specification action statements and limiting conditions for operation informed by actual plant state could offer significant operational flexibility, without safety reduction, and improved regulatory predictability and certainty. It should be noted that DTs may be equally applicable to other complex plant SSC condition determinations such as SSC availability considered within plant probabilistic risk assessment (PRA) space [19].

DT capabilities could be leveraged in novel ways to support other regulated activities considered within the NRC oversight process. For example, anomaly detection could be employed in a licensee's fitness for duty (FFD) program to detect individuals who are not fit to perform their duties [20]. DTs could assess the anomalous behavior of individuals by comparing the true performance of individuals with an expected or baseline behavior. Such an assessment can provide the early detection of individuals who are not fit for duty and provide insights and recommendations on the effects of factors such as fatigue and degraded alertness on an individual's abilities to perform.

Additionally, a DT could be used for facility inspections and audits. Current efforts at Westinghouse include the use of DTs for an automated analysis of inspection or monitoring data, exemplified by concrete crack detection using drones, neutron noise monitoring of reactor structures aging, and managing a severe reactor accident in real time [3]. A DT may provide staff improved plant information to enable more effective and efficient inspections and assessments. The DT capabilities could support virtual inspection and reviews by improving accessibility to relevant information while protecting proprietary information and reducing licensee burden. For example, the DT could monitor spent fuel pools in real time to support the review of a plant's heat rejection and criticality management.

During plant operation, the licensee should engage in dose prediction activities to ensure all planned operations satisfy ALARA requirements [16]. A DT has the potential to significantly improve task dose estimates with live 3-D radiation mapping and task-specific dose predictions which will help ensure compliance with ALARA requirements [21]. Furthermore, the DT could be used to maintain personnel dose tracking data. If the DT is used for these dose prediction and dose tracking, the NRC could then use the DT to perform the regulatory reviews to ensure compliance with ALARA requirements.

Another opportunity for DT to affect a regulated activity is using live feedback between the emissions models and the plant status to monitor emissions during routine operations as required by the NRC to monitor the discharges and analyze nearby environmental samples to ensure that the impacts of plant operations are minimized [22]. Part of this monitoring can include integrating advanced sensors for environmental monitoring with the DT. Having integrated live environmental monitoring with the DT means AI/ML could detect emission changes, predict events, and provide real-time recommendations for safe plant operations.

Maintenance

An opportunity for DT to affect regulated maintenance activities is its application for efficient maintenance practices in NPP, and this application is already an active area of research and development across nuclear stakeholders [3]. 10 CFR 50.65, commonly known as the Maintenance Rule [26], states the requirements for monitoring the effectiveness of maintenance at NPPs and establishes three broad licensee actions: (1) performance- or condition-monitoring of SSCs against licensee-established goals to provide reasonable assurance that these SSCs are capable of fulfilling their intended functions, (2) periodic evaluation of maintenance activities to achieve balance between preventing SSC failure and component unavailability due to maintenance, and (3) assess and manage the risk that may result from a planned maintenance before performing the maintenance activity.

DT capabilities may find wide application across these licensee maintenance rule activities. Leveraging state concurrence and state cognizance, DTs may complement or replace the existing performance- and condition-monitoring activities by automatically gathering and analyzing highly integrated, detailed, and live SSC performance and condition data. The embedded data analytics and ML/AI algorithms could provide insights into the effectiveness of existing preventive maintenance programs and even recommend optimum maintenance activities for SSCs. Integrating maintenance information and SSC data with risk-assessment models, DTs can perform live and long-term assessment and management of risk resulting from SSC availability or unavailability due to maintenance.

APPLICATION

Arizona Public Service relies on their in-house ML/AI algorithms that utilize component monitoring data to enable anomaly detection and work management automation and optimization [23]. Exelon is using data analytics to identify maintenance rule functional failures from the historical maintenance data of its plants [24] and is using the physics-based analytics suite FAMOS/PMAX to model and optimize thermal performance monitoring. EDF is using Metroscope, which combines AI and physics-based models, for performance monitoring analyses. GE Hitachi and Exelon are implementing the Predix analytics suite to manage and predict asset performance and enable condition-based maintenance. PKMJ Services, in collaboration with INL and Public Services Enterprise & Group Nuclear LLC, has developed and demonstrated a fully integrated risk-informed condition-based maintenance capability on an automated platform at their Salem NPP [25]. Several advanced reactor developers, such as Kairos Power, X-energy, GE, and Westinghouse, are developing DT-enabling technologies aimed at predictive maintenance, downtime reduction, aging, and degradation management in future reactors.

Safeguards and Security

The NRC's domestic safeguards program is aimed at ensuring special nuclear material 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 due to radiological sabotage [27]. The users of the special nuclear and certain quantities of byproduct material apply safeguards to protect against sabotage, theft, and diversion, including physical protection of facilities and/or special nuclear material at both fixed sites and during transportation and material control and accounting for special nuclear material [27]. Through the integration of subject-matter expertise, live data streams from physical assets, and ML/AI algorithms, DTs may be applied to significantly affect nuclear safeguards activities. For example, DT capabilities may be used to determine if data streams received from the asset are nominal, identify locations in the asset that deviate from expected behavior, characterize those discrepancies, and provide recommendations for safeguards experts. Efforts at INL are currently exploring the use of safeguards-relevant DT capabilities through test cases, specifically focusing on sodium-cooled fast reactors, sodium-cooled fast reactor breeder scenarios, pebble-bed reactors, and the nuclear fuel cycle, especially solvent extraction processes.

The NRC regulation 10 CFR Part 73.55 [28] states the requirements for the physical protection of licensed activities in an NPP against radiological sabotage. The intrusion detection and assessment system at NPPs is a complex network of sensors, alarms, and communication hardware and software that must operate with high levels of effectiveness at all times. DTs with capabilities of interacting with real-time data from intrusion detection system, ML/AI-based computer vision algorithms, and virtual sensors can enhance the effectiveness of security and address regulatory requirements for demonstrating security effectiveness and for periodic testing and monitoring of intrusion detection system. Additionally, because DTs may offer increased levels of integrated plant state cognizance, DTs may be used to inform security response and tailor actions to those most suitable for current plant conditions.

Traditionally, physical security at commercial NPPs can be labor intensive, and a DT holds significant potential to enhance physical security effectiveness at current plants and to enable design of efficient physical security of advanced reactors. DT-based analytics could enable integration of traditional physical security effectiveness assessment tools such as force-on-force analysis with risk-assessment tools and plant models to provide risk-informed performance-based insights on security effectiveness [28]. Such enhanced analytics enabled by a security DT could support demonstrating a high assurance of protection against the design basis threat of radiological sabotage for existing plants [28] and to meet the advanced reactor policy statement [30]. The technical challenges and regulatory considerations associated with the use of DTs for safeguards and security are explored more extensively in a dedicated task within this effort.

NRC Emergency Response

The NRC ensures that NPPs have emergency plans in place to protect public health and safety if an accident were to occur. Emergency preparedness programs enable emergency personnel to rapidly identify, evaluate, and react to a wide spectrum of plant events. There are various opportunities to leverage a regional or national system of systems DT to support and coordinate emergency response. An event response DT could obtain and evaluate event information and analyze the event's potential impact on public health and safety and the environment. Use of such a DT could avoid or reduce the severity of the events by increasing response efficiency and facilitating communication among responders. A DT could also integrate live data and models, including interdependencies between facilities during and leading up to an event, and coordinate the request for emergency response support from agencies on the local, state, and federal level. Further, the use of DT would enable the licensees to make enhanced recommendations for evacuation zones, based on real-time data and information. An additional opportunity is related to the Emergency Response Data System (ERDS), which provides a direct transfer of live data from licensee plant computers to the NRC Operations Center for use during emergencies. The ERDS could be enhanced using DT for real-time decision support during plant emergencies by using a DT to provide on-demand, detailed plant information, predictions, and recommendations.

Operations	
Considerations	**Opportunities**
IST programs and technical specifications surveillance	Enable real-time inputs in technical specifications Develop appropriate IST programs and technical specifications for components and systems based on DT lessons learned
Operability determination	Track and trend system health and performance and integrate with real-time operability determination
FFD assessment	Assess operator FFD to ensure compliance with 10 CFR 26
Facility inspections and audits	Provide regulatory staff access to plant or SSC data and models to conduct inspections, audits, reviews, etc. Support virtual regulatory inspection and reviews, including accessibility and protecting information
Radiation Dose Prediction	Leverage DT based advanced models for achieving and assessing ALARA goals
Environmental impact and public health dose limits	Facilitate real-time feedback between emissions models and plant status for routine operations Integrate advanced sensors for environmental monitoring Integrate with live environmental data to predict severe events Provide real-time recommendations for safe plant operation (e.g., activation of argon in air) Report across stakeholders

Maintenance	
Considerations	**Opportunities**
Monitoring performance or condition of SSCs to provide reasonable assurance of fulfilling their intended function	Conduct performance or condition monitoring based on real-time SSC data and inform, complement, or replace existing monitoring program
Controlling performance or condition of SSC through preventive maintenance	Evaluate effectiveness of existing preventive maintenance program on SSC performance or condition Inform or recommend an optimum preventive maintenance schedule to maximize plant safety and minimize SSC unavailability
Assessing and managing the increase in risk due to proposed preventive or corrective maintenance activities	Integrate real-time SSC data, condition monitoring algorithms, and risk-assessment tools and recommend maintenance practices to minimize risk

Safeguards and Security

Considerations	Opportunities
Theft detection	Integrate sensors, data analytics, and ML for radioactive material theft detection
Intrusion detection and assessment system	Support the testing and monitoring of sensors and alarms with virtual sensors and analysis Augment the detection and assessment system through ML/AI algorithms for computer vision and automated assessment
Physical security analysis of design	Provide a high assurance of protection against the design basis threat of radiological sabotage Assess the effectiveness of physical security provisions during attack scenarios Integrate physical security assessment into the design process for physical security Support the design to meet the Advanced Reactor Policy Statement Enable real-time data-integration with a target set data for analysis and assessment

Emergency Response

Considerations	Opportunities
NRC's incident response program	Obtain and evaluate event information, and assess the event's potential impact on public health and safety and the environment Leverage the regional and national system of systems DT to support NRC emergency response Integrate real-time data and models, such as weather, climate, geological, intelligence, and interdependencies among facilities. Coordinate real-time targeted information among local, state, and federal agencies Enhance ERDS with real-time DT information and decision support system

3.4 OPERATIONAL EXPERIENCE

The NRC established the Reactor Operating Experience (OpE) Program to collect, communicate, and evaluate lessons learned from operating nuclear reactor events, research and test reactor events, events or issues identified at nuclear reactors under construction, security-related reactor events, and emergency preparedness issues. The DT capabilities for information collection, management, and communication could directly affect the core objectives of OpE to (1) collect, evaluate, communicate, and apply OpE to support the NRC's goal of ensuring safety and security, (2) improve the effectiveness, efficiency, and realism of NRC decisions, and (3) provide stakeholders with timely, accurate, and balanced information. Informational updates within DTs across the fleet could enhance the existing NRC Reactor Operating Experience Data Website (NROD) to enable efficient information sharing; and analytics within DT could support updates in PRA parameter estimates using NROD.

The NRC event assessment process requires each licensee to send information to the NRC about certain reportable events [31]. Based on the type of event and information, there can be different mechanisms of information exchange between NRC and licensee, such as event notification reports, preliminary notifications, licensee event report, and others. DT with capability for information sharing among permitted stakeholders in a secure environment can potentially make the event assessment process more efficient. Combined with advanced modeling, such a DT could not only share information but also potentially replay significant events with high detail in a virtual environment.

Since radioactive discharges from NPPs can impact environmental and public health and safety, the NRC requires licensees to perform radiological effluent and environmental monitoring and analysis. This ensures that impacts of plant operations are minimized, and radiation exposures are kept within the NRC's specified dose limits and ALARA. The NRC analyzes discharge and emission data obtained within the operational experience process to provide a technical basis for related regulations. DT technology can be utilized for efficient reporting and data collection across stakeholders, allowing the NRC to review and analyze reportable information to determine appropriate regulation and limits.

Operational Experience	
Considerations	**Opportunities**
Operating experience	Determine the safety significance and potential consequences of operating experience issues and the applicability of lessons learned Enable updates, notifications, and information exchange in NROD Use analytics for updates in PRA parameter estimates from NROD
Event assessment	Share information securely and efficiently among stakeholders Replay significant events in a virtual environment

3.5 SUPPORT FOR DECISIONS

In order to provide technical and scientific bases for NRC decisions, the NRC gathers information and performs analysis on a wide range of current and potential future regulated activities. The agency integrates and analyzes data such as risk information, performance measures, and operational experience to inform decision-making and development within all other NRC regulatory processes. The DT's capabilities to gather, communicate, analyze, and integrate novel information have the potential to significantly enhance NRC activities to develop technical bases. A DT could support decisions regarding both deterministic and risk-informed regulatory approaches by providing new and improved nuclear data sets, analysis methods, and visualization tools. For example, the novel cognizance of an integrated plant state provided by DT may support new technical bases for rules regarding dynamic, state-informed technical specifications, technology-inclusive risk-management frameworks, and safety margin calculations. Because a DT may enable a significantly improved understanding of actual plant state and performance, the technology has the potential to develop novel insights for both current and future regulatory processes.

A specific example of an opportunity for DT to affect an important NRC analysis tool involves NRC's PRA tools. PRA is used to quantitatively estimate risk and provide insights into design and operations of a NPP. The integration of DT with PRA could advance risk assessment in several ways. Analysts may improve existing model precision by collecting new and more relevant data. A DT could inform PRA models with dynamic parameters by updating the model with current values of SSC availability, reliability, and failure probability. In this way, the PRA could be augmented to reflect actual plant system states more accurately and perhaps even provided with updated internal structures to model novel failure modes, correlations, and dependencies identified by DT. DT technology itself may also offer a much more dynamic, granular, and realistic model of plant performance than current PRA models and may have use as enhanced method for establishing quantitative risk-insights. For example, DT can more flexibly and dynamically model such events as multiple failures, partial failures, and functional degradations as well as producing results that are independent of predetermined accident sequences. Also, advanced modeling used by DT could employ stochastic approaches and output probability distributions and expected values with high accuracy and fidelity. In this way, DT may provide improved and independent methods to support NRC decision making.

Support for Decisions

Considerations	Opportunities
Modeling and simulation to inform safety analyses	Support risk-informed and deterministic regulatory conclusions with new data and insights Support decision-making with integrated M&S
Integration of DT with PRA	Inform PRA models with internal and external data and analysis and provide dynamic parameter estimation, SSC availability, or risk triplets for advanced reactor SSCs, etc. Upgrade and augment PRAs using DTs (e.g., use of advanced models, physics-based or AI/ML, in DT for identifying novel failure modes, correlations, and dependencies) Estimate human error probabilities and make recommendations for minimizing human errors and their consequences Develop internal NRC models within DTs (i.e., independent models for decision-making)

CONCLUSION

This report presents a description of a nuclear DT system and its capabilities, and identifies and discusses potential DT effects on regulated activities that merit consideration and present novel or unique opportunities for change within that activity.

This report is aimed at identifying areas that may benefit from future regulatory focus and at enabling and encouraging collaborative efforts among nuclear stakeholders toward research, development, design, and demonstrations that address opportunities within these areas. Because of the potential, general application of DT-enabling technology to new and advanced reactors, as well as the limited, near-term application of DT for operating reactors, identifying and addressing these considerations and opportunities are important steps toward preparing for the future. Increasing industry application of DT technology may result in greater confidence in these technologies and their subsequent nuclear application. Such applications may have direct and indirect impacts on NRC-regulated activities.

Of the regulated activities grouped under the five main components of NRC's regulatory process, regulated activities involving oversight appear to have a significantly broad intersection with DT capabilities. As current and future licensees continue to explore the use of DT for increased efficiency in reactor O&M, such applications may have significant impacts on these regulated activities and may merit future considerations regarding the impacts on NRC processes, such as inspections and performance assessment. Several efforts are currently underway toward adopting DTs at a system and sub-system level to support O&M among operating reactors [3]. For new and advanced reactors, DT has the potential to be applied across the reactor life cycle, from design certification and licensing through decommissioning. Regulated activities considered with NRC's operational experience and support for decision processes may be widely impacted by the enhanced and efficient information management and communication capabilities of DT, enabling not only real-time information exchange among stakeholders but also novel insights into risk-informed decision-making.

The regulatory considerations identified in this report suggest the need for additional efforts to be undertaken by research institutions, national laboratories, reactor systems designers, vendors, licensees and the NRC staff to address opportunities in data, modeling, and real-time integration of data and models consequential to the implementation of a nuclear DT system. The NRC staff continues to assess the regulatory viability of DT for NPPs by identifying and evaluating technical challenges associated with the application of a DT in reactors with the goal of preparing the NRC for future use of DT technologies. In addition to past work exploring state-of-the-art applications of DTs [3] [4] and continuing outreach to nuclear stakeholders, the NRC staff is pursuing research activities in the application of advanced sensors for monitoring system performance and integration of safeguards and security within DTs. These activities will help identify and explore additional areas of intersection between DT and nuclear stakeholders.

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