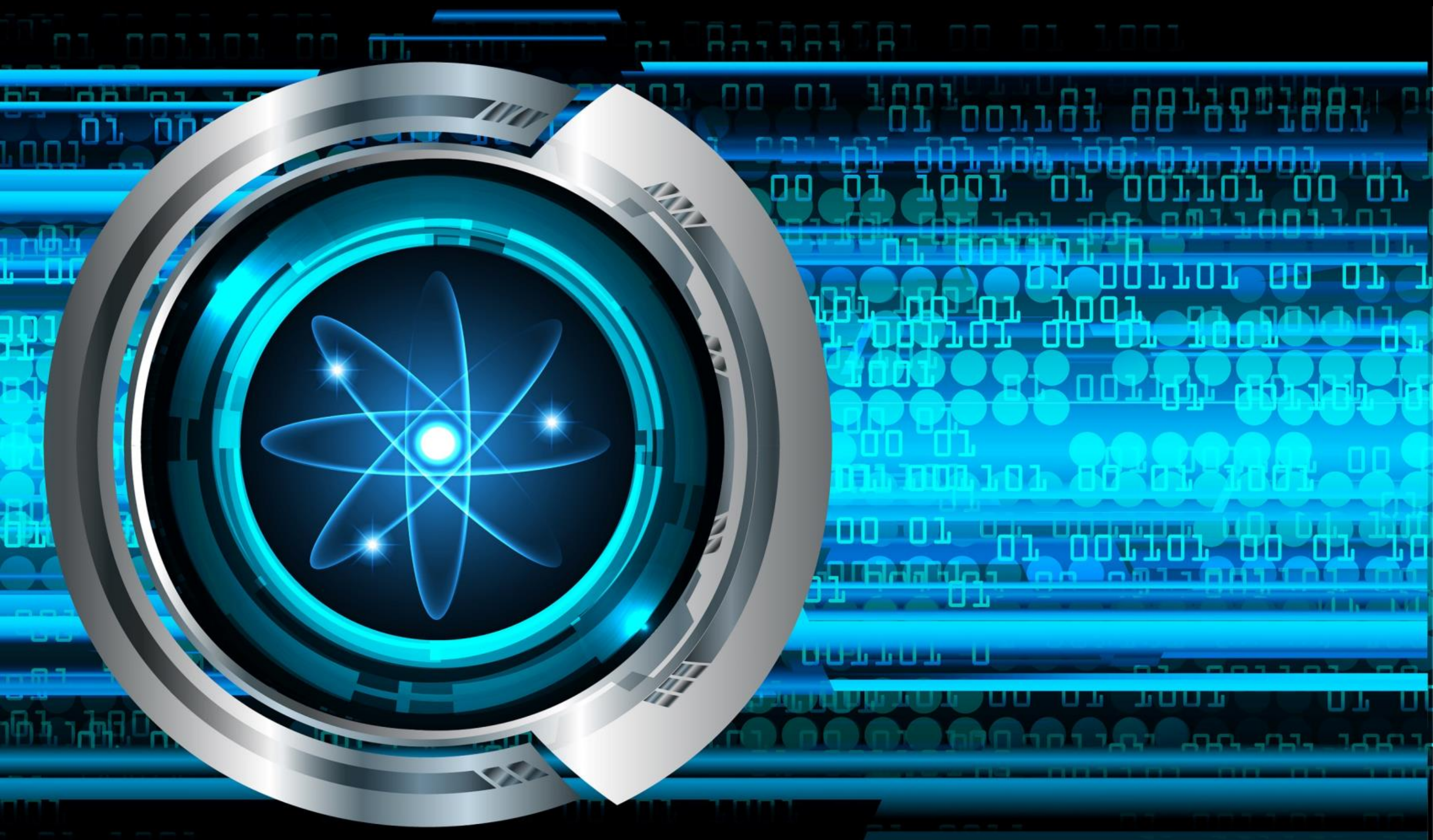
Letter Report
TLR-RES/DE/REB-2022-07

PROJECT SUMMARY OF DIGITAL TWIN REGULATORY VIABILITY IN NUCLEAR ENERGY APPLICATIONS



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PROJECT SUMMARY OF

Digital Twin Regulatory Viability in Nuclear Energy Applications

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PROJECT OVERVIEW

Objective

The Office of Nuclear Regulatory Research at the U.S. Nuclear Regulatory Commission (NRC) completed a future-focused research project aimed at assessing the regulatory viability of digital twins (DTs) for nuclear power plants (NPPs). This project was led by Idaho National Laboratory (INL) in collaboration with Oak Ridge National Laboratory (ORNL). The objectives of this project were to:

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

Overview of Activities Performed

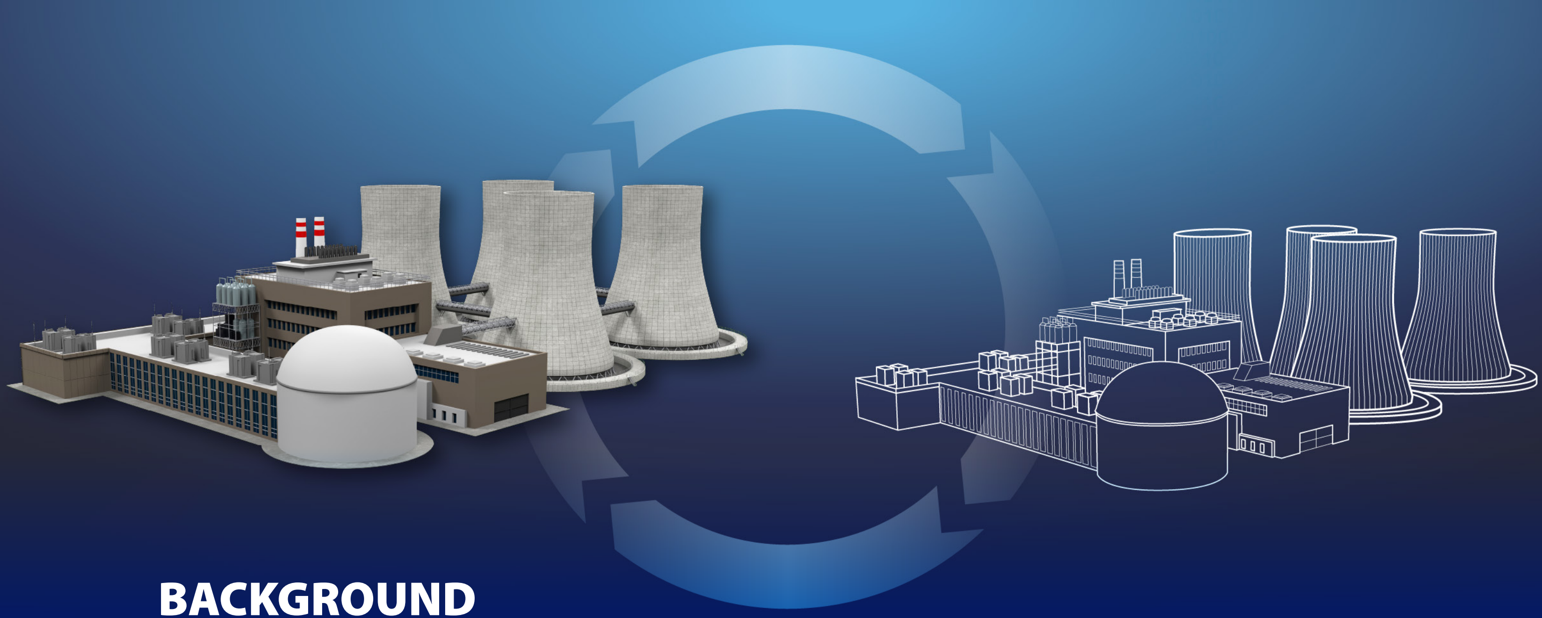
To prepare the NRC for potential future applications of DTs in the nuclear industry, a team of researchers and experts across INL, ORNL, and the NRC conducted the following key activities over the course of 18 months:

- Organized two virtual workshops on DT applications and enabling technologies for advanced reactors and plant modernization; the two workshops together featured more than 75 presenters and more than 700 attendees from across the globe and provided a forum for nuclear industry and DT stakeholders to discuss the state of knowledge and research activities related to DTs and their applications in the nuclear industry
- Assessed the spectrum of DT technologies and identified current efforts in the nuclear industry focused on specific DT-enabling technologies
- Compiled a set of challenges and gaps for implementing DT-enabling technologies in current and advanced reactor applications
- Hosted an NRC observation public meeting to solicit input from the industry and the public on DT regulatory considerations and opportunities
- Reviewed NRC-regulated activities that may be impacted by DT-enabling technologies and identified activities meriting special considerations and potential opportunities for the application of DT technology

The findings of this project are discussed in detail in the published reports and workshop proceedings, and this report presents a summary of key findings.

PUBLICLY AVAILABLE RESOURCES FROM THIS EFFORT

1. *Proceedings: Workshop on DT Applications*
2. *Proceedings: Workshop on DT-Enabling Technologies*
3. *Report: The State of Technology of Application of Digital Twins*
4. *Report: Technical Challenges and Gaps in Digital-Twin-Enabling Technologies for Nuclear Reactor Applications*
5. *Report: Regulatory Considerations for Nuclear Energy Applications of Digital Twin Technologies*
6. *Summary: Public Meeting on Regulatory Considerations*



BACKGROUND

In recent years, there have been active efforts in research, development, and demonstration of digital and advanced technologies across a variety of applications such as advanced sensors and instrumentation, predictive maintenance, load-following, advanced simulators for training and qualification, data analytics, machine learning (ML), and artificial intelligence (AI) [1] [2]. NPPs, both currently operating and future plants, will make increasing use of digital technologies for the monitoring and control of plant systems, structures, and components, and decision-making supporting operations and maintenance. Many utilities and other nuclear stakeholders are exploring the integration of these digital technologies to form a "digital twin" to provide novel insights, increase operational efficiency, improve communication and information transparency, and enhance safety and reliability. The DT project was initiated to prepare the NRC for the potential future use of these DT technologies in nuclear applications.

DT Problem Space

The scope of the project included an assessment of the technologies and the integration of those technologies associated with an NPP DT system. While the focus of this project was on NPPs, the concepts herein can be applied to other nuclear applications, such as fuel production and waste processing facilities.

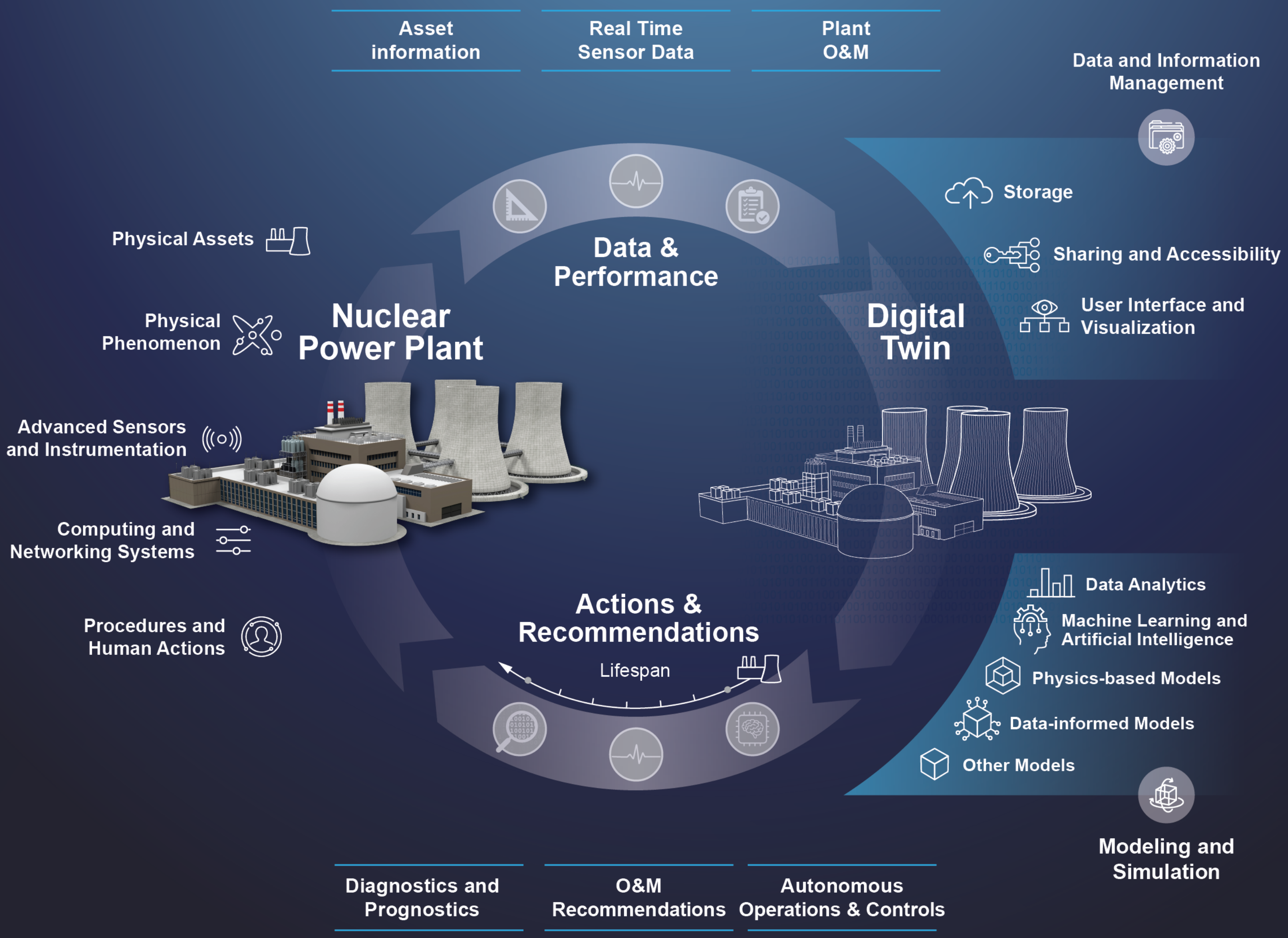
As a first step in understanding the DT problem space, the project team engaged extensively with stakeholders and experts in DT-enabling technologies to develop a description of a DT system for NPP applications. The report [1] presents a detailed framework for an NPP DT system that broadly comprises four elements: (1) NPP, (2) DT, (3) data and response from NPP to DT, and (4) actions and recommendations from DT to NPP. As information flows from the physical plant to the DT, that information is processed and analyzed through various methods (e.g., data analytics and data-informed models), and then ultimately, recommendations are made to inform or carry out actions regarding areas such as operations and maintenance.

The remaining portion of this report includes a discussion of the technologies, applications, and regulatory implications associated with an NPP DT system. The report is organized according to the following general project activities:

1. Gathering information about DTs
2. Analyzing the information
3. Summarizing observations

These activities aim to increase knowledge, enhance communication, and build common understanding of DT technologies in nuclear applications.

Nuclear Digital Twin System



1 | GATHERING DIGITAL TWIN INFORMATION

In the information-gathering portions of the project, the project team conducted activities such as stakeholder outreach, literature reviews, and identification of past and current efforts in the research, development, and implementation of DTs for nuclear and non-nuclear applications.

Workshop on DT Applications for Advanced Nuclear Technologies

The project team organized a virtual public workshop held December 1–4, 2020, to accomplish two main purposes:

- Review and exchange information on the current understanding of DT technologies
- Identify the potential benefits, opportunities, and challenges of applying DT technologies to nuclear reactors

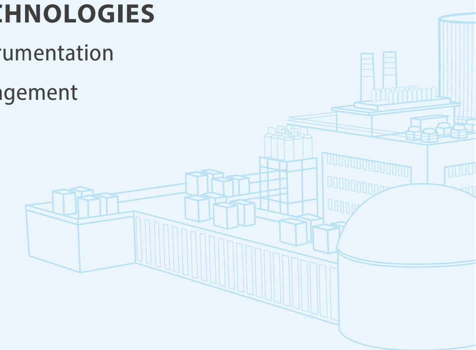
The 4-day workshop was attended by over 400 participants across the globe and featured 13 technical and panel sessions with over 50 presenters from a wide range of national and international organizations, including universities, national laboratories, government agencies, nuclear vendors, advanced reactor vendors, and DT vendors. The workshop proceedings [3] provide a detailed discussion on the technical and panel sessions, as well as major DT applications identified in the workshop.

State of Technology

In conjunction with the workshop, the project team conducted an in-depth assessment on the state of DT technologies, particularly focusing on the applications of those technologies for nuclear reactors and facilities. To that end, the team assessed the current efforts and future vision for DT implementation at several nuclear and non-nuclear entities, including Kairos Power, Framatome, Westinghouse, X-energy, IBM, General Electric, Siemens, ANSYS, and Dassault. A comprehensive evaluation across eight different industries, engineering, manufacturing, aerospace, education, oil and gas, construction, automotive, and medical equipment, was performed to understand the definition and use of DT technology within those respective areas. A literature review conducted as part of this effort found 46 different definitions of a DT [2]. Realizing the need to develop a common understanding of the problem space, the project team developed a description of a nuclear DT system. Based on the information gathered at this stage, the team also developed a preliminary set of key DT-enabling technologies including advanced sensors and instrumentation, data and information management, data analytics, and modeling and simulation (e.g., AI/ML, physics-based models, data-informed models). The description of a nuclear DT system, its key enabling technologies, and findings of the state of technology assessment are discussed in detail in [2].

KEY DT-ENABLING TECHNOLOGIES

- Advanced sensors and instrumentation
- Data and information management
- Data analytics
- Modeling and simulation
  - AI/ML
  - Physics-based models
  - Data-informed models



Workshop on DT-Enabling Technologies for Advanced Reactors and Plant Modernization

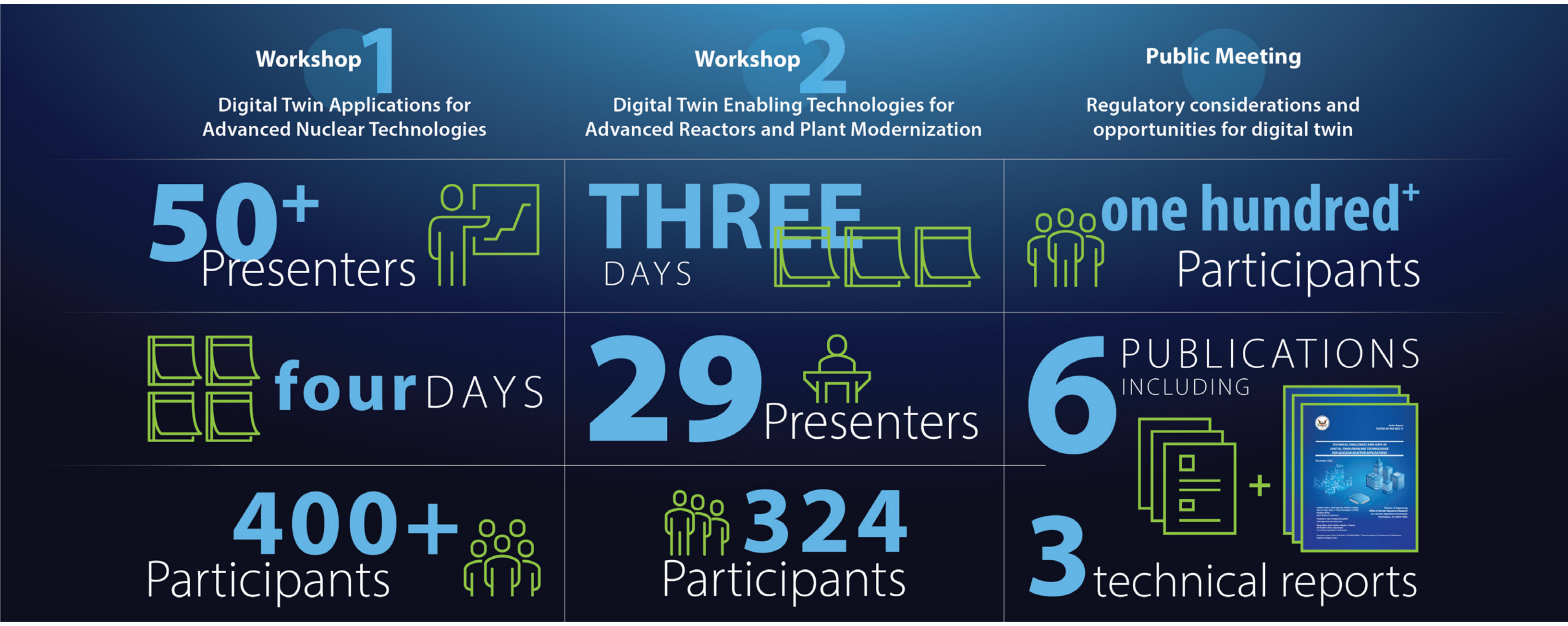
After identifying key DT-enabling technologies, the project team organized a second virtual workshop held on September 14–16, 2021, to review current applications of DT-enabling technologies and identify potential steps toward regulatory realization of DTs in the nuclear industry. This 3-day workshop was attended by 324 global participants and featured five technical and panel sessions with 29 presenters from various research and industry organizations. In addition to project partners INL and ORNL, the workshop was coordinated with the Electric Power Research Institute (EPRI) and the Advanced Research Projects Agency – Energy (ARPA-E). The workshop covered topics such as DT applications in advanced reactors, use cases of DT-enabling technologies in operating nuclear plants, advanced sensors and instrumentations, and steps toward regulatory realization of DTs. The workshop proceedings [4] provides a detailed discussion on the technical and panel sessions and major conclusions from the workshop.

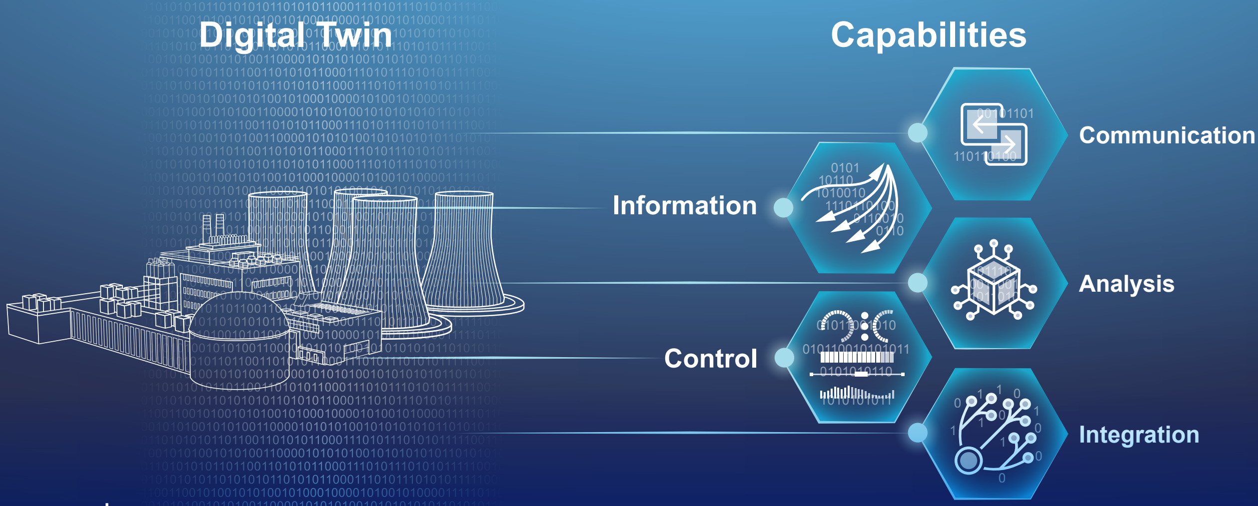
Public Meeting on Regulatory Considerations and Opportunities

The project team held a public observation meeting on March 1, 2022, with representatives from ARPA-E, EPRI, and the Nuclear Energy Institute (NEI). Each organization provided updates regarding relevant research efforts and discussed regulatory considerations and opportunities for DTs in nuclear reactor applications. Comments were solicited from nuclear stakeholders and the general public. Some of the specific topics discussed included approaches to implementing DTs and the need for DT business cases, lessons learned, reductions in regulatory uncertainty, and the development of common frameworks, standards, and guidance [5].

Additional Stakeholder Engagement

The project team conducted periodic meetings with ARPA-E and EPRI and engaged directly with several organizations including the Department of Energy's (DOE) Office of Nuclear Energy (DOE-NE), DOE's Light Water Reactor Sustainability Program, Halden Labs, NEI, many national laboratories such as INL, ORNL, and Sandia National Laboratories (SNL), as well as other national and international stakeholders to gather information, perspectives, meaningful insights, and understanding regarding potential nuclear DT applications.





2 ANALYZING THE INFORMATION

Information gathered about DT was analyzed to develop meaning, context, and insights related to the nuclear DT problem space. Activities included identification, development and discussion of a DT research methodology, appropriate DT terminology [2], key DT-enabling technologies [2], technical challenges and gaps related to DT technologies [1], and regulated activities that merited special consideration and presented novel opportunities for nuclear application [6].

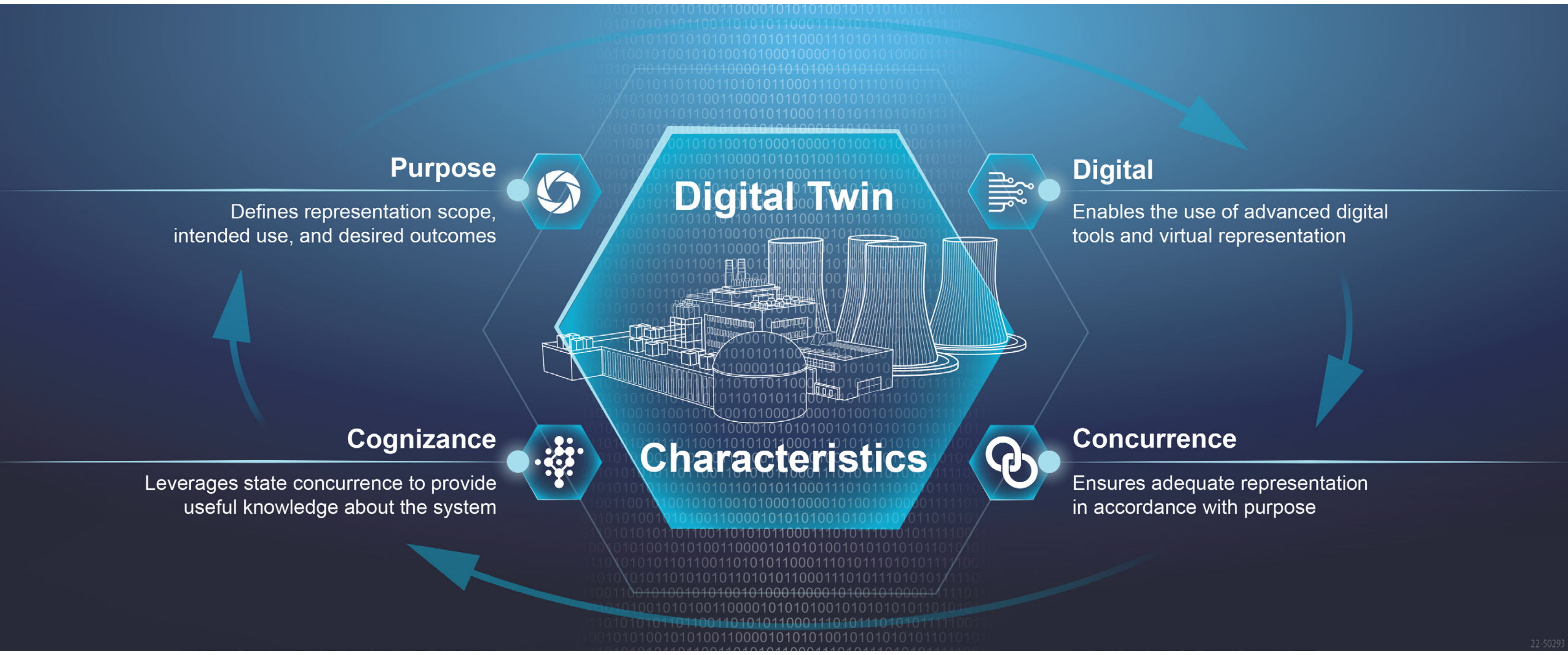
While all areas of potential regulatory intersection were considered, the project team focused on identifying those elements of intersection that presented novel or unique aspects because those aspects would likely require special efforts and considerations related to DT implementation. Additionally, current, planned, and potential future applications were identified to provide clarity and context.

Technical Challenges and Gaps for Enabling Technologies

Current development trends in the nuclear industry include DT-enabling technologies that may form a unified system or plant DT. This portion of the project focused on identifying the challenges associated with the implementation of each DT-enabling technology and the gaps in knowledge, technologies, or resources available to meet those challenges. The challenges and gaps are identified for activities conducted throughout a plant's lifecycle such as research, development, design, manufacturing, licensing, qualification, deployment, and operations and maintenance. The report [1] provides a detailed discussion on technical challenges and associated gaps for each of the DT-enabling technologies. The gaps identified in this work suggest the need for additional efforts by research institutions, national laboratories, reactor systems designers, vendors, and licensees to address challenges in data, modeling, and real-time integration of data and models consequential to implementing a nuclear DT system.

KEY CHALLENGES IN DT-ENABLING TECHNOLOGIES

- Building adequate sensor and instrumentation infrastructure
- Developing real-time, data-informed models
- Implementing scalable, integrable data analytics
- Establishing AI/ML trustworthiness and explainability
- Constructing real-time, high-fidelity physics-based simulations
- Verifying and validating integrated models
- Developing user interfaces for data and information



DT Characteristics and Capabilities

Evaluation of potential DT applications revealed fundamental DT capabilities and characteristics. These capabilities and characteristics provide context for understanding DT applications and help inform stakeholders on potential DT use and impact on regulated activities.

This effort identified four foundational characteristics of a nuclear DT system:

- **Serves an Underlying Purpose:** the technology must have an underlying purpose related to an NPP lifecycle activity
- **Exists in Digital Form:** the technology must exist in a digital form that can be managed, processed, and executed on a digital device
- **Maintains State Concurrence:** the technology must be capable of updating dynamically to represent the current state of a physical entity or physical phenomenon and must maintain that state concurrence
- **Ensures State Cognizance:** the DT must have the capability to provide novel and integrated sets of insights, information, and outcomes related to the physical entity that were not possible, feasible, or efficient prior to implementing the DT [6]

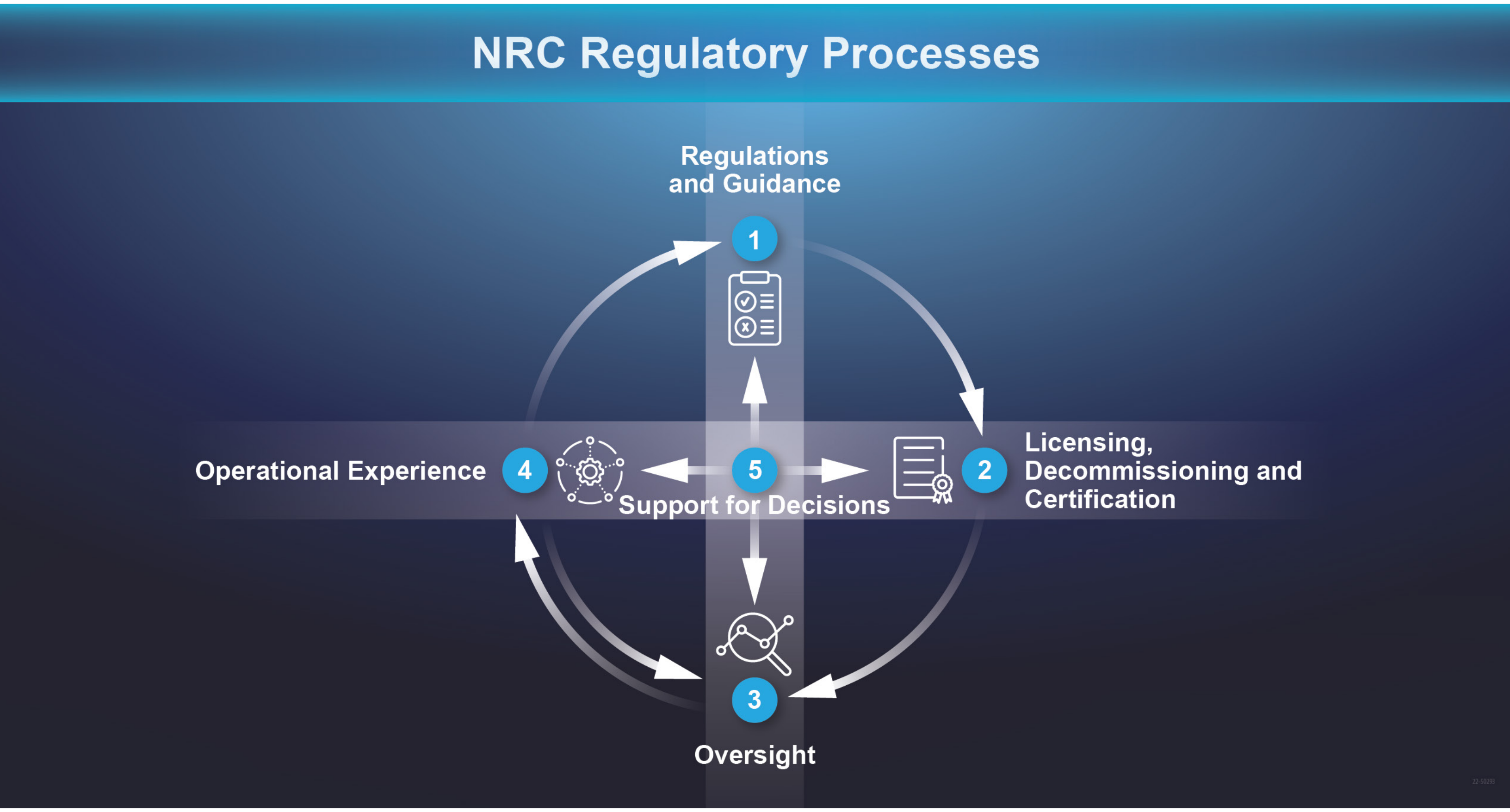
Across various industrial applications, DT holds promise for significant enhancement in several capabilities. Recognized for their potential to significantly impact regulated activities, these capabilities are broadly classified as: (1) information, (2) communication, (3) analysis, (4) integration, and (5) control. These capabilities are described in detail in [6].

- **Information:** Provides new and improved plant information that is trusted, timely, on-demand, correct, and complete
- **Communication:** Propagates information among the various DT-enabling technologies and among nuclear DT stakeholders to facilitate deeper insights and new cognizance of plant states
- **Integration:** Establishes a centralized hub and enabler for the integration of a variety of data, information, models, and analytics to address the underlying DT purpose in a reliable and accurate manner
- **Analysis:** Leverages advanced analytical products and tools to produce, process, and represent information about a plant's current, past, and future states, as well as provide insights to support decision making and risk assessments
- **Control:** Combines 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 to enable operations that are adaptive, optimal, robust, and autonomous

Regulatory Considerations and Opportunities for DTs

To identify specific regulatory aspects of DT applications, this work focused on regulated activities considered under the five main components of the NRC's regulatory processes:

1. *Developing* regulations and guidance for applicants and licensees,
2. *Licensing* or certifying applicants to use nuclear materials or operate nuclear facilities or decommissioning that permits license termination,
3. *Overseeing* licensee operations and facilities to ensure that licensees comply with safety requirements,
4. *Evaluating* operational experience at licensed facilities or involving licensed activities, and
5. *Conducting* research, holding hearings to address the concerns of parties affected by agency decisions, and obtaining independent reviews to support regulatory decisions.



Regulated activities within the scope of the NRC's regulatory processes can potentially be significantly impacted by the use of DTs. Such impacts include new, enhanced, and alternate methods of meeting regulatory requirements, novel quantitative insights, changes to plant processes, safety, security, and more. The NRC Technical Letter Report [6] presents the findings from the review of NRC-regulated activities to identify specific regulatory areas where DT and its enabling technologies can potentially support, replace, or complement the existing regulated activity.

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

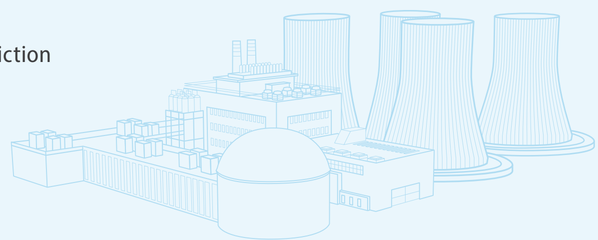
- Modeling and Simulation to Inform Safety Analyses
- Integration of DTs with Probabilistic Risk Assessment

3 | SUMMARY AND OBSERVATIONS

This report presents a summary of activities, outcomes, and findings of the NRC's future-focused research project aimed at assessing the regulatory viability of DTs for NPPs, fuel cycle facilities, and other nuclear energy applications. The project activities included conducting a comprehensive state of technology assessment of DT-enabling technologies, engaging stakeholders in the form of workshops and public meetings, identifying challenges and gaps in the application of DT-enabling technologies, developing a DT problem space for nuclear applications, and identifying areas that may benefit from future regulatory focus. The project team published two reports on workshop proceedings, one report summarizing an observation public meeting, and three technical letter reports providing detailed discussions on various project activities and findings.

KEY DT APPLICATION AREAS IN NUCLEAR

- Design and licensing
- Plant construction
- Training simulators
- Predictive operations and maintenance
- Autonomous operation and control
- Failure and degradation prediction
- Safety and reliability analysis
- Safeguards and security
- Fuel management
- Plant decommissioning

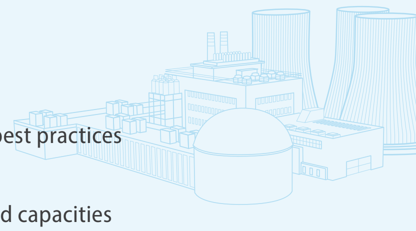


In general, interest in DTs continues to grow, and several DT-enabling technologies are experiencing rapid development and advancement in the nuclear industry. DTs are being considered for application in many stages of the nuclear lifecycle, from design and licensing to decommissioning. The technical challenges and regulatory considerations in the application of DT-enabling technologies identified in this project suggest opportunities to address capability gaps in data, modeling, and integration of real-time data and models. Addressing these gaps is important for implementation of a comprehensive nuclear DT system. Ongoing efforts for DT implementation at the system, subsystem, and component level in non-safety systems and processes may result in greater confidence and wider application of these technologies. Such applications may have direct and indirect impacts on regulated activities, and may highlight corresponding areas of regulatory focus, especially oversight, inspections, and performance assessment.

Stakeholders have several opportunities related to the research, development, demonstration, implementation, operation, and maintenance of DTs in nuclear applications. In the near term, a common language or taxonomy for DT stakeholders could be developed to enhance communication, collaboration, and research. New and advanced reactors will likely accelerate the adoption of DTs for nuclear power, and a community of practice with a specific focus on DT applications for advanced nuclear technologies would benefit these activities. Developing and implementing DTs for nuclear applications can take various shapes and forms such as reactor design, neutronics, fuel performance, plant operation and maintenance, power generation, and more. Importantly, the community of diverse but disconnected technical experts should be brought together to share models, algorithms, and best practices for DT-enabling technologies. This community could develop holistic lifecycle models of nuclear energy applications such as power generation or fuel cycle activities that can be integrated within a DT, covering requirements, design, testing, implementation, operations, and change management. Developing novel codes and standards for DTs would help ensure the predictable, repeatable, continuous, and long-term implementation of DTs in NPPs. Nuclear stakeholder engagement with non-nuclear stakeholders and standards development bodies would assist in the identification of relevant existing standards and development of new standards or guidance. Finally, developing a talent pipeline that prepares the future workforce of nuclear experts in DT-specific skillsets, capabilities, competencies and capacities is crucial to the successful implementation of DTs in the nuclear industry.

AREAS OF DT DEVELOPMENT OPPORTUNITIES

- Common language or taxonomy
- Lifecycle models
- Community of practice
- Shared models, algorithms, and best practices
- Consensus codes and standards
- DT capabilities, competencies, and capacities



The NRC staff continues to assess the regulatory viability of DTs for NPPs by identifying and evaluating technical and regulatory challenges associated with the implementation of DTs in nuclear energy applications. A key focus area is the development of institutional knowledge and staff competencies in DT-enabling technologies to facilitate effective and efficient reviews of DT-related applications. The NRC staff is actively pursuing further DT research activities in the application of advanced sensors for monitoring system performance and integration of safeguards and security. The NRC staff is also considering future research in the assessment of standards and digital communication technologies. Based on nuclear stakeholder interest and activity, the NRC staff will continue to evaluate further industry DT efforts and their regulatory implications, including assessment of potential regulatory frameworks and guidance relevant to DT development and implementation.

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