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STATE-OF-TECHNOLOGY AND TECHNICAL CHALLENGES IN ADVANCED SENSORS, INSTRUMENTATION, AND COMMUNICATION TO SUPPORT DIGITAL TWIN FOR NUCLEAR ENERGY APPLICATION

February 2023

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FIGURES

ACRONYMS

AI	Artificial intelligence
AP	Access point
AR	Advanced reactor
ASI	Advanced sensors and instrumentation
BS	Base stations
CT	Communication technology
DOE	Department of Energy
DT	Digital twin
EMDA	Expanded Materials Degradation Assessment
EPRI	Electric Power Research Institute
FIIW	Future of Instrumentation International Workshop
HART	Highway Addressable Remote Transducer
INL	Idaho National Laboratory
IoT	Internet-of-things
ITS	Important-to-safety
LTE	Long-term evolution
LWR	Light-water reactor
LWRS	Light Water Reactor Sustainability
M&S	Modeling and simulation
ML	Machine learning
MPI	Message passing interface
NEET	Nuclear Energy Enabling Technologies
NPP	Nuclear power plants
NRC	Nuclear Regulatory Commission
O&M	Operations and maintenance
ORNL	Oak Ridge National Laboratory
PRA	Probabilistic risk assessment
QoS	Quality-of-service
RFID	Radio frequency identification
SAM	Scalable, agile, and modular
SR	Safety-related
SSC	Structures, systems, and components
TRL	Technology readiness level
UQ	Uncertainty quantification
WAN	Wide area network
WLAN	Wireless Local Area Network

EXECUTIVE SUMMARY

This report explores integrating advanced sensor, instrumentation, and communication technologies with digital twin (DT) technologies for nuclear energy application. Digital twins and digital-twin-enabling technologies are expected to integrate with future nuclear reactor designs and have the potential to impact currently operating nuclear power plants. Greater digital integration, advanced instrumentation and control systems, and advanced operations and maintenance practices are all associated with digital-twin-enabling technologies. Advanced sensors and instrumentation (ASI) and communication technology are expected to comprise important elements of the infrastructure required to develop and operate a nuclear digital twin system. This report identifies and discusses challenges and gaps in developing and implementing advanced sensors and instrumentation and communication technology to be integrated with a digital twin in current and advanced reactor applications. It is important to address some of the challenges and gaps to enable a successful near-term deployment of advanced sensors, instrumentation and communication technologies integrated with digital twins. The following are some key challenges and gaps discussed in this report:

- Inherent challenges and gaps in implementing advanced sensors and instrumentation and communication technology
  - **Meeting the requirements for environmental qualification, performance, reliability, and maintainability:** new technologies may establish new requirements and associated methods and data for meeting and maintaining these requirements that may require significant effort to identify and develop.
  - **Enabling the implementation of multimodal sensors:** multimodal ASI may reduce penetrations and space dedicated to sensors, but qualification methods, codes and standards, and reliability data may need further efforts.
  - **Ability of communication technology to evolve as scalable, agile, and modular:** implementing and expanding ASI applications increases communication demands which must be accommodated by communication technology.

- **Supporting edge computing and smart sensors:** signal processing at the sensor enables rapid data processing and relieves communication burden.
- **Cybersecurity:** new applications of communication and processing technologies such as wireless and edge computing may pose novel cybersecurity challenges and considerations.

• Challenges and gaps in integrating advanced sensors and instrumentation and communication technology with a digital twin

- **Addressing data heterogeneity and usability:** each ASI may produce data at different sampling rates and in different formats.
- **Identifying and standardizing communication protocols:** managing the different forms of communication technology streamlines the ASI data to be combined into a DT.
- **Supporting real-time integration of advanced sensors and instrumentation and communication technology with a digital twin for state concurrence:** enables DTs to represent current state of the physical entity.
- **Ensuring adaptability of a digital twin to accommodate different technological advancements in advanced sensors and instrumentation and communication technology:** the DT should be adaptable to increased and new data flows, replacement of obsolete equipment, and new communication features such as advanced encryption.
- **Developing a digital twin for performance and reliability of advanced sensors:** an ASI DT could monitor performance, predict failure, assess sensor drift, and make recommendations for sensor recalibration or replacement.

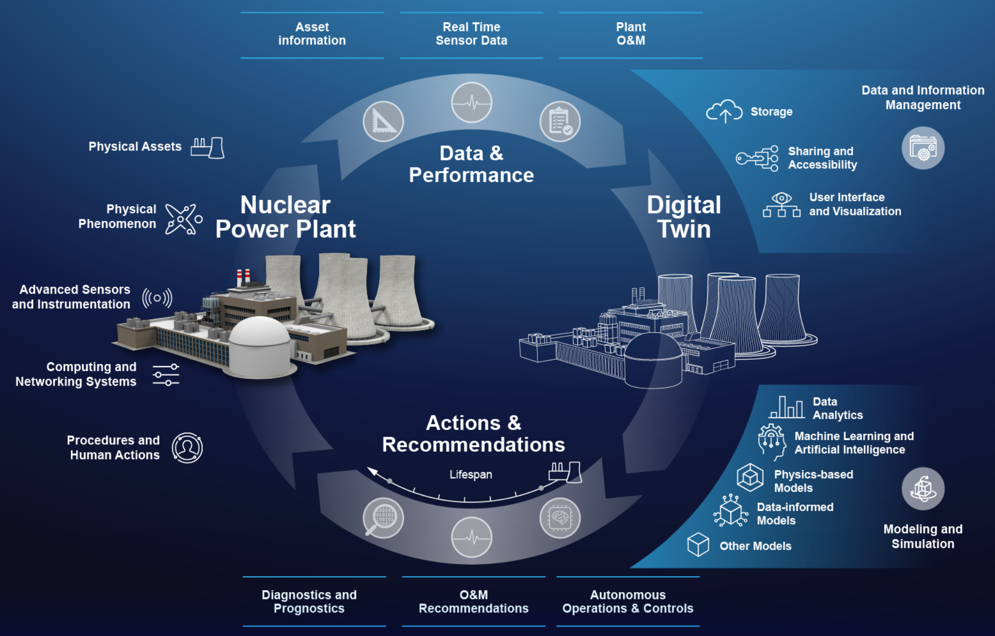
Digital twins in complex industrial and engineering applications have proven benefits that include increased operational efficiencies, enhanced safety and reliability, reduced errors, faster information sharing, and better predictions. The interest in digital twin technologies continues to grow, and 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 advanced sensors and instrumentation and communication technology in nuclear reactors.

BACKGROUND

Staff in the Office of Nuclear Regulatory Research at the U.S. 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 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], and identifying areas that may benefit from future regulatory focus [6]. The NRC continues to assess the regulatory viability of DTs for NPPs by identifying and evaluating technical and regulatory challenges associated with implementing DTs in nuclear energy applications. The NRC is actively pursuing further DT research activities in the integration of safeguards and security.

This report identifies challenges and gaps inherent to advanced sensors, instrumentation, and communication technology, as well as those associated with their integration with digital twins.

This report's main focus is to discuss the integration of advanced sensors and instrumentation (ASI) and communication technology (CT) with DTs at NPPs and identify challenges and gaps inherent to ASI and CT and in their integration with a DT. The terms ASI and CT refer to broad classes of sensors & instrumentation and communication technologies, respectively, for NPPs and, in the context of this document, exclude the technologies that are currently in use in NPPs. Instead, the focus is on technologies that are either commercially available but not used in nuclear energy applications or are in advanced stages of technology maturation and may apply to emerging data needs or measurement interests in NPPs. Section 1 presents a brief overview of the DT-NPP problem space and its integration with ASI and CT [5], Section 2 describes the ASI and CT for common needs in NPP, and Section 3 presents a detailed discussion on potential challenges and gaps associated with integrating ASI and CT with nuclear DTs.



1 NUCLEAR DIGITAL TWIN

Various interpretations of a DT may exist based on different technologies, applications, or other criteria. The description of an NPP-DT system or simply a nuclear-DT system is provided in [1] which identifies the following four characteristics of a nuclear-DT system illustrated in Figure 1:

1. **Exists in Digital Form:** The technologies and information that form part of the DT must exist in a digital format 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 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 unique and novel value to the selected application.
4. **Serves an Underlying Purpose:** The technology must have an underlying purpose that relates to an NPP lifecycle activity, and that purpose should inform decisions about the system or component being represented.

A DT system for NPPs can consist of four parts as discussed below [6].

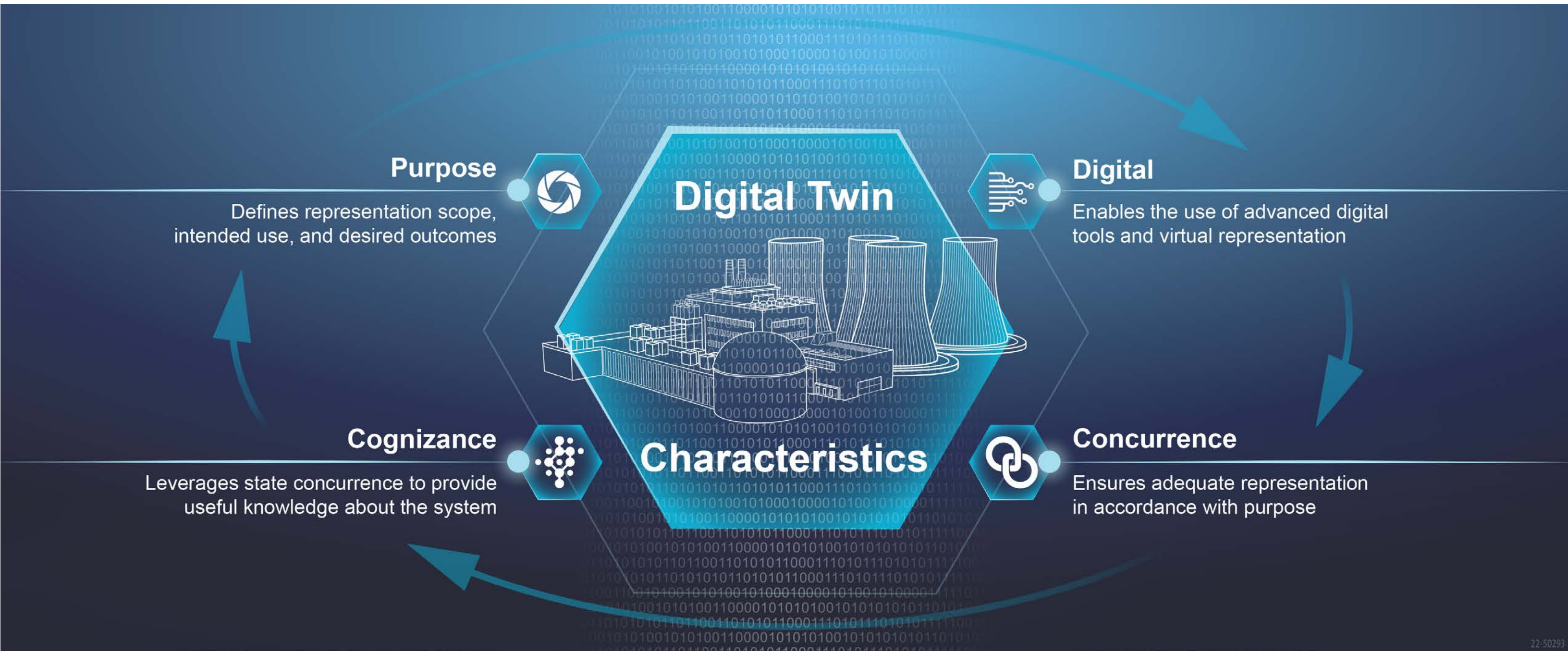


Figure 1. Characteristics of a nuclear digital twin system [6].

Nuclear Power Plant

NPPs contain complex parts that can be categorized in numerous ways, depending on their objective and purpose. From a DT system perspective, these parts can be categorized into the following five broad technical areas [5]:

1. **Physical Assets:** These are commonly referred to as systems, structures, and components (SSCs). As examples, they include the reactor and plant buildings (structures); the cooling, feedwater, power generation, and electrical systems (systems); and pumps, motors, valves, chillers, circuit breakers, compressors, fans, and batteries (components).
2. **Physical Phenomena:** These are forms of reactor thermal hydraulics, corrosion, concrete degradation, etc., that influence both the plant performance and changes to plant states.
3. **Advanced Sensors and Instrumentation:** Generally, sensor and instrumentation systems provide NPP state and process measures necessary for DT operations and include power requirements and communication or data transfer infrastructure (e.g., cable or wireless technologies). Advanced sensors and instruments, a subset of sensors and instruments within the NPP, 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:** This category includes both hardware and software for enabling regular plant operation and maintenance (O&M) and ranges from complex computing clusters to simple handheld devices.
5. **Procedures and Human Actions:** This category includes normal reactor operations, refueling, engineering, maintenance, safe shutdown, chemical control, etc., as well as control actions. These actions can be continuous (e.g., procedural operator actions to control power) or periodic (e.g., scheduled testing, maintenance, and upgrades).

Of these technical areas, physical assets, physical phenomena, and procedures and human actions can be considered the physical twin, meaning they encompass those entities that can be potentially modeled in digital form, resulting in their respective DT. The other two—ASI and computing and networking systems—would be required not only for plant operations but also to enable and support the DTs of the NPP physical assets, physical phenomena, and procedures and human actions.

Digital Twin

DTs represent one or more NPP entities that fall into the relevant areas identified in the previous section. For producing a DT, especially one for an NPP, two broad technological needs must be met are: (1) modeling and simulation (M&S) and (2) data and information management [5].

M&S elements within a DT include the following: data analytics, artificial intelligence (AI) and machine learning (ML), physics-based models, data-informed models, and other model types. These elements are used to make estimates of the current and future states of the physical twin. 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 [5]. Included within this umbrella are data storage systems, such as local plant servers, fleetwide data infrastructure, and cloud-based storage systems; software solutions to ensure seamless integration of the heterogenous plant data, uninterrupted data availability, and real-time interaction across DT models and data storage; and user interfaces outside the 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 and its SSCs, physical phenomena, procedures and actions, and sensor/instrumentation data is vital for enabling sustained, accurate, reliable, and efficient DT operation [5]. Asset information includes dimensions, geometries, topologies, materials, chemical makeups, etc., all of which depend on factors such as SSC type/function and the requirements of the digital representation. Real time data acquisition in NPPs is primarily intended to support NPP control room information (e.g., reactor-power level and pressurizer level/pressure). In the rest of the plant, it is aimed at ensuring safe, reliable operation of SSCs and is generally performed both manually and periodically. Advanced digital sensors that foster wireless capabilities, high bandwidths, and quick installation enable real time data acquisition and many sensor modalities (e.g., vibration, temperature, pressure, flow rate, voltage, and current) on a much larger and more diverse subset of plant SSCs. Data on plant O&M activities include corrective and preventive work order logs, outage logs, and licensee event reports, all of which provide comprehensive details on O&M activities—details that can be valuable to DT applications.

Actions and Recommendations

The objective of implementing a DT system is to provide actions and recommendations in support of safe, reliable, and efficient system operations. To this end, DT actions and recommendations have been classified into the following categories: diagnostics and prognostics, O&M recommendations, and autonomous operations and controls [5]. Diagnostics and prognostics (e.g., anomaly detection, sensor malfunction identification, differentiation between true anomalies and sensor malfunctions, failure predictions, and critical event predictions) can be enabled in real time by DTs, thus providing plant staff with real time notification and recommendations on emergent or future conditions. Predictive algorithms in DTs can even go beyond diagnostics and prognostics to generate recommendations for efficient O&M practices. Most operations and controls in existing NPPs are manual in nature; however, DT technologies offer the potential to not only recommend but also autonomously perform certain operations and control actions in NPPs. 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 can foster reliable, accurate, consistent, rapid, and autonomous or semi autonomous control with optimal human supervision and inputs.

Successful design, implementation, and continued operation of a DT hinges on reliable and efficient sensors and instrumentation infrastructure to support various capabilities of a DT. In a recently published report [6], this project has identified five capabilities of DT as information, communication, analysis, integration, and control as illustrated in Figure 2. This section presents a discussion on integrating ASI with nuclear DT to support and enhance the five capabilities of DT.

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. ASI integrated with DT should be able to support automatic, continuous, and real-time data acquisition from plant SSCs, as well as manage the heterogeneity of plant information, and enable the shared information flow, within and outside DT elements.

Communication

Communication is an overarching capability that propagates information among the various DT-enabling technologies such as advanced sensors, information management, and M&S, as well as 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 cognizance of plant states. The ASI infrastructure at an NPP must be equipped with robust, reliable, efficient, and secure communication capabilities that enable timely, efficient, clear, and continuous communication, as well as potentially remote communication that enables remote operation and control with DT.

Integration

A DT serves as a centralized hub and enabler for integrating 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 [5] digital and nondigital form; historical and real time; different time resolutions ranging from milliseconds to DT lifetime; different sensor modalities; manually collected or automated acquisition; and numerical, textual, categorical, or other formats. In order for a DT to integrate such complex data and information continuously or on demand, with variable granularity and over the long term, the ASI infrastructure at the NPP must be capable of handling the heterogeneity and volume during data acquisition and data transfer.

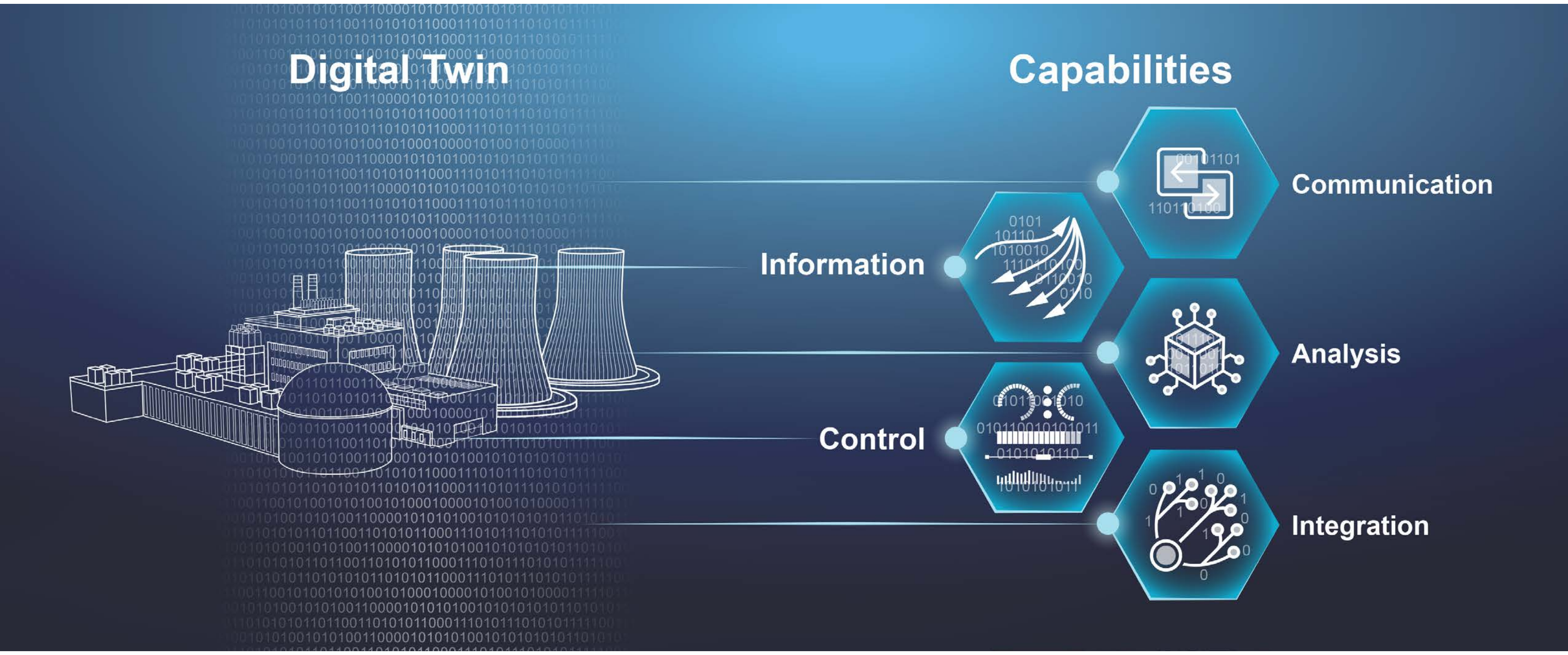


Figure 2. Capabilities of a digital twin [6].

Analysis

DTs offer a 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. Performing analysis within DT using tools such as data analytics, ML algorithms, or physics-based models may pose unique requirements for the ASI infrastructure. For example, to enable real-time analytics for such variety of M&S elements, the ASI infrastructure may need to measure and transmit data with a much wider diversity of domains, granularity, and temporal resolution than is currently employed within NPPs.

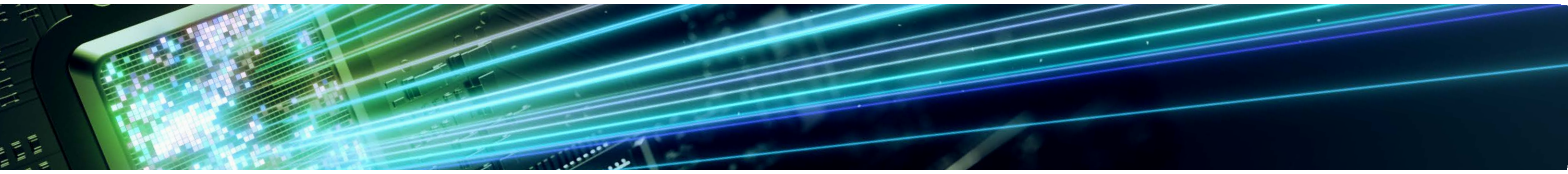
Control

A control system enabled by or integrated with a DT can combine classical controls with novel AI/ML-driven control, predictive controls, and virtual sensor measurements as well as leveraging multiple real-time input and output systems. Accurate, on-time, and reliable performance of a DT-driven control depends on data acquisition by an accurate, responsive, and reliable ASI infrastructure.

2 ADVANCED SENSORS, INSTRUMENTATION, AND COMMUNICATION TECHNOLOGY IN NUCLEAR

The terms ASI and CT refers to a broad class of sensors and instrumentation and communication technologies, respectively, and this section presents a discussion on ASI and CTs that are either commercially available but not used in NPP applications or are in advanced stages of technology maturation and may apply to emerging data needs or measurement interests in NPPs. Examples of desired measurements include but are not limited to distributed temperature measurements in core, measurements of higher temperatures (> ~300 °C) in advanced reactors (ARs) during normal operation, non-light-water coolant flow rates in ARs, light-water coolant flows in advanced light-water reactor (LWR) concepts such as convective flow, neutron flux monitoring in high-temperature environments, in-situ fuel burnup, and coolant level measurements especially in two-phase systems such as steam and water [7]. While some of these quantities are measured in the existing fleet, advances in sensors and instrumentation are expected to enable a greater spatial density of measurements and longer-term monitoring of these quantities in both current and ARs. Together, these characteristics are expected to enable more detailed insights into the state of the NPP—a necessary step for developing and maintaining a DT. Previous assessments have indicated that, while the technologies for monitoring these quantities in AR environments exist, there are still gaps in the ability to measure some of these quantities reliably and with the necessary resolution over extended time frames (several years) [7]. Advances are now enabling longer-lived sensors capable of more precise measurements in regions previously difficult to instrument [21]. This capability is expected to benefit DTs by providing direct measures of important quantities (e.g., temperature, flow, and chemistry) used to calibrate and adjust DTs (i.e., maintain state concurrence).

ASI features technologies that may be used to address emerging data needs or measurements interest in NPPs.



2.1 ADVANCED SENSORS AND INSTRUMENTATION IN NUCLEAR

Recent technology advances have begun to address these aspects of ASI. The U.S. Department of Energy's (DOE's) Nuclear Energy Enabling Technology's (NEET) ASI program, for instance, funds several efforts toward research, development, qualification, testing and demonstration of sensors, instrumentation, control systems, and communication technologies for existing and AR applications [29]. A non-exhaustive list of technology advances enabling ASI include advanced manufacturing leading to the embedding of sensors; advanced materials; nanotechnology; advanced batteries; power harvesting; edge, cloud, or fog computing; optical sensors; and radiation-hardened sensors. Current efforts in advancing the state of the art for ASI span across several technology readiness levels (TRLs) that may range from concept testing to demonstration or qualification [30] and a discussion of such is beyond the scope of this report. The following writeup therefore focuses on the ASI discussion based on sensor modalities that are key to NPP application.

Temperature

Temperature is one of the most common parameters measured across plant systems, ranging from reactor coolant temperature to secondary system feedwater temperatures to ultimate heat sink temperatures and is an important input into reactor-power calculations as well as safety assessments. Temperature sensors use different types of devices such as Chromel-Alumel thermocouples, Tungsten-Rhenium thermocouples, high-temperature irradiation resistant thermocouples, acoustic thermocouples, resistance temperature detectors, ultrasonic thermometry, and optical fiber sensors. These temperature sensors differ in their form factor, application areas, sensitivity, temperature range, and output formats. Advances in temperature measurement technology include new alloys for thermocouples that allow significantly higher irradiation tolerance at higher temperatures [8] and the use of alternate measurement physics, such as acoustic [9-10] and optical techniques [11].

Pressure

Typically, in NPPs, pressure transmitters are designed to measure direct and differential pressure. Traditional pressure transmitters are categorized into two types to include motion balance and force balance, depending on how the movement of the sensing elements is converted into an electrical signal [12]. These pressure transmitters, like temperature sensors, have different form factors, applications areas (high-radiation area to no radiation areas), output range, and output formats. In addition to traditional pressure transmitters, there are optical pressure sensors currently at different TRLs [13-14]. Novel or developing pressure transmitters sensors, like optical pressure sensors, have shown success in some applications such as biomedical pressure measurements, but they still need to be evaluated for high-temperature and high-radiation applications [15].

Flow

There is an abundance of flow measurement techniques employing various operating principles [16–19]. Among those techniques, differential pressure-based sensors are the most common for legacy NPPs, in which Venturi tube flowmeters are a mainstay and have been used extensively in industry. Flow nozzles and elbow taps are other examples of differential pressure-based flowmeter designs. Differential pressure methods are generally useable for piping submerged in a high-temperature working fluid, but some designs require internal structures [16], and the deposition of corrosion products or fouling on the internal sensor surface can be a concern [18].

Ultrasonic flow sensors of both Doppler and transit-time types are non-intrusive devices. The latter type has seen commercial success with water flow and is actively being pursued for flow measurement of AR fluids such as liquid salts. Despite its availability and viability, this metering technique needs further testing and validation for operation on non-water piping, and higher temperature ultrasonic transducers will be necessary [16-17]. Variable area meters (e.g., rotameters) are another flow measurement technique regularly employed in LWRs but are not yet commercially available for high-temperature applications. They are not suitable for large flows such as the main reactor flow loop [16].

While some other flow sensors—including those based on electromagnetic induction, thermal transport, cross-correlation, and neutron activation—are also potentially applicable depending on the medium and operational characteristics, they require extensive research and development to increase their TRL in non-water fluids [17]. Examples of recent efforts are microwave cavity-based flow sensing under the DOE NEET ASI program [29] and thermal anemometry with a patented high-temperature operable probe design under the DOE Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) programs [30].

Vibration

The SSCs in a plant generate vibrations of different magnitudes at different frequencies based on their operating requirements and functionalities. For example, a motor-driven pump setup is common across different plant systems; however, based on their orientation (vertical or horizontal), operational needs (constant speed vs. variable speed), and applications, the vibration signal could vary. Generally, piezoelectric accelerometers (uniaxial, bi-axial, or tri-axial) are used to measure vibration signals at different locations on plants systems. These could include measurement at bearing locations of pumps and motors, on structural piping systems, near valves, turbine gearboxes, condensers systems, and so on [19-20]. Based on the need and applications, these vibration sensors could be permanently mounted (like proxy vibration sensors) or temporarily mounted at specific measurement locations on a periodic basis to collect data. Besides accelerometers, there are other types of vibration sensor types such as laser displacement, strain gauge, and acoustic-telemetered sensors. Also, some wireless vibration sensors are multimodal as they have the ability to also measure temperature.

Fluid Level

The most common fluid level measurement principle in current LWRs is differential pressure, which has been widely used in many reactor systems (e.g., reactor vessel, pressurizer, and steam generator) for decades. Differential pressure-based level sensors are simple and easy to install but can be prone to errors [31]. Other commercially available techniques include heated thermocouple probes, ultrasonic methods, capacitance detectors, and microwaves. Water-level measurement techniques based on optical fiber sensor networks have been the focus of recent research efforts [32–34] for their inherent benefits such as small footprint, electromagnetic immunity, high-sensitivity, high-speed, and multimodal capability [35].

Guided microwaves have emerged as an excellent candidate technology for liquid-salt level measurement owing to their non-contact standoff sensing nature. However, the long-term survivability of the head-end of microwave transceivers is yet to be demonstrated [17]. Several other techniques—including heated lance, bubbler (i.e., dip tube), mechanical float, and electrical conductivity—are also mature and feasible, given that level probe materials are compatible with the liquid-salt coolant. Guided-wave ultrasonic methods are currently less versatile but potentially applicable [9].

The sensors that have been tested for liquid-metal level measurement include resistance, induction, buoyancy, and ultrasonic probes. Induction and buoyancy probes are the two most common level sensors that showed moderate success in meeting the requirements in the operation of fast reactors (e.g., EBR-II). These level probes are all insertion-type sensors and have limitations with reliability and accuracy. Laser-based and radio frequency-based rangefinders are recent laboratory-scale advances that may be applicable for standoff non-contact real-time measurement of liquid-metal levels, which can be more reliable for long-term operation because they are not directly exposed to the harsh environment [17].

Neutron Flux

The neutron monitoring systems monitor the neutron flux level of the reactor core by detecting leakage neutrons from the core (i.e., ex-core) and by detecting neutron flux levels from within the core (i.e., in-core). For U.S. LWRs, gas-filled detectors—including BF3 proportional counter, compensated ion chamber, and uncompensated ion chamber—are currently used in the ex-core instrumentation system [36]. In contrast, miniature fission chamber detectors are used in the in-core instrumentation system [37, 38].

While similar ex-core equipment at existing NPPs will be potentially compatible with other types of reactors, the DOE NEET ASI program has recently focused on advanced sensors to improve the reliability and operational performance of in-core neutron monitoring for existing and ARs. No high-sensitivity neutron flux measurement technology is commercially available that functions at temperatures above 550°C [39]. Several existing activities involve demonstrating and qualifying real-time self-powered neutron detectors of various types given their high TRL, which are being tested in different reactor environments (e.g., Transient Reactor Test Facility - TREAT, Advanced Test Reactor - ATR, Neutron Radiography Reactor - NRAD, and the Aerojet General Nucleonics model - AGN-201) [29, 35]. Another recently completed project investigated high-temperature micro-pocket fission detectors—miniature fission chambers capable of simultaneously measuring thermal and fast neutron flux and temperature within a single package for temperatures up to 800°C—and advancements have led to several projects that continue to develop and deploy the technology for a variety of irradiation testing programs [40, 41]. Finally, semiconductor (e.g., silicon carbide and gallium nitride) neutron detectors have also gained some attention [42], such as a high-temperature-tolerant and radiation-resistant in-core GaN neutron sensor recently developed under the NEET program [43].

Chemistry

Existing and future reactors will use different fluids and different means to measure required chemistry information. Most of the chemistry measurements (e.g., pH, dissolved oxygen, hydrogen, and key gases in transformers) are performed offline—in that the sample, such as the primary coolant, is removed from the harsh conditions inside the primary loop. Depending on the reactor design and chemical environment, a range of current technologies will suffice for offline measurements of chemistry parameters [16]. Although available, some existing measurement techniques can be labor and maintenance intensive. Future sensors will focus on various spectroscopic methods—such as optical absorption spectroscopy, acoustic resonance spectroscopy, and many others—where each provides a range of chemistry information, as well as their automation with fully automated data sampling and analysis [17]. Online monitoring and measurement of certain key parameters will also be desired, should they be reasonably achievable.

Radiation

Radiation monitoring systems continuously measure radiation levels of various plant process streams and areas and provide alarms and/or automatic actions if limits are exceeded. They are further divided into two subsystems: process radiation monitors and area radiation monitors [44, 46, 49]. There are various types of radiation detectors used in monitoring nuclear systems, among which Geiger counters and scintillation detectors are the most prevalent [44]. Geiger counters are the most used portable radiation instrument but cannot measure high count rates due to large dead time; it is therefore only useful in certain radiation fields. Unlike Geiger counters, a scintillation detector can accurately measure different types of radiation and is constructed such that it is sensitive to only one type of radiation. Semiconductor detectors and other gas-filled detectors are also commercially available. While the operating principles of radiation monitoring remain unchanged for ARs, one major challenge is the higher temperature and higher dose rates at which measurements need to be performed. One example of ongoing efforts under the DOE Small Business Innovative Research (SBIR) or Small Business Technology Transfer (STTR) programs is the development of a new high-performance detector with fast, high-sensitivity, dual-mode scintillation materials that can handle high count rates and high temperatures [45].

In addition to the key modalities discussed above, the technical advances in ASI are enabling new sensing approaches that integrate multimodal sensors within a single sensor. Examples of this are new technologies to jointly sense temperature and pressure using a single sensing element or the use of bimodal optical sensors for measuring strain and temperature. Such multimodal sensor arrangements take advantage of the sensitivity of the sensing element (piezoelectric element, electromagnetic coil, magnetostrictive sensing element, optical fiber, resistive wire, etc.) to multiple physical quantities [50]. For example, the wave speed in piezoelectric elements is a function of temperature and applied strain, and an appropriate sensor design can be used to distinguish the wave speed effects of temperature and strain and measure the two physical quantities, thus resulting in a multimodal sensor [50]. Often, the sensitivity of a sensor to multiple quantities is used to derive an accurate measurement of one quantity by compensating for the effects of another, effectively reducing the measurement uncertainty.

Several ARs which are currently in design or concept stage are expected to operate in higher thermal output range, a variety of non-light-water coolants, different fuel cycle, and distinct flux and radiation characteristics. Such unique and novel attributes of ARs would require novel ASI technologies or applications distinct from currently applied ASI.

Key Advanced Reactor Applications of ASI

1. High-temperature and harsh environments
2. Flux and radiation measurement
3. Online monitoring of component performance
4. Motor-pump systems
5. Flow-induced vibration of mechanical systems
6. Corrosion behavior and redox potential in MSRs
7. Off-gas control
8. Waste streams
9. Electro-chemical processing
10. Structural material characterization
11. Photo-thermal radiometry

2.2 COMMUNICATION TECHNOLOGIES IN NUCLEAR

Resilient, secure, and real-time communication at NPPs is critical for enabling asset monitoring, control strategies, and data analytics. Traditionally, NPPs have used wired communication in their instrumentation and control systems and operations. Wired communication refers to the transmission of data over a wire-based CT in the form of cables. Wireless communication such as Wi-Fi, LoRa WAN, WirelessHART, WLAN have been explored for some reactor applications, although these applications relying on wireless communication in existing NPPs are still in early stages of research and development. The U.S. DOE's NEET ASI program funds several efforts towards research, development, qualification, testing and demonstration of nuclear plant communication technologies to enable real-time transmission of sufficient data for online monitoring and advanced data analytics and AI/ML capabilities to enable semi-autonomous operations and maintenance by design. CT for NPP application can be broadly classified in two categories — wired and wireless communication — and are discussed in the rest of this section.

> ***Communication technologies in NPPs must be resilient, secure, and facilitate real-time transmission to enable asset monitoring, control strategies, and data analytics.***

Wired Communication

There are hundreds of types of cables and over 1,000 km of cabling typically found within an NPP [22]. Typical cable architecture consists of one or several conductors individually wrapped with electrical insulation and bundled inside of a protective jacket. Traditional electric cables are considered to be passive, long-lived components with high historical reliability, and their aging and degradation could lead to expensive replacement or repair activities for the licensee. Longer service life of cables entails increased material exposure to environmental (e.g., temperature, radiation, vibration, moisture, and humidity) and operational (external interference, voltage stress, materials defects, electrical transients, etc.) stressors [23]. The number of cable failures is found to increase with plant age, and extended operation of LWRs will likely exacerbate the cable failures. While the licensed operating life of ARs may be different from that of the existing fleet, cables in next-generation reactors may be exposed to harsher operating environments and have more limited access to the physical space for deployment.

The aging degradation of the cable jacket, electrical insulation, and other cable components are key issues for assessing the ability of the currently installed cables to operate safely and reliably for 20 or 40 years beyond the initial operating life of LWRs. Regulatory requirements exist for condition monitoring and aging management of cables and cable systems in nuclear environments [23, 24, 25]. These cables are often limited in communication bandwidth, speed, transmission distance, and signal quality. They are also susceptible to interference and electrical surges. The excessive installation and maintenance costs and associated logistics are another major concern; installing cables in an NPP can yield one of the largest costs involved in upgrading existing facilities [26]. Despite their limitations and the promising alternative solutions offered by non-wired (i.e., wireless) communication as described in the next section, several factors justify the continued use of cables in NPPs; in other words, why it is more feasible/desired to use cables. The factors include operating experience, cybersecurity, reliability, compliance with regulatory guidelines, coverage and connectivity, and integration with existing data networks.

Fiber optic cables were recently introduced in digital I&C systems of next-generation NPPs for their significant benefits over electric cables, including much higher bandwidth capability and faster speed over much longer distances, higher robustness to environmental/operational stressors (e.g., immunity to electromagnetic interference), and reduced size and weight. Fiber optic cables are generally more expensive than conventional metallic copper or aluminum conductor cables, and they may not be compatible with other hardware and communication infrastructure of existing reactors. Since optical fibers serve as the conducting medium in these cables, the aging and degradation mechanisms are unique to these cables as compared to electric ones [23].

Wireless Communication

While ARs are still planning to use wired architecture in conjunction with projected ASI applications, the reactors of future may use a wide range of wireless communication protocol such as wide area network (WAN), Bluetooth, Zigbee, radio frequency, long-term evolution (LTE), and others. Irrespective of reactor technologies (existing or advanced), wireless communication technologies to be deployed would likely support multiple frequencies [26] to meet multiple applications and data requirements for DT. The frequency bands of wireless CT can be broadly classified as follows:

900MHz Band: Low-power long-range WAN (LoRaWAN) is a communication protocol that operates in the frequency band of 902–928 MHz in the United States. LoRaWAN has a low-power consumption and a long-range communication of up to 5 km.

2.4GHz Band: There are several wireless communication technologies that operate in the 2.4 GHz unlicensed frequency band including:

- Bluetooth, a short-range IEEE 802.15.1 communication protocol that uses profile information to transfer the data between devices. It operates with a spectrum range of 2.402 GHz to 2.4880 GHz.
- Highway Addressable Remote Transducer (HART) Communication Foundation's (i.e., HART field communication protocols) WirelessHART [27]. WirelessHART is based on the IEEE 802.15.4. standard.
- Zigbee, another IEEE 802.15.4 communication protocol [28] that is used to support communication requirements of sensor nodes of low-cost and low-power requirements. Due to low-power requirements, it has a low-transmission distance. However, by leveraging star, tree, and mesh topologies, data can be transmitted from a source node to a base station irrespective of their location and distance.
- Wireless Local Area Network (WLAN) systems are low-coverage and limited capacity access points capable of providing a high data rate internet connection to any cellular technology. IEEE 802.11 is the foremost standard for WLAN. Wireless Fidelity (Wi-Fi) is a trademark name used to label devices that are complaint to IEEE 802.11 standards. There are many notable 802.11 versions (802.11b [Wi-Fi 1], 802.11a [Wi-Fi 2], 802.11g [Wi-Fi 3], 802.11n [Wi-Fi 4], 802.11ac [Wi-Fi 5], 802.11ax [Wi-Fi 6]) some of which operate in the 2.4 GHz band and others in 5 GHz.

5GHz and Higher Frequency Band: Ultra-wide band Wi-Fi is an IEEE 802.15.3a communication protocol that operates in a frequency range of 5 GHZ and is most commonly used for high data rate communication. Similarly, WiMax is an IEEE 802.16 communication protocol that operates in >5 GHz and in the range of 10–60 GHz to provide high data rate and broadband wireless access.

Multiple Frequency Band: Radio frequency identification (RFID) is an automatic identification and data acquisition technology. Based on the distance between the system and the objects to which the RFID tags are adhered, there are different frequency range communication of data that can occur. These RFID frequency bands include 125-150 Hz,13,56 MHz, 433-928 MHz, 2.45-5.8 GHz, and 3-10.5 GHz. LTE is a broadband cellular communication that is aimed at providing high data throughput data with low latency. LTE frequency bands are discrete slabs of frequencies that are used for telecommunication. It has 38 frequency bands to support different modes of data transfer based on application requirements. The 5G is the fifth generation of broadband cellular communication that is aimed at achieving three objectives: higher speed compared to LTE, low latency of less than 1 millisecond, and high coverage (i.e., concept of mmWave enable single to multiple point communication). There are two frequency ranges; the first is <6 GHz, and the second is over the range of 24–54 GHz.

The above discussion covers a broad range of CT that are either currently in application at NPPs or could be applied in near future. CT is constantly undergoing rapid innovation and in last 10 to 20 years has evolved phenomenally in terms of novel technology and performance. The nuclear reactors of future could implement CT that may not be covered in the above discussion.

3 | TECHNICAL CHALLENGES

This section presents a description of major technical challenges and gaps associated with implementing the ASI and CT as part of an NPP DT. Challenges are identified as new or difficult tasks and problems associated with ASI and CT implementation, while gaps describe what is needed beyond available resources to address those challenges. The section is divided in two parts. The first part presents a discussion on major challenges and gaps associated with implementing ASI and CT by itself in an NPP, without considering an integration with a DT. The second part of this section focuses on major challenges and gaps that are unique to integrating ASI and CT with a DT at an NPP. The challenges and gaps presented in this section are identified based on complexities and roadblocks related to different aspects of ASI and CT such as research, development, design, manufacturing, licensing, qualification, deployment, and O&M. Exploring such a wide range for each technology results in an extensive set of challenges and gaps, some of these are beyond the scope of this work. Therefore, this section provides a detailed discussion of only those challenges and gaps that have a significant or novel impact on the use of the ASI and CT within a DT. Each part concludes with a table summarizing the challenges and gaps identified in this work.

3.1 CHALLENGES INHERENT TO ADVANCED SENSORS AND INSTRUMENTATION AND COMMUNICATION TECHNOLOGY

Implementing advanced sensors and communication infrastructure at NPPs could be inherently a complex endeavor with several challenges that need to be addressed. Even when the goal is to integrate the ASI and CT at a plant with a future DT, it is critical to first take a step back to understand and address the challenges associated with implementing novel ASI and CT at NPPs. Addressing the inherent challenges in ASI and CT could ensure to a large extent that these technologies are ready to be integrated with a DT when needed. This section presents a discussion of major challenges and gaps that might be faced by nuclear stakeholders in implementing ASI and CT in currently operating plants as well as ARs.

3.1.1 INHERENT CHALLENGES: ADVANCED SENSORS AND INSTRUMENTATION

A wide range of sensor modalities, inclusive of existing, novel, multimodal, and smart sensors, is expected to be used across the vast array of reactor technologies to measure parameters of interest. The ongoing research, design, development, and installation of sensor modalities [29] covers both in-vessel and ex-vessel locations within an NPP. Common challenges could be faced by difference sensor modalities based on operating environment requirements, type of sensor technologies (analog and/or digital) [46], and the communication network available or envisioned by the nuclear stakeholder. For example, with respect to cabling requirements, some sensors require two cables, one to provide power and another to carry measured parameters (i.e., data) to a location, where they are further processed. In the case of passive or self-powered sensors, the power cable requirement is eliminated. For wireless digital sensors with an electronics system (referred to as a sensor node), the specific cabling requirements to transmit the data are eliminated, as they communicate the data wirelessly to a remote location.

There are some commonalities and differences in challenges associated with different sensors and instrumentation installed for in-vessel and ex-vessel measurement applications. These common challenges are discussed as follows:

Environmental Qualification: For many ASI, there could be a lack of experimental and scientific evidence to measure drift and quantify uncertainties in measurements. This is challenging when the sensor data is collected under high temperature, high radiation, and in some cases a corrosive operating environment. Environmental factors such as radiation and electromagnetic interference affects the quality and reliability of a transmitted signal and is a challenge for both in-vessel and ex-vessel installation of sensors and instrumentation with electronic systems that have a programmable digital device. Environmental factors may impact performance of some ex-vessel sensors (for instance, instruments located in the drywell), but the impact of the operating environment may be less severe in many cases. Both in-vessel and ex-vessel environments, such as different radiation and temperature could impact cable degradation and aging over time [48]. Managing cable aging and degradation is a challenge in the existing fleet, and for ARs, it could be valuable to collect data for cable performance assessment and monitoring.

Sensor Reliability: A performance-based and reliability-based design of sensors is required to ensure survivability and applicability of sensors operating in harsh in-vessel environment and ex-vessel environmental conditions such as seismic events, fire, and flooding (e.g., environmental qualification). Quantitative or qualitative assessment of the reliability of advanced sensors also depends on successfully addressing the challenges associated with collecting performance data. Qualification practices for some ASI may not require statistical or reliability data. For such ASI, it would be valuable to collect data for a population of sensors over a considerable period of performance to obtain statistical performance data. Collecting reliability data for novel ASI can be challenging owing to handling a large sensor population and a long time-scale necessary for obtaining statistically significant data. The sensor and instrumentation infrastructure at an NPP could have interdependencies such that reliability of one sensor can have an impact on the overall reliability of the ASI system. Understanding and ensuring reliability of the ASI infrastructure would require dedicated efforts such as failure modes and effects analysis that conduct a qualitative and quantitative assessment of reliability characteristics such as failure modes, common cause failures, likelihood estimation, etc. A software common cause failure is a dependent failure in which two or more component faults or failure states exist simultaneously, or within a short time interval, and are a direct result of a fault or failure in a shared software [47]. Common cause failures represent a frequent challenge for sensors that are part of programmable digital devices to measure parameters, irrespective of the sensor placement.

Reliable communication: Communication of data for in-vessel applications is currently achieved by establishing a wired connection between the sensor and the receiver, which could be inside or outside the reactor vessel. The use of wireless communication technologies is considered for in-vessel applications; however, it raises concerns for the survivability of an electronic system with a tunable antenna within harsh in-vessel environments and high-radiation fields. For ex-vessel applications, a wide range of mature wireless communication technologies exist, but a network architecture to integrate multi-band and multi-frequency requirements of different ex-vessel applications needs to be developed.

Powering requirements: Sensors and instrumentation require a wide range of power levels and power supply solutions to operate. In-vessel location of sensors could have added challenges that need to be addressed such as restrictions on vessel penetrations for power cables, environmental limitations for battery lifetimes and replacement opportunities, and limited space for large power supplies. For ex-vessel applications, sensors and associated instrumentations may be battery-powered or have a dedicated power outlet. Potential remote deployment of some reactor technologies could present a unique challenge in terms of longevity of battery-powered sensors and communication systems. Developing power harvesting technology is an attractive proposition to ensure a sustained power source for in-vessel sensors or for sensors in remotely deployed advanced reactors of the future.

Maintainability: Maintenance and calibration of ASI systems to meet regulatory requirements has traditionally been a demanding and extensive effort at a plant [59]. Repair, replacement, or calibration of sensors can be a difficult exercise due to their location, radiation level, or plant state for both in-vessel and ex-vessel locations. Frequent sensor maintenance or replacement is particularly impractical for reactors with extended operating cycles and harsh environments. To reduce costs and qualify for long-term service in these unique operating conditions, ASI systems must be fault tolerant, self-validating, in-situ testable, and possibly self-calibrating as installed in the plant for calibration and response time [60].

Inherent Challenges for In-Vessel and Ex-Vessel Sensors	
Challenges	**Gaps**
Meeting environmental qualification requirements	Testing ASI performance and reliability in harsh environments Obtaining environmental qualification data Addressing cable degradation issues due to harsh environment Identifying appropriate electromagnetic interference shielding methods and testing
Ensuring sensor reliability	Designing sensors to ensure survivability and applicability for in- and ex-vessel locations Obtaining statistically significant data for sensor reliability assessment Performing qualitative and quantitative assessment of reliability characteristics of ASI infrastructure Addressing software common cause failures in ASI reliability assessment
Ensuring reliable communication infrastructure	Developing radiation-hardened communication devices and systems Developing network architecture to integrate multi-band and multi-frequency requirements
Meeting powering requirements unique to in-vessel and ex-vessel locations	Developing power harvesting technology to ensure a sustained power source for sensors Developing self-powered sensors for in-vessel performance Addressing power requirements specific to in-vessel locations, such as vessel penetrations for power cables, and limited space
Ensuring the maintainability of ASI and CT infrastructure	Developing sensors that ease the maintenance of in-vessel sensors such as repair and recalibration Developing sensors with novel characteristics such as fault tolerant, self-validating, and in-situ testable, to minimize or eliminate periodic maintenance

Multimodal Sensors: In the context of this report, multimodal sensors refer to single sensors that are capable of separate simultaneous measurements of more than one quantity. An example is a piezoresistive sensor, as described in [50], that can simultaneously measure normal and shear force along with temperature. In contrast to these types of multimodal sensors, the literature frequently identifies multimodal sensing as corresponding to measurements from multiple separate sensors with each sensor monitoring a single quantity. While multiple separate sensors, each measuring one quantity, are of potential interest in existing and future NPPs, limitations on available space for sensor deployment and the complexity of necessary cabling or wireless mechanisms for data transfer are likely to limit the number and type of sensors that can be deployed. Instead, the expectation is single sensors capable of measuring multiple quantities simultaneously will become more prevalent in ARs. Technology advances enabling these types of advanced sensors include a better understanding of sensor materials, new approaches to fabrication that allow complex sensing structures to be realized, design approaches that leverage computing advances and techniques for fast design optimization, and algorithms for extracting multiple measurands from a single sensor.

Multimodal sensors are expected to be especially important for realizing the vision of a DT in NPPs by enabling greater sensor deployment density and measurements of key quantities at necessary points within an NPP. Such sensors may be deployed in LWRs as the technology matures, given the advantages of monitoring multiple quantities using a limited set of sensing wells/penetrations into the reactor. However, it is expected that the deployment in existing reactors will only be viable if multimodal sensors can demonstrate added value, for instance, lower uncertainty leading to greater operational efficiency and safety or the ability to obtain an earlier warning of off-normal conditions.

Understanding the propagation of uncertainty, and uncertainty quantification (UQ) is challenging for any data from sensor and instrumentation. Multimodal sensors with several measurands could pose increased challenges in UQ and in tracing the true sources and paths of uncertainty propagation. Measurand could affect the uncertainty in other modalities making the UQ in multimodal sensors a difficult challenge to address. Many of these challenges arise from the cross-sensitivity of each measurement to others, as a single sensing element is often used.

Lack of qualification methods and associated codes and standards for multimodal sensors, reliability of multimodal sensors and the impact of failure in any individual or more than one measurement mode, and instrumentation design and integration with multimodal sensors. The cross-sensitivity among measurands in a multimodal sensor could also have an impact on overall sensor reliability. It is important to understand the failure modes, including common cause failure modes, in a multimodal sensor and to quantify the impact of failure of one or more modalities on overall sensor performance.

Inherent Challenges for Multimodal Sensors	
Challenges	**Gaps**
Uncertainty quantification and cross-sensitivity of measurands in multimodal sensors	Identifying sources of uncertainty in multimodal sensors Defining measures of cross-sensitivity that may be widely applicable across different types of multimodal sensors
Qualification standards of multimodal sensors compared to those for unimodal sensors	Identifying potential qualification requirements for multimodal sensors Developing qualification techniques and standards for multimodal sensors in nuclear power applications Developing calibration procedures for multimodal sensors
Ensuring overall sensor performance and reliability of multimodal sensors	Quantifying the impact of failure of one or more modality on overall sensor performance in multimodal sensors Defining failure modes for multimodal sensors, including common cause failure modes

3.1.2 INHERENT CHALLENGES: COMMUNICATION TECHNOLOGY

Implementing a communication infrastructure at NPPs could have its own set of challenges which should ideally be addressed prior to integrating any DT-enabling technology with a CT. Some of the key challenges in establishing a CT at NPPs are discussed in the following paragraphs.

Meeting Performance Requirements: With the diversity of wireless technologies available today, it is not possible to develop a "one-size-fits-all" solution to enable communication from plant asset to DT. Different types of data are transmitted over a wireless network with different quality-of-service (QoS), latency, and bandwidth requirements. In this regard, it is important to identify some key aspects such as data rate, traffic type, distance, energy consumption, and network density, as part of the network design that would permit communication to a DT. For any chosen wireless technology, some technical features and capabilities to be considered include coverage, capacity, latency, and QoS. Primarily, the link budget (which defines the power losses and gains from a transmitter through a medium) should be designed for the corresponding area to decide the number of base stations, antennas, access points, transmission power, and ultimately the separation between base stations or access points. Each frequency band has a different link budget that makes the network design different for each wireless technology. If more than one wireless technology is considered, then the mutual interference should also be considered to build a co-existing heterogeneous network serving a wide range of applications and user requirements.

To have a reliable wireless communication system, following key performance indicators should be monitored:

- **Uptime:** The amount of time a wireless network is available for use.
- **Network jitter:** Measures the consistency in network's data transfer rate and variability in delay time. Real-time applications expect very low jitter, and the performance is impacted when jitter is present. Jitters are prone to interference and congestion issues, particularly for wireless technologies operating in unlicensed spectrum bands.
- **Bandwidth and throughput:** Bandwidth is the amount of data that a network is expected to transfer from source to destination, within a set amount of time. Throughput is the amount of data that gets transferred from source to destination within a set amount of time. Both bandwidth and throughput are referred in terms of Kbps, Mbps, and Gbps. The difference between bandwidth and throughput determines wireless network performance.

- **Signal strength:** Factors such as the required throughput and number of nodes in the network, determine the signal strength. Signal strength is typically measured in terms of decibel milliwatts (dBm), and the greater the signal strength, the higher the network throughput will be. It is crucial to make sure that the desired coverage area offers a signal strength above the minimum value to meet minimum required throughput of the network.
- **Packet loss:** Packet (also called a packet of data) loss is an indicator of low bandwidth, congestion, and interference in the wireless network. Packet loss is determined by the number of packets received by the destination out of total number of packets sent by the source. Acceptable packet loss differs for each application, and in general, packet loss less than 3% is acceptable.
- **Latency:** Latency is the measure of time consumed in transferring data from the source to destination. Higher latency indicates low network connection and poor performance due to congestion or interference. Latency requirements are different for each application. Machine-to-machine communication or real-time communications require latency less than 10 ms.

Setting Up Communication Infrastructure: To ensure coverage and connectivity across the nuclear plant site, informed and optimized installation of transmitters, receivers, and communication backhaul is required. There are several applications at a plant site with different communication requirements in terms of QoS, transmission frequency, security, and others. Deploying a communication infrastructure that includes hardware and software and addresses all requirements is a challenging problem. Currently operating reactors would require an extensive effort for retrofitting a setup of ASI that complements or replaces the existing sensor infrastructure. Planning and implementation of ASI infrastructure should incorporate considerations for cyber-informed engineering and techno-economic analysis.

Managing Data Heterogeneity: Communication of data and information within a complex entity like an NPP along with its DT system is heterogeneous. Addressing heterogeneity in CT is application driven (e.g., in-vessel vs. ex-vessel communication, inter- vs. intra-physical assets and DTs, and on-site vs. remote) and should cover the different types of heterogeneity, including communication modality and frequency, security protocol, volume of data/information, and quality requirement with indicators like latency and throughput. There is currently a lack of established methodology and/or protocol to address these heterogeneity types as well as hardware and software technology in the infrastructure to support integrating heterogeneous communication in the network so that different communication streams will be synchronized and made available for analysis. The coexistence of multiple communication technologies—such as those in wireless communication—and its significance on different applications must be investigated. Understanding the impact of communication heterogeneity and its requirements will help establish well-defined QoS.

Ability of Communication Technology to Evolve—Scalable, Agile, and Modular (SAM): The DT system is expected to be heterogeneous supporting a wide range of data transportation over different wireless communication protocols and meeting performance requirements. With the emergence of new communication technologies, for example, 6G, the foundational wireless architecture is expected to be scalable as more devices and information are added or made available. This scale up in wireless architecture should not degrade the performance of the foundational wireless architecture. While scaling up allows a user to add more devices and information, it is also one of the design requirements that the wireless architect must consider to ensure an agile and modular architecture to support the future wireless communication protocols, on-demand needs, and reconfiguration as per application requirements in most cases. The ability to develop a scalable, agile, and modular wireless architecture to ensure long-term application of DT system must take into consideration future regulatory guidance.

Ensuring Quality of Service: This is another key challenge with CT, for which different aspects of QoS and their state of balance under the impact of heterogenous information types through different communication channels need to be clearly defined and understood. Examples of those aspects are latency, throughput, bandwidth utilization, and attenuation level. There is currently a lack of simulation capabilities to support the analysis and evaluation of communication quality and performance for each aspect under different scenarios (e.g., wired vs. wireless technology and on-site vs. remote location). For instance, in wireless communication, common network simulators are yet to develop mature modules dedicated to 5G network and beyond.

To ensure and optimize the QoS, there is also a need for a standardized message passing framework or mechanism—analogous to the message passing interface for parallel computing architectures—across different devices/entities (physical or virtual) to ensure proper data sharing from sender to receiver. Developing and supporting such a framework will improve the stability of the overall communication network and reduce the probability of erroneous data transmission between devices. In addition, given the large volume of information being processed and shared within the DT system, advanced techniques for data compression/expansion/fusion are required to enhance data transportability and improve efficiencies in data and information management.

Support Edge Computing: Edge computing refers to a communication paradigm in which the client data is processed at the periphery of the network, as close as possible to the originating source. The ASI devices in the future will most likely be equipped with computer hardware that is ready to store and process the acquired data and information in real-time in the most beneficial way. Such information will need to be shared with other edge devices on the network or to a central hub for further processing or synchronizing of various pieces of information with varying resolution across the plant. The CT supporting a DT deployment will need to be flexible enough to integrate with a variety of different hardware (e.g., sensor types and resolution) and agile enough from the software standpoint to adopt to various emerging needs for data processing, sharing, and interaction. There may also be a need for different tiers of edge devices on the network with different purposes, such as edge-to-edge, edge-to-hub, or data consolidation and synchronization interactions. There will also be a need to define specific communication protocols and data redundancy measures for an edge-computing-driven, distributed paradigm of information processing across the plant.

Cybersecurity: Adequate protection of the communication technology against cyberattacks at a nuclear facility is an overarching challenge that can be broken down into several technical areas. One of the primary challenges is to identify the potential threats and vulnerabilities on a system from the attacker's point of view and the risk of an attack and decide whether to address it immediately or to ignore it safely. Use of wireless communication in safety-related (SR) and important-to-safety (ITS) functions at NPPs might pose a considerable burden on the licensee for additional analysis and expense required for NRC approval. To adopt wireless communication within SR/ITS functions, the utility may need to develop an alternative wireless system with substantial validation in terms of cybersecurity analysis. The cybersecurity analysis should consider all the attack vector scenarios such as supply chain, wired network, portable devices, and the physical access along with the wireless network.

Secure one- or two-way communication is essential to ensure the safe and reliable operation of nuclear plants. Three of the cybersecurity objectives for secure communication are (1) confidentiality, protection of data from unauthorized access and misuse, thus ensuring data or information is not accessible by an unauthorized user at any stage of transmission, (2) integrity, protection against improper and unauthorized modification of data and information to prevent tampering at any stage of transmission when transmitted over a wireless channel, and (3) availability, protection against denial of service or denial of access, thus ensuring access to and use of the information is not interrupted.

Inherent Challenges for Communication Technology	
Challenges	**Gaps**
Meeting performance requirements of CT	Identifying key performance attributes for novel CTs in NPPs Establishing monitoring practice for key performance indicators
Setting up an optimized and economically feasible communication infrastructure	Developing optimized setup, retrofitting, and accessibility for currently operating reactors Developing approaches that combine consequence driven cyber-informed engineering and economics during design phase of ARs
Managing heterogeneity of data	Establishing hardware and software methodologies and protocols to manage heterogeneity Developing hardware and software technology to support integration Addressing technical hurdles for the coexistence of multiple technologies (e.g., different wireless communication technologies working together)
Ability of CT to evolve: SAM	Understanding the technical basis of developing technologies (e.g., with 6G, what is the technical basis and requirement?) Understanding the impact of technology evolution Developing the long-term vision of technology evolution Developing/revising the regulatory vision/roadmap to address technology evolution, risk-informed performance-based requirements Developing legal and contractual framework to address technology obsolescence and ensure continuity of service throughout the reactor lifecycle
Ensuring QoS of CT	Defining the quality of communication across different technologies (e.g., latency, throughput, and attenuation level) Developing simulation capabilities to evaluate the quality and performance under different scenarios Enhancing efficiencies in data and information management
Support edge computing	Identifying communication requirements of edge-computing devices across the plant Integrating with hardware: the interaction of the edge-computing hub with hardware nodes
Cybersecurity	Defining cyber threats for CT Exploring existing defense mechanisms Ensuring reliability of data and communication channel against cyberattacks Meeting the regulatory requirements for cybersecurity: hardware, software, supply chain, wired or wireless network, and others Developing methodologies to address confidentiality, integrity, and availability

3.2 CHALLENGES IN INTEGRATION WITH DIGITAL TWIN

DT-enabling technologies or simply enabling technologies are described in [5] as a set of technologies that are needed to successfully implement a nuclear DT. Advanced sensors, instrumentation, and CT along with M&S and data and information management are part of DT-enabling technologies [5]. For ASI and CT, which are formative technologies of a DT, the term "integration with DT" functionally means interaction of data and information to and from ASI and CT with other DT-enabling technologies such as M&S and data and information management. In currently operating reactors, implementing a novel DT would require integration with the plant's existing sensors, instrumentation, and CT infrastructure, while for future reactors the ASI and CT could be designed to be implemented together with other DT-enabling technologies. This section presents a description of a unique set of challenges and gaps that need to be addressed in integrating ASI and CT with DTs at currently operating or future reactors.

3.2.1 INTEGRATION CHALLENGES: ADVANCED SENSORS AND INSTRUMENTATION

Data Heterogeneity: Current sensor and instrumentation in NPPs mostly operate in a narrow range of heterogeneity, in that the sampling rate or resolutions would either be constant or have limited variation. When used in integration with DT, sensors could have limitations regarding the amount, spatiotemporal resolution, and heterogeneity of the data that they can capture and transmit to a DT. Some examples of plant data and response heterogeneity [5] are different time resolutions ranging from milliseconds to DT lifetime; different sensor modalities; manually collected or automated acquisition; and numerical, text, categorical, or other format. Therefore, the data-receiving element within a DT will need to be designed appropriately to utilize the data feed and interpolate or extrapolate it as required. This will ensure that there is a smooth data translation from a heterogenous to homogenous stream and vice versa. In addition, the need for integrating the real-time data streams with any historical data archives (e.g., NDE data and structuring monitoring data) should be explored.

Communication Requirements: One of the fundamental elements of the DT framework in [5] is the connection between the digital and physical systems, carrying data and action (such as actuation) information between them. To achieve this seamless real-time exchange of information, there are aspects of communication that need to be considered. These include low-latency communication, data security and privacy, data synchronization, high spectrum efficiency, and network capacity. It is understood that information exchange is expected to rely on different wireless and even wired communication technologies that operate at different frequencies and utilize varied protocols. Therefore, it presents a challenge to integrate information communicated from different wireless and wired technologies in a standardized manner to be useful for varied DT applications. Within the DT space, the interaction might span within DTs, referred to as intra-twin communication, and between DTs, referred to as inter-twin communication [51, 52], to achieve application-specific outcomes. In either case, successfully meeting the above-mentioned communication requirements is critical.

Usability of ASI Data: As an essential DT-enabling technology, the ASI module of an NPP should be equipped with interface mechanisms to allow the DT to continuously manage, analyze, and convert sensor data into actionable information in real time for information-driven asset management with operators and DT use cases, such as autonomous control systems. Such interface mechanisms should incorporate a diverse set of complex, heterogeneous data streams—including historical and real-time plant data, data at different spatiotemporal scales, data from different types of sensors, and data in digital/nondigital forms and in different formats—and automatically feed into the DT. They should also promptly reflect improvements in data acquisition; for example, from manual, periodic legacy approaches to automated, real-time capabilities enabled by ASI. The effective use of improved data acquisition capabilities should be reflected in the DT through online updates to the implemented algorithms and analytics in relation to the ASI data and the resulting DT models.

ASI Integration with Real-time M&S Capabilities: M&S within a DT can take different shapes and forms such as data analytics, ML, AI, physics-based models, risk-assessment models, and more. An ASI infrastructure that feeds real-time data to a variety of M&S must be equipped to meet the diverse requirements of different models such as different sampling rates, spatial and temporal resolutions, time lag, decomposition of multimodal data, etc. For instance, real-time data acquired by the same sensor on the same asset might provide input for two different models: a sensor that measures neutron fluence can input its data into a reactor criticality model and a reactor pressure vessel embrittlement model, the former would need a much higher sampling rate. Traditional sensors with fixed sampling rates and frequencies may not be able to meet the diverse requirements of multiple and diverse models running simultaneously within a DT. It is therefore critical to understand the data requirements of each model running within a DT and ensure that the ASI infrastructure is designed to work in synchronization with such a DT.

ASI to Maintain State Concurrence in DT: The ability to provide the real-time representation of the current state of a physical entity or physical phenomenon and continue maintaining that state concurrence is one of the vital conditions for a DT to exist. ASI technology integrated with a DT must be capable of meeting specific technical requirements and challenges toward maintaining state concurrence. Ideally, to maintain state concurrence each time there is a state change, the sensor must be able to detect and transmit information about the change to the DT. SSCs in an NPP change states at various rates; therefore, a primary functional requirement of ASI to support state concurrence is the ability to adapt to different sampling rates, temporal frequency, and resolution requirements based on different applications or operating conditions in an NPP. For example, the requirement for frequency and resolution of data acquisition at a pump vibration sensor could be different for a diagnostic DT and a maintenance DT for the same pump. Additionally, the required data acquisition frequency could be higher during abnormal operating conditions compared to normal operating conditions for the same asset. ASI might possess analytics capability at the sensor node capable of performing anomaly detection and differentiating a true process state from a spoofed state. Such an ASI capability can also be part of a synchronization check in a DT that can detect drift or spoof in the DT itself.

Flexibility in ASI: Implementing a preliminary DT and supporting ASI may focus on a specific component or application. Maximizing the value of DT infrastructure at an NPP depends upon the ability to scale up the DT application beyond initial or pilot implementations. Several currently planned DT applications, for instance, are focused on non-safety components and applications, such as predictive maintenance of components on a secondary side [5]. The ASI infrastructure at an NPP must be sufficiently flexible, adaptable, and scalable to support the scaling up of the volume, capabilities, and scope of a DT.

The ASI module should have the ability to receive feedback from the DT and to correct or improve itself based on the feedback before connecting back to the DT with updated information. The DT may require higher resolution data from sensors to train and test its data-driven models or to calibrate and validate its

M&S tools. The ASI infrastructure should be able to adjust the sampling frequency of data acquisition on demand and in real time. The DT may also identify needs for additional data at new locations of the physical asset or new time scales. The needs are conveyed to the ASI module, which should be able to address the spatiotemporal gaps in data by (1) installing new physical sensors, (2) collecting extended continuous, real-time data from existing sensors, or (3) using virtual sensors enabled by the DT.

Integrating Different Sensor Modalities: Effective integration of data from different sensor modalities requires that the measurements are time-stamped to allow synchronization in time. This is more of a challenge when dealing with spatially distributed sensors across a large system (the whole power plant, for instance) where small transmission delays and hardware differences can cause data to lose time synchronization. Integration within a DT can also be a challenge with the need to validate the data streams prior to integrating with the DT. While the DT can serve as the hub for information integration from different sensor modalities, it is not clear how such data integration can be achieved with data from sensors of different fidelities/resolution, reliabilities, and data acquisition rates/bandwidths. There is a need therefore to define the interface and interoperability requirements up front to address these challenges, and the development of the DT will need to account for these aspects.

Using Computer Vision Technologies: Non-contact technologies relying on computer vision and image processing could be applied to automate O&M activities in existing and future reactors. Technologies like digital image correlation, remote sensing, thermal cameras, drones, robotics, and laser vibro-acoustic modulation are attracting interest from nuclear stakeholders for wide applications such as structural health monitoring, leak detection, fire detection, and thermal transient. A key challenge of ASI is understanding and meeting the requirements of extensively high-resolution data acquisition to support the underlying computer vision algorithms in a DT.

DT for ASI and CT: Performance assessment and maintenance of plant sensors and instrumentation is key to ensuring long-term and reliable operation of plant ASI infrastructure. The plant staff typically performs periodic manual procedures that assess sensor performance and conducts maintenance activities, such as repair, recalibration, or replacement of sensors. A DT integrated with ASI can support the maintenance of plant ASI through inherent analytics within the DT that does performance monitoring, failure prediction, sensor-drift assessment and makes recommendations for actions such as sensor calibration or sensor maintenance scheduling. A DT integrated with risk-assessment models such as probabilistic risk assessment (PRA) could even perform real-time and accurate reliability assessment of ASI in a plant safety-system. Such DT capability can address several major factors in risk assessment of digital sensors and instrumentation, such as sensor qualification, common cause failures, inform defense in depth, and more. DT can monitor and adjust communication flows based on the actual plant state and data requirements and could model or optimize wireless communication paths given its knowledge of plant structures and components and their failure or abnormal operating states, in real time. A DT could be implemented for detecting cyberattacks and even autonomously respond or recommend actions such as isolating certain data and communications.

Smart Sensors: Smart sensors, which have internal compute resources to perform predefined operations on measured data before passing them on, are likely to play a significant role in DTs for NPPs. Commonly used for internet-of-things (IoT) applications, smart sensors can help lower communication bandwidth requirements through local processing while enabling the rapid deployment of new measurement technology in hard-to-access locations. The primary needs with smart sensors include improving cybersecurity of smart sensors used in IoT solutions, developing methods for monitoring and validating the processing algorithms implemented within the smart sensors, and qualifying algorithm changes to meet DT requests. Also of interest is the need to define the necessary communication resources between the smart sensor and DT which include the bandwidth and data transfer rates, type of data/information to be transmitted or received by the smart sensor, and the allowable error rates.

Virtual Sensors: The concept of virtual sensing is to infer unmeasured process variables from a combination of available physical sensors and process physics embodied in the DT [53, 54]. Although this concept is not new, there is a need to develop a unified, acceptable definition of virtual sensor technology for nuclear energy application. Such a definition should also clearly articulate (1) the respective role of ASI and DT in virtual sensing, (2) the functions of virtual sensors, and (3) the implications of virtual sensors to safe and reliable operation of NPPs.

It is important to perform measurements without interfering with reactor operation [55], especially for small-scale ARs where availability of space and physical access can be a challenge. Under a unified definition, robust virtual sensors will need to be developed in the design process using a DT—which represents its physical asset as a set of analytic relations representing the physical mechanisms of degradation and performance—to inform optimal sensor number and placement and determine the selection of new sensors [56] needed for adequate and minimally intrusive coverage. During plant operations, virtual sensors may be used to (1) augment available plant information with information that cannot be directly measured, (2) temporarily replace identified faulty sensors to extend operation to the next convenient maintenance opportunity [56], and (3) compensate for missing data in physical measurements, requiring development of imputation and inference techniques—especially those for time series data—within the DT and information exchange between measurements and DT.

ASI Integration with Digital Twins

Challenges	Gaps
Developing technical solutions to address data heterogeneity between ASI and DT	Designing the interface in DT to handle the various forms of data heterogeneity Translating data from heterogenous to homogenous streams Developing the application for ontology-based data structures Considering real-time data integration with non-real-time data (i.e., historical data, NDE data, and structural monitoring data which is not real-time)
Identifying and standardizing communication requirements between ASI and DT	Identifying optimum QoS balancing latency and throughput Identifying bandwidth and spectrum sharing requirement Standardizing communication protocols within DT
Ensuring usability of data by DT	Managing, analyzing, and converting ASI data into actionable information for both operators and control systems Integrating historical as well as real-time data within DT to provide useful information Developing analytics for effective use of improved data acquisition enabled by ASI
ASI integration with real-time M&S	Understanding the current state of M&S (physics-based models, ML, hybrid, other analytics, etc.) and their requirement for real-time data Developing ASI capabilities to support M&S requirements in DT Supporting high-fidelity simulation in real-time
Maintaining state concurrence	Adapting to different temporal frequency and resolution requirements of different applications Verifying true vs. spoofed state through a discrepancy checker at the sensor node and within DT Checking a potential DT-drift through synchronization checks in DT

ASI Integration with Digital Twins, cont.	
Challenges	**Gaps**
Ensuring flexibility in ASI	Receiving requirements and feedback from DT using ASI (e.g., an ML algorithm in DT requires higher resolution of sensor data and conveys that to the sensors, and a DT identifies spatiotemporal gap in data and conveys the need of installing new sensors) Utilizing a DT for informing, establishing, or updating an ASI infrastructure Identifying novel sensor modality required and the associated ASI
Integrating different sensor modalities	Developing DT as a centralized hub for information integration across different sensor modalities Ensuring time synchronization of different measurement channels Performing real-time verification and validation of measurement using cross-device or cross-modality data Articulating interoperability requirements between different sensor modalities
Using computer vision for monitoring and diagnostics	Enhancing ASI to support the development of computer vision for monitoring, inspection, diagnostics, and other applications Developing, testing, and validating computer vision algorithms within DT
Developing DT for performance and reliability of ASI	Developing digital representation and/or models of various performance attributes of ASI and CT Performing testing, maintenance, reliability assessment, and calibration of sensors using DT Integrating sensor risk-assessment with traditional PRA using DT
Implementing smart sensors	Developing cybersecurity requirements for the application of IoT sensors Defining optimum communication burden in edge computing
Implementing virtual sensors in DT	Developing an acceptable definition of virtual sensors for nuclear application Optimizing sensor placement specific to nuclear-DT application Developing analytics and computational techniques for virtual sensors

3.2.2 INTEGRATION CHALLENGES: COMMUNICATION TECHNOLOGY

Communications technology integration with DTs brings an additional layer of challenges that need to be addressed to ensure operability, reliability, and trustworthiness of DT technologies for nuclear energy applications. Specific challenges in this context are discussed as follows.

Identifying optimal DT applications: DT in nuclear is explored to inform reactor design, O&M, transportation, construction, and even disposition. The communication architecture might differ for different nuclear energy applications of DT, but the underlying hardware, software, and performance requirements are going to be similar. The platform that is used to develop DTs must be able to accommodate different communication requirements discussed as part of real-time communication, DT evolution, and DT performance. In addition, as the communication network between the physical system and DTs is expected to support continuous integration and deployment as new services or software are available.

DTs are being considered for applications over the lifecycle of nuclear energy systems, ranging from design and construction to operations, maintenance, and decommissioning. Within each of these lifecycle elements, DTs are expected to contribute to a number of applications, such as predictive maintenance, monitoring and tracking, operations optimization, etc. Each of these applications is expected to have different requirements for communication technologies—hardware, software, protocols, latency requirements, etc. At this stage of the DT technology development, the communication system requirements are undefined and may be considered a gap that needs to be addressed. It should be noted that the requirements for the DT-related communication systems are unlikely to be considered required for AR operability and, as such, will not be part of the technical specifications for the plant. However, the requirements for the DT communication systems might need to be defined based on the AR design, operation, and maintenance requirements. A particular aspect of this need is the expectation that the underlying measurement instrumentation providing the data for the different DTs (each DT corresponding to a different application in an AR) will be the same and the communication systems for each DT will likely utilize parts of the same communication infrastructure. At the same time, the available instrumentation will have different characteristics with respect to measurement resolution, volume, and timing. In addition, the feedback requirements (such as latency, volume of information, and type of information) from the DT to the system or the control room will also be application and DT dependent. As a result, the requirements defined will need to be aligned with the expected heterogeneity of application requirements and available measurements.

Real-time Communication: The term "real time" in communication implies updating frequencies dictated by the purpose of the DT and the dynamics of the represented physical system in the closed NPP-DT feedback loop. Given the wide range of update frequencies—from a fraction of a second to weeks/months—that are application and user dependent, it is essential to clearly define and identify the real-time requirements for different applications. Real-time communication requires seamless exchange of data and information between the digital and physical systems and between DTs, in which various spatiotemporal scales need to be properly considered. It is also important to integrate information communicated from different technologies (wired and wireless) with different latency characteristics in a standardized manner to be useful for varied DT applications. Latency, as a key performance indicator of real-time communication, is technology specific. Similar to how requirements for system state update frequency, latency requirements are different for each DT application and therefore need to be inherently incorporated in the definition of "real time." Low-latency communication shall correspond to rapidly changing, highly dynamic systems, whereas higher latency is allowed for systems with less dynamic change.

Reliable Communication: Another key challenge with CT in DT systems is to ensure a reliable communication network for both physical-to-DT and DT-to-DT communications. Different quantitative and qualitative approaches are needed to assess communication reliability and requirements. High reliability requires hyperconnectivity of the communication network. Hyperconnectivity means that critical communication channels/streams and their interconnection must stay uncompromised under all operating conditions. This requirement needs to be met by incorporating redundancies in the communication infrastructure. Bridging this gap will help increase the availability of DTs and the operating efficiency of corresponding physical assets.

Communication reliability is also concerned with reliability of data and information. Similar to ensuring the QoS as an inherent CT challenge, but in the context of CT integration with DTs, data reliability requirements are elevated when sharing a large amount of information between DTs or between a physical asset and a DT. Data integration/fusion are needed in areas where sudden dense communications occur, and the loss of critical information should be avoided or minimized.

Another requirement of reliable communication is built-in high-fault tolerance, which shall be met by implementing tools in the communication infrastructure that can detect and alleviate incipient communication errors in a timely manner before they may progress and impact the entire network. Related to fault tolerance is the need for a data reconciliation process within DTs. Data reconciliation refers to a verification phase during information sharing where the received data is compared against original source data to ensure that information is transferred correctly within a reasonable error margin. Establishing this process using comparative reconciliation techniques will help identify and correct systematic mistakes made during data migrations and improve the accuracy and reliability of data on the receiver end. Last but not least, ensuring reliability of the communication infrastructure closely depends on ensuring its resilience and survivability in the face of threats and challenges to its normal operation within the DT system. For this purpose, risks that will potentially compromise the integrity of critical communication systems need to be identified and appropriate resilience metrics need to be properly defined and evaluated.

Performance Requirements: As suggested in the real-time communication requirements of DT, latency is one of the important performances metrices that needs to be identified and established across different applications. Synchronization of several transmitted information between digital and physical twins might be required for some critical cases such as remote monitoring. Other performance requirements related to DT maintainability, DT performance and accuracy, DT security, DT reliability, DT verifiability, and others needs to be considered as DT evolves.

Ability of DT to evolve: The DT design must take into consideration its long-term usage as new ASI generated data is expected to be integrated over a period of time that could be as long as the licensed life of the reactor and must be capable of adopting to technological evolution and even obsolescence. To ensure that DT supports these evolving needs, the network bandwidth and capacity should be able to adapt to the changes without impacting latency and transmission reliability. Also, DT must support ways to accommodate continued advances in AI, such as narrow intelligence to more artificial general intelligence [61, 62]. As the DT architecture or framework evolves, addressing security of DT with respect to data, model, and computational platform, needs to be an integral part of the design consideration.

CT Integration with Digital Twins	
Challenges	**Gaps**
Identifying optimal DT applications	Identifying, defining, and addressing various hardware and software communication requirements for different applications Establishing technical basis for AR communication systems requirements
Ensuring real-time communication	Defining or identifying the real-time requirements for different applications Integrating data and information across various spatiotemporal scales Addressing latency of different communication technologies and incorporating latency in the definition of "real-time"
Developing reliable communication between DT-enabling technologies	Developing quantitative and qualitative techniques for assessing reliability Ensuring hyperconnectivity (i.e., different communication channels must stay connected) Incorporating redundancies in communication infrastructure Developing an inherently high fault tolerant communication infrastructure Ensuring data reconciliation within DTs: systematic error identification and correction
Meeting performance requirements of CT specific to DT	Identifying heterogeneity in communication requirement across plant asset from DT perspective Exploring and addressing specific performance measures (e.g., data error-rate, latency)
Creating ability in DT to evolve	Ensuring ability of DT to adapt to the changes in CT and communication requirements of various applications Addressing the constant increase in network bandwidth and capacity with time Identifying the balance between optimum CT deployment vs. existing Developing the ability of DT to adapt to evolving and ever-changing CT (e.g., nuclear industry catching up with 5G, 6G)

The increased interest in DTs in nuclear energy applications has highlighted the various technologies that form a DT (including data management platforms, sensor and instrumentation technologies, data streaming and communication, data analysis, etc.). While there appears to be no existing standards covering DTs, though several organizations are working toward this goal, it is likely that several existing standards endorsed by the NRC that cover each of the technical areas may be relevant. For example, in the ASI area, standards exist on sensor and instrumentation qualification for nuclear energy such as IEEE and IEC and in sensor testing such as ASTM and IEEE, etc. [57, 58]. Some of these may need to be updated to address AR needs, for instance, environmental qualification in AR relevant conditions. Such needs for updating existing standards and identifying areas for developing new standards for ASI in DT applications should be determined.

SUMMARY

This report presents some key challenges and gaps associated with advanced sensors, instrumentation, and communication technology including those associated with integration within a nuclear DT system. Advanced sensors, instrumentation, and communication technology are key DT-enabling technologies, and identifying and addressing the challenges and gaps associated with DT-enabling technologies is an important step toward preparing for advancements within nuclear power. Such advancements may feature integrated digital technology, more fully instrumented plants, improved plant information and control systems, and advanced operations and maintenance practices, all of which may be integrated within a DT system.

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 the areas of design, development, demonstration, testing, qualification and powering of sensors, instrumentation, and communication technology of the future. Key challenges in implementing advanced sensors and instrumentation and communication technology are meeting the requirements for environmental qualification, performance, reliability, maintainability, and cybersecurity; ability of communication technology to evolve as scalable, agile, and modular; identifying standards and communication protocols; and achieving real-time integration of advanced sensors & instrumentation and communication technology with a digital twin for state concurrence. Addressing these challenges is important for long-term sustained operation of current nuclear power plants and for demonstration and successful deployment of future nuclear reactor technologies. If left unaddressed, these challenges and gaps could result in delays or inefficiencies in adoption and implementation of DT-enabling technologies for nuclear energy 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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