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Light Water Reactor Sustainability Program

Technology Deployment Plan for Emerging Technologies in Nuclear Power Plants

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ABSTRACT

Many in the nuclear power industry recognize the substantial cost savings that can be achieved by migrating from the manual, labor-intensive monitoring of critical plant systems to data-driven, intelligent approaches and technologies. Recognizing the importance of this development, the U.S. Department of Energy's Light Water Reactor Sustainability Program has taken proactive steps to support this evolution. This program has launched several collaborative initiatives with utility partners implementing pilot projects that explore and validate advanced techniques, resulting in a series of comprehensive public reports that detail innovative methodologies.

This document will consolidate these efforts, for researchers as well as the industry as a whole, for a selected and critical set of technologies. The report intends to provide a clear path forward for further research efforts that align with the challenges faced by nuclear utilities in deploying emerging technologies.

The report focuses on three key technology areas: drone and robot use, work management automation, and digital twins for plant condition monitoring. Through conducting in-depth discussions with a large North American nuclear utility, and by synthesizing recent and relevant research initiatives from Idaho National Laboratory (INL) researchers, this report assesses the current state of these technologies, the challenges faced in their implementation, and the opportunities for future research to advance the effective deployment and utilization of these technologies in nuclear power plants.

For each of the three technology areas discussed, the report uses the same structured approach. First, it presents current deployments based on extensive discussions with utility partners. It then examines deployment challenges faced by utilities (including regulatory obstacles, cybersecurity risks, resource limitations, infrastructure demands, feasibility issues, and cultural barriers), identifying potential applications of the technology area that have yet to be realized at the utility. The report then summarizes relevant INL ongoing research efforts in each technology area, highlighting ongoing progress and technology readiness. Finally, it discusses potential future research paths, informed by the progress of existing INL research and the real-world gaps and challenges identified during utility discussions.

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EXECUTIVE SUMMARY

This report supports the Light Water Reactor Sustainability (LWRS) program's ongoing efforts to modernize processes and approaches for intelligent and cost-effective nuclear power plant systems. It synthesizes the progress made in three key technology areas, documents the deployment of these technologies in the field, and identifies potential future research initiatives to address challenges and gaps in their adoption by the nuclear industry. The report's findings are based on a review of existing literature and in-depth discussions with researchers from the LWRS program, Idaho National Laboratory, and representatives from a large North American nuclear utility.

Technology Areas Covered

1. **Drone and Land-Based Robot Use**: This technology area explores the deployment of aerial drones and land-based robots for various applications, including conducting inspections, walkdowns, and periodic field operator rounds. Current deployments range from manually operated drones for specific inspection tasks to dog robots for automated radiation surveys. The LWRS program research has focused on developing autonomous navigation capabilities and exploring the use of these technologies for security applications.
2. **Work Management Automation:** This technology area encompasses the digitalization and streamlining of maintenance, operations, and administrative processes. Current industry deployments include systems for mobile work execution platforms and streamlined planning tools for preventative maintenance. Recent LWRS program research has made strides in enabling automated work processes, corrective action program automation, and frameworks for evaluating work reduction opportunities.
3. **Digital Twins and Condition Monitoring Tools**: This technology area involves the development of digital twins—virtual representations of physical assets for improved monitoring and predictive maintenance—and the broader tools used for condition monitoring. Current tools in use by industry include advanced pattern recognition software for anomaly detection and thermal performance monitoring. Recent LWRS program research includes developing a suite of tools for anomaly detection models, explainable artificial intelligence (AI) for predictive maintenance, and risk-informed asset management techniques.

Key Technology Deployment Challenges in Industry

For drones and robots, the need to overcome doubts about the safety of the technology is particularly crucial while regulatory hurdles such as those related to the Federal Aviation Administration's Part 107 requirements present additional considerations. Plants also grapple with resource constraints, particularly the availability of skilled personnel to implement and manage these advanced technologies. The nuclear industry's aging workforce and the potential loss of institutional knowledge complicate the deployment and long-term sustainability of these technologies.

Common challenges are hindering the deployment of technologies across all three technology areas. A significant challenge is the processing, integration, and effective use of large amounts of heterogeneous and unstructured data from various sources. For work management automation, the challenge lies in combining structured data from work order systems with unstructured data from technician notes and equipment manuals to optimize maintenance planning and execution. Multiple legacy systems that do not communicate effectively with each other make it challenging to implement end-to-end process automation. Upgrading these systems is costly, and reasonable skepticism of the viability and benefits of these upgrades will need to be overcome. Those tasked with modernization initiatives must work hard to demonstrate the value and reliability of innovations, such as AI-derived diagnostic insights.

In condition monitoring, one challenge involves integrating real-time sensor data with historical performance records and maintenance logs to accurately assess equipment health and predict potential failures. Also, sensors are thought to be a major cause of data reliability issues, which the utility's current anomaly detection software's diagnostic capabilities struggle to overcome.

Potential Future Research Initiatives

Discussions with utility personnel indicate that several current LWRS program research paths are on the right track and are aligned with the deployment challenges encountered by the industry. Various research initiatives are working on developing advanced techniques for processing and analyzing diverse data types, which aligns well with the needs expressed by utilities.

In terms of potential future research areas for drones and robots, failure modes and effects analysis specific to nuclear plant environments and the integration of advanced autonomous navigation and obstacle avoidance systems designed for use with human operators are two important domains.

For work management automation, future research on overcoming challenges with managing inventory and resource constraints could bring benefits, while the application of AI techniques for automating complex decision-making processes in work planning and scheduling is another potentially promising area of future research.

In the realm of digital twins and condition monitoring, the emphasis on improving diagnostic capabilities and overcoming issues with faulty sensors in condition monitoring research is particularly relevant given the challenges utilities face with this infrastructure. Additionally, the focus on explainable AI in research is crucial, considering the cultural challenges and the need to build trust in these new technologies among plant personnel. Future research that can be applied to mitigate issues with sensor technology and data validation, and enhancing the diagnostic capabilities of anomaly detection algorithms will likely be highly sought after.

Indeed, the discussions suggest that some research may be ahead of utilities' ability to implement it, both technically and culturally. This highlights the importance of future research focusing on demonstrating clear business cases for specific technological changes. Research initiatives that aim to quantify and clearly articulate the benefits of implementing these technologies in terms of cost savings, improved plant reliability, and enhanced safety will undoubtedly be extremely important in facilitating adoption. Furthermore, it is crucial that this research remains cognizant of the importance of effective change management strategies tailored to nuclear power plants.

Table 1. Key deployment challenges for industry.

Challenge	Technology Area
Proving and Demonstrating Low Safety Risk	Drone and Robot Use
Building Use Cases and Demonstrating a Return on Investment	
Pilot Proficiency and Meeting Industry Regulatory Requirements	
Federal Aviation Administration's Part 107 Visual Line of Sight Regulations for Drone Use	
Cybersecurity Challenges	
Lack of Use Cases for Land-Based Robots	
Data Integration and Consistency	Work Management Automation
Planning Processes Bottlenecks	
Parts and Materials Management	
Uneven Automation Adoption Across Legacy Systems	
Change Management and Adoption	
Resource Allocation and Scheduling	
Continuous Improvement Process	
Sensor Degradation and Unreliability of the Monitoring Infrastructure	Digital Twins & Condition Monitoring Tools
Diagnostic Capability of Analytics and Anomaly Detection Software	
Human Resource Concerns and Aging Workforce	
Inconsistent Buy-In and Adoption from Plant Personnel	
Absence of Real-Time, Automated Data Sharing Across Platforms	
Accurately Monitoring and Reporting Transient Conditions	
Integration with Work Management and Predictive Maintenance	

Table 2. Potential future research initiatives.

Research Initiative	Technology Area
Research Into Common Failure Modes for Aerial Drones and Land-Based Robots	Drone and Robot Use
Integration of Obstacle Detection Capabilities in Human-Operated Drone Systems	
Developing NPP-Specific Standards for Drone and Robot Deployment	
Economic and Business Cases for Specific Applications	
Tools and Data Analytics for Nuclear-Specific Applications	
Cybersecurity and Integration with IT and Operational Technology Systems	
Integrated Parts and Material Management with Automated Work Management Systems	Work Management Automation
Research on Integration Techniques for Heterogeneous Data	
Research to Address Resource Allocation, Scheduling, and Planning Inefficiencies	
Change Management and Organizational Readiness	
Research to Mitigate Sensor Degradation and Unreliable Monitoring Infrastructure	Digital Twins & Condition Monitoring Tools
Digital Twin and AI Explainability and Integration with Human Operators	
Research to Improve the Diagnostic Capability of Anomaly Detection Programs	
Effective Training to Overcome Shortage of Data Analysis Personnel	

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ACRONYMS

AEWBMR	Arm Enabled Wheel Based Mobile Robot
AI	Artificial Intelligence
ALARM	Automated Latent Anomaly Recognition Method
APR	Advanced Pattern Recognition
ARMOR	Advanced Remote Monitoring for Operational Readiness
AWP	Automated Work Package
CAP	Corrective Action Program
CBM	Condition-Based Maintenance
CRA	Critical Rotating Asset
CWS	Circulating Water System
DOE	Department of Energy
DT	Digital Twin
DVR	Data Validation and Reconciliation
EAM	Enterprise Asset Management
GPS	Global Positioning System
GPUs	Graphic Processing Units
HVAC	Heating, Ventilation, and Air Conditioning
IMAC	Instrumentation, Monitoring, and Control
IMUs	Inertial Measurement Units
INL	Idaho National Laboratory
ION	Integrated Operations for Nuclear
ISI	In-Service Inspection
KPI	Key Performance Indicator
lidar	Light Detection and Ranging
LWRS	Light Water Reactor Sustainability
M&D	Monitoring & Diagnostic
MBSE	Model-Based Systems Engineering
ML	Machine Learning
MIRACLE	Machine Intelligence for Review and Analysis of Condition Logs and Entries
NLP	Natural Language Processing
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
OT	Operational Technology

RCP	Reactor Coolant Pump
RFID	Radio-Frequency Identification
RIM	Reliability and Integrity Management
ROUNDS	Route Operable Unmanned Navigation of Drones
SSCs	Systems, Structures, and Components
TER	Technical Economic Risk
VAR	Vector Autoregressive
WMS	Warehouse Management System
WRO	Work Reduction Opportunity

DEFINITIONS

Anomaly Detection: The identification of data points, events, or observations that deviate from a dataset's normal behavior.

Automated Work Package (AWP): An evolution of electronic work packages that incorporates advanced technologies to address inefficiencies in current nuclear power plant work processes.

Condition-Based Maintenance (CBM): A maintenance strategy that electronically monitors the actual condition of equipment and suggests when maintenance should be performed.

Digital Twin (DT): A virtual representation of a physical asset or system that is continuously updated with real-time data to mirror the asset's current state and behavior.

Explainable Artificial Intelligence (AI): Artificial intelligence systems that provide clear explanations for their decisions, allowing human users to understand and trust the artificial intelligence's decision-making process.

In-Service Inspection (ISI): Regular examinations of nuclear power plant components to ensure their continued integrity and safe operation.

In-Service Testing: Periodic testing of nuclear power plant components to verify their operational readiness and performance.

Machine Learning: A subset of AI that involves algorithms improving automatically through experience gained from data usage.

Model-Based Systems Engineering (MBSE): An engineering method that uses digital models as the primary means of information exchange between engineers, rather than document-based information exchange.

Natural Language Processing (NLP): A branch of AI focused on processing text representing the human's natural language.

Predictive Maintenance: A technique that uses data analysis tools and techniques to predict defects in equipment and structures, so they can be fixed before they result in failure.

Reliability and Integrity Management (RIM): A systematic approach to managing the reliability and integrity of plant assets throughout their lifecycle.

Risk-Informed Asset Management: An approach to managing assets that considers both the probability and consequences of asset failure when making decisions.

Semisupervised Learning: A machine learning approach that uses a small amount of labeled data with a large amount of unlabeled data during the training phase.

Technical Economic Risk (TER) Assessment: A framework for evaluating work reduction opportunities in nuclear power plants, considering technical feasibility, financial impact, and associated risks.

Unsupervised Learning: A type of machine learning where the algorithm learns patterns from unlabeled data.

Work Reduction Opportunity (WRO): Nuclear power plant work processes that are targeted for streamlining and automation for the purpose of improving efficiency and reducing costs.

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Technology Deployment Plan for Emerging Technologies in Nuclear Power Plants

1. INTRODUCTION

The U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program develops technologies and solutions that support the long-term operation of the nation's nuclear power plants (NPPs). Since it was appropriated, the program has invested in research, development, and demonstrations to drive the industry toward more cost-effective operations. Several studies, technologies, and solutions prompted industry into adopting new operational concepts that had been considered high investment risk. This study evaluates the progress, potential, and adoption challenges of emerging technologies being investigated by industry and identifies the necessary program focus to facilitate their successful implementation. The specific objectives of this effort are:

To document progress on the emerging technologies and map them to activities occurring in the nuclear power industry

To evaluate the technology readiness levels for each focus area for deployment in NPPs and compare against other available solutions

To identify gaps, in collaboration with utility partners, that require research and development to advance the developed solutions into deployable technologies. Key factors considered include regulation, cybersecurity, resources, supporting infrastructure, feasibility, and cultural change.

1.1 Emerging Technologies Included in the Report

The following key technology focus areas were identified for inclusion in this report:

- Drone and land-based robot use: This involves deploying drones and land-based robots equipped with cameras and sensors to automate conducting inspections, walkdowns, and periodic field operator rounds to collect monitoring data of power plant components. The use of these technologies offer the potential to reduce field time, improve personnel safety (e.g., by decreasing radiation exposure), increase data collection frequency, and enable access to hard-to-reach areas.
- Work management automation: This involves applying digital technologies to automate routine work management processes, such as screening, work order and package generation, scheduling, and records management. Automating these essential processes can improve the productivity of maintenance planners and coordinators, improve work execution, and increase data quality and fidelity.
- Digital twins (DTs) and condition monitoring tools: A DT is a virtual representation of a physical asset continuously updated with data to mirror the asset's real-time condition. Equipment monitoring algorithms can be developed using data from the plant. Together, these technologies enable more accurate condition monitoring to both optimize maintenance activities and real-time performance. Custom solutions for the local monitoring of equipment focusing on developing low-cost, noninvasive monitoring solutions that can be tailored to specific equipment types were also explored throughout. Such solutions may leverage advances in sensors, wireless communications, and edge computing to enable the continuous, localized monitoring of key parameters to support condition-based maintenance (CBM).

1.2 Approach

This effort was conducted through research into three sources of information:

1. A review of literature to assess the state-of-the-art technologies in the identified focus areas. This included a survey of LWRS program reports, scientific publications, industry reports, vendor

literature, and conference proceedings related to the application of the technologies in nuclear and other industrial sectors. The review helped the research team benchmark the maturity of the technologies in the research domain.

Discussions with lead LWRS Program and INL researchers engaged in developing and demonstrating the selected technologies to:

a. Gather details on current research activities, progress to date, and future plans
b. Discuss technology readiness levels and key deployment considerations, such as cybersecurity, human factors, and tech-to-market strategies
c. Solicit input on research priorities.

Discussions with utility representatives to:

a. Gain an understanding of the major applications of the technology at nuclear facilities
b. Quantify key economic benefits to the utility
c. Discuss key implementation considerations and challenges, such as integration with existing plant systems and processes, cybersecurity, training needs, and cultural factors
d. Gather input on technology maturity and readiness for industry adoption
e. Solicit feedback on perceived research gaps and development needs to enable deployment.

The discussions ultimately aimed to align the LWRS program research activities with industry needs and priorities. The consolidated feedback from the literature review, and LWRS Program and INL researchers, and utility discussions is then used to inform the technology deployment plan.

1.3 Participants

In total, 12 INL researchers were interviewed to provide input on the technologies covered in this report. Most of the researchers hold leadership roles within the LWRS program and are exposed to several previous and ongoing efforts.[a] The remainder have worked with emerging technologies for other INL research pathways or applications.

In addition, to obtain utility perspectives, detailed discussions were conducted with representatives from a major U.S. nuclear operating company. To protect business-sensitive information, the name of the company is withheld. However, the company operates a large fleet of reactors and is actively engaged in initiatives to innovate and modernize their plants in support of long-term operational improvements.

Seven prominent individuals representing different parts of the organization participated in the discussions:

- A leader in the central engineering organization responsible for evaluating and implementing new technologies across the fleet, with a focus on drones and sensor technologies
- A leader in the central engineering organization responsible for evaluating and implementing new technologies across the fleet, with a focus on work management automation
- A manager in the central engineering organization responsible for advancing efforts on DTs and predictive analytics
- A senior plant engineer responsible for advancing a plant robotics program
- A senior plant engineer responsible for advancing a plant drone program

[a] LWRS Program research is executed by INL among others, on behalf of the U.S. Department of Energy's Office of Nuclear Energy, with INL serving as a research hub and providing expertise, facilities, and coordination for the program's activities.

- A senior leader in the central engineering organization with responsibilities that include oversight for modernization initiatives
- A leader in the central engineering organization with a focus on innovation in the nuclear fleet.

1.4 Structure of Findings

The findings of this report are organized into three main sections, each focusing on a key technology area: drone and land-based robot use, work management automation, and DTs and condition monitoring tools. Despite their distinct focuses, these sections follow a similar structure to provide a comprehensive and consistent analysis across all three technology areas:

- Introduction and Overview: Each section begins with a short introduction to the technology area, providing context and explaining its relevance to NPP operations
- Current Deployment by Industry: This part examines how the technologies are currently being implemented in real-world NPP operations and provides specific examples and case studies of utilities adopting these technologies, offering insights into practical applications and benefits
- Deployment Challenges: This subsection identifies and analyzes the obstacles hindering widespread adoption of these technologies; covers technical, regulatory, organizational, and human factors challenges, providing a comprehensive view of the barriers to implementation; and if appropriate, will call out specific gaps in the deployment of the technology
- INL and LWRS Program Research Progress in the Technology Area: This subsection details the advancements in research, development for each technology, and general technology readiness and covers key initiatives, projects, and technological innovations, highlighting the work done by INL in the context of the state of industrywide research
- Potential Future Research Initiatives: Each findings section concludes by proposing areas for future research and development to address the identified challenges and gaps, advancing the technologies toward more effective and widespread implementation in NPP operations.

2. FINDINGS: DRONE AND LAND-BASED ROBOT USE

2.1 Introduction

Recent technological advancements in aerial drones and land-based robots have significantly enhanced their viability and benefits for deployment in industrial and utility settings. Improvements in energy storage systems and materials science have increased their operational endurance and durability.

These systems now incorporate multiple advanced sensors, including high-resolution optical cameras, thermal imaging devices, light detection and ranging (lidar) systems, and specialized detectors. This suite of sensors enables comprehensive data collection, which is now augmented by artificial intelligence (AI) and machine learning (ML) algorithms for real-time analysis. These developments allow drones and robots to perform a range of basic tasks without human intervention.

A number of aerial drones with advanced capabilities exist on the market and are being deployed by utilities and in other related sectors, for example, the Elios 3, used for confined space operations and featuring lidar mapping, 4k video recording, and visual and thermal cameras [1]; the Skydio X2E is a drone with advanced autonomy and global positioning system (GPS) based night flight capabilities [2], and; the DJI Matrice 300 RTK, a heavy industrial drone with long flight time and range. Examples of land-based robots include Spot, an agile, all-terrain robot with advanced mobility and autonomous navigation capabilities [3]; Ghost Robotics Vision 60, a robust quadruped with modular sensor and payload options designed for real-world environments; and ANYmal: a versatile legged robot designed for autonomous inspection and data collection [4]. Examples of the successful application of this technology include Pacific Gas and Electric Company's use of drones to string energized overhead lines [5] and Avangrid's use of SPOT robots at its substations for thermal inspections and gauge reading [6].

2.2 Aerial Drones

2.2.1 Current Deployment by Industry

The utility has explored the use of drones across its NPP fleet, with varying degrees of success. While some sites have embraced the technology and found valuable applications, others have found integrating drones into their operations to be more challenging. The current deployment of drones at the utility is limited to manually operated drones, as some regulatory concerns could complicate the deployment of fully autonomous drones.

2.2.1.1 Manually Operated Drones

Manually operated drones are being applied in numerous plants across the utility's fleet, with success dependent on a range of factors explored in this report. The engineers trained on the use of drone operations have been proactive in working with plant engineers and other personnel to find avenues to deploy aerial drones. The information about the use of and applications for drones is drawn mostly from an interview with a plant site drone operator, as well as conversations with a member of the utility's corporate team responsible for developing and executing plant modernization strategy.

Inspecting Overhead Areas in the Condenser

Drones have proven to be a valuable tool for inspecting previously inaccessible areas in the condenser, enabling proactive maintenance and plant performance optimization. Drones equipped with high-resolution cameras have been able to inspect structures and search for material degradation in areas previously difficult to access, such as the condenser overhead. This discovery has led to significant recoveries in power generation, with one unit recovering 2 MW (35,000 MWh) and another unit recovering 5 MW (87,000 MWh).

Inspecting Steam Leaks in High-Radiation Areas

Steam leaks in areas with high radiation, in this case a 2–3 REM field, pose risks to radiological safety. Typically, inspecting these areas requires workers to physically enter the high-radiation area, increasing dose and limiting the time available to perform work. Utilizing drones has allowed for the remote inspection of steam leaks while keeping drone operators and workers in a low radiation area of the plant. Drones provide detailed visual data, allowing for accurate assessment and characterization of the leaks.

Characterizing Steam Leaks in Main Steam Isolation Valve Pit Plug and Locked Closed Valves

The main steam isolation valve pit plug is an area where hazards make personnel entry strictly prohibited. Using a drone, a plant was able to characterize a steam leak in this critical location while its thermography capabilities allowed for the identification of a leak past two locked closed valves. It is unlikely that traditional inspection methods would have been able to identify these leaks. The use of drones was critical in accurately diagnosing a system fault and helped prevent potential equipment failure.

Precision Planning of Work with Drone Photography

Drones have been employed to capture high-quality photographs of various plant components, aiding in more precise planning of work activities and leading to improved overall efficiency. For example, the in-core instrumentation group at the plant utilized drone-captured photos of a penetration to plan their work more effectively. By having detailed visual information readily available, work groups can better assess the scope of the task, identify potential challenges, and develop more accurate plans.

Inspections of Snubbers and Components in High-Dose Overhead Areas

Drones have been used to inspect snubbers and other components located in high-dose overhead areas that would typically require personnel to construct scaffolding for working at heights in high-radiation environments. Deploying drones allowed inspecting these components without exposing workers to elevation risks or high radiation levels. The drones provided detailed visual data, allowing for the assessment of component condition and the identification of any potential issues. This enhanced worker safety and reduced the need for costly and time-consuming scaffolding or other access methods.

Inspecting Turbine Building and Reactor Building Cranes

Drones have been utilized to inspect the turbine building crane and reactor building crane at the plant. These inspections are critical for ensuring the safe and reliable operation of the cranes, which play a vital role in various plant maintenance activities. The deployment of drones allowed for comprehensive visual inspections of the cranes, including hard-to-reach areas, without the need for personnel to physically access the equipment. The drone-captured imagery provided detailed information on the condition of the cranes, enabling proactive maintenance and reducing the risk of failures or accidents.

Inspecting Roof Drains in the Turbine Building

The roof drains in the plant turbine building plant are uniquely routed and prone to deterioration at the hard-to-reach upper sections, making them challenging to inspect using traditional methods. Drones have been employed to overcome this challenge. By flying drones inside the turbine building, drone operators captured detailed footage of the roof drains. The visual data collected by the drones allowed for a thorough assessment of the drain conditions and the identification of any blockages or damage. This information facilitated targeted maintenance efforts and helped prevent potential water infiltration issues.

Inspections of HVAC Systems

Drones have been used to inspect the heating, ventilation, and air conditioning (HVAC) systems at the plant, which are critical for maintaining a safe and comfortable working environment. By deploying drones, the plant was able to conduct comprehensive inspections of the HVAC ductwork, fans, and other components. The drones provided access to hard-to-reach areas and captured high-resolution images and videos of the system's condition. This data can aide in identifying leaks, damage, and debris accumulation, enabling preventative maintenance and ensuring optimal HVAC performance.

Inspecting the Main Stack for NRC Civil Inspection

During a civil inspection by the Nuclear Regulatory Commission (NRC), the plant utilized a drone to capture pictures of the main stack, which is a tall structure that requires regular inspections to ensure its structural integrity and regulatory compliance. By using a drone, the plant was able to provide the NRC with detailed visual documentation of the main stack's condition. This high-quality imagery facilitated a thorough assessment of the stack's exterior, including potential cracks, corrosion, or other anomalies. This use of drones streamlined the inspection process and provided valuable data for regulatory compliance.

Inspecting Emergency Planning Sirens

Drones have been employed to inspect the dozens of emergency planning sirens located within a specific radius of the plant. These sirens are part of the plant's emergency preparedness system and require regular inspections to ensure their functionality. These inspections are typically conducted using bucket trucks. By utilizing drones, the plant was able to efficiently inspect the sirens during their 5 year preventative maintenance cycle. The drones captured high-resolution images of the sirens, allowing for a detailed assessment of their condition without the need for personnel to access each siren location. This use of drones has greatly reduced the time and costs associated with siren inspections while enhancing worker safety.

2.2.2 Deployment Gaps

2.2.2.1 Automated Navigation of Drones

The utility has expressed an interest in utilizing autonomous drones for tasks like equipment inspections, radiation surveys, and security purposes, but so far, they have not been deployed within their fleet. Their efforts have been hindered by the regulatory issues surrounding the Federal Aviation Administration's Part 107 requirements for beyond visual line of sight operations. This is discussed further in Section 2.2.3.

The potential use of autonomous drones for security purposes has been recognized and the utility's security team has also explored their potential application for tasks such as perimeter surveillance, intrusion detection, and rapid response to security incidents. It is thought that automated drones may provide a cost-effective and efficient means of enhancing the overall security posture of nuclear facilities by supplementing traditional security measures.

2.2.3 Deployment Challenges

2.2.3.1 Proving and Demonstrating Low Safety Risk

Among the primary challenges in deploying aerial drones is ensuring—and convincingly demonstrating to decision makers—that they pose minimal risk to the safety of the plant, notably in the ability to avoid collisions with sensitive equipment or workers. Currently, there are a lack of studies on the specific failure modes of drones and their associated risks within NPPs, and the industry as a whole lacks formalized and effective guidelines, protocols, or standards that address the mitigation of these risks.

A particular aspect of this challenge is the size and stability of the drones. INL testing has shown that smaller airframes, while more maneuverable in confined spaces, are more sensitive to air currents and disturbances. NPPs often have complex ventilation systems and airflow patterns that can create turbulence, making it difficult for small drones to maintain steady flight. The utility indicated that these stability issues have raised safety concerns with plant operators. There have been incidents, such as one during a containment inspection at a nuclear plant where a drone became stuck on a pipe cap due to strong air currents, requiring manual retrieval. Larger drones, while more stable, present cost and accessibility challenges in tight spaces within plants. Additionally, smaller drones have limited payload capacity for sensors and batteries, reducing their flight time and overall viability for use in NPPs.

Another safety concern is the reliability of drone performance within the plant. One aspect of this concern is the drone's ability to withstand a plant's harsh environmental conditions, particularly in high-radiation areas. A second aspect of this reliability is a lack of knowledge about the precise operational limits of drones and the extent of interference or impact from structural elements or equipment on communication signals, remote control, and data transmission. Even experienced drone operators have faced challenges maintaining constant communication with drones inside NPPs when flying around concrete walls, into closed rooms, and through long hallways. For example, operators lost control of a drone due to signal interference from the concrete lining of a service water bay. Concern exists among plant staff that a loss of communication with a drone could lead to its failure and potential impact on sensitive equipment within the plant. Finally, unlike advanced robots, the drones deployed by the utility often lack automated obstacle detection and crash prevention technology.

2.2.3.2 Building Use Cases and Demonstrating a Return on Investment

Demonstrating the utility of aerial drones in NPPs remains a challenge due to the lack of established applications and corresponding economic justifications to support a comprehensive implementation program. The high costs associated with acquiring and maintaining these technologies, as well as training and licensing of multiple operators, is a potential barrier to their use in the absence of specific proven applications. Additionally, the relevance of drones may vary between plants. Discussions with utilities indicate that there may be fewer use cases for drones at pressurized-water reactors compared to boiling water reactors due to differences in plant layout, accessibility, and the lower dose environments of pressurized-water reactors.

Costs are a particular hindrance for the business case of fully automated drones. The presence of doors and separate rooms within the plant requires drones to be stationed in every room for comprehensive coverage. This limitation increases the complexity and cost of implementing an autonomous drone-based system, as multiple drones would need to be purchased, maintained, and coordinated to ensure seamless operation throughout the facility. This challenge is compounded by the constraints on using smaller and cheaper drones because of stability issues. A larger fleet of drones also raises the demands of program management and maintenance, much of which remains uncertain due to the emerging nature of the technology.

2.2.3.3 Pilot Proficiency and Meeting Industry Regulatory Requirements

For drones, maintaining pilot proficiency is a significant challenge. The current requirements set by the Basic Aviation Requirements standard, which the utility voluntarily adheres to, mandate that pilots complete three flights per quarter to remain current and qualified. These requirements were previously even more stringent, with pilots needing to complete three takeoffs and landings per airframe every 14–15 days. But meeting even these proficiency requirements can be difficult for certain operators, particularly for sites with infrequent drone missions or personnel with competing responsibilities. Pilots must invest significant time and effort to maintain their qualifications, which can be burdensome when the plant wants multiple persons qualified but has infrequent opportunities to fly missions.

2.2.3.4 Federal Aviation Administration’s Part 107 Visual Line of Sight Regulations for Drone Use

Navigating regulatory requirements for outdoor drone flight, specifically the Federal Aviation Administration’s Part 107 regulations, is an important consideration when deploying drone technologies at NPPs. Part 107 regulations govern the outdoor commercial use of drones in the United States and mandate that drone operators maintain visual line of sight with the drone at all times during operation. Waivers are available for beyond visual line of sight operation requirements, but the application process necessitates a comprehensive safety case, risk assessments, and detailed operational procedures to ensure the safe integration of automated drones into the airspace. To utilize automated drones for security purposes, obtaining a waiver for this requirement is essential.

While Part 107 is only mandatory for outdoor flights, the utility has voluntarily chosen to apply these standards to indoor flights as well, in the absence of other specific guidance. This self-imposed requirement affects both manual and automated drone operations within the facility. According to discussions with the utility, this has led to the security team putting their plans for deploying autonomous drones on hold until the path to deploying drones beyond visual line of sight becomes clearer. It should be noted that, according to discussions with the NRC held by INL, there are no additional regulatory limitations on indoor drone use except those related to digital instrumentation and control systems, such as electromagnetic interference and radio-frequency interference.

2.2.4 INL Research Progress in the Technology Area

2.2.4.1 Overview of INL Research

INL is in the early stages of research on drone applications for the nuclear industry, and since 2019, research has been focused on developing innovative and cost-effective solutions for autonomous navigation in NPPs. The research aims to enable applications such as operator rounds and inspections.

2.2.4.2 Autonomous Drones: ROUNDS

INL has been pioneering the development of the Route Operable Unmanned Navigation of Drones (ROUNDS) technology to enable autonomous drone navigation in GPS-denied environments, such as the interior of NPPs. The primary objective of ROUNDS is to automate routine tasks, including operator rounds, security patrols, radiation surveys, and warehouse inspections, which are all currently performed by human personnel.

The ROUNDS technology leverages visual features—notably QR codes—to accurately determine the drone's location without relying on GPS. By analyzing the distortion of the QR code in the drone's camera view, the system can calculate the drone's position within an accuracy of inches. This visual navigation capability allows drones to autonomously navigate along predefined routes, ensuring consistent and repeatable inspection paths [7].

To ensure ROUNDS incorporates effective obstacle detection capabilities, trials tested two methods: one based on analyzing a sequence of video frames to infer relative depth, and another using an ML model trained on custom datasets with depth annotations with the latter demonstrating a higher level of accuracy in detecting and avoiding obstacles [7]. Trials explored several use cases for drones in NPPs, including safeguards, operator rounds, inspections, radiation surveys, and warehouse surveys [7].

2.3 Land-Based Robots

2.3.1 Current Deployment by Industry

2.3.1.1 Introduction

The utility is increasing its use of advanced land-based dog robots across several NPPs. Based on discussions with personnel, the adoption of the dog robot has been an important development in the plant's capabilities. The robot is being deployed for various applications to enhance safety, efficiency, and reduce radiation exposure to personnel. Unlike aerial drones, a limited degree of automation for specific tasks has already been implemented. As well as dog robots, the utility continues to use arm-enabled wheel-based mobile robots (AEWBMRs) extensively for various purposes.[b]

2.3.1.2 Reducing Radiation Dose to Personnel

The utility has deployed the dog robot to enter the basements of the reactor buildings, areas known to have higher radiation levels. By sending the robot into these areas instead of human personnel, the plant has been able to reduce the radiation dose received by workers. In the first year of operation, the dog robot's entries into the reactor building basements saved over 500 millirem of personnel dose. Its ability to traverse uneven surfaces and navigate in confined spaces has made it well-suited for this application.

2.3.1.3 Assisting in Moving High-Dose Objects

The dog robot has been used to assist in moving high-dose objects, such as resin liners, within the plant. In the past, these moves required a crane operator to manipulate the object using a pendant while standing at a distance to minimize radiation exposure. By incorporating the dog robot into the process, the crane operator can now control the move from a low-dose waiting area, relying on the robot's video feed for visual confirmation.

2.3.1.4 Monitoring Valve Strokes in Hazardous Environments

Dog robots have been utilized to monitor valve strokes in rooms with elevated radiation levels or high temperatures. In these hazardous environments, it is not always feasible or safe for an operator to directly observe a valve's operation. The dog robot is deployed to the valve and positioned to provide a clear view

[b] An AEWBMR is a rugged and remote-controlled robot adapted for used in nuclear plants for tasks such as inspecting reactors, handling hazardous materials, and performing maintenance in high-radiation areas.

of the valve's movement. The robot's camera system transmits a live video feed to the operator, allowing the observer to assess the valve's functionality from a safe distance.

2.3.1.5 Automated Radiation Surveys and Monitoring

A dog robot has been programmed to conduct automated radiation surveys in the protected area of the NPP. This is done by setting a predetermined route for the robot that mimics the path a radiation protection technician would typically walk for monthly routine surveys. The robot follows this route autonomously, navigating the area and collecting radiation data using its onboard sensors. After completing the survey, the robot returns to its designated charging station. The process of setting up these automated surveys is relatively straightforward, with the robot's path being mapped out and programmed using its onboard systems. While the robot can perform the survey without constant human control, it is not a fully autonomous operation as cybersecurity considerations currently prevent the implementation of fully autonomous operations, as discussed in more detail in Section 2.3.2.1.

2.3.1.6 Conducting Inspections and Performing Tasks During Reactor Building Entries

The AEWBMR has been used for many years and is a reliable and durable robotic platform, particularly for conducting inspections and performing tasks during reactor building entries. Some robot's rugged design and military-grade components, such as interchangeable military grade (milspec) batteries, make them well-suited for operating in the challenging environments found within the reactor building. During entries, the AEWBMR is deployed to access areas that may be difficult or hazardous for human personnel, providing visual feedback and performing tasks as needed. While the AEWBMR used has proven to be a valuable tool for reactor building entries, it lacks some of the advanced features found in newer robotic platforms, such as obstacle avoidance and more user-friendly control systems

2.3.1.7 Performing Fence Checks for Security

The AEWBMR has been utilized to assist the security force at NPPs by performing fence checks. The robot is deployed along the perimeter fence to verify the proper functioning of the fence sensors, which are designed to detect any attempts at intrusion. By using the AEWBMR for this task, the security personnel can reduce the need for physical patrols, particularly during adverse weather conditions or high-temperature periods. The AEWBMR's ability to navigate along the fence line and transmit video feedback to the security team has made it an effective tool for this application, enhancing the efficiency and comfort of the security personnel.

2.3.2 Deployment Gaps

2.3.2.1 Performing Fully Autonomous Inspections

Although dog robots might be capable of fully autonomous operations, its deployment is currently limited because of corporate restrictions placed on the use of the company's server due to cybersecurity concerns. According to discussions with plant personnel, operators are planning to use fully autonomous dog robots to conduct automated inspections in different plant settings, in the case that these restrictions are eased. An example is the use of the dog robot for monitoring gauges and detecting steam leaks. The dog robot has a fluke meter attachment which allows it to collect data on temperature and other parameters during navigation. The data collected by the robot can be analyzed to identify potential issues or anomalies.

2.3.3 Deployment Challenges

According to discussions with the utility, safety concerns for using land-based robots are generally lower than those of aerial drones, likely due to several factors related to their design, operation, and deployment environments. Robots operate on the ground, navigating through hallways, rooms, and other indoor or outdoor spaces within the nuclear plant, reducing the risk of colliding with critical infrastructure. Robots in use at the utility can be equipped with advanced obstacle avoidance systems, including cameras and sensors, and the effectiveness of these systems has been demonstrated in testing. In the event of a malfunction, dog robots, for example, are designed to stop in place or sit down, minimizing the risk of damage to equipment or injury to plant workers.

2.3.3.1 Cybersecurity Challenges

Navigating the cybersecurity and information technology (IT) approval processes is a significant barrier in deploying fully automated dog robots in NPPs. In the case of deploying robots for autonomous missions, the utility encountered difficulties in obtaining approvals for setting up the necessary servers due to cybersecurity concerns. The process of satisfying cybersecurity requirements and obtaining IT approvals can be time-consuming and complex, delaying the implementation of full automation for more complex tasks. This barrier to automation considerably reduces the realizable benefits of land-based robots for NPPs.

2.3.3.2 Lack of Use Cases for Land-Based Robots

Similar to aerial drones, the nascent nature of this technology means there is a lack of established research and proven case studies demonstrating the applicability of robots. For example, dog robots have not been systematically tested in a research context on specific NPP applications, such as physical security and radiation protection.

The scarcity of established research and validated case studies demonstrating the efficacy of these robots hinders the ability of robotics specialists within NPPs to advocate for their deployment in specific scenarios. This knowledge gap extends to operational effectiveness in unique NPP environments, a cost-benefit analysis compared to traditional methods and integration with existing systems. Without comprehensive studies and an established set of use cases, it is challenging to quantify the potential return on investment and address concerns about adherence to existing regulations.

2.3.4 INL Research Progress in the Technology Area

2.3.4.1 Robot for Security Applications in Remotely Operated Advanced Reactors

INL researchers have begun investigating the use of dog robots for physical security at NPPs, particularly in advanced reactors. To that end, a team has carried out exploratory research on the existing capabilities of dog robot technology and their potential use at NPPs. Although this research focused on the potential use of the robots for physical security, other uses such as radiation detection have also been reviewed.

The exploratory research project gained insights into the capabilities and limitations of current dog robot technologies. The research reviewed the ability of different types of currently available dog robots to navigate indoor environments autonomously, detect potential security breaches, and transmit video and data to remote operators. The integration of sensors to enhance their situational awareness, such as thermal cameras and lidar, has been explored [4]. INL team is currently exploring funding opportunities to be able to carry out field testing for security and radiation detection applications.

2.4 Potential Future Research Initiatives

Based on the current deployment of drones and land-based robots in NPPs, as well as the identified gaps and challenges, opportunities exist for various future research initiatives to advance the safe, secure, and effective use of these technologies in the nuclear industry. The following subsections outline potential research areas that the future research could focus on to support the integration of aerial drones and land-based robots in nuclear facilities. Many of the proposed initiatives leverage INL's existing research and target areas for further exploration.

2.4.1 Research Into Common Failure Modes for Aerial Drones and Land-Based Robots

A future area of research could be the creation of comprehensive failure modes and effects analysis associated with deploying aerial drones and land-based robots in nuclear facilities. Accurate quantification of the level of risk associated with both drones and robots—for example through the probability of failure modeling or probabilistic risk assessments—can provide valuable insights for risk mitigation strategies.

Additionally, rigorous testing to develop quality assurance protocols to ensure the safety and reliability of autonomous systems is needed. By identifying specific risks and their associated probabilities, research could guide the development of measures to overcome any challenges encountered. These measures may include redundant communication systems, fail-safe mechanisms, and robust emergency response protocols.

Research in safety and risk assessments would provide utilities with the necessary information to make informed decisions regarding the use of drones and robots, ensuring the benefits of these technologies are realized while maintaining the highest standards of safety and reliability in NPPs. Additional tools could measure the consequences of robotic system failures, including collision dynamics and radiation dispersion, helping utilities understand the potential impact on plant safety and operations. Finally, this research could be used to expedite the process of obtaining waivers for Part 107 requirements for outdoor drone flight.

2.4.2 Integration of Obstacle Detection Capabilities in Human-Operated Drone Systems

The integration of certain features from the ROUNDS program, particularly obstacle detection capabilities, could significantly enhance the safety and effectiveness of drone operations in NPPs. Thus, a potential area of research could be in researching and developing solutions that combine the benefits of human operators' situational awareness and decision-making capabilities with the advanced obstacle detection and avoidance features of autonomous systems.

Research efforts could be directed toward improving the autonomy and decision-making capabilities of drones in nuclear environments, enabling them to adapt to changing conditions and responding to potential anomalies or human failures. By striking a balance between human control and autonomous capabilities, research could help leverage the benefits of obstacle detection technology to address safety concerns about drone use, while avoiding the additional complexities associated with and barriers to the use of fully autonomous drone systems.

2.4.3 Developing NPP-Specific Standards for Drone and Robot Deployment

In collaboration with regulatory bodies and industry stakeholders, research could help to advance nuclear-industry-specific standards and regulatory frameworks for the safe and secure deployment of aerial drones and land-based robots in nuclear facilities.

One key area of focus could be the adjustment of pilot requirements for drone operators in NPPs. Currently, pilots face challenges in maintaining their drone licenses, particularly with the need to complete a specified number of flights per quarter on specific airframes and the time-consuming process of repeat training required to regain authorization to fly if these requirements are not met. Research could help in developing alternative approaches to ensure pilot competency while minimizing the burden of having to perform multiple flights per period. This could involve the development of performance-based assessments, simulator training, or the establishment of industry-specific pilot certification programs that align with the unique requirements of nuclear facilities. The research could also explore the potential for creating standardized training materials and best practices for drone pilots in the nuclear industry, promoting consistent safety practices across plants.

Another area of research could focus on developing a new standard for drone operations *inside* NPPs to allow for operations and encourage NPPs to not apply any relevant regulation indoors. This research would aim to establish a set of standards that address the specific risks, operational needs, and safety considerations of both indoor and outdoor drone flights in nuclear environments.

2.4.4 Economic and Business Cases for Specific Applications

To encourage the adoption of aerial drones and land robots in the nuclear industry, case studies and cost-benefit analyses will undoubtedly be useful to demonstrate the tangible benefits of these technologies. By quantifying the economic impact and return on investment of implementing robotic solutions, research can help utilities justify the upfront costs and make informed decisions regarding the deployment of these technologies.

Future research is likely to focus on identifying specific applications where drones and robots can provide the greatest value in the nuclear industry and then preparing a demonstration business case for a typical power plant.

2.4.5 Tools and Data Analytics for Nuclear-Specific Applications

Research could be highly beneficial on expanding the capabilities of drones and land-based robots to carry out a wide range of useful tasks specifically tailored to the needs of NPPs. This could involve the development of advanced perception and data analytics techniques that enable robotic systems to collect, process, and analyze data relevant to nuclear plant operations accurately and efficiently. For example, research could enhance the ability of drones to detect and characterize potential hazards, such as radiation leaks, steam leaks, or material degradation, through integrating specialized sensors and anomaly detection algorithms.

Based on discussions with the utility, research on expanding the ability of robots and drones to perform security functions would also be highly beneficial. This could include developing autonomous patrol capabilities, improving real-time threat detection, and enhancing the drones’ ability to operate effectively in various weather conditions and lighting scenarios.

2.4.6 Cybersecurity and Integration with IT and Operational Technology Systems

Cybersecurity and seamless integration with existing IT and operational technology systems are critical considerations for the successful deployment of drones and land-based robots in NPPs. Research may be able to assist in developing a standardized framework for integrating these technologies into NPP IT systems while ensuring robust cybersecurity measures. This could address secure communication protocols, encryption methods for data transmission between robots, control systems, and plant networks. Collaborating with technology vendors and industry partners to develop drone platforms that adhere to the highest standards of cyber security can also facilitate easier integration with plant systems.

3. FINDINGS: WORK MANAGEMENT AUTOMATION

3.1 Introduction

Work management automation in the nuclear industry refers to the systematic digitalization and streamlining of maintenance, operations, and administrative processes that have traditionally been performed manually on a computer or using paper. This automation encompasses a wide range of activities, from scheduling and planning maintenance tasks to executing work orders, conducting inspections, and managing regulatory compliance. By leveraging advanced technologies, such as AI, ML, and integrated digital platforms, work management automation aims to significantly reduce human error, increase operational efficiency, and optimize resource allocation.

3.2 Current Deployment by Industry

3.2.1 Workflow Tracking Using WISE (Wireless Identification and Sensing Equipment)

The utility implemented the WISE system, which leverages RFID (radio-frequency identification) chips embedded in employee badges, which are read by strategically placed RFID readers throughout the facility. This enables real-time tracking of worker location and movement, providing valuable data on workflow patterns and bottlenecks. The system was initially piloted at a single facility to capture data on key congestion points during outages, with a specific focus on contractor flow, a known pain point. The data collected by WISE, although not perfect, provided valuable insights into work patterns, equipment interactions, and process inefficiencies.

The utility utilizes WISE data to conduct in-depth analyses of various aspects of work processes. For instance, the data is used to examine the time spent by employees in the work control center, identifying any excessive delays or unproductive periods. By comparing this data to established benchmarks and management expectations, the company can pinpoint areas where processes deviate from intended outcomes. This enables them to distinguish between knowledge gaps and genuine barriers, facilitating targeted improvements. Furthermore, the WISE data is used to assess the alignment between actual work practices and management expectations, highlighting discrepancies that may require attention.

3.2.2 Streamlining Preventative Maintenance Using Targeted Data Portal

Targeted data portal was developed to streamline the planning process for preventative maintenance work, which constitutes a significant portion of the utility's maintenance activities. It aims to simplify the user experience by consolidating data and attributes required by planners into a single, centralized tool. This consolidation involves integrating data from various sources, such as work order management systems, asset databases, and historical maintenance records. By bringing all relevant information together in one place, planners can access the data they need without navigating through multiple systems or screens. This streamlined approach reduces the time and effort required to gather and analyze information, enabling planners to make informed decisions more efficiently.

3.2.3 Mobile Work Execution Using eTool

A mobile application designed to bridge the gap between electronic work packages and a fully mobile, technician-centric experience is used. To bridge the gap between electronic work packages and a mobile-centric experience, the tool incorporates several essential features:

- Clearance management: streamlines this process by allowing technicians to request, view, and manage clearances directly from their mobile devices
- Work package validation: enables technicians to validate work packages electronically, ensuring that all necessary documents, procedures, and safety requirements are met before starting a job
- Document selection: provides technicians with easy access to all relevant documents, such as procedures, drawings, and technical specifications, directly from their mobile devices
- Pre-job brief preparation: assists technicians in preparing for pre-job briefings by providing a centralized platform for reviewing job scope, hazards, and safety requirements.

3.3 Deployment Challenges

3.3.1 Data Integration and Consistency

The utility faces significant challenges in integrating data from various systems, which severely limits their analytics capabilities essential for work management automation. Their nuclear facilities operate with multiple legacy systems, each storing data in proprietary formats and structures. This fragmentation creates substantial barriers to implementing complete automation solutions across their fleet. The inconsistency of data across these systems further complicates the utility's automation efforts. Equipment nomenclature may vary between maintenance, operations, and engineering databases, making it difficult to create unified work processes or conduct a comprehensive analysis. This lack of standardization also hinders their ability to perform fleetwide analyses and benchmarking.

Additionally, the utility generates a large volume of unstructured data, including handwritten logs, equipment photographs, and scanned documents. These data types are challenging to incorporate into their automated systems due to their lack of standardization and the difficulty in extracting meaningful information from them. Valuable insights from field technicians might be captured in free-text comments on work orders but remain largely inaccessible for automated analysis. The utility recognizes the need for better tools to analyze historical data for predictive planning purposes. They have explored the use of an open-source search and analytics engine to process data from different repositories but have been unable to apply it to all relevant data sources.

3.3.2 Planning Processes Bottlenecks

The utility is not currently applying work management automation tools and techniques in its work planning stages but is experiencing significant bottlenecks, leading to inefficiencies and reduced productivity. The utility is exploring various approaches to overcome these bottlenecks, including the use of automated scheduling tools and digital work packages that streamline the planning process.

The crucial issue is that detailed planning often does not align with the scope of work. The period between T-12 and T-10 (scope freeze) is crucial for validating this alignment, and the process often reveals discrepancies, necessitating work to be unbundled or removed from the schedule. These planning bottlenecks can have cascading effects on resource allocation, materials management, and overall plant efficiency. An important cause is a lack of real-time visibility into resource availability and constraints during the planning process meaning that planners may create work packages without full awareness of conflicting maintenance activities, outage schedules, or resource limitations, leading to overcommitment and subsequent schedule disruptions. The late identification of these issues can lead to rushed procurement processes, potentially increasing costs or causing further delays. In some cases, work may need to be deferred to the next maintenance cycle due to inadequate planning, impacting the plant's overall maintenance backlog and potentially affecting regulatory compliance.

The current planning process also struggles to accommodate emergent work effectively. When urgent, unplanned tasks arise, they often disrupt the existing schedule, forcing planners to hastily reorganize work packages and reallocate resources. This reactive approach can lead to an inefficient use of resources and potentially compromise the quality of both the emergent and planned work. The planning process is further complicated by the need to comply with numerous regulatory requirements and technical specifications. Ensuring that each work package meets all applicable regulations and safety standards within the compressed planning timeline can be challenging, sometimes resulting in overly conservative plans that may not optimize resource utilization.

3.3.3 Parts and Materials Management

The utility faces significant challenges in parts and materials management, another area in which the utility is not currently deploying work automation management tools and techniques. Unexpected obsolescence and parts availability issues frequently cause delays and necessitate rework, disrupting carefully planned maintenance schedules. This problem is particularly acute due to the long operational lifespans of their plants and the specialized nature of many components. When jobs are planned and then deferred due to parts unavailability, it has serious detrimental effects on the utility's long-term scheduling. The difficulty in identifying parts issues in a timely manner exacerbates this problem. Often, information on inventory availability is not received until right before work is scheduled to begin, leaving little time to source alternatives or adjust plans.

The consequences of parts availability issues can be significant. Jobs that are deferred or re-planned due to parts shortages can create a ripple effect on the entire maintenance schedule, leading to resource reallocation, delays, and inefficiencies. The constant reshuffling of work orders and the associated start and stop nature of the process result in wasted effort and reduced productivity. The challenge is further complicated by the utility's move toward CBM. While CBM may optimize maintenance schedules and reduce unnecessary work, it also requires more responsive and agile parts management systems. The tighter planning windows associated with CBM mean that parts need to be available on shorter notice, putting additional strain on the utility's procurement and inventory management processes.

To address these challenges, the utility recognizes the need for better integration between their parts data and work planning and scheduling systems. They are exploring the implementation of advanced automated parts and materials management systems that provide real-time visibility into inventory levels, lead times, and supplier information.

3.3.4 Uneven Automation Adoption Across Legacy Systems

As noted, the automation of many parts of the planning process has not yet been achieved. The different pace of the adoption and deployment of automation within different legacy systems presents a significant challenge for the overall deployment of work automation management.

When using the planner hub, for example, and despite advancements in parts of the process, significant manual effort is still required from planners. This results in a hybrid process where automated systems handle basic tasks, but human intervention is necessary for more nuanced aspects of planning. The planner hub often lacks seamless integration with other critical systems like asset management, inventory control, and regulatory compliance databases. This lack of integration necessitates manual data transfer and validation, increasing the potential for errors and inefficiencies. For example, planners may need to manually cross-reference equipment availability, maintenance history, and regulatory requirements across multiple systems to develop a comprehensive work plan. This process is not only time-consuming but also prone to human error.

For field-facing technicians, the need to switch between multiple systems, manually transfer data, or rely on printouts to access critical information leads to inefficiencies and increased risk of errors. Many of their existing procedures and workflows are built around desktop-centric paradigms, which are not designed for the mobile and interconnected nature of contemporary work environments. Additionally, their legacy systems often operate on outdated software platforms that lack the flexibility and integration capabilities required for modern work automation. For instance, some of the utility's facilities still rely on paper-based work orders or standalone digital systems that do not communicate effectively with other plant systems.

These challenges are exacerbated by the unsystematic variations in processes and systems across different sites within the organization. Each site has its own unique procedures, workflows, and legacy systems, which makes it difficult to implement standardized, fleetwide automation solutions. The lack of consistency in processes across sites hinders the seamless deployment of automation tools and requires significant effort to accommodate site-specific needs, posing a significant challenge to automation efforts.

3.3.5 Change Management and Adoption

The utility faces resistance to adopting new tools and processes due to past negative experiences. For example, the introduction of electronic work packages was initially met with skepticism as it was perceived as a mere replacement of paper with tablets, without significant improvements to the underlying process. This resistance stems from the belief that new tools often fail to address the real pain points and inefficiencies experienced by the workforce.

Relatedly, the utility encounters difficulties in getting busy staff to invest time in learning new systems. In an environment where employees are fully committed, allocating time for training and familiarization with new tools can be challenging. The company recognizes that without adequate training and support, the adoption of new technologies will be hindered, and the potential benefits may not be fully realized.

3.3.6 Resource Allocation and Scheduling

The utility faces significant challenges in resource allocation and scheduling as part of their work automation management. A primary issue is the need for better integration of qualifications data with scheduling systems. Their current scheduling systems often lack the sophistication to automatically match worker qualifications with job requirements, leading to situations where skilled workers are underutilized or jobs are delayed due to lack of qualified personnel.

The difficulty in optimizing resource allocation across the utility's multiple nuclear facilities is another significant challenge. Each site often has its unique scheduling system and resource pool, making it challenging to efficiently share resources or balance workloads across the fleet. This siloed approach can result in situations where one site is overstaffed while another struggles with resource shortages.

The utility's move toward more flexible CBM strategies introduces additional complexity to resource allocation and scheduling. Once an anomaly is diagnosed, maintenance must be performed promptly, potentially straining available labor if multiple issues are identified simultaneously. This shift highlights a fundamental tension in resource management: the need to maintain enough flexibility to respond to emergent issues while also ensuring efficient utilization of the workforce.[c]

3.3.7 Continuous Improvement Process

The utility faces difficulties in capturing and incorporating lessons learned into their automated systems and processes. As work automation management tools become more prevalent within the organization, they recognize the importance of establishing mechanisms that facilitate the continuous improvement of these systems based on real-world experiences and feedback.

One of the challenges the utility encounters is the structured and rigid nature of their automated systems. Once a process or workflow is automated, making modifications or incorporating changes becomes a significant effort and can potentially cause disruptions. The lack of flexibility in these systems hinders the ability to quickly adapt to new insights or implement improvements identified through field experience. Another challenge for the utility is the lack of effective mechanisms to update plans based on field feedback. While utilities have processes for post-job reviews or lessons learned sessions, the insights gained from these activities often fail to translate into concrete changes in work planning and execution processes. This disconnect can result in the perpetuation of inefficient practices or the repeated occurrence of avoidable issues.

3.4 INL Research Progress in the Technology Area

3.4.1 Overview

INL has conducted various research initiatives in work management automation for the nuclear industry. Starting with early initiatives on automated work packages (Section 3.4.2) in 2016, INL has progressed to developing more advanced solutions. A key achievement is MIRACLE (Machine Intelligence for Review and Analysis of Condition Logs and Entries; 3.4.3), an AI-based platform that streamlines corrective action programs. INL has also developed a technical economic risk assessment framework (Section 3.4.4) to evaluate work reduction opportunities (WROs), leading to collaborations with utilities and potential cost savings. Current research focuses on comprehensive work process

[c] The authors of this report have experience with another large North American peer utility that faced similar challenges in resource allocation and scheduling. By ensuring that the right personnel, tools, and materials are available for each task, automating resource allocation has reduced delays and led to significant quantifiable improvements in the efficiency of the corrective maintenance process.

mapping and automation, including a robotic process automation project to optimize maintenance activities, as well as developing the next phase of the MIRACLE initiative. Additionally, INL is working on risk-informed asset management (Section 3.4.5) and plant outage optimization (Section 3.4.6) projects, utilizing advanced tools for scheduling and textual analysis, among other tools and methodologies.

3.4.2 Early Initiatives: Automated Work Packages (AWPs)

Early work from 2016 on the subject of work automation management began examining the potential for AWPs. AWPs represent an evolution from electronic work packages by providing dynamic, context-specific guidance, automated data collection, real-time communication, and integration with plant systems.

The research findings envisaged a future scenario of a fully automated work planning process, from work request initiation, planning, approval, distribution, and archiving, and identified potential functions an AWP system could incorporate to address current inefficiencies and human performance issues. Fifty such functions were identified, each with a description of how they could be implemented through advanced automation technologies to automate various aspects of the work package creation process.

Results from LWRS-initiated surveys with utilities indicated a strong desire from industry to apply advanced technologies and automation to the work package process, with functions such as automatic work tracking, integration with plant systems, automatic population of work package information, mobile job aids, and remote supervision identified as having the highest potential benefits [8]. The research concluded that the majority of the proposed AWP functions could be feasibly developed with current or near-future technologies and that there was significant industry interest in collaborating with INL to further mature the AWP concept.

The report laid out the next steps for INL to progress the research effort, including developing functional prototypes of selected AWP capabilities and conducting pilot implementations with industry partners to demonstrate the real-world benefits. Overall, the research advanced the defining of a vision and technical basis for AWP systems, paving the way for their development and deployment to improve the efficiency of nuclear plant work processes.

3.4.3 Corrective Action Program Automation—MIRACLE

MIRACLE is an AI-based solution designed to streamline and automate the corrective action program (CAP) in NPPs and is intended as a significant advancement in work management automation for the nuclear industry [9]. The manual review of condition reports in NPPs is traditionally a time-consuming and labor-intensive process, prone to subjective interpretation and human error. Experienced staff spend several hours each week manually reviewing condition reports, which can range from minor incidents to significant events [9].

To address these challenges, MIRACLE was developed. Leveraging natural language processing (NLP) and ML techniques, it can analyze both fixed and free-form text fields in condition reports. The software is trained on historical data from multiple nuclear power utilities, allowing it to predict decisions that human reviewers would make. MIRACLE accomplishes this analysis in milliseconds, compared to the several minutes required by a human reviewer for each report. Importantly, the system maintains consistency across all reviews, eliminating the potential for subjective bias. As it processes more reports, MIRACLE continues to learn and improve its analysis capabilities [9]. MIRACLE is not intended to replace human expertise entirely but instead aims to augment human capabilities by speeding up the evaluation process, reducing errors, and allowing staff to focus on more complex tasks.

The MIRACLE platform has moved beyond the conceptual stage and has been successfully implemented in real-world nuclear industry settings. For a large North American utility, MIRACLE was used to automate and enhance the Nuclear Regulatory Commission (NRC) inspection preparation process, as part of a broader compliance automation project. The system was used to process and analyze large volumes of plant data, helping to answer specific questions and provide insights relevant to NRC inspections, significantly reducing the manual effort required for inspection preparation. This project served as a proof of concept for MIRACLE's potential to address different challenges in NPP work management processes. It also highlighted the platform's ability to interface with existing plant systems and databases, a crucial factor for its widespread adoption in the industry.

Building on the success of the development of the MIRACLE platform, INL researchers are now expanding their focus to comprehensive work process mapping and automation. This initiative aims to map and automate the entire work management process in NPPs. This evaluation considers two primary factors: the effort required for each task (measured in staff hours) and the frequency of the task occurrence. This granular approach allows the researchers to precisely quantify the potential impact of automating each task. By analyzing these metrics, the team aims to identify high-impact automation opportunities that can significantly reduce manual effort and improve process efficiency.

The team is leveraging the MIRACLE platform to further develop AI tools tailored for work management processes. These tools are designed to analyze both structured and unstructured data from work orders, condition reports, and other relevant documents. The AI classifiers can categorize work orders based on various criteria such as urgency, type of work, and required resources. Topic models are being developed to automatically extract and organize key information from textual descriptions, facilitating faster and more consistent decision-making throughout the work management process.

3.4.4 Technical Economic Risk Assessment (TERA) Framework

Under a separate initiative, INL has developed an innovative Technical Economic Risk Assessment (TERA) framework to rigorously evaluate work reduction opportunities (WROs) in the nuclear industry. The framework integrates technical, economic, and risk perspectives to identify high-priority opportunities that can deliver substantial benefits to NPPs while mitigating potential risks. By employing standardized methodologies and metrics, the TERA framework enables an objective screening of WROs, detailed cost-reduction analysis, and comprehensive risk assessment [10]. This supports data-driven decision-making for plant modernization investments, ensuring that proposed changes enhance operational efficiency without compromising safety or regulatory compliance. The TERA framework starts with a screening phase using Lean Six Sigma principles like suppliers, inputs, process, outputs, customers [11] and integrated operations for nuclear (ION) principles [12]. It maps processes, identifies inefficiencies, and evaluates solutions. The process map is then converted into a Markov model for steady-state and sensitivity analyses, offering insights into costs, risks, and improvement areas [10].

Using the TERA framework, INL researchers collaborated with a nuclear utility to screen and evaluate several WROs. This analysis revealed that work management processes, particularly those related to planning, scheduling, and condition reporting, presented significant opportunities for automation and optimization. One key outcome was the potential for developing a research aid tool for system engineers to streamline condition reporting (like MIRACLE). Using NLP and ML techniques, this tool could automatically compile relevant information from various databases, reducing the time and effort required for manual research. Modeling and analysis using the TERA framework predicted that implementing such a tool could reduce condition report process costs by approximately 25% annually, translating to $570,000 in yearly cost savings [10].

Building upon the insights gained from the TERA assessment, an ongoing research project aims to develop and implement innovative technologies and processes that optimize planning, scheduling, and execution of maintenance activities. This includes exploring the integration of AI and advanced analytics to streamline workflows, enhance decision-making, and reduce human error. The project will evaluate the technical feasibility, economic viability, and risk implications of proposed automation solutions, ensuring their alignment with the stringent requirements of the nuclear industry.

3.4.5 Risk-Informed Asset Management

The risk-informed asset management project contains tools and techniques that may contribute to the advancement of work management automation in the nuclear industry. The project aims to optimize maintenance activities and resource allocation, which are important components of work management. The effort's unique textual analysis may be a useful tool for advancing work management automation through its ability to glean insights from unstructured data, such as handwritten notes and images. The LOGOS tool is particularly relevant to work management automation. LOGOS is an open-source library that contains discrete optimization methods for scheduling maintenance tasks across multiple time windows, considering various constraints, such as budget and resource availability. By integrating the margin-based health assessment of assets and systems with the optimization capabilities of LOGOS, the project may help to enable a more efficient and risk-informed approach to work management. Section 4.4.4 has more details about this project.

3.4.6 Plant Outage Optimization Project

Building upon the techniques and tools developed for the risk-informed asset management project, INL researchers are working on a project focused on NPP outage optimization. This project aims to improve the efficiency and cost-effectiveness of outage planning and execution by developing methods and tools to support plant staff in creating an outage schedule with a high probability of completion within the desired timeframe. One of the key challenges addressed by the project is the complexity and scale of outage activities. A typical NPP outage involves scheduling thousands of activities within an average of 30 days. The project focuses on assessing the resilience of the outage schedule and identifying potential risks that could lead to delays or cost overruns using probabilistic and Monte Carlo approaches [13].

In addition to advanced outage schedule modeling, the project is also developing methods for mining activity duration data from historical outage records. It explores two approaches: NLP approach and a semantic text-mining approach. As discussed further in Section 4.4.4, INL has developed a suite of tools, including RAVEN (Risk Analysis Virtual ENvironment) and other methods to assess critical path uncertainty, robustness, and resilience, which together aim to help identify activities that may negatively impact the critical path and outage completion time.

3.5 Potential Future Research Initiatives

The following recommendations for potential future research initiatives aim to address the major challenges identified through discussions with the utility. It should be noted that many of the work management challenges discussed above align closely with current or completed LWRS program research. In some cases, existing research may sufficiently address these challenges, in which case the utility's primary task is implementation. This section concentrates on challenges that demand research beyond current LWRS program efforts.

3.5.1 Integrated Parts and Material Management with Automated Work Management Systems

A potentially beneficial area of research is in the development of automated supply-demand modeling tools to provide recommendations for parts procurement and inventory management. This research could tackle the challenges the utility faces related to parts and materials management, leading to unexpected obsolescence and parts availability issues. These tools would potentially leverage advanced analytics and ML techniques to predict demand, optimize inventory levels, and identify potential obsolescence risks. Implementing real-time parts issue identification and resolution tracking could support on-time work execution by enabling the quick identification and mitigation of parts-related problems.

Research that helps to integrate parts and materials data with the utility's planning and scheduling systems could be another area of focus. By ensuring that parts availability information is readily accessible and integrated into the planning process, schedulers may be able to make more informed decisions and minimize the risks due to parts shortages.

3.5.2 Research on Integration Techniques for Heterogeneous Data

As discussed in Section 3.3.1, the utility faces significant challenges in data integration due to multiple legacy systems with proprietary formats and structures, hindering comprehensive automation and advanced analytics implementation. The utility is well-aware of these challenges and is actively investigating solutions. For example, the utility is working on an initiative to consolidate their disparate time-entry processes and data architecture into a single point of time entry system. It is expected that such a system will centralize the process of entering work hours, task completions, and project updates to reduce the time spent on administrative tasks and reduce errors and inconsistencies. By consolidating and integrating time-related data into a centralized platform, planners and schedulers will gain a more comprehensive view of resource availability and allocation. This integration could enable more accurate and efficient planning, reducing the likelihood of bottlenecks and delays.

INL has conducted extensive research into consolidating and utilizing the vast reems of data of different qualities, types, and legacy system sources. Discussions with utility stakeholders emphasize the continued importance of this work. Further research should look to address the inconsistency of data across utility systems and the existence of large amounts of unstructured data. Equipment nomenclature variations, and the use of handwritten logs and equipment photographs, pose significant challenges for their automation efforts. Investigating the application of advanced technologies, such as NLP and ML, could help extract valuable insights from these unstructured data sources. Research around application programming interfaces that are written to standardize data formats and exchanges could enable a more seamless data exchange between disparate systems. Finally, developing intelligent algorithms that understand and interpret this data could enable the utility to harness the full potential of their information assets and facilitate more effective automation and decision support.

3.5.3 Research to Address Resource Allocation, Scheduling, and Planning Inefficiencies

A potential research initiative could focus on integrating qualification matching with dynamic scheduling algorithms to optimize resource allocation and work planning within a nuclear facility. Such research could help to address the challenges related to nonintegrated scheduling systems, worker qualification databases, and inefficient worker allocations discussed in Section 3.3.6. The research should aim to create a system capable of aggregating and analyzing worker qualification data in real-time, matching worker qualifications with job requirements throughout the facility, and developing algorithms that can dynamically adjust schedules in response to emergent work, changing resource constraints, and CBM triggers. Research could also investigate scaling this system to encompass an entire fleet of nuclear plants. The goal would be to develop a fleetwide perspective on worker qualifications and resource availability, enhancing the allocation of specialized skills across multiple sites. This fleetwide integration would be beneficial for highly specialized job types, such as drone operators.

3.5.4 Change Management and Organizational Readiness

Researching and developing effective change management strategies tailored to the unique needs of the nuclear industry is an area of importance. This research could investigate best practices for introducing new technologies and processes, considering the complex regulatory environment and the critical importance of safety and reliability. Investigating strategies for managing the transition from legacy systems and processes to new automated solutions while minimizing disruption to ongoing work could involve the development of phased implementation plans, pilot programs, and risk mitigation strategies to ensure a smooth and successful transition.

4. FINDINGS: DIGITAL TWINS AND CONDITION MONITORING TOOLS

4.1 Introduction

4.1.1 Condition Monitoring in the Nuclear Industry

Condition monitoring is the process of continuously assessing the operational state of machinery and systems to identify changes that could indicate potential failures, aging, or degradation. In the nuclear industry, condition monitoring is critical for ensuring the safety, reliability, and efficiency of plant systems and components. It involves the real-time assessment of critical components like reactor coolant pumps, turbines, and feedwater systems, enabling prompt corrective actions to prevent failures that could lead to catastrophic consequences. Effective condition monitoring is essential for managing aging infrastructure, optimizing maintenance schedules, and extending operational lifespans.

Historically, condition monitoring in nuclear plants relied on manual data collection, periodic visual inspections, in-field and laboratory testing, and time-based preventative maintenance schedules. Traditional monitoring practices are labor-intensive and require routine data gathering and analysis. Recent advances in sensor technologies, data analytics, and AI are enabling more sophisticated condition monitoring capabilities, facilitating advanced predictive maintenance strategies. Many utilities have established monitoring and diagnostic (M&D) centers that continuously monitor plant equipment and provide early indications of equipment performance anomalies [14].

4.1.2 Digital Twins in the Nuclear Industry

This evolution in condition monitoring technology and methods has set the stage for the emergence of DTs in NPPs. DTs represent the move toward a comprehensive integration of plant monitoring and response capabilities, building upon the foundation of advanced sensors, data analytics, ML and AI, and centralized M&D centers. Recent report has defined DTs as possessing four key characteristics: being digital, connected to the physical plant, maintaining fidelity to the current state of the physical asset, and maintaining a purpose. These characteristics enable DTs to provide accurate, up-to-date insights for plant operations and maintenance [15]. Compared to other sectors, the nuclear industry is still in the early stages of DT adoption, with recent literature focusing on the challenges and gaps associated with deploying and integrating enabling technologies for DTs in the nuclear industry [16].

4.2 Deployment by Industry

The utility is implementing a comprehensive condition monitoring and predictive analytics (CBM) program across its nuclear fleet, leveraging sensor technology and advanced analytics for real-time monitoring. The program involves installing various sensors to collect data on the health and performance of critical plant assets. This data is transmitted through networks to plant monitoring centers and to a centralized M&D center, where it is analyzed using advanced software tools by the M&D team, consisting of experienced engineers and analysts. The program uses this data to identify trends, anomalies, and insights that inform maintenance planning and decision-making.

4.2.1 Sensors and Instrumentation

The utility is expanding its deployment of a suite of sensors across its nuclear fleet to improve its predictive analytics capabilities and enable condition monitoring. The sensors focus on critical plant assets, particularly critical rotating assets (CRAs) such as turbines, generators, and large pumps. Vibration sensors are used to monitor the vibrational behavior of CRAs, enabling the early detection of developing faults. Motor current signature analysis sensors collect current and voltage waveform data from electric motors to identify electrical and mechanical anomalies. According to discussions with the utility, several hundred machines are monitored by vibration and motor current signature analysis sensors.

Thermal performance monitoring is another key aspect of the CBM program. According to discussions with the utility, wireless thermal couples are installed on tens of secondary cycle isolation valves per unit to detect steam leakage, which can reduce a plant's generation output if left uncorrected. Infrared cameras monitor transformer bushings, and other high-voltage equipment are used for hot spots or thermal anomalies that could indicate impending failures of the transformer.

Several hundred wireless gauge readers are also deployed to digitize analog gauge data, transmitting readings to a central data historian every 15 minutes for trending and analysis. This approach reduces labor requirements associated with manual gauge reading during rounds while at the same time providing more granular data for condition monitoring.

Additionally, the fleet is also in the early stages of integrating cycle isolation valve and local temperature and humidity monitoring sensors into the fleet. For the former, wireless thermocouples on pipes downstream of secondary isolation valves have been installed in tens of valves at a single plant, in a single case identifying leaking valves. For local temperature and humidity monitoring, the installation of magnetically attached battery-powered wireless sensors has been limited so far. Once installed across the plant, it is anticipated that the data from these sensors will be used in environmental qualification calculations to extend the qualified life of components.

In total, over tens of thousands of data points are monitored across the utility's nuclear fleet by the centralized M&D center, a tenfold increase from pre-project levels. The dramatic expansion in data collection, enabled by wireless devices and automated monitoring software, feeds data historians, pattern recognition programs, and ML algorithms. These systems identify anomalies or adverse trends requiring investigation, allowing the monitoring team to work with station personnel to address degrading equipment conditions before failures occur, realizing the potential of CBM practices.

4.2.2 Machine Learning and Anomaly Detection Software for Predictive Maintenance

The utility's CBM program leverages a suite of advanced software tools and ML algorithms to analyze the vast amounts of sensor data collected from its nuclear fleet. At the heart of this technology stack is the data historian, which serves as the central repository for all sensor data. The data historian acts as the data gateway, incorporating data streams from multiple plant systems and making them available for analysis to be conducted by other tools in the CBM ecosystem.

A key analytical tool used by the utility is an advanced pattern recognition (APR) platform. This platform uses algorithms to model normal operating behavior for plant assets, learning from historical data to identify deviations or anomalies that could indicate developing faults. When the program detects a potential issue, it alerts the M&D team, providing them with actionable insights to investigate and address the problem. According to discussions with the utility, the APR platform has helped plants by catching degrading conditions early, which has prevented equipment failures.

For CRAs, such as turbines and generators, the utility utilizes a specialized software package for monitoring and analyzing vibration data from rotating machinery. It uses advanced signal processing techniques to identify changes in vibration signatures that could indicate developing mechanical faults. By providing early warning of these issues, it allows the utility to proactively schedule predictive maintenance activities, minimizing the risk of unplanned equipment failure and extending the life of critical assets.

Tying the various tools together is another APR modeling framework, which the utility has used extensively across its nuclear fleet. It uses ML algorithms to build predictive models of plant behavior, leveraging data from the data historian, APR platform, CRA monitoring software, and other sources. These models are trained to recognize normal operating patterns and flag any deviations that could indicate potential issues. The utility has deployed approximately over one thousand models covering a wide range of plant assets and systems, providing a comprehensive view of equipment health and performance.

4.2.3 Thermal Performance Monitoring—“Digital Twin”

Another key component of the utility’s CBM program is the use of technology for monitoring and optimizing the thermal performance of its NPPs. The company has deployed advanced thermal performance monitoring software to create virtual replicas of its plants’ thermal cycles. Although this system does not fulfil the typical requirements to meet the earlier mentioned definition of a DT, it is being referred to as a DT within the utility. These DTs allow engineers to compare actual plant performance against design expectations, identify inefficiencies, and take corrective actions to improve output and reduce costs.

At the heart of the utility’s thermal performance monitoring program is the data validation and reconciliation (DVR) software. A key benefit of the DVR program is to identify and quantify performance gaps in the thermal cycle. The software calculates the expected output for each unit based on the current operating conditions and equipment health and compares this expected value to the actual gross output measured at the plant. Any deviation between the expected and actual output is flagged as a generation difference indicating a potential performance issue. The model calculates a series of “accounted MW deviations” that quantify the impact of various factors on the unit’s output. By identifying and addressing these efficiency losses, the utility can optimize the performance of its plants and recover valuable megawatts.

4.3 Deployment Challenges

4.3.1 Sensor Degradation and Unreliability of the Monitoring Infrastructure

The utility’s CBM program heavily relies on the reliability and quality of its monitoring infrastructure and sensors. The current system faces challenges in terms of generating a high number of false positives and negatives, which can account for up to 80% of the detected anomalies. This high rate of false alarms not only reduces confidence in the monitoring system but also places a burden on the team responsible for investigating and validating these anomalies, leading to an inefficient use of time and resources.

It is believed that the unreliability of plant sensors is the primary cause of erroneous data. Although it is thought that this unreliability is typically a result of aging infrastructure, the precise cause of this sensor and instrumentation unreliability is unclear to plant staff. The complexity of the monitoring infrastructure, which comprises a vast array of sensors, data acquisition devices, and network components, makes it challenging to effectively identify and address the sources and root causes of these false alarms. The lack of precise understanding of the cause of the unreliability makes it difficult to implement comprehensive health monitoring capabilities that could proactively detect and diagnose issues within the plant and implement the appropriate fixes.

4.3.2 Diagnostic Capability of Analytics and Anomaly Detection Software

While the utility has made significant investments in analytics and anomaly detection software to support its CBM program, the current diagnostic capabilities of these tools are limited. The software is effective at identifying deviations from normal operating conditions, but it struggles to accurately pinpoint the root causes of these anomalies. This limitation poses a significant challenge, as it requires plant personnel to invest time and effort in investigating and troubleshooting issues that may not be critical or may have already been addressed.

The current software relies on compressed data and simplified representations of plant conditions, which can omit valuable information necessary for an accurate diagnosis. Utility personnel noted that the anomaly detection software primarily uses traditional statistical methods rather than more advanced ML algorithms. This approach may limit the system's ability to identify complex equipment degradation patterns and estimate remaining useful life.

Another factor contributing to this challenge is the limited ability to leverage historical plant data and maintenance records effectively. This data may contain valuable insights into past equipment failures, maintenance activities, and operational conditions that could inform the development of more accurate diagnostic models. However, the sheer volume and variety of this data, along with potential quality and consistency issues, make it difficult to integrate and utilize effectively.

A related challenge in anomaly detection and ML models for predictive maintenance arises when the normal operating behavior of a machine changes over time. Existing models, trained on historical data representing previous "normal" operating conditions, may not be equipped to handle these changes. This can result in the model incorrectly flagging new patterns of operation as anomalies or failing to detect actual anomalies in the new operating regime. The lack of appropriate training data that accommodates these evolving "normal" conditions highlights the need for continuously updating and retraining models.

Overcoming these challenges requires significant investments in data management, data integration, and the development of advanced algorithms that can effectively learn from historical data to improve diagnostic accuracy.

4.3.3 Human Resource Concerns and Aging Workforce

The aging workforce and impending retirement of experienced subject matter experts pose significant challenges to the sustainability and effectiveness of the utility's CBM program. As a substantial portion of the M&D team approaches retirement age, the organization faces the risk of losing critical knowledge and expertise that has been accumulated over decades. This loss of expertise can lead to knowledge gaps, reduced diagnostic accuracy, and a diminished ability to effectively troubleshoot complex issues.

The transfer of knowledge from experienced experts to new team members is a complex and time-consuming process. Much of the expertise held by senior team members is gained through years of hands-on experience, making it difficult to document and convey through traditional training methods. The development of effective knowledge management and transfer strategies is critical to ensuring the continuity of the CBM program, but it requires significant investment in terms of time, resources, and organizational commitment.

4.3.4 Inconsistent Buy-In and Adoption from Plant Personnel

Securing buy-in and support from operators is a typical challenge for all NPP modernization initiatives, and this utility has navigated its share of such situations. Challenges faced during the roll out of various plant sensors highlight the importance of a detailed communication and change management plan, which engages personnel early and anticipates potential problems and likely concerns. In instances where operators perceived a lack of initial consultation, the consequences have been a reluctance to effectively advocate for the new technology and variations in its application.

The perception that new monitoring technologies may negatively impact job security is another factor contributing to a lack of buy-in. Some plant personnel may view the introduction of automated M&D systems as a threat to their roles and responsibilities, leading to a lack of cooperation and support for the implementation process. Overcoming these perceptions requires a concerted effort to communicate the benefits of the new technology and to actively involve end users in the planning and deployment process.

Resource constraints and competing priorities within the organization can also hinder the ability to dedicate sufficient time and effort to change management and user engagement activities. Implementing new monitoring technologies requires significant investment in terms of training, documentation, and support, which can strain already limited resources. Balancing these implementation needs with the day-to-day operational demands of the plant can be challenging, particularly when faced with competing priorities and budget constraints.

4.3.5 Absence of Real-Time, Automated Data Sharing Across Platforms

The lack of real-time, automated data sharing between the M&D center and plant operations staff limits the effectiveness of the utility's CBM program. Currently, the insights and recommendations generated by the M&D team are not integrated into the operational decision-making process, leading to potential delays in addressing emerging issues and optimizing plant performance.

One example of this challenge is the limited ability of the thermal performance anomaly detection system to directly inform control room operators of needed adjustments. While the system can identify potential performance issues, such as inefficiencies in heat exchangers or steam turbines, this information is not automatically communicated to the control room in a way that enables rapid operational changes. This disconnect between the monitoring system and plant operations can lead to missed opportunities for optimization and an increased risk of equipment degradation.

The absence of real-time data sharing also hinders the ability to make informed decisions about plant operations and maintenance activities. For example, the use of DVR models for measurement uncertainty recapture uprates has the potential to provide significant benefits in terms of increased plant efficiency and output. However, the lack of integration between these models and plant control systems limits the ability to fully realize these benefits. Operators may not have access to the latest insights from the DVR models, leading to suboptimal decision-making and potentially missed opportunities for performance improvement.

4.3.6 Accurately Monitoring and Reporting Transient Conditions

The utility's current anomaly detection software faces challenges in effectively monitoring and analyzing transient conditions. While the system can detect the downstream effects of these transients, such as changes in temperature, pressure, or vibration, it struggles to accurately identify and characterize the events themselves as transients. This limitation arises from the fact that the monitoring sensors are not directly integrated with the actions and decisions of plant operators, creating a disconnect between the data being collected and the operational context in which it occurs.

Transient conditions are inherently complex and dynamic, involving rapid changes in plant parameters and interactions between multiple systems and components. The ability to accurately monitor and analyze these conditions is critical for ensuring the safe and efficient operation of the plant, as well as for detecting potential equipment degradation or failure modes. However, the current monitoring system relies primarily on steady-state data and models, which may not adequately capture the nuances and complexities of transient behavior.

4.3.7 Integration with Work Management and Predictive Maintenance

The integration of condition monitoring data with work planning systems to enable predictive maintenance is an area where the utility faces significant challenges. While the M&D team generates valuable insights and recommendations based on the analysis of plant data, the process for incorporating this information into the work planning and maintenance scheduling process is not yet fully optimized. This lack of integration limits the ability to realize the full potential of predictive maintenance and can lead to inefficiencies in maintenance planning and execution.

One of the key challenges in this area is the limited ability to prioritize and schedule maintenance activities based on the insights generated by the M&D team. The current process relies heavily on manual intervention and decision-making, with maintenance planners and schedulers reviewing the recommendations generated by the team and determining how to incorporate them into the existing maintenance schedule. This manual process can be time-consuming and may not always result in the optimal prioritization of maintenance activities based on equipment condition and risk.

Another challenge is the lack of standardization and interoperability between the various data sources and systems involved in the maintenance planning process. Condition monitoring data, work order history, spare parts inventory, and other relevant information may be stored in disparate systems with limited integration, making it difficult to access and analyze this data in a holistic manner. This fragmentation of data can lead to incorrect decisions, as maintenance planners may not have access to the most up-to-date and accurate information about equipment condition and maintenance requirements.

4.4 INL Research Progress in the Technology Area

4.4.1 Overview of Research Efforts to Date

INL's research on condition monitoring and advancing DTs for NPPs has evolved from addressing challenges such as differentiating between equipment and sensor faults to examining both active systems (such as pumps and motors) and passive structures (like concrete and piping). In recent years, research has focused on making NPPs more efficient and economically viable by automating manual processes and leveraging increased computational power to analyze large volumes of data. As such, recent INL research has advanced predictive-based maintenance and CBM through the use of "multiphysics models" (Section 4.4.2.1) and ML-derived diagnostic models and transferable "federated learning" approaches (4.4.2.2). Recent work has also looked at solving problems associated with integrating advanced condition monitoring with human operators through improving explainability (4.4.2.3) and the visualization of condition monitoring findings (Section 4.4.2.4) as well as developing approaches to improve the efficiency and usefulness of deploying anomaly detection algorithms (4.4.2.5). For real-time applications of DTs in control rooms, INL is at the forefront of research on advancing autonomous control and self-adjustment capabilities (4.4.3.1). Other recent work in the DT and condition monitoring domain includes developing risk-informed asset management solutions (4.4.4.1), addressing the regulatory challenges of DTs for in-service testing (Section 4.4.4.2) and in-service inspections (Section 4.4.4.3), and developing the digital infrastructure (Section 4.4.4.4) necessary for effective DTs.

4.4.2 Equipment Monitoring and Predictive Maintenance

4.4.2.1 Hybrid Modeling of a Circulating Water Pump Motor

This initiative represents an important example of INL research that helped to develop the DT and condition monitoring concept for predictive maintenance applications in NPPs. It aimed to develop a comprehensive DT of the circulating water system (CWS) by combining deterministic and stochastic operation characteristics. The project's approach created a model of the circulating water pump motor, including the use of multiphysics software [17].

The hybrid modeling approach addressed limitations of purely data-driven methods by incorporating physics-based information related to plant asset structure and operation. This integration allows for a more comprehensive understanding of the system's behavior, potentially improving the efficacy of predictive maintenance strategies. The project demonstrated the ability to capture key operational characteristics, such as dominant vibration frequencies, while also revealing areas for further refinement through integrating a risk-informed approach.

4.4.2.2 Machine Learning and Economic Models to Enable Risk-Informed Condition-Based Maintenance of a Nuclear Plant Asset

Building upon the "hybrid modeling" report, this project advanced the development of a comprehensive DT of the CWS by incorporating predictive maintenance and risk-informed decision-making. While the "hybrid modeling" project combined deterministic and stochastic operation characteristics, this phase leveraged ML to create diagnostic models using diverse data sources like plant process data, work orders, and vibration data. These models aimed to detect potential degradation in the CWS and its motor, enabling condition-based monitoring and maintenance. NLP techniques were used to analyze work orders, providing insights into equipment reliability. Additionally, a three-state Markov chain economic model assessed the economic impact of shifting from time-based to condition-based predictive maintenance, demonstrating potential cost savings and operational benefits [18]. Integrating physics-based modeling, data-driven techniques, and economic considerations, this project showcased how a DT can optimize maintenance activities, improve asset reliability, and reduce operational costs in NPPs.

An important aspect of this project is the transferability and scalability of the developed models, so they could be transferred from one plant to another with minimal retraining, thereby reducing the effort required to deploy the models at scale (although some performance loss was observed due to differences in instrumentation between the two plants). The transferred model's performance could be significantly improved with minimal retraining using additional data from the new plant. Known as "federated learning," the idea behind this approach is to create a global model that captures the dynamics of multiple plants, making it easier to deploy at new locations without the need for extensive data collection and model development efforts [19].

4.4.2.3 Explainable Artificial Intelligence Technology for Predictive Maintenance

The effective utilization of more advanced condition monitoring approaches was limited by the operators' unease at using AI and ML [20]. The "Explainable Artificial Technology for Predictive Maintenance" project (or "app") aimed to address explainability and trustworthiness challenges for human operators when adopting AI and ML technologies for predictive maintenance. The project focused on improving the use of these technologies to advance their technical readiness and acceptability. The research presented solutions focusing on three key aspects, performance, explainability, and trustworthiness, of AI technologies. The project demonstrated the inherent trade-off between ML performance (accuracy) and explainability. Highly accurate methods like deep learning tend to be less explainable, while more explainable methods like decision trees may be less accurate. The trade-off was explored by considering techniques for developing training datasets and addressing data imbalance concerns [21].

A key outcome of the project was the development of a user-centric visualization application designed for maintenance and diagnostics personnel with limited ML expertise. This app presents ML model outputs along with explanations of how and why the model reached its conclusions, historical context of the data, and tools for users to verify results independently. The app was tested with conference attendees of varying ML experience levels and received positive feedback. The researchers emphasize a "trust but verify" approach, where the AI/ML tools augment rather than replace human decision-making. Overall, the project aims to increase the likelihood of NPPs adopting AI/ML technologies by making them more explainable, trustworthy and aligned with human-in-the-loop processes [21].

4.4.2.4 VIPER: Visual Insights for Predictive Maintenance Recommendation

INL researchers are working on a related initiative, VIPER (Visual Insights for Predictive Maintenance Recommendation). VIPER builds upon and extends the work done in the "explainability" project, improving the trust and adoption of AI/ML technologies in NPP maintenance. While the explainability app focused on making ML models more transparent and understandable to maintenance and diagnostics personnel, VIPER takes this concept further by creating a more comprehensive and interactive visual interface for predictive maintenance.

The VIPER project emphasizes the importance of the "human-in-the-loop" approach, where the ultimate decision-making responsibility lies with the plant personnel. To facilitate this, the visualization tool will incorporate explainability metrics, historical context, and the ability for users to explore and verify the AI/ML model's conclusions independently. The project also intends to address technical challenges and user readiness barriers to AI/ML adoption identified in previous work by actively engaging with subject matter experts, incorporating human factors engineering principles, and conducting user studies. VIPER integrates advanced features such as fault diagnosis and prognosis models, probabilistic analysis for maintenance decision support, and the incorporation of a large language model to enhance user interaction and provide context-specific explanations.

4.4.2.5 Advanced Remote Monitoring for Operational Readiness

ARMOR (Advanced Remote Monitoring for Operational Readiness) is an ongoing project advancing CBM techniques for the nuclear industry through developing automated and transferable anomaly detection models. It resulted in a tool called ALARM (Automated Latent Anomaly Recognition Method). A key innovation and benefit of ALARM is an automated sensor grouping algorithm that can efficiently sort through thousands of plant sensors and group them into optimal sets for training anomaly detection models, without requiring manual effort from subject matter experts. This allows anomaly detection to scale monitoring to an entire plant in an automated fashion. ALARM algorithms use historical plant data tailored to the sensor group, employing both unsupervised and semisupervised techniques, the latter using the limited anomaly labels that can be obtained at an NPP [22]. This tool can also isolate sensor failures from process issues and assist in investigating the cause of an issue and has been successfully demonstrated on an NPP feedwater system.

ALARM consists of modules for data quality checking, automatic signal grouping, transient operation, and anomaly localization [23]. Future research aims to improve model transferability between nuclear units, demonstrate long-term performance, and validate the semisupervised approach using actual corrective action reports, ultimately supporting predictive maintenance and fleetwide adoption of online monitoring.

4.4.3 DT Use for Reactor Operations and Control

4.4.3.1 AGN-201 Microreactor

INL researchers developed a DT for the AGN-201 reactor at Idaho State University, a small 5 watt research reactor serving as a real-world test bed for DT technology. The project aimed to demonstrate the ability to monitor reactor operation by combining live data with physics models and ML to understand behavior and detect anomalies. The DT was designed to flag off-normal conditions, such as experiment insertions into the core, by comparing expected and actual reactor performance. This was achieved through integrating live sensor data, ML algorithms for anomaly detection, and physics-based models, with the importance of the “digital thread” in connecting data from various sources being emphasized.

While the previous Microreactor Agile Non-Nuclear Experimental Test Bed project focused on a single heat pipe and demonstrated autonomous control capabilities, the AGN-201 project aimed to validate the DT concept on a complete, albeit small, nuclear reactor system. Future work in this area will build upon these successes to scale the technology to larger, more complex reactor systems, address challenges such as adapting to rapid changes in operating conditions, incorporate multiphysics modeling when insufficient data is available, and demonstrate the ability to optimize reactor performance and extend component lifetimes.

4.4.4 Asset Management, Regulatory Aspects, and Digital Engineering

4.4.4.1 Risk-Informed Asset Management

Another relevant area of research is a project initiative called “risk-informed asset management.” This research focuses on developing methods to assess and manage system health by integrating equipment reliability data, process models, and decision-making tools. The approach is structured into three main parts: data analytics, integration, and optimization.

The data analytics part involves preprocessing and analyzing both numerical and textual equipment reliability data. For numerical data, the team employs anomaly detection, diagnostic, and prognostic methods to identify degradation trends and faulty states. The textual data, such as work orders and issue reports, are processed using advanced NLP techniques to extract relevant knowledge. The INL team has developed a unique approach called “technical language processing” that focuses on extracting semantic information and context from the text, rather than just classification [24]. This enables researchers to identify entities (such as equipment names or component parts), assess health status, determine the timing and sequence of events, and understand the relationships between events mentioned in the text.

For the integration component, INL has developed a new approach to assess asset and system health using a margin-based methodology. This method is different from traditional reliability approaches that focus on failure probabilities. Instead, it measures how close an asset's current condition is to an unacceptable performance level or failure state [25]. This approach allows for integrating heterogeneous data (e.g., temperature, pressure, vibration) into a single health measure. The values are then propagated from the asset level to the system level using model-based system engineering (MBSE) models to identify critical assets and prioritize maintenance activities. The integration of a margin-based health assessment and MBSE models can support the development of more accurate and comprehensive DTs, enabling better condition monitoring and predictive maintenance strategies.

To support the optimization of maintenance activities and resource allocation, INL has developed a suite of tools, including LOGOS, SEIM (Safety and Economic Impacts Metamodel), and RAVEN. LOGOS is an open-source library that contains discrete optimization methods for scheduling maintenance tasks across multiple time windows, considering various constraints such as budget and resource availability. SEIM is a soon-to-be-available tool that assesses the safety and economic impacts of proposed operational changes or maintenance strategies. RAVEN is a complex tool that enables model optimization when input-output relationships are available, supporting the continuous improvement of asset management strategies. These tools, combined with the margin-based approach and MBSE models, provide a comprehensive framework for risk-informed decision-making in the nuclear industry.

4.4.4.2 Addressing Regulatory Aspects of DT Use: In-Service Testing of Reactor Coolant Pumps

The NRC is sponsoring an ongoing project that focuses on creating a use case to address the regulatory aspects of using ML and data analytics for reactor coolant pump (RCP) in-service testing requirements. The project aims to develop a DT-based approach for the condition monitoring of RCPs, which are critical safety-related components in NPPs. By focusing on a safety system, the project ensures that the developed approach aligns with the NRC's primary concern of maintaining plant safety. The value of this project lies in its potential to provide a risk-informed, performance-based approach for RCP condition monitoring, helping NRC staff prepare for future scenarios where licensees may propose using DT technologies for RCP in-service testing.

The project is currently developing the RCP use case from a regulatory standpoint, exploring the integration of a graded risk approach to connect the RCP health determination with its potential impact on plant safety, such as core damage frequency. This risk-informed approach would allow for a safety determination based on the evolving risk profile of the RCP over time, supporting regulatory decision-making and enhancing plant safety. The findings and insights will inform future research and regulatory guidance on the application of DT technologies for CBM in NPPs. Additionally, the project will pave the way for the development of similar approaches for other critical components and systems in both existing and advanced reactors.

4.4.4.3 Reliability and Integrity Management Based In-Service Inspection

A related project is the Reliability and Integrity Management (RIM) based In-Service Inspection (ISI) project, which aims to develop a new approach for conducting ISIs in NPPs. The project focuses on transitioning from the traditional periodic ISI to a more efficient and effective RIM-based ISI approach, which aligns with the principles of DT technology and its potential application in condition-based monitoring. Although the RIM-based ISI project does not explicitly mention DTs, their potential role is significant. The RIM-based ISI project's focus on passive component monitoring aligns with DT principles. The project is currently developing its methodology, aiming to transition nuclear plants from periodic inspections to a RIM-based ISI approach. Future research and pilot projects will validate this methodology, potentially leading to collaborations with reactor designers and plant operators.

4.4.4.4 Digital Infrastructure and Digital Engineering

An important part of DT research at INL is in the realm of digital engineering, particularly in the areas of MBSE (as referenced in Section 4.4.4.1) and digital threads. INL's work on creating virtual representations of systems using MBSE, which involves capturing requirements, system functions, and architecture in software models, can serve as early-stage DTs.

The digital thread is a key concept in INL's DT research and connects data and models across the system lifecycle, allowing for seamless information exchange between design, construction, and operation phases of DTs. An important product INL is working on is their open-source digital thread tool DeepLynx, which is designed to address challenges related to real-time data exchange and integration with various modeling tools. Enhancing DeepLynx's capabilities will facilitate the deployment of DTs and condition monitoring solutions across multiple industries, promoting better communication and collaboration among stakeholders.

4.5 Potential Future Research Initiatives

4.5.1 Research to Mitigate Sensor Degradation and Unreliable Monitoring Infrastructure

A critical area for future research is the development of strategies to mitigate sensor degradation and improve the reliability of monitoring infrastructure. The effectiveness of DTs and condition monitoring systems heavily relies on the quality and consistency of the data collected by sensors and other monitoring devices. As discussed in Section 4.3.1, the unreliability of infrastructure and potentially harsh operating conditions in NPPs means that sensor drift, calibration issues, and data quality problems are common and are heavily impacting the accuracy of anomaly detection and diagnostic capabilities. Future research could focus on developing more robust and resilient sensor technologies or testing various systems and sensors in a typical NPP environment. This could help NPPs maintain the accuracy, reliability, and health of these components over extended periods in challenging environments. Additionally, research into advanced data validation, reconciliation, and quality assurance techniques could help identify and correct sensor data issues in real time, ensuring DT models and condition monitoring algorithms are working with the most accurate and up-to-date information possible.

4.5.2 Digital Twin and AI Explainability and Integration with Human Operators

Demonstrating the value of existing LWRS research in this area, discussions with the utility have demonstrated the importance of future research that ensures the explainability of AI-driven DTs and condition monitoring systems. Encouraging human operators to trust and act upon the insights generated by these systems requires providing clear, understandable explanations of how the underlying models and algorithms arrive at their conclusions. Future research could focus on developing advanced explainable AI techniques that can provide intuitive visualizations, natural language explanations, and interactive interfaces that allow human operators to explore and validate the reasoning behind specific recommendations or alerts. Additionally, research into human-machine interaction and collaborative decision-making that optimizes the integration of DT insights into existing operational workflows will help to improve the ability of human operators to effectively leverage these tools to improve plant performance and safety. This may involve developing new user interface designs, decision support systems, and training programs that help operators understand and utilize the capabilities of DTs and condition monitoring systems in their day-to-day work.

4.5.3 Research to Improve the Diagnostic Capability of Anomaly Detection Programs

As discussed in Section 4.3.2, improving the diagnostic capabilities of anomaly detection programs is an essential focus area for future research. While existing systems are effective at identifying deviations from normal operating conditions, they often struggle to pinpoint the root causes of these anomalies accurately. This limitation can lead to false alarms, unnecessary maintenance interventions, and reduced trust in the system among plant personnel.

Continuing research to improve diagnostic models that leverage a combination of physics-based models, ML techniques, and historical failure data to accurately identify the underlying causes of anomalies is undoubtedly beneficial. This may involve integrating additional data sources, such as maintenance records, operator logs, and design specifications, to provide a more comprehensive view of plant operations and equipment health. By enhancing the diagnostic capabilities of anomaly detection programs, future research can help plant personnel make more informed decisions about maintenance interventions, reducing downtime and improving overall plant reliability.

4.5.4 Effective Training to Overcome Shortage of Data Analysis Personnel

A final potential area for future research is developing effective programs to address the shortage of skilled operators and analysts who can manage the growing complexity of condition monitoring systems. As the deployment of DTs and condition monitoring systems continues to expand, there is a growing need for experts who can interpret and act upon the vast amounts of data generated by these systems. As discussions with the utility highlighted, high-quality personnel are dropping out of the workforce and not being replaced. Future research could focus on developing innovative training approaches that combine traditional classroom instruction with hands-on experience, simulations, and mentorship programs. These programs should aim to rapidly upskill new hires and existing personnel, while also promoting knowledge transfer from experienced experts to the next generation of data analysts. Additionally, research could explore the use of AI-assisted tools and automation to augment human expertise and reduce the burden on individual analysts, enabling them to focus on higher-level tasks and decision-making.

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