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Automation of Data Collection Methods for Online Monitoring of Nuclear Power Plants

Ahmad Y Al Rashdan, Shawn W St Germain

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ABSTRACT

The workforce cost of operations and maintenance (O&M) in the United States nuclear power industry is mostly attributed to manual activities supplying information to a human decision-making process. Several manually-collected labor-intensive processes generate information that is not typically used beyond the intended target for collecting that information. The information is therefore expensive to collect, yet of limited use. This especially applies to surveillance activities and preventive maintenance, which represent most of the plant workforce activities.

The industry has recognized the benefits of both reducing labor-intensive tasks by automating them and increasing the fidelity and uses of the data collected to enable advanced remote monitoring using data-driven decision making for O&M activities. These data-driven methods could include capabilities from performance trending to machine learning and advanced forms of artificial intelligence. This shift in O&M strategy results in significant cost savings, because it reduces labor requirements by automating the data-collection process and reduces the frequency of activities by using an on-need model. The frequency reduction results in additional cost savings by lowering labor and materials demand.

This specific effort focuses on automation of monitoring data-collection processes. It is one in a series of efforts planned by the Department of Energy (DOE) Light-water Reactor Sustainability (LWRS) program to target multiple elements in migrating current O&M activities to a data-driven approach. These elements are data collection, data analytics, data management, visualization, value analysis, and change enablement. This effort will focus exclusively on data collection while the other five elements are explicitly researched in multiple ongoing efforts, or planned for future efforts. Out-of-the-box thinking was followed in this effort, which assumed no constraints from the other five elements.

The effort identified fifteen data sources and associated collection methods in nuclear power plants that could be automated for an integrated data platform that enables comprehensive and informed decision making. Three collection states are identified for each data source. The base state describes how data is typically collected in nuclear power plants today. This represents the least capable spectrum of data-collection methods. The modern state of data collection reflects a state achievable with the currently available technology, or the recognized best practices currently in place at some nuclear power plants or related industries. State of the art (SoA) represents a future state of the data collection process, using future and emerging technologies resulting from research and development (R&D). This will provide guidance for the industry and research community on potential technologies and methods to advance current data collection to both the modern state and SoA. Identification of the modern state is directed towards industry use while SoA aims to inform the R&D community, including the industry R&D organizations.

This effort found a huge potential for data-collection automation and data fidelity improvements by evolving current industry data collection to both the modern state and SoA. The majority of processes analyzed were found to be manual labor-intensive methods that fell into the base state. As a result, the

modern state often targets a reduction in manual logging efforts by using electronic and semi-intelligent means, or complementing the work with sensors and technologies (mobile and fixed) that can reduce labor demand. The SoA often required the application of advanced methods of data mining and machine learning to extract data from text or imagery forms, increasing the time and spatial coverage of sensors, data integration for creating new sources of useful data, enabling the use of sophisticated mobile and autonomous technologies to remotely capture data, and using intelligent equipment or instruments that eliminates the need for human activities.

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The authors would also like to thank and acknowledge Atos for sharing their experience in migration of manual processes to automated processes for nuclear and non-nuclear power industries.

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ACRONYMS

COA	course of action
DCS	distributed control system
DOE	Department of Energy
EAM	Enterprise Asset Management
EAMS	Enterprise Asset Management System.
EPPM	Enterprise Project Management system
I&C	instruments and control
IR	infrared
LWRS	Light-water Reactor Sustainability (program)
MEMS	microelectromechanical sensors
NASA	National Aeronautics and Space Administration
O&M	operation and maintenance
OCR	optical character recognition
R&D	research and development
RFID	radio-frequency identification
SME	subject-matter expert
VDE	virtual decision environments

1. INTRODUCTION

In 2016, the operating and fuel cost of a 1000 MWe plant was estimated to fall between $200M and $300M (NEI, 2017a). Out of this cost, the operation and maintenance (O&M) cost is around twice the cost of fuel (World Nuclear Association 2017). One key element of O&M cost is workforce cost. This demonstrate that the nuclear power industry relies heavily on labor-intensive activities. A large portion of this workforce cost is associated with core O&M work activities. The remaining cost is associated with support organizations such as security, management and administration, procurement, and radiation protection.

Operations activities in the United States nuclear power industry can be categorized into two major types of activities:

Surveillance: activities performed on a periodic or as-needed basis to comply with technical specifications requirements (e.g., NRC 2011). These activities are safety related and are performed by operations, as the license holder, but are delegated to maintenance in some cases. The nature of surveillance activities can be a simple check, inspection, measurement, reading acquisition, testing, or analysis.

Non-surveillance: activities performed on a periodic or as-needed basis and are not required for complying with the license and are, therefore, not safety related. The nature of these activities is similar to surveillance activities, but also includes activities to change the plant configuration and support maintenance work.

Maintenance activities in the United States nuclear power industry can be categorized into:

Preventive maintenance: activities performed on a periodic basis to prevent the condition of the equipment from degrading at a rate that is faster than the projected safe rate of degradation due to aging.

Corrective maintenance: activities performed to restore the condition of an equipment item to a running state after a failure has occurred.

While it is desirable to reduce the frequency of preventive maintenance, this could result in an increase of corrective maintenance activities, which are usually more expensive and time consuming to perform. This implies the need to move to another type of maintenance, known as predictive maintenance (Sullivan et al. 2010).

Predictive maintenance: activities performed on a variable time basis and dependent on the predicted condition of the equipment, therefore optimizing the schedule of the activities to an on-need approach.

Predictive maintenance can be classified as a type of preventive maintenance if the definition of preventive maintenance were expanded to include periodic and on-demand activities (Tulay and Rogers 2007). The advantage of predictive maintenance is that it optimizes the frequency of maintenance activity with respect to the individual item of equipment. Another type of maintenance identified in Sullivan et al. (2010) is proactive maintenance, defined as replacing equipment with another to eliminate root-cause failures.

Predictive maintenance treats all plants equipment and maintenance activities equally. If equipment importance and benefit vs cost and risk of a maintenance activity is taken into consideration, value-based maintenance (NEI 2017b), also referred to as reliability-centered maintenance (Sullivan et al. 2010 and NASA 2008), is followed.

Value-based maintenance: activities performed on a variable- or fixed-time basis, depending on the condition of the equipment, its importance and risk impact to the plant, and the value added by performing the maintenance. For example, value based maintenance recognizes that it might be cost effective to run unimportant equipment to failure.

NEI (2017c) estimated that at least 80% of work historically performed was surveillance activities and preventive maintenance. The DOE LWRS realized the need to automate both O&M activities and, accordingly, has launched multiple research efforts to optimally reduce the frequency of O&M to effect an overall cost saving to the plant and to replace labor-intensive activities process with automated methods to reduce workforce costs. This shapes the vision of an automated plant where many O&M activities are performed by dedicated sensors or automated processes that feed into a decision-making platform that analyzes the data and risk models to present the optimal recommended actions. The ultimate outcome of automating O&M activities is reduction in detection and diagnosis time, streamlined actions, improved long-term planning, maximized outage utilization, optimized periodic O&M activities, reduced management costs, and increased plant and equipment insight. This reduces labor and materials cost, improves plant and equipment reliability, and lowers downtime or service interruption.

To migrate O&M activities to value and data-based activities, multiple elements of current O&M activities need to migrate. These are:

Data collection: measurement acquisition methods to convert a plant to a data form that is easily transferable to a centralized location for processing.

Data management: data architecture and data communication methods to transfer sensor data from the plant to a centralized location for processing, the infrastructure needed for long-term data analysis, storage, and retrieval, and the means to protect the information during the process (cyber security).

Data analytics: simple trending, statistical analysis, or intelligent methods to analyze collected data and make informed decision on plant performance or equipment condition and required actions. The outcome of the analytics can be fully autonomous decisions or reformed data that can be visually perceived by a human who makes decisions.

Visualization: human-factors methods to optimize the human perception of highly dimensional data to make a decision on plant performance or equipment condition and actions needed. Visualization methods are useful for activities where human-assisted decision making is important and the amount of collected data is large.

Value: methods to achieve the highest benefit and cost savings, and lowest deployment cost and risk impact from automation of the O&M activities.

Change: methods to enable successful adoption of process and organizational changes. This includes ensuring regulation compliance and resource availability (staff, training, spare parts, etc.), supporting infrastructure availability, ensuring feasibility (power, fitness, environment tolerance, facilities), and enabling cultural change.

Each O&M migration element must be considered independently and in the context of the overall process. This report presents a recommended approach for nuclear plant migration to data-driven monitoring from the base state, which represents plants that have almost no automation of O&M processes, to a future state in 5 to 10 years. The plants would apply a strategy similar to that shown in Figure 1 for every important activity or equipment group. It will assist in defining milestone states to allow each plant to identify its current state (dashed curve at t_0), specify future states to be achieved after a period of time ($t_0+\Delta t$), and develop a plan to achieve the new state. The base state is how data is typically collected in nuclear power plants today. This represents the least capable state within the spectrum of methods. The modern state reflects a state achievable with currently available technology or recognized best practices currently in place at some nuclear power plants or related industries. An SoA capability represents a future state using future technologies or the applications of technologies as used in more-advanced industries or emerging through research and development (R&D). Naturally these definitions are time dependent. Today's SoA will likely be the modern state five years from now. Therefore, the intent of this report is to provide a guidance from the perspective of the industry and technologies as they exist today. This report focuses on the *data collection* activities of Figure 1 that are performed as part of the O&M activities in the nuclear industry, and the path to automate these activities.

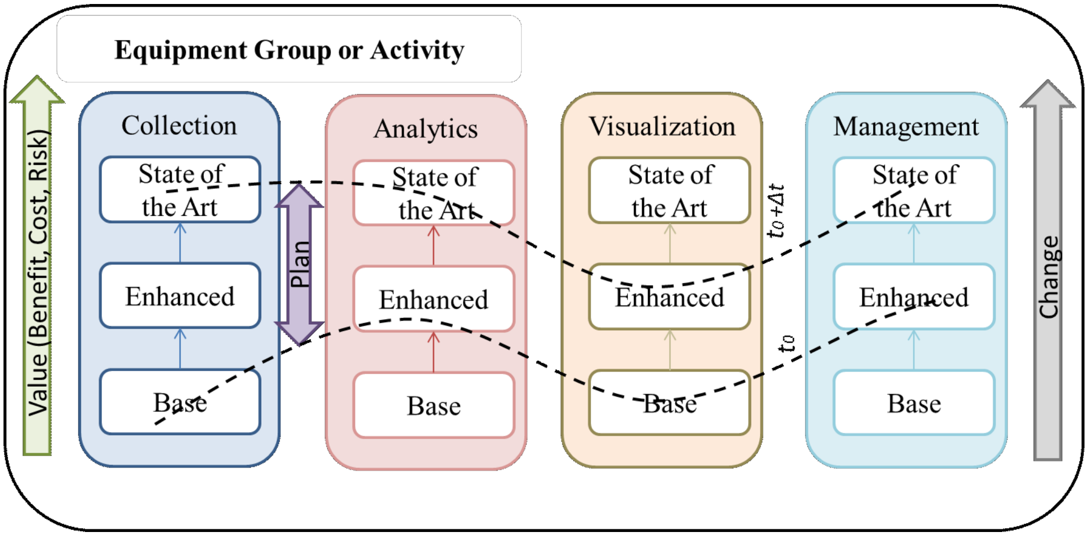

Figure 1. Equipment or activity-based strategy development.

2. METHODS OF DATA COLLECTION

The data at a nuclear power plant are typically available in dedicated paper or electronic data forms, but not necessarily easily available outside of their native use. The following sections outline typical data sources based on data use. As described in Figure 1, the sections will list three states for each data source. The states describe a current method for collecting the data, an existing, but more efficient method of collecting data that has not yet been implemented, and a new, but not yet developed method for collecting data. The ultimate aim of both modern state and SoA migrations is to automate data collection to reduce labor demand and improve data fidelity, enabling a machine to make an informed decision on plant performance and equipment conditions.

2.1 Process Instruments and Control

Process instruments and control (I&C) data include data that are logged into the plant computer and data that are available in the main or remote/local control room, but not on the plant computer. A plant computer system consists of a hub where process information is collected and stored. It collects common process parameters such as temperature, flow, pressure, flow rate, liquid level, and equipment states. It often relies on process and instrumentation diagram-based displays to show the process. Due to their less-frequent use, plant computer data have a higher uncertainty, which causes control-room operators to rely primarily on manually logging data from control-room indicators and controls, either on paper or using electronic logging systems.

2.1.1 Base State

Most of the control rooms in nuclear power plants currently use analog-boards and analog instrumentation. Most controls in an analog control room are manually logged. This includes switches, breakers, knobs, buttons, handles, and potentiometers. Remote or field controls include levers, handles (for valves), switches, and breakers. Control room indicators are also manually logged, even though many of the indicators are recorded into the plant computer. Remote or field indicators that are not available in the control room are also manually logged by operators. This includes gauges, lights, recorders, and descriptor labels.

The plant computer is connected through the input/out panels of a plant. It stores data for various plant systems and processes. This data collection process does not require manual activities aside from computer and data maintenance, and the only cost of this process arises from the cost of upgrading or maintaining the plant computer. The plant computer is primarily used for trending process data when needed. Almost all data coming into the plant computer are from analog devices.

2.1.2 Modern State

In the control room, evolution to distributed control systems (DCS) replaces manual logging of indicators and controls with an electronic, integrated, historical-trending capability in addition to an alarm- and event-logging system. The role of the plant computer would be integrated into the plant DCS. Because plants will still rely, to various extents, on different systems to supervise or control specific parts of the plants—e.g., a dedicated turbine control system or a programmable logic controls to control a specific process or equipment—the DCS would interface with process data in various form, including interfacing with common power-industry systems. These might include system-specific controllers and recorders. The interface would use standard communication protocols and methods, such as Modbus (Schneider 2006) or open-platform communication (Rinaldi 2016) to streamline data collection and enable process-data integration to occur.

For fields I&C, retrofit devices can be attached to analog field indicators to digitize and process images of the gauge reading (Sim 2013) or to track actions by retrofitting a sensor to track movement in the handle of a manual valve (Agarwal et al. 2018a). Direct replacement of local analog instruments with wireless transmitters is also possible. The DCS should be able to connect and log wireless-instruments' data. Wireless instruments are needed if additional monitoring instruments are deemed necessary and cable infrastructure does not exist. These wireless-enabled technologies would be battery-operated, use a power source when it exists in proximity to the instrument, or use power-harvesting technologies that are available (e.g., Perpetua Power 2015) and the performance of which is being advanced through research (Agarwal et al. 2018b). With the introduction of wireless networks, such as Wi-Fi, distributed antenna systems (EPRI 2015), and associated wireless-enabled instruments, an interface could be used (e.g., OMEGA 2011) to convert the data from the instrument's form into a form that can be used.

2.1.3 State of the Art

A dedicated platform would integrate and analyze data from multiple sources described in this report. The platform could be part of a dedicated monitoring center that has responsibilities for one or multiple plants. The plant would add environment and indirect-measurement instruments to more typical process I&Cs to provide additional process information not currently acquired. The added instruments could capture the visual, infrared (IR), acoustic, and electromagnetic spectra of the plant. In addition to these instruments, it is possible to augment the plant with assistive technologies, such as visual-data acquisition technologies and image-processing methods to automate logging of data and to track actions. The monitoring center would integrate this multi-source and multi-spectrum data with traditional process data for the monitoring center watch staff, as well as single-spectrum plant-wide monitoring for individual spectrum staff. For instance, individual operators could monitor a single view of the entire plant based on a specified spectrum (e.g., IR) and would manage the sensors in the plant that operate in that spectrum. The watch staff would be able to select a specific spectrum or an integrated view that fuses multiple spectra. Advanced machine-learning tools will correlate these additional data with currently collected process data to predict or diagnose even more accurately system or component failures.

2.2 Maintenance

While maintenance activities include adjustments, cleaning, lubrication, and parts replacement, the data collected are mainly focused on the use of inspection instruments to collect data related to the performance of plant components. These instruments capture time- and space-dependent measurements of a certain physical phenomenon to provide insight into equipment condition for diagnostic and prognostic purposes.

2.2.1 Base State

The base-state process relies on manually installing a sensor to capture data on a local device. These sensors or devices are periodically and temporarily installed on equipment of interest. The data are transferred manually to a subject-matter expert (SME) to study the measurement and evaluate it with respect to the equipment history and conditions. Any change of the inspection frequency requires an extensive review by a dedicated committee. Examples of inspection types of measurement are listed in Table 1 and include:

- Vibration sensing using accelerometers or piezoelectric sensors
- Thermography for abnormal heated spots
- Ultrasonic for subsurface inspection
- Resistance for materials integrity
- Oil analysis for viscosity and impurities measurement
- Radiography for pipe thickness
- Visual inspections of cables and concrete
- Electric current measurement of equipment (e.g., motor circuit evaluation or batteries)
- Physical parameters such as valve clearance.

The measurements performed above could require certain equipment conditions to be present. For example, a pump may need to be running to capture vibration information.

2.2.2 Modern State

Migration to a continuous measurement is the key aspect of the modern state. This implies refinement of processes to include detailed recording of sensor data rather than a pass\fail methodology. Raw data are stored and fed into predictive models. To achieve this, fixed sensors would be installed and connected through a wired connection if cabling infrastructure exists, through wireless connection if wireless infrastructure exists instead, or enabled to continuously store data in onboard memory to be periodically transferred into an external storage medium. For the wireless or onboard memory scenarios, the sensor data could be downloaded, either manually or automatically, using technologies such as Wi-Fi Direct to send data to passing craft with Wi-Fi Direct enabled devices.

A list of the modern replacement options are listed in Table 1. For some equipment, it is necessary to identify hot spots to use to provide the best predicted insight (e.g., vibration of a turbine) while others have single or fixed points of measurement (e.g., electrical current of a pump). The methods and applications of every process of replacement will be targeted in future efforts. A list of sensors uses for each type of equipment and expanded discussion on maintenance automation can be found in several existing documents (NASA 2008, Sullivan et al. 2010, and Kerr and Taylor 2018).

Table 1. Main inspection methods in the base, modern, and SoA states.

Data-collection Method	Example Application	Base (Periodic and Local)	Modern (Continuous Time)	SoA (Continuous Space)
Oil analysis	Transformers	Acquiring samples from dedicated openings	Permanently installed local sensors	Suite of permanently installed sensors on equipment to provide broader insight Optimized sensors placement (when applicable) to cover the whole space of equipment Coupled with other plant information
Current	Pumps	Measuring current using a portable meter (Warren &Cavi 2009)		
Voltage	Batteries	Measuring voltage using a voltmeter (Johnson 2002)		
Resistance	Breakers	Placing instrument on specific location		
Thermography (visual)	Heat Exchangers	Taking pictures of equipment	Cameras installed and facing area of interest	
Optical (Visual)	Cables, Concrete, and civil structures	Sample selection based on hot spot (Alonso et al. 2012)		
Vibration sensing	Turbines	Placing prop on specific locations and record maximum	Permanently installed sensors at hot spots	
Ultrasonic	Concrete	Placing prop on specific locations (Naus 2009)		
Electrochemical	Civil structures	Placing prop on specific locations (Naus 2009)		
Radiography	Pipes	Placing instrument on specific location		

2.2.3 State of the Art

The SoA capability would replace individual sensors with a suite of sensors that provide multiple forms of measurement to enable high-confidence decision making. For example, instead of measuring pump vibration and using it independently as the decision-making data source, other sensors, such as temperature, acoustic, thermography, and electromagnetic measurements can be combined to evaluate equipment performance. Future maintenance-activity sensors would couple equipment data with other equipment and plant data to provide additional benefit from the existing sensor data in the plant. For example, the vibration of one pump might be due to a problem in an upstream or downstream process that is associated with another equipment item, such as a generator in proximity, and the only means to isolate the two causes is to use the holistic data view of the process and plant. Future maintenance measurements enable high-fidelity spatial coverage of equipment. For example, instead of sampling pipe-wall thickness at specific locations, it is envisioned that future sensor locations will be optimized to provide a continuous measurement of wall thickness between the sensors. It is also possible to follow a proactive approach, to replace current equipment with equipment that provides both real-time condition monitoring and a complete picture of equipment health.

2.3 Equipment Performance Testing

Validation of equipment performance is often performed by conducting periodic test runs that result in the actuation of equipment to confirm it function as planned. These test runs are controlled by periodically scheduled surveillance procedures. The frequency of these tests is typically set by the plant's technical specifications. These surveillances create data that are important for monitoring the health of these components. Equipment performance testing may also be performed as a post-maintenance task to ensure the maintenance was performed correctly.

2.3.1 Base State

The plant is required by technical specifications to periodically test equipment and manually log its performance in dedicated logs. Testing of equipment such as valves, pumps, and generators is typically performed using dedicated surveillance test procedures. These procedures collect performance data and ensure the equipment meets the technical-specification performance requirements. The test results (e.g., whether the pump in question passed or failed) are marked down. The logs are stored as part of the compliance documents. In instances where the equipment does not meet its required performance metrics, corrective-action work orders may need to be created to troubleshoot and repair the equipment. For example, in the base state, if a pump trips unexpectedly during testing, a vibration sensor might be attached to the pump to determine whether vibration is the cause.

2.3.2 Modern State

Equipment test results are logged automatically by wired or wireless-enabled dedicated sensors—e.g., an acoustic sensor to indicate a pump is running or a downstream flow sensor for valve strokes test—that transmit the test results. The choice to use sensors instead of human operators depends on the frequency of surveillances. Some equipment will have permanent sensors attached that track the measurements in specified formats and feed data back into a database (Agarwal et al. 2018a). Others will be manually logged via a dedicated electronic tool that stores the test data. The raw data are collected and stored along with information about the performed action. These data can also be used with other process-sensor data to explain abnormalities that might occur later as part of equipment-failure-predictive algorithms.

2.3.3 State of the Art

In the SoA, the actuation process would be automated, along with the sensing process described in the modern state. Actuation automation can be performed by retrofitting the equipment with attachable actuators that can be remotely activated and logged along with the sensors to confirm the test success or failure, or by replacing manual actuators with remotely operated and logged actuators that are commercially available. The actuation and logging process can also be performed by mobile actuators such as drones or robots that are equipped with an arm or tool to perform the task.

To provide an additional level of data to monitor the success or failure of the test, it is possible use the environment sensors in correlation with the plant-process sensors and equipment-specific sensors (as described in Sections 2.1 and 2.2). For equipment items that are not tested frequently, mobile sensing units can be temporarily installed at a certain location, on a portable holder, or drone and robot to monitor the tests or perform supplemental test tasks such as monitoring the area for fire or radiation measurement.

2.4 Calibration

Instrument calibration is a labor intensive form of equipment testing that is performed in the field or in a lab environment. Unlike most equipment performance testing, calibration is usually performed by I&C maintenance staff. The frequency of calibration may be vendor-determined or dictated by the plant's technical specifications for certain equipment. However, a safety multiplier is usually applied by plant staff to increase the calibration frequency beyond the vendor recommendation. Plants are required to comply with all vendor recommendations for the frequency of calibration, and in some instances, the safety multipliers are also regulated.

2.4.1 Base State

The calibration process is performed manually, oftentimes by disassembling the calibrated equipment, inserting external physical sources or a simulated signal, and then logging device performance. This process can be applied to equipment such as process transmitters, gauges, and switches. The calibration is performed in the field or at a facility in the plant. The data are logged on dedicated logs and procedures.

2.4.2 Modern State

Smart instruments can be installed to replace current instruments. These devices can, to varying degrees, provide continuous data on their calibration status. They have a smart fault-detection indicator that supplies information from analog current and process measurements, and develop that information into other actionable intelligence. The data intelligence results in fewer service interruptions, as well as the resulting reduction in labor costs. This allows a proactive determination of impending instrument issues using data prior to outright failure, as with classical instruments.

2.4.3 State of the Art

To progress beyond diagnosing calibration issues with smart instruments, the next level of capability would be to replace manually calibrated equipment with self-calibrating equipment. The equipment efficiently uses onboard memory to determine how multiple coefficients change in regard to the primary measurement. An error map can then be created mathematically to allow a sensor to identify when it is out of calibration. Elimination of undetected calibration drift, as well as the reduction of frequent calibrations, are significant benefits. The sensor can store hundreds of calibrations for verification purposes and generate auditable calibration certificates using asset management software. The sensor literally monitors itself and sends warnings of failure, drift, or other measurement errors.

2.5 Operator Rounds

Observant plant staff, touring plant spaces, is another important data source that contributes to diagnosis and prognosis. Operator rounds are set to comply with certain technical-specification surveillance requirements and create data that are both required by the plant's operating license, but also potentially useful for trending and correlating with other data. Whether accidently or intentionally observed, the human element acts as a mobile sensor in the plant. Predefined routes are established for equipment operator rounds, security rounds, fire watch rounds. Ad hoc inspections by various plant staff cover nearly every physically accessible space in the power plant.

2.5.1 Base State

Operators log the information on a paper form or with electronic tools, and then transfer that information into a dedicated database that is used to demonstrate that the plant is within normal limits. The process is manual and requires the operators to walk throughout the plant in order to capture the information.

2.5.2 Modern State

All operator log entries are accomplished using wireless mobile tablets to capture surveillance observations and to access checklists and reference data. The information captured is supplemented by video and still-picture capture using the mobile tablet. This provides a visual context to the data points collected. These structured and unstructured data are then immediately available for additional analysis and parsing for critical operational data.

For areas that require more frequent rounds, a fixed wireless unit with a suite of the mentioned sensors can be installed in optimal locations to eliminate the need for operator rounds. Environment sensors can be used in correlation with the plant-process sensors and equipment-specific sensors (as described in the Sections 2.1and 2.2) to reduce the need for operator rounds. For temporary round locations, mobile sensing units, equipped with sensors and other data collection methods, such as optical and thermal cameras, can be mounted at a certain location or on a portable holder to monitor a specific area.

2.5.3 State of the Art

To eliminate the need for operator rounds, drones or moving robots would have preconfigured or on-demand routes of movement, stopping, sensing, and logging. Drones or robots would also monitor spaces that are not accessible by humans, such as areas with high radiation exposure or high temperatures during plant operations. The drones or robots would be equipped with multispectral continuous environment sensors (visible spectrum, IR-thermal, acoustics including outside of human range, and electromagnetic field) along with application-specific sensors, such as air chemical sensors for fire detection or gas- and liquid-leak detectors. They could also be equipped with props to conduct vibration measurements or sense surface temperature along with location-identification technologies such as GPS, Wi-Fi triangulation, radio-frequency identification (RFID), or beacons (Al Rashdan et al 2017). Baseline profiles would be established for all equipment types for each of the acquired spectra, with alerts established for out-of-limit alarms. The drones can be equipped with wireless communication modules or transfer their captured data when they return to the drone charging station. These drone inspections will, of course, require an additional layer of intelligence in order to optimize their inspection capability. For example, image processing methods may be needed in addition to IR-thermal sensors to detect fire during fire watches.

Microelectromechanical sensors (MEMS) commonly referred to as smart dust (Ilyas and Mahgoub, 2016) could also be used. These MEMS are millimeter-sized self-contained sensors that can detect a variety of conditions from light to vibrations. They possess simple onboard computational capability with an autonomous power supply, and transfer data wirelessly.

2.6 Radiation Protection

One unique data source in nuclear power plants is radiation levels and contamination. Though currently used for regulatory compliance and safety purpose, radiation and contamination monitoring provides another source of data that could indicate plant performance or equipment condition. Radiation data can be used to detect steam or water leakage, even at a level that is hardly detectable by the current approach. This data can, for example, benefit the thermal performance analysis of the plant.

2.6.1 Base State

Radiation data are collected by both fixed and mobile dosimeters and periodic and on-demand manual contamination surveys. Mobile dosimeter data are acquired periodically and logged into a dedicated system that is primarily used by radiation-control staff for compliance and safety verification. Contamination surveys are performed on a periodic and on-need basis as well, and logged into dedicated databases.

2.6.2 Modern State

The mobile dosimeters are coupled with the plant wireless network or mobile devices carried by the staff to stream real-time radiation data into a central dedicated database. The data will be timestamped, and the location will be logged (using the location-identification technologies described in the previous section) to enable the coupling of radiation with other plant-process data. Contamination surveys are performed by wireless-enabled survey coupon analyzers or are manually logged into portable tools that log the survey results, location, and a timestamp and transmit data in real-time through a wireless network or when in range of a wireless access point.

2.6.3 State of the Art

The plant would be entirely covered by fixed radiation dosimeters that feed into radiation monitoring systems. Each dosimeter would be identified with a location and would continuously stream (wired or wirelessly) the radiation data into a central tool that uses radiation data as another indicator for equipment performance.

To increase the collection frequency of contamination data, tasks conducted by radiation-control staff could be augmented by drones or robots conducting inspection rounds and collecting contamination samples from pre-defined locations within the plant. As described earlier, drones and robots can be equipped with wireless communication modules or transfer their captured data when they return into the charging station. They can use coupons to collect the surveys, or alternately be equipped with survey meters to determine and log the contamination level.

2.7 Security

Security information is collected for the purpose of tracking personnel and enabling physical protection. Security information contains primarily data related to personnel access to certain locations in the plant. This can be coupled with plant information to provide additional insight. For example, if a valve condition is changed when a compartment was not accessed, this might indicate failure in a valve limit switch.

2.7.1 Base State

Cameras, electronic or mechanical locks, and tampering sensors or seals are the main means of security used in the plant. Access to vital areas is controlled by locked doors monitored by access-control computers. Electronic access transactions are logged and stored in a dedicated database. Manual locks are accessed by keys that are checked out only after a log is updated. A protected zone can be controlled via badge or key access, video monitoring, and physical inspection and escort by security personnel. The video is recorded and kept for a period of time. The electronic or paper logs and video recording are currently used only for security visual inspection and auditing. Seals, whether electronic or just mechanical, are checked and logged in paper or electronic logs.

2.7.2 Modern State

Access logs are all electronic, and tampering seals are complemented with electronic transmitters to identify state changes of certain equipment or access data concerning a certain location. These data are coupled with process data to provide additional process insight. Video streams or recordings are analyzed using image-processing methods to capture plant performance data of interest. Several methods exist to extract data from a video stream or recording. For example, the video stream or recording can be used to track human presence and waiting time at certain equipment locations. It thereby creates a stream of work-performance data (e.g., Tang et al. 2016). The video stream or recording can also be used to track change actions performed on equipment, such as a breaker panel, and log status using change recognition (Menser 2017).

2.7.3 State-of-the-Art

The advances of security processes introduce a new type of data stream that can be used for online monitoring. Capabilities developed or under development include facial recognition systems for automated access control, smart video cameras (Hampapur et al. 2005) , three-dimensional video motion detection, and perimeter surveillance radar systems. In addition, security sensors can scan for radio frequency emissions emanating from various types of equipment, millimeter-wave imaging (Sheen et al. 2001) and acoustic sensors can be used to search or monitor through walls or objects, and multi-frequency laser systems that can produce internal and external 3D images for inspection of a structure. Space-based-lasers can also provide accurate imaging/position of ground-based objects and personnel. These may become more cost effective with further development of mini-satellites and laser miniaturization. All these technologies result in data sources that can be coupled with plant data to provide addition insight for fault detection.

2.8 Condition Reporting System Data

Every plant maintains a robust corrective-action program which provides a mechanism for any plant staff member to report a deficient condition. Each condition report is evaluated by dedicated staff and assigned to the appropriate organization for disposition. These data could be extremely valuable if available to an advanced data-integration system because they capture important events that can used for online monitoring.

2.8.1 Base State

Plants rely on a system to manually log a wide variety of notes from plant staff. These notes are analyzed by dedicated staff and filtered to determine whether further action is needed. In some cases, this data source triggers other actions in the plant. However, a significant portion of these data do not result in any action and are simply archived. The fundamental capability presented by human monitoring is multi-sensory fusion, with random sampling (i.e., whatever “catches the attention” of the observer). The human observations rely on sensing an anomaly by:

- Listening for local alarms, an increase of acoustic emission level, or changes in the tone of equipment audio emissions
- Visual examination for misalignment, deformation, or damage
- Smell for abnormal overheating, burning materials, or abnormal chemical odor
- Touch for detecting increased vibration, temperature, and/or mechanical resistance.

The current process does not systematically require a human to observe and log all of these observations. However, a human observation can be logged into an action system that initiates further investigation of the observed issues. The baseline used in this process is solely based on human experience and memory.

2.8.2 Modern State

Process and tools are used to streamline all action, logging into categorized data sets to be directly used in condition monitoring. To better use the data collected by the plant staff, the action logging by the plant staff relies on the plant staff to log the event or condition observed in preset conditions. The condition reporting relies significantly less on generic text to describe the issue. This ensures the data are in a form that can be directly coupled to plant data and, therefore, result in a useful data stream. Tagging such as bar-codes or RFID tags could also be affixed to the item of interest in order to alert others that issues have already been detected.

To complement, improve, and log human observations, it is possible to consolidate human senses by equipping personnel with multi-sensor tools or suits (e.g., visual and IR helmet-cams, haptic sensing gloves for thermal and vibration measurements, chemical sensors, dosimeters, and acoustics recording devices). The benefit of these sensors is not only higher accuracy and reduced reliance on the human, but also an ability to automatically log and store the data. This creates a new valuable data source and reduces the need for operators to manually log anomalies. The location of the measurements can be logged concurrently with the measurement data using location-identification technologies described earlier.

2.8.3 State of the Art

All logged data are categorized and sorted. Text-mining methods can be used to convert generic text data into an actionable data source. In addition, the data collection process can be automated by enabling new technologies to automate condition reporting. For example, mobile tablets with visual recognition systems could match a picture of a piece of equipment with items in an image database to automatically identify the equipment item. Observations using the sensors described in the modern state could then be recorded. Equipment-relevant information would be presented to the operator immediately to help create the condition report as soon as an anomaly is observed or to provide information on current issues already logged for that item.

2.9 Work Orders

Because the nuclear industry is oriented toward procedures, it relies on work orders to execute a significant part of the work. Whether paper or electronic, work orders capture a significant amount of plant data that can be used as a data source for online monitoring. Work orders will log measurements, observations, and plant configuration as part of the procedure. In addition, work orders capture actions performed in the plant. They also assign relevant documents and information to work activities. Most of the captured information in the work order are not reflected in other logs. These data are not typically used beyond the scope of the associated work order.

2.9.1 Base State

The nuclear power industry most often uses paper-based work packages or portable document format (PDF) versions of electronic work packages (eWPs). The PDF eWPs contain data fields that enable some flexibility in using the procedure inputs. Few nuclear power plants are using extensible markup language (XML) or Java Script Object Notation (JSON) or other advanced forms of procedures input acquisition forms. The data captured are stored locally or to a dedicated centralized server.

2.9.2 Modern State

All work orders are electronic and performed on mobile devices. Inputs are logged into dedicated data fields that include the timestamp, equipment information, and work-order identifiers. Data are stored in a structured database (e.g., Al Rashdan et al. 2016) on dedicated servers. If stored locally, data are transferred to a dedicated database at a predetermined frequency. The frequency of data transfer depends on the available wireless infrastructure.

2.9.3 State of the Art

In addition to capturing the mobile work-management input, the work-order instructions and forms text is mined into their data elements to provide insight into the work being performed. For example, if the instruction states “bolt flange nuts using wrench ID” and a check box is included, this would be parsed into the action “bolt,” the component “flange nuts,” and the tool “wrench ID.” These data streams can then be associated with equipment-condition monitoring (e.g., using wrench ID demonstrates a pattern of sealing issues when used with flange nuts).

2.10 System Engineer's Notebooks

System engineers at nuclear power plants are decision makers on equipment condition and maintenance-activity frequencies. They conduct inspections, review documentation, and capture measurements or information in dedicated notebooks.

2.10.1 Base State

The system engineer manually logs the measurement into spreadsheets or notebooks, manually trends the data, and makes decisions on system conditions accordingly. The engineer uses vendor or custom-made tools and procedures to determine whether equipment is in satisfactory condition or needs replacement. No prognostic analysis is performed, and raw data are usually not stored.

2.10.2 Modern State

Data captured by the system-engineer inspection tools include raw data, are time stamped, and include equipment identification. The tools transmit the captured data remotely or store the data, and then the data are uploaded into a structured database on a server when the job is completed. The used tools have screens to guide the system engineer on where to inspect and adaptively decide on the next point of inspection based on the data collected. Also, as part of the modern state, fixed sensors need to be installed and connected as explained in Sections 2.1and 2.2, and Table 1.

2.10.3 State-of-the-Art

The system engineer's data-acquisition process is replaced by a suite of sensors that enable continuous spatial measurements of the equipment in addition to environment sensors that provide additional insights that would not be captured by more typical sensors (as described in Sections 2.1and 2.2). Human decision making (human knowledge) is automated by creating a fully autonomous decision-making system that learns from patterns or system engineer's decision-making process and replaces it.

The systems-engineer function can also be performed using extended decision-support systems to incorporate engineer log data into virtual decision environments (VDEs). A VDE is enabled by a software platform that provides interactive modeling, "what-if" simulation, and advanced analysis/decision-making using dynamic simulation and artificial intelligence (Bishop et al. 2009). It specifies prospective courses of action (COAs) for issues that require resolution by generating and evaluating the strengths and weaknesses of those COAs. What-if simulations are used to present possible outcomes using projected performance metrics to allow SMEs to evaluate and choose a final course-of-action.

2.11 Schedule

Due to the fast-track nature of work in the nuclear power industry, scheduling tools are used extensively and contain a wealth of data that include multiple types of work-progress information, resource allocation and use, and plant actions and activities performed. Current scheduling tools are used solely for scheduling purposes in both online and outage planning. However, the data can be used to explain condition-monitoring data of the plant and directly feed into predictive O&M, and proactive maintenance decision making for equipment and resources that are inherently good or bad performers. The schedule information can be used to build a historical behavior model of plant equipment and can be used to project equipment performance based on corrective-action to preventive-action ratio per equipment.

2.11.1 Base State

The current scheduling tools are used solely for scheduling purposes. Plants use dedicated enterprise project-management (EPPM) system tools for scheduling. The EPPM system tracks task-level maintenance work for planning and tracking purposes. Data logging is performed by schedulers using scheduling tools, and the data are stored in an independent database.

2.11.2 Modern State

Resource-location tracking is the main source of scheduling data that need to be automated. This can be achieved through the location-identification technologies described earlier. The fidelity of schedule data logging is significantly increased and automated by coupling the EPPM suite with other plant tools that provide resources and action-tracking capabilities, such as eWPs. This would increase data fidelity on schedule tracking. For example, tasks created on an eWP system will automatically populate within the EPPM suite. Status updated in the EPPM suite will automatically be synched with the eWP system.

2.11.3 State-of-the-Art

Complementary technologies to track progress, such as dynamic image actions or gesture recognition, can be used to track work activities for steps that involve multiple actions. This can be achieved by implementing image-recognition methods on fixed or mobile cameras on helmets or glasses. Video recognition, coupled with facial recognition, can track people's movement in the plant for updating human-resources work progress (e.g., Tang et al. 2016).

2.12 Logistics

Nuclear power plants have a systematic approach to manage procurement, tracking, stocking, performance, and need for parts and materials. The management of these parts and tools can be correlated with the performance of equipment and are, therefore, an important source of data to improve the condition of the equipment. For example, spare-part stocking conditions can be correlated to a certain type of equipment failure. This type of data is currently not coupled to equipment condition.

2.12.1 Base State

The procured parts are logged into an enterprise asset management system (EAMS) database that is managed by warehouse workers and logistics staff. The procurement process is triggered by the planners or schedulers. The parts data are often comprehensive, but are not tracked after arrival or coupled with the work process data, except for cases where tools need to be calibrated or for expensive equipment.

2.12.2 Modern State

A comprehensive list of parts information must be created. Parts are tracked as they are used in the plant. Technologies such as bar codes and RFID (Al Rashdan et al. 2017) are used to automate this process. The parts storage and transportation conditions, usage, events, and feedback are tracked. Parts removed from failed equipment are also logged to enable the development of patterns for high- and poor-quality parts. Vendor data related to equipment performance is also made available for comparison by equipment health monitoring systems.

2.12.3 State of the Art

All parts information would be provided by the suppliers in a unified electronic form that can be automatically logged into the EAMS with minimal human interaction. This should include the part's specifications, usage requirements, and limitations. In addition, image recognition methods are used to track parts use in the plant. The craft or warehouse staff would be required to take a picture of a part that does not have bar code or RFID tag as it is being checked out, checked in, or used. Visual parts patterns would be created to identify parts and categorize them. This would help automate the parts data-logging process and allow tracking parts specifications with minimal human actions.

2.13 Clearance Orders

Clearance orders are part of the work process that requires operators to isolate plant systems or components to enable maintenance staff to perform work on specific equipment. The clearance process could require operators to tag-out equipment to ensure it is not operated while work is performed on it or on equipment that it could impact. When work is completed, tags are removed and the equipment is released. The tag-out and tag-in process is logged in a dedicated clearance-order database system. The data from the clearance orders provide additional information about the current configuration of plant systems. These types of information can be coupled with other process data to generate an additional level of plant insight.

2.13.1 Base State

Operators receive a clearance request as part of the work order. They remove the systems and components from service, tag them, log the actions needed to issue the clearance, and then issue the clearance to the requesting staff to perform the job. The process is manual, and the actions taken are manually logged in the clearance-order database. The tag-out and tag-in requires the operator to manually place and remove paper tags or locks on the equipment-actuation mechanism.

2.13.2 Modern State

The clearance actions as well as the tag-out and tag-in are captured from a set of standard actions and are logged into an electronic structured database (e.g., ABB 2015). Paper tags can be scanned via barcode directly from portable barcode readers to automatically log the tag data. Mobile electronic tags can automate the data-logging process and are being explored by other industries (e.g., NAVSEA 2013). Electronic tags can contain sensors that identify the tag status and wirelessly transmit the condition to a centralized database. They are used mostly for tampering detection, but are finding their way into the tag-out tag-in process of nuclear power plants.

2.13.3 State of the Art

A proactive approach to capturing clearance data would streamline the actions data-logging process. As soon as a clearance is issued, the actions associated with the clearance orders are automatically logged. The operator would not be required to specifically log every action. Permanent and remote-controlled electronic tags would be installed on all major equipment items. These tags could be switched on and off remotely to indicate either flagged or cleared status by operators during rounds and/or from the control room. Mobile tablets would automatically receive indicator signals from flagged devices whenever the mobile device is within proximity to that item. Because the tags would be enabled to sense the equipment status, the tags would be used as a running indication sensor.

2.14 Vendor and Plant Documentation

Vendor information contains multiple forms of data that are directly relevant to equipment condition. Relevant information available in vendor documentation largely relates to failure-rate testing, calibration requirements, drawings and schematics, and procedures and manuals for maintenance and inspections.

2.14.1 Base State

The vendor and plant documents are manually read by the system engineer or planner to extract information such as inspection procedures steps. Once extracted, these data are included in the system engineer documents and used in the work-order development process. Sophisticated analyses are sometimes listed in the vendor documentation, but are usually not used.

2.14.2 Modern State

A standard data structure is defined for the key information that applies to the main type of plant parts. This structure is used to store the most relevant vendor and plant information. This enables the availability of a consistent level of data from all parts that can be utilized.

For more comprehensive manuals, documentation is digitized and indexed using optical character recognition (OCR). This enables easier access to the documentation for data collection. The data collected are indexed and stored to reduce repetition of work in the future when the same documentation is used.

2.14.3 State of the Art

Documents would be automatically mined, indexed, and stored in a ready-for-use format. This applies methods similar to internet search engines. It uses textual-analysis methods to comprehend the text context and provide meaningful data for documentation use when needed. For example, the mined data can be useful when certain vendor documents are missing information that are available in other vendor documents for similar equipment. The mined data can be used to compare vendor specification and provide missing performance insight to improve decision making regarding equipment condition.

2.15 Industry Operating Experience

Industry operating experience is represented by multiple documents, standards, regulations, and databases that reflect the broader experience of the nuclear power industry. These resources are widely used by the nuclear industry and generated through dedicated industry organizations such as Institute of Nuclear Power Operations and Nuclear Energy Institute.

2.15.1 Base State

Except for regulations or mandatory policies, industry operating documents are usually used to gain insight about specific issues once they occur, or opportunities for improvement once they are discovered. The issue resolving process involves a manual search for and reading of documents, engaging experts in the field, meetings, and discussions. This approach is more corrective, driven by the need to resolve a specific issue. The knowledge sustainability process of the nuclear industry is currently driven by entities that support the industry, and the flow of data between the nuclear power plants is limited.

2.15.2 Modern State

A holistic industry view of the industry experience is created. A guidance architecture model is created to map the data content of guidance artifacts (documents, knowledge repositories, etc.) to related guidance artifacts and map those blocks of content to the relevant processes at the task and component level, if possible. This enables work performers to speed resolution of issues for a specific task or component and understand where specific knowledge or guidance is lacking so that they can initiate acquisition of needed content.

2.15.3 State of the Art

The guidance data would be instantiated in a centralized database that contains industry-wide content as well as local content that could be shared by permission of local custodians. The centralized guide is accessed by the plants to gain national insight of performance of resources, equipment, vendors, methods, tools, and skills, in addition to opportunities for success, lessons learned, and potential cost savings. Standardized ontologies are developed along with normalized access patterns to create a portal for automatic and rapid access to the consolidated and harmonized guidance information that is most relevant to plant issues.

3. CONCLUSION

Current nuclear practices log data collected in different systems and forms that are neither integrated nor used beyond the main intended purpose of data collection. Data collection frequency and fidelity vary depending on the data source. In some cases, data are already automatically and continuously collected (e.g., through data-acquisition instruments continuously connected to a plant computer). In contrast, most of the time, data that are collected periodically from sensors installed in the plant or human activities are not continuously available. Even though this study targeted a comprehensive list of means to automate data-collection activities and improve fidelity of data, this represents part of a potential workforce-cost savings for the nuclear power industry. Other cost saving results from using data analytics and predictive models to replace periodic activities with on-need activities. The latter objective can only be achieved when a continuous and high-fidelity flow of data is created, which is the objective of this work.

This effort demonstrates that a huge potential for data collection automation and data fidelity improvements can be realized by evolving current industry data-collection methods to either the modern state or SoA. The majority of processes analyzed were found to be manual and labor intensive. They fell into the base state and, as a result, the modern state often targeted a reduction in manual logging efforts by using electronic and semi-intelligent means or complementing the work with sensors and technologies (mobile and fixed) that can reduce labor demand. The SoA often required the application of advanced methods of data mining and machine learning to extract data from text or imagery forms, increasing the time and spatial coverage of sensors, integrating data to create new sources of useful data, enabling the use of sophisticated mobile and autonomous technologies to remotely capture the data, and using intelligent equipment or instruments that eliminate the need for human activities.

Fifteen sources of data are herein identified, and the methods to advance data collections are described. This effort is aimed as a guidance for the industry on potential technologies and methods to advance current data collection methods to the modern state and SoA. The evolution of data-collection processes is a deployment effort for the modern state, but is an R&D effort for the SoA. As a result, descriptions of the modern state are aimed towards the industry for their use while the SoA descriptions are aimed to assist the R&D community, including the industry R&D organizations, in determining future research directions. Several of the SoA technologies described in this report are already active research efforts for research organizations and programs, including the LWRS program.

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