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Light Water Reactor Sustainability Program

Developing a Strategy for Full Nuclear Plant Modernization

Jeffrey C. Joe and Casey Kovesdi

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EXECUTIVE SUMMARY

Recognizing the important role commercial nuclear power generation plays in powering the nation's economy and providing energy security to the nation, the U.S. Department of Energy (DOE) has established the Light Water Reactor Sustainability (LWRS) program to perform research and development (R&D) that further establishes the technical foundations for managing the long-term, safe, and economical operation of nuclear power plants (NPPs). One particular R&D area in the LWRS program is the Plant Modernization pathway, which includes human factors R&D and instrumentation and control (I&C) systems engineering to enable full plant modernization. By funding R&D on plant modernization, the LWRS program provides important technical information that can be used by decision makers on how to best proceed with modernizing the existing fleet of NPPs.

Under the LWRS Plant Modernization pathway, a considerable amount of R&D has been performed in the human factors and I&C engineering areas. This work has been done in collaboration with many different U.S. utilities, and focused on I&C upgrades in both the control room and in the field. The work performed to date under the LWRS program has had a notable impact on the ability for these utilities to continue to operate their respective fleets of reactors, and LWRS program researchers are intent on doing even more. In order to do this, a more unified strategy for full nuclear plant modernization needs to be developed. This report documents the latest step LWRS program researchers have taken to develop this strategy. Taken together with prior reports written on this specific topic, the work described here provides an even clearer picture on what the strategy for full nuclear plant modernization should look like.

CONTENTS

FIGURES

ACRONYMS

DCS	Digital Control System/Distributed Control System
DOE	Department of Energy
EPRI	Electric Power Research Institute
HFE	Human Factors Engineering
HSI	Human System Interface
HSSL	Human Systems Simulation Laboratory
I&C	Instrumentation and Controls
INL	Idaho National Laboratory
LAR	License Amendment Request
LWRS	Light Water Reactor Sustainability
NEI	Nuclear Energy Institute
NGT	Nominal Group Technique
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
O&M	Operations and Maintenance Costs
R&D	Research and Development
SRP	Standard Review Plan
SSC	System, Structure, and Component
U.S.	United States

Developing a Strategy for Full Nuclear Plant Modernization

1. INTRODUCTION

Recent announcements by various utility owners and operators of commercial nuclear power plants (NPPs) in the United States (U.S.) on their plans for continued operation of their plants have generally fallen into one of two categories. Some have announced their plans to cease commercial operations and shut down the plant, but many others have announced plans to continue operating and are actively pursuing solutions to the technical and licensing issues associated with life extension. For example, the Tennessee Valley Authority recently made a substantial investment in one of the Browns Ferry NPP units by installing new equipment to boost its power output by 14 percent, and plans to make similar investments in the other two units at Browns Ferry (Flessner, 2018). Other utilities, including Exelon, Duke Energy, Dominion, Southern Company, and Arizona Public Service (Thomas, Boring, Hugo, & Hallbert, 2017) have performed, or are planning to perform, upgrades to their NPPs, including modernizing the instrumentation and control (I&C) systems in the main control rooms of these plants. Modernizing these mostly analog and first generation digital I&C system technologies is important because the manufacturing and product support base for them no longer exists and spare parts are scarce. That is, because other energy sectors and process control facilities have replaced their analog I&C with digital technologies, analog I&C replacement parts are no longer available. As a result, analog I&C systems, although still reliable, have reached the end of their useful service life and limit the continued operation of NPPs.

Recognizing the important role commercial nuclear power generation plays in the powering the nation's economy and providing energy security to the nation, the U.S. Department of Energy (DOE) has established the Light Water Reactor Sustainability (LWRS) program to perform research and development (R&D) that further establishes the technical foundations for managing the long-term, safe, and economical operation of NPPs. One particular R&D area in the LWRS program is the Plant Modernization pathway, which includes human factors R&D, human factors engineering (HFE), and I&C engineering to enable full plant modernization. By funding R&D on plant modernization, the LWRS program provides important technical information that can be used by decision makers on how to best proceed with modernizing the existing fleet of NPPs. This is exemplified in the two primary goals of the LWRS Plant Modernization pathway:

1. Ensure that legacy analog I&C systems are not life-limiting issues for the LWR fleet
2. Implement digital I&C technology in a manner that enables broad innovation and business improvement in the NPP operating model.

Within the Plant Modernization pathway, one key activity of this work is to develop a strategy for full nuclear plant modernization, which previous LWRS performance milestone reports (Thomas & Scarola, 2018; Joe, Hanes, & Kovesdi, 2018) for this pathway have begun to describe. Thomas and Scarola (2018) described the philosophy and approach to creating a seamless digital architecture that integrates plant systems, plant processes, and plant workers, and how significant cost savings, reductions in errors, and increased efficiencies can be realized. Joe, Hanes, and Kovesdi (2018) provided more detailed guidance to utilities to support their development and evaluation of an HFE program management plan and an end state vision for plant modernization, and discussed how those activities need to be effectively integrated with a business case for modernization and the technical approach for transitioning the existing analog I&C architecture to a full digital I&C architecture.

To further support this comprehensive plan and vision for full plant modernization, however, additional details need to be further developed. In particular, the factors that must be considered when engaging in full nuclear plant modernization needs to be identified and described. For example, the cost to implement a new digital technology relative to the value or benefit it provides is an important factor to consider as one develops a strategy for full nuclear plant modernization. Additionally, the methods, techniques, and tools that can and should be used to help weight these decision factors need to be specified.

This report further elaborates on these two points. Section 2 provides a more detailed summary of the previous LWRS reports that discussed foundational aspects of the strategy for full nuclear plant modernization (e.g., Thomas & Scarola, 2018; Joe, Hanes, & Kovesdi, 2018). Section 3 identifies the factors that must be considered when developing a strategy for full nuclear plant modernization. Section 4 presents methods, techniques, and tools that can be used to weight the factors affecting the strategy, and Section 5 presents a conclusion and proposes next steps.

2. PRECEDING WORK TO DEVELOP A STRATEGY FOR FULL NUCLEAR PLANT MODERNIZATION

The LWRS performance milestone reports written by Thomas and Scarola (2018) and Joe, Hanes, and Kovesdi (2018) document the initial work to develop a strategy for full nuclear plant modernization. This report builds upon this previous work and present additional aspects that need to be included in this strategy.

Thomas and Scarola (2018) stated that the fundamental premise for a strategy for full nuclear plant modernization is the transition away from a hybrid analog-digital I&C solution for plant operations to a seamless digital environment or architecture that merges 1) plant systems, 2) plant processes, and 3) plant workers. These are defined as follows:

- **Plant systems**. Beyond centralized monitoring and awareness of plant conditions, deliver plant information to digitally based systems that support plant work and directly to workers performing these work activities.
- **Plant processes**. Integrate plant information into digital field work devices, automate many manually performed surveillance tasks, and manage risk through real-time centralized oversight and awareness of field work.
- **Plant workers**. Provide plant workers with immediate, accurate plant information that allows them to conduct work at plant locations using assistive devices that minimize radiation exposure, enhance procedural compliance and accurate work execution, and enable collaborative oversight and support even in remote locations.

Figure 1 illustrates the interconnections of these areas.

Figure 1. Seamless information architecture.

If this premise regarding what the I&C end state is for commercial NPPs is not accepted, it will be difficult, if not impossible, for the strategy for full nuclear plant modernization to be realized in the manner envisioned (i.e., where cost-savings, efficiencies, and reductions in errors are realized). This is illustrated by the following example.

Commercial NPPs frequently rely on hybrid digital I&C systems to provide information to plant workers who are typically forced to use analog tools as they perform their plant processes. For example, control room operators use paper-based procedures, and are often the plant process in that they combine or integrate the disparate pieces of information received from a combination of analog and digital I&C systems. In this example, the paper-based procedures are the analog tool the plant worker (i.e., operator) uses. The operator is also the plant process because she or he is the integrator of information received from the hybrid analog-digital I&C. The plant systems the operator relies upon in this example is a hybrid combination of analog-digital I&C systems. While this system works, it is very human-labor intensive and less efficient than a system where the I&C is fully digital, the plant processes are appropriately digitized or automated, and the plant worker is given digital technology and tools to perform their work (e.g., computer-based procedures).

Joe, Hanes, and Kovesdi (2018) added details to the strategy for full nuclear plant modernization by specifying that a core aspect of it is an HFE program plan and an end state vision for plant modernization that is well-integrated with both 1) a technically defensible approach to migrating the existing, mostly analog I&C infrastructure to a digital I&C infrastructure, and 2) a valid business case methodology to cost-justify the modernization activity. An HFE program plan provides guidance to help ensure that a plant's modernization efforts satisfy regulatory requirements and expectations regarding HFE, and to ensure safe and reliable plant operation meeting human performance expectations as plant modifications are made over time. An end state vision is simply a description of an expectation for the control room at the completion of the modernization process. It needs to include:

- A description of the physical layout of the control room following the modernization process, if physical changes are planned
- Descriptions of digital I&C systems and equipment that the modernization process will introduce into the control room
- The concept of operations following completion of the modernization process.

A key point in Joe, Hanes, and Kovesdi is that the HFE program plan and end state vision for plant modernization need to be developed with both cost and technical feasibility in mind. That is, these HFE activities need to be combined with 1) methods that can provide the cost-justification for modernization activities and 2) technical analyses that show how to migrate legacy I&C systems to a fully digital I&C architecture. The integration of these factors is shown in Figure 2.

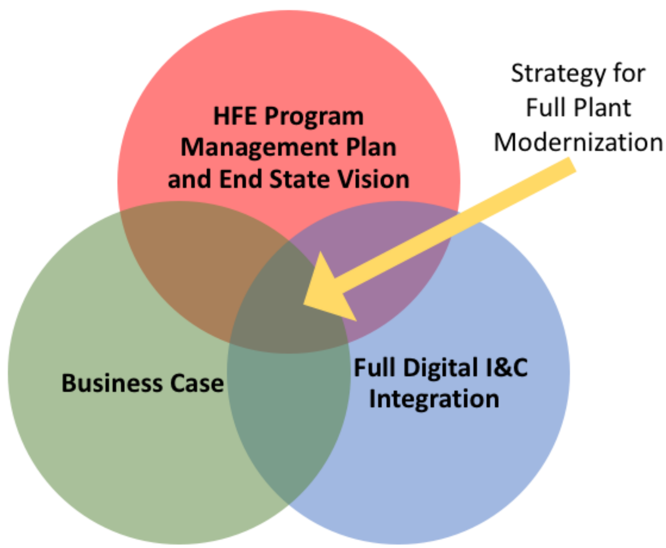

Figure 2. The integration of HFE to other key aspects of a strategy for full nuclear plant modernization.

3. FACTORS IN DEVELOPING A STRATEGY FOR FULL NUCLEAR PLANT MODERNIZATION

There are many factors that must be considered when developing a strategy for full nuclear plant modernization (e.g., the cost to implement a new digital technology relative to the value or benefit it provides). This section presents the most significant known factors that need to be evaluated in order to develop a coherent modernization strategy.

One set of factors that need to be considered are barriers or challenges to modernization. Based on informal conversations with various utility partners and other industry experts, the most frequently mentioned barriers are:

1. **Cost to implement relative to the expected value or anticipated benefits.** The cost of investing in new digital I&C relative to its expected benefits is essentially a generalized cost-benefit utility function.
2. **Licensing and regulatory processes for digital upgrades.** There are two licensing paths for regulatory acceptance of digital upgrades: a) by submitting a license amendment request (LAR) or b) by going through the 10 CFR 50.59 process. The industry's perception of these two pathways is that there are challenges and risks associated with both[1].
3. **Cyber-security for digital upgrades.** While digital I&C offers many advantages over analog I&C in terms of functionality and precision, analog I&C is significantly less vulnerable to cyber-attacks.
4. **Overcoming the inertia of status quo solutions developed by I&C and other digital solutions vendors.** Designing, developing, and deploying an I&C system that meets the functional specifications and passes regulatory licensing is expensive. Therefore, once a system is commercially available for one application, there is a tendency to want to market this solution for other applications. However, there is always room for improvement for a deployed I&C solution, and there are often important differences between the first application and the potential subsequent applications that may require modifications. These opportunities for improvement and 'customized' modifications can add significant costs to the modernization effort, so there can be considerable inertia for maintaining the status quo that needs to be overcome.
5. **Insufficient process expertise and operational experience with digital upgrades.** The concern is that inexperience and lack of expertise will lead to mistakes, costly delays and re-work.
6. **Lack of an end-state vision.** Changes to complex systems need to have a vision that describes what the system looks like at the end of the modernization process, but sometimes this vision is not clearly established at the beginning of the process.
7. **Limited time windows in which to install the upgrades.** A typical NPP in the U.S. generates between $1M and $2M in revenue per day when it is in operation (Collins, 2011; Negoescu, 2011). Therefore, utilities want to minimize the number of days an NPP is in refueling outage and not generating electricity. This constrains the time window in which many I&C modernization

[1] The industry's perception of the experience with performing a digital upgrade through a LAR at the Oconee NPP has, perhaps until recently, discouraged most of the industry from considering this path for digital upgrades. There were some reports written shortly after the upgrade, however, that presented a more nuanced assessment of this upgrade (see Collins, 2011; Negoescu, 2011), and other utilities have more recently indicated interest in safety system digital upgrades. Additionally, the NRC and industry representatives have spent years trying to revise and update the established 10 CFR 50.59 guidance (e.g., NEI 96-07, NEI 01-01), but as of the writing of this report, have not produced new guidance on an approach that is acceptable to both the NRC and industry.

tasks can occur, as the reactor needs to be shut down in order to install all significant control room digital I&C upgrades.

Another set of factors to consider in developing a strategy for full plan modernization are the anticipated benefits, and quantifying (or at least characterizing) how much impact they are expected to have. Expected benefits include:

1. Reduced operations and maintenance (O&M) costs
2. Reducing in staffing levels
3. Improved plant efficiency
4. Potentially improved plant capacity
5. Consistency among multiple NPP units (i.e., NPP-to-NPP consistency)
6. Reduced outage time
7. Improved human-system performance.

It should be noted here that the work performed for the LWRS Plant Modernization pathway on developing a business case methodology has elaborated on many of these benefits. More details on these benefits can be found in Thomas, Lawrie, Vlahapolis, and Hart, (2014), Thomas, Lawrie, and Niedermuller (2016), and Adolfson, Thomas, and Joe (2017). It should also be noted that these LWRS reports essentially provide a coherent set of analytical tools that can be utilized to perform the cost-benefit analyses of these factors, and the method and tools produce as its output a standardized metric called harvestable cost savings.

An additional set of factors to consider in developing a modernization strategy is the outage implementation strategy. That is, when planning these digital I&C upgrades, an important question that needs to be answered is whether the upgrades will be installed during one extended refueling outage, or in a step-wise fashion over multiple standard-length refueling outages. There are pros and cons to either option. If the strategy is to install the digital upgrades in one extended outage, the advantages are that all the systems are qualified and installed at once, and the utility only has to go through the licensing review process with the NRC once. The disadvantage to this approach is that it is potentially more difficult to contend with issues that were previously unknown but emerge, or are discovered, during the outage installation process. If the discovered issue is serious, it can add a significant number of days to the outage, causing substantial revenue loss (Collins, 2011; Negoescu, 2011).

If the strategy is to take a phased approach and install the digital upgrades over a series of outages, the benefit is that the utility is better able to manage the discovery of previously unknown issues that emerge during the outage. The down side to this approach is that the utility will need to go through the licensing process with the NRC multiple times, because each time the plant is ready to come out of the outage, its digital I&C architecture is different, and each one of these interim states will need to be approved by the NRC in their review of the plant's operating license. The time and money spent on going through the licensing process for each interim control room configuration may be very expensive, so the trade-off in costs and the relative risks the utility takes on with either outage approach needs to be evaluated closely and carefully considered.

The next set of factors to include in the modernization strategy involve the technologies to install and the effect they will have on the conduct of operations. For full plant modernization, it is assumed that all I&C systems (e.g., safety-related systems, systems important to safety, and non-safety related systems) will be replaced with digital I&C. As such, what this set of factors refers to are the design and technology decisions that the utility must make for full nuclear plant modernization. For example, in the control room, the utility will need to decide on whether the following technologies and design concepts will be used, and the extent to which they will be applied:

- Desktop-based operator workstations
- Operator-at-the-boards controls
- Soft controls
- Large overview displays
- Intelligent alarm systems
- Computer-based procedures
- Wireless technologies
- Advanced diagnostic tools to aid in detection, diagnosis, and troubleshooting by integrating additional sensors and field information with existing control room indications
- Automation.

Associated with this factor are the following additional considerations: a) the vendor or vendors that a utility selects and the future maintenance costs for the upgraded software and hardware, and b) the costs to re-qualify and re-train plant staff.

Overall, there are a number of different factors that play a significant role in the process of developing a strategy for full nuclear plant modernization. Some of the factors, and in particular the barriers and their significance (how much weight they carry in the decision-making calculations), can have a significant influence on the strategy a utility adopts and can dictate any number of tactical implementation decisions. Each factor described here, and potentially others, need to be considered in concert with all of the other factors in order to develop a workable strategy for full nuclear plant modernization.

4. METHODS AND TOOLS FOR STRATEGY DEVELOPMENT

This section presents methods, techniques, and tools that can be used to weight the factors affecting the development of a strategy for full nuclear plant modernization, starting with a discussion of the conceptual relationship between the costs of implementing digital I&C technologies and their expected benefits.

4.1 Conceptual Relationship of Economical Barriers and Proposed Value for Digital Technologies

Conceptually, the adoption of a new digital technology within a given NPP may be described as a decision-making process based on weighting the technology's value to its associated costs. Potential values of new digital technologies may include but are not limited to reduced O&M costs, reduced staffing levels, and enhanced plant performance and availability while maintaining or improving plant safety (see Thomas & Scarola, 2018 for details). To this end, potential unforeseen costs with digital technology adoption may be associated with insufficient technical, process, and operational experience, a lack of an end-state vision, cybersecurity concerns, regulatory and licensing, as well as overcoming the inertia related to the status quo of existing digital control systems (DCS) solutions. One way of conceptualizing a plant's decision process in adopting a new digital technology is through a generalized utility function, where a given technology's hypothesized value is weighed against its costs (Winterfeldt & Edwards, 1986). Figure 3 below illustrates two hypothesized value functions of adopting a given digital technology. In this case, the specific parameters tied to value and costs in the value function are left generic.

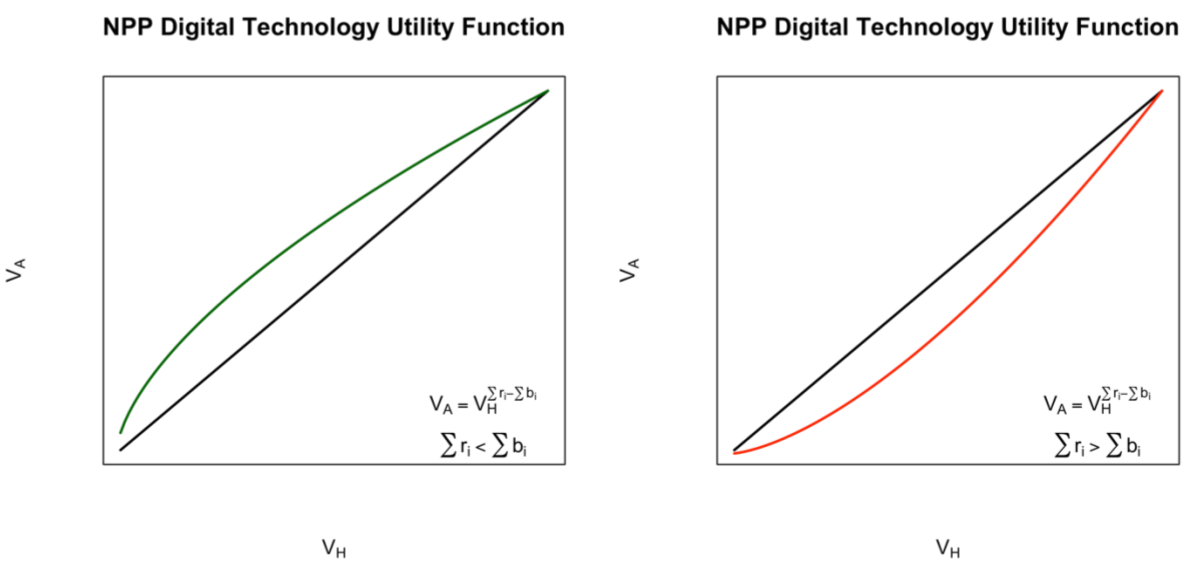

Figure 3. Generic value (utility) function to describe the relationship of a technology's value to its potential costs.

As illustrated, when a technology's sum of risks (r_i) exceeds the sum of its benefits (b_i), then the value function suggests that the technology's actual value to the plant (V_A) is lower than its hypothesized value (V_H). Such results would indicate that the technology may not be particularly valuable for the NPP. On the other hand, when a technology's sum of benefits (b_i) exceeds the sum of its risks (r_i), then the value function suggests that the technology's actual value to the plant (V_A) is greater than its hypothesized value (V_H). It should be noted that often times, the contribution of a given risk (r_i) may be reduced through the inclusion of a robust modernization strategy. That is, a given technology's actual value (V_A)

for a plant may be improved through the reduction of its associated risks and costs (r_i) by identifying and overcoming these barriers, using robust modernization strategies. Various tools that can be used to support a robust strategy are described next.

4.2 Evaluating the Value Proposition of Digital Technologies

Several tools are offered to support 1) identifying a digital technology's benefits and costs, 2) assessing the strength of each benefit and cost, as well as 3) determining whether a candidate digital technology presents value to the plant. These tools are adaptations from the Design for Six Sigma (DFSS) methodology, which is a "fact-based, data-driven philosophy of improvement that values defect prevention over defect detection" (Kubiak & Benbow, 2009). Lastly, it should be emphasized that these tools are neither exhaustive nor prescribed. A plant may use other tools, or a subset of the tools listed; however, each tool may offer a unique lens to the given challenge, allowing for a broader range of solutions. As mentioned previously, a potential set of alternative tools that can be used have been presented in previous LWRS reports (e.g., Thomas, Lawrie, Vlahapolis, & Hart, 2014; Thomas, Lawrie, & Niedermuller, 2016; Adolfson, Thomas, & Joe, 2017) on the development of a business case methodology to support plant modernization activities.

4.2.1 Identifying the Benefits and Costs

Tools associated with identifying a digital technology's benefits and costs are designed to map the key offerings of a technology to a plant's critical requirements, identify gaps or areas for improvement in the existing infrastructure, as well as identify cause-and-effect relationships to known plant issues that can be mitigated through new digital improvements. Potential tools include: 1) identifying and considering critical-to-CTx requirements, 2) gap analysis, 3) fishbone (Ishikawa) diagrams, as well as 4) other methods such as interviews, focus groups, and surveys. All of these tools are described in more detail below.

4.2.1.1 Identifying and Considering Critical-to-CTx Requirements

Critical-to-CTx requirements, a common term in DFSS, regard specific requirements that have a significant impact to the NPP such as safety, costs, efficiency, quality, and regulatory requirements (Chi & Zhang, 2007). For instance, the NRC (2016) provides a Standard Review Plan (SRP), NUREG-0800, which provides specific regulatory considerations of an NPP that support plant safety. These considerations may serve as a foundational resource in informing subsequent critical requirements for the design and implementation of new digital technologies. For example, a new digital technology that is associated as a system, structure, and component (SSC) of the offsite power system should be capable of withstanding the effects of natural phenomena including atmospheric temperature variants, high wind, rain, lightning discharges, ice and snow conditions, and other significant weather events (i.e., see NUREG-0800 Section 3.2.1 SRP Acceptance Criteria 1, 2016). Similarly, a new digital technology that is intended to be implemented into the main control room should reflect state-of-the-art human factors principles (i.e., see NUREG-0800 Chapter 18 Acceptance Criteria 1, 2016). These regulatory considerations as well as other resources (e.g., operator experience reviews) should serve as a foundation in ensuring that any given new technology being integrated fulfills or enhances the plant's critical requirements of safety, reduced costs, quality, and met regulatory requirements.

4.2.1.2 Gap Analysis

A gap analysis is a tool used to identify unfavorable differences between the current state of a system to a desired state (Kubiak & Benbow, 2009). In regard to emerging digital technology deployment in NPPs, gap analysis can be used in identifying where there might be opportunity to improve the safety and capabilities of the plant (e.g., DOE, 2015). Areas of focus may be informed by the identified critical-to-CTx requirements, or through other mechanisms such as competitive analysis and benchmarking. Gap analysis can be completed at different levels such as at a business level (e.g., compare performance to other plants or energy markets), process level (e.g., current O&M costs, outage time, etc.), or product/system level (e.g., gaps in existing capabilities such as a need for online monitoring, wireless technologies, or advanced decision-support tools). Identified gaps may be used to inform the use of candidate technologies that will have a high impact on the overarching goals of the NPP such as safety and overall plant capacity and efficiency. A final point worth mentioning with gap analysis is that identified gaps are rarely static in nature; for example, new or more cost-effective technologies may be arise through time, potentially increasing identified gaps. Thus, recognizing and accounting for these identified gaps should accommodate this dynamic nature (Kubiak & Benbow, 2009).

4.2.1.3 Fishbone (Ishikawa) Diagram

In some cases, it may be valuable to describe the linkage between an undesirable effect or barrier with its potential contributors or causes (Kubiak & Benbow, 2009). In such cases, the fishbone, or Ishikawa, diagram may be used to identify the potential contributors or causes and sub-causes of the identified barrier.

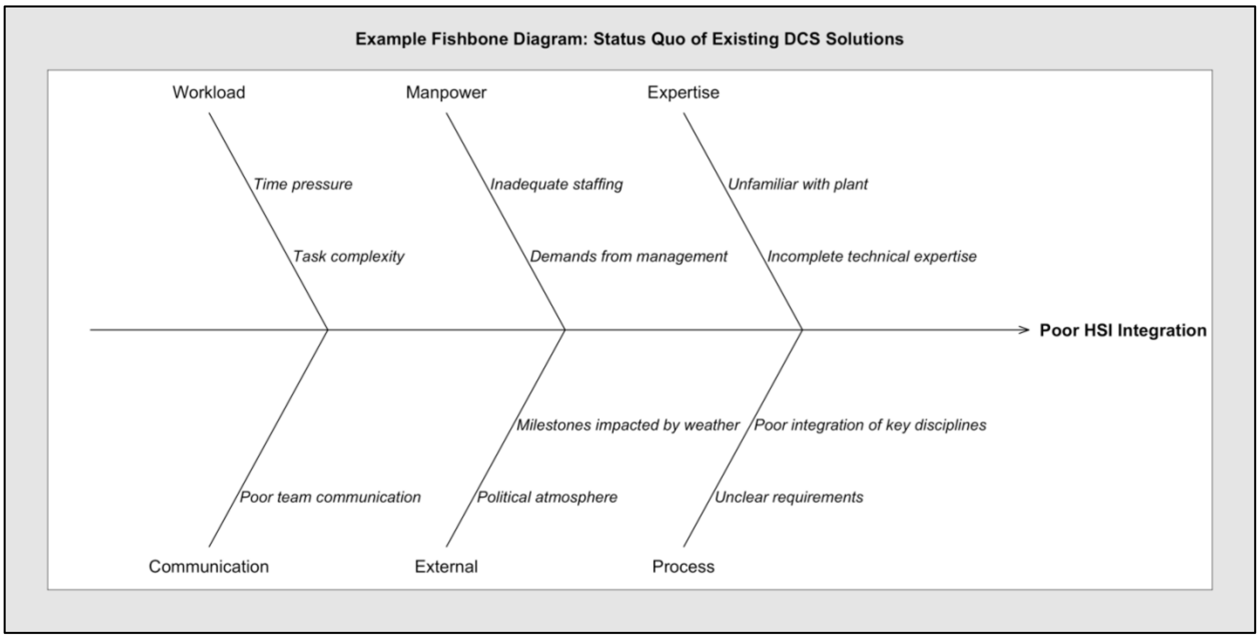

Figure 4. Example fishbone diagram.

For example, Figure 4[2] provides an example of how the fishbone diagram can be used to identify causes and sub-causes for poor human-system interface (HSI) integration into an NPP control room. Once identified, these barriers can be considered in an overall strategy to reduce their negative impact on the technology's value to the plant. The fishbone diagram in this example identified 'unclear requirements' as a major sub-cause for poor HSI integration. By identifying this potential barrier, a subsequent strategy may focus attention on improving the requirements gathering process for a new HSI technology going into the control room.

4.2.1.4 Other Common Methods: Interviews, Focus Groups, and Surveys

There are other tools that may be used to gather input as part of identifying the benefits and costs of a candidate digital technology. Common methods such as interviews, focus groups, and surveys with industry experts and subject matter experts may be used to collect such input, especially at the earliest phases of requirements gathering. For example, a workshop in 2018 sponsored by the DOE's Advanced Sensors and Instrumentation program through the Gateway for Accelerated Innovation in Nuclear was held to gather input from key stakeholders related to advanced digital technologies needed to support

[2] This figure was completed using the qcc package in R (Scrucca, 2004).

deployment of advanced reactors (INL, 2018). This workshop used a combination of interviews, focus groups, and surveys to gather input from stakeholders. The input collected entailed the identification of plausible research areas for emerging digital technologies, each with a ranking score used to help prioritize their importance for industry.

4.2.2 Assessing the Strength of Each Benefit and Cost

Identifying benefits and costs is an initial step in deciding whether to pursue a candidate technology. A logical subsequent step entails assessing the strength of each identified benefit in order to support prioritization. This section describes common tools that can be used to help with prioritization and weighting of importance. Potential tools include the 1) nominal group technique (NGT) and 2) Pareto analysis.

4.2.2.1 Nominal Group Technique (NGT)

The NGT is a powerful tool used to prioritize a list of items such as identified solutions (i.e., candidate technologies) or barriers, as part of reaching quick team consensus (Evans & Lindsay, 2013). Several advantages of NGT include the ability to collect input from all available team members, allowing each member to rank issues individually (without peer pressure), as well as to quickly establish a consensus (or lack of consensus) between team members. The steps of NGT first include generating a list of unique items (e.g., solutions or barriers), clarifying each item to the team, establishing and clarifying a ranking scheme, having each team member individually rank each item, and finally combining each of the team member's rankings into a master form. Typically, a higher-ranking number is assigned to denote greater significance. Figure 5 illustrates an example of NGT applied to prioritizing identified barriers.

No.	Barrier	Rater 1	Rater 2	Rater 3	Total	Weight	Rank
1	Insufficient Process Expertise and Operational Experience	1	1	3	5	0.06	7
2	Lack of End-State Vision	2	3	4	9	0.11	4
3	Costs	7	6	6	19	0.23	1
4	Cyber Security	4	7	7	18	0.22	2
5	Regulatory/Licensing	6	5	5	16	0.20	3
6	Status Quo of Existing DCS Solutions	5	2	1	8	0.10	5
7	Limited Time Windows in Which to Install the Upgrades	3	1	2	6	0.07	6
					81	1.00	

Figure 5. Example NGT Output.

As shown in Figure 5, the NGT results would suggest that cost was the greatest priority barrier; however, cyber security and regulatory/licensing were only slightly lower, compared to the other barriers. Rankings between individual raters were fairly consistent as illustrated by the embedded bar graph. Collectively, results from this example NGT suggest that particular attention should be focused on costs, cyber security, and regulatory/licensing aspects of a given candidate technology.

4.2.2.2 Pareto Analysis

Pareto analysis offers an approach to prioritizing mutually exclusive root causes of a known problem through an ordered visualization of their frequency and cumulative proportion (Kubiak & Benbow, 2009). Pareto analysis offers a way of quickly determining the most frequent (and assumed to be the most significant) root causes to a problem to help focus on the 'vital few' from the 'trivial many.' The key elements of Pareto analysis are a bar chart to show frequencies for each root cause where the bar height is proportional to the number of occurrences for a given problem category (i.e., root cause); the y-axis to the left corresponds to those frequencies. Additionally, there is a cumulative proportion of those problem categories (i.e., root causes) represented as a line graph where its y-axis is presented to the right ranging from 0 to 100 percent.

Pareto analysis is most helpful when frequency of a given problem can be a key metric and there needs to be focus on a subset of the most critical issues. For instance, there may be instances where a particular initiative may need to first focus on the most significant known plant issues in its modernization strategy. In such circumstances, Pareto analysis offers a way of supporting the decision-making process of determining the significance of each known issue or barrier.

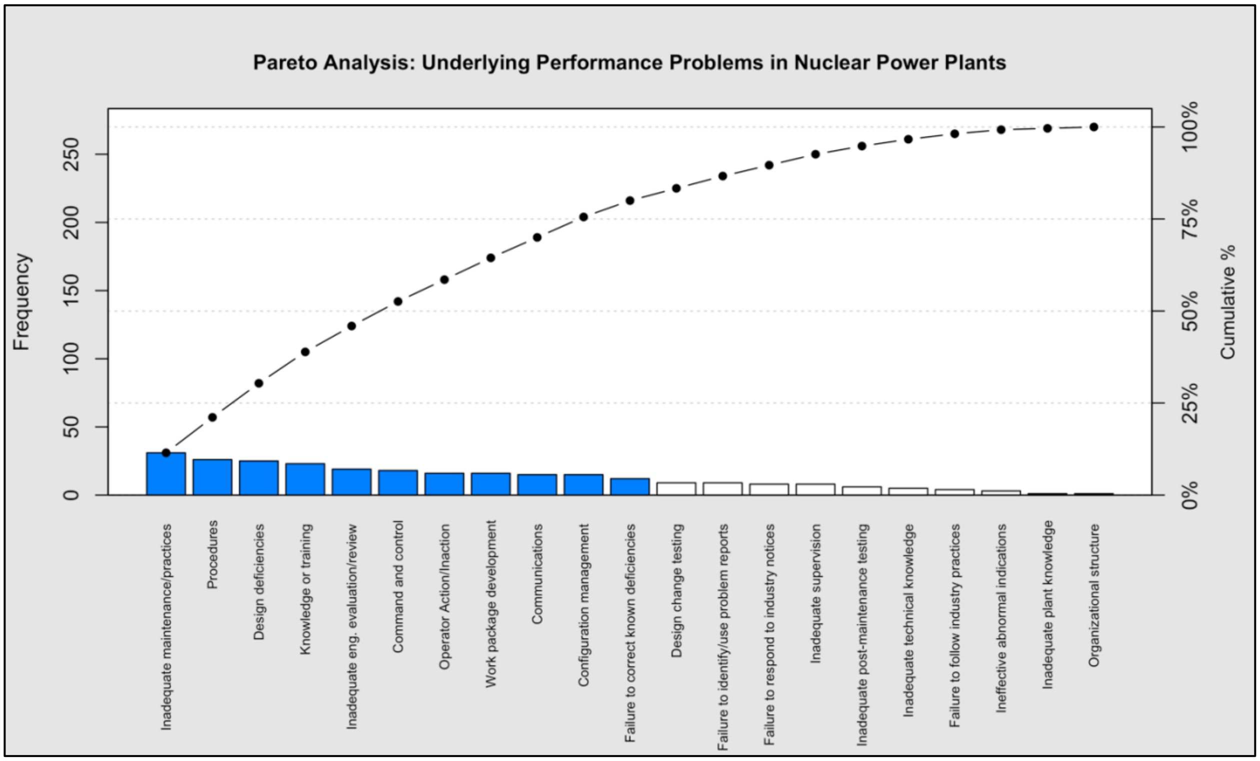

Figure 6. Example Pareto analysis. Data adopted from INEEL/EXT-01-01167 (NUREG/CR-6775) for demonstration purposes.

Figure 6 provides an example Pareto analysis, using data from Table 2.3 of NUREG/CR-6775 (Gertman, Hallbert, & Prawdzik, 2002), in order to demonstrate characteristics of a Pareto chart. The 'vital few' are illustrated in blue and are determined using the 80/20 rule; that is, the most frequent root causes that cumulatively represent 80 percent of all known issues are highlighted here as a way of supporting in prioritizing these as most significant.

4.2.3 Determining the Overall Value of a Digital Technology

A final step entails using the information collected from the previous activities to decide whether to pursue or reduce the known barriers for a candidate technology. This section describes common tools that can aid in the decision-making process. Potential tools include 1) a force field analysis and 2) the Pugh analysis (decision matrix).

4.2.3.1 Force Field Analysis

Force field analysis is a team decision-support tool used to compare all 'driving forces' to all 'restraining forces,' as part of deciding whether to support or not support a specific initiative (Kubiak &

Benbow, 2009). The steps involved in performing a force field analysis include generating a list of all driving forces (i.e., benefits) and restraining forces (i.e., barriers) of a related initiative (e.g., adopt a soft control system into the main control room of an NPP). This list of forces can be generated from the previous activities described in this Section. Graphically, the force field analysis presents each list of forces as separate columns where the green/left-side column consists of the driving forces and the red/right-side column consists of the restraining forces. Next, the team ranks or weights each list based on their impact on the initiative. The team may use the NGT or a related methodology to create weights or ranks for each driving and restraining force. Interpretation of the force field analysis may be at a holistic level or at an individual force level. That is, the summation of each force may be evaluated holistically to make a decision, or each individual force may be evaluated to determine where specific resources should be allocated to support deploying a new digital technology. For example, the latter application of this force field analysis may be used to decide where to focus resources as part of reducing the impact of individual restraining forces whereas the former application may be used to make a go/ no-go decision on deploying a digital technology.

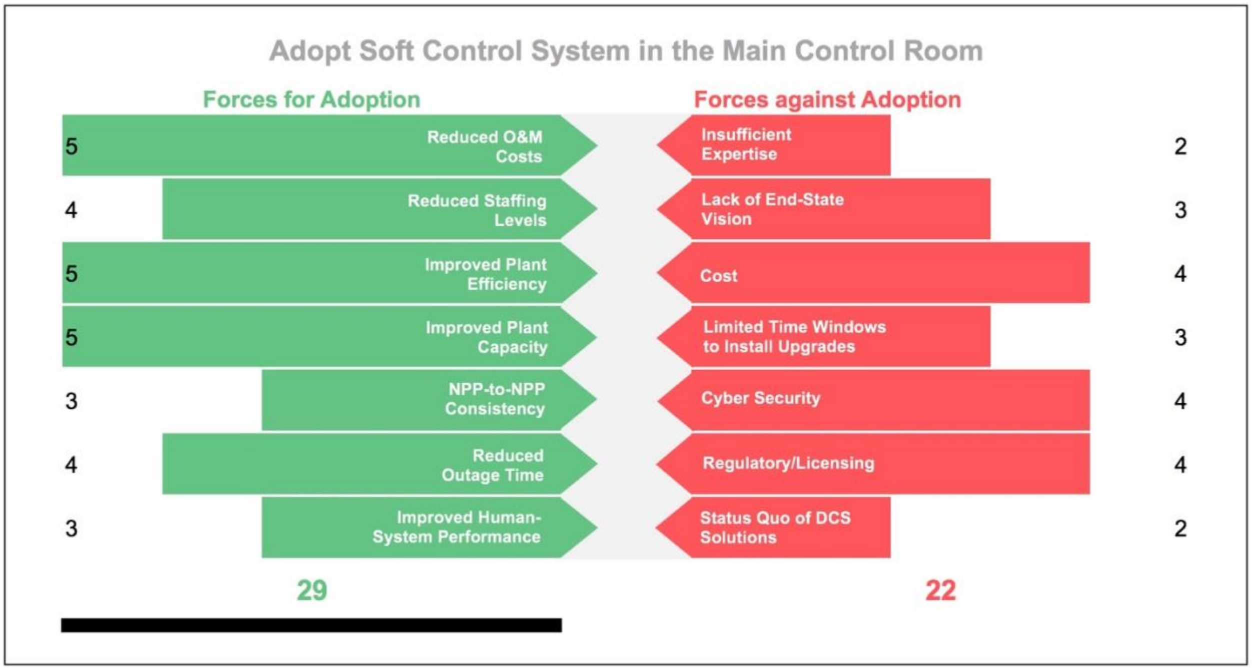

Figure 7. Example Force Field Analysis.

Figure 7 illustrates a hypothetical use for force field analysis in making a go/ no-go decision for adopting soft control systems in a main control room. As shown, the driving forces for adoption are listed in the left-side column in green whereas the restraining forces for adoption are listed in the right-side column in red. A weighting scheme was used to show the most significant forces where greater values denote higher significance. The summation of these weights is provided below suggesting that there is a greater overall driving force than restraining force with adopting a soft control system; thus, the decision to pursue a soft control system would be what the force field analysis recommends.

One criticism of the weighting or ranking scheme using force field analysis, NGT, or other related methodologies is that an assumption is made that each item being used in the analysis is relatively comparable. That is, a value of ‘1’ given for cyber security is the same as a ‘1’ given for reduced O&M costs. There may be cases where the given forces are qualitatively different and therefore quantified differently, making them difficult to directly compare. Thus, care should be taken when performing an activity that uses a weighting or ranking scheme.

4.2.3.2 Pugh Analysis (i.e., Decision Matrix)

Pugh analysis, also known as a decision matrix, is a tabular-based decision support tool used when a single path or option must be chosen from a list of options (Kubiak & Benbow, 2009). Further, the decision is based on several criteria. A common format is to have the decision criteria presented in rows and each option presented as columns, creating a tabular matrix (e.g., like Figure 8). Each criterion is then weighted by importance with higher numbers indicating greater importance. A baseline may be established and used for comparison against each option. A common scoring scheme may use ‘0’ for at baseline level. Values may range from -2 to 2 where a value of -2 indicates significantly worse than baseline, and a value of 2 indicates significantly better than baseline for a given criterion. The final step entails multiplying the comparison scores to a criterion’s weight and then calculating a total score. The option with the highest score is treated as the best path or option.

Pugh Analysis: Comparing DCS Vendors

Criteria	Weight	Alt. DCS Supplier 1	2	3
Initial design and development costs	3	-2	0	-1
Easy to use technology	4	0	2	-2
Offers complete functionality requested	5	2	-2	2
Integration with major plant functions	5	-1	-2	2
Training costs	2	-2	2	-2
Maintenance and support costs	4	1	1	-1
Total		**-1**	**-4**	**1**

**3 DCS suppliers compared to a baseline supplier.*

Figure 8. Example Pugh Analysis.

A hypothetical example Pugh analysis is shown in Figure 8, illustrating how it could be used to select a specific DCS vendor in part of a control room modernization initiative. This example shows that the most important criteria for vendor selection are ensuring that the DCS solution offers the plant complete functionality as intended by the DCS platform and that the DCS integrates with all targeted major plant functions and systems being affected by the upgrade. Vendor 3 (highlighted in green) had the highest overall score, suggesting that it is the best option.

5. CONCLUSION

Existing commercial NPPs are valuable assets in the infrastructure portfolio of the U.S. because they safely and reliably provide approximately 19% of all the electricity generated. While other non-carbon emitting renewable electrical generation technologies are making advances, their intermittency poses challenges to their large-scale integration into the U.S. electric grid. Furthermore, historical analyses (Smil, 2010) have shown that previous energy transitions have taken decades (see Figure 9), and so NPPs are still needed for the foreseeable future to generate base-load electricity.

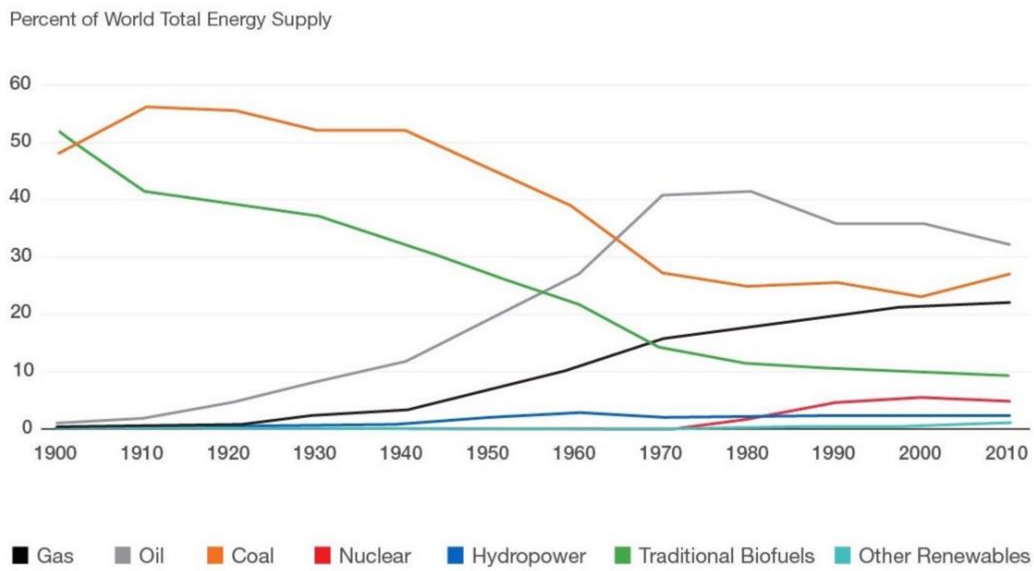

Figure 9. Percent of World Total Energy Supply for the Primary Energy Generation Sources.

The mission of DOE's LWRS program is to perform R&D that further establishes the technical bases to extend the operating life of commercial NPPs. The Plant Modernization pathway in the LWRS program focuses on performing R&D and then deploying and demonstrating digital I&C technologies that enable full plant modernization through broad innovation and through improving the business case for operating NPPs. In doing this, the LWRS program helps ensure I&C systems are not life-limiting issues for U.S. commercial NPPs.

A considerable amount of R&D has been performed in the human factors and I&C engineering areas under the LWRS program. This work has been done in collaboration with many different U.S. utilities, including Duke Energy, Palo Verde (Arizona Public Service), Exelon, Southern Company, and Dominion, and focused on I&C upgrades in both the control room and in the field. The work performed to date under the LWRS program has had a notable impact on the ability for these utilities to continue to operate their respective fleets of reactors, and LWRS program researchers are intent on doing even more. In order to do this, a more unified strategy for full nuclear plant modernization needs to be developed. This report documents the latest step LWRS program researchers have taken to develop this strategy. Taken together with prior reports written on this specific topic (e.g., Thomas & Scarola, 2018; Joe, Hanes, & Kovesdi, 2018) the work described here provides an even clearer picture on what the strategy for full nuclear plant modernization should look like. The end-state for full nuclear plant modernization is a seamless digital architecture that merges plant systems, plant processes, and plant workers that also considers the business case, technical feasibility, and the human factors of the solution. With this report, the decision factors to consider and the evaluation approaches to take are identified and described in detail, thereby completing the next phase of development of a strategy for full nuclear plant modernization. The next steps include engaging with LWRS utility partners, so they can review this strategy as it currently stands and provide feedback on it. Once agreements are reached, LWRS will look for utilities to provide plant specific technical information so that full nuclear plant modernization strategies populated with specific technical and operating information can be developed to help guide utilities on their path to full nuclear plant modernization.

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