METHODS AND MEASURES FOR CHARACTERIZING NUCLEAR POWER PLANT OPERATOR PERFORMANCE TO SUPPORT CONTROL ROOM MODERNIZATION

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ABSTRACT

An International Nuclear Energy Research Initiative (I-NERI) is being carried out between the US Department of Energy and Republic of Korea to develop methods and measures for characterizing nuclear power plant control room operator performance to support light water reactor control room modernization. Researchers from the Idaho National Laboratory (INL) and the Korea Atomic Energy Research Institute (KAERI) have completed the first year of a three-year project. The results of the first year's effort focus on the characteristics and differences between operator performance as dictated by the technologies that are employed in three reference case control rooms: analog control rooms; hybrid control rooms; and digital control rooms. A survey of literature and operating experience has been performed for the three reference cases. The reference cases are analog control rooms, hybrid control room that include a mixture of analog and digital instrumentation and control technologies, and digital control rooms. Recent efforts related to design of advanced light water reactors that employ digital systems are also included in the comparisons.

A number of issues have been identified from the literature and operating experience reviews that relate technology factors in control room design to efficient and reliable control room operator performance.

I. BACKGROUND

The Department of Energy (DOE) is conducting research and development activities through the Light Water Reactor Sustainability (LWRS) program to develop the scientific knowledge, methods, and technologies to sustain the current fleet of light water reactors in the US. This includes conducting research into advanced Instrumentation, Information, and Control (II&C) technologies such as the main control room (MCR) in order to support planned refurbishments, replacements, and modernization of existing analog instrumentation and control with newer digital instrumentation and control technologies. A key aspect of this involves a public-private partnership between the DOE, via the LWRS program, and owner-operators of commercial nuclear power plants (NPPs) to conduct research and development on projects together that result in development of technologies, methods, and results that are regularly published and promulgated to the commercial nuclear power industry and its various stakeholders (i.e., other owner-operators, vendors, original equipment manufacturers and suppliers, industry advocacy organizations, regulatory agencies, and others). In the area of advanced II&C research, the US DOE and the Republic of Korea through the Korean Atomic Energy Research Institute (KAERI) are conducting an International Nuclear Energy Research Initiative (I-NERI) project to study and develop methods and measures for characterizing nuclear power plant operator performance with control room I&C technologies. The purpose of this research is to develop methods that can be used to characterize the effects that new I&C technologies and the resulting mixtures of analog and digital I&C technologies in the MCR have on nuclear power plant main control room operator performance. This paper summarizes research published in a joint technical report produced through the I-NERI project (Park et al, 2015).

II. INTRODUCTION

Of the total 447 nuclear power plants operating worldwide, over 50 percent were built more than 30 years ago (IAEA, 2014). In most plants in the U.S., for example, analog instrumentation and controls (I&C), continue to be used, although for periods of long-term operation (i.e., 60 years and longer), refurbishments will be needed. The Republic of Korea has already begun some modernization of its existing Light Water Reactor (LWR) fleet I&C, and that experience could be valuable to leverage to support U.S. efforts. The 99 currently operating commercial Nuclear Power Plants (NPPs) in the U.S. were originally licensed to operate for 40 years. As these plants reach the end of their 40-year operating licenses, the majority are applying for license extensions for another 20 years. Additionally, some plants are considering an additional 20 years license extension beyond the extended 60-year operating license.

In parallel to license extensions, the planning for life extension and management of the capital assets of these facilities includes the refurbishment of the main control room and supporting I&C systems throughout the plant. In addition to addressing the aging of existing analog I&C technologies that prevail in today's control rooms, plants are also looking to these investments to increase efficiencies and reduce costs associated with maintenance and operations, compared to today's technologies. New technologies must also meet or improve the current levels of reliability overall so that availability and safety of the resulting solutions are assured. Some of the other challenges facing existing control rooms are summarized below.

- *The availability of spare parts for existing analog I&C.* NPPs have, out of necessity, stockpiled replacement parts for existing equipment of the MCRs. Broken parts are also serviced or rebuilt to extend their service lifetimes. These reserves are finite, though they have to date provided a needed supply to keep the plants functional, thereby obviating the immediate need for upgrades or new technology. However, in the longer term – especially for periods of longer operations – analog instrumentation needed to maintain an entire array of control room instruments is unlikely to be available.

- *The viability of like-for-like replacement technologies.* While there are truly no remaining large-scale manufacturers of analog I&C, many vendors provide equivalent digital systems. These technologies do not fundamentally change the control room but rather extend the life of the original design, in a manner of thinking. Few utilities can probably depend on a strategy of like-for-like replacements as a means of sustaining or extending the operability of their existing control rooms, except for the most limited, safety-critical I&C components, in the long run.

- *Needed return on investment from new control room technologies.* Investments in control rooms, like other plant systems, are needed to ensure continued operability. In addition, owner-operators may seek additional returns on their invested capital. This may come in the form of added functionality, expected improved efficiency of staff, reduced workload through minimized administrative functions, fewer errors and rework, improved safety or safety margins, and other tangible additive returns on the investments.

- *Regulatory Environment.* In addition to the direct costs associated with replacement of aging analog I&C, any significant design alteration that exceed certain regulatory thresholds undergo a validation and verification process to comply with the plant's operating license issued by the U.S. Nuclear Regulatory Commission (NRC) or equivalent national regulator. This process can result in significant financial and investments of other resources that have the potential to add delays and uncertainty to the design and implementation process. Research efforts are underway to reduce some of the ambiguity of the modification process to the control room (Boring et al., 2013).

- *The lack of experience in performing upgrades.* The lack of industry experience is a hurdle to performing control room upgrades. To date, none of the NPPs in the U.S. have completed significant modernization of the I&C in the MCR. A lack of experience compounds the challenges above, because there are few precedents, if any, for a clear path that industry can follow to progress on control room modernization. What limited experience there is, has been punctuated by considerable unplanned regulatory review, longer than planned time and cost for completion of upgrades, and has resulted in a chilling effect on utility willingness to undertake modernizations. Clear precedents for planning and executing digital upgrade projects in the MCR are needed to establish an environment of interest and willingness to make these sorts of investments.

- *The limited offline time of the control room.* Most NPPs operate 18 months between refueling outages. During this 18-month period, many plants now operate the entire cycle without a single trip or forced shutdown. During refueling, the MCR is still the control center of the plant, along with an outage control center to coordinate maintenance and refueling activities across the plant. Because systems are constantly in use, there are very limited time windows in which to make changes to the control room. U.S. plants would be unwilling to extend outages for significant change out of systems in the control room. The large-scale control room modernization with accompanying extended outages witnessed in some European and Asian markets, therefore, do not readily translate to the U.S. marketplace. Control room modernization efforts must be accomplished reliably, and in a time frame afforded by a typical refueling outage.

- *The training requirements for upgraded systems.* Licensed operators must be qualified to operate a new control system, just as they are to operate its predecessor. Qualification training is normally conducted in plant-specific training facilities. In order to facilitate such training, the new system is introduced into the training simulator prior to implementation in the actual MCR. This sequencing must be performed in an expedient manner to ensure that all operating crews are adequately training without having a training simulator that is different from the actual MCR for any significant period of time.

III. METHOD

As a part of developing and evaluating candidate digital technologies for control room refurbishment and modernization projects, the DOE LWRS program and KAERI through the I-NERI project initiated efforts in 2015 to evaluate data and published reports from available sources regarding the effects of analog, digital, and mixtures of analog and digital technologies – hybrid systems – on main control room operator performance. Data sources from both the nuclear sector and non-nuclear sector were included in our reviews, including data from reports issued from general industry, fossil power plants, health/tele-intensive care systems, manufacturing industry, aviation industry, mineral processing plants, refinery plants, and unmanned aircraft systems. Operators from existing analog control rooms in the U.S. nuclear industry were interviewed to obtain insights into the processes of operating an existing conventional, analog control room. Human performance data were also collected from the full-scope simulator of the APR-1400 (Advanced Power Reactor 1400MWe) (Lee et al., 2011; Seong, 2014), which is a representative source for understanding performance requirements of human operators working with mainly digital HSIs.

IV. ANALYSIS

IV.A. Common Human Performance Issues

A set of common human performance issues were identified in the preceding sources and were divided into sixteen categories based on subsequent analysis. These are shown in **Table 1**. The sixteen categories in the left hand column serve as grouping factors for the human performance issue subtopics identified from the available sources that we reviewed. The right-hand column denotes whether the research team considered the human performance issue to be applicable to a particular type of control room I&C environment, such as Analog, Digital, or Hybrid, denoted as A,H, or D in the table. The table of cross-cutting human performance issues is important as it represents known issues that have been encountered in prior design efforts resulting in fielded systems that could also be a challenge in the future for main control room operating crews if not addressed through a human-centered design and development process. These issues were considered in each of the control room environments under study; analog, hybrid, and digital control rooms, and are discussed subsequently.

Table 1. Human performance issues identified from published sources relevant to control room design.

Category	No.	Human performance issue description	CR type*
Human-Machine Interface (HMI) complexity	1	Complicated manipulations to use a digital system	H, D
	2	Additional manipulations to use a digital system	H, D
	3	Too many screen navigations	H, D
	4	High information density	A, H, D
	5	Increase of available information sources from a digital system	H, D
	6	Distributed information	A, H, D
	7	Misplaced salience (inappropriate HMI design)	A, H, D
Situation assessment	8	Keyhole effect (tunneling effect)	H, D
	9	Decrease of the range of vision (visual momentum)	D
	10	Loss of contextual information (spatial/functional information, visual patterns etc.)	A, H, D
	11	Out-of-the-loop with the level of automation	H, D
	12	Weak correlations between alarms and the associated process parameters or actions	A, H, D
	13	Lack of early detection support (monitoring failure, loss of vigilance)	A, H, D
	14	Missing task critical information	A, H, D
	15	Lack of in-depth insight of critical process dynamics	A, H, D
	16	Lack of big picture (e.g., process overview)	H, D

	17	Requisite memory trap (over reliance on previous memory)	A, H, D
	18	Lack of feedback information (including time delay)	A, H, D
Cognitive workload	19	Cognitive workload due to HMI complexity	A, H, D
	20	Cognitive workload due to alarm overload (too many alarms)	A, H, D
	21	Cognitive workload due to excessive nuisance alarms	A, H, D
	22	Cognitive workload due to data overload (large amount of process information)	A, H, D
Physical workload	23	Physical workload	A, H, D
Crew performance	24	Coping with complex disturbances (e.g., failure of indicators)	A, H
	25	Crew performance in the failure of a digital system (or degraded digital system)	H, D
	26	Communications among crew members	A, H, D
	27	Coordination among crew members and group decision making	A, H, D
Opacity in a digital system	28	Complexity creep (systems with too many features make it difficult for a person to develop an accurate mental model of how the system works)	H, D
	29	Difficulty in understanding automation (visibility of automation system)	H, D
	30	Information hand-off among different crews	A, H, D
	31	Confusing and unstructured presentation of indicators or display	A, H, D
Absence of physical texture	32	No haptic response from a digital system	H, D
Novel human error in a digital system	33	Mode error	H, D
	34	Task management error (task initiation/monitoring/prioritization/termination error)	H, D
	35	Human errors related to the loss of automation	H, D
	36	Recovery of human error in a digital system	H, D
Dealing with diverse information across different sources	37	Alignment of controls and information displays to clarify their interrelations	A, H, D
	38	Concurrent use of analog and digital systems	H
	39	The effects of HMI consistency on alternating use of HMI components	A, H, D
Fatigue due to environment	40	Anxiety, time pressure, work criticality, and other stressors	A, H, D
	41	Digital fatigue including musculoskeletal system disorder, and VDT syndrome (eye strain and headache, etc.)	H, D
Confirmation/trust on a (digital) system	42	Low trust in sensor readings	A, H, D
	43	Personnel acceptance of upgrades (to digital systems)	H, D
	44	Control initiative between human operators and digital systems	H, D
	45	Low/over reliance on a digital system	H, D
	46	Complacency	H, D
Change in the role/function of human operators (teamwork)	47	Change in the role/function of human operators with respect to the level of automation	H, D
	48	Change in the role/function of human operators with respect to the use of new digital systems	H, D
	49	The effects of HMI design on crew coordination and cooperation	A, H, D
Training	50	Loss of skills since automated tasks are seldom performed	H, D
	51	Training in HMI skills (training for less experienced human operators)	A, H, D
Maintenance	52	Impact to human performance of maintenance activity	A, H, D
Perceptual demand	53	Lack of emergent features	A, H
	54	Poor HMI display legibility	A, H
	55	Induced parallax effect due to distorted view of needle meter to value (analog display)	A, H
Control room/ component layout	56	Mismatch between physical and functional workflow	A, H
*A, H, and D analog, hybrid, and digital control rooms, respectively.			

IV.B. Analog Control Room

As the name implies, the defining feature of an analog nuclear control room is the expansive and continuous representation of plant statuses and controls based on analog instrumentation and controls. Large control boards or control panels are required to house the indication and controls for all the necessary plant systems and components. In general these analog control boards wrap around the exterior of the control room, though due to various design differences and plant vintages, the physical layout can vary extensively. A typical main control room from a nuclear power plant is show in **Figure 1**. The control boards themselves have somewhat more consistency in their design than the control room layout. The control boards are typically subdivided horizontally into panels that house related plant systems. Each panel can be further subdivided into vertical sections with fairly standard design schemes. The uppermost portion of the panel houses alarm tiles, which consist of a series of binary light indicators for each possible alarm. Below the alarms are the indications that represent component sensor values. These indicators can vary in their format, but the typical suite of indicators consist of radial, vertical, and horizontal gauges with physical needles that convey the value for a component sensor at the current point in time. The indicators use varying scales depending on the value of the component sensor they are linked with, which requires the operators to learn the scale for each indicator in order to interpret the information correctly. Below the indication section of each panel is a control section. Unlike the alarm and indication sections, the control sections are not vertically positioned, but rather they are slanted horizontally to make manipulation of the controls easier for the operators. Numerous types of controls are used, but typical controls that can be found in an analog nuclear control room include rotary multiple position switches, push buttons, key operated switches, and spring operated pull levers. Controls used for conservative actions, such as reactor or turbine trip actions, use a mechanism to prevent accidental activation. The mechanism can vary, but common methods involve using two separate controls where both must be activated, a key switch that can only be manipulated with the key inserted, and guards that must be opened before the control can be activated. These physical controls serve as one of the defining features of an analog nuclear control room, because they require physical manipulation of a three dimensional device for actions that are commonly completed with a mouse click and virtual button in applications found outside of nuclear.

The human performance issues related to analog control rooms have implications regarding the perceptual, cognitive, and physical demands for operators. Specifically, operators must deal with a diverse set of non-integrated information adding to HMI complexity. The sheer number of indicators coupled with small font sizes and difficult-to-reach locations can have a negative impact on legibility and ergonomics, respectively. Additionally, the non-sequential workflow and lack of emergent features can tax mental and physical workload when dealing with this diverse information across the control room. Mechanically driven controls can require an unnecessary level of proficiency for making fine-tuned adjustments to various parameters. Likewise, failed instruments that do not indicate their failure and overly sensitive alarms can provide misleading information, which can threaten operator trust in the indicators. Paper-based procedures (PBPs) are constrained by their static nature, requiring operators to commonly place-keep across several procedures concurrently. These PBPs can also be onerous with maintaining accuracy, especially when accounting for changes to the plant. Finally, analog alarm panels present unique challenges to the operator such as alarm flooding, nuisance alarms, and alarm panel cluttering, which induce information overload.

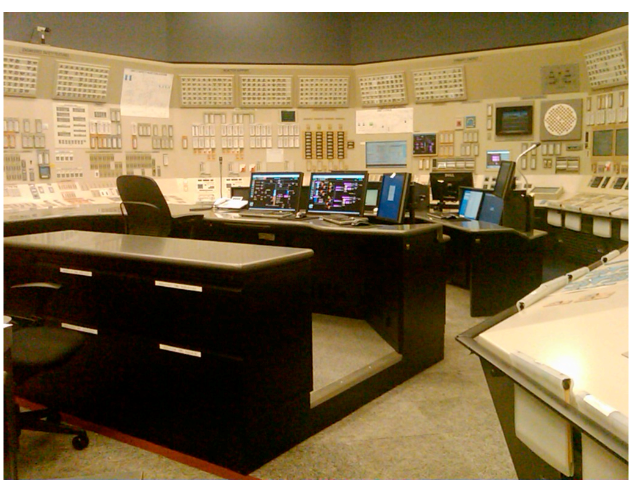

Figure 1. Example of a mostly analog I&C nuclear power plant main control room

IV.C. Hybrid and Digital Control Rooms

Although there are several definitions for the hybrid replacement, the following definition seems to be sufficient for the scope of this project:

> "The term hybrid system denotes any system that is built on heterogeneous technological solutions. Examples are combining hard and soft controls, different generations of analog and digital equipment, and different control system technologies." (IAEA, 2010; p. 1)

That is, a hybrid control room means a control room equipped with various kinds of HMIs, of which some parts are operated by analog technologies and other parts are designed by digital technologies. In this regard, it is well known that typical digital technologies available for use in hybrid control room include: workstations, large display screens, soft controls, automations, computerized procedures, digital alarm systems, and various kinds of operator support systems (NEA, 2007; IAEA, 2007; IAEA, 2010).

A review of sources from nuclear and non-nuclear sources was conducted to study potential impacts to individual operator and crew performance from the introduction of or transition to a hybrid control room in which digital and analog I&C technologies are mixed, requiring operating crew members of the main control room to know and understand how to use both types of technologies to accomplish control room operations tasks in the same control room I&C environment. The focus of the review was not on evaluating whether one type of technology was better than the other, but rather on identifying what new types of performance issues - including error traps - might be introduced and therefore need to be systematically addressed through design processes to ensure a highly reliable and usable design as an end product. Issues from prior research carried out in the nuclear power sector resulted in identification of fifteen potential human performance issues that could arise in the transition from an analog to hybrid main control room. It is likely that these not only reflect, in part, some of the challenges of introducing newer digital technologies to accomplish tasks conducted previously with analog devices, but also differences in the degree of attention paid to human factors engineering and human-centered design processes employed throughout the design engineering process. **Table 2** summarizes these issues below.

Table 2. Potential human performance issues with hybrid systems from prior efforts in the nuclear industry

No.	Category
1	Change in the role/function of human operators
2	Cognitive workload
3	Confirmation/trust on a digital system
4	Crew performance
5	Dealing with different information available across different sources
6	Decrease of the range of vision (visual momentum)
7	Digital environment
8	Digital fatigue
9	HMI complexity
10	Novel human error in a digital system
11	Opacity in a digital system
12	Physical workload
13	Recovery of human error in a digital system
14	Situation assessment
15	Training

For digital control rooms, MCRs in which the preponderance of I&C technologies are digitally based input/output devices and displays, the results of reviews indicated that most of the issues associated human performance in migrating from analog to either hybrid or digital resulting MCRs are similar. That is, the issues and their relative importance to main control room operator performance by the transition from a mostly analog to mostly (or completely) hybrid or digital I&C main control room are similar. Of course, such a generalization is limited by the nature of the specific design of the resulting main control room and is influenced, in particular, by the design engineering process to a great extent.

V. CONCLUSIONS

A detailed review of analog, hybrid, and digital control rooms was completed to identify human performance issues that have implications for future modernization efforts. This review involved an intensive literature review spanning both nuclear and non-nuclear sectors, a review with SMEs, and results of the ISV and workload comparison for the APR-1400. The review uncovered cross-cutting issues across all three control room technologies, suggesting these issues uncovered were comprehensive for control room modernization. It is evident that the human performance can be impaired or degraded by issues associated with a particular I&C technology, or by cross-cutting issues that are relevant to more than one type of I&C technology, irrespective of what kinds of HMIs are used. Similarly, an increase in cognitive workload owing to overloading of data through newly developed technologies is also one of the cross-cutting issues to be properly addressed regardless of the type of HMIs. Here, if by acknowledging that most of the MCR refurbishment and modernization programs will include the use of analog and digital HMIs together (i.e., a hybrid MCR), it is possible to say that all the cross-cutting issues have the potential to become relevant and must be considered through human-centered design processes to facilitate continued reliable human performance in the main control room.

Plans for this project in 2016 include the identification or development of methods and measures for characterizing operator performance with analog and digital I&C technologies, including those needed for characterizing operator performance in hybrid I&C main control rooms.

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