INL/CON-16-40650
PREPRINT

Comparison of Mutual Awareness in Analog vs. Digital Control Rooms

1st International Conference on Human Error, Reliability, Resilience, and Performance

Kateryna Savchenko, Heather Medema, Ronald Boring, Thomas Ulrich

July 2017

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Kateryna Savchenko,[1] Heather Medema,[1] Ronald Boring,[1] and Thomas Ulrich[1]

[1] Idaho National Laboratory, PO Box 1625, Idaho Falls, ID 83415
{kateryna.savchenko,heather.medema,ronald.boring,thomas.ulrich}@inl.gov

Abstract. Control rooms in nuclear power plants are complex, collaborative working environments rife with potential for human error. As control rooms evolve from analog to digital interfaces, crew communication strategies must change as well. With the increase in automation and the use of digital HMIs, operators no longer rely on large annunciator panels, but have instead moved to personal sitting workstations. The technology shift causes operators to focus only on their screens, reducing interaction between crewmembers. Therefore, the collaboration and coordination of task demands requires greater attention to communication, vigilance and mutual awareness, or collective knowledge of the situation. This paper will investigate, through literature review and expert interviews the impact of the technology shift and identify significant and critical improvements that can be implemented in the main control rooms to increase safety and reliability.

Keywords: Nuclear Power Plants · Main Control Rooms · Human-Computer Interaction · Situation Awareness · Mutual Awareness · Teamwork

1 Introduction

Nuclear power plant (NPP) main control rooms (MCRs) are complex, dynamic environments. As such, operators must monitor and control complex systems while under stressful conditions with the potential for severe consequences if performed incorrectly [14]. Therefore, teamwork culture serves a vital role in enabling this complex monitoring and control in a safe manner. Work environments, such as NPP MCRs, organize teams hierarchically and assign specific roles and functions to support successful integration, synthesis and sharing of information [23].

The majority of work within the MCR centers on procedures carried out by two reactor operators (ROs) overseen by one senior reactor operator (SRO). ROs primarily are tasked with maintaining safe and correct plant operations, optimizing parameters, coordinating the functioning of the reactor and its systems, and detecting and reacting to plant deviations from the normal conditions and states. SROs are responsible for the safe manipulation of the controls of a nuclear reactor and give direction of ROs to manipulate these controls. Furthermore, they are required to effectively plan, maintain, and supervise efficient plant operations in the MCR, as well as direct and implement emergency operating procedures and event reporting [16], [23].

SROs and ROs often experience high levels of workload in such a complex environment where they have to cope with multiple information sources, performance pressure, and changing scenarios. Furthermore, this high workload strains the operators' ability to perform multiple activities in parallel, which can lead to various problems such as inaccurate communication.

Management of the NPP during normal and abnormal situations requires effective team communication and coordination. Standardization of communication and support technology is critical for a number of reasons 1.) to reduce the potential impact of human errors attributed to the increasing complexity of new digital main control rooms, 2.) to balance the crew demands and available resources to keep mutual awareness between SROs and ROs at a high level and, 3.) to prevent the immediate and severe consequences of poor team performance [17].

This paper will investigate, through a literature review and expert interviews, the impacts resulting from the increasing complexity of new digital main control rooms. Comparison of the new digital interfaces with existing analog interfaces in NPPs has the potential to shed light on the lack of mutual awareness and communication breakdowns between the SROs and ROs in the MCRs. This paper describes the concept of teamwork and teams in terms of situation awareness and mutual awareness within crews in MCRs. Additionally, we will compare mutual awareness in analog and digital control rooms and discuss ways to mitigate the potential decrease in mutual awareness suffered in crews operating digital control rooms.

While this paper highlights potential breakdowns in communication and mutual awareness, it is important to note that a simple failure of this sort does not automatically equate to an unsafe condition at an NPP. Plants entail multiple redundant safety systems, processes, and second-checking staff. Where breakdowns occur, for example, in threeway communication, these issues are typically identified on the spot by fellow crew members and remedied. However, many of the safeguard processes to prevent mishaps may need to be revisited in light of new technologies in the MCR. Where there is the potential for established and trusted safeguard processes to fail in new contexts, these must be identified and mitigated.

2 Situation Awareness

Situation awareness is central to achieving optimal performance in the MCR. Endsley[3] defined Situation Awareness (SA) as "the primary basis for subsequent decision making and performance in the operation of complex, dynamic systems..." At the lowest level of SA, the operator takes in relevant information from the environment, the system, and self. Within the mid-level stage, information is integrated relative to task goals. Finally, in the highest levels of SA, the operator uses information gathered to predict future events as well as system states. In a dynamic environment such as an NPP MCR, seeing a big picture could reduce risks by identifying potentially problematic situations. Situation awareness operates at both the individual and at the team level. Operators must first build SA individually from the information they have immediately available to them. Then the team can form situation awareness at a higher level by communicating aspects from each individuals SA into a collective team SA.

Team SA is shared SA about plant conditions. In contrast, mutual awareness is the crews' awareness of each other. The next section will discuss in more detail the concept of mutual awareness within MCR operating crews.

3 Mutual Awareness

For a team to operate effectively it is important that the whereabouts, actions, and intentions of each individual can be communicated to other team members so that mutual awareness can be created. Mutual awareness (MA) can be defined as "an awareness of the state of a cooperative effort [18]". It is the knowledge of what other team members are doing, how they are doing it, as well as how and when they can affect each other's activities. Mutual awareness is important for individuals to be informed about each other's actions throughout the task. Team members try to fine-tune their own activities to provide their colleagues with cues about their intentions and other different kinds of information relevant to their activities. This awareness is established through various actions of individuals and is affected by the type of action, the number of actions, and when the actions occurred. Mutual awareness can be maintained through the oral exchange of the information, gestures, body language, and artifacts [25]. Furthermore, the crew can access mutual awareness through vision, sound, odors, vibrations, touch, and movement present in the shared work environment [18].

4 Changes in Mutual Awareness Due to Technology Shift

Interviews with five subject matter experts on control rooms highlighted a number of concerns regarding mutual awareness in the face of changing technology. As MCR technology shifts from analog displays to digital interfaces, significant changes to MA become apparent due to the differences between the two information display formats. In the traditional MCR, the large analog control panels span large areas primarily due to the sheer size of the instruments themselves. These larger panels naturally afford working as a team, simply because the information is distributed in many places. Operators each check individual values and relay these values back to the SRO to build the SA. This distribution of information assists the operators in understanding how their small aspect of the system relates to the larger operation of the plant and makes them aware of each other's activities and actions [25].

Control panels are associated with specific plant functions and components, i.e., the reactor, main steam and steam generators, and are each housed on their own control panel. These analog boards also contain arrays of indicators, buttons, and controls with which ROs and SROs monitor and control to support the functions for each plant system [23]. Each panel has a larger prominent array of annunciators that provide contextual cues to help operators quickly orient themselves to the functions occurring within each control panel. This analog representation also enables multiple operators to simultaneously see all the information at-a-glance and mentally integrate information across the boards to build a comprehensive high-level representation of the plant. Analog interfaces offer the advantage of a tactile feedback from pushing the buttons and using the controls only accessible on specific boards. Furthermore, instant immediate tactile, audio, and visual feedback is available, including click sounds and visual changes in positioning of the physical control. Thus, the operators' mental model and expectations of how equipment and controls are supposed to operate are supported with physical mapping of plant components to controls and indicators arranged along the control panels.

Mutual awareness is enhanced through the salient and visible cues of the operators themselves physically positioned around the analog MCR [23]. Therefore, ROs and SRO are able to coordinate and align their own activities with each other. For example, seeing ROs at the certain control board provides cues to the SRO about plans and procedures they are engaging in at the moment, thus confirming or not the correct actions of the ROs as well as expectations of the SRO [7].

New digital control rooms introduce a variety of new technologies, increased automation, and employment of graphical interfaces [23]. Operators typically sit at separate workstations with a digital control system where they have different small displays which enable them to navigate and operate the plant [25]. Digital interfaces are more compact, flexible, and configurable to particular tasking of the operator including useful trending displays and overall consistency with the design of indicators and controls. Furthermore, information about the whole system can be available at any location of the control room. Operators focus on their own screens and can perform their activities autonomously [9]. System functions are increasingly allocated to the automated computer controller, which moves the operator to the position of supervisors [12]. MA is expected to be supported by human-system interfaces (HSIs) with integrated information and a common overview display. However, separate workstations and inability to share information between ROs as well as the SRO creates an opportunity for error due to the lack of communication [11]. The SRO may lose the ability to supervise the activities of ROs and becomes a passive observer with higher workload due to higher responsibility [10]. Thus MA is maintained through the oral exchange of information that requires more increased communication frequency [11], [25], [26].

5 Communication Issues Due to Technology Shift

Despite the many benefits of automation, there are noted ramifications as well. A number of critical HSI factors must be considered as MCR technology shifts from conventional, analog displays to new digital instrumentation and control (I&C) systems. There are a number of human factors concepts that arise with the transition and potentially affect SA and MA.

In new digital control rooms, operators remain in shared space, yet the means by which operators obtain and share critical plant information has critically changed. Rather than visualizing plant system data and status via large wall hung annunciator panels and other plant control panels, information is now available via digital interfaces. These visual display units (VDU) bring benefits for safety and flexibility by combining information from various sources [20]. A great breadth of information may be concentrated within one interface and may be difficult to sort through for the desired piece of information or tool. This phenomenon, coined the Keyhole Effect [21],

[22], was named to describe the idea of "peeping through a keyhole to find the relevant piece of data in a room full of possibilities behind the closed door [1]." A keyhole effect in an MCR creates difficulty in fully understanding the system in question, because the operator is only afforded partial system information at any given time and must search for additional information within the display.

Another human factors concept is operator-out-of-the-loop performance problems. The term *operator out of the loop* (OOTL) refers to both system performance and human performance problems that arise as the MCR operator struggles to maintain situation awareness [8]. Operator reliance on the automation leads to a number of potential, critical missteps including lack or loss of adequate skills, a shift from an active to passive state in information processing, a change in the feedback provided to the operator, and finally to vigilance and complacency obstacles for accurate situation awareness. These ultimately lead to an inability to take back the reins from the automation and operate the plant in manual mode should automation failure occur [4].

6 Conclusions

In this paper, we've explored the field of research concerning the potential negative impact of changes in MA between SROs and ROs with technology shifts in the MCR of NPPs. Table 1 summarizes several of the issues found in interviews with subject matter experts. Team collaboration and coordination play an important role in digital operating systems as well as in causing incidents. With the use of fixed analog control boards, ROs and SROs could see the big picture of the plant, but digital systems may place the operators at spread out workstations. ROs may be less able to share information with each other and maintain high MA. Below are the ways we propose to combat the lack of MA.

- *Training*. The procedural and strategic knowledge of the system benefits operators in providing more time and attention resources to communicate with each other as well as understanding how the system works [7], [25]. The knowledge can be gained through the proper training. Causes of human error in the nuclear industry can be a lack of proper training and understanding of operational procedures [5], [6], [15]. The nuclear industry needs to train operators to reduce the potential knowledge and experience gap during the emerging technology shift in the MCR. Every operator must be able to work productively and safely around other operators to share the critical information and increase MA. Training on plant's procedures, capabilities, vulnerabilities, limitations, and hierarchy of priorities is necessary to achieve that goal.
- *Staff briefings and peer checking*. Briefings of operators can support high levels of MA as well as peer checking (PC). Briefings are good to get everyone back on the same page, and to promote and ensure the coordinated effort in accomplishing the goal of safe operations of the NPP [19]. During the PC, two people self-check in parallel and agree on the correct action to be carried out on the appropriate component. Action is the primary focus of PC. This also brings a fresh set of eyes

to the issue. The peer who has knowledge and familiarity with the activity and intended results might notice the hazard that the performer cannot see [2].

- *Mimic screen.* Redesign of the display interfaces can improve MA and support communication between operators under task conditions as well. Adding a mutual awareness tool (MAT) or "mimic screen" to the digital interfaces of a NPP could improve crew's MA [13], [25]. The tool would "mimic" what ROs are doing, which procedure and step in the procedure they are using, and systems each team member is on. The SRO would have the means to monitor and verify the parallel activities of ROs. Less time would be spent on the discussion and exchange of information promoting operators working in isolation.

Table 1. Summary of experts' interviews.

	Issue	**Solution**
Teamwork	Failures of team coordination cause disruptions in plant operations.	Proper training, peer checking and briefings to improve effective communication is needed.
Mutual Awareness	Team members are not aware of each other's activities and intentions.	Increased frequency of communication and exchange of information is needed.
Communication	Lack of MA causes breakdowns in three-way protocol.	Operators can increase the use of briefings and peer checking as well as enlist in additional training to effectively communicate.
Control Room Environment	Technology shift causes operators to perform plant operations in isolation, experiencing overload of information.	Regular peer checking, briefings, proper training and use of mimic screen can help to exchange information.

Any design flaws have an opportunity to bury critical information and create overload of information for the ROs and SRO. This is the first of a series of papers exploring MA and investigating means for effectively reducing issues linked to transitions of technology in the MCR. In terms of future research, a thorough development and evaluation of the new technologies in terms of potential negative and positive effects is needed to ensure the appropriate application in the control room to support team performance, MA, and plant safety [23]. Further, the researchers will expand the knowledge base by gathering and evaluating input from actual operator users.

7 Disclaimer

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