Use of Simulator Experience and Insights in the Design of Control Room for New Nuclear Plants

Archana Yadav, Alpana Goel, and P. V. Varde

1 Introduction

Nuclear Reactors have evolved from the early prototype power reactors in the 1950s to evolutionary generation IV+ reactors, with advanced safety features and minimal waste generation. The commercial power reactors began operations in the 1960s with an expected lifetime of 40 years. With the advancements in technology and more emphasis on passive safety systems, the lifetime of generation III reactors could be extended to 60 years [1]. With more than seven decades of safe reactor operations, nations are still struggling to expand their fleet of nuclear reactors either due to lack of public acceptance or due to political hindrances. A nuclear incident and accident anywhere in the world make a significant impact on the fate of these sociotechnical complex systems. Probabilistic risk assessment (PRA) has, to some extent succeeded in imbibing faith in the technology. An important aspect of maintaining and assuring reliability on the technology is by utilization of reliable systems, structures, and manpower. Humans are an integral part of system operation. In almost all the nuclear accidents namely Three Mile Island (TMI), Chernobyl, or Fukushima: Humans and their erroneous interpretation of the situation have emerged as a potential error causing factor [2]. Taking this fact into consideration better understanding of the human factor is essential. Human reliability (HR) and human error rate prediction are of immense importance to ensure the smooth functioning of facilities and avoid incidents that might collate and grow into big accidents. Although the need for human factor study and reliability has been under consideration since the earliest

A. Yadav (✉) · A. Goel
Amity Institute of Nuclear Science and Technology, Amity University Uttar Pradesh, Noida Sector 125, Noida, India
e-mail: ayadav3@amity.edu

P. V. Varde
Bhabha Atomic Research Centre, Mumbai, India

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PRA documents were in place, with evolving technologies, the approach must be reviewed and must consider effects due to digitalization [3] and include cultural and organizational factors.

For the past many years HR analysis has gained immense importance due to the increasing contributions of humans in the progression of accidents specifically in nuclear accidents. The creation of HRA software and its validation requires data. The data available is either not enough or the models rely completely on expert judgments. Another prominent way of generating data is with the aid of training simulators. The full scope simulators appear as an option for getting data for the development of human reliability software. Power plant and research simulators are a way of closely looking at some of the features like plant functionality, parameter evolution, and crew behavior analysis, human factor analysis etc. They are being used for training, authorization, licensing, and development purpose and have proved their efficacy [4].

Catering to the evolving control rooms in complex systems, human–computer interactions have been studied in dynamic scenarios and evolving technologies with the aid of video recordings, operator action evaluations, and activity tracking [5]. This paper gives brief insights into the control rooms, simulators, and their role in the determination of human reliability.

2 Control Room

The control rooms in complex systems are one such important locations wherein there is strong human–machine interaction. Through the control room, the plant can be operated either automatically or manually in almost all operational states. Plant activities are controlled and managed from the control room. The plant is spread out into different areas and zones. The status of equipment, as well as various processes and safety parameters, are brought to the control room for improved surveillance and monitoring of the plant to perform an action, coordination, and communication with various plant agencies that support reactor operation. These are manned by a highly trained and experienced crew.

The control room depicts the plant state with help of alarms, signals, indicators, and display units. The trip and alarm windows are lined up on top for operator attention and prompt action. The console offers operations like power maneuvering, startup, shutdown, safety system actuation etc.

With technological advances, a significant change has been witnessed in the way new reactors are designed and developed. So has been with control rooms, from big, bulky analog systems to compact and more user-friendly digital control rooms is what we can see in the advanced reactors. Supervisory control and data acquisition systems (SCADA) provide relevant information to control room operators [6]. The present technology focuses on building systems taking humans/operators at the center and then building systems around them, rather than a no participatory older approach. The newer control rooms come with a higher degree of automation and offer a better understanding of dynamic plant states to the operator giving more time to think and respond particularly in emergency or non-routine tasks. The operators are now managers rather than operators.

The operator performance factors both physiological and psychological affect their performance along with the ergonomics. The human factors are dynamic and evolving in such evolving atmospheres of digitalized control rooms. Guiding documents and guidelines from IAEA, IEEE, and IEC, like IEC60964 along with ISO documents (ISO 11064, ISO 92415, EEMUA 991, EEMUA 201) are in place to help design control rooms and focus on the functional aspects right from the design stages. Detailed guidelines are available regarding both software and hardware reliability requirements. The focus is to ensure safe and secure plant operations along with a better equipped and informed operator [7].

2.1 Control Room Evolution

There has been significant technological development that has taken place in control rooms since the early reactor operations. The first-generation control rooms had fixed components and analog operations. Mostly hard panels, physical switches, and knobs to carry out operations. The second generation moved to visual display units and operations were carried out with help of keyboards. Through the improvement in ergonomics and anthropometric standards, human factor incorporation is also made possible, while designing control systems having strong human–machine interactions. With advancements in computers, communication methods, and digital systems, the third-generation control rooms emerged with better and improved performance parameters, which are augmented with operator support systems. The control rooms have been designed with high-density visual display units, larger displays, color-coded indicators, and with operator support systems [8, 9] to help operators make decisions in less time and have better utilization of their cognitive features (Fig. 1).

This is of importance in stressful situations like accidents or unanticipated operations. While this can also induce additional stress due to complex digital environments as embedded screens and panels can be difficult to trace. Studies reveal that humans fall short of cognition in stressful and non-routine situations [11]. Another challenging factor here is to create an interface between safety and non-safety systems. Complete overhauling of systems may be cost-intensive, better would be to digitize, and automate systems required during design basis accidents wherein response expected is quick and accurate. The areas requiring attention deal with the incorporation of attention and alertness aspects along with situation management and plant state assessment [12]. It has been observed that more automation is also increasing the possibility of human errors [13]. Humans are becoming more reluctant and completely relying on systems for guidance and actions to be taken.

Fig. 1 Control room of Dhruva [10]

3 Simulator

The control room evolution and up-gradation can be supported with simulator operations. The utility of simulators has been exploited across nations to both upgrade their existing control rooms and design modifications [2] suggested for newer ones. Simulators in an exact replica of control rooms and miniature versions are being utilized for various functionality evaluations. A Research reactor simulator is shown in Fig. 2. Personal computer-based versions of simulators are also available for majorly all reactor types [14].

Simulator exercises, drills, training, and procedure amendments can be suggested based on operator feedback, operating experience reports, and data collected during the operation of real-time systems. This can also be augmented with expert elicitation techniques and data collection from experienced operators and crew. Control room evaluations have been done with help of operator activity analysis (log of actions), questionnaire [15], and improvement in ergonomics with inputs from operators [16]. Further several quantitative analysis methods like analytical hierarchy processes and fuzzy logic can be used to arrive at subtle numbers to be utilized in PRA studies for risk calculation.

Fig. 2 Simulator of a research reactor [17]

3.1 Merits and Demerits of Simulator-Based Studies

Replica simulators, full-scope simulators are being utilized for a few decades for operator training and procedural developments. These have helped in training and development. Dynamic scenarios and design basis accidents can be simulated, and results will help improve the real systems. Significant work done [18–20] provide an insight into the development and application of operator support systems, particularly designed for maintenance of normal operation and if the need arises then for emergency scenario handling. Many beyond design accidents can also be simulated which do not lead to core damage [21].

Advantages of the technology are that the non-routine and emergency scenario training for example Loss of coolant accident and complete power failure scenarios can be simulated, and operator behavior recorded and analyzed. This will help in the development of training documents, procedures, and guiding documents for future reactors and emergency scenarios. This gives an opportunity to check for nonconformity to national and international standards which can be subsequently corrected. Through these exercises, the identification of safety–critical scenarios, components, and alarms can be established. Which will help in improved operator training and development of checklists, and guiding documents, not only for design basis accidents but for hypothetical and beyond design basis accidents.

Upgradation of simulators before actual control rooms gives a better understanding of system vulnerability and design amendments required. This also gives a better understanding of error-causing factors, aids human factor analysis and subsequent improvement in human reliability through the identification of appropriate performance shaping factors. Digital systems have testing and self-check features which is an added advantage.

The results of exercises done on simulator systems will aid the development and up-gradation of operator support systems, which is the need of the hour for newer and advanced control rooms as they might be completely digitalized [22].

With regards to licensing and regulatory aspects, these will support the identification of risk-significant scenarios and the identification of safety–critical systems. Since there is the feasibility of controlling experiment progression (speed and common mode failure induce) and with the possibility of tailoring of scenarios.

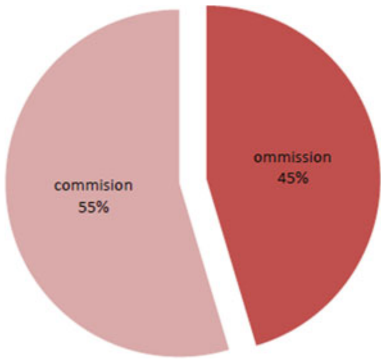
While the approach looks promising at the outset. There are some limitations and shortcomings as well, the economical liability is higher, and hence mostly full scope simulators are not preferred. While systems are being upgraded for real control rooms, up-gradation of the simulator before the actual control room increases the cost further.

Complete digitalization of control rooms can reduce human cognitive actions and has the potential to make operators error prone. Simulator bias (knowing that it's not a real system, propensity to hit and try with solutions) might be a potential challenge to develop data applicable for the real-time scenario. There is a need to eliminate the bias in data obtained due to environmental (different and unreal setup) and motivational (realization of no major consequences) effects introduced in the simulator experiments. Methods like the structural equation modeling approach quantitatively assess the motivational bias [23].

While identification and analysis of all potential error-prone conditions is a time-consuming task. Also, the possibility of simulating all possible combinations is quite improbable. A complete list of possible scenarios and analysis of all components can be a tedious task.

Simulator proficiency might also induce casual operator behaviors in routine situations due to prior positive simulator experiences. This may also induce faulty execution, omission, and deletion of crucial steps in procedures due to simulator exercises and end state prediction. An analysis with plant-specific data analyzed with help of the Technique for Human Error Rate Prediction (THERP) handbook shows the categorization of errors committed in the research reactor [24] (Fig. 3).

Fig. 3 Commission and omission error categorization for research reactor: THERP database



Lack of attention of operators due to over-reliance on technology can also be witnessed. With more and more digitalization and support systems for decision making error-prone conditions arise due to misinterpretation of the situation by computer or wrong logic interpretation. Further there would be significant difficulty encountered while modifications are taken up with control systems in both safety and operational aspects.

4 Human Reliability Assessment Tool Development

Probabilistic risk assessment has important contributors in terms of the human reliability factor. Humans being an important part of the system play a very crucial role. The need here is to remember that human error is a consequence rather than a cause; errors are shaped by workspace and organizational factors. There is a pressing need to change the conditions under which humans work and this would eventually improve the reliability of the entire complex facilities like nuclear power plants. While the first-generation methods (THERP, SPAR-H etc.) focus on humans being the sole contributors for creating errors the second-generation methods (ATHENA, CREAM) shift the focus on organizational and regulatory bodies (error producing conditions). Countries with sufficient data available from simulator exercises have also gone beyond the second-generation methods [25]. Human error behavior is determined by both environmental and human factors (physiological and psychological). Organizational factors play an important role in determining human error probability. Many well-developed methods are in place for the determination of Human reliability, but there is an increasing need to incorporate ergonomics, organizational and environmental factors like digital stress, safety culture, state/event-oriented procedures into the model. Owing to the lack of sufficient data and concerning guidelines there is a need for the development of methods that can provide satisfactory results within the available data either taken from operator logs, simulator exercises, and with the incorporation of expert opinions.

5 Analysis and Inference

Taking the reference and guidance of the THERP document (detailed handbook for HR analysis), Human error probability calculations were done and compared for plant-specific data from the research reactor. The pie chart at Fig. 4 shows the difference between the two. It is quite evident that there is a significant difference between the plant-specific values and that obtained from the standard document. This implies that for data under consideration THERP document might not be a suitable guiding document. The Human error probabilities might be very specific to the plant under consideration, the interface (HMI), safety culture, procedures, training, etc.

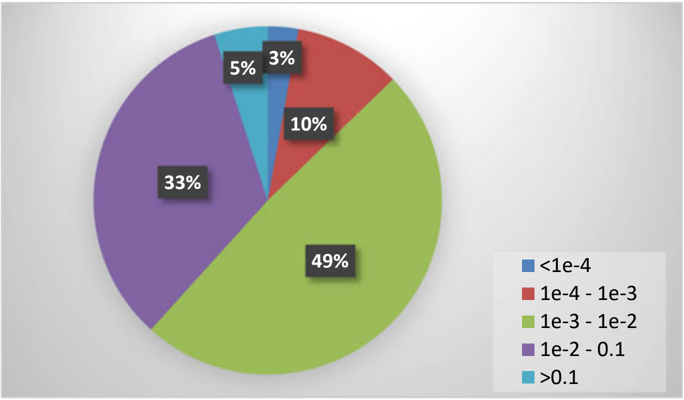


Fig. 4 Difference between THERP and plant specific values

Subsequently, the need for the identification of human factors arises. Factors like operator training, working environment, procedures, safety culture, human–machine interface, work timings, etc. require attention and quantification for the determination of human reliability.

6 Conclusions and Future Scope

For a better understanding of the Human–Machine Interface in a control room scenario, the advanced training simulators have proven their effectiveness and utility. This gains further importance when the control rooms are changing with the advancements in technology. There has been a significant reduction in the size of control rooms, which ensures major information about the state of the plant is available to the operator on large screens at the click of a button. This reduces the work stress of moving across panels and accessing controls that were conventionally done on hardwired panels. Further, the incorporation of simulators would help us understand the difficulties or shortcomings of digitalization. The simulators can be built with a reduced spaced requirement ranging from 10 to 30%, as compared to real control rooms. Artificial intelligence-based Techniques like operator support systems can be exploited to better equip operators in the control rooms to ensure the digital stresses are reduced [26]. Reducing the size of real control rooms with experience gained from simulators will bring down the cost of construction, improve communication between the team (reducing team errors), improve situation awareness of operators (better equipped with plant state), and have lesser space requirements. All these systems can be tested, validated, and improvised with aid of replica/non-replica simulators. Eventually, significant improvements can be seen in design, construction, and user-friendly interfaces being utilized in future reactors. This may further reduce the manpower requirements in control rooms without compromising the safety and security of complex systems.

For analyzing operator behaviors and actions in a simulator environment for human reliability assessment, apart from video camera recordings and logbook data, information can be gathered from eye movements, brain waves, facial expressions, and language processing. Experiments can be executed for operator licensing, certifications, evaluations, and for these dynamic scenarios can be provided to assess the efficiency and efficacy of systems placed and humans operating them. This can be executed in full-scope or non-replica simulators. Experts like human factor analysts along with behavioral analysts can provide details about the state of an operator in stressful situations by evaluation of physiological and psychological parameters, giving insights about the decision-making capability in emergency and non-routine situations. This can be further verified with simple tests and diagnoses like blood pressure, pulse rate monitoring. The overall impact of a better understanding of HMI and human factors will strengthen the risk calculations with the incorporation of contributions from humans. Eventually, procedures, systems, culture at the workplace can be amended to have improved the reliability and availability of complex facilities like nuclear power plants [27, 28].

Methodological changes in terms of utilization of internet-based techniques, artificial Intelligence-based approaches, and mobile tracking devices are suggested for advanced systems like newer control rooms in advanced reactors to better equip the operators and prevent incidents and accidents.

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