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Digital Control Room Design Framework with Human Performance Considerations for SMR Deployments

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Abstract

The research is aiming to develop an integrated framework to achieve new designs of digital control rooms (DCR) with multidimensional views and human factor considerations to support the safe deployments of Small Modular Reactor (SMR). The proposed integrated research framework included control room physical model, human factors analysis with interfaces to the control room system, and co-simulation to analyze plant operation for different scenarios. The proposed digital control room platform will support the evaluation of different digital control room design features for different operation scenarios and human factors. The impacts of digital control rooms on situational awareness are analyzed using the proposed digital control room setup, which supports decision-aiding systems in plant operation. Integrated human performance management system is described that includes human health monitoring and human performance semantic networks to accumulate human performance, operation performance, and the coupling with digital control room design features. Selected operation scenarios are modeled and used to evaluate human performance while mapping to control room design features. The proposed integrated digital control is demonstrated using co-simulation platform using IAEA SMR simulator and different operator interactions and scenarios within the digital control room are used to evaluate human performance and reflected to the plant operation performance using the proposed control room design.

Keywords: Digital Control Room Design; SMR; Human Performance; Human Health Monitoring; Co-Simulation Interfaces.

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Highlights:

- Integrated Framework for Digital Control Room Design for SMR Deployments.
- Integrated Framework for Human Health and Performance Monitoring for Digital Control Rooms.
- Evaluation of Plant Operation Scenarios with Simulator and Human Health Monitoring Platform.

1. Introduction

With the increase in energy demands around the world, there is a great need for advanced nuclear power technology. Various strides have been taken to advance nuclear power technology, the latest being the Small Modular Reactors (SMR). In the recent years SMRs are becoming more and more popular. SMR offers flexible operation with potential load following practices, and adaptive ways to supply energy as integrated with renewable energy sources [[1]-[4]]. As they are smaller and modular, they are cheaper to manufacture in the assembly lines and assemble each module separately on the site, unlike the conventional nuclear reactors. Different modules of SMR can be hauled by transport truck and assembled on site in a short time. More capacity can be added as and when necessary. SMRs are advanced nuclear reactors that have a power capacity of up to 300 MW(e) per unit, which is about one-third of the generating capacity of a traditional nuclear power reactor.

While inspiration can be taken from the existing nuclear reactors, the existing main control rooms (MCR) lack ergonomic and attention capacity principles, which can impact the decision-making process for operators. A control room update is long overdue. Based on the conceptual designs developed by Nuclear Control Design (NCD), the team focused on developing a detailed design for a digital control room for SMRs. The proposed design focused on the digital control room layout, especially focusing on human factors.

An SMR typically has reduced staffing requirements due to their smaller size and simplified design compared to conventional large-scale nuclear power plants [[3]]. The exact staffing needs may vary depending on the specific SMR design and operational characteristics. However, even with reduced staffing, it is critical to ensure that the personnel operating SMRs possess the necessary qualifications, training, and expertise [3]. Control rooms of conventional reactors were designed in the last century, so the controls are mostly dials and knobs with analog displays with some digitisations.

In this study we would explore the option of further digitization of the controls and integrate human behaviour with machine behaviour so that fewer people are needed for operation, operation is smooth, and the cost of operation is more economical.

There are several key areas of human performance that are important to consider in SMR operation [[5]]. Operator training and qualifications are essential areas where SMRs require operators with specialized training and qualifications to ensure safe and effective operation [[6]]. The use of Electroencephalogram (EEG) is proposed as a tool to assess operator’s performance [[7]-[12]]. EEG stands as a pivotal innovation in neuroscientific tools, offering a window into the brain's electrical activities. This technology captures the brain's electromagnetic waves, a product of synaptic activities within the neural network.

In the context of control room operations, especially in high-stakes environments like nuclear and process industries, EEG has emerged as a critical tool for assessing operator performance. Studies have demonstrated the effectiveness of EEG in monitoring cognitive load, attention, and stress levels among control room operators. By analyzing EEG data, researchers can gain insights into the mental workload, decision-making processes, and overall cognitive state of operators during various operational scenarios.

NUREG-700 included useful guidelines for control room with human-system interface design [[13]]. The basis of this standard is primarily focused on guidelines for designing a nuclear control room considering human factors. It highlights existing features within current control rooms, and it identifies the characteristics to improve operator performance, within the main control room. It looks at various methods to improve time optimization, foot traffic, operator organization, human error optimization, and layout simplicity. It highlights various human-machine interfaces, alarm interfaces, control room parameters, and even communication within the control room [[5]].

Eye tracking is another method used to evaluate human performance. Track eye movements indicating to the point of the user's visual gaze fixated on the screen [[14]]. There are ways to identify whether the operator is paying attention or not [[15]] from the pupil condition. Blink rate and PERCLOS features are used to analyze and detect fatigue in automobile driving [[16]], aircraft flying [[16]] and human–computer interaction [[18]]. Eye aspect ratio (EAR) has been successfully used in operator fatigue detection in automated control systems [[19]-[21]]. High levels of stress are associated with control room decision making tasks required for nuclear power plant (NPP) operations [[21]-[23]].

This standard focuses on multiple-step processes including the planning phase, review phase, assessment phase, and human factor guideline. During the planning phase, various documents and literature reviews regarding human factors are considered within a control room design. It must undergo a review process while ensuring all objectives are met prior to design development. In addition, a detailed work plan must be implemented to ensure that the set objectives are met while incorporating human factors. By ensuring a planning phase, all the required documentation and reviews will be present for a detailed analysis. During the review phase, using the documentation collected throughout the planning stage, various human factors must be tested. These parameters include work demands, distractions, human errors, fatigue, attention, colour, fonts, and spacing. This can be understood using mathematical evaluations, computer analysis, human trials, and consultations with industry partners. Once the set parameters are collected, the data must be verified to ensure it is optimal for human performance. During this stage, the errors in the design can be understood and corrected. Once the data is collected, the design can be shifted into the assessment phase. The proposed design must be tested against various operation scenarios and compared with current operating control rooms to see the effectiveness of the proposed design. The parameters that must be considered include communication, alarms, controls, labels, illumination, panel layout, room layout, response time, visual awareness, and simplicity [[5]].

A study was conducted on Human-Machine Interface of ABWR (Advanced Boiling Water Reactor) [[24]]. In their system hardwired switches and software switches through CRTs (cathode ray tube) and FDs (fixed display) are available for plant operation. Normally, hardware switches are used for fast initiation of ECCS (emergency core cooling system) and for mode switches to initiate sequential routine operations during normal operation. On the other hand, software switches are used for the operation of individual pieces of equipment, such as pumps and valves during periodic tests.

The improved standard ABWR MCR PNL (main control room panel) is designed with the following features: incorporate operators' advice into the design; introduce the latest HMI technology so that operators can monitor and operate the plant more effectively; and supervise isolated equipment more precisely and effectively by means of introducing an isolation management system.

Several general situations have been identified [[25]] about the contribution of human errors in incidents, as shown below. The study suggested incidents can be avoided by more education and training.

- Activities, such as testing and maintenance, are a common cause of errors. Implementation of automatic procedures may alleviate some problems.
- Human errors are more frequent in systems having low levels of availability or redundancy, or those not sufficiently automated.
- Human errors in abnormal conditions are more frequent just after alarms have been initiated.
- Bad design (from viewpoint of system engineering, control-room layout, and ergonomic principles) is a major cause of human error.
- The transfer of information during shift changes of personnel is a general cause of error

The Institute of Nuclear Power Operations (INPO) is an organization established in 1979 by the U.S. nuclear power industry in response to the investigation of the Three Mile Island accident. INPO published a study (INPO 91-008) of NPP industry events from 1945 to 1990 [[26]].

These example events are mainly attributed to "Personnel Performance," while no events were caused by team performance. One telling piece of information from the above table is that equipment or design issues rarely cause events but instead are caused by human error. It is essential to understand and quantify human error probability (HEP) and correlate with human performance and teamwork, which are essential in the control room. The report discusses nine significant NPP events and asses them by direct deficiencies in teamwork or other areas critical for effective teamwork. The results revealed:

- Supervisory oversight – leadership (7 of 9 events)
- Reactivity control – Improper Action (3 of 9 events)
- Teamwork (6 of 9 events)
- Crew decision-making (9 of 9 events)
- Application of knowledge Sensing / Understanding (2 of 9 events)

The analysis of these operation events with respect to human health monitoring, performance, activities, and mental models [[27]-[30]] will provide essential data to support the design of the target digital control rooms in view of SMR design, physical system modeling, environmental modeling, safety and emergency modeling, and integration with other systems and applications.

There are many different types of SMRs. CANDU SMRs (CSMR) are designed in Canada. CSMR are land-based heavy-water-cooled SMR. CSMRs have incredible fuel flexibility and fuel is available in Canada, no need to import enriched fuel. So, we would keep our discussion focused on CSMR. The output of this research would be modular and scalable so that it can fit other types of SMRs.

This study proposed an integrated approach to enhance control room design by incorporating human performance monitoring the physical ability, physical condition, mental condition, and mental alertness of the operator using cameras, microphones and wirable devices during the operation of the reactor. The proposed human performance monitoring is integrated within the control room for supporting decision aiding based on operator performance and health monitoring. In addition, the correlation among plant operation, human performance, and control room design features are assessed and optimized to maximize plant operation performance and safety, control room design, and human performance. The structure of the paper is shown in Figure 1.

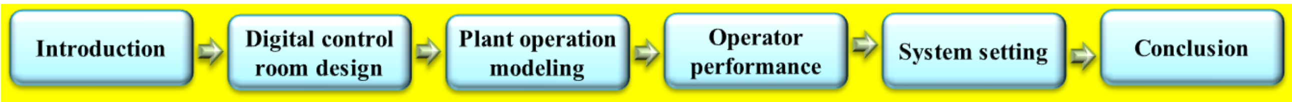


Figure 1: Structure of the paper

2. Digital control room design

To achieve the stated goal, the main research objectives include: (a) study digital control room design, inputs, outputs, visualization, and technologies; (b) environmental state variables and monitoring systems related to the SMR site; (c) human state variables including physical and mental models, human reliability, performance, and monitoring systems; (d) SMR process state variables, including physical system models, performance measures, efficiency, reliability, risk, and resiliency; (e) state variables of SMR integration with the grid, renewables, storage, and other applications; (f) co-simulation to integrate the digital control to provide evaluation of different scenarios based on number of SMR operating conditions to support operation; (g) standards related to SMR design and operation of digital control and systems and human factors; (h) safety, reliability, resiliency, and emergency state variables and monitoring systems and their implementations within the digital control system. The proposed integrated digital control room will be demonstrated using co-simulation, monitoring, visualization, and data analytics to evaluate different design technologies, and operation scenarios. The proposed design framework of digital control room is shown in Figure 2.

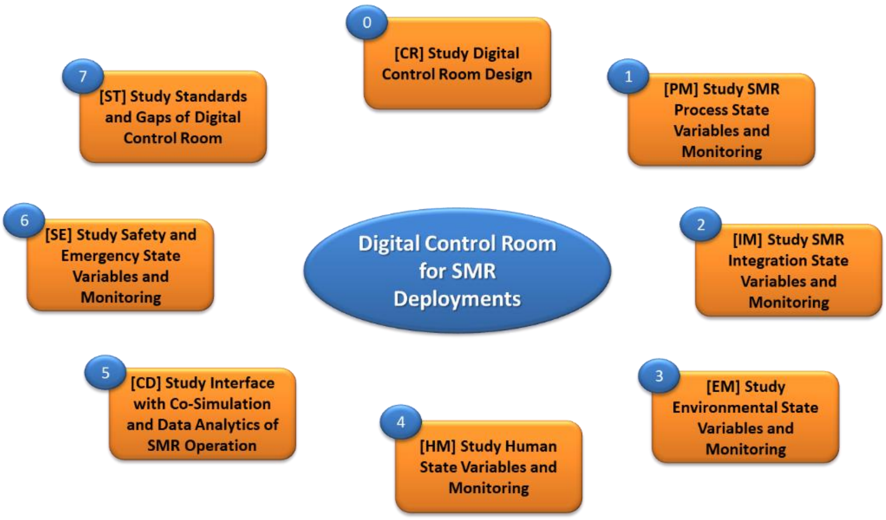


Figure 2: Framework for digital control room design

The detailed process for the digital control room design based on the above framework is transformed into Figure 3. The process starts with defining control room design features based on hierarchical grouping, such as layout, displays, windows within each display, and other features within the digital control room. Similarly, plant operation is modeled into scenarios, tasks, and sub-tasks hierarchically. Human factors are defined for each operation task to be evaluated accordingly. Human performance measures are monitored as related to each human activity, behavior, and corresponding human errors, by identifying related performance shaping factors. Co-simulator is used along with the proposed digital control room setup to execute these operation scenarios for different control room design features and human performance is captured and analyzed and reflected to the control room design tuning.

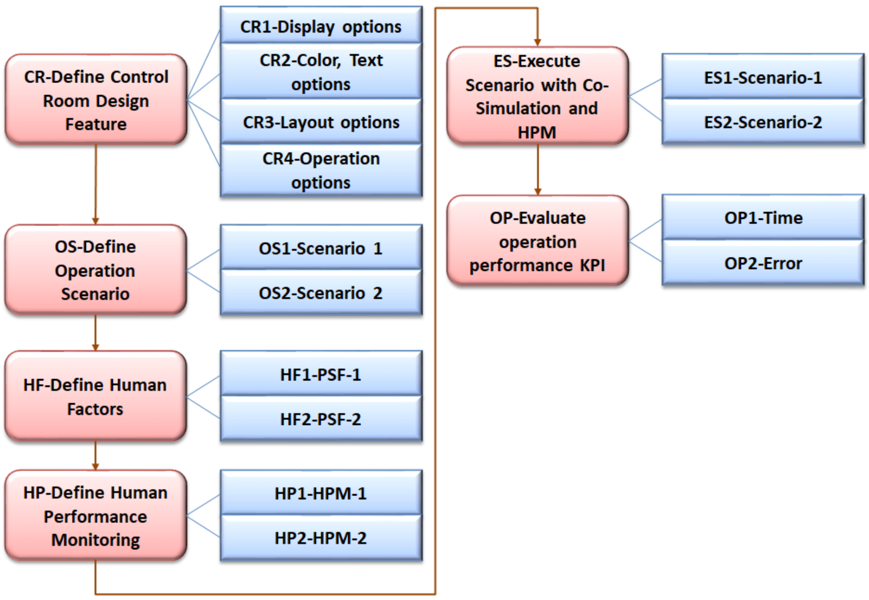


Figure 3: Detailed control room design process

The integrated digital control room systems will include human monitoring and controller, environment and external controller, control room controller, energy simulator interface, and the interface with the SMR co-simulator. The proposed digital control room design is shown in Figure 4.

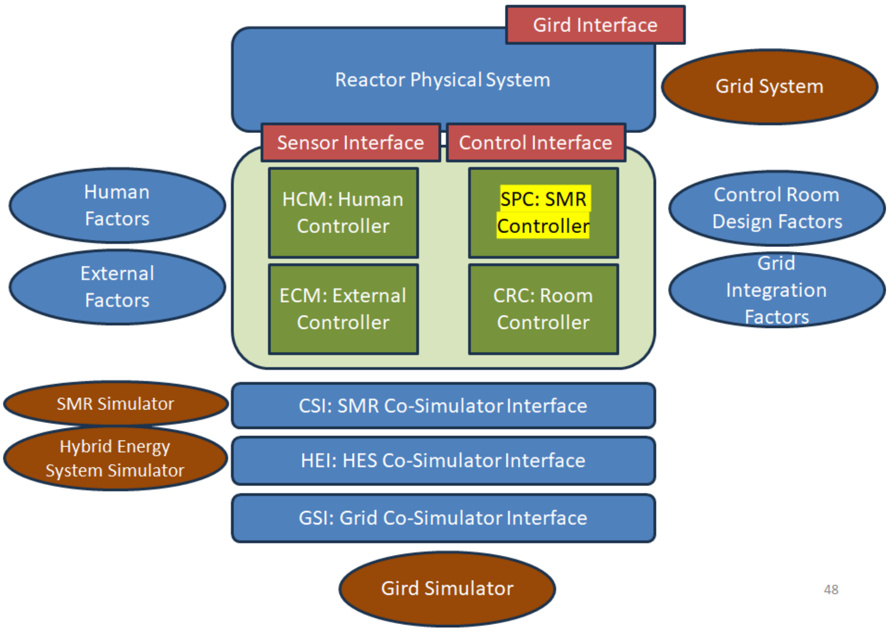


Figure 4: the proposed Integrated digital control room systems

The proposed digital control room includes key features to enable the considerations of human performance for effective and safe operation of SMR installations. The main features include displays, control room sensors, PIR sensors, cameras, desks, chairs and other room physical systems such as doors, supervisory room, wearable technologies for operators, and control room associated facilities. The design requirements are categorized into functional requirements, performance requirements, interface requirements, and safety requirements. The proposed design is reflected onto an example of the main control room of SMR, as shown in Figure 5. The design features might vary based on number of displays, types, sizes, technologies, location, and other features that we can evaluate for different operation scenarios and human factors. The grouping of operation functions within each display, sequence of variable navigation within each operation scenario, and other parameters are evaluated accordingly. The design of emergency control room is also developed to support situations where the main control room is not accessible, in situations such as Fukushima accident. The use of emergency control room could be implemented as a remote or mobile system that could be interfaced quickly with the main control room for immediate and urgent use. In addition, offsite control room is also developed to support the remote monitoring of plant operation, which is suitable in situations where there are needs to monitor plant operation for different purposes such as validation, regulations, or licensing requirements.

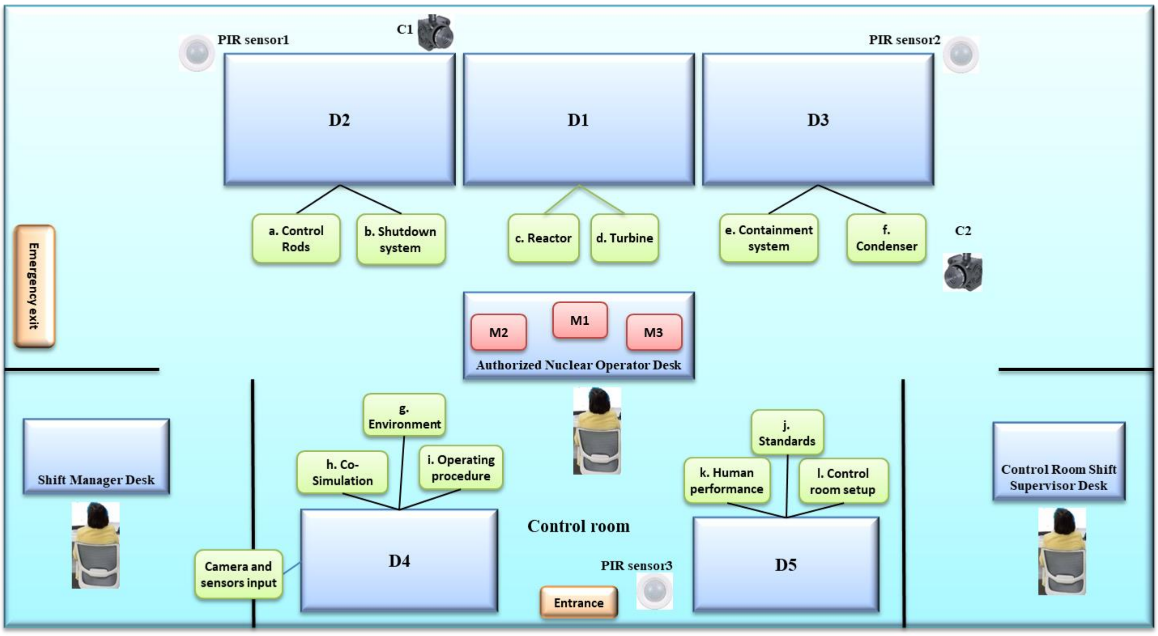


Figure 5: a proposed Digital control room design

The different control room design features are defined and structured, as shown in Table 1, so that they are tested and evaluated for different operation scenarios and human performance criteria.

TABLE 1: CONTROL ROOM DESIGN FEATURES

Feature	**Options**	**Sub-Options**
CR-Define Control Room Design Feature	CR1-Display options	Digital displays Multiple monitors May be one or two separate display(s) for the most important parameters
	CR2-Color, Text options	Color and text visible as much as possible Important parameters in more visible color, e.g., red
	CR3-Layout options	Layout as comfortable as possible for the operator Modular to fit specific need

The design of the input-output lines is modeled based on the selected design of SMR, while the digital control room will be generic and could be interfaced with different SMR reactors. The digital control room will have inputs from sensors and output signals are linked to the control system, as shown in Figure 6. Sensors from the reactor, such as level, power, and temperature are linked to the reactor operating software. The output signals are linked with the different control systems including the reactor, turbine, generator, governor volve, and control functions.

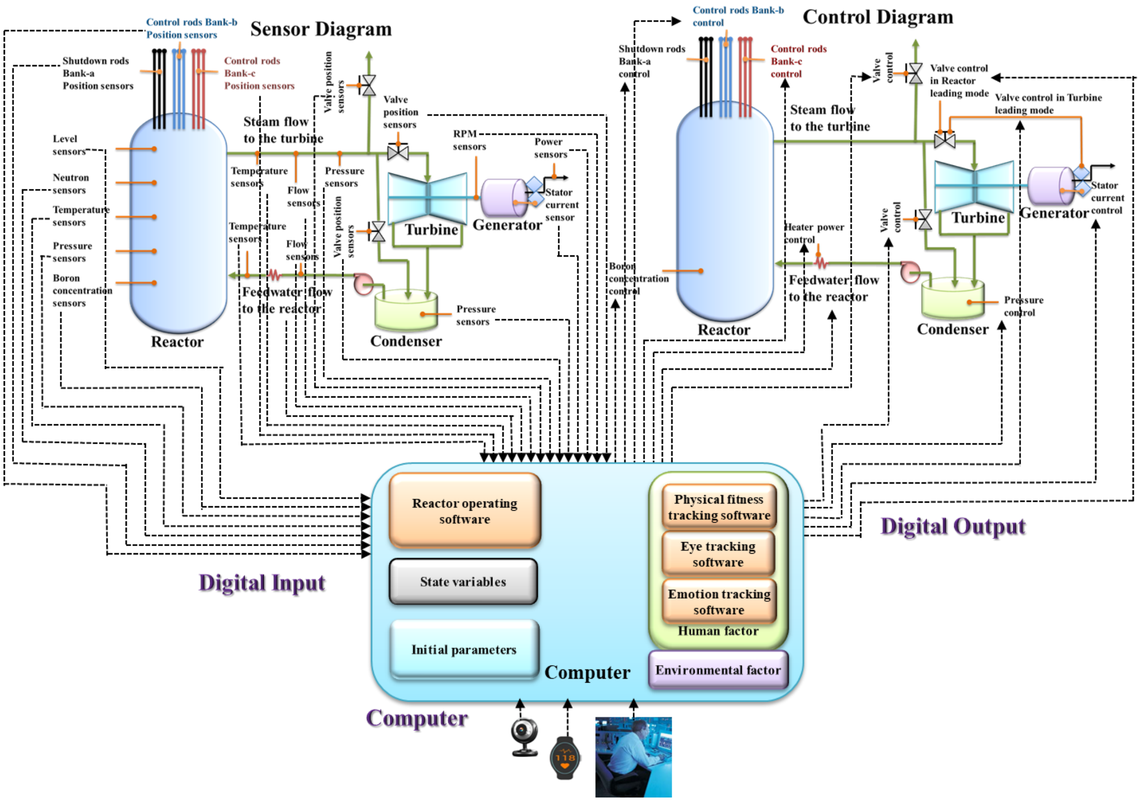


Figure 6: Input-Output Signals in the Digital Control Room

3. PLANT OPERATION MODELING

3.1 Operation Categories

The classification of plant operation will include different operation tasks as shown in Table 2 below.

Table 2: Operation categories

Tasks	Operations
Planning Tasks	Plan operation manipulation based on current states and target states
Diagnostic Tasks	Diagnose abnormal conditions
Recovery Tasks	Return plan state to normal condition based on the required corrections
Validation Tasks	Validate plant states based on correlation among process variables and expected states
Execution Tasks	Execute operation commands to change states from current ones to the target ones
Communication Tasks	Communicate current states to relevant plant personal accordingly to workflow processes
Monitoring Tasks	Monitor plant states to ensure alignment with expected values and states
Analysis Tasks	Analyze plant states and conditions to enhance or confirm plant operation
Reporting Tasks	Report plant states and conditions based on the analysis and workflow processes

These operation categories are comprehensive and will allow proper identification of different operation scenarios and analysis of human performance in these operational views.

3.2 Operation Scenarios

To evaluate human performance, set of selected operation scenarios are defined as shown in Table 3. These operation scenarios are coupled with operation performance measures and evaluated for different control room design features.

Table 3: Selected Operation Scenarios

Operations	**Operations**	
OS-Define Operation Scenario	OS1-Scenario 1	Operation at full power: 1. Monitor the state variables at full power
	OS1-Scenario 2	Operation at different power rate 2. Reduction from 100% to 90%, turbine leading mode 3. Reduction from 100% to 80%, turbine leading mode 4. Reduction from 80% to 60%, turbine leading mode 5. Increase from 60% to 100%, turbine leading mode 6. Reduction from 100% to 90%, reactor leading mode 7. Reduction from 100% to 80%, reactor leading mode 8. Reduction from 80% to 60%, reactor leading mode 9. Increase from 60% to 100%, reactor leading mode
	OS1-Scenario 3	Reactor trip, maintaining shutdown condition 10. Monitor the concentration of liquid poison Monitor the position of the shutdown rods

The performance measures are assessed for different operation scenarios, where time and error are analyzed for the coupling among operation scenarios, control room design, and human factors.

4. Operator performance

4.1 Human Factors

Before we integrate human behaviour with the operation of a reactor a few human variables have to be considered. Human state variables include physical and mental models, human reliability, performance, and monitoring systems. Human factors may be macro variables or micro variables. According to [[26]] there are eight human performance shaping factors. Human factors and the related performance measures are defined, as shown in Table 4, to be evaluated for different control room design features and operation scenarios.

Table 4: Human Factors and Performance Measures

Human Factors	**Performance Shaping Factor Category**	**Performance Shaping Factors**
HF-Define Human Factors	HF1-Performance Shaping Factor (PSF): Micro (Personal) factors	PSF1 - Experience: correlate operating performance with experience PSF2 - Training: correlate operating performance with training PSF3 - Fitness to work: correlate operating performance with health condition
	HF2: Macro factors	PSF4 - Environmental conditions: correlate operating performance with environmental conditions PSF5 - Equipment and MMI: correlate operating performance with equipment and MMI PSF6 - Procedures: correlate how complexity of procedures affects operating performance PSF7 - Task complexity: correlate task complexity with operating performance PSF8 - Organization and working conditions: correlate working conditions with operating performance
HP-Define Human Performance Monitoring	HP1-HPM-1: Eye tracking	Set a buzzer to go off The reactor is set to operate at a safer mode, i.e., the margin of errors may be set to more stringent parameters The supervisor may be alerted
	HP2-HPM-2: Health tracking	Heart rate Blood sugar Exercise record Sleeping record

4.2 Human Health Monitoring System

The key aspect of the proposed digital control room is the accurate and comprehensive monitoring of human health. An Integrated Human Health System (IHHMS) will augment brain, mental, and physiology and physical. The assessment will correlate heart, blood pressure, stress, and brain condition. The proposed system structure is shown in Figure 7.

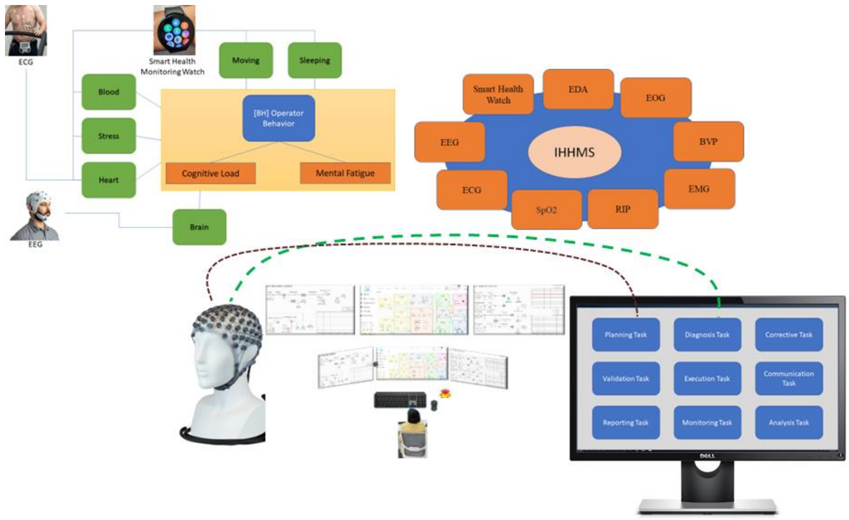


Figure 7: Integrated Human Health Monitoring System (IHHMS)

4.3 Human Performance Management System

The use of health monitoring will support the management of human performance based. The figure below shows the detailed design of the IHHMS, which includes main monitoring devices that will be used in real time mode and offline for data collection and analysis with correlation to operation tasks in normal and abnormal conditions. The integrated monitoring will enable capturing human performance and state variables and correlate to other SMR process and state variables, which is essential to build better understanding of capabilities and limitations related to each operation task and activity with better understanding of human performance and monitoring of risk factors with early detection and prevention measures. The Integrated Human Performance Management System (IHPMS) is shown in Figure 8. The development of human performance semantic network (HPSN) is essential to accumulate human health and couple with control room design, operation performance, and key performance indicators of SMR operation. The dynamic knowledge structure of HPSN will continuously capture human behavior and activities for different plant operations and in view of digital control room design and settings, which will support answer questions related to the coupling among plant operation, operator performance, and control room design. The high level HPSN is shown in Figure 9.

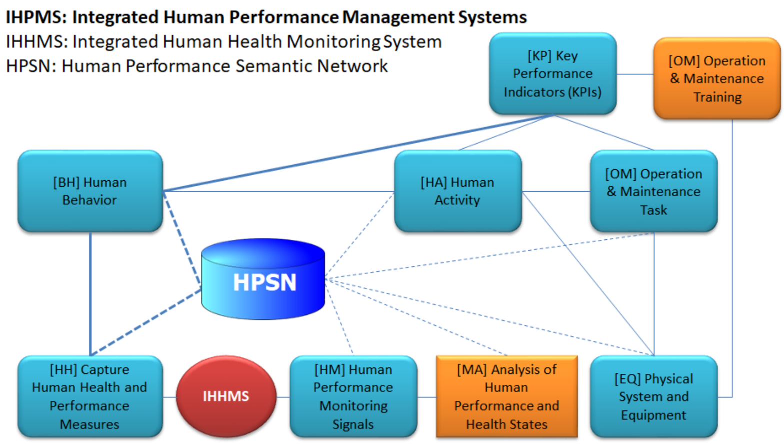


Figure 8: Integrated Human Performance Management System (IHPMS)

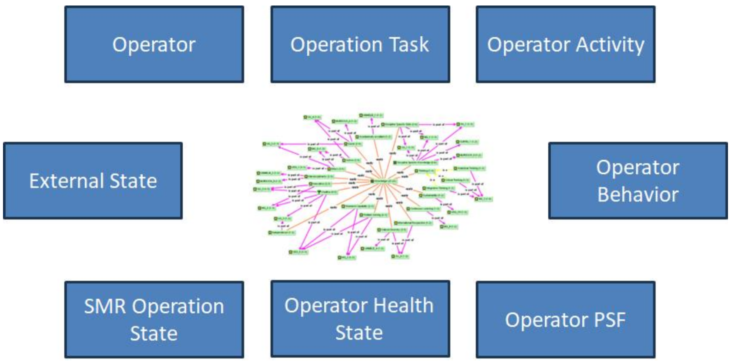


Figure 9: HPSN High Level Structure

5. System testing

The proposed digital control room with human performance monitoring is tested using selected operation test cases, as shown in Table 5.

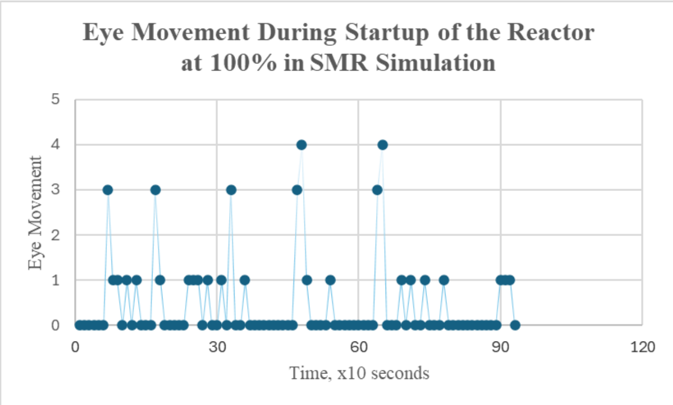
Table 5: Test Cases

Case	Operation Modes
Case-1	Monitoring of 100% Full Power, with Turbine Leading Mode
Case-2	Power Reduction from 100% to 90% in Turbine Leading Mode
Case-3	Power Reduction from 100% to 80% in Turbine Leading Mode
Case-4	Power Reduction from 80% to 60% in Turbine Leading Mode
Case-5	Power Increase from 60% to 100% in Turbine Leading Mode
Case-6	Power Reduction from 100% to 90% in Reactor Leading Mode
Case-7	Power Reduction from 100% to 80% in Reactor Leading Mode
Case-8	Power Reduction from 80% to 60% in Reactor Leading Mode
Case-9	Power Increase from 60% to 100% in Reactor Leading Mode
Case-10	Reactor Trip

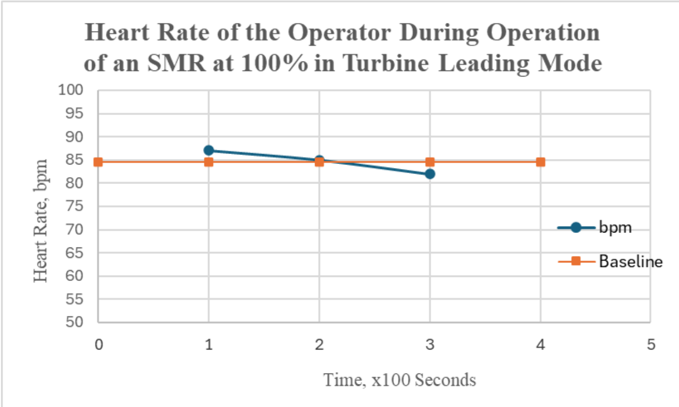
SMR simulator from IAEA is used to evaluate different operation scenarios.

5.1 Case-1

Eye tracking and heart rate of the operator during initialization of the reactor at 100% operation scenario, as shown in Figure 10.



(A)

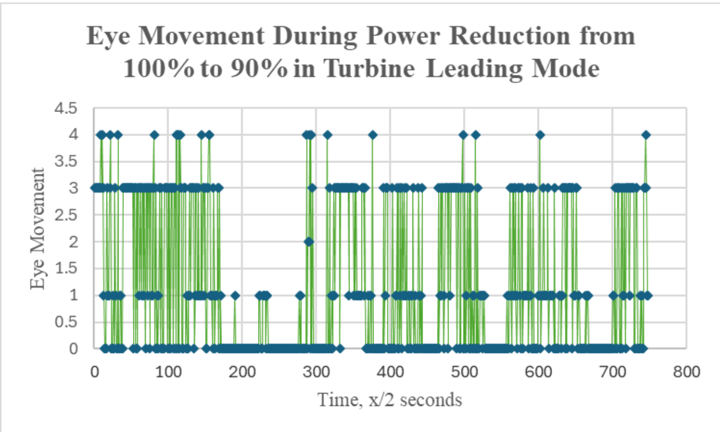


(B)

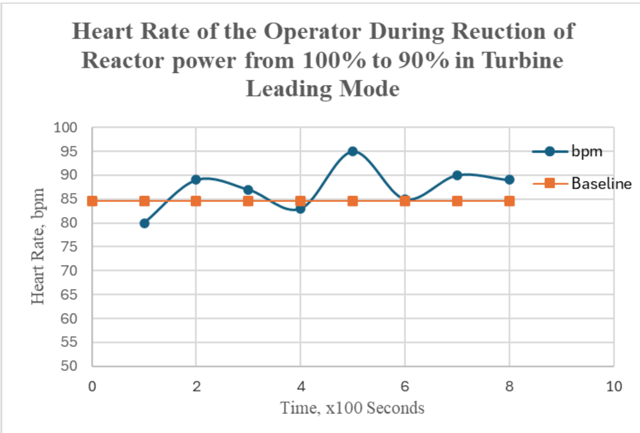
Figure 10: (a) Eye tracking and (b) Heart Rate measurement reactor running at 100% full power

5.2 Case-2

Observation of eye tracking and heart rate during power reduction from 100% to 90% power in turbine leading mode as shown in Figure 11.



(A)

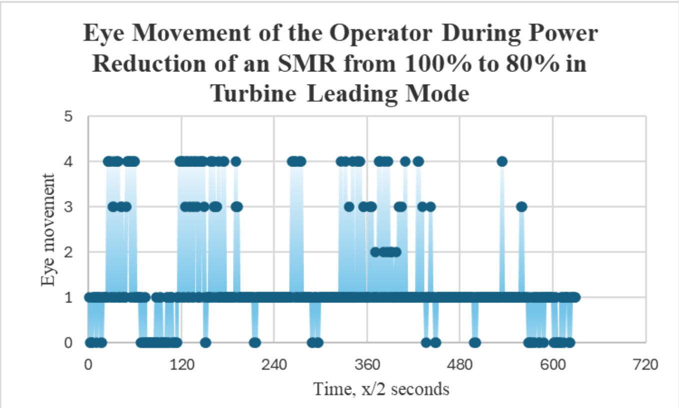


(B)

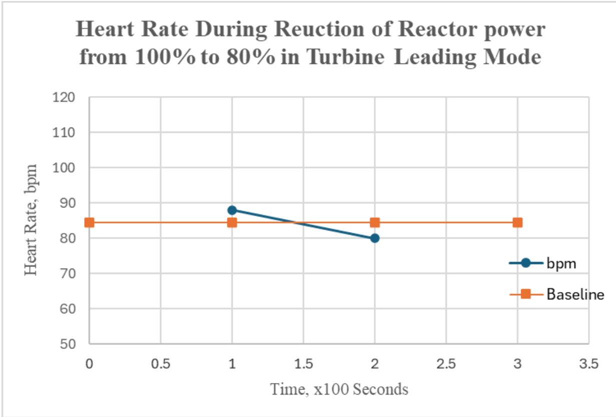
Figure 11: (a) Eye tracking and (b) heart rate measurement at 90% of full power

5.3 Case-3

Observation of eye tracking and heart rate during power reduction from 100% to 80% power in turbine leading mode as shown in Figure 12.



(A)

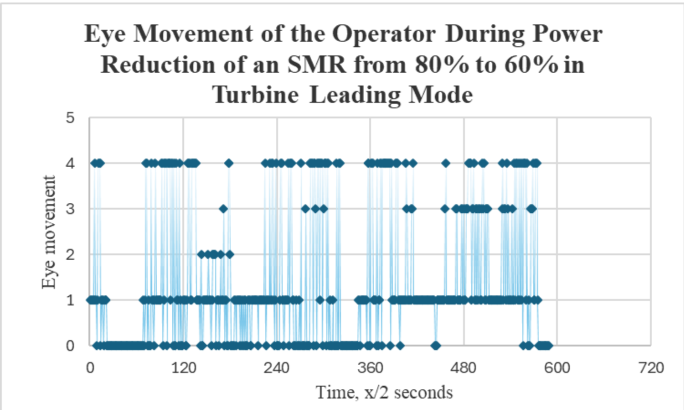


(B)

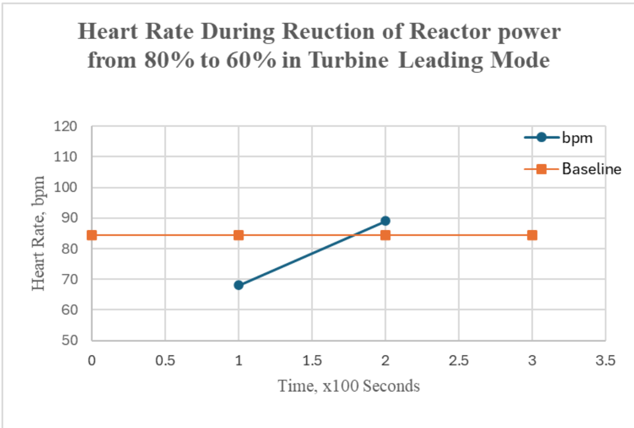
Figure 12: (a) Eye tracking and (b) heart rate measurement during power reduction from 100% to 80% power in turbine leading mode

5.4 Case-4

Observation of eye tracking and heart rate during power reduction from 80% to 60% power in turbine leading mode as shown in Figure 11.



(A)

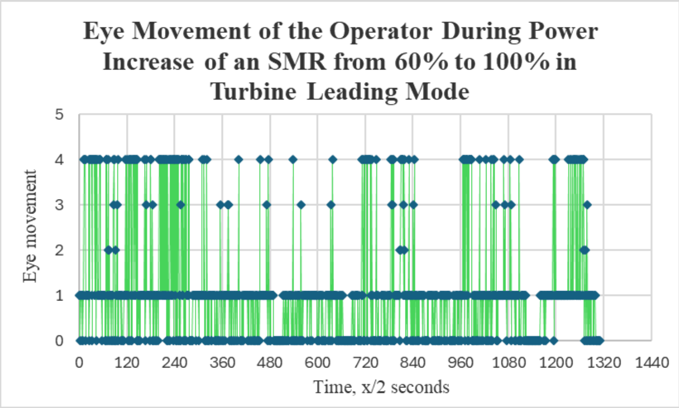


(B)

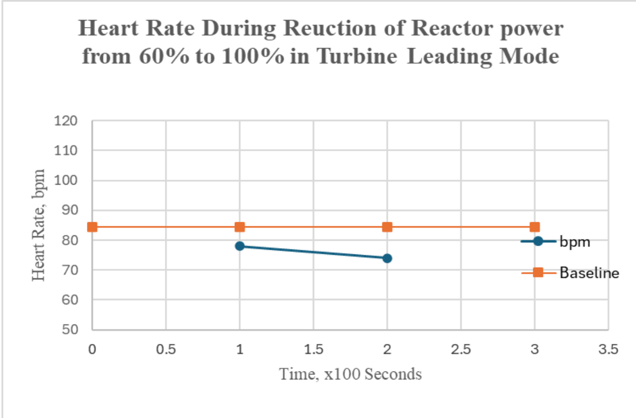
Figure 13: (a) Eye tracking and (b) heart rate measurement during power reduction from 80% to 60% power in turbine leading mode

5.5 Case-5

Observation of eye tracking and heart rate during power increase from 60% to 100% power in turbine leading mode in Figure 14. As during running the reactor at 60% Xenon concentration builds up, it takes a long time to reach 100% again. As such, recording of data had to be stopped at about 94% power level.



(A)

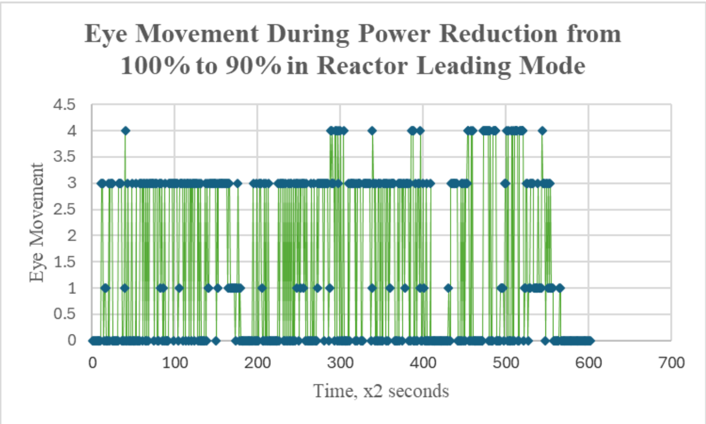


(B)

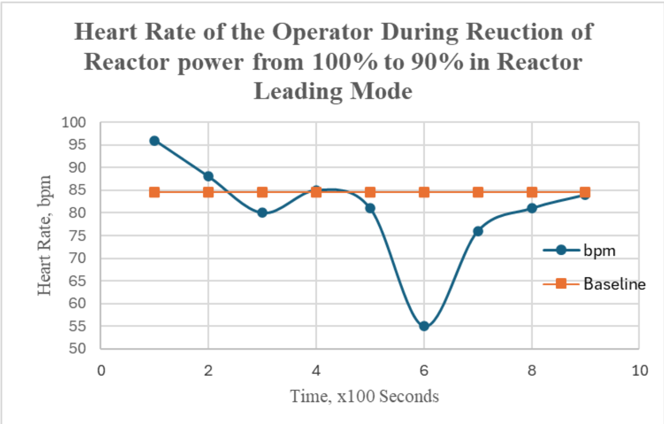
Figure 14: (a) Eye tracking and (b) heart rate measurement during power increase from 60% to 100% power in turbine leading mode

5.6 Case-6

Observation of eye movement and heart rate during power reduction from 100% to 90% power in reactor leading mode as shown in Figure 15.



(A)

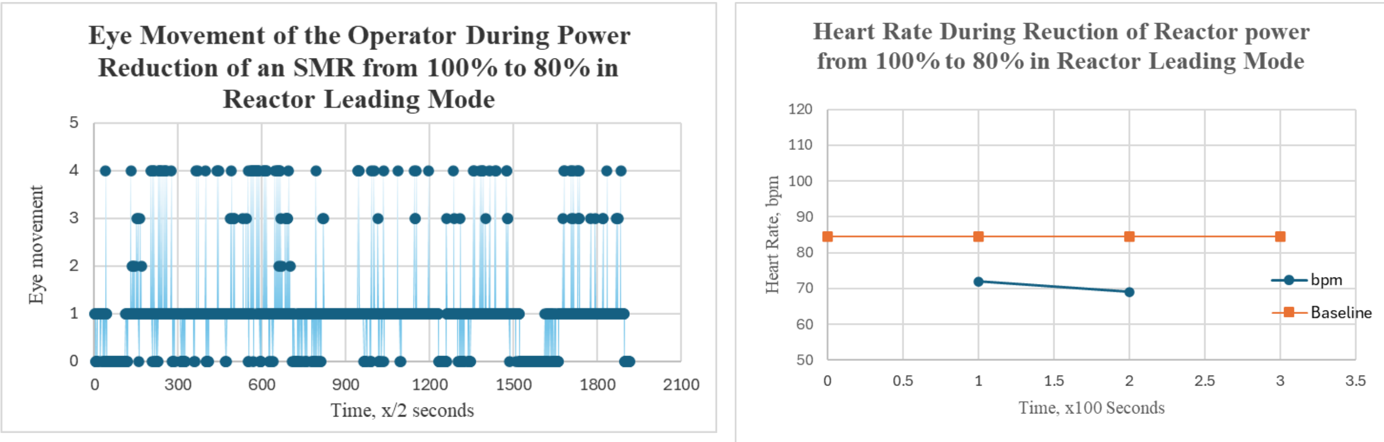


(B)

Figure 15: (a) Eye tracking and (b) heart rate during power reduction from 100% to 90% in reactor leading mode

5.7 Case-7

Observation of eye tracking and heart rate during power reduction from 100% to 80% power in reactor leading mode as shown in Figure 16.

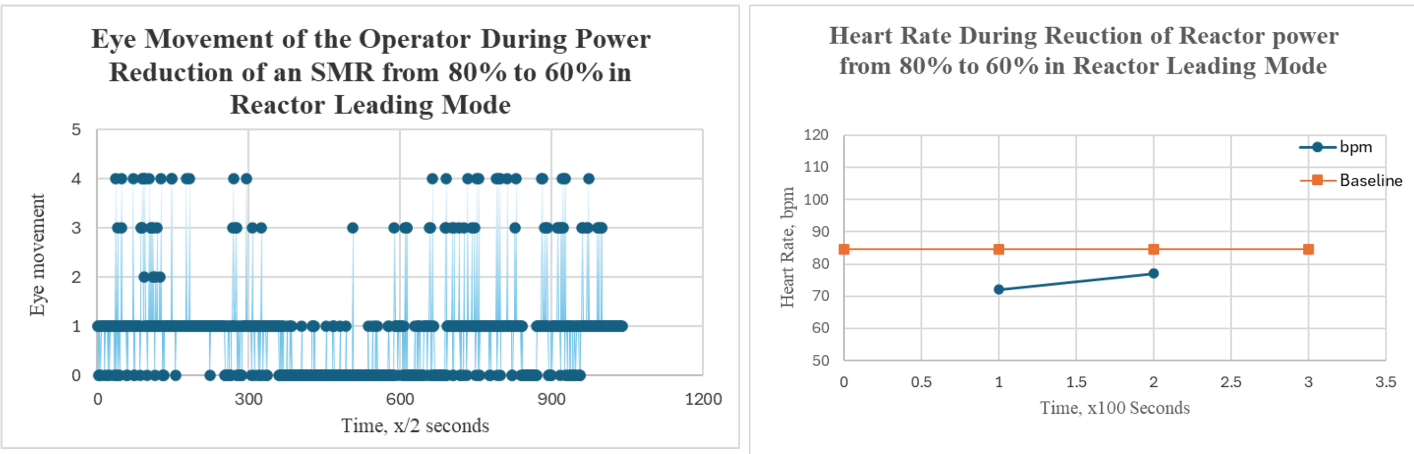


(A) (B)

Figure 16: (a) Eye tracking and (b) heart rate measurement during power reduction from 100% to 80% power in reactor leading mode

5.8 Case-8

Observation of eye tracking and heart rate during power reduction from 80% to 60% power in reactor leading mode as shown in Figure 17.

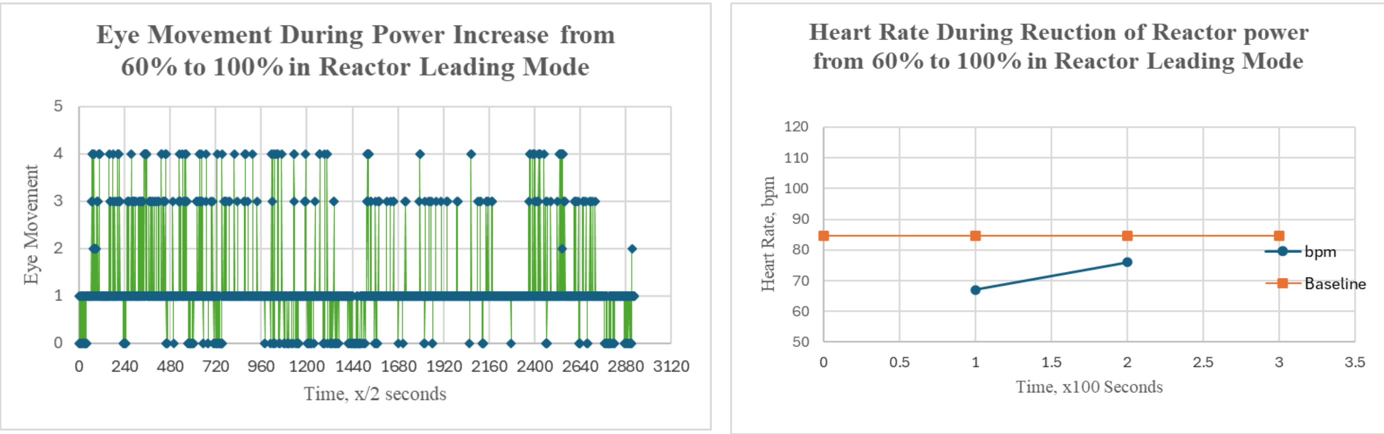


(A) (B)

Figure 17: (a) Eye tracking and (b) heart rate measurement during power reduction from 80% to 60% power in reactor leading mode

5.9 Case-9

Observation of eye tracking and heart rate during power increase from 60% to 100% power in reactor leading mode in Figure 18. As during running the reactor at 60% Xenon concentration builds up, it takes a long time to reach 100% again. As such, recording of data had to be stopped at about 94% power level.

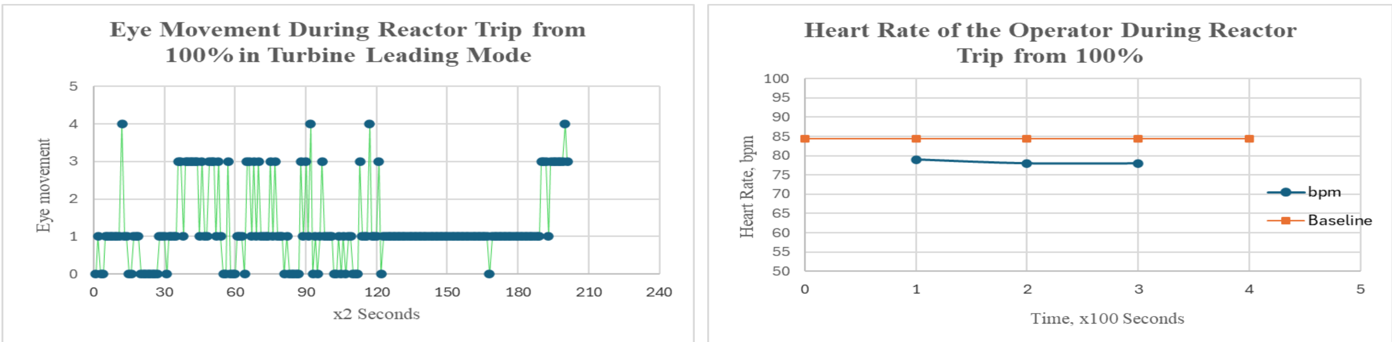


(A) (B)

Figure 18: (a) Eye tracking and (b) heart rate measurement during power increase from 60% to 100% power in reactor leading mode

5.10 Case-10

Eye tracking and heart rate during a reactor trip from 100% operation scenario is shown in Figure 19.



(A) (B)

Figure 19: (a) Eye tracking and (b) heart rate measurement during reactor trip from 100% in turbine leading mode

5.11 Summary Comparison Among Test Cases

Based on the selected test cases, eye tracking datasets are gathered and analyzed to evaluate human performance in different operation scenarios. The purpose was to determine where the user's visual gaze fixated on the screen. The collected datasets give us an idea whether the operator is conscious or not and whether he/she is looking at the screen or not. The detailed study of eye tracking requires further study to evaluate different human factors and correlate with human performance and control room design alternatives. We used gaze tracking software capture images which uses Dlib library in the background to analyze the image. Dlib is used in the academia and in industry [[21]].

Smart Watch data comparison: Smart watch collects many different sets of health data. Only the heart rate data has been analysed here. Heart rate bits per minute (bpm) were recorded by a smartwatch. Observation of eye movement and heart rate from eleven test cases are summarized in Table 6.

Table 6: Observation from heart rate in the four operation scenarios

Test	**Eye Tracking**			**Heart Rate**		
Case	**Blink**	**Eye Movement**		**Average**	**Standard Deviation**	
1.	155	198			2.5	
2.	144	228			5.5	
3.	453	101			5.7	
4.	250	156			17.1	
5.	688	199		84.6	12.3	
6.	56	261			11.9	
7.	1403	140			19.9	
8.	586	81			14.6	
9	2049	236			19.5	
10.	125	39			7.6	

From the blink rate and eye movement data it can be inferred that the operator is not fatigued, he/she is paying attention to the operation. The operator’s stress was mild to moderate as the heart rate was about 123.5% from the baseline/average [[22]-[23]].

6. Operator Response

Operator responses for different control room design features are analyzed. The operator responses based on different fonts are shown in Table 7 and Figure 20.

Table 7: operator responses based on different fonts

Font	Things to Find	Things to Click	Response Time, Seconds						
			User1	User2	User3	User4	Font Average		
							Experience†	New††	Total†††
Ariel	'GV'	'GV'	4.43	4.45	4.21	4.85	4.44	4.53	4.485
Times New Roman	'PHTP1'	'PHTP1'	2.25	2.71	6.23	16.37	2.25	11.3	6.89
Helvetica	'ASDV'	'ASDV'	2.71	1.68	4.19	17.13	2.195	10.66	6.4275
Calibri	'FCV153'	'FCV153'	4.3	4.11	4.89	5.78	4.205	5.335	4.77
	Person Total		13.69	12.95	19.52	44.13			
	Person Average		3.4229	3.2375	4.88	11.0325			

† Font Average - Experience: Is the average time it took for Neal and Zain to complete the tasks.

†† Font Average - New: Is the average time it took for Manu and Farhan to complete the tasks.

††† Font Average - Total: Is the average time it took for all four subjects to complete the task.

Experience - Who are familiar with the simulator

New - Who are not familiar with the simulator

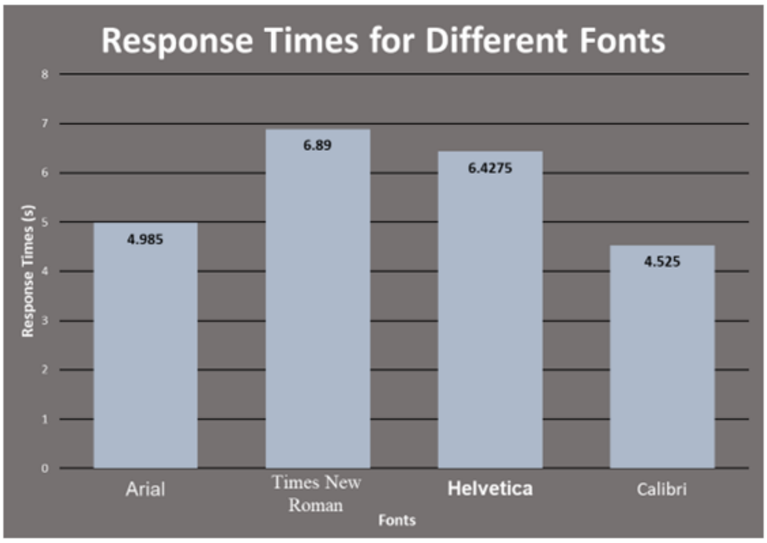


Figure 20: Operator responses based on different fonts in the HMI

Operator responses with variable working conditions such as fatigue, with and without obstacles are shown in Figure 21. Different experiments are conducted when the HMI display is placed within 1.5m, the data indicated that it took approximately 3.46s with no obstacles, 5.11s with obstacles, and 6.30s for operators experiencing fatigue. These human performance measures are used to enhance control room design.

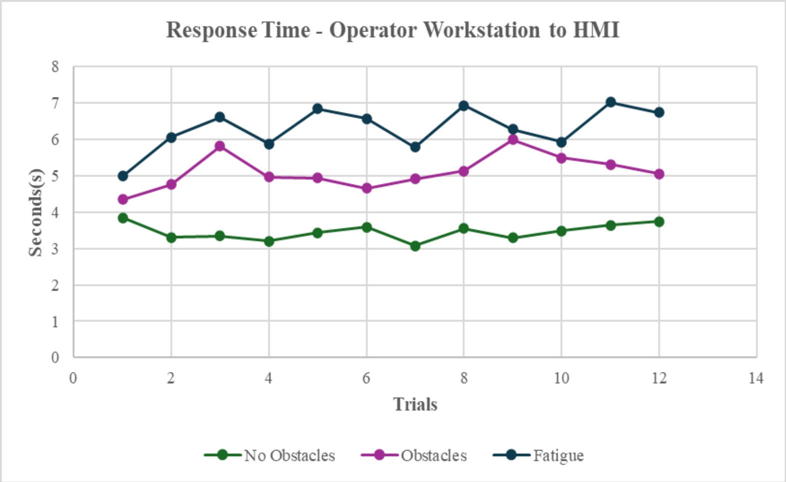


Figure 21: Operator responses based on different working conditions

More tests are conducted based on different vision effects, font color, window contract, line spacing, button grouping, and other control room parameters to reflect best operator performance and correlate with plant operation and control room design. Research is also conducted on the interfaces between the simulator and the real time operation displays to synchronize interface parameters with improved response time and real time coordination to enhance overall plant operation.

7. Conclusion

The proposed control room design framework provides a novel and comprehensive approach to enhance plant operation and safety considering human factors and performance. The framework includes human health monitoring and couple with human performance monitoring that are used with different control room design features and various operation scenarios. The proposed design framework facilitated the accurate analysis of three dimensions, namely (1) digital control room design; (2) plant operation; and (3) human performance. The selected scenarios are evaluated for different digital control design features such as layout, font size, and display distance, and correlated with human performance such as eye tracking, heart rate, and brain condition. The analysis showed accurate evaluation of different critical plant operation scenarios for different fonts that are reflected to different human performance such as blinking, eye movement, heart rate, and human response time. The proposed approach could be used to evaluate other human performance shaping factors (PSF), mental and physical models with respect to different SMR operation is new and will open the door for enhanced performance and safer operation while building the capacity to promote SMR deployments in Canada and worldwide. The proposed research provides strong basis to design and implement an integrated digital control room with human performance using an integrated human performance management system that include integrated human health monitoring system. The use of integrated co-simulation will enable the evaluation of different control room design alternatives and assess human performance. The use of human performance semantic network (HPSN) will accumulate useful knowledge about control room designs and couple with human performance for improved SMR deployments and reuse of these design and operation experiences across different SMR models and installation sites.

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