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Electroencephalogram-Based Human Performance Analysis for Improved Small Modular Reactor Operation

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Abstract

In the wake of the rapid deployment of Small Modular Reactors (SMRs), this study aims to enhance the efficiency, reliability, and safety of SMR operations through a deeper understanding of human factors in their interaction within digital control room systems. Recognizing the pivotal role of human understanding in this new era of nuclear power, we employed electroencephalogram (EEG)-based monitoring to provide an unparalleled real-time view into operators' cognitive states. By interfacing detailed human models, informed by EEG metrics, with specific operational tasks, we recreate potential operational scenarios using an SMR simulator and capture intricate human responses therein. Our results elucidated the intricate relationship between EEG-derived data and human performance shaping factors, indicating a marked correlation between certain EEG patterns and operational efficiencies. Conclusively, these findings underscore the potential of EEG monitoring not only as a diagnostic tool but as an instrumental aid in the design and operation of future SMR digital control rooms. The insights derived offer a roadmap for the development of practical strategies, ensuring more effective and safer SMR operations.

Keywords: Human Performance, Human Factors, EEG, SMR, Small Modular Reactor, Plant Operation.

1. Introduction

1.1. NPP and SMR Plant Operation

Nuclear power plants have comprehensive safety features to ensure the safe operation of the reactor and prevent the release of radioactive materials (Canadian Nuclear Safety Commission, 2007). These features include redundant and diverse safety systems. For instance, emergency core cooling systems (ECCS) consist of multiple independent cooling mechanisms that provide coolant flow to the reactor core in case of an accident (Ahmed, 2019).

The control room also houses safety systems, control rods, and emergency shutdown mechanisms that allow operators to initiate a safe shutdown of the reactor if necessary [Simonsen & Osvalder, 2015; Densmore & Duffy, 2021). The operators are trained to handle various plant conditions, identify potential safety issues, and follow strict safety protocols and emergency procedures (Acuna *et al., 2023)*

On the other hand, Small Modular Reactors (SMRs) incorporate advanced passive safety features that enhance their inherent safety and reduce reliance on active systems (Mi *et al.*, 2019). Passive safety systems utilize natural processes such as gravity, convection, and natural circulation, making them simpler, more reliable, and less susceptible to failures (Gaikwad *et al.,* 2023). Passive heat removal mechanisms, such as passive heat exchangers or passive residual heat removal systems, utilize natural heat transfer processes to remove decay heat from the reactor during shutdown conditions (Gaikwad *et al.,* 2023).

These passive safety features are designed to operate without human intervention or external power, providing robust safety even under challenging conditions (Butt *et al.,* 2016). Small modular reactors typically have reduced staffing requirements compared to large-scale nuclear power plants due to their smaller size and simplified design (Popov *et al.,* 2023). 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 (Popov *et al.,* 2023).

SMRs have unique characteristics and design features compared to larger reactors. The training programs for SMR operators focus on these specific aspects, such as the operation of passive safety systems, understanding the modular nature of the reactor, and familiarity with the specific control and instrumentation systems employed in the SMR design (Blackett *et al.,* 2023). Operators undergo simulator-based training to enhance their skills and decision-making abilities. Simulators provide a realistic representation of the control room and allow operators to practice various scenarios, including normal plant operation, abnormal conditions, and emergency response. Simulator training helps operators develop familiarity with the unique characteristics of SMRs, improve their situational awareness, and enhance their ability to handle potential challenges or malfunctions (Blackett *et al.,* 2023).

While the overall staffing requirements for SMRs may be reduced, there is still a need for maintenance and support staff to ensure the safe and efficient operation of the reactor. Maintenance technicians, engineers, and other specialists play essential roles in routine maintenance activities, equipment inspections, troubleshooting, and repairs (Butt *et al.,* 2016). These personnel receive training specific to the SMR design and its unique maintenance requirements.

The relatively smaller number of SMRs compared to large-scale nuclear power plants makes collaboration and knowledge sharing among operators and industry experts crucial (Blackett *et al.,* 2023).

Herein lies the necessity for a more sophisticated approach to monitoring and understanding operator cognitive states, leading to the application of electroencephalogram (EEG) technology. EEG provides a window into the real-time cognitive workload and stress levels of operators, offering invaluable insights for enhancing control room design and operational protocols. Furthermore, other vital signs, such as blood pressure, collected in conjunction with the EEG data can aid in this process, giving us a better picture of what is happening within the mind of the operator.

1.2. Control Room Challenges

A critical aspect of designing a control room for an SMR is to ensure that operators have access to the information they need to monitor and control the reactor effectively (Poresky *et al.,* 2022). Plant operation information presented on the displays should be designed to be easy to understand and interpret (Poresky *et al.,* 2022). This involves using clear and simple language, avoiding technical jargon, and presenting information in a logical and intuitive manner (Liu *et al.,* 2016). The displays should also use graphical elements such as color coding, symbols, and graphs to help operators quickly and accurately understand the information (Santoso *et al.,* 2022). Information organization and presentation on the displays should be organized logically and meaningfully. Alarms are an important tool for alerting operators to abnormal conditions in the reactor (Ren *et al.,* 2015). Alarm design should consider the frequency and type of alarms, as well as the response time required by the operator (Ren *et al.,* 2015). Alarms should be designed to avoid overloading the operator with too many alarms at once and should be presented in a way that makes it easy for the operator to respond quickly and effectively (Sompura *et al.,* 2017).

1.3.Human Factors and Performance Analysis in Plant Operation

Human factors are heavily involved in the design and operation of SMRs. It is able to highlight the unique challenges associated with SMRs, such as the need for complex system integration and the potential for increased human error due to the smaller workforce required to operate them (Henderson *et al.,* 2002). There are several key areas of human performance that are important to consider in SMR operation (Blackett et al., 2023). Operator training and qualifications is an essential area where SMRs require operators with specialized training and qualifications to ensure safe and effective operation (Liu et al., 2016). The report discusses the importance of developing effective training programs and qualification requirements to ensure that operators have the necessary skills and knowledge to operate SMRs safely. Human-systems integration is important due to the complex nature of SMRs, which requires the integration of multiple systems and subsystems, which can create potential sources of human error (Henderson *et al.,* 2002). The report emphasizes the importance of designing SMRs with human-systems integration in mind to minimize the potential for errors. Human factors engineering is widely analyzed in view of the operation activities of SMRs, such as the physical and cognitive abilities of operators, to ensure that they can operate SMRs effectively and safely (Gofuku & Niwa, 2001). Organizational and management factors are linked with plant operation, such as communication and decision-making processes, in ensuring safe and effective operation of SMRs.

The tasks a nuclear reactor operator performs are integral to the function and safety of the reactor. The operators create a mental model of the situation to complete their tasks. A mental model is a mapping of the properties of the task to its representation in the Operator's mind. (Gofuku & Niwa, 2001) Mental models used by an operator can be broadly categorized as skill-based, rule-based, and knowledge-based (Rasmussen, 1983, Sepanloo & Jafarian, 2004). A skill-based model is used when operators perform repetitive tasks that do not require any cognitive effort (e.g., reading data from charts or meters). Rule-based models are used primarily when a checklist or manual is required to complete the task (e.g., following the steps documented in a manual to fix a specific problem in the reactor). Lastly, the knowledge-based model is a complex model used when operators are met with a new problem in which skill or rule-based models are unavailable (Lee *et al.,* 2004; Kim *et al.,* 2020).

From the Operator's perspective, while operating and maintaining the reactor requires all three mental models, on a task-by-task basis, only one form of mental model is used (Burgy *et al.,* 1982). Adjusting or slight repairs on the machinery and other procedural activities are predominantly done using a rule-based mental model. A skill-based model best maps to day-to-day tasks like controlling generator output, starting, and stopping equipment at appropriate times, and communicating with supervisors, subordinates, and peers (Hari & Puce, 2023).

NPP Operators play a crucial role in the running of an NPP. They can control all of the aspects of the reactor, as shown in Fig. 1. The Control room is the center of the plant, where the function and safety of the reactor, steam generator, and other plant areas must be maintained.

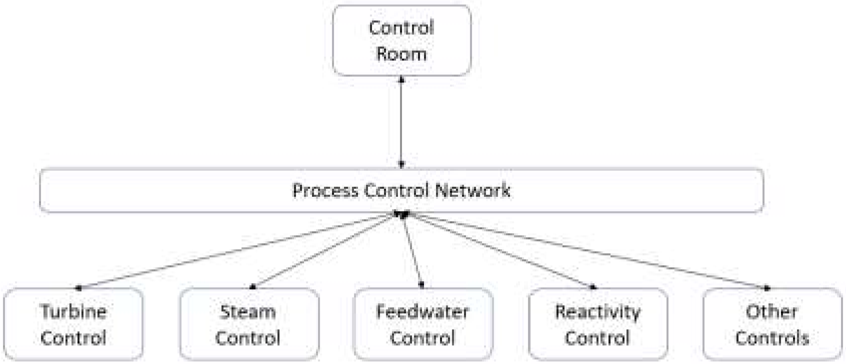


Fig. 1: Chain of Commands in NPP Control Room

This paper will present analysis of human factors and performance shaping factors and relate to SMR operator in the designated control rooms for improved performance. Understanding human factors in SMR operation is crucial. The complexity of SMRs, along with their reduced staffing needs, underscores the importance of comprehensively analyzing human performance. This includes examining operator training, qualifications, human-systems integration, and the mental models used during operations. The integration of EEG-based monitoring into this analysis forms the cornerstone of our approach, enabling a deeper understanding of how operators interact with and respond to the unique demands of SMR control rooms.

2. Electroencephalography

2.1. Fundamentals of EEG Technology

The Electroencephalogram (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. While the activity of a single neuron may be subtle, the collective firing of thousands creates an electrical field that transcends the barriers of tissue and bone, making it detectable on the scalp's surface (Hari & Puce, 2023).

EEG signals are primarily categorized into distinct frequency bands: delta, theta, alpha, beta, and gamma, each correlating with different cognitive and neurological states. These frequency bands range from the slow, deep delta waves (0.1 - 4 Hz) to the fast, high-frequency gamma waves (above 30 Hz), providing a comprehensive spectrum of brain activity (Kandel et al., 2021).

2.2. EEG in Diagnosing and Understanding Brain Functions

Since 1929, EEG has been integral in diagnosing and studying a plethora of neurological conditions, including seizures, traumatic brain injuries, and dementia. By analyzing the brain's electrical patterns, EEG aids in uncovering abnormalities and dysfunctions in neural processing (Kandel et al., 2021). However, EEG data interpretation is nuanced, requiring careful differentiation between true neural signals and 'artifacts' – extraneous signals arising from heartbeat, breathing, or muscle contractions.

EEG in Control Room Operator Performance Assessment

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.

For instance, research by Kim et al. (2020) employed EEG to study attentional focus in nuclear plant operators, revealing how different brainwave patterns correlate with task engagement and situational awareness. Other studies have sought to develop and validate EEG based tools to determine mental workload in Plant Operators.

In the study "Development of an EEG-based workload measurement method in nuclear power plants," the methodology involved using EEG to monitor brainwave activities of nuclear power plant operators (Choi et al. 2018). The focus was on identifying patterns correlating with different levels of mental workload. The researchers specifically developed the EEG-based Workload Index (EWI) to objectively quantify the mental workload. This involved recording EEG data during various simulated control room tasks and analyzing the brainwave patterns, particularly focusing on frequency bands that have been previously associated with cognitive load and stress levels.

Furthermore, the study "Dynamic assessment of control room operator's cognitive workload using Electroencephalography (EEG)," researchers focused on evaluating cognitive workload dynamically in a control room setting (Iqbal et al. 2020). They employed EEG to track brain activities of operators during simulated scenarios in nuclear power plants. The methodology involved analyzing EEG data to observe changes in brainwave patterns under different operational conditions, helping to understand the cognitive stressors and workload experienced by operators. The study's innovative approach was to provide real-time insights into the cognitive states of operators, which could be crucial for enhancing safety and efficiency in high-stakes environments like nuclear power plants.

Another significant study was at the Kursk Nuclear Power Station involved examining the EEG patterns of 105 operators, comparing workers post-shifts with others during rest days (Laskova et al., 2010). This study aimed to understand the impact of work shifts on operators' neurological states.

Findings revealed notable changes in EEG patterns, specifically in the alpha and theta rhythms, for the post-shift group. These changes, observed in the parietal and posterior temporal brain regions, were indicative of increased mental strain and autonomic dysfunction, linked to higher cerebrovascular risk.

This research underscores EEG's utility in monitoring NPP operators' cognitive load. EEG provides real-time, objective measures of brain activity, essential for effective workload management and fatigue prevention. Incorporating EEG assessments can significantly enhance operational safety by ensuring operators are functioning within safe cognitive load levels, thus contributing to overall plant safety.

Our study builds upon these foundations, extending the application of EEG into the realm of Small Modular Reactor (SMR) operations. Unlike prior research, our approach integrates EEG monitoring with a comprehensive analysis of human performance factors, such as stress and cognitive load, in relation to specific SMR operational tasks. Utilizing an advanced SMR simulator, our research captures detailed human responses in scenarios tailored to SMR environments, offering a nuanced understanding of EEG metrics in this emerging field. This distinctive approach not only contributes to the existing literature but also paves the way for more effective and safer SMR control room design and operations.

2.3. The Future of EEG in Operational Safety and Efficiency

The integration of EEG in control room settings goes beyond mere diagnosis; it offers a proactive approach to enhancing operational safety and efficiency. By continuously monitoring brainwave patterns, it is possible to identify signs of cognitive overload or fatigue before they impact performance, thereby proactively mitigating risks. This approach marks a significant leap in human factors engineering, paving the way for safer, more efficient control room operations.

EEG technology, with its ability to non-invasively map and analyze brain function, stands as a cornerstone in understanding and enhancing control room operator performance. Its application in nuclear and process industries, particularly in high-stakes control room environments, underscores its potential as a transformative tool for safety and efficiency in modern industrial operations.

2.4.Significance of 10Hz Frequency

The increase in band power at the 10Hz frequency is particularly noteworthy. This 10Hz activity falls within the alpha band, which has been previously correlated with varying levels of cognitive load and stress (Bazanova & Vernon, 2014; Klimesch, 1999). Other studies found that frontal lobe asymmetry can also appear if one is performing a cognitively demanding task (Coan *et al.,* 2006).

2.5.Significance of 50Hz Frequency

Meanwhile observed surges in the 50Hz frequency correspond to the gamma band, a frequency that has been linked with various cognitive processes. Gamma band activity has previously been proposed as an EEG marker for acute psychosocial stress, especially the kind induced by paradigms like the Montreal Imaging Stress Task (MIST) (Dedovic *et al.,* 2005). Further supporting the significance of gamma activity in stress-related contexts, research has highlighted its relevance in meditation-related studies, which often share parallels with relaxation or stress conditions (Lutz *et al.* 2004). However, it should be noted that while there's a wealth of EEG-based methods hinting at the role of gamma in reflecting stress, a universally recognized EEG marker for stress remains to be established.

While increased alpha band power has been studied as a marker for stress and cognitive load, the gamma band activity, particularly at 50Hz, may be considered a more sensitive and immediate marker for high-stress scenarios (Minguillon *et al.,* 2016).

2.6.Electrocardiogram Hardware

Recent advancements in wearable technology have revolutionized the field of physiological monitoring. Devices such as Samsung's smartwatches now provide a suite of non-invasive tools for the continuous tracking of vital health metrics, including electrocardiograms (ECGs), heart rate, blood pressure, and stress levels. These devices stand out for their ability to record ECGs, offering insights into the heart's electrical patterns which can be pivotal in assessing the cardiovascular status of SMR operators (Tison et al., 2020).

The utility of such wearable technology is particularly evident within the high-stakes environment of SMR control rooms. Here, monitoring heart rate variability, a derivative of ECG readings, serves as a barometer for stress and cognitive load. Fluctuations in this parameter may prelude the onset of stress responses or cognitive overload during critical operations, providing an early warning system for potential human error (Shaffer & Ginsberg, 2017).

Moreover, the integration of photoplethysmography (PPG) sensors in these smartwatches further augments our capacity to discern stress levels and blood pressure changes in real-time. Elevated stress levels, discernible through diminished heart rate variability, point towards a state of increased mental arousal, which is critical to recognize during emergency scenarios (Shaffer & Ginsberg, 2017).

Nevertheless, the adoption of such sophisticated monitoring tools necessitates a cautionary approach. Factors such as the device's position on the body and the operator's physical movements can skew data accuracy. Hence, a robust calibration and data interpretation protocol must be established to ensure the reliability of these readings.

When combined with EEG data, the physiological metrics gathered from Samsung smartwatches could significantly enrich our comprehension of the human factors influencing SMR operation. This synergy of data not only supports the real-time monitoring of operator states but also provides actionable insights for enhancing safety protocols and operational procedures, thereby fostering a safer and more efficient SMR work environment.

2.7.EEG-Assisted Operator Performance Monitoring System

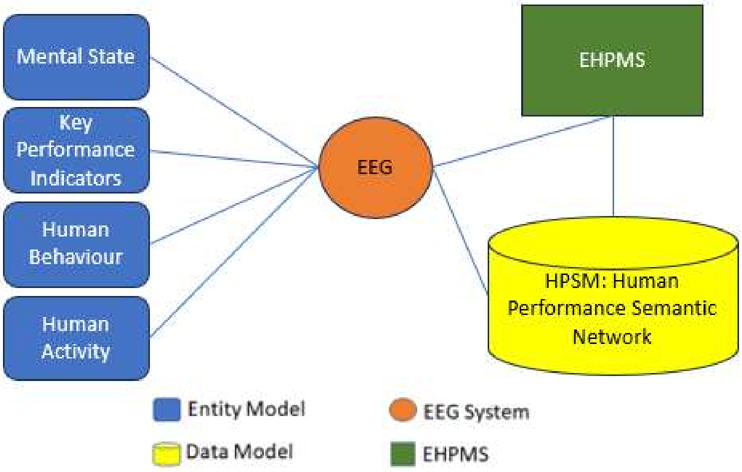


Fig. 2: Integrated System Design

The proposed integrated system, called EEG-based Human Performance Management System (EHPMS), shows the analysis of plant operation tasks and link with operator activities and behavior and correlate with EEG signals. Fig. 2 shows the proposed design of EHPMS. The EHPMS is an innovative system designed to holistically assess human performance during operational tasks. By using advanced EEG capabilities to record essential brain activity, it offers a view of an operator's mental state and performance. Human Performance Semantic Network (HPSN) is developed to structure knowledge about human performance in different operation tasks and associated behavior. Human performance indicators and PSFs are defined and evaluated for different operation tasks and human responses, which are dynamically updated in HPSN. The HPSN will act as a database on which the EHPMS will retrieve the important connections between operator mental state and operator task.

Fundamental Principles: Electroencephalography (EEG) is a non-invasive method that records the electrical activities of the brain. The utilization of EEG in EHPMS allows for the mapping of human brain signals to behavioral and operational activities, leading to insightful evaluations of human behavior.

Real-Time Monitoring: One of the pivotal advantages of EEG incorporation is its capacity for real-time monitoring. EEG data offers an instantaneous view into the operator's cognitive state, granting the opportunity for timely interventions if any anomalies or concerning patterns are detected.

Objective Measures: EEG not only offers real-time monitoring but also ensures the objectivity of the data. Stress and cognitive load, traditionally gauged through self-reports which can be influenced by individual biases, are more accurately and reliably assessed with EEG. This adds a layer of precision and credibility to the EHPMS's assessments.

Identifying Stressors: The EHPMS, with its EEG component, is instrumental in pinpointing conditions or procedures that induce excessive stress or cognitive load on the operator. By recognizing these specific stressors, interventions can be timely, ensuring the operator's safety and the integrity of the operation.

Enhancing Operational Procedures: Beyond just identification, the insights derived from the EHPMS can assist in the optimization of performance shaping factors and human-centric operational protocols. By doing so, it ensures a more streamlined, effective, and safer operational environment.

Additional Physiological Measures: To complement the EEG data and provide a more comprehensive view of an operator's state, the EHPMS integrates other vital physiological measurements. These include monitoring the blood pressure, heart rate, and other pivotal signs, offering a more rounded view of the human state during operations.

3. Human Performance Shaping Factors

The effectiveness of Small Modular Reactor (SMR) operation hinges upon a multitude of Performance Shaping Factors (PSFs) that encompass both internal and external elements.

3.1. PSF Classifications for SMR Plant Operation

The PSFs can be broadly divided into several categories as shown in Table 1 (Henderson *et al.,* 2002).

Table 1: PSF Categories

Operator Factors
Fatigue: This includes prolonged work hours without breaks, irregular shifts, sleep deprivation, and low vigilance.
Expertise: Factors such as time elapsed since training, lack of regular upskilling opportunities, experience, system familiarity, and training quality play an essential role.
Stress: Stressors include perceived urgency, nervousness tied to the importance of events, physical tension, fear of failure, perceived threats, and high-stakes risk.

Responsibility: This relates to the sense of duty towards society, individuals, and the plant itself.
Bias: Biases, such as overconfidence, risk-taking tendencies, and cognitive biases, influence operator performance.
Team Factors
Communication Needs: The necessity for extensive and external discussions, often with offsite entities.
Communication Accessibility: Issues can arise from unreliable communication systems, non-standardized communication protocols, and delayed information exchange.
Communication Quality: Misinterpretation or misunderstanding of information, noise and interruptions, and the use of similar sounding words can negatively impact the quality of communication.
Leadership: Factors include inadequate oversight, overconfidence, and failing to clearly define team members' tasks and duties.
Team Cohesion: Trust and interpersonal relationships among team members contribute to team cohesion.
Collaboration: The degree of collaboration is influenced by members' familiarity with their roles, experience of working together, and the focus on their individual tasks.
Organizational Factors
Safety Culture: Routine safety violations, decision-making trade-offs between safety and production, poor communication, and non-compliance with regulations impact the overall safety culture.
Resource Management: Inefficient deployment of personnel and tasks influences resource management.
Human-System Interface Factors
Information Availability: Missing or masked key indicators, alarms, and feedback can result in information gaps.
Information Ambiguity: Factors include small indications of issues, non-obvious cues or alarms, and overlapping symptoms from multiple faults.
Information Reliability: Misleading or conflicting information, false alarms, and failed indicators can lead to unreliable information.
Information Overload: Overloading of alarms, information displays, and simultaneous changes of information may confuse operators.
System Factors
System Reliability: Multiple faults and equipment unavailability impact system reliability.
System Complexity: Complexity is influenced by the number and interdependencies of sub-systems and components, as well as system transparency.
System Dynamics: Dynamic changes in variables and critical parameters contribute to system dynamics.
Work Environment Factors
Habitability: Noise levels, temperature extremes, lighting, radiation, smoke, and toxic gases influence the habitability of the work environment.
Workplace Quality: Factors such as workplace layout, space constraints, and inappropriate signs affect the workplace quality.
Procedure Factors
Procedure Complexity: Complexity is influenced by the number of steps, multiple procedures, and complicated logic between steps.
Procedure Quality: Quality is determined by the clarity of instructions, correctness, completeness, and compatibility with the scenario and industry practice.
Task Factors
Goal Complexity: Multiple or conflicting goals add complexity.
Information Acquisition Complexity: Memorization, mental calculations, continuous tracking, and

information integration contribute to complexity.
Information Analysis Complexity: Ambiguity, prioritization of faults, and prediction of future plant states contribute to analysis complexity.
Decision-Making Complexity: Multiple alternative diagnoses and procedures add to decision-making complexity.
Action Implementation Complexity: Complexity increases with the number of manual actions, required sequencing, precision, and constant monitoring.

3.2.Internal PSFs

Operators experiencing high levels of stress or excessive workload are more prone to fatigue, which can decrease cognitive performance and increase error rates. Implementing measures to manage workload effectively, providing support to handle stress, and ensuring appropriate shift lengths and rest periods are vital for maintaining operator alertness and performance (Henderson *et al.,* 2002).

The operator's level of training and experience greatly influences their ability to perform tasks and respond to operational anomalies effectively. Comprehensive training programs, simulation exercises, and ongoing learning initiatives prepare operators for various operational scenarios and equip them to respond appropriately during routine and emergency situations.

Each of these PSFs plays a unique role in shaping operator performance in SMRs. By focusing on these areas, potential for human errors in SMR operation can be minimized, thereby contributing to the overall safety and efficiency of the operation.

3.3.External PSFs

Ergonomics and Human-Machine Interface in SMRs often incorporate advanced digital and artificial intelligence-enhanced technologies (Henderson *et al.,* 2002). The design of these interfaces, as well as the physical control room, heavily influences operator understanding and error rates. Poorly designed or cluttered interfaces can lead to misinterpretation of critical data, while well-organized, user-friendly interfaces enhance operator decision-making and performance (Henderson *et al.,* 2002).

Procedures and Protocols should be clear and succinct to guide operators through both routine and emergency operations. Complex or ambiguous protocols can lead to confusion and potential errors. Regular review and streamlining of procedures, with operator feedback, contribute to increased procedural adherence and reduced risk of operational errors.

Effective communication is vital during shift changes, emergencies, or when dealing with unexpected events. Ineffective or unclear communication can lead to misunderstandings, potentially causing significant operational errors. Protocols for clear, concise, and timely information exchange among operators and other team members can mitigate these risks.

Organizational culture and policies directly shape operator behaviors. A safety-conscious culture that encourages open communication, prompt error reporting, and continuous learning can significantly reduce the incidence of human error, thereby enhancing the safety and reliability of SMR operations.

3.4.Operator Task Classification

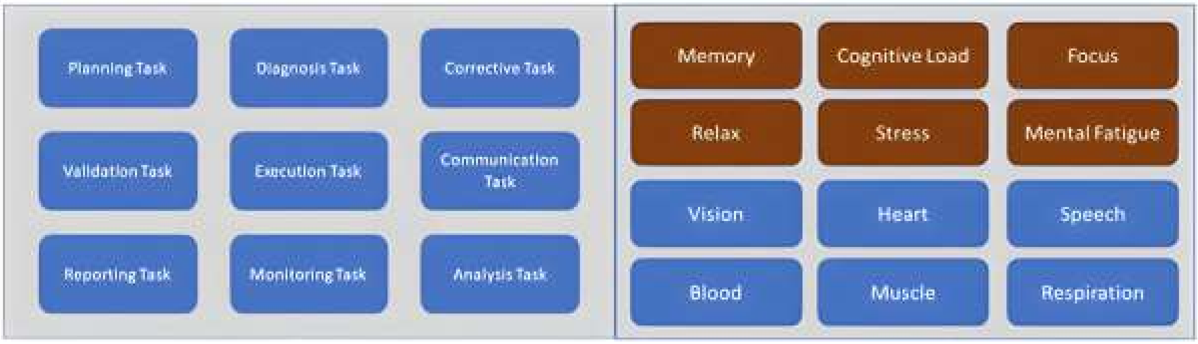


Fig. 3: Human Model and Task Classification

In the realm of SMR operations, the classification of operator tasks is a critical component that directly influences the efficacy of Performance Shaping Factors (PSFs). As depicted in Fig. 3, our dual-method approach for task classification not only categorizes tasks based on human mental and physical models but also integrates these with the operational task categories to ensure a harmonious alignment with PSFs.

a) Classification Based on Human Mental and Physical Models:

This classification, illustrated on the left side of Fig. 3, prioritizes tasks according to the cognitive and physical demands they place on operators. Tasks are assorted into categories such as Planning, Validation, Reporting, Monitoring, Execution, and Diagnosis. Each category is mapped against specific mental and physical skills required, like memory recall for Reporting or complex problem-solving for Diagnosis, ensuring that the cognitive load and physical exertion align with the operator's capabilities.

b) Classification Based on Operation Task Category:

The right side of Fig. 3 adopts a more operational perspective, categorizing tasks into Communication, Analysis, and Corrective Actions. This segmentation is vital in assigning tasks to operators with the corresponding skill set and expertise level, which is essential for efficient task execution and error minimization.

Integrating these classifications enables a comprehensive approach to task assignment in control rooms, ensuring that each task's mental and physical demands are appropriately matched with the operators' abilities. This is crucial for mitigating errors and enhancing operational efficiency, directly impacting the PSFs. Moreover, this structured classification forms the foundation for applying our EEG-based human performance monitoring system. By tailoring this system to these classifications, we can accurately assess and enhance operator performance in specific operational scenarios, making our approach distinctive in addressing the nuances of SMR operations.

This dual-method classification system not only optimizes task allocation based on operator capabilities but also provides a framework to analyze and improve task performance in light of PSFs, making it an integral part of our study's aim to enhance SMR operation safety and efficiency.

4. Method

4.1. Monitoring System & Test Environment

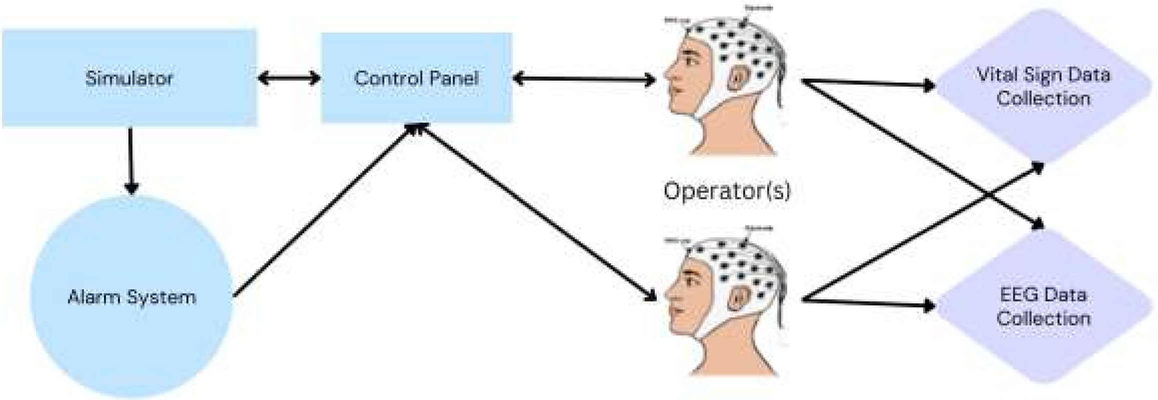


Fig. 4: The Proposed Test Environment

The Operator(s) will start the SMR simulator with the EEG cap equipped, reading brain waves as the operator(s) complete the test scenario. EEG data is collected for analysis.

The test environment, as depicted in Fig. 4, is designed to emulate the operations of a Small Modular Reactor. At the heart of the setup is the SMR Simulator, providing a realistic and interactive representation of SMR operations and potential accident scenarios such as a gradual coolant leak. Operators, situated within this simulated control room environment, interact with a detailed Control Panel, designed to mimic the operational interface of actual SMR systems. The environment is further enhanced with a sophisticated Alarm System, which is configured to alert operators to specific incidents, enabling the assessment of response times and decision-making efficiency. To gauge the operators' cognitive states and stress levels during the simulation tasks, EEG Data Collection is seamlessly integrated into the setup. Real-time EEG data are captured. This meticulously structured test environment ensures a thorough evaluation of operator performance in simulated SMR accident scenarios.

The EEG data processing begins post data acquisition, the cleaned and organized EEG data undergo a detailed analysis. A frequency analysis is conducted to explore the brain rhythms, and their relationships with the observed responses to the stimuli.

4.2.EEG System

The EEG cap selected for this project was the EMOTIV EPOC Flex, a 12-channel, wireless EEG cap with EmotivBCI, a Brain-Computer Interface that provides quantitative performance scores (Strmiska & Koudelkova, 2018). To enhance the EEG data processing, our study employs the EmotivBCI tool for further data refinement. This tool aids in the amplification of the EEG data, performing an additional round of artifact removal. Stress is a measure of comfort with the current challenge. High stress can result from an inability to complete a difficult task, feeling overwhelmed and fearing negative consequences for failing to satisfy the task requirements. Generally, a low to moderate stress level can improve productivity, whereas a higher level tends to be destructive and can have long-term consequences for health and wellbeing (Kumar& Kumar, 2016). Focus measures fixed attention to one specific task. Focus measures the depth of attention and the frequency that attention switches between tasks. A high level of task switching indicates poor focus and distraction. Studies testing the efficacy of these performance metrics found that the levels of stress calculated by the BCI correlate with the task's difficulty (Gofuku & Niwa, 2001; Kumar & Kumar, 2016). The task tested was a set of two math problems, the first more complex than the second. When participants completed both problem sets while being monitored by the BCI system, the levels of stress were elevated for the duration of both tests, with the first problem set having a high-stress level than the second (Kumar & Kumar, 2016).

The EmotivBCI assists in the quantification of the data, providing insightful performance metrics based on their proprietary analysis of the EEG signals, examples shown in Fig. 5, where multiple performance metrics are being recorded live from a single subject. In summary, the EEG data processing in our study is a structured and detailed pathway from initial artifact correction to data analysis.

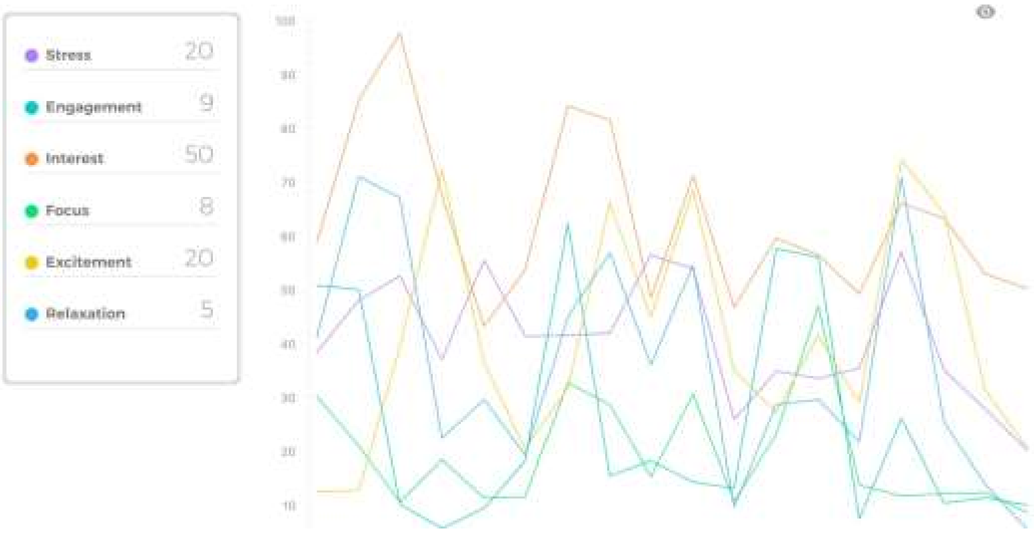


Fig. 5: Emotiv BCI with Real-Time Performance Metrics. Each Curve Represents a Performance Metric Recorded of One Individual

4.3.SMR Simulator

The simulator used for SMR trials is the integral Pressurized Water Reactor (iPWR) simulator, shown in Fig. 6, as a sophisticated tool endorsed by the International Atomic Energy Agency (IAEA). Its high-fidelity simulation environment meticulously replicates real-time iPWR operations, providing a framework for the examination of various operational and safety facets of nuclear reactor systems.

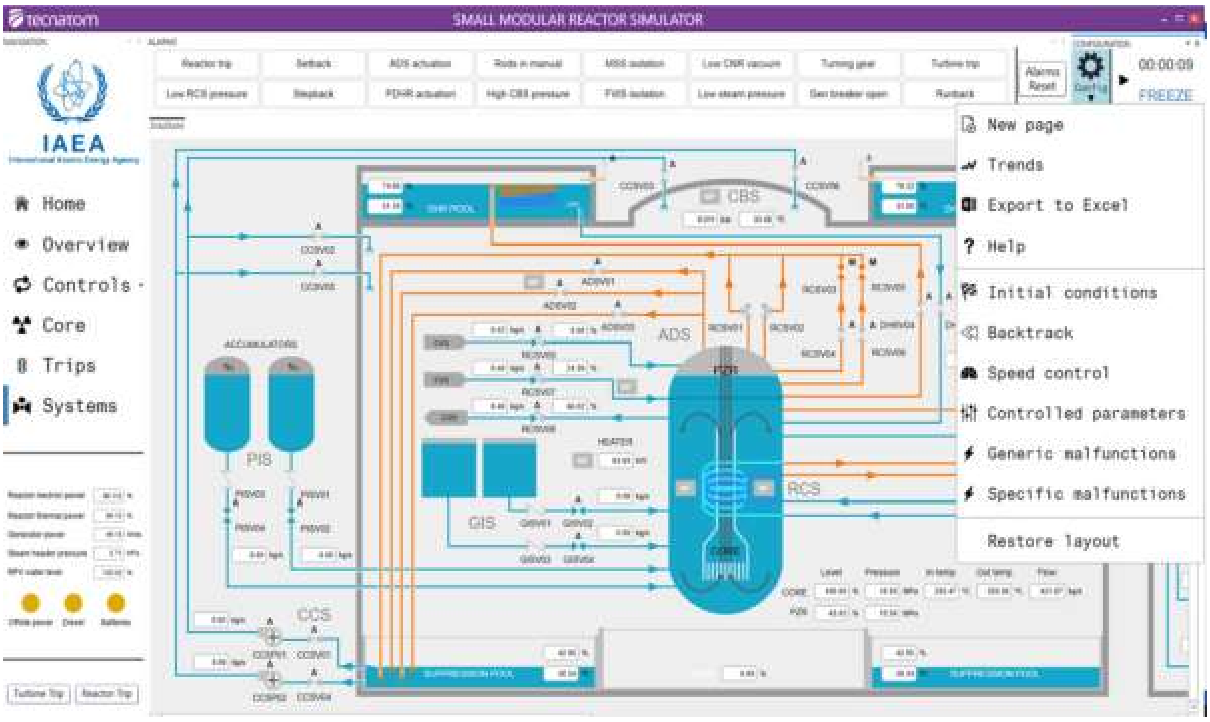


Fig. 6: iPWR Simulator for SMR Scenario Testing

The utilization of the iPWR simulator in this research, combined with the use of the EEG , facilitates an exploration into the mental states of operators within a simulated reactor context. This advanced simulation environment affords an insight into the impact of different operational scenarios on cognitive load and stress markers, as observed through electroencephalographic (EEG) data.

5. Case Study

In the subsequent case study, we delve into the dynamics of operator performance in Small Modular Reactor (SMR) control rooms under simulated conditions. Utilizing an SMR simulator, the study meticulously records and analyzes operators' responses to operational cues, focusing on stress levels and cognitive load. Complementing this, a Nuclear Power Plant Simulator trial offers additional data. Central to this investigation is the integration of EEG monitoring, aiming to unearth patterns between neurological activity and operator conduct.

5.1. Simulated Operational Scenarios

A demo scenario was used to analyze the risks of SMR and NPP Operators in simulation. The Operator will begin the scenario by completing a task when an alert sounds. The scenario execution framework is proposed, as shown in Fig. 7. The framework starts when the operator receives alerts from the control system and attempts to interpret. The mental model is established for the selected situation. A series of steps are identified and executed to satisfy the alert. These steps are recorded in the logbook.

The EEG will monitor the Operators brain waves while the BCI calculates the Operator's

Fig. 7: Scenario Execution Framework Designed for Operators

performance metrics. This Demo scenario will be conducted multiple times, with different operators are different times of the day and shifts. Longer shifts and late-night shifts increase the likelihood of accidents occurring and high levels of mental fatigue.

In the proposed test scenarios, two volunteer operators were used to simulate SMR/NPP operation. All participants are members of the lab.

5.2.Test Run-1: Interaction with SMR Simulator

The operator is placed in a simulator with the plant running under normal conditions. Fig. 8 shows the test framework. The Operator is initially tasked with recording various meters and values relevant to the proper operation of the plant, such as turbine speed, and steam pressure. Unknown to them, a scenario is initiated where a small leak develops in the reactor's primary coolant system. This leak results in slow but steady changes in several control panel parameters. The EEG data will be extracted using the OpenBCI EEG Electrode Cap. This test run will also include the use of a smartwatch to gather Blood pressure Data.

The operator is asked to observe the control panel without intervening and report any perceived anomalies. They are not informed about the planned leak, making it a true test of their observational skills and system knowledge.

Over time, the control panel would show:

Slight Decrease in Coolant Pressure: A gradual drop in the reactor coolant system pressure would be the first noticeable sign of the leak.

Increase in Reactor Core Temperature: As the coolant leak continues, there would be less coolant to remove heat from the reactor core, leading to a gradual increase in core temperature.

Increase in Coolant Makeup Flow: To compensate for the lost coolant, the makeup water system would start to increase its flow, which could also be noticed by the operator.

Change in Radiation Levels: If the leak is severe enough, there might be a slight increase in radiation levels in the containment building, as detected by radiation monitoring systems.

The operator's task would be to notice these changes, understand their significance, and report their findings to the experiment supervisor. The operator's performance could then be evaluated based on how accurately and quickly they identify the signs of the coolant leak.

Fig. 8: Scenario Execution Framework to Test Multiple Tasks

5.3.Test Run-2: Interaction with NPP Simulation

This Test Run will utilize an NPP Simulator to record measure performance metrics from the operators. The test operators were tasked with recording values of different parts of the reactor (Turbine speed, Generator Power, Steam Hdr Pressure ETC.). While completing their task, a malfunction occurs in the reactor, resulting in a Steam Generator Valve Failing Open. The Operator must promptly record the values and the valve malfunction. This scenario is meant to evoke levels of stress and mental fatigue in a short period; this allows us to experiment many times in different conditions such as time of day and length of shift. Each participant will conduct the scenario at 6 A.M., 1 P.M., and 9 P.M.

1. EEG Setup

Attach EEG electrodes to the participants' scalps according to the default electrode layout provided by EMOTIV. Ensure the EEG equipment is calibrated for accurate data collection using a benchmark session with the patient to record baseline values. Set the sampling rate and ensure a sufficient number of channels to capture relevant brainwave activity.

2. Experimental Conditions

Set up a simulated NPP control room environment Using CANDU simulator. Introduce stress-inducing elements such as time pressure, simulated alarms, equipment malfunctions, and communication challenges. Ensure the scenario is safe and realistic but not overly hazardous to participants.

3. Sample Selection

Recruit volunteers who are familiar with emergency response procedures.

4. Stress Induction

Simulate an emergency scenario, such as a reactor malfunction, loss of power, or cooling system failure. Create time pressure by imposing strict deadlines for response actions. Incorporate realistic stressors like simulated alarms, flashing lights, and communication interruptions.

5. Experimental Protocol:

Provide participants with a pre-simulation briefing, explaining the emergency scenario and their role in responding to it. Start the simulation and monitor participants' responses, including decision-making, communication, and task execution. Continuously record EEG data throughout the simulation.

6. Data Collection:

Capture EEG data, focusing on relevant brainwave activity associated with stress and cognitive load.

An EMOTIV - EPOC Flex Kit made of sintered Ag-Ag chloride will be used for the scenario. The system includes the EMOTIV electrode cap with a bandwidth of 0.16-43Hz and digital notch filters at 50Hz and 60Hz. The NPP simulator used for this experiment is the CANDU simulator by Cassiopeia technologies, which provides accurate timing and control of an NPP control room, shown in fig. 9. The simulator is capable of programming malfunctions to occur at certain times and contains a separate panel for alerts for clear reading.

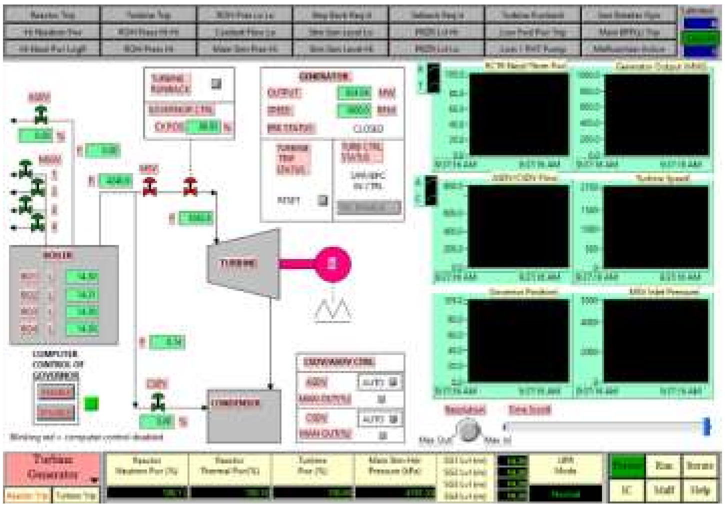


Figure 9: Turbine Screen on Cassiopea Simulator

5.4.Key Performance Indicators

Key Performance Indicators (KPIs) are specific, measurable values that demonstrate how effectively an organization or individual is achieving key objectives. For Gradual Coolant leak accident simulation for SMR operators, KPIs can help gauge the effectiveness of training and operator performance.

Table 3 shows the list of Key performance indicators relevant to the two experimental scenarios and to the designing of the SMR control room and other human factors.

Table 3: Key Performance Indicators for SMR Plant Operation

Detection Time: The time it takes for operators to identify that an accident has occurred from the initial onset of symptoms. Quicker detection times indicate a higher level of awareness and understanding.

Response Time: The time from when the accident is identified to when the first corrective action is initiated. This measures the operators' knowledge of procedures and their decision-making speed.

Procedure Adherence: The degree to which the operators follow the established procedures for responding to an accident. This can be measured by noting any deviations from the procedures during the simulation.

Corrective Actions: The number and significance of correct actions taken by the operators during the scenario. More correct actions indicate better understanding and application of the procedures.

Communication Effectiveness: Assessment of the quality and timeliness of communication between the operators, particularly during critical moments. Effective communication is crucial for coordinating actions and sharing information.

Error Rate: The number and significance of errors made during the simulation. This could include procedural errors, communication errors, or technical errors.

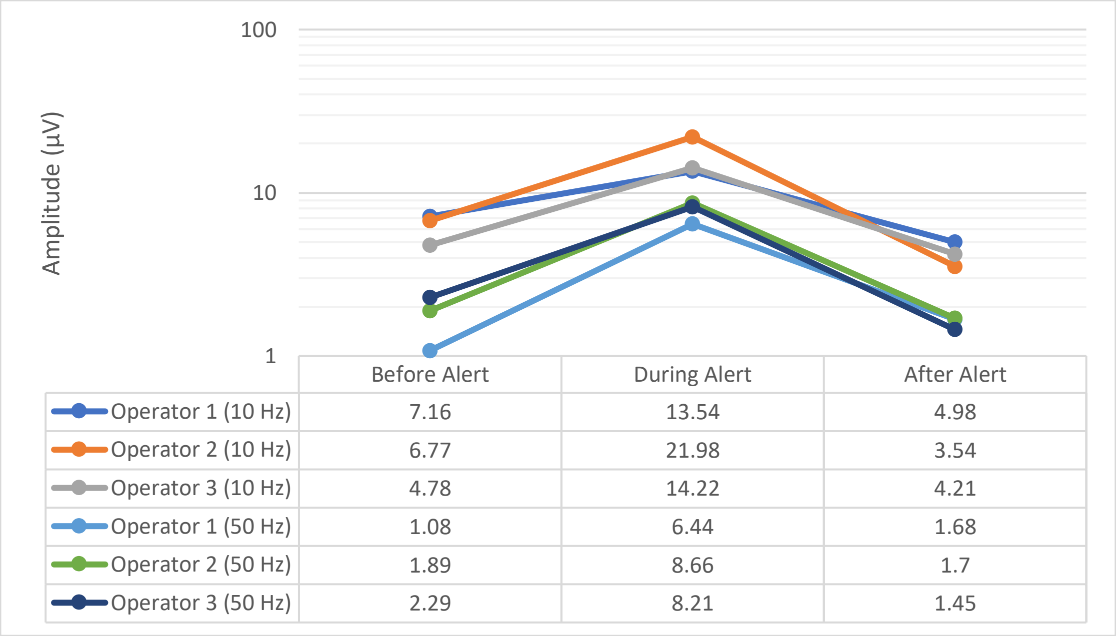
Mitigation Success: The extent to which the operators were able to mitigate the consequences of the accident. This could be measured by the final condition of the reactor and containment systems at the end of the simulation.

Stress Management: Observations or self-reports of stress levels during the simulation. High stress levels can impair performance and indicate a need for additional training or support.

6. Results

6.1. EEG Data Analysis

The EEG data analysis was conducted using a Fast Fourier Transform (FFT), which decomposes the brainwave signals into their constituent frequencies. This method allowed for the precise quantification of amplitude changes in the alpha (10 Hz) and gamma (50 Hz) bands during the SMR simulation tasks. The 10 Hz frequency, associated with relaxed alertness, showed an increase post-simulation. The 50 Hz frequency also saw a rise, suggesting an increased cognitive load. These results demonstrate changes in operators' cognitive states in response to operational demands.



	Before Alert	During Alert	After Alert
Operator 1 (10 Hz)	7.16	13.54	4.98
Operator 2 (10 Hz)	6.77	21.98	3.54
Operator 3 (10 Hz)	4.78	14.22	4.21
Operator 1 (50 Hz)	1.08	6.44	1.68
Operator 2 (50 Hz)	1.89	8.66	1.7
Operator 3 (50 Hz)	2.29	8.21	1.45

Fig. 102: Comparative EEG Amplitude Responses of Three Operators at 10 Hz and 50 Hz Frequencies Before, During, and After SMR Simulation Alert

Results of the NPP trials, showing the Stress and Focus performance modalities provided by the EMOTIV BCI are shown in Table 4 below. The three values captured are the performance metric recorded at the start of the simulation in percentiles, at the moment of the malfunction, and 1 minute after the malfunction.

Table 4: Performance Metric Values at different times of day

[Format: (Before Test Start, 30s after alert, 5 mins after alert)]

	6 A.M.	1 P.M.	9 P.M.
Operator 1	Stress: 28, 84, 59 Focus: 36, 77, 56	Stress: 23, 79, 55 Focus: 40, 82, 60	Stress: 35, 86, 66 Focus: 31, 75, 52
Operator 2	Stress: 27, 89, 62 Focus: 39, 77, 52	Stress: 30, 83, 59 Focus: 43, 84, 57	Stress: 32, 93, 71 Focus: 33, 74, 49

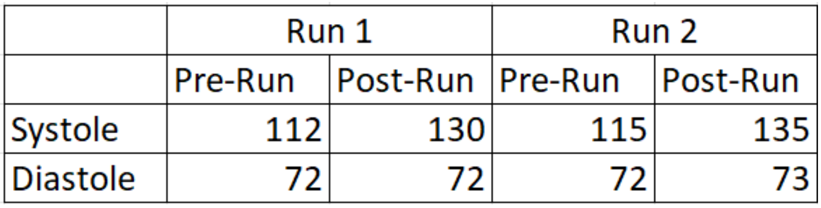
In The NPP Simulation, Both Operators experienced an increase in stress in all three zones, spiking immediately after noticing the malfunction and gradually reducing afterward. The Focus modality also saw an increase when the malfunction was noticed. The morning and night scenarios had higher stress levels and lower focus levels. Whether or not an operator performs better in the morning or night scenario.

6.2.ECG Data Analysis

During the initial execution of the scenario, without any external interferences, there was a notable elevation in both systolic and diastolic BP levels post-test. This rise in BP corresponded with the operator's detection of a malfunction in the simulation (Table 5).

To further understand the implications of distractions on the operator's stress levels and response time, the scenario was repeated. However, in this iteration, additional visual and auditory distractions were introduced. The results indicated a more pronounced increase in BP, suggesting heightened stress. Additionally, the time taken by the operator to correctly diagnose the malfunction was extended, indicating potential challenges in cognitive performance amidst distractions.

Table 5: Blood Pressure Measurements by Smart Watch Pre and Post Test-run



	Run 1		Run 2	
	Pre-Run	Post-Run	Pre-Run	Post-Run
Systole	112	130	115	135
Diastole	72	72	72	73

7. Discussion

In the analysis of EEG data following SMR simulation trials, a consistent increase in the 10Hz frequency band was noted, which is indicative of a state of relaxed alertness. This state is often associated with heightened cognitive readiness, a desirable condition for operators managing complex tasks. Moreover, the notable surge in the 50Hz gamma band suggests an intense cognitive engagement with the task, particularly during the simulated reactor malfunction. Such a spike in gamma activity could be attributed to the operator's focused efforts to address the critical incident, underscoring the utility of EEG in monitoring acute mental processes.

The differential EEG responses across various channels imply that the changes in brainwave patterns are not uniform across all regions of the scalp. They likely represent distinct aspects of the cognitive and emotional responses elicited by the simulated emergency. The data, derived from individual participants, illustrate the immediate impact of the malfunction on the operator’s mental workload. A significant peak in one of the EEG curves post-malfunction raises questions about individual variability in stress response. This peak could reflect a unique neural reaction to the simulated stressor, influenced by personal resilience and the mental state at the time of the event. The y-axis units, measured in microvolts, reflect the amplitude of the brainwave activity, providing a quantitative measure of the electrical activity of the neurons.

The prominent peak at 50Hz warrants consideration of potential line noise interference, a common artifact in EEG data. Overall, the application of EEG in monitoring real-time cognitive load and stress among SMR operators holds promise for enhancing operational safety. By enabling the identification of mental states indicative of stress or cognitive overload, EEG data can inform the development of adaptive support systems. These systems could adjust task demands dynamically, contributing to improved operator performance and well-being, as well as ensuring the safe running of the plant.

8. Solution Implementation

An EEG alert system was developed that notifies the user when they succumb to high mental fatigue or cognitive load levels. The proposed solution could work in active or passive modes. Active Monitoring System: Once a qualitative value for the Operator's performance is calculated, a baseline is set. The Active Monitoring system consists of real-time monitoring of the 6 Performance metrics, which are being compared to their baseline levels; if the current levels pass the acceptable limit for the metric, the system will then alert the Operators and other relevant persons. Passive Monitoring System: The Passive monitoring system controls the background monitoring of the Operator, such as the duration of work, facial expressions, eye movements and motion sensor data. Benchmarks are also required for proper calibration. These other metrics also contribute to determining mental fatigue levels, as factors such as long work shifts, and certain facial expressions are symptoms or causes of high mental fatigue. Both systems will work together to pinpoint mental fatigue states, alert the Operator, and prevent mental fatigue-caused accidents. The developed solution is shown in Fig. 11, with a user interface depicting the proposed solution shown in Fig. 12.

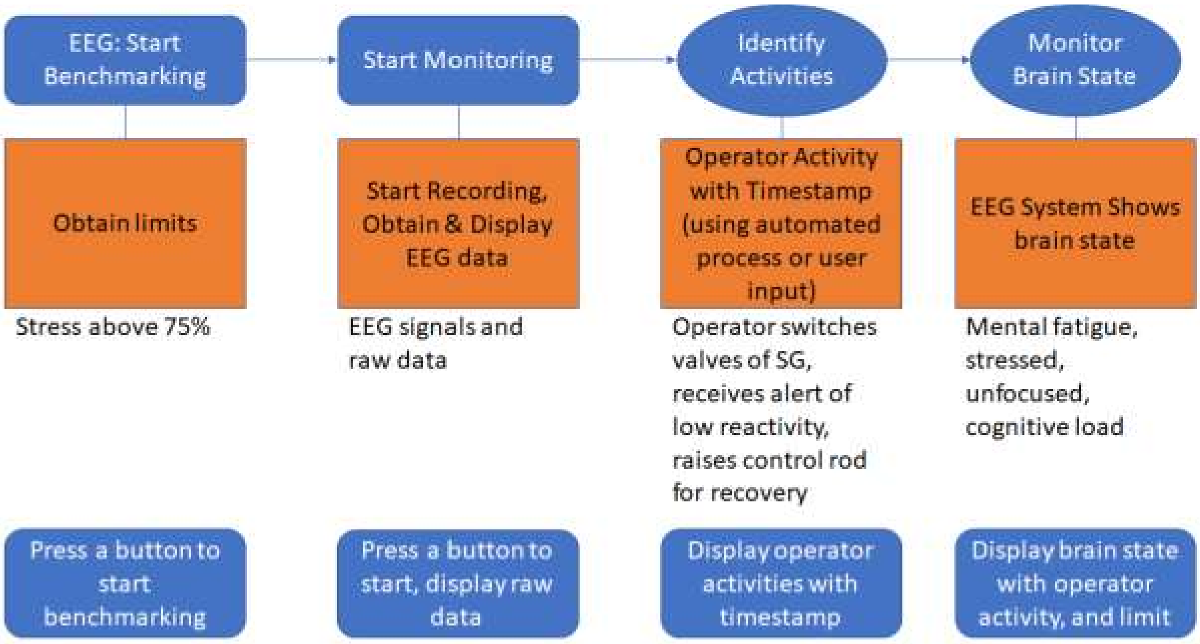


Fig. 11: EEG-Based Operator Performance Monitoring System

Detailed Human Activities

Relation ID	User ID	Task ID	Activity ID	Date Created	Remove
1	1000783	1.1	1.1	2022-09-12 00:56:02.098378	Delete

Relations ID:
User ID:
Task ID:
Activity ID:

Fig. 12: User Interface for Operator Task Analysis

By implementing our solution, operator performance and safety measures are improved in nuclear power plant and SMR operation.

9. Conclusion

Through the comprehensive analysis of EEG data during SMR accident simulations, it highlights an observable increase in certain brain frequencies, indicative of elevated levels of stress among operators during simulation. These findings underscore the crucial need for robust and refined training approaches, particularly focusing on stress management and effective communication. The implementation of Key Performance Indicators (KPIs) is advocated to rigorously assess and enhance operator responses, aiding in the continual improvement of safety and operational protocols. The developed EEG alert system, functioning in both active and passive modes, proves to be an effective tool for the real-time monitoring of performance metrics, ensuring timely intervention in case of emerging mental fatigue and potentially reducing the incidence of related errors or accidents. This research contributes to the enhancement of operator safety and performance in SMR operations. Future studies are encouraged to build upon these findings for the continued improvement and innovation in SMR operational safety and efficiency.

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Highlights

- Human performance analysis for nuclear power plant operation
- EEG-based human performance monitoring

- SMR plant operation analysis with human performance

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Biography

John Gaber is currently pursuing a B.Sc. in Health Science with a specialization in Kinesiology at York University, Toronto. His primary research emphasis lies at the intersection of neuropsychology and industrial applications. His work includes the analysis of human activities in critical settings, especially in nuclear power plants, and the utilization of EEG systems to understand human mental states and activities. Through collaborations, he has published extensively, examining risk factors in nuclear power plant operations using EEG systems and exploring EEG-based solutions for diverse applications, from drivers' health to nuclear plant operator performance. His contributions have been recognized at various international conferences, including the International Conference on Neuropsychology and the Symposium on Plasma And Nuclear Systems. Gaber continues to expand the landscape of his research.

Dr. Jing Ren is an associate professor in the Faculty of Engineering and Applied Science at Ontario Tech University. She obtained her MASc and PhD both from Western University in 2003 and 2005 respectively. She has published more than 90 journal and conference papers in the fields of deep learning, robotics, image processing and automotive technologies. She received the University Faculty Award in 2006 for her pioneer work in medical simulations using haptics.

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