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# An Ergonomic Approach in Designing Nuclear Reactor Simulator Console for Local Operator

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**A B S T R A C T**

The construction of a Nuclear Power Plant (NPP) using Small Modular Reactor (SMR) technology is an interesting scheme to support Net-Zero Carbon Emission. The SMR design is an advanced generation reactor with high safety and utilization features, especially for the electricity needed and industry. Its modular size can also be applied to remote areas with lower construction costs compared to other types of power plants. Considering the geographical location and territory of Indonesia, which is an archipelagic country, this type of reactor is suitable for application in Indonesia. To ensure the safety and increase in mastery of the technology, it is necessary to create a simulator to support this program. However, specific regulations governing human-machine interactions (HMI) that cover nuclear reactor simulators are not yet available in Indonesia. This research reviews the US regulations regarding the design of reactor main control rooms, offering options for Indonesian operators by considering anthropometric and ergonomic aspects. In conclusion, the research presents a set of recommendations for developing an appropriate simulator based on these factors.



## 1. INTRODUCTION

Indonesia, a developing country with substantial energy demands for industry and civilians, simultaneously grapples with future carbon emission challenges. Dependency on fossil fuels contributes significantly to carbon emissions. Transitioning to a mix of new and renewable energy sources is a viable step to reduce carbon emissions. One of the available options is to utilize nuclear energy, considering its substantial energy production, carbon-free operation, minimal waste generation, and the ability to meet basic needs consistently throughout the year regardless of weather conditions [1]. One suitable design for a nuclear power plant (NPP) in Indonesia is a small modular reactor (SMR), which offers advantages such as ease of construction, high safety features, and adjustable power output for remote areas. However, despite the numerous advantages and potential applications of nuclear energy, several considerations must be addressed before implementation in Indonesia [2]. NPP construction and operation must ensure the sufficient safety and security of the technology used. Adequate human resources must be available, and the HMI aspect is crucial as it affects work safety, efficiency, and error

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reduction. These aspects can potentially be related to the safety culture within NPP [3]. Small errors can potentially initiate incidents and larger accidents, necessitating attention for each basic event [4][5].

Simulating NPP operations is essential to understand processes both under normal conditions and during accidents [6][7][8]. Simulators also serve as training facilities for NPP operators. The design of the simulator and its supporting facilities indirectly affects operators if used for extended periods. The HMI factor is crucial in such conditions. However, specific regulations governing NPP control rooms and simulators in Indonesia are currently lacking. This study encompasses an overview of HMI based on Indonesian regulations to ensure its safety aspects. The study also compares local regulations with existing global ones to provide options or recommendations for future Reactor Control Console designs in Indonesia. The goal of this study is not to draft new regulations, but rather to offer design options specifically tailored to SMR operators in Indonesia, considering anthropometric and ergonomic factors adjusted to the size of Indonesian operators.

## 2. METHODOLOGY

The study of the main reactor control room design was based on the operational experiences of NPP in other countries. Data from available experiments were collected and used as references to create regulations and minimum user requirements. Although there is limited experimental data available for SMR, considering the fundamental similarities with larger reactors, some data from larger reactors can be used as additional references [9]. However, it is important to note that this approach may lead to miscalculations because SMRs employ a simpler scheme compared to conventional NPP designs. For example, the number of operators required in the control room may differ from the operational power of a conventional NPP.

The design of the HMI also requires careful consideration based on regulations, both in terms of nuclear aspects and labor regulations set by the government. In Indonesia, Minister of Manpower Regulation No. 15/2018 [10] provides guidelines for standard human working conditions, limitations, and recommendations. This regulation explains the standards for a good working environment by applying anthropometric and ergonomic aspects. However, this regulation does not specifically accommodate nuclear-related work. On the other hand, the Indonesian Nuclear Regulatory Authority has issued nuclear regulations in Indonesia for non-energy and energy purposes. Standard requirements for nuclear power plants in Indonesia cover control from basic design to decommissioning processes.

The study focuses on comparing available regulations with regulations in other countries as a new perspective to provide recommendations or options in designing the operator console for the control room. Existing data provided by companies like NuScale, which is one of the SMR industry players, can serve as a reference for a general overview of the main control room conditions. Specific sizes for workstations or operator consoles will be adjusted to the average size of Indonesians to enhance anthropometric and ergonomic aspects. In the design and evaluation of the main control room, attention must be paid to six measurement categories, including system performance, task performance, cooperation, resource utilization, user experience, and design differences [11]. This research will also be closely related to the IAEA Safety Guide, No. NS-G-2.10 on the periodic safety review of Nuclear Power Plants and NS-G-2.8 Recruitment, qualification and training of personnel for nuclear power plant.

## 3. RESULTS AND DISCUSSION

Simulators can be used to ensure the safety and security of the system during normal operation and critical conditions. Digital control technology has become a global standard in the field of NPP technology. Its adoption has also extended to power plant simulators, where the integration of touch screens and widescreen displays has significantly increased their prevalence. This is in contrast to the previous generation, where simulators or control rooms were dominated by physical buttons. This development affects various aspects such as space efficiency, the number of operators, accuracy, response time, and aesthetics. Several consequences of transitioning from traditional analog instrumentation and control technology to digital technology also need to be prepared. The ergonomic aspect in this transition process should be consider as important point to design a good simulator. Some of these are related to basic ergonomic design principles in simulator area, such as:

a. Displaying an easy to read for any information (font size, format, color contrast, etc.).
b. Avoid the overload numerical data – graphical information would be better.
c. Only use functional icon with proper size.
d. Setpoint and actual parameter have clear deviation information.
e. Static - Dynamic processes shown effectively in task performance.

f. Minimize combining various media to present operational information (digital displays and paper procedures) which requires different cognitive resources to handle.

Nuclear power plant operators must be well-versed in emergency procedures to take necessary mitigation actions when emergencies occur. Each NPP design has different protocols for handling its emergency conditions. Human error plays a significant role in NPP safety. A well-designed HMI can enhance nuclear power plant safety assurance and serve as a support system to prevent human errors at certain stages [12]. Human factor should also be considered not only during operations but also during maintenance, training, design, and normal operations to ensure the safety of the NPP [13]. Sometimes, it is difficult to distinguish whether human errors in control room operations are due to design flaws. The human factor aspect becomes crucial because operators and personnel involved in nuclear power plants generally work under pressure and perform complex tasks, from engaging in various input-related activities to making decisions. The primary elements of mental state include cognitive load, stress, time limitations, and task complexity. Memory information mainly comprises of knowledge, experience, and professional skills. Some of these factors encompass fatigue, ergonomic factors, cognitive demand, stress, time constraints, task intricacy, knowledge, expertise, and proficiency [14].

The aim of HMI design is to enhance operator control and actions to improve efficiency in normal and abnormal conditions, such as accidents or natural anomalies. The implementation is closely tied to human factors, which will play a crucial role in nuclear safety management [15]. Designing a good human-machine interface should allow for new operator actions based on operational experience and create layered confirmation needs for actions that can affect the entire plant.

Another challenging issue is improving human-system integration. Systems and procedures related to fundamental ergonomic principles, such as display design (font size, format, color contrast), enhanced displays with better numerical information using graphics, presentation of unstructured data, dynamic-static data, mixed paper-digital procedures. These issues are actually regulated by Indonesian Ministry of Manpower Regulation No. 5/2018.

Most of the control over NPP operations is carried out in the main control room. This room contains numerous adjustable indicators and control variables that are continuously monitored to ensure that the plant operates under normal conditions. The main control room design is important to consider. Some key parameter data displayed on larger monitors must be maintained in stable conditions. Instruments and controls in the NPP connected to the main control room need to be efficiently organized. HMI, especially in the main control room, is one of the crucial aspects compared to other parts because operators will spend most of their time there. Some human error may occur here from many possibly action by the operators. Types of human errors that can occur in the maintenance of digital protection system components include:

a. Resetting error
b. Calibration error
c. Installation/repair error
d. Quality error
e. Bypass error
f. Restoration error

Besides designing operator performance effectiveness, interrelated issues must be measured, such as alarm systems, screen information, components, and visual displays, navigation, and control. Considering so many factors, the system should be designed to support actions, adapt to new situations, so it is better if operators are involved in simulator design [16].

The application of human factor aspects in technology related to NPP HMI has an impact on control room design, customization of data displays according to operator needs, and emergency facility design becomes an integral part of the control room. Designing comfortable workspace for operator can be done by developing a human-centered workspace. Additionally, it is important to consider Human Reliability Analysis [17]. In the development of a simulator specifically designed to develop human error experiments, it is necessary to determine experimental scenarios, success criteria, procedures to be performed, and simple descriptions that are easily understood by operators. Some experiment scenarios that can be selected include: automatic startup, shutdown, startup with manual control rods, startup with manual feedwater flow control, reactor cooling pump failure under full power operation, control rod failure under full power operation, main feedwater pump failure under full power operation, abnormal turbine trip under full power, ruptured steam generator tube with indicator failure, and loss of feedwater pump [18].

From a human factor perspective, there is also the possibility of accidents that often occur due to human error. Human factor also have to calculate some aspect such as efficiency, operator safety, and operator health [21]. There are five nuclear power plant maintenance tasks closely related to human factors and human errors, including [19]:

a. Replacing reactor cooling pump seal,
b. Testing reactor protection system,
c. Overhauling motor-operated actuator valves,
d. Overhauling main feedwater pumps, and
e. Overhauling main steam isolation valves.

Based on characteristics obtained from maintenance task modeling, the causes of errors in nuclear power plant maintenance can be classified into the following four categories:

a. Design-related deficiencies in software and hardware
b. Human capability-related limitations
c. Induced conditions
d. External environmental disturbances

NuScale SMR designs its control room to operate with enhanced safety features, reducing operator interactions and improving security. The safety system is designed with passive and fail-safe features, and decay heat is discharged into a containment pool without the use of pumps, meaning electrical cooling is not required. Several factory design attributes have a significant impact on the human-system interface, including [20]:

a. Fully digital control room.
b. Monitoring and control of multiple units in the main control room with varying levels.
c. Optimized size of the main control room staff, considering passive safety systems, fail-safe design features, high-level automation, and minimal essential human interaction, with staffing levels selected during plant operation.
d. Integrated human-system interface to optimize the use of information management, automation, alarms, controls, indications, and computer-based procedures to support effective and efficient control under normal, abnormal, and emergency conditions, as well as during maintenance activities.

The number of modules used in the NuScale SMR plant design will affect the minimum operator staffing requirements. Training is conducted at a training center using a full-scale simulator. The developed simulator, compared to the previous generation, has added several features related to protection and safety systems, artificial intelligence, and integration with emergency systems [21][22]. In large NPP operations, the field staff replacement and control room (CR) design is shown in Table 1.

**Table 1.** Formation of operator staff per Power Generation Unit

| Plant | Position | 1 unit | 2 unit | | 3 unit | |
|---|---|---|---|---|---|---|
| | | 1 CR | 1 CR | 2 CR | 2 CR | 3 CR |
| 0 | Senior operator | 1 | 1 | 1 | 1 | 1 |
| | Operator | 1 | 2 | 2 | 3 | 3 |
| 1 | Senior operator | 2 | 3 | 2 | 2 | 2 |
| | Operator | 2 | 3 | 3 | 4 | 4 |
| 2 | Senior operator | | 2 | 4 | 3 | 3 |
| | Operator | | 3 | 4 | 5 | 5 |
| 3 | Senior operator | | | | 3 | 4 |
| | Operator | | | | 5 | 6 |

The number of operators in one shift can vary depending on several factors, including operational needs and complexity of the plant. The presence of a supervisor is crucial to ensure effective work under normal circumstances or when the workload exceeds what is usual. If a situation arises where one operator is unavailable, operator replacement can be done, but it takes some adjustment time for the new operator to become accustomed to the job. This situation should be handled by supervisor based on standard guidance. NuScale designs the concept of the operational control room to help identify the roles and responsibilities of each member of the plant's operational team. The layout of the control room affects the hierarchy of human-system interactions, navigation concepts, control allocation, and the number of individual video display units at each workstation. Other aspects to consider in control room design include simulators, software, hardware, and human-system interfaces. Human factor and human reliability are important aspect to enhance effectiveness and safety of plant operations while reducing the risk of human errors in nuclear power plant operation. System interface to facilitate operator with the system and alarm as early warning system. Process automation to reduce operator workload and improve accuracy.

In general, an ideal control room design typically consists of several components, including a main display, a few video display units (up to three) operated by each operator, a dedicated area for the supervisor, and a separate section for setting up the simulator room. This design is much simpler compared to previous generations that used many physical buttons and operated in larger control rooms. The Main Control Room design for NuScale SMR incorporates multiple monitors and controls, including unit control panels, a general workstation panel with larger monitors, and operator workstations. Many controls are executed through touchscreen commands.

**Fig. 1.** Overview of the LAyout of NuSCale's Main Control Room Simulator

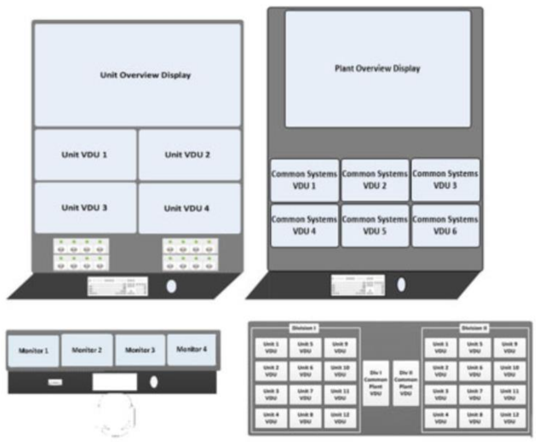


**Fig. 2.** Standing Unit Simulator Display (left); Sitting Unit Simulator Display (right)

Overall, the human-system interface design supports the recognition, tolerance, and recovery from human errors for safe operations, as well as the monitoring and control of the plant. NuScale's simulator consoles have been designed to be user-friendly and minimize the number of operator controls per unit. A simple layout also allows for faster responses to any potential anomalies that may occur in the power plant. Minister of Manpower Regulation No. 5/2018 provide informations according the criteria of the ideal workstation conditions. Based on local regulations, a good workstation should meet the following requirements:

a. The dimensions of the workstation area should correspond to specific body dimensions such as object height and eye level, making it easier to observe work at an optimal distance. Seated positions should be facing each other, and smaller objects should be placed closer.
b. Handling, tools, and other supporting devices should be placed in an optimal working area.
c. Static muscle work can be eliminated or significantly reduced by providing elbow support for the lower arm or hand support. The support should be soft and adjustable.

In regulations, the optimal working area height is divided based on the operator's height into three types of work: high, medium, and low. The optimal area is intended for visual inspections and precision work. For work performed in a standing position, there are three hand positions:

a. For tasks requiring precision, elbow support should be used.
b. For light work, the hands should be positioned parallel to the elbows.
c. For heavy work involving pressing, the hands should be placed 10 cm below the elbows.

When designing standing consoles, attention should be given to leg movement space, a writing area that does not force the operator's back and neck into a bent position, with the optimal angle being 110 degrees, and adequate space for other devices without interfering with operations. Minor adjustment should accommodate different body size of the operator based on antrophometry calculation for Indonesian operator [5]. On the other hand, regulations should also establish maximum working duration limits for operators. Operators working excessively long hours experience reduced performance, leading to suboptimal results. To reduce mental strain, operators should not be scheduled for shifts longer than 12 hours without breaks. Additionally, each operator should be equipped with documentation related to nuclear power plant operations. Operators should be provided with a manual containing comprehensive information about potential incidents, accident scenarios featuring diagnostic flowcharts, action manuals corresponding to each flowchart, and detailed procedures for each stage. The information conveyed should be concise and clear [23]. Based on this consideration, this research proposes some criteria leveling on some equipment which vital to simulator design ergonomics.

There are three devices that will frequently interact with the operator and simulator, which include the monitor, keyboard, and mouse. Some recommendations that can be applied in designing a simulator can be outlined as follows. Monitor aspect, especially to minimize reflection from other light sources and optimize the visual environment for tasks involving monitors and screens, should consider the following design principles:

a. **Minimize Reflection from Other Light Sources:** Reduce ambient light sources in the vicinity of the monitors to prevent unwanted reflections.
b. **Use Radiation Filters:** Employ radiation filters or anti-glare screens on monitors to reduce glare and reflections from the monitor's surface. These filters help improve visibility and reduce eye strain.
c. **Adjust Monitor Height and Angle:** Position monitors at an ergonomic height and angle to reduce neck and eye strain. The top of the screen should be at or slightly below eye level, and the screen should be tilted back slightly.
d. **Brightness and Contrast Control:** Proper adjustments ensure that the information displayed is easily visible without causing discomfort.
e. **Monitor Size and Clarity:** Choose monitor sizes that are appropriate for the tasks performed and ensure they can display information clearly. Larger monitors would be necessary for tasks that involve detailed graphics or multitasking.

The primary goal of applying these design principles is to achieve the condition where a workspace with minimal distraction and optimal visual comfort.

The second hardware is keyboard, as input instrument of the simulator. For this ergonomic design should be consider to following the additional principles such as:

a. **Position of Keyboard and Mouse:** Ensure that the keyboard and mouse are aligned parallel to the monitor. This alignment reduces the need for awkward wrist and arm movements while typing and using the mouse.
b. **Comfortable Typing Height:** Set the keyboard and mouse at a comfortable height, ideally at the elbow level or slightly below.
c. **Ergonomic Keyboard:** Apply an ergonomic keyboard that is designed to promote natural hand and wrist positions. These keyboards often have split layouts and angled keys to reduce wrist strain.
d. **Separate Numeric Keypad:** This allows for more efficient input and can be placed on the left or right side, depending on preference.
e. **Shortcut Keys:** Make efficient use of keyboard shortcuts to reduce reliance on the mouse for tasks such as copying, pasting, and switching between applications.

Mouse as an additional ergonomic design principles for a workspace involving monitors and computers, should adhere tosome considerations:

a. **Moderate Size of Peripheral Devices**: Proper size would avoid discomfort and awkward hand positions.
b. **Positioning Near the Keyboard**: This minimizes unnecessary arm and hand movements and reduces strain.
c. **Utilize Bluetooth and Optical Connectivity**: Wireless devices increase flexibility in operation and should provide precise tracking without the need for a mousepad.

Keyboard and Mouse setting from ergonomic aspect have advantages in reducing musculoskeletal issues of operator handling.

**Table 2.** Example of Ideal Workstation Criteria and Priority Levels

| Item | Criteria | Level |
|---|---|---|
| Monitor | Minimize Reflection from Other Light Sources | 2 |
| | Use Radiation Filters | 2 |
| | Adjust Monitor Height and Angle | 5 |
| | Brightness and Contrast Control | 3 |
| | Document Holder | 2 |
| | Monitor Size and Clarity | 4 |
| Keyboard | Position Parallel to the Monitor | 3 |
| | Comfortable Typing Height | 4 |
| | Use an Ergonomic Keyboard | 3 |
| | Separate Numeric Keypad | 3 |
| | Shortcut Keys | 4 |
| Mouse | Moderate Size of Peripheral Devices | 4 |
| | Positioning Near the Keyboard | 4 |
| | Utilize Bluetooth and Optical Connectivity | 3 |

Monitors, keyboards, and mouse are crucial hardware aspects when designing a simulator setup. There are many requirements to meet the criteria of a good workstation. Based on the applicable regulations, if a classification is created in the form of levels, it could be structured as shown in Table 2. Levels are divided from level 1 to level 5, with higher levels indicating higher priority. For example, the adjustment of monitor height and angle has a high level because it will impact the operator's comfort during extended periods of work. Incorrect settings in these parameters can lead to back, eye, and hand discomfort. This ergonomic factor can increase the likelihood of human error. Therefore, indirectly, these settings will also influence the human factor aspect. In other parameters, by using assumptions about their impact on operator comfort and anthropometric aspects of the operator's body, it is essential to note that standards cannot be directly applied from foreign countries because Indonesian operators have different body proportions. Variations in height will result in variations in the dimensions of the workspace used.

Modifying the NuScale simulator in the main control room to comply with local regulations requires several adjustments. A single simulator setup would be more suitable for Indonesian operators. The new design also accommodates better ergonomics and anthropometrics for new operators. However, the new simulator setup design does not account for the main display positioned above eye level and the duration of observation because local regulations do not provide specific guidance on the use of higher monitors. The regulation states that the ideal display should be at eye level and allow for a ± 30$^{o}$ change in viewing angle. In the modified design, the main monitor placed above the smaller monitor has a larger and wider screen with higher resolution, and the viewing angle can be adjusted by the operator. This position may cause some operators to step back to increase the distance to the monitor if they want to view the main monitor better. This situation can be addressed with various alternative solutions, such as using semi-standing chairs and lowering the monitor device panel. The current position of the main monitor can put strain on the neck for continuous observation over a long period. Shifting operators optimally for work will be very helpful. Keyboards and mouse as control and input devices for the simulator use wireless devices, as they offer flexibility so that operators can adjust their positions as needed.

**Fig. 3.** Prototype of SMR Simulator Console

This setup console consists of six monitors connected virtually to one another, allowing operators to easily configure the display of each monitor. In the general design, the top monitor with the widest screen can be used to display critical parameters for control. This layer can be viewed by supervisors or senior operators from a distance. The middle monitors, organized using four panels, will display multiple parameters that need adjustment to maintain the output displayed on the top screen. The panels on this side are at eye level, and operators will spend most of their time observing this panel. This panel has the lowest potential ergonomic risk for operators. The small monitor display uses a touchscreen, and this display can be used for input and output to the simulator. The simulator modification adjusts the design using conventional input methods instead of a full touchscreen panel. This choice is made considering the possibility of touchscreen malfunctions. On the other hand, it may take some time for some operators to adapt. In accident conditions, faster actions can be taken using physical buttons. Physical buttons will minimize the possibility of accuracy errors when pressing virtual buttons.

The design for the simulator console has two main components that can be adjusted separately. The height of the display support and the viewing angle of the top monitor can be adjusted to the operator's height. The placement of the desktop can be adjusted to hand height for typing and mouse movement purposes. The main CPU for running the simulator and managing display cables is placed inside the desktop box. The future simulator technology can be designed using augmented reality and virtual reality to collect some data including operator training, ergonomic studies, radioactive dose analysis, safety and security staff training, virtual device development, remote handling, nuclear waste management, reactor design, and fuel loading from safer place[24][25].

**Fig. 4.** Experimental Study on SMR Simulator

## 4. CONCLUSION

In this research, the design of the simulator and the main control room significantly impacts the operation of nuclear power plants since the human factor is inseparable from the continuous process. Future regulations for the design of the main control rooms of nuclear power plants should be proposed by regulatory bodies. There is a need to provide an extra and compile data for SMR operations so that future regulations do not rely on commonly used NPP types as references. Experiments to obtain specific data related to Indonesian operators should follow the measurement standards for ideal nuclear workstation conditions. This data will enhance the anthropometric and ergonomic data of Indonesian workers in nuclear applications. The use of virtual technology can also be considered as an alternative to gather data on operator behavior during simulations. For the current situation, adapting regulations from other countries, such as US, using the measurements of Indonesian operators is the best option until specific regulations regarding the standards for the main control rooms of nuclear power plants and their workers in Indonesia are established.

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## AUTHOR CONTRIBUTION

All the names listed as authors contributed as main contributors.

## REFERENCES

1. Imran M., Zaman K., Nassani A.A., Dincă G., Khan R., Haffar M. Does Nuclear Energy Reduce Carbon Emissions Despite using Fuels and Chemicals? Transition to Clean Energy and Finance for Green Solutions. Geosci. Front. 2023.:101608.
2. Wisnubroto D.S., Sunaryo G.R., Susilo Y.S.B., Bakhri S.B., Setiadipura T. Indonesia's Experimental Power Reactor Program (RDE). Nucl. Eng. Des. 2023. **Volume 404**(112201)
3. Situmorang J., Kuntoro I., Santoso S., Subekti M., Sunaryo G.R. Analysis Respons to the Implementation of Nuclear Installations Safety Culture using AHP-TOPSIS. J. Phys. Conf. Ser. 2018. **962**(1)
4. Zhao F., Zou S., Xu S., Wang J., Xu T., Tang D. Safety Analysis of Marine Nuclear Reactor in Severe Accident with Dynamic Fault Trees Based on Cut Sequence Method. Nucl. Eng. Technol. 2022. **54**(12):4560–70.
5. Czerniak J.N., Brandl C., Mertens A. Designing Human-machine Interaction Concepts for Machine Tool Controls Regarding Ergonomic

Requirements. IFAC-PapersOnLine. 2017. **50**(1):1378–83.

6. Hall A., Joe J.C., Miyake T.M., Boring R.L. The Evolution of the Human Systems and Simulation Laboratory in Nuclear Power Research. Nucl. Eng. Technol. 2023. **55**(3):801–13.
7. Malec J., Toškan D., Snoj L. PC-based JSI Research Reactor Simulator. Ann. Nucl. Energy. 2020. **146**:107630.
8. Ayo-Imoru R.M., Cilliers A.C. Hybrid Nuclear Plant Simulator Design Requirements to Enable Dynamic Diagnostics of Plant Operations. Ann. Nucl. Energy. 2017. **101**:447–53.
9. Kiser L., Otero L.D. Multi-criteria Decision Model for Selection of Nuclear Power Plant Type. Prog. Nucl. Energy. 2023. **Volume 159**(104647)
10. Kemenaker Peraturan Menteri Tenaga Kerja No 5/2018 K3 Lingkungan Kerja. Peratur. Menteri Ketenagakerjaan Republik Indones. No 5 Tahun 2018. 2018. **5**:1–258.
11. Simonsen E., Osvalder A.L. Categories of Measures to Guide Choice of Human Factors Methods for Nuclear Power Plant Control Room Evaluation. Saf. Sci. 2018. **102**(October 2016):101–9.
12. Kang J.S., Lee S.J. Concept of an Intelligent Operator Support System for Initial Emergency Responses in Nuclear Power Plants. Nucl. Eng. Technol. 2022. **54**(7):2453–66.
13. Asadayoobi N., Taghipour S., Jaber M.Y. Predicting Human Reliability Based on Probabilistic Mission Completion Time using Bayesian Network. Reliab. Eng. Syst. Saf. 2022. **221**(July 2021):108324.
14. Chen D., Zhu M., Qiao Y., Wang J., Zhang X. An Ergonomic Design Method of Manned Cabin Driven by Human Operation Performance. Adv. Des. Res. 2023. **1**(1):12–20.
15. Teperi A.-M. Applying Human Factors in Nuclear Industry - people as a Presence of Positive Capacity. Hum. Factors Nucl. Ind. 2021.:Pages 25-54.
16. Stevens J., LaFerriere K., Flamand NuScale R. Small Modular Reactor Control Room Workstation Demonstration. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 2019. **63**(1):479–80.
17. Hugo J. Human-system Interfaces (HSIs) in Small modular reactors (SMRs).Woodhead Publishing Limited; 2015.
18. Park J., Boring R.L., Ulrich T.A., Lew R., Lee S., Park B., et al. A Framework to Collect Human Reliability Analysis Data for Nuclear Power Plants using a Simplified Simulator and Student Operators. Reliab. Eng. Syst. Saf. 2022. **221**:108326.
19. Dhillon B.S. Human Factors and Human Error in Nuclear Power Plant Maintenance. Safety, Reliab. Hum. Factors, Hum. Error Nucl. Power Plants. 2018.:163–80.
20. LaFerriere K., Stevens J., NuScale R.F. Small Modular Reactor Human-System Interface and Control Room Layout Design. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 2019. **63**(1):516–20.
21. Kang J.S., Lee S.J. An Operator Support System Framework and Prototype for Initial Emergency Response in Nuclear Power Plants. Proc. 31st Eur. Saf. Reliab. Conf. ESREL 2021. 2021. **54**:330–5.
22. Huang Q., Peng S., Deng J., Zeng H., Zhang Z., Liu Y., et al. A Review of the Application of Artificial Intelligence to Nuclear Reactors: Where We are and What's Next. Heliyon. 2023. **9**(3):e13883.
23. De Carvalho P.V.R. Ergonomic Field Studies in a Nuclear Power Plant Control Room. Prog. Nucl. Energy. 2006. **48**(1):51–69.
24. Hagita K., Kodama Y., Takada M. Simplified Virtual Reality Training System for Radiation Shielding and Measurement in Nuclear Engineering. Prog. Nucl. Energy. 2020. **118**(February 2019)
25. Nash B., Walker A., Chambers T. A Simulator Based on Virtual Reality to dismantle a research reactor assembly using Master-slave Manipulators. Ann. Nucl. Energy. 2018. **120**:1–7.