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# REDESIGNING INTERLOCK SYSTEMS FOR THE UPGRADE OF MINIATURE NEUTRON SOURCE REACTORS (MNSRS): A CONCEPTUAL APPROACH

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*Abstract:* **Interlock systems are vital safety components integral to the secure functioning of safety-critical industrial plants. They play a crucial role in preventing or minimizing potential hazards by automatically triggering shutdowns or other protective measures when specific predefined conditions are detected. These systems are an essential part of the safety architecture, contributing to the overall risk mitigation in industrial settings. This paper underscores the successfulconceptual redesign and validation through simulation of the proposed interlock system for the upgrade of miniature neutron source reactor (MNSR) safety. Emphasizing its robust functionality, precise timing control, and strategic incorporation of on-delay functions. The comprehensive assessment of different operational conditions highlights the system's responsiveness and crucial role in ensuring safety, stability, and efficiency across a diverse range of scenarios. This is to introducea higher safety margin for MNSR operation.**

## I. INTRODUCTION

Interlock systems are crucial safety features designed to ensure the safe operation of all safety-critical industrial plants by preventing or mitigating potential hazards[1]. These interlocks are a part of the overall safety architecture of asystem. Interlocks are automatic safety mechanisms that act to shut down the plant or take other protective actions when certain conditions are detected[2].In manufacturing and industrial facilities, interlock systems are used to control machinery, monitor production processes, and ensure worker safety.In power plants, interlock systems are crucial for managing the safe operation of turbines, reactors, and other energy-related equipment. Interlock systems are employed to prevent chemical spills, control reaction processes, and mitigate the risks associated with handling hazardous substances. In automotive ensure safe vehicle operation by preventing certain actions under unsafe conditions, such as openingdoors during transit[3].Elevators, escalators, and fire safety systems often use interlock mechanisms to prevent unsafe or unauthorized operations.The configuration of interlock systems allows for straightforward bypassing. A more stringent strategy involves employing a blend of sturdier interlocks and conducting safety-criticaltask analysis to manage bypasses during emergencies[4]. In small nuclear reactor systems such as nuclear research reactors, interlock systems are critical for ensuring the safe operation of reactors by responding to parameters such as temperature, pressure, and reactor power. Many interlock systems incorporate redundancy to enhance reliability. Redundant sensors, controllers, and actuators reduce the risk of a single-point failure compromising safety.Some nuclear reactors incorporate a safety interlock that inhibits the opening of the reactor bottom valve in the event that the reactor pressure surpasses a certain limit, a circumstance that could occur in emergencies[4]. The Fukushima accident created a unique, although unfortunate, framework to learn and improve worldwide nuclear safety, not only for nuclear power plants (NPPs) but also for research reactors. It is realistic to think that future safety reviews will require facing such severe scenarios; therefore, it is important to identify the design of engineered safety features that can mitigate undesirable consequences [5]. The Fukushima Daiichi nuclear accident reinforced the importance of having adequate safety systems and standards in place so that nuclear facilities and technology remain safe and continue to provide reliability [6]. By recognizing the lessons learned from the March

2011 accident, the International Atomic Energy Agency (IAEA) has been revising its global safety standards to ensure that member states continue to update their systems. The Fukushima Daiichi accident has left a huge footprint on nuclear safety thinking. The IAEA Board of Governors adopted a 12-point action plan on nuclear safety, a key element of which is an agreement by all member states with nuclear programmes to promptly undertake a national assessment of the design of nuclear plants, focus on the lessons learned from Fukushima, and take corrective action where necessary[7], [8]. In the implementation of the 12-point action plan, a review of relevant standards, including the IAEA safety standard on design safety, experts found that a higher level of safety could be incorporated into existing nuclear facilities by adhering to more demanding requirements for control and protection against accidents and nuclear exposure by enhancing the independence of safety levels so that, even if one layer fails, another layer is unimpacted.The purpose of this paper is to propose a design for a more comprehensive and integrated approach for the upgrading of the current interlock regime ofminiature neutron source reactors (MNSRs) which is solely temperature and power dependent, and also by manual scram.

## II. MNSR DESIGN FEATURES

Miniature Neutron Source Reactors (MNSRs) are small-scale nuclear reactors designed for specific applications such as neutron radiography, neutron activation analysis, and nuclear education [9]. Some MNSRs also provide a source of neutrons for various applicationssuch as materials testing and imaging. These reactors typically have a power output in the range of a few kilowatts to a few megawatts, making them significantly smaller than conventional nuclear power reactors.Miniature neutron source reactors have been designed and manufactured by the China Institute of Atomic Energy since the mid-1980s. A total of nine MNSRs have been built: four in China and one each in Pakistan (1989), the Islamic Republic of Iran (1994), Ghana (1995), the Syrian Arab Republic (1996), and Nigeria (2004) [10]. The Chinese-built MNSR is a compact research reactor based on the Canadian SLOWPOKE reactor design. The MNSR is accepted worldwide because of its inherent safety features, simple auxiliary facilities, and reliable shielding and cooling systems. The MNSR is a tank-in-pool type research reactor that typicallyuses low-enriched uranium (LEU) or other low-grade fuels. The use of LEU reduces the risk of nuclear proliferation and enhances the safety aspects of these reactors. It also employs light water as a moderator and coolant, and metal beryllium as a reflector. MNSRs are characterized by their compact size, both in terms of physical dimensions and power output. Their design is optimized for specific purposes, and they are often lightweight and transportable.Figure 1 is a typical simplified MNSR complex with its auxiliary systems.

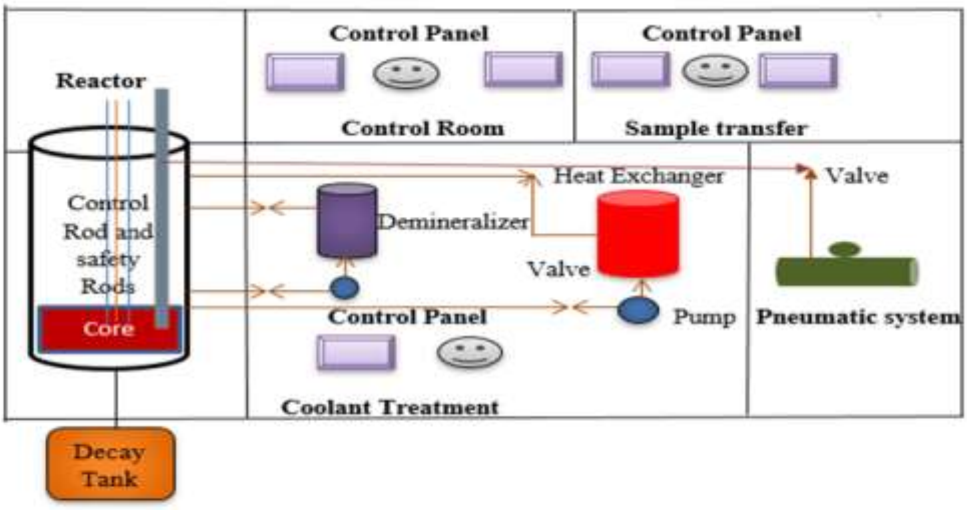

Figure 1. Typical simplified MNSR complex

## III. CURRENT MNSR INTERLOCK REGIME

Presently, all Miniature Neutron Source Reactors (MNSRs) in operational use are equipped with a singular interlock system, serving as the process control mechanism for reactor trip initiation. Activation of this interlock system occurs when predefined thresholds for reactor power level and fuel temperature are exceeded, in conjunction with manual initiation of a scram procedure. Notably, the control infrastructure of MNSRs incorporates a manual SCRAM switch situated on their console interface, affording operators the capacity to execute a rapid reactor shutdown by depressing a button and inserting a rod into the core. This procedural step encompasses the deactivation of voltage supply to the electromagnetic carrier of the rod and the air valves governing transient rod movements, facilitated through the interlock circuit and SCRAM logic. The provision of a manual SCRAM mechanism equips operators with the capability to promptly intervene in instances of hazardous or aberrant operational conditions.

### 3.1 MNSRs Interlock Upgrade Design Motivation: Safety analysis

The incorporation of multiple interlocks in nuclear reactors systems are imperative for enhancing safety measures and mitigating potential risks; thereby contributing to the overall security and stability of the nuclear reactor. This further increases the reactor safety assurance as proposed by the IAEA experts[8]. In the event of an emergency, having multiple interlocks provides operators with more control and options to address unforeseen situations. The redundancy in safety measures can be instrumental in enabling swift and effective responses during crisis scenarios. Nuclear reactors are complex systems with inherent risks. Incorporating multiple interlocks not only aligns with regulatory requirements but also demonstrates a commitment to maintaining the highest standards of safety. These interlocks not only provide a layered defense against potential hazards but also contribute to the ongoing evolution of nuclear technology in alignment with the highest safety standards.The development of industrial systems prone to significant accidents, encompassing nuclear reactor systems, offshore installations, and high-risk process facilities, routinely incorporates varying degrees of risk analysis. This strategic approach fosters the cultivation of designs characterized by enhanced safety parameters and optimizes resource utilization for risk mitigation endeavors. Specifically, within the nuclear sector, components or systems may be engineered with provisions wherein, upon failure, their operational mode is configured to minimize the likelihood of hazardous outcomes or automatically engage predefined safety mechanisms. The IAEA specific safety guides provide a systematic approach on the implementation safety and risk analysis.[11], [12]. This analysis prompted thenew design of multiple interlocks. While a complete mathematical model for complex safety systems is beyond the scopeof this paper, we canmathematically demonstrate the safety benefits of multiple interlock systems over single interlocks through reliability modeling or probability theory. The following assumptions were considered for the analysis.

- We'll assume a simple system with two interlocks, one being a single interlock (Interlock A) and the other being part of a multiple interlock system (Interlock B).
- Each interlock has a certain probability of failure, denoted as $P\text{fail}$ ($A$) for interlock A and Pfail(B) for Interlock B.
- The reliability ($R$) of the system with only Interlock A is given by: $R\text{A}=1-P\text{fail}(A)$
- The reliability of the system with Interlock B is given by: $R\text{B}=(1-P\text{fail}(B))2$. This is because both Interlock A and Interlock B must function properly for the system to operate safely.)
- To compare the reliability of the two systems, we can calculate the ratio of their reliabilities: $R\text{B}/R\text{A}=$ $(1-P\text{fail}(B))2$ /1−Pfail(A)
- If $P\text{fail}(B)<P\text{fail}(A)$, then $R\text{B}/R\text{A} >1$, indicating that the system with multiple interlocks is safer than the one with a single interlock.

## IV. GENERAL OVERVIEW AND EVOLUTION OF NUCLEAR REACTOR INTERLOCKS.

Interlock systems are engineered to surveil diverse parameters and, upon the detection of irregular conditions, enact automatic protective measures. Within nuclear systems, various classifications of interlock systems fulfill distinct safety functions. These encompass Process interlocks, reliant on process parameters such as reactor power, coolant temperature, and pressure, intended to constrain reactor operation within safe limits. Equipment interlocks monitor the status of components like control rods, valves, and pumps to prevent operational configurations that may jeopardize equipment integrity. Conditional control interlocks enforce predefined conditions before permitting specific actions, ensuring, for instance, that the reactor remains inactive until all control rods are fully inserted. Furthermore, additional classifications of interlocks augment safety protocols within nuclear reactors. Administrative interlocks are rooted in procedural mandates, such as mandating the presence of multiple operators before executing certain actions. Maintenance interlocks prevent maintenance operations from interfering with safety systems, while test and calibration interlocks avert inadvertent activation of safety mechanisms during testing procedures. Interlocks responsive to predetermined thresholds, denoted as trip or limit interlocks, are pivotal in mitigating hazardous conditions by promptly triggering reactor shutdown or corrective measures upon surpassing established safety thresholds. In industries such as nuclear power, chemical processing, and transportation, trip interlocks serve as indispensable safety components.The evolutionary trajectory of nuclear reactor interlock systems is shaped by technological advancements, safety standard enhancements, operational experiences, and deeper insights into reactor dynamics. The nascent stages of nuclear power saw rudimentary interlock systems primarily focused on monitoring fundamental parameters like temperature, pressure, and coolant flow. Early interlock systems, prevalent during the 1950s and 1960s, relied on electromechanical relays[13] subsequently succeeded by solid-state relays (SSRs) in the 1970s, offering heightened reliability and agility[1].The Three Mile Island incident of 1979 catalyzed a paradigm shift in nuclear safety paradigms, prompting the development of more robust interlock systems informed by lessons gleaned from the event. Technological advancements ushered in the era of programmable logic controllers (PLCs) in the 1990s, introducing greater flexibility and sophistication in interlock logic[1].The transition from analog to digital control systems marked a watershed moment, endowing interlock systems with enhanced adaptability, diagnostic capabilities, and reliability.Moreover, the integration of redundancy and diversity in safety systems, including interlocks, emerged as a paramount concern, bolstering fault tolerance and reliability. Risk-informed safety approaches gained traction, optimizing resource allocation and bolstering safety protocols. Human factor engineering assumed prominence, ensuring optimal operator response during emergencies. Moreover, anticipation and mitigation of severe accidents became integral to interlock system design, accentuating the importance of international collaboration and standardized safety guidelines.The burgeoning integration of modern technologies like artificial intelligence, machine learning, and advanced analytics holds promise for further elevating the predictive and responsive capacities of interlock systems, underscoring an ongoing evolution poised to enhance nuclear safety and operational efficacy.

## V. PROPOSED MNSR INTERLOCK DESIGN

The MNSR reactor interlock systems provide trip signals thatserve the purpose of triggering a reactor trip if the operational parameters surpass safe limits. The proposed designconsiders all initial control conditions which must be conditions precedent. This enforces specific conditions before allowing certain actions to take place. The reactor protection system's philosophy is inculcated in this design which is to define an acceptable operationallimit in terms of power,axial power distribution, radiation dose levels, primary coolant temperature and levels. This ensures that the reactor is tripped when approaching the boundaries of a designated limit of concern. These limits are monitored by sensors andare compared to predetermined setpoints. If a processed parameter exceeds its setpoint, a reactor trip is activated. When the protection system receives signals indicating an impending unsafe operating condition, it activates alarms, restricts control rod withdrawal (if applicable), and/or opens the reactor trip mechanism. Seventeen interlocks were considered for the design of the MNSR and simulated successfully. Figure 2 and3showsthefirst and second sets of interlocksconsidered for the design and their respective domain of interlock type.Each interlock parameter was simulated with respect to its influence on the overall status of the reactor. Figure 4 Shows the logical design of the proposed MNSR interlock system using functional block diagram (FDB) programmingimplemented in LOGO! Soft Comfort version 8 software.

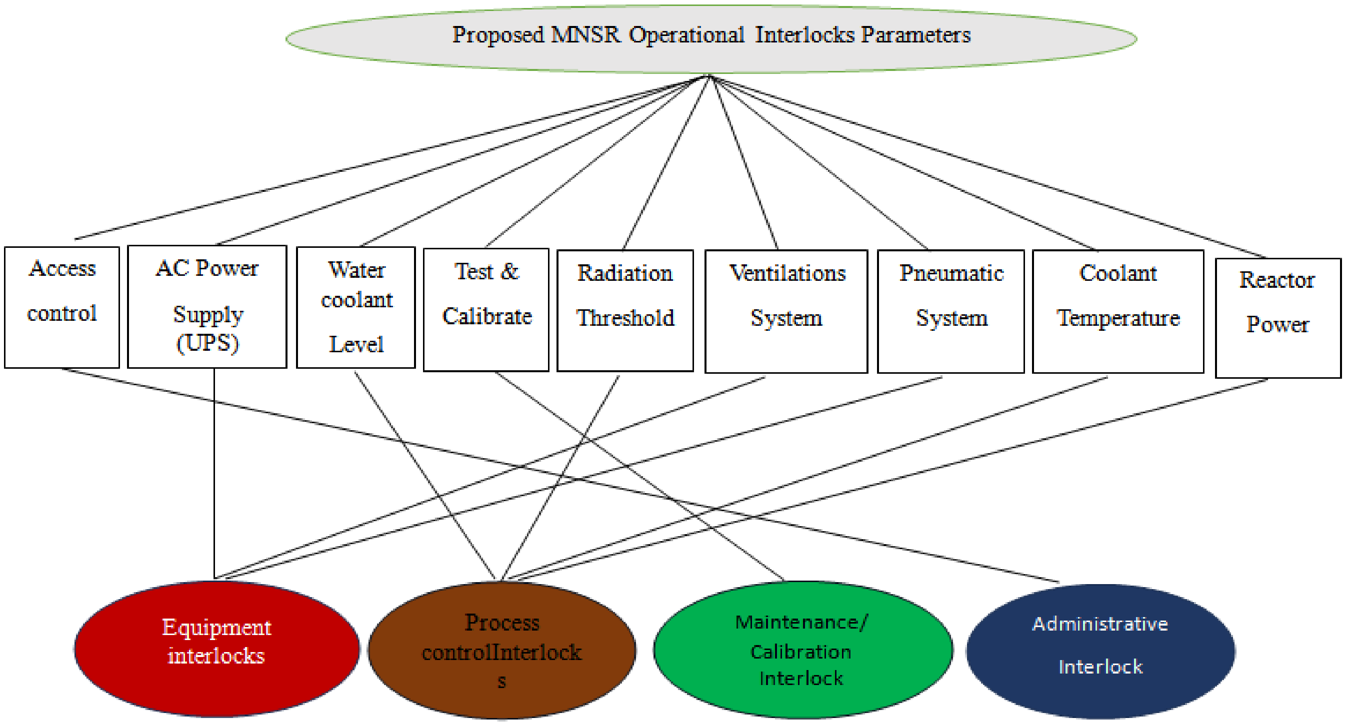

**Figure 2. First set of operationalparameters considered with their respective interlock systems.**

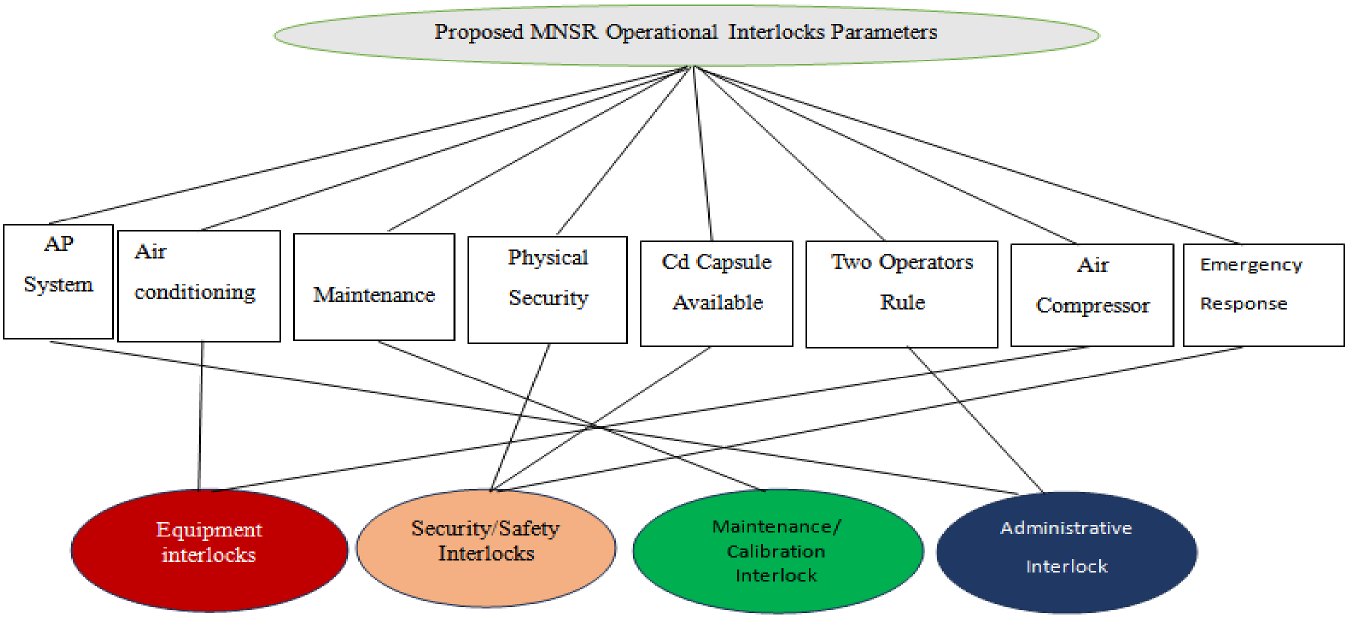

**Figure 3. Second set of operational parameters considered with their respective interlock systems.**

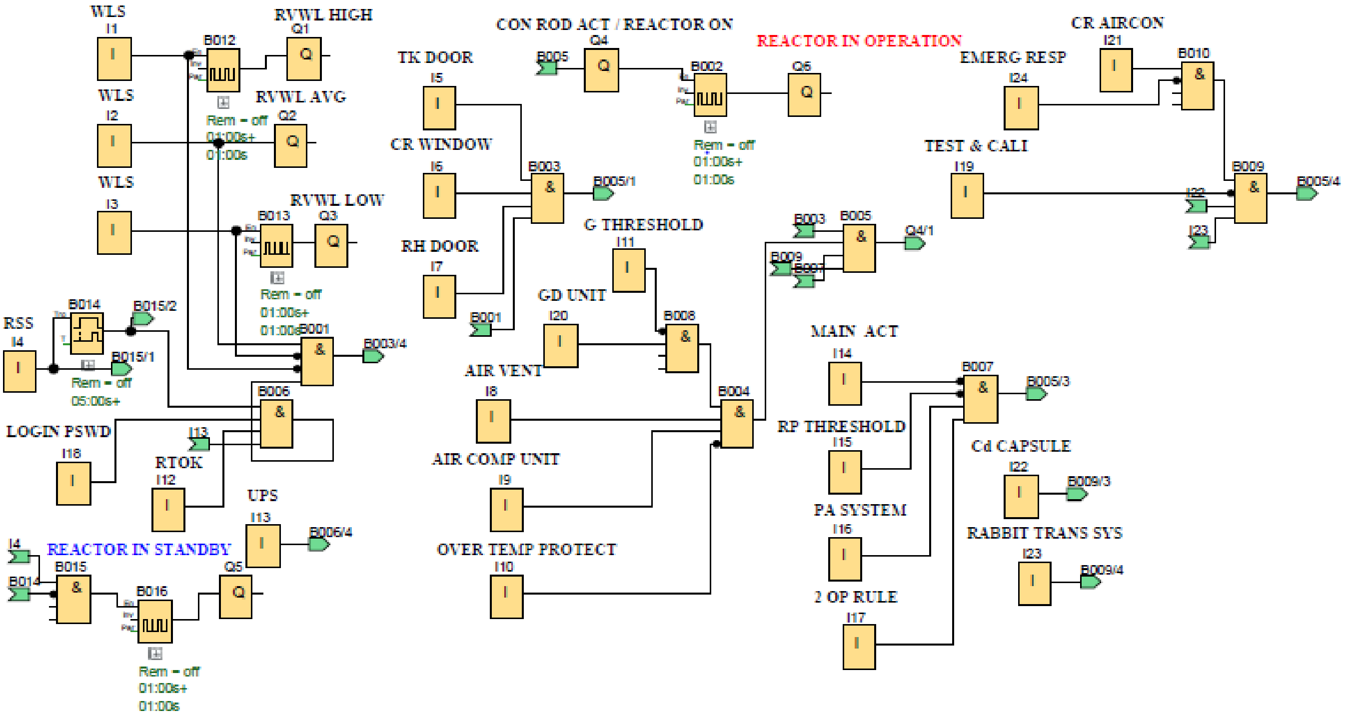

**Figure 4. Proposed MNSR interlock design using functional block diagram.**

### 5.1 Program assignment control

Input and output point assignment specifies which input and output points on the designed program correspond to sensors, actuators, and other devices in the field. Each input is designated tohandle a particular function. The assignment control provides easy identification and meaning of each input and output interlock. Table 1 shows the identification and meaning of each assignment.

Table 1. Assignment control identification

| Assignment | Meaning |
|---|---|
| WLS | Water level sensor |
| RVWL HIGH | Reactor vessel water level High |
| RVWL AVG | Reactor vessel water level average |
| RVWL LOW | Reactor vessel water level low |
| RSS | Reactor startup switch |
| LOGIN PSWD | Login password |
| RTOK | Reactor turn on key |
| UPS | Uninterrupted power supply |
| TK DOOR | Truck door |
| CR WINDOW | Control room window |
| RH DOOR | Reactor hall door |
| G THRESHOLD | Gamma threshold |
| GD UNIT | Gamma dosimeter unit |
| AIR VENT | Air ventilator |
| AIR COMP UNIT | Air compressor unit |
| OVER TEMP PROTECT | Over temperature protect |
| 2 OP RULE | Two operator rule |
| PA SYSTEM | Public address system |
| RP THRESHOLD | Reactor power threshold |
| MAIN ACT | Maintenance activities |
| Cd CAPSULE | Cadmium capsule |
| RABBIT TRANS SYS | Rabbit transfer system |
| TEST & CALI | Test and calibration |
| EMERG RESP | Emergency response |
| CR AIRCON | Control room air-conditioner |
| CON ROD ACT | Control rod activated |
| REACTOR IN OPERATION | Reactor in operation |

### 5.2 MNSR designed interlock significance.

The significance of the engineered interlock system for the Miniature Neutron Source Reactor (MNSR) is paramount within the domain of nuclear reactor safety and operational integrity. Through the meticulous orchestration of interlock mechanisms, the MNSR can avert potential malfunctions, deviations, or hazardous scenarios that may compromise reactor performance or pose risks to personnel and the environment. Each integrated interlock serves as an intricate safeguarding apparatus, meticulously crafted to identify anomalies, instigate appropriate responses, and mitigate adverse outcomes. Through the intricate amalgamation of sensors, monitoring devices, and control mechanisms, the primary importance of the coolant level interlock provides safety assurance, thus preventing core damage and minimizing risks. The coolant level interlock systems aim to maintain the coolant at an adequate level to prevent the reactor from overheating. Should coolant levels drop below a specified threshold, the potential consequences could include insufficient cooling of the reactor core, leading to overheating, fuel damage, and even core meltdown. Therefore, the interlock system functions as a safety mechanism to avert such scenarios by initiating automatic shutdown or other safety measures. The start-up interlock system, as a critical component of administrative control in nuclear reactors, holds significance in various crucial areas, including safety assurance, prevention of criticality accidents, and preservation of system integrity. By enforcing predetermined sequences of actions and preempting unsafe conditions, the start-up interlock system ensures the safe progression of the reactor startup process. It meticulously verifies that all necessary conditions are met before allowing the reactor to commence operations, thereby mitigating the risk of accidents or incidents that could compromise personnel safety or public health. The Uninterrupted Power Supply (UPS) interlock plays a pivotal role in nuclear reactor systems, ensuring the continuous and reliable provision of power to essential safety systems. By guaranteeing uninterrupted power supply to safety-critical systems, such as reactor coolant pumps and emergency cooling systems, the UPS interlock is essential for sustaining safe operating conditions, even amidst power grid failures or electrical disturbances. Access control interlocks serve as physical barriers, impeding unauthorized personnel from entering critical areas within the reactor system. Integrated within the reactor design, these interlocks, for instance, may prevent the initiation of a reactor startup sequence if a door in a critical area remains open. Over temperature and gamma radiation threshold interlocks serve as vital safety features, designed to avert catastrophic events and safeguard personnel and the environment. By ensuring reactor operation within safe temperature and radiation levels, these interlocks automatically trigger shutdowns or other safety measures upon exceeding predefined thresholds, thereby forestalling accidents, equipment damage, or core meltdown. Interlocks within air ventilation and pneumatic transfer systems act as safety mechanisms to prevent unauthorized or unsafe operations, incorporating features such as pressure sensors, flow monitors, and emergency shutdown systems to automatically halt operations during abnormal conditions or malfunctions. These interlocks help ensure proper filtration and airflow, thereby minimizing the dissemination of airborne radioactive particles and other contaminants that could pose health risks to personnel within the reactor facility. The two-operator rule and cadmium capsule interlocks epitomize different layers in the defense-in-depth approach to nuclear safety. While the two-operator rule emphasizes human factors and procedural controls, cadmium capsule interlocks provide automated safeguards for reactor control and shutdown. Their combined application significantly diminishes the risk of human error during control rod manipulation and ensures safe reactor operation under diverse conditions. In sum, maintenance, test, calibration, and emergency response interlocks collectively contribute to a comprehensive safety strategy for nuclear reactors. By ensuring adherence to maintenance protocols, verifying system functionality, maintaining accurate data, and facilitating rapid emergency responses, these interlocks play a pivotal role in minimizing the risk of accidents and enhancing the overall safety and reliability ofnuclear reactor systems.

### 5.3State transition diagram and block diagram of functional design for MNSR proposed interlocks system.

A state transition diagram (STD) is a graphical representation of the possible states of a system and the conditions that trigger transitions between those states. In the context of interlock systems, an STD can be used to model the different operating states of the system and the events that cause transitions between those states.Theround-head rectangle (oval) boxes represent the state, and the arrows represent transition. The system interlock can assume several states such as idle state; where the system is in a safe state and all interlocks are satisfied. Pre-active state is when the system is being prepared for operation and some interlocks may not be satisfied. Active state is when the system is operating, and all interlock must be satisfied. Fault state represents when the system has detected a fault and has shut down. For transitions between states, the transitions are idle to pre-active. In this transition, a start signal is received from the operator. Pre-active to active transition involves a case in which all interlocks are satisfied. Pre-active to active idle represents a situation where a stop signal is received from the operator, or an interlock is violated. For activeto fault, an interlock is violated, or a system failure is detected. Fault to idle connotes when a fault has been cleared and the system is reset. Figure 5 shows the STD for the proposed interlock system. Figure 6 presents a functional block diagram that delineates the system's high-level functionalities and their interrelationships. The diagram depicts a hierarchical structure with three distinct process levels: initiation, logic and control, and operational control activation. Additionally, it illustrates the signal control flow, tracing its path from sensor acquisition to the actuation of individual interlocks

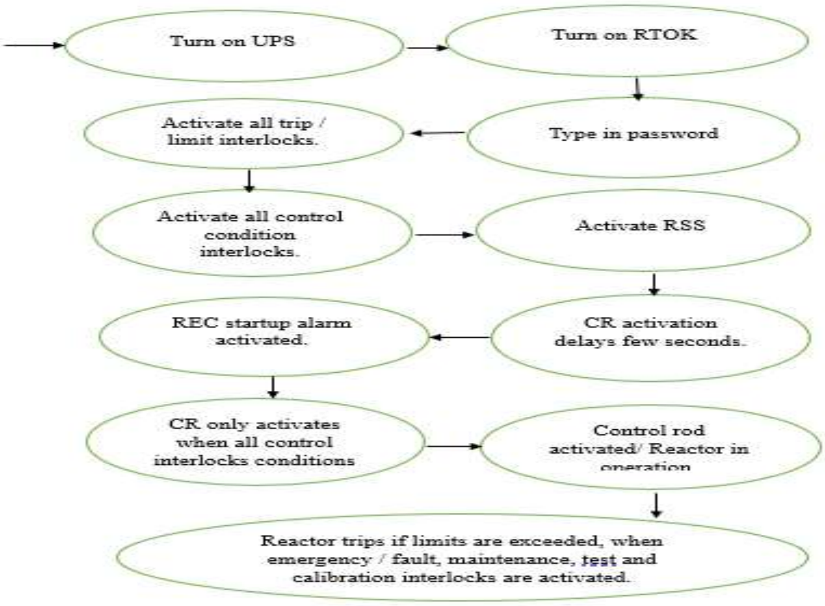

Figure 5. STD for the proposed interlock system.

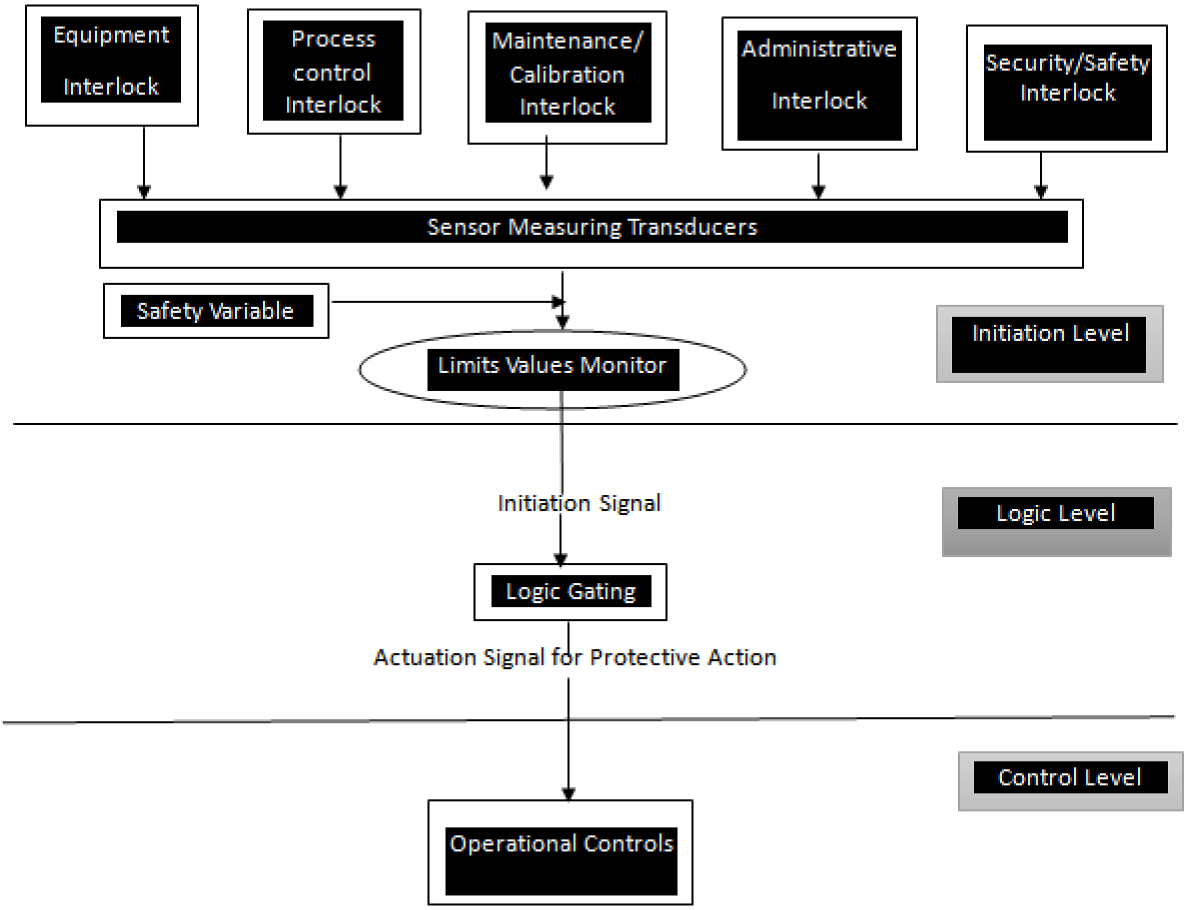

Figure 6. Block diagram of functional design

## VI. SIMULATION RESULT AND DISCUSSION

The simulation of the proposed design interlock was performed taking into consideration trip interlocks and controlconditions interlocks. For functionality verification, the simulated results first and foremost verified that the interlock system functions as intended. This involves confirming that the specified conditions for enabling or disabling a process are accurately reflected in the simulation. The timing and sequencing of logic control are checked whether the interlock conditions are being detected and enforced in the correct order and within the specified timeframes; as timing issues can lead to unintended consequences or system failures.Figure 7 shows the simulation of the designed MNSR interlock system when the reactor is in standby mode and ready for operation. All control condition interlocks had been engaged except for trip interlocks. A time on-delay function (B013) was incorporated into the system, so the reactor does not start at the instant of a startup command. A system on-delay, in the context of control systems and automation, refers to a delay imposed before a system responds to a change in input or a triggering event. The importance of a system on-delay lies in its ability to address specific operational considerations and improve the overall performance. It provides the advantage of stability and avoidance of transient conditions, prevention of chattering and oscillations, control of start-up transients,avoidance of false alarms and protection against rapid changes. This can be critical in maintaining safe and efficient operation acrossa range of industrial and automated processes. The output LED (Q5) stays ON and blinks for the stipulated set time for on-delay. Output LED (Q2) stays ON; this indicates the status of the reactor coolant level in an acceptable limit for safe reactor utilization. The output LED (QI and Q3) are in the OFF condition, indicating coolant levels in upper and lower positions, respectively. This OFF condition is safe, and their ON condition will set a trip-off to the reactor as it indicates an unsafe coolant limit for reactor utilization.The OFF state ofthe output LED (Q4 and Q6) indicates that the control rod has not been activated and hence the reactor is not in operation.Figure 8shows the reactor in operation. In this condition, the on-delay time has elapsed, and the output LED (Q5) is OFF; with the output LED (Q4 and Q6) ON indicating the controlrod is activated and the reactor is in operation. In this condition, all trip interlocks are inactive, but control conditions interlocks are all activated. Figure 9 shows a condition when allconditional control interlocks are engaged, except for cadmium (Cd) capsule interlock. Due to the logical control design of the interlock, the absence of a Cd capsule to complete the conditional control system will render the reactor operation inactive.Figure 10shows the activation of all trip and conditional control interlocks. In this condition, when all set limits have been exceeded and the reactor was in operation before the set limit was exceeded, the reactor will trip automatically. However, in the event when any of the trip interlocks was activated before the startup of the reactor, the reactor will at most be in standby mode, but the control rod will never be activated for a reactor operation. Safety-critical processes often prioritize the implementation of interlock systems to guarantee operational integrity. However, these systems remain susceptible to transient misinterpretations (TMIs) triggered by sensor malfunctions, environmental disturbances, or electromagnetic interference. To alleviate the impact of TMIs, a measured approach is adopted whereby the system initiates an alarm instead of an immediate shutdown. This facilitates a qualified operator's evaluation of the situation, enabling them to diagnose the potential root cause (e.g., sensor anomaly) and implement appropriate corrective measures before a safety incident materializes. For instance, a transient power outage may not necessitate an immediate safety shutdown. The interlock system, in this case, would simply maintain the process in its current state until power is restored. The efficacy of such a designed interlock can be verified through simulations and comprehensive functional testing conducted subsequent to any modifications or maintenance procedures. This rigorous testing regimen serves to validate the system's proficiency in adhering to established operational parameters under normal conditions. Furthermore, it assesses its effectiveness in detecting and responding appropriately to relevant anomalous conditions or potential failure scenarios.

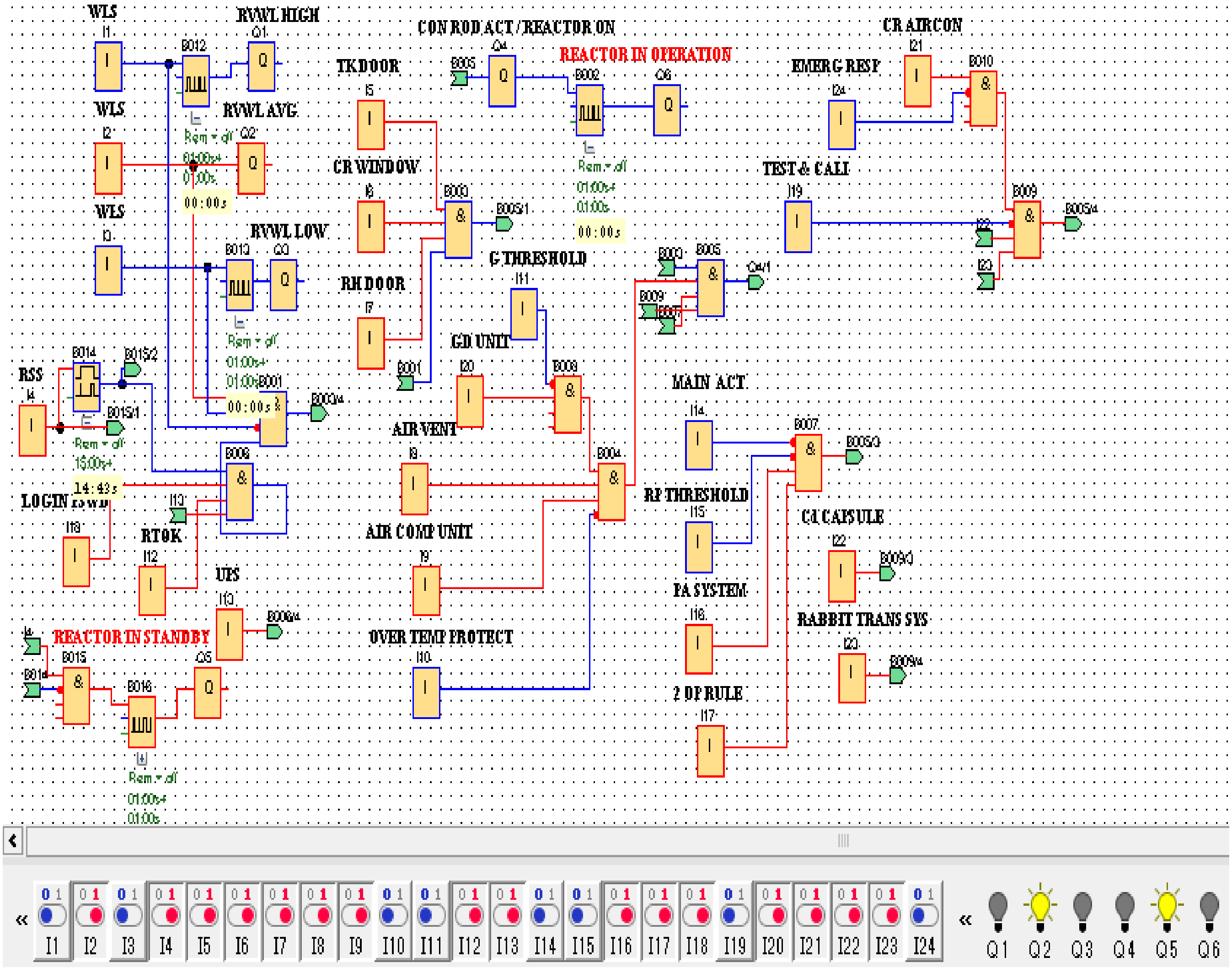

Figure7. Simulation of proposedinterlock reactorsystemin a standbystate

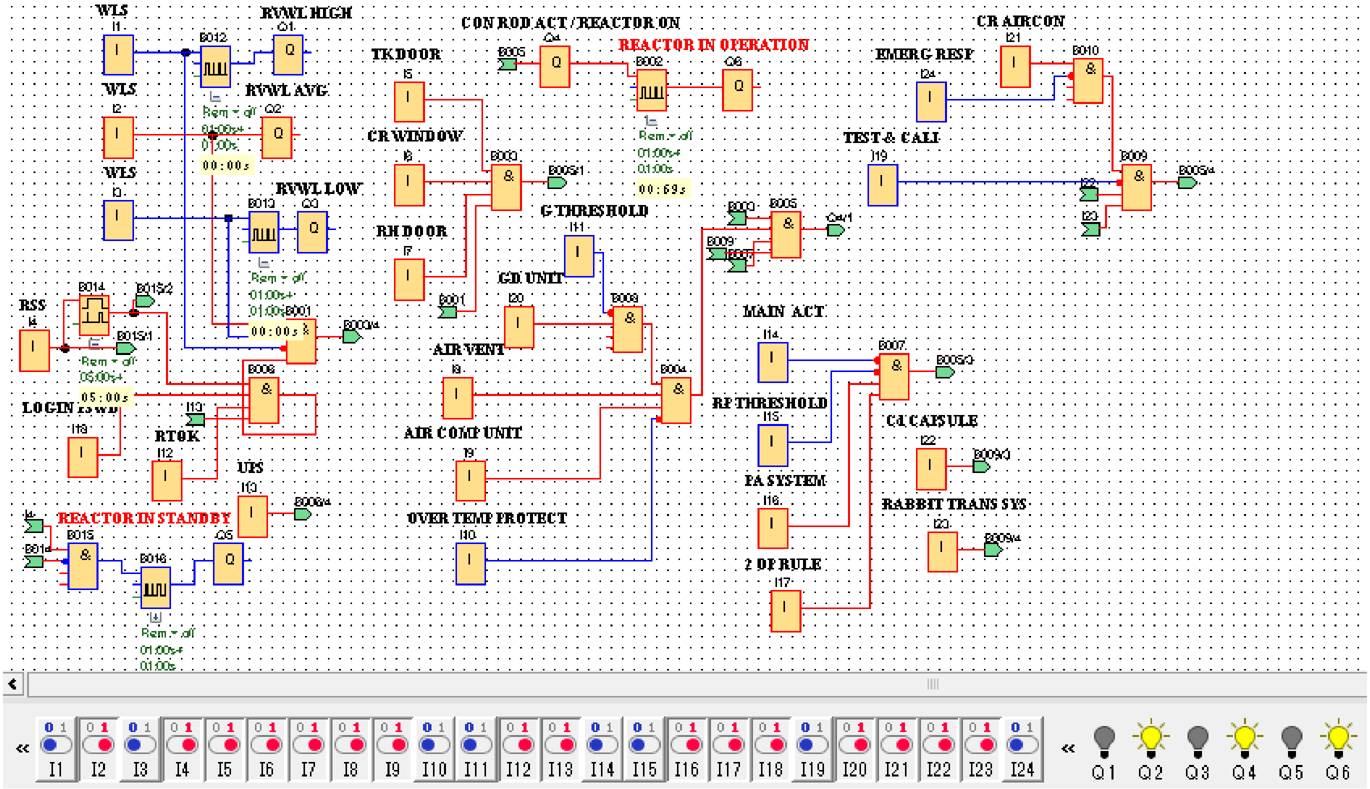

Figure8. Conditional controlinterlocks engaged with their respective switch status.

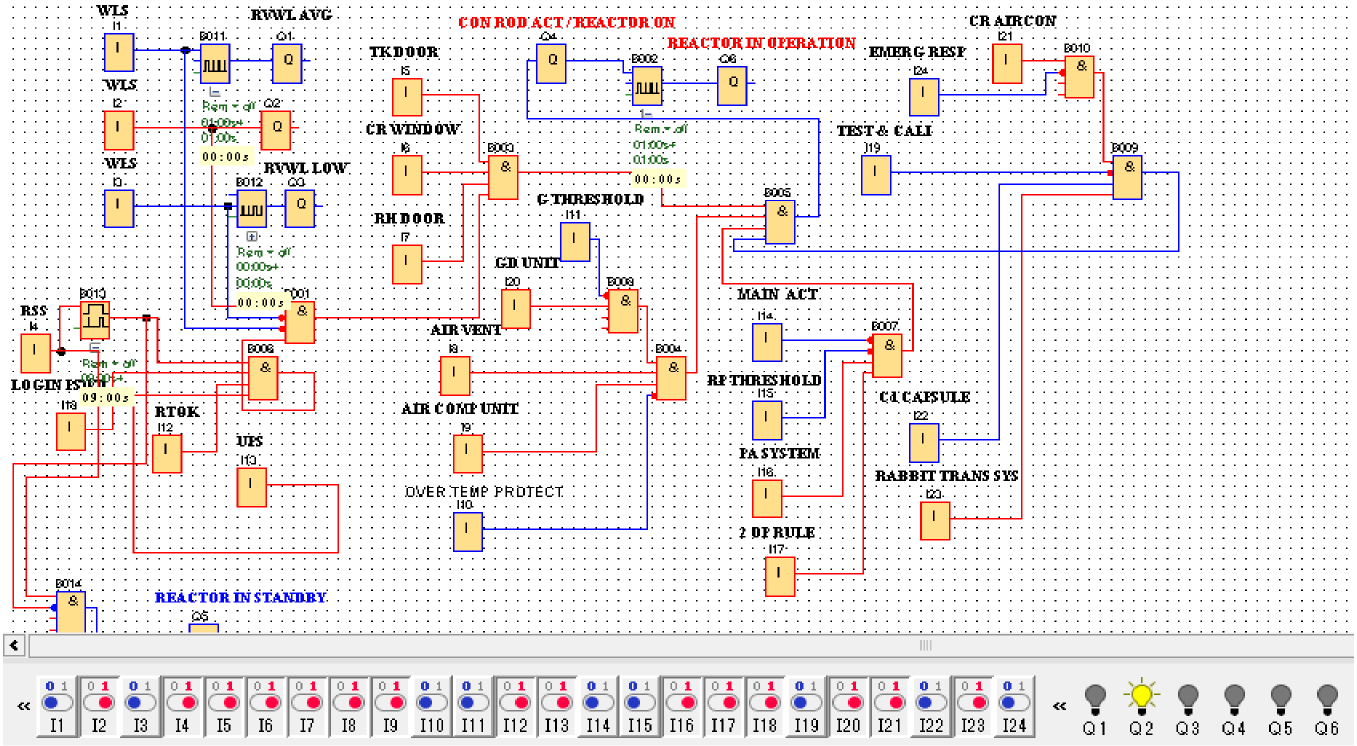

Figure 9. Conditional control interlocks engaged with the exception of Cd capsule interlock.

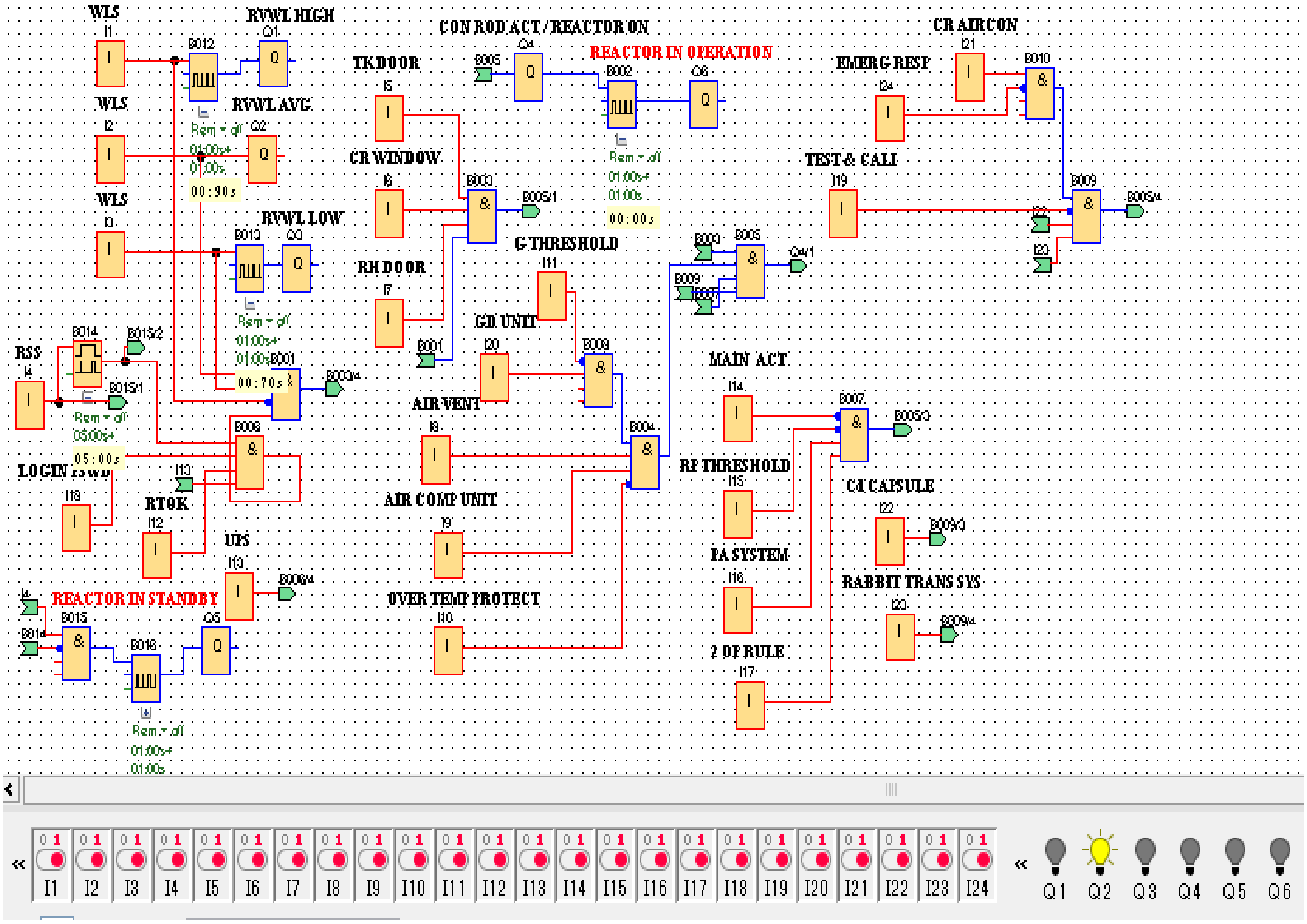

**Figure 10. Activation of all trip and conditional control interlocks with their respective switch and output status.**

## VII. CONCLUSION

The simulation of the proposed design for the interlock system for the Miniature Neutron Source Reactor effectively validated its functionality, emphasizing the critical aspects of trip interlocks and control conditions interlocks. The paper presents a comprehensive assessment that includes a meticulous examination of timing and sequencing to ensure the accurate detection and enforcement of interlock conditions within specified timeframes. The integration of a time on-delay function (B013) was a noteworthy feature, strategically preventing instantaneous reactor startup and contributing to operational stability.The significance of the on-delay function in control systems was highlighted, showcasing its role in addressing operational considerations and enhancing overall system performance. Specifically, the benefits included stability, avoidance of transient conditions, prevention of chattering and oscillations, control of start-up transients, prevention of false alarms, and protection against rapid changes. These advantages play a crucial role in maintaining safe and efficient operation across a spectrum of industrial and automated processes.The detailed analysis of the interlock system's outputs (as illustrated in Figures 7 to 10) provided a clear understanding of the reactor's status during different operational scenarios. The visual representation of the reactor in standby mode, operation, and engagement of conditional control interlocks convey the system's responsiveness to specific conditions. Notably, the absence of the Cd capsule interlock (in Figure 9) demonstrated the logical control design's effectiveness in rendering the reactor inactive when a crucial component was missing, ensuring a robust safety mechanism.The simulation outcomes demonstrated the interlock system's ability to respond dynamically to varying conditions, with a particular focus on trip interlocks and conditional control interlocks. The automatic tripping mechanism (in Figure 10), activates when set limits are exceeded during reactor operation, showcases the system's commitment to safety. Importantly, the distinction has been drawn between the reactor being in standby mode and a state where trip interlocks prevent startup, emphasizing the nuanced control mechanisms in place.The primary focus of interlock systems is to ensure operational safety, but they can still experience transient misindications due to various factors such as sensor malfunctions or environmental disturbances. To address these issues, the system is programmed to trigger alarms instead of immediately shutting down, allowing qualified operators to thoroughly assess potential causes and implement corrective measures before safety hazards arise. Temporary power outages are also managed by the system, maintaining the process until power is restored. Verification of the interlock system involves simulation and comprehensive testing after any modifications or maintenance. The proposed enhancement of the interlock system from three to seventeen interlocks in the MNSR aims to address specific vulnerabilities within the reactor system. This augmentation stems from several factors, including insights derived from operational experiences, industry-wide incident analyses, and advancements in safety analysis methodologies. Additionally, the rationale behind this initiative is to adhere to the principle of defense-in-depth, which emphasizes the deployment of multiple layers of safety measures to mitigate the risk of accidents. By incorporating additional interlocks, the reactor system gains supplementary safeguards, thereby augmenting its resilience and reducing the likelihood of accidents, even in the event of partial failure of individual safety systems.

Data Availability.
This review article draws upon information from publicly accessible academic journals, with detailed references listed in the reference section to enhance transparency and facilitate easy access to the source material.

Conflicts of Interest.
The authors declare no conflicts of interest.

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