Strengthening Emergency Preparedness for Station Blackout Using a GPWR Simulator

Ryuichi T. Kishimoto, Albert C. Dairo, Jaclyn F. Natividad, Mark Gino E. Aliperio, Ryan U. Olivares
Philippine Nuclear Research Institute
Commonwealth Avenue, Diliman, Quezon City, Philippines
rtkishimoto@pnri.dost.gov.ph, acdairo@pnri.dost.gov.ph, jfnatividad@pnri.dost.gov.ph, mgealiperio@pnri.dost.gov.ph, ruolivares@pnri.dost.gov.ph

ABSTRACT

Station blackout (SBO) is a rare but potentially critical scenario that places significant pressure on nuclear power plant operators due to the loss of offsite electrical power, during which emergency diesel generators (EDGs) are automatically activated to supply essential safety systems. Despite EDG availability, SBO conditions still pose substantial challenges in maintaining key safety functions, requiring rapid decision-making, seamless coordination, and sustained operational control under uncertainty. Because such scenarios cannot be practiced during routine plant operations, effective emergency preparedness relies on realistic simulations and carefully structured drills. In this regard, simulator-based exercises are indispensable for developing operator competencies to manage SBO situations effectively.

This study aims to assess emergency preparedness and operator response during station blackout (SBO) events in a pressurized water reactor. To achieve this objective, a Generic Pressurized Water Reactor (GPWR) simulator was utilized to conduct scenario-based simulations that emphasize the practical challenges of emergency response under blackout conditions rather than theoretical analysis alone. The simulated scenarios begin with a loss of offsite power and progressively escalate to the failure of onsite alternating current sources due to emergency diesel generator malfunctions. Each scenario is designed to replicate realistic plant transients and demonstrates the behaviour of key safety systems such as the reactor protection system, engineered safety features, and emergency core cooling systems, as well as sequencer-driven actions and the increasing operational demands placed on operators as the event unfolds. The evaluation is based on qualitative observations and basic timing considerations commonly applied in emergency preparedness assessments.

The results indicate that effective preparedness for station blackout (SBO) events relies on early recognition of plant conditions and timely, conservative decision-making in accordance with established procedures. The simulated scenarios highlight the importance of structured response strategies and coordinated system management to maintain core cooling and ensure decay heat removal during prolonged power loss. Lessons from past nuclear accidents involving SBO conditions, particularly the Fukushima Daiichi accident, underscore how delays in response and limited preparedness can worsen accident progression.

This study demonstrates that the use of a Generic Pressurized Water Reactor (GPWR) simulator provides practical insights into emergency preparedness for SBO events. By modelling severe accident scenarios, simulator-based training enhances operator readiness by improving understanding of plant response behaviour, reinforcing adherence to emergency procedures, and clarifying response priorities under extreme power loss. These findings highlight the effectiveness of scenario-based simulation as a reliable tool for strengthening emergency preparedness programs in pressurized water reactor facilities.

Keywords: *station blackout, simulator, pressurized water reactor, emergency, safety*

1 INTRODUCTION

Station blackout (SBO) remains one of the most critical initiating events in nuclear power plant safety analysis due to its potential to disable all power systems required for core cooling and decay heat removal. According to International Atomic Energy Agency (IAEA), SBO scenarios represent low-probability but high-consequence events that demands robust mitigation strategies and highly trained nuclear power plant operators [1].

The significance of SBO was highlighted by the Fukushima Daiichi nuclear incident, where prolonged Loss of Offsite Power (LOOP) led to core damage and hydrogen explosions. Post-accident analyses conducted by the IAEA and U.S. Nuclear Regulatory Commission (NRC) identified that delays in operator response and insufficient preparedness contributed significantly to accident progression [1,2]. These findings emphasize the critical role of operator performance in managing SBO conditions.

In response to such events, international safety standards have increasingly emphasized the need for enhanced emergency preparedness including improved training programs and the development of severe accident management guidelines. Operator performance during SBO scenarios is influenced not only by technical knowledge but also by the ability to interpret rapidly changing plant conditions and implement appropriate procedures under time pressure. Previous studies have demonstrated that simulator-based training can significantly improve operator response time, decision-making accuracy, and adherence to emergency procedures [3,4].

However, conducting real-world training for SBO is not feasible due to inherent risks involved. As a result, high-fidelity simulators have become essential tools for replicating complex plant transients and enabling operators to gain practical experience in managing rare but high consequence events. While existing research has established the general benefits of simulator-based training, there remains a need to examine how such training supports operator preparedness under progressively worsening SBO scenarios.

This study aims to evaluate emergency preparedness and operator response during SBO scenarios using GPWR simulator with particular emphasis on how simulator-based training supports operator readiness under the loss of power conditions. It examines plant system behavior during SBO events and demonstrates how structured simulator scenarios enhance operator understanding of system responses, reinforce adherence to emergency procedures and improve decision-making.

2 METHODOLOGY

This study utilized a Generic Pressurized Water Reactor (GPWR) simulator to simulate station blackout (SBO) events and assess emergency preparedness. The simulator is designed to replicate the operational environment of a pressurized water reactor (PWR), offering a realistic platform for testing operator response to critical power loss scenarios. The simulations begin with a loss of offsite power, followed by the failure of emergency diesel generators (EDGs), resulting in a total power loss within the plant. These scenarios are structured to closely mimic real-world plant transients, providing operators with the opportunity to manage safety systems under challenging conditions.

The primary focus of the simulations is to assess the behavior and effectiveness of critical safety systems, including the Reactor Protection System (RPS), Engineered Safety Features (ESF), and Emergency Core Cooling Systems (ECCS), in maintaining core cooling and heat removal during prolonged power loss. Through these simulated events, operators are tested on their ability to manage these systems, maintain plant stability, and adhere to emergency procedures during a station blackout.

By engaging with the GPWR simulator, operators are able to improve their decision-making and system management skills. The simulated scenarios highlight the importance of early recognition of plant conditions and the need for timely, conservative decision-making. The escalating nature of the scenarios ensures that operators are tested on their ability to respond effectively under pressure, reinforcing their understanding of plant behavior and reinforcing adherence to established emergency procedures. Additionally, the simulations foster improved coordination and communication among operators, as they work together to manage safety systems and mitigate risks.

The GPWR simulator progressively escalates the station blackout scenario, starting with a loss of offsite power and continuing through the failure of onsite power sources. The scenarios are designed to challenge operators to maintain control over essential systems, such as core cooling and decay heat removal, ensuring plant stability throughout the emergency event. By using the simulator, operators are better equipped to handle similar real-world events, enhancing their preparedness and ability to respond effectively during SBO situations.

3 RESULTS AND DISCUSSION

The simulation of the Station Blackout (SBO) event in the Generic Pressurized Water Reactor (GPWR) simulator demonstrated the critical vulnerability of reactor systems when backup power and pumps are unavailable. As shown in Figure 1**,** the plant overview clearly indicates that all safety injection pumps, including the core cooling pumps and were inoperable during the SBO event. This lack of operational pumps led to the depletion of Steam Generator (SG) water levels over time. The failure of these essential systems resulted in the reactor's inability to circulate coolant, compromising heat removal, which is critical for maintaining core stability during an SBO. Despite the activation of safety systems like the Residual Heat Removal System (RHR) and Engineered Safety Features (ESF)**,** as illustrated in the subsequent figures, the inability to circulate coolant prevented the maintenance of the necessary SG levels for proper cooling.

This finding aligns with previous research by Zhou and the group which demonstrated that SBO events severely challenge plant safety systems when emergency cooling and backup power systems fail. In their study, emphasized that without active coolant circulation, even well-designed safety systems like ESF and RHR cannot prevent the depletion of SG water levels, leading to potential core damage. Similarly, our simulation results emphasize that safety systems alone are insufficient to maintain reactor stability during SBO events when critical components like pumps are non-operational [5].

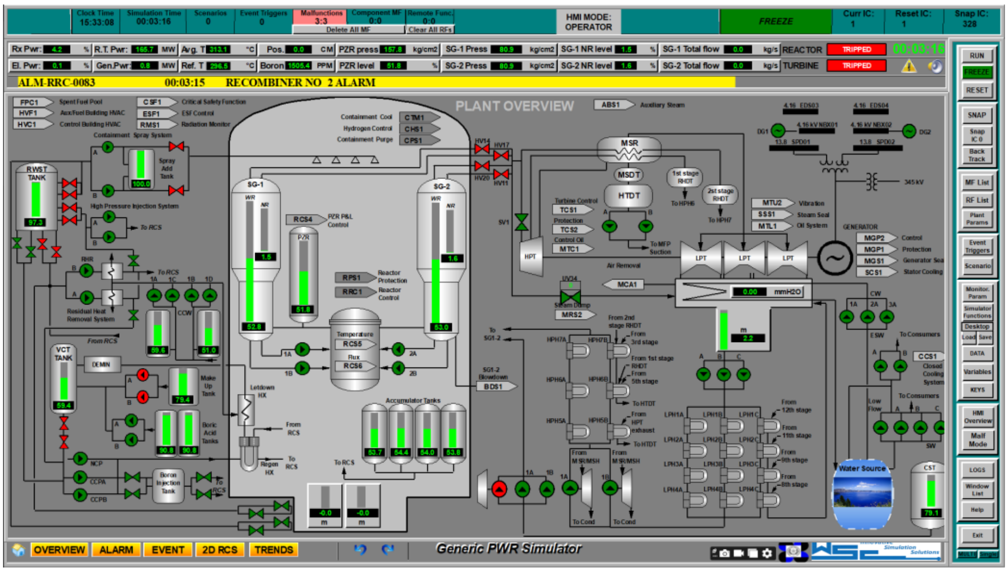

Figure 1: Plant Overview Under 3 Minute of SBO Simulation

Figure 2 further illustrates the activation of Engineered Safety Features (ESF) during the SBO event. Despite triggering key safety systems such as containment isolation and emergency feedwater actuation**,** the absence of operable pumps continued to drive the SG water levels to dangerously low points. This highlights the vital role of operational pumps in ensuring the continuous circulation of coolant and the removal of decay heat under emergency conditions. This observation aligns with Pati and the group, where the study showed that in extreme SBO scenarios, even the activation of emergency safety systems cannot compensate for the lack of active cooling, resulting in a gradual depletion of water levels in SGs [6].

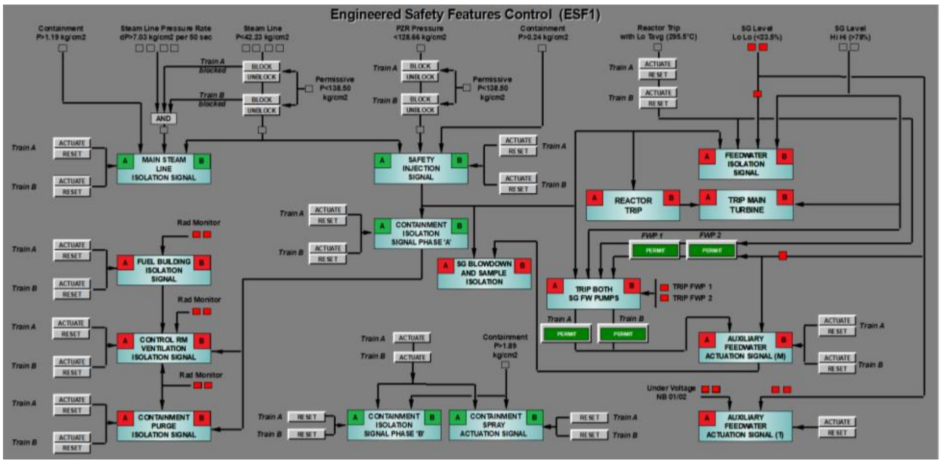

Figure 2: Engineered Safety Features Control During SBO Event

In Figure 3, the Reactor Protection System (RPS) is shown during the Station Blackout (SBO) event. The alarm system, highlighted in red under the Trip Actuation column, indicates a series of critical alarms that were triggered in response to the deteriorating reactor conditions. These alarms, such as the Reactor Trip (REACT TRIP), PZR Pressure Low (PZR Press LO), and SG Low Level (SG Level LO), reflect major failures in the reactor's ability to maintain core cooling. The presence of SG-1 and SG-2 alarms, both showing 0.00 kg/s flow, indicates that the safety pumps and coolant circulation have failed, leading to the depletion of the Steam Generators' (SGs) water levels.

The red highlighted alarms signify that the reactor is in a state of critical instability, with the RPS activating various protective actions, such as trip states for both SGs and reactor components. These actions, however, were insufficient to stabilize the plant due to the non-operable cooling systems. This finding is consistent with Salazar and his group, who observed that RPS activations during SBO events often signal cascading system failures. They found that while RPS alarms are essential for detecting anomalies, their effectiveness is limited when core cooling systems are compromised, as seen in our simulation where the reactor could not maintain stability despite the trip actions [3].

Throughout the simulation, it became evident that the lack of active cooling and the depletion of the SG levels posed a significant risk to reactor safety. With no operable pumps to circulate coolant and support the cooling systems, the reactor's core temperature rises as shown in Figure 4, and heat removal capabilities diminish, increasing the potential for core damage. The simulation also highlighted the importance of ensuring operability of emergency power and pumps to prevent prolonged thermal stress on the reactor. This finding is supported by Gupta and his group, who emphasized the importance of maintaining reliable cooling systems during SBO events to prevent core damage [7].

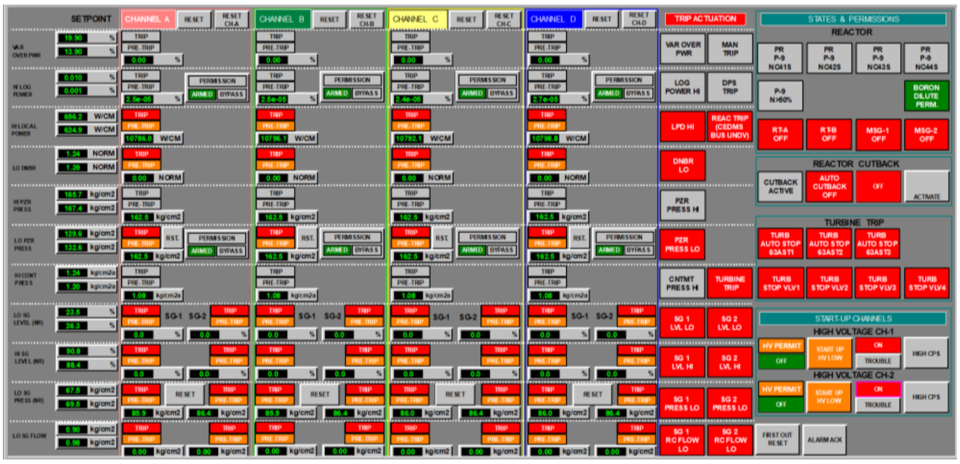

Figure 3: Reactor Protection System

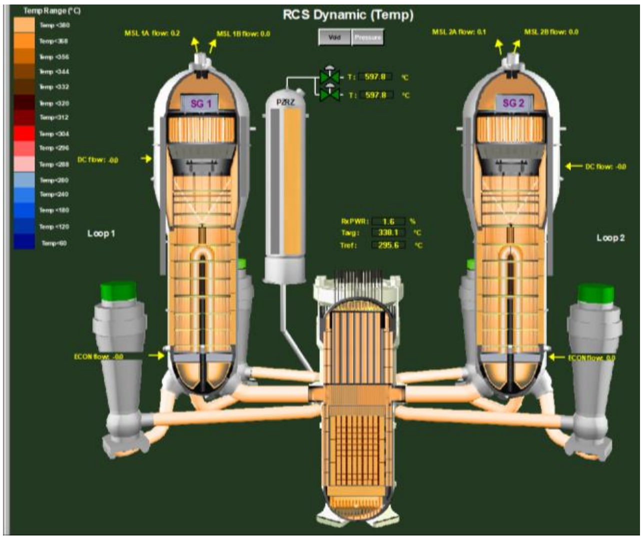

Figure 4: RCS Temperature During Extended Loss of Power Supply

As depicted in Figure 5, the SG-1 and SG-2 levels were completely depleted after several hours of no power, reflecting the failure of coolant circulation systems. This depletion significantly impaired the plant's ability to remove decay heat. Comparable to the study conducted by Kim and his group, noted that in SBO conditions, SG depletion and loss of coolant flow directly result in rising core temperatures and cooling system failure. Their work suggests that prolonged power loss, combined with pump failure, can lead to catastrophic core damage if the system is unable to remove heat efficiently [8].

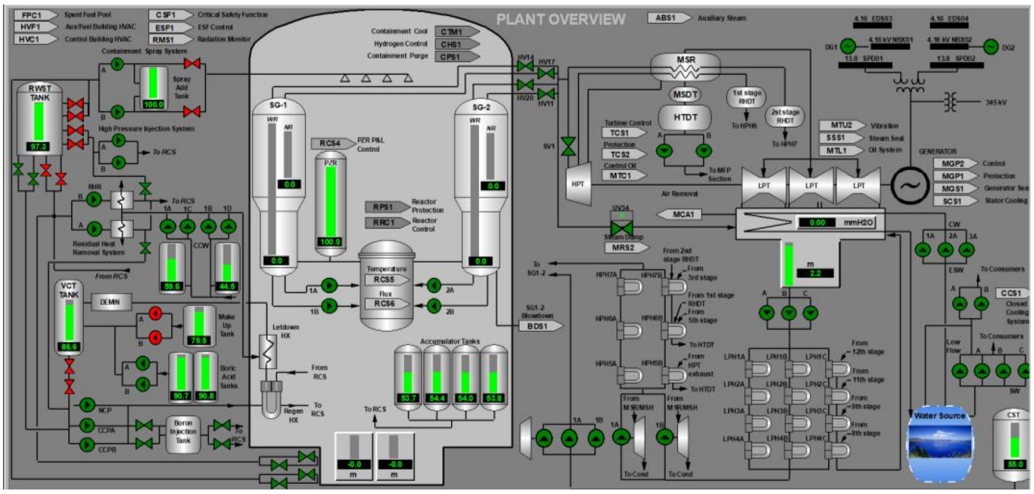

Figure 5: SG Levels at Prolonged SBO Event

4 CONCLUSION

This study highlights the importance of strengthening emergency preparedness for SBO events in PWRs. Through the use of GPWR simulator, we observed that while safety systems such as the RPS and ESF were activated, the ability of the plant to maintain core cooling was significantly challenged due to the non-operability of cooling pumps.

The simulation showed that, despite the activation of emergency protocols, the depletion of SG levels and the inability to circulate coolant underscored the critical need for functional backup power and cooling systems. These findings suggest that, while safety systems are essential, effective emergency preparedness goes beyond just activating these systems, it requires ensuring the operability of key components like cooling pumps and backup power sources during prolonged power loss.

The practical implications of these results emphasize the importance of training operators to respond swiftly and effectively during such events, and ensuring the reliability of emergency systems. The use of the GPWR simulator offers a valuable approach to improving operator readiness and preparing for SBO scenarios, helping to enhance overall reactor safety.

REFERENCES

[1] International Atomic Energy Agency, The Fukushima Daiichi Accident Report, Vienna, Austria: IAEA, 2015.

[2] U.S. Nuclear Regulatory Commission, Station Blackout Rulemaking and Regulatory Guidance, Washington, DC, USA: US NRC, 2012.

[3] M. Salazar, et al., "Simulation of SBO events: Reactor protection and cooling system failures," *Nuclear Safety Review*, Vol. 66, No. 2, pp. 98–113, 2018.

[4] International Atomic Energy Agency, *Advances in Nuclear Power Plant Training Simulators*, Vienna, Austria: IAEA, 2020.

[5] Zhou, Y., et al., Evaluation of Emergency Cooling Systems During Station Blackout Events in Nuclear Reactors, Safety Science, 77, 1-8, Vienna, 2015.

[6] Pati, P., et al., Analysis of Emergency Safety Features during SBO in Nuclear Reactors, Journal of Nuclear Engineering and Technology, 52(2), 204-215, Vienna, 2020.

[7] R. Gupta, et al., "The role of cooling systems during SBO events: Preventing core damage in nuclear power plants," *Nuclear Engineering and Design*, Vol. 355, p. 110471, 2020.

[8] J. Kim, et al., "Integral effect test on station blackout (SBO) scenario with steam generator tube rupture (SGTR) in ATLAS facility," *Nuclear Engineering and Design*, Vol. 336, pp. 98-112, 2018.