Simulated Small-break Loss-of-Coolant Accident (SBLOCA): A Transient Analysis in PWRs

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ABSTRACT

A Small Break Loss-of-Coolant Accident (SBLOCA) involves a small rupture (≤10% of the cold leg cross-sectional area) in the Reactor Coolant System (RCS) of a Pressurized Water Reactor (PWR), resulting in gradual coolant loss and depressurization. This study analyzes the transient response of a cold leg SBLOCA using a Generic PWR (GPWR) simulator. The simulation was performed at PNRI's NuSIM facility for a 1400 MWe, two-loop PWR operating at 100% full power under mid-cycle conditions, with the break initiated in cold leg 2B. Following the event, the RCS exhibited gradual depressurization, reduced subcooling margin, and decreasing pressurizer level, accompanied by coolant discharge to containment. Degraded core cooling led to a reduction in departure-from-nucleate-boiling ratio (DNBR), triggering automatic reactor trip, turbine trip, and steam dump actuation. Safety systems functioned as designed, and the plant transitioned to a stable shutdown condition with decay heat removal maintained by the steam generators and emergency core cooling systems, demonstrating an appropriate response to a design-basis SBLOCA.

Keywords: *Small Break Loss-of-Coolant Accident; Pressurized Water Reactor; Transient Analysis; Emergency Core Cooling System; Nuclear Power Plant*

1 INTRODUCTION

A Small-Break Loss-of-Coolant Accident (SBLOCA) is a design-basis accident in a Pressurized Water Reactor (PWR) characterized by a breach in the RCS with an equivalent flow area typically less than 10% of the cold leg pipe cross-section. Unlike large-break LOCAs, SBLOCAs involve relatively slow coolant inventory loss and gradual system depressurization, resulting in complex thermal-hydraulic behavior and delayed system responses. As emphasized by the International Atomic Energy Agency, SBLOCA scenarios are among the most analytically challenging transients due to the coupled effects of natural circulation, two-phase flow development, and safety system actuation timing [1,2].

In the event of an SBLOCA, the RCS initially maintains near-nominal pressure conditions, allowing forced circulation to persist for a limited duration. As coolant inventory decreases, subcooling margin is reduced, leading to the onset of nucleate boiling and eventual transition to two-phase flow regimes. This progression can degrade core heat removal capability and reduce the DNBR, a critical safety parameter. If unmitigated, these conditions may result in fuel heat-up and potential cladding damage. Automatic safety systems—including reactor trip, Emergency Core Cooling Systems (ECCS), and auxiliary feedwater systems—are designed to actuate in sequence to preserve core cooling and maintain plant integrity [1,3]. The causes of SBLOCA events are varied and may include small pipe ruptures, valve seal failures, instrumentation line breaks, or degradation mechanisms such as corrosion and thermal fatigue. Although such breaks are limited in size, their subtle progression poses diagnostic challenges for plant operators, particularly during the early phase of the transient when system parameters deviate gradually from nominal values.

Key plant parameters that must be monitored during an SBLOCA transient include RCS pressure and temperature, pressurizer level, core exit temperature, steam generator levels and pressures, containment conditions, and reactor power. These parameters provide essential indicators of core cooling performance, system inventory, and the effectiveness of engineered safety features. Their evolution over time is critical in assessing whether the plant remains within acceptable safety limits or approaches conditions that may challenge fuel integrity. The analysis of plant dynamics during SBLOCA events is essential for validating safety system performance, improving operator training, and supporting regulatory compliance. This study analyzes the plant dynamics and transient response following a cold leg SBLOCA using a generic PWR (GPWR) simulator

2 METHODOLOGY AND SIMULATION SET-UP

2.1 Simulation Facility and Reactor Model

The transient analysis was conducted using the Generic Pressurized Water Reactor (GPWR) simulator installed at the NuSIM Facility of the Philippine Nuclear Research Institute (PNRI). The simulator represents a two-loop, 1400 MWe-class PWR, with design features including standard primary and secondary system configurations and engineered safety systems. Each primary loop consists of one steam generator (SG) and two reactor coolant pumps (RCPs), connected to the reactor pressure vessel (RPV) through hot and cold legs. The model incorporates key thermal-hydraulic, neutronic, and control system behaviors necessary to simulate design-basis transients such as an SBLOCA.

2.2 Initial Conditions and Steady-State Operation

Prior to transient initiation, the plant was stabilized at 100% full power under mid-cycle operating conditions. All primary and secondary system parameters—including reactor thermal power, RCS pressure and temperature, pressurizer level, and steam generator levels—were maintained within nominal design values. The steady-state initialization ensures that the system response observed during the transient is solely attributable to the imposed SBLOCA disturbance.

2.3 SBLOCA Scenario Definition

The SBLOCA scenario was initiated as a 1% equivalent break area relative to the coolant flow cross-sectional area in cold leg 2B of the RCS. The break was introduced at 10 seconds into the simulation time to allow stabilization of initial conditions prior to disturbance. The selected break size falls within the SBLOCA classification, representing a small but continuous loss of primary coolant inventory. The break location in the cold leg is particularly significant, as it directly affects coolant flow entering the reactor core and influences system depressurization behavior, loop seal dynamics, and core cooling capability. The leak was modeled as a continuous mass discharge from the primary system to containment, resulting in a gradual reduction in RCS pressure and inventory.

2.4 Monitored Parameters and Data Acquisition

To characterize the transient response and evaluate overall plant performance, key parameters from the primary, secondary, and safety systems were continuously monitored throughout the simulation. These include reactor coolant system (RCS) pressure, temperature, and mass inventory; pressurizer pressure and water level; steam generator secondary-side pressure, water level, and heat removal rate; and core neutronic behavior such as reactor power and reactivity feedback. In addition, critical thermal-hydraulic safety indicators, particularly the departure from nucleate boiling ratio (DNBR) and subcooling margin, were tracked to assess core cooling conditions. Containment response was evaluated through sump level monitoring to confirm coolant discharge, while the actuation and performance of engineered safety systems—such as the reactor protection system (RPS), emergency core cooling system (ECCS), turbine trip, and steam dump system—were also recorded. The transient simulation was performed using a time-dependent approach, capturing the evolution of plant conditions from steady-state operation through SBLOCA initiation and progression toward a stabilized shutdown state.

3 RESULTS AND DISCUSSION

The transient response of the plant following the initiation of a 1% cold leg SBLOCA at 10 s demonstrates the expected progression of a small-break loss-of-coolant accident, characterized by gradual depressurization, degradation of core cooling conditions, and subsequent actuation of engineered safety systems.

3.1 Early Transient Phase: Coolant Loss and Pressurizer Response (10–20 s)

Immediately after SBLOCA initiation, the primary system begins to lose coolant inventory, resulting in a measurable impact on pressurizer behavior. At normal operation condition, the pressurizer pressure is 157 kg/m2. However, due to the initiated SBLOCA, at approximately 15 s, a pressurizer low level deviation alarm is triggered, indicating a reduction in system inventory due to continuous coolant discharge through the break. This is accompanied by control system responses, including changes in pressurizer heater status and pressure control mechanisms. By 16 s, additional pressurizer-related alarms (e.g., low-pressure protection signals) are observed, confirming the onset of primary system depressurization. These early indicators are consistent with the expected response of a PWR under SBLOCA conditions, where the pressurizer initially attempts to maintain pressure despite ongoing mass loss.

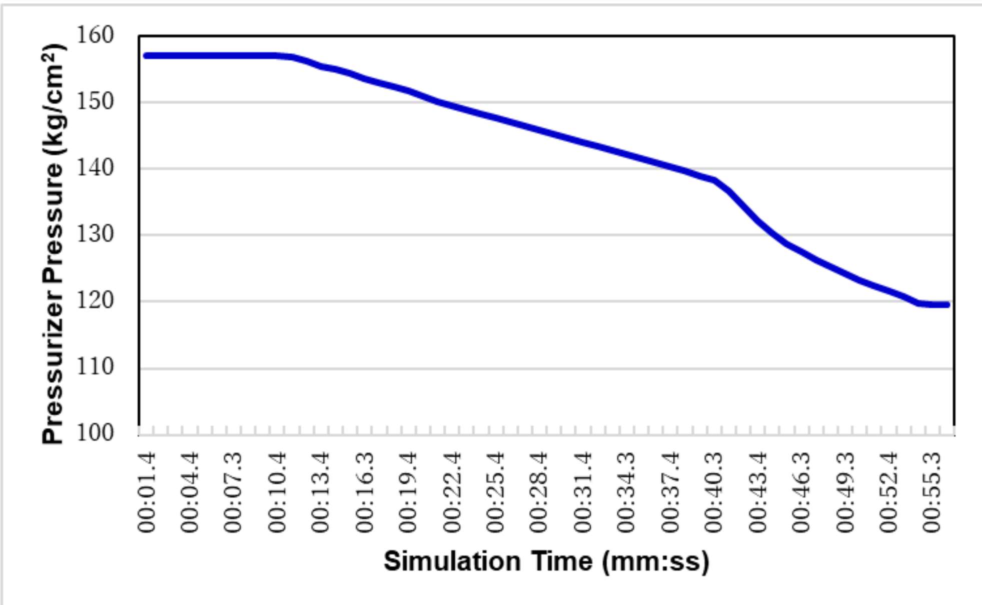

Figure 1: Trend of Pressurizer pressure from normal condition of 157 kg/m^2 until stabilizing at 120 kg/m^2 from 55 seconds of simulation time and onwards.

3.2 Degradation of Core Thermal-Hydraulic Conditions (20–35 s)

As the transient progresses, the reduction in primary pressure and coolant inventory leads to a deterioration of core cooling conditions. At 21 s, the system registers a loss of subcooling margin, indicating that the coolant temperature is approaching saturation conditions. By 32 s, the RCS reaches saturation, signifying the onset of two-phase flow conditions within the primary system. This transition is critical, as it reduces heat transfer efficiency in the reactor core and increases the likelihood of departure from nucleate boiling (DNB). At 34 s, a low DNBR pre-trip alarm is activated, marking a significant safety threshold where local heat flux conditions approach critical limits. This confirms that core thermal margins are being challenged, consistent with the expected consequences of reduced coolant inventory and pressure during an SBLOCA.

3.3 Reactor Protection System Actuation and Reactor Trip (35–40 s)

As core conditions continue to degrade, the reactor protection system (RPS) initiates automatic shutdown. At approximately 38 s, multiple reactor trip signals are recorded, including Low DNBR trip (multiple channels); High local power density trip; and Reactor trip circuit breaker opening. These signals collectively result in a full reactor scram, terminating the fission chain reaction. The rapid actuation of the RPS demonstrates proper system response to deteriorating core conditions, ensuring that fuel damage thresholds are not exceeded. Simultaneously, control rod drive mechanisms are de-energized, and electrical system responses (e.g., bus undervoltage signals) confirm the insertion of control rods into the core.

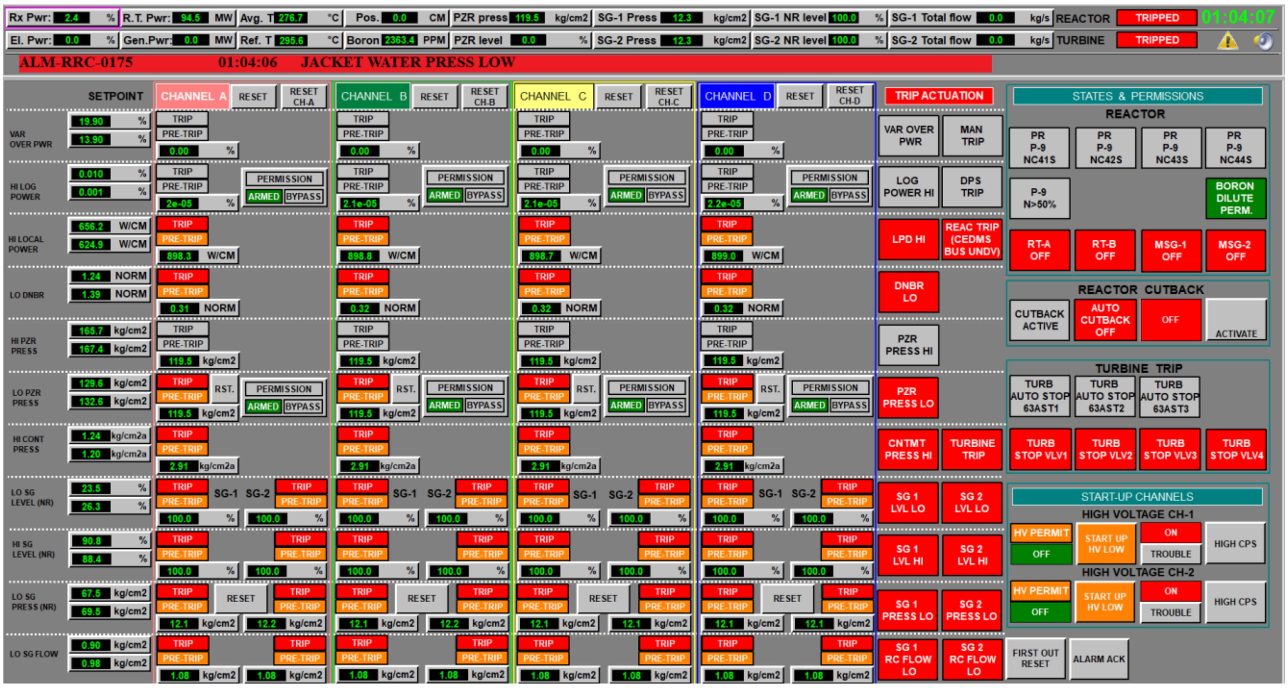

Figure 2: The Reactor Protection System page of the simulator that shows parameters that actuates the trip initiation signal

3.4 Secondary System Response and Heat Removal (38–45 s)

Following the reactor trip, the plant transitions to decay heat removal via the secondary system. At 38–39 s, a turbine trip is initiated, accompanied by closure of turbine stop valves and activation of steam dump valves. The steam dump system rapidly opens to discharge steam directly to the condenser or atmosphere, maintaining heat removal from the primary system through the steam generators. Multiple valve position changes and dump activations observed between 39–42 s confirm the effectiveness of this response. This behavior is critical in stabilizing the plant, as it ensures continued heat removal despite reactor shutdown, thereby preventing excessive temperature rise in the core.

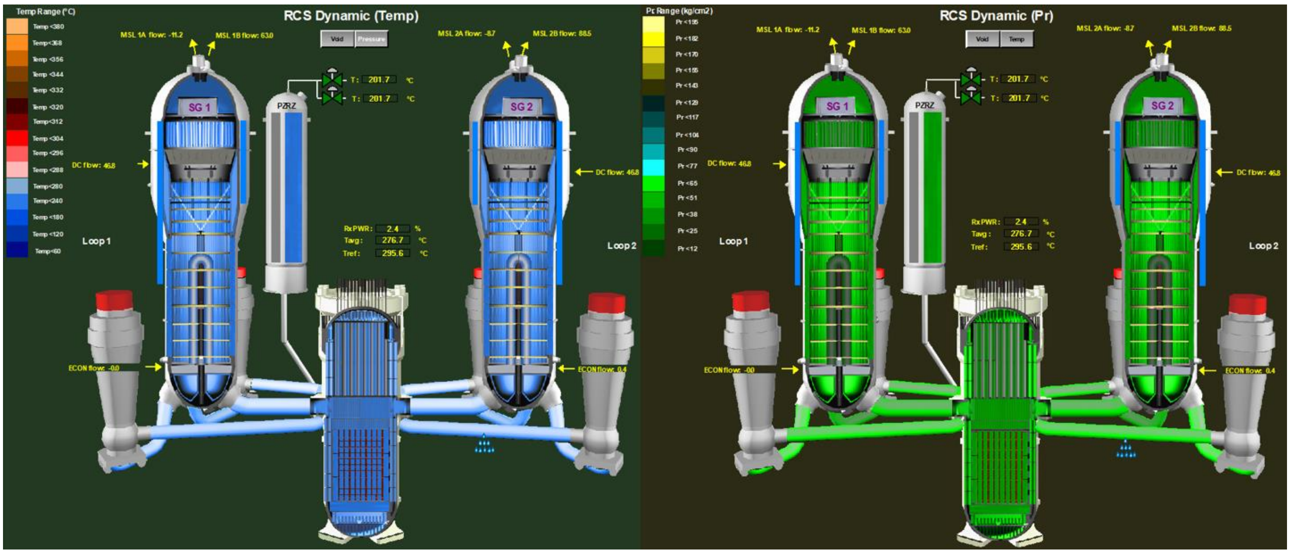

Figure 3: Temperature and Pressure profiles of the RCS after SBLOCA. Average temperature was maintained at around 276 °C preventing fuel degradation.

3.5 Continued Depressurization and Safety System Engagement (>40 s)

Beyond 40 s, additional pressurizer-related alarms—such as low pressure pre-trip signals and heater control anomalies—indicate ongoing system depressurization and challenges in pressure control due to sustained coolant loss. The continued decline in pressurizer level and pressure reflects the persistent nature of the break flow, while the activation of protective signals confirms that the plant remains within the designed safety response envelope. Although not explicitly shown in the early event log excerpt, such conditions typically lead to the eventual initiation of Emergency Core Cooling Systems (ECCS) to restore coolant inventory and ensure long-term core cooling, consistent with design-basis accident mitigation strategies.

3.6 Integrated System Behavior and Safety Implications

Overall, the transient behavior observed in the simulation follows the characteristic progression of a small-break loss-of-coolant accident (SBLOCA), beginning with a gradual loss of coolant inventory that leads to a decrease in pressurizer level and a corresponding reduction in reactor coolant system (RCS) pressure. This depressurization results in the loss of subcooling margin and eventual transition to saturation conditions, promoting the onset of two-phase flow within the primary system. As heat transfer efficiency in the reactor core deteriorates, the departure from nucleate boiling ratio (DNBR) decreases, indicating increasing thermal stress on the fuel. These conditions trigger the reactor protection system, resulting in an automatic reactor trip that effectively terminates the fission process. Subsequently, the secondary system assumes a critical role in decay heat removal through turbine trip and steam dump actuation, ensuring continued heat extraction from the core via the steam generators. The close coupling between thermal-hydraulic degradation and automatic safety system response underscores the importance of monitoring key parameters such as RCS pressure, DNBR, and subcooling margin, as identified in the methodology. The results demonstrate that the GPWR simulator successfully captures the dynamic interaction between primary system behavior and engineered safety features, consistent with deterministic safety analysis approaches recommended by IAEA. Despite the progressive deterioration of primary system conditions, the timely and coordinated response of protection and safety systems enables the plant to transition to a safe shutdown state, with adequate decay heat removal and preservation of core integrity.

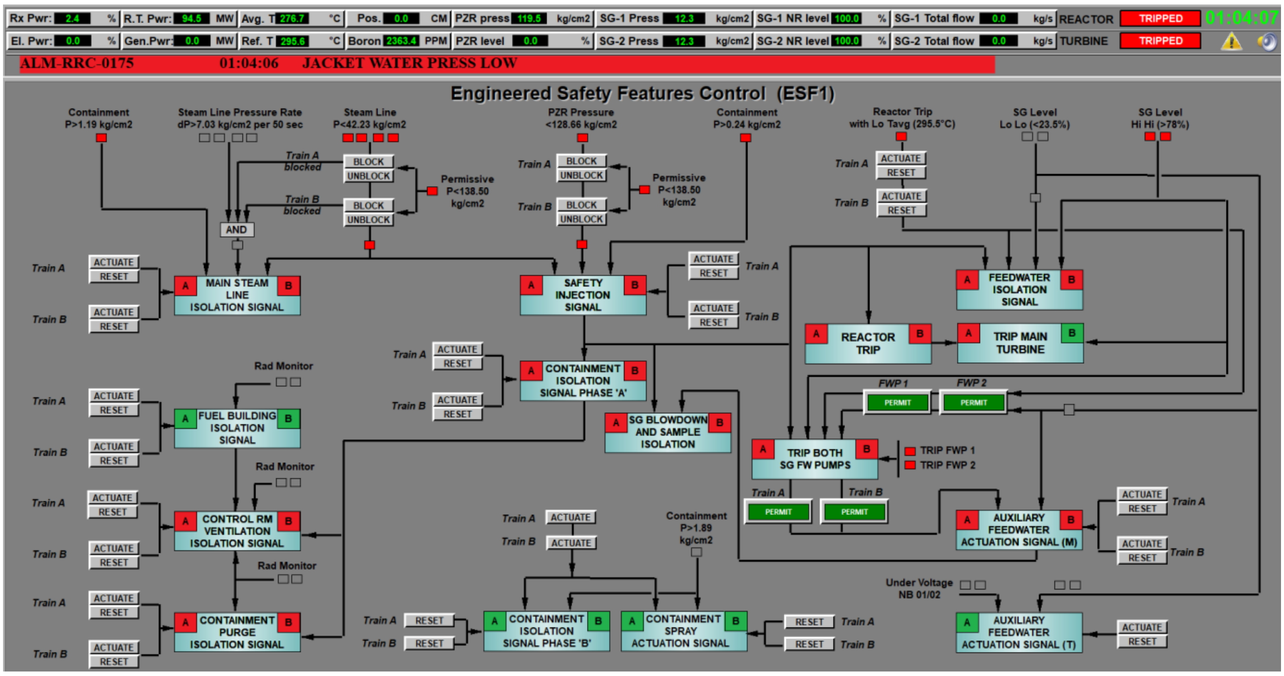

Figure 4: Engineered Safety Features Control page of the GPWR Simulator

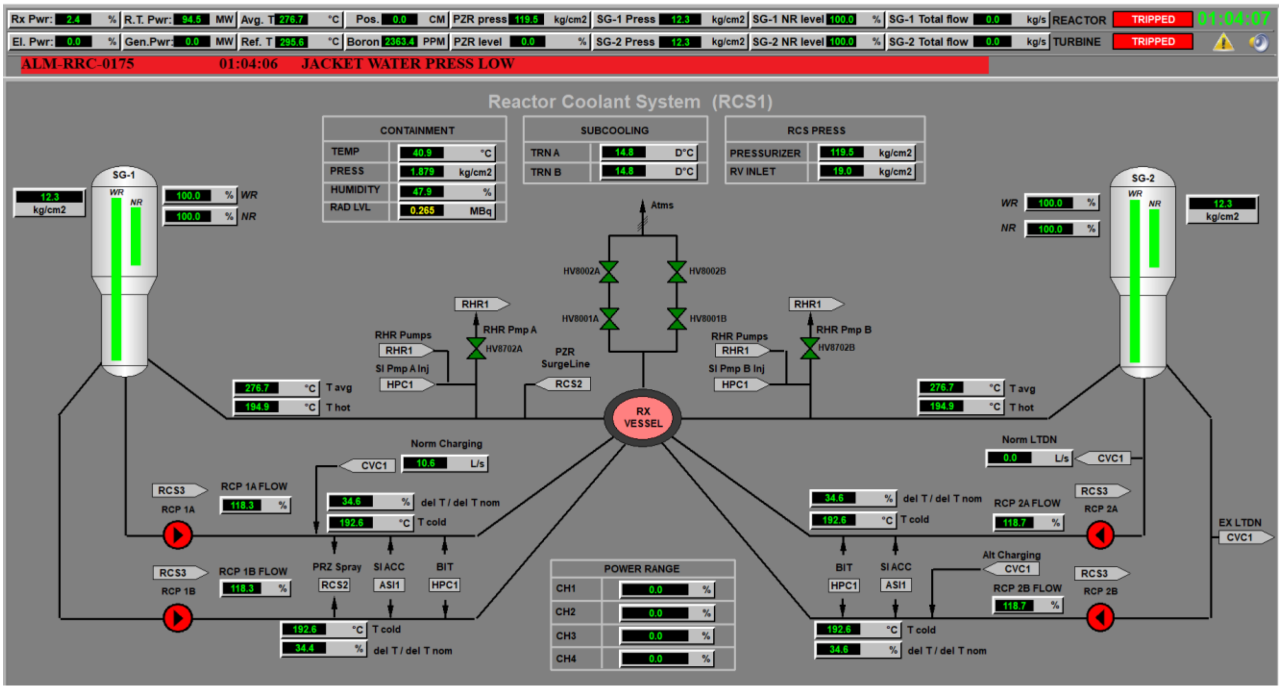

Figure 5: RCS Profile at 1:04:07 of simulation time. Reactor power is around 2.4%.

4 CONCLUSION

This study presented a transient analysis of a simulated SBLOCA in a pressurized water reactor using the GPWR simulator. A 1% break was introduced in cold leg 2B at 10 seconds of simulation time under full-power, mid-cycle operating conditions. The analysis focused on the dynamic response of key plant parameters, including RCS pressure and inventory, pressurizer level and pressure, steam generator performance, core thermal-hydraulic safety indicators such as subcooling margin and DNBR, and the actuation of engineered safety systems. The results demonstrated the characteristic progression of an SBLOCA, beginning with gradual coolant loss and system depressurization, followed by the loss of subcooling margin and transition to two-phase flow conditions. The degradation of core cooling capability led to a reduction in DNBR, which triggered the reactor protection system and resulted in an automatic reactor trip. Subsequent activation of the turbine trip and steam dump system ensured effective decay heat removal through the secondary system. The coordinated response of these safety features enabled the plant to transition to a safe shutdown condition, maintaining core integrity despite the ongoing coolant loss.

The findings highlight the capability of the GPWR simulator to realistically capture the coupled neutronic and thermal-hydraulic behavior of the plant during design-basis accidents. More importantly, this study underscores the critical importance of conducting such simulations in the context of nuclear power plant safety. Transient simulations provide valuable insights into system behavior under abnormal and accident conditions, allowing for the validation of safety system performance, operator training, and the development of effective accident management strategies.

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