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Regulatory Review of Light Water SMR Coping Capability for Station Blackout

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1. Introduction

A Station Blackout (SBO) in a nuclear power plant refers to the loss of offsite power (LOOP), followed by the failure of the emergency diesel generator (EDG), resulting in the complete loss of alternating current (AC) power. Offsite power is essential for reactor cooling and maintaining the operation of key safety systems. However, external factors such as earthquakes, typhoons, and transmission line failures can lead to LOOP, necessitating the successful startup of EDGs to ensure continued reactor cooling and safety system operation.

In large light water reactors, SBO mitigation strategies rely on the rapid startup of EDGs and alternate AC power (AAC) sources to maintain core cooling for at least 72 hours. These reactors are designed with active safety systems that require external power sources for operation.

If EDGs also fail, the reactor must rely on station batteries (125V DC) and emergency cooling systems to remove decay heat for a limited duration. Once this period is exceeded, reactor cooling becomes impossible, leading to core damage, pressure vessel failure, and containment breach, resulting in a severe accident.

The 2011 Fukushima Daiichi nuclear disaster highlighted the catastrophic consequences of SBO when LOOP was followed by the flooding and failure of EDGs and AAC. The subsequent loss of reactor cooling led to core melting, hydrogen explosions, and radioactive material release into the environment. In response, global regulatory frameworks were revised to enhance SBO response capabilities, requiring new reactor designs to sustain core cooling without external power for at least 72 hours. This has emphasized the necessity of passive safety systems that function independently of electric power.

The innovative small modular reactor (i-SMR) under development in South Korea incorporates passive safety systems to maintain reactor safety during SBO events without relying on external power. Unlike large light water reactors, where rapid restoration of AC power is critical for SBO mitigation, i-SMR employs passive cooling mechanisms such as natural circulation and gravity-driven cooling systems, enabling automatic heat removal without external intervention.

This fundamental difference suggests that the traditional SBO coping duration of 72 hours may not be directly applicable to i-SMR designs. However, systematic evaluations of i-SMR's SBO coping capability remain limited. Furthermore, existing SBO regulatory requirements, such as 10 CFR 50.63 in the United States and domestic regulations in South Korea, are primarily based on large light water reactor designs. This raises the need to assess whether new regulatory requirements should be developed to reflect the unique characteristics of i-SMR.

2. Methodology

This study aims to analyze the differences in SBO concepts between i-SMR and large light water reactors and evaluate the adequacy of existing regulatory requirements. Since i-SMR is designed with passive safety systems, its ability to sustain core integrity without external power needs to be thoroughly investigated. To achieve this, a thermal-hydraulic analysis using MARS-KS will be conducted in the future by simulating an SBO scenario in i-SMR to assess whether passive safety systems can maintain adequate core cooling.

2.1 SBO Scenarios in APR-1400

In large light water reactors, SBO scenarios are categorized into two main types based on EDG performance: SBOS (Station Blackout with Startup Failure of EDGs) and SBOR (Station Blackout with Running Failure of EDGs). While both scenarios result in complete AC power loss, the sequence and response time vary.

2.1.1 SBOS (Station Blackout with EDG Startup Failure)

SBOS occurs when LOOP is followed by the failure of both EDGs to start, leading to an immediate loss of AC power. The inability to restore external power within a limited timeframe significantly increases the risk of core damage.

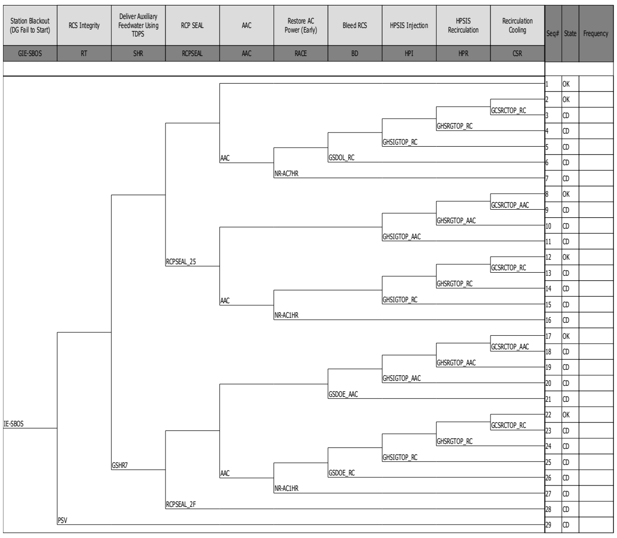

Fig. 1. APR-1400 SBOS Event Tree

2.1.2 SBOR (Station Blackout with EDG Running Failure)

SBOR differs from SBOS in that EDGs initially start successfully but subsequently fail after operating for a certain period. This delayed failure leads to an SBO event, with implications for available response time and system operation.

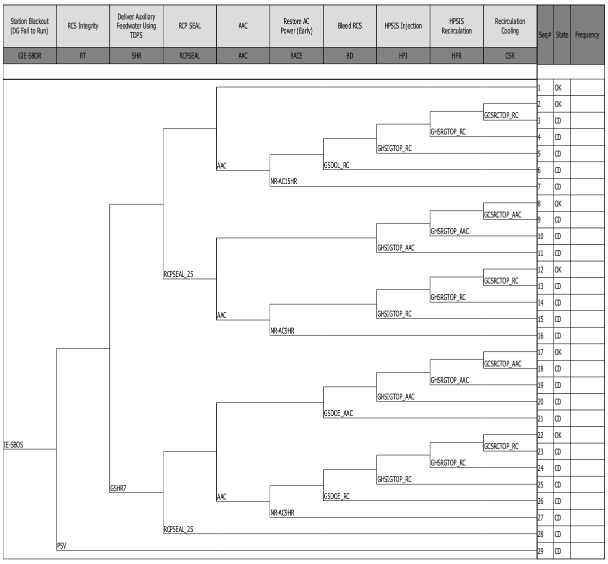

Fig. 2. APR-1400 SBOR Event Tree

2.2 The Regulatory Requirements for Large Light Water Reactors

The SBO regulatory requirements for domestic large light water reactors are specified in Article 24, Paragraph 6 of the Regulations on Technical Standards for Nuclear Reactor Facilities, Etc. This provision stipulates that if a nuclear power plant lacks the capability to cope with an SBO event, it must install an AAC to ensure reactor safety.

Furthermore, U.S. NRC regulation 10 CFR 50.63 states that if an analysis demonstrates that a plant can maintain the necessary safety functions from the onset of an SBO until AAC power is restored and all required safety systems are operational, the plant is considered to have adequate SBO coping capability. Therefore, under the current regulatory framework, nuclear power plants must either demonstrate their ability to withstand SBO or install an AAC to comply with SBO regulatory requirements.

2.3 Regulatory Case of NuScale

The Design-Specific Review Standard (DSRS) for NuScale SMR outlines specific criteria for SBO analysis. Section 8.4 of the DSRS states that if a passive SMR design demonstrates the ability to maintain all safety functions for 72 hours without AC power, the requirement for an alternate AC power source may be waived. Additionally, passive SMRs without AAC must undergo a Regulatory Treatment of Non-Safety Systems (RTNSS) evaluation to verify their SBO coping capability. This suggests that for passive reactors like i-SMR, demonstrating a 72-hour passive cooling capability and justifying RTNSS classification are essential for regulatory acceptance.

2.4 Passive Safety Systems in i-SMR

The i-SMR design incorporates passive safety systems to maintain core integrity without external power during SBO events. Since i-SMR aims to eliminate the need for AAC, a thorough assessment is required to confirm whether passive safety systems alone can sustain core cooling for at least 72 hours.

i-SMR is in the process of designing three passive safety systems.

2.4.1 PAFS(Passive Auxiliary Feedwater System)

The Passive Auxiliary Feedwater System (PAFS) is a key system designed to remove decay heat from the reactor core using only natural circulation, without the need for external power. Unlike conventional large light water reactors, which rely on motor-driven auxiliary feedwater pumps, the PAFS is designed as a passive safety system utilizing natural circulation.

The PAFS consists of two independent trains, each comprising the following major components:

- Emergency Cooling Tank (ECT)
- PAFS heat exchanger
- Piping connected to the steam generator

The operational principle of the PAFS is based on transferring heat release from the reactor to the steam generator, which subsequently transfers it to the PAFS heat exchanger. The cooling water from the emergency cooling tank circulates naturally through the system, removing heat from the reactor. The PAFS is designed to reduce the reactor coolant system (RCS) temperature to a safe shutdown level within 36 hours and to provide sufficient cooling capacity for at least 72 hours to remove decay heat.

2.4.2 PECCS(Passive Emergency Core Cooling System)

The Passive Emergency Core Cooling System (PECCS) is designed to maintain core cooling without external power by utilizing natural circulation and condensation processes. It operates through the Emergency Depressurization Valve (EDV) and the Emergency Recirculation Valve (ERV), both of which are fail-safe and automatically actuated in the open position during an accident to ensure safety.

The PECCS consists of the following key components:

- Two ERVs
- Three EDVs
- A condensation system within the containment

Upon reactor shutdown, the EDVs open, allowing reactor coolant—either in vapor or liquid form—to be released into the containment. The released coolant condenses on the inner surfaces of the containment and the Passive Containment Cooling System (PCCS) heat exchanger, collecting at the bottom of the containment. As the coolant level rises, it flows back into the reactor vessel through the ERVs, enabling continuous recirculation and passive core cooling.

Additionally, PECCS operates in conjunction with the Passive Auxiliary Feedwater System (PAFS), ensuring long-term cooling. Even after the Emergency Cooling Tank (ECT) is depleted, the system can continue to remove decay heat via the containment cooling mechanism, maintaining core integrity without the need for operator intervention or emergency power supply.

2.4.3 PCCS(Passive Containment Cooling System)

The Passive Containment Cooling System (PCCS) is designed to remove heat from the containment structure, thereby ensuring stable cooling core. This system consists of PCCS heat exchangers, which are connected to the Emergency Condensate Tank (ECT) through dedicated piping, enabling natural heat dissipation without external power.

During an accident, steam released into the containment is condensed by the PCCS heat exchangers. The cooling water inside the heat exchanger absorbs the heat and evaporates, effectively reducing the containment temperature and pressure. The PCCS operates continuously through natural convection, driven by gravitational forces, ensuring sustained cooling until the ECT inventory is depleted.

Through this design, the i-SMR is engineered to sustain long-term cooling without the need for emergency power or operator intervention.

2.5 SBO Accident Scenario of i-SMR

The i-SMR maintains core integrity during an SBO event due to its passive safety systems that operate independently of electrical power. This study aims to verify whether these passive safety systems can effectively sustain core integrity without relying on external power. The i-SMR's SBO scenario will be analyzed using the thermal-hydraulic analysis code MARS-KS.

Below is the nodalization of the i-SMR, which was developed for the analysis, and the SBO event was applied to this model.

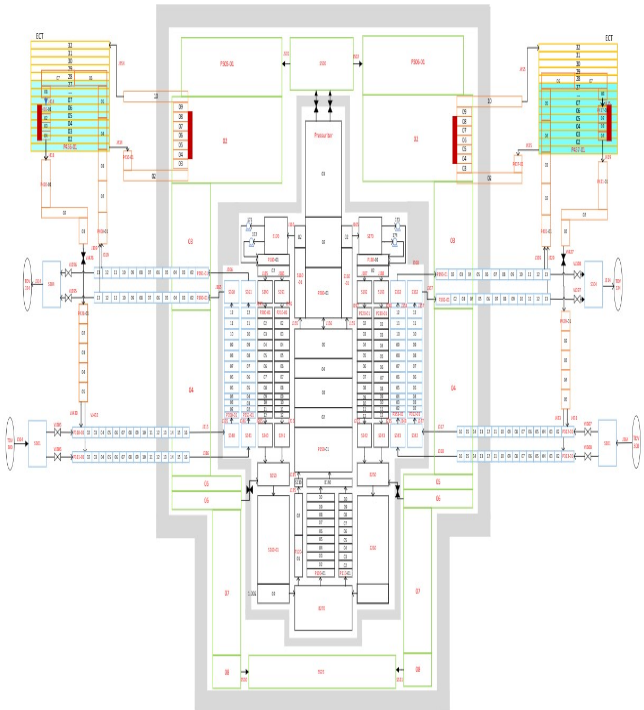

Fig 3. The nodalization of i-SMR

2.6 Differences in SBO Concept of Large Light Water Reactor Nuclear Power Plant and i-SMR

Large light water reactor nuclear power plants and i-SMR have fundamental differences in their approach to SBO scenarios. Large light water reactor nuclear power plants primarily rely on active safety systems, which require a continuous power supply to maintain reactor and fuel integrity in the event of an accident. In an SBO scenario, once offsite power is lost, the EDG must be activated. If the EDG fails to operate, AAC is necessary to restore power and maintain core cooling. Therefore, the SBO response strategy in large light water reactor nuclear power plants focuses on rapidly restoring emergency power to prevent core damage.

In contrast, i-SMR is designed based on passive safety systems, allowing core cooling to be maintained without external power. It utilizes natural circulation, gravity-driven cooling, and condensation mechanisms to passively remove decay heat from the core. As a result, even in an SBO event, i-SMR can sustain reactor safety for at least 72 hours without relying on AAC or operator intervention.

Due to these differences, large light water reactor nuclear power plants require a prompt power restoration strategy in an SBO scenario, whereas i-SMR is fundamentally designed to maintain safety without power recovery. This distinction also affects regulatory requirements, highlighting the need for a new regulatory framework that accommodates the unique characteristics of passive reactors, as opposed to traditional SBO regulations tailored for large light water reactor nuclear power plant designs.

3. Conclusions

In this study, SBO accident scenarios of large light water reactor nuclear power plants and i-SMR were analyzed, along with a review of regulatory requirements for SBO mitigation in both large light water reactors and passive reactors

The analysis confirmed that i-SMRs do not result in core damage during an SBO accident due to the operation of passive safety systems that do not rely on external power. In contrast, large light water reactor nuclear power plants depend on active safety systems that require electrical power, making an AAC essential to maintain core integrity in the event of an SBO accident.

Since i-SMR is designed to maintain core integrity for at least 72 hours without external power, the installation of an AAC system is not required. This study provides a technical basis for optimizing SBO response strategies for next-generation nuclear power plants and highlights the need to improve regulatory frameworks to accommodate passive safety system designs.

Given that existing SBO regulations are primarily based on large light water reactor designs, a mere revision of current regulations is insufficient. Instead, a new regulatory methodology is required to properly reflect the characteristics of passive reactors. Establishing a regulatory framework suitable for passive reactors, such as i-SMRs, which can maintain core cooling without an alternative AC power source, will enable the development of more effective and practical safety standards.

Acknowledgements

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