Conceptual Design of the Diverse Investment Protection System for Industrial Process Heat Supply High-Temperature Gas-cooled Reactor

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1. Introduction

The safety of nuclear power plants is fundamentally ensured by the Reactor Protection System (RPS), where both reliability and diversity play critical roles. To address the risk of Common Cause Failure (CCF) and Anticipated Transient Without Scram (ATWS) event, Article 27 "Diverse Protection System" of the Technical Standards for Nuclear Reactor Facilities, etc. mandates the implementation of a Diverse Protection System (DPS)[1]. This regulatory requirement is intended to prevent a complete loss of protection capability arising from common vulnerabilities.

In contrast, the Xe-100, a next-generation High-Temperature Gas-cooled Reactor (HTGR) currently being developed by X-Energy in the United States, does not employ a separate DPS[2]. Instead, its design incorporates an Investment Protection System (IPS) that safeguards critical components against high-temperature hazards.

While this design philosophy supports equipment protection and economic objectives, it is inconsistent with the Korean established requirements that explicitly require the implementation of a DPS. Consequently, supplementary measures are necessary for domestic deployment. To address this gap, this study proposes the Diverse Investment Protection System (DIPS), a novel concept that integrates IPS and DPS functionalities into a unified, hierarchical protection system.

2. Related Research and Technical Background

2.1 Review of Domestic and International Regulatory Positions

Article 27 of the Regulations on Technical Standards for Nuclear Reactor Facilities, etc[1] stipulates that reactor instrumentation and control (I&C) systems must include a DPS to safeguard against CCFs of the RPS. This regulatory requirement is critical to ensuring that the entire protection system is not rendered inoperative by a single failure mechanism, thereby strengthening the overall reliability of nuclear safety systems.

In the United States, the Nuclear Regulatory Commission (NRC) has addressed the need for diversity and defense-in-depth through regulatory policies such as SECY-93-087[3] and the requirements of 10 CFR 50.62[4] concerning Anticipated Transients Without Scram (ATWS). These provisions emphasize the importance of ensuring that the RPS is not solely rely on a single protection mechanism, thereby recognizing the necessity of incorporating diverse and independent means of protection.

Therefore, future reactor designs, particularly HTGRs, must incorporate an integrated approach that satisfies the IPS requirements inherent to HTGRs while simultaneously fulfilling the domestic and NRC's regulatory expectations for diversity and defense-in-depth.

2.2 Xe-100 IPS Design Overview

The Xe-100, developed by X-Energy, is a high-temperature gas-cooled reactor (HTGR)-based SMR that adopts an IPS. The IPS is intended to prevent equipment damage and protect economic performance during high-temperature or abnormal operating conditions. In terms of diverse means of RPS, the RPS of Xe-100 employs an FPGA-based Highly Integrated Protection System (HIPS) platform, incorporating heterogeneous redundancy, utilizing different FPGA technologies.

While the IPS provides a degree of functional diversity and emphasizes economic safeguards, it does not fully satisfy the domestic regulatory requirement for a separate DPS requirements.

3. Conceptual Design of DIPS

3.1 Concept and Rationale of DIPS

The Diverse Investment Protection System (DIPS) proposed in this study is an advanced reactor protection concept that integrates the functionalities of conventional IPS and DPS. By hierarchically combining the preemptive investment protection of IPS with the regulatory-compliant diverse protection of DPS, DIPS establishes a dual-layer safety mechanism that complements the RPS. This integrated approach simultaneously enhances operational safety, economic efficiency, and regulatory adherence. The classification of DIPS will be designed as safety clas non-safety, seismic category II, software class ITS(important-to-safety).

Figure 1 shows the high level functional design and interfaces between control system, DIPS and RPS. During normal operation, reactor control is maintained by the control system. If operational parameters exceed the investment protection setpoints, the DIPS investment protection function is activated. Should conditions progress further and exceed the RPS setpoints, the RPS is initiated. In cases where the RPS setpoints are exceeded but reactor shutdown or actuation of engineered safety features does not occur, the DIPS diverse protection function is initiated once the diverse protection setpoints are reached.

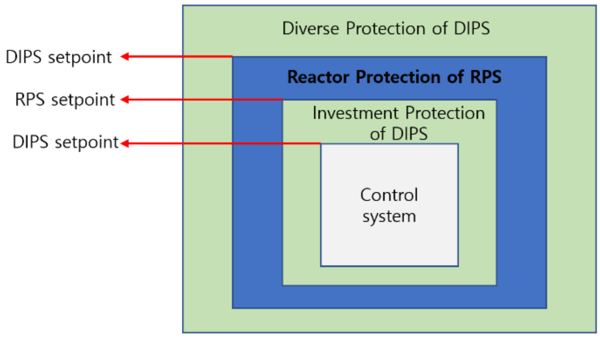

Fig. 1. High level functional design and interfaces between control system, DIPS and RPS

3.2 Investment Protection Function (Pre-RPS Layer)

The first layer of DIPS implements the investment protection function. It continuously monitors critical operational parameters, such as temperature, flow, and neutron power, to detect abnormal conditions before initiation of RPS trip logics. Early intervention prevents equipment damage and unnecessary reactor trips, minimizing economic losses while maintaining high plant availability.

3.3 Diverse Protection Function (Post-RPS Layer)

The second layer provides the diverse protection function. In cases where the RPS fails due to CCF or anticipated transients without scram (ATWS), DIPS intervenes to safely shut down the reactor. Technological diversity of DIPS is achieved by employing a distinct hardware platform from the RPS, such as heterogeneous FPGA or microprocessor-based systems.

3.4 Comparative Analysis with Existing IPS and RPS

Traditional IPS focus primarily on equipment and facility protection, while RPS are designed to ensure reactor safety via automatic shutdown. However, IPS alone do not meet regulatory requirements for diversity, and RPS may be vulnerable to CCF or ATWS scenarios. By integrating investment protection and diverse protection functionalities, DIPS provides a novel architecture that simultaneously:

- Secures economic feasibility through the investment protection layer,
- Ensures regulatory compliance via the diverse protection layer.

4. Conclusions

This study examined the differences between domestic regulatory requirements and international HTGR designs and proposed the DIPS as an integrated protection framework. DIPS combines the functionalities of IPS and DPS to provide a hierarchical and robust safety mechanism.

The key advantages of DIPS are as follows:

- Preemptive investment protection: The IPS layer operates prior to the activation of the RPS, mitigating equipment damage and minimizing economic losses.
- Post-RPS diverse protection: In the event of RPS CCF or during ATWS, the diverse protection function intervenes to ensure safe reactor shutdown.
- Layered safety architecture: The integration of IPS and DPS establishes a dual-layer framework that achieves both operational efficiency and compliance with domestic regulatory standards.

Future work should focus on advancing DIPS toward practical application in HTGR instrumentation and control systems. However, as higher-level design areas, such as thermal-hydraulic and safety analyses, and the overall structure of the I&C system are still in progress, the detailed design of DIPS will be carried out in future.

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