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# Design Issues of the Protection System for Industrial Process Heat Supply High-Temperature Gas-cooled Reactor (HTGR)

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## 1. Introduction

With the advancement of next-generation nuclear reactor technology, High-Temperature Gas-cooled Reactors (HTGRs) are gaining attention in various applications, including industrial process heat supply and hydrogen production. Small HTGRs with a thermal output of 90MWt require reactor designs that ensure both economic feasibility and safety, making the reliability and functionality of their protection systems a critical design challenge.

Compared to Light Water Reactors (LWRs), HTGRs exhibit superior inherent safety and the capability to incorporate passive safety systems. However, unique design challenges arise due to the high-temperature environment (above 750°C) and the use of helium coolant. This paper provides an overview of the protection systems for industrial process heat supply HTGRs and analyzes key design issues.

## 2. Overview of the Protection System for Industrial Process Heat Supply HTGRs

In this section we describe the protection system for industrial process heat supply HTGRs, which ensures reactor safety and equipment protection. We also include case studies from HTR-10, HTR-PM, and Xe-100 to offer insights into optimizing HTGR protection system design.

This section delineates the protection systems employed in HTGRs for industrial process heat supply, emphasizing their role in ensuring reactor safety and safeguarding equipment. It also presents brief case studies from the HTR-10, HTR-PM, and Xe-100 reactors to provide insights into optimizing HTGR protection system design.

### *2.1 Protection System Function*

The protection systems in HTGRs are integral to maintaining reactor safety, facilitating shutdown procedures, and protecting the reactor core. The primary components of these protection systems include the Reactor Protection System (RPS), the Investment Protection System (IPS), and the Passive Safety System[2].

- Reactor Protection System (RPS): This system is designed to automatically initiate reactor shutdown in response to conditions such as overheating, loss of coolant, or abnormal power output.
- Investment Protection System (IPS): This system offers supplementary protection for critical components, including heat exchangers and turbines.
- Passive Safety System: This encompasses the Reactor Cavity Cooling System (RCCS), which operates without an external power supply.

### *2.2 Case Studies of HTGR Protection Systems*

Existing case studies can inform the optimization of HTGR protection system designs. Notable examples include the HTR-10, HTR-PM, and Xe-100 reactors, each providing valuable insights into the application of protection systems.

- HTR-10 (China, 10MWt Experimental Reactor)[1,2]: This reactor implemented an independent digital protection logic within the RPS and utilized the RCCS for core cooling, while the IPS was streamlined to focus on protecting essential equipment.
- HTR-PM (China, 250MWt Modular HTGR)[3]: Designed for dual-reactor module operation with a shared steam generator, this reactor incorporated the RCCS and digital protection systems to facilitate rapid response during incidents.
- Xe-100 (USA, 80MWt Modular HTGR)[4]: This reactor fully adopted a passive safety design, ensuring continuous heat removal through the RCCS. It also enhanced cybersecurity measures within its digital protection systems and introduced redundant RPS and IPS for equipment protection. Figure 1 illustrates the structure of the Xe-100 RPS, while Table 1

presents the parameters associated with this system. Notably, the number of protection system parameters in HTGRs is significantly lower than that of conventional light water reactors, attributable to their inherent safety features and simplified engineering configurations.

Considering the critical functions of these protection systems, appropriate protective functionalities must be integrated into the design of HTGRs intended for industrial process heat applications.

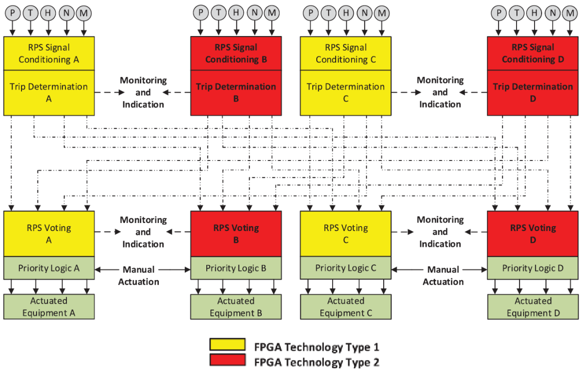


Fig. 1. Xe-100 Reactor Protection System [4]

Table I: Xe-100 RPS Parameter [4]

| RPS Parameter | Location | Parameter State |
|---|---|---|
| Helium Pressure Boundary Pressure | Steam Generator Tube Outlet | High |
| Helium Pressure Boundary Pressure | Steam Generator Tube Outlet | Low |
| Neutron Flux | External Wide Range N.D. | High |
| Intermediate Range Super-heated Steam | External Wide Range N.D. | High |
| Helium Pressure Boundary Humidity | SGPV Circ. Inlet/Outlet Bypass | High |
| Hot Helium Temperature | Steam Generator Inlet | High |
| Cold Helium Temperature | Steam Generator Outlet | High |
| Mass Flow Ratio (He/H2O) | CV and FW Pump Outlet | High |
| Manual Trip - RCSS | MCR and RSR | True |
| Manual Trip - Moisture Ingress | MCR and RSR | True |

## 3. Design Issues in HTGR Protection Systems

### *3.1 Ensuring Protection System Reliability in High-Temperature Environments*

HTGRs operate at temperatures above 750°C, making it important for protection system instrumentation and sensors to withstand extreme heat condition while ensuring long-term reliability. Compared to LWRs, they require high-temperature-resistant materials and radiation-hardened measurement technologies to maintain accurate and stable performance in demanding conditions.

### *3.2 Application and Verification of Digital Protection Systems*

As digital-based protection systems become more widespread, integrating FPGA-based protection logic and conducting rigorous software verification and validation (V&V) are essential. Robust protection algorithms and diverse design strategies should be implemented to enhance reliability and mitigate the risk of common-cause failures (CCF).

### *3.3 Integration of Passive Safety System (RCCS) with Protection Systems*

RCCS plays an important role as a passive safety system in HTGRs, helping to prevent core overheating. To ensure its effectiveness, continuous monitoring and protection mechanisms are essential, supported by highly reliable temperature and flow sensors that provide real-time assessments of RCCS heat removal performance.

### *3.4 Instrumentation issues of HTGR*

When an HTGR generates steam through a heat exchanger, any leakage in the steam generator's heat transfer tubes could allow moisture to enter the primary system. To address this, a moisture monitoring system is essential for immediate detection. Moisture detection signals can be integrated with the RPS and IPS to automatically shut down the reactor or change the speed of helium circulator in the event of steam leakage. Additionally, since helium has a low heat capacity and responds rapidly to temperature changes, continuous monitoring of the core outlet temperature distribution at multiple points is necessary to detect localized overheating.

### *3.5 Optimization of Protection Systems for Multi-Module Operation*

HTGRs intended for industrial process heat applications may be designed for multi-module operation. To ensure both efficiency and reliability, protection systems must be carefully optimized to either operate independently for each module or be interconnected to enhance overall safety and performance.

### *3.6 Enhancing Cybersecurity in Digital I&C Systems*

The adoption of digital-based protection systems introduces greater vulnerability to cyber security threats. To mitigate these risks, it is important to maintain both physical and logical separation between the RPS and the plant's Distributed Control System (DCS). Additionally, robust network security measures must be implemented to ensure the safe and reliable operation of the reactor.

## 4. Conclusions

The design of protection systems for HTGRs supplying industrial process heat must consider environmental factors that differ from those affecting light water reactors (LWRs), particularly the high-temperature operating conditions, the characteristics of helium coolant, the application of digital protection systems, and the integration with passive safety systems.

Ensuring the reliability of digital protection technologies and high-temperature instrumentation is vital for developing a robust protection system. Furthermore, enhancing the functions of the RCCS and helium coolant protection is necessary to improve the long-term safety of HTGRs. Future research should continue to address these design challenges to optimize protection systems for HTGR applications.

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