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Conceptual Design of Plant Limitation System for Mitigating Moisture-Induced Degradation in High-Temperature Gas-Cooled Reactors

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1. Introduction

High-temperature gas-cooled reactors (HTGRs) use helium as the coolant and graphite as the moderator to achieve high outlet temperatures with improved thermal efficiency. Compared to water-cooled reactor designs, HTGRs are free from issues associated with coolant boiling. Although helium is chemically inert, the ingress of impurities (e.g., moisture) into the helium circulation system may initiate oxidation reactions, potentially compromising the integrity of core materials and reducing the functional reliability of mechanical components.

Prolonged exposure to low moisture concentrations may cause cumulative degradation without triggering protective actions. Such degradation can reduce structural margins through graphite oxidation and impair the functionality of the control element drive mechanism (CEDM). Therefore, moisture control should be addressed as an integrated design issue encompassing reactor protection, reactor control, and investment protection.

This study introduces a Plant Limitation System (PLS) that extends the conventional limitation system concept by incorporating moisture control. In addition, fundamental governing equations and a conceptual moisture-control framework are presented.

2. Background

2.1 Helium Circulation and Moisture Exposure in HTGRs

HTGRs are strong candidates for next-generation reactors and small modular reactors (SMRs) owing to their favorable temperature reactivity coefficients and high heat capacity. HTGRs employ chemically inert helium as the coolant, circulating dry, high-purity helium during operation.

Unlike light water reactors (LWRs), HTGRs use gaseous helium as the coolant. The heat-exchange interface between the primary helium system and the steam generator (SG) creates a pathway for water or steam ingress [1]. Moisture ingress into the helium circulation system induces oxidation of graphite and metallic components, potentially compromising core material integrity and mechanical reliability.

The impact of moisture ingress is not limited to core material degradation. In systems such as the Control Element Drive Mechanism (CEDM), where reliable mechanical insertion is essential, moisture accumulation within internal cavities, changes in surface conditions, increased friction, and the buildup of oxidation products can increase insertion resistance, creating a risk of sticking.

The Fort St. Vrain (FSV) reactor, an HTGR that operated in the 1980s, experienced control rod–related operational issues, with decreased reliability reported in moisture-related conditions [2]. In subsequent HTGR designs, such as the Xe-100, HTR-10, HTR-PM, and modular HTGR (MHTGR), moisture ingress has been classified as a significant event, generally treated as an Anticipated Operational Occurrence or Design Basis Event. Moisture ingress scenarios are widely incorporated into safety analysis codes. Research institutions such as BNL [3] and INL [4] have developed dedicated analysis methodologies for moisture ingress events. Furthermore, the Korea Atomic Energy Research Institute (KAERI) has developed the GAMMA code, which simulates moisture ingress effects by modeling graphite oxidation phenomena in HTGRs [5].

2.2 Conventional Limitation System and European Utility Requirements

In the Angra 2 unit [6] and Konvoi-type [7] nuclear power plant designs developed in the 1980s, the reactor limitation system (RLS) [8] comprises multiple functional blocks such as RELEB, STAFAB, and MADTEB, each responsible for limiting specific plant variables, namely, reactor power, secondary system conditions, and primary coolant thermodynamic states, respectively. These functions operate before the actuation of the reactor protection system (RPS) to prevent unnecessary reactor trips.

In the early 1990s, European utilities initiated the development of the European Utility Requirements (EUR) [9] to harmonize design expectations for next-generation LWRs. EUR was established on the basis of accumulated European and international operational data, with standardized designs such as the Konvoi plants serving as important references. EUR defines functional requirements, including automatic limitation features, to prevent unnecessary reactor shutdowns and improve operational stability. In addition, it emphasizes enhanced defense-in-depth, including operational reliability and investment protection.

In 1992, KAERI proposed the plant operations regulator (POR) concept as an intermediate limitation system [10]. The POR framework introduces a limitation layer that functions as a boundary between normal control and safety systems, acting as a buffer that prevents unnecessary activation of protective actions.

In advanced SMR designs, conventional setpoint-based protection and PID-based feedback control systems alone may not be sufficient to meet operational performance requirements under diverse conditions. Therefore, advanced limitation system concepts are warranted. The proposed PLS extends this concept by incorporating cumulative degradation–based indices, rather than relying solely on instantaneous process variables.

2.3 Operation of the Investment Protection System in HTGRs

The Investment Protection System (IPS) is intended to prevent economic loss caused by damage to major plant components such as turbines, SGs, pumps, heat exchangers, and fuel assemblies. It typically operates as a non-safety system that is independent of RPS.

In the MHTGR design, the IPS includes mitigation measures for moisture ingress events, such as initiation of the Shutdown Cooling System and primary coolant depressurization (pumpdown) to reduce material degradation and equipment damage [11].

3. Approach

3.1 Moisture Exposure Experience at FSV

In June 1984, the FSV plant experienced a persistent leak through the bearing seal of a helium circulation pump, leading to moisture ingress into the primary coolant. During this event, six of the thirty-seven control rod pairs failed to insert in response to a scram signal, and the situation was eventually resolved by manually dropping the affected control rods [2]. This incident was attributed to a combination of moisture ingress and degradation of the helium purification (purge) system, which is responsible for maintaining coolant purity. This case underscores the critical role of effective moisture control in ensuring long-term operational reliability and integrity of HTGR systems.

The event demonstrated that moisture-induced mechanical degradation extends beyond graphite oxidation, contributing to increased insertion resistance and the possibility of control rod sticking. Because the shutdown function relies on reliable control rod insertion, moisture ingress directly affected the reliability of the RPS function during this event. The operational experience at the FSV reactor highlighted the need to consider moisture management as a factor influencing the reliability of safety functions in subsequent HTGR designs.

3.2 Moisture Exposure from the RPS Perspective

The protection philosophy of conventional nuclear power plants is primarily based on deterministic, threshold-based tripping of the RPS. This approach effectively manages rapid transients and limit exceedances.

The operational experience at the FSV reactor led to the recognition of sudden ingress of high-concentration moisture into the primary coolant as a significant protection parameter in HTGR designs. In several HTGR designs, including the HTR-10 [12], HTR-PM [13], Xe-100 [14], Peach Bottom [15], and MHTGR [11], dew point measurement systems are employed to monitor the moisture content of the primary helium. The measured values are transmitted to the RPS, serving as input parameters that trigger protective actions when predefined thresholds are surpassed.

Table I. Comparison of moisture measurements in HTGRs

HTGRs	**Instrument location**	**RPS parameter**
HTR-10	Outlet of the helium blower	High helium pressure boundary humidity (Reactor trip at 800 ppmv)
HTR-PM	Outlet of the helium blower	High helium pressure boundary humidity (Reactor trip at 800 ppmv)
Xe-100	SG pressure vessel circulator bypass	High helium humidity
Peach Bottom	Outlet helium stream from each SG	High helium humidity (Reactor trip and isolation of a loop)
MHTGR	Unspecified	High moisture concentration (Reactor trip at 1000 ppmv)

A moisture ingress analysis report [4] suggests that substantial amounts of water may be generated during startup due to outgassing from newly installed graphite components. In addition, it notes that elevated moisture levels have also been observed during shutdown in AVR reactors. In light of these findings, a reexamination of the FSV reactor case suggests that control rods may be exposed to substantial moisture not only during normal operation but also during refueling and shutdown periods. Furthermore, prolonged exposure to moderate- to low-concentration moisture may occur before, during, and after startup.

Moisture monitoring and control are also critical in thermal and gas-fired power plants, where limit or block logic and cumulative degradation management are implemented to protect turbines, piping, and heat exchangers. Considering such established practices in conventional power plants, the moisture ingress issue in HTGRs similarly underscores the need for long-term degradation management to protect core and auxiliary equipment. However, the conventional high-humidity trip logic employed in existing RPSs may have limitations in addressing cumulative degradation effects. Therefore, moisture management must not be treated solely as an RPS function but as part of a broader investment-protection strategy.

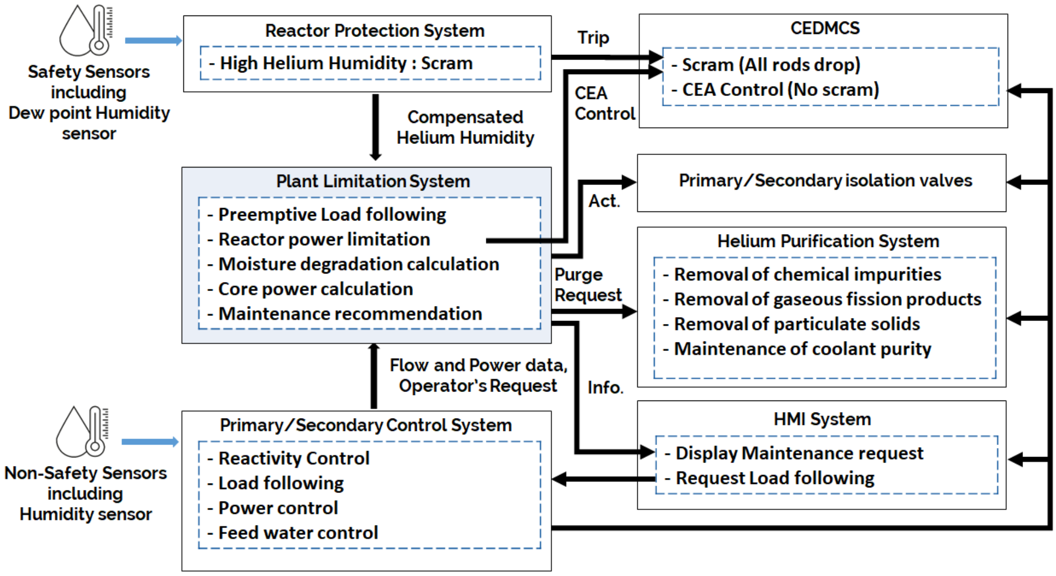

Figure 1. Conceptual diagram of the PLS

3.3 Limitation System for Cumulative Degradation Management

The concepts of IPSs and limitation systems have been established in various nuclear reactor designs. However, there is limited research addressing the need for cumulative degradation management specifically linked to moisture ingress in HTGRs. Therefore, this study redefines moisture-induced degradation not merely as an “accident variable,” but as a continuous operational management parameter, and proposes a hierarchical management structure reflecting this perspective. The proposed hierarchy comprises the following:

1) High-concentration rapid ingress:
Immediate reactor trip (scram event) when a critical moisture setpoint is exceeded.

2) Moderate-concentration long-term exposure:
Implementation of cumulative degradation monitoring and management.

To implement this hierarchical structure, this study proposes a new operational limitation system termed PLS. PLS integrates the investment protection concept with the limitation system design philosophy emphasized in the EUR.

PLS is conceived as a non-safety operational limitation system positioned between the plant control system and the RPS. Its functions may be modularized depending on plant performance requirements and design objectives. The proposed functions are as follows:

1) Algorithms for tracking moisture accumulation and degradation (e.g., purge enhancement and isolation control logic)

2) Preemptive load following and reactor power limitation (e.g., runback or cutback)

3) CEA movement limitation

4) Coolant pressure, coolant inventory, and temperature limitation

5) High-resolution reactor core power calculations (e.g., refined core power distribution monitoring)

6) Operator support functions, including shutdown recommendations for planned maintenance

The PLS primarily interfaces with the helium purification/purge system to improve moisture-removal efficiency and with the CEDM control system (CEDMCS) for synchronized adjustment of control elements. Figure 1 presents a conceptual diagram of the proposed PLS, highlighting its functional architecture and system interfaces.

3.4 Cumulative Degradation Index

Even with moisture concentrations below predefined trip thresholds, prolonged exposure can result in cumulative degradation phenomena such as graphite oxidation and metallic corrosion.

In thermal power plants and gas turbine systems, cumulative damage is typically assessed by time integration of a damage rate expressed as a function of environmental conditions. Similarly, moisture-induced graphite oxidation and metal degradation in the CEDM may be conceptually expressed as “damage rate due to moisture exposure × time.” However, degradation does not necessarily increase monotonically. Recovery effects caused by mitigation actions or sustained dry operating conditions must also be considered. Such recovery mechanisms include improved helium purification (purging), natural drying under low-moisture steady-state conditions, and system isolation measures. These recovery effects help offset accumulated degradation and limit the growth of the damage index. From this perspective, a simplified conceptual governing equation may be proposed:

$$\frac{dF}{dt} = \alpha\, V_{GO} + \beta\, V_{CF} - \gamma\, V_{RE}, \quad (1)$$

where

F = *cumulative degradation index*

V_{GO} = *graphite oxidation rate*

V_{CF} = *CEDM functional degradation rate*

V_{RE} = *recovery (removal/mitigation) rate*

α, β, γ = *weighting factors*

This equation is analogous to the fouling balance equation reported in [16], which describes the deposition and removal processes of corrosion products in reactor systems:

$$\frac{dI}{dt} = V_{SD} + V_{PD} - V_{EC}, \quad (2)$$

where

I = *quality of fouling in the core*

V_{SD} = *deposition rate of soluble corrosion products*

V_{PD} = *deposition rate of particle corrosion products*

V_{EC} = *removal rate*

Because graphite oxidation and metallic corrosion exhibit different physical and chemical characteristics, weighting factors are introduced to adjust their relative contributions to the overall degradation index.

The cumulative degradation at time *t* can thus be expressed as follows:

$$F(t) = \alpha GO(t) + \beta CF(t) - \gamma RE(t) + \varepsilon, \quad (3)$$

where

$GO(t)$= *accumulated graphite oxidation*

$CF(t)$= *accumulated CEDM functional degradation*

$RE(t)$= *accumulated recovery effect*

ε= *baseline fouling constant*

The detailed mechanistic degradation models for each term have not yet been fully established and require further investigation. Nevertheless, their structural form is expected to follow a similar rate-balance formulation.

Considering the discrete scan time of a digital controller implementing PLS, equation (4) may be discretized as follows:

$$F(t) = F(t-1) + \alpha\, V_{GO}(t)\Delta t + \beta\, V_{CF}(t)\Delta t - \gamma\, V_{RE}(t)\Delta t. \quad (4)$$

3.5 Utilization of PLS

PLS evaluates cumulative degradation resulting from moisture ingress—specifically graphite oxidation and CEDM functional degradation—and implements suitable operational control measures, including power rate limiting, automatic power runback, helium purification enhancement (including intensified purge operation), and primary and secondary boundary isolation. Among these actions, helium purification enhancement is prioritized to remove moisture and prevent moisture-induced scram events. Because certain degradation effects may partially recover under sufficiently dry operating conditions, the primary operational objective is to secure adequate recovery time. When necessary, additional measures such as boundary isolation and power reduction can be implemented to limit further degradation. Through this approach, PLS reduces unnecessary reactor trips while playing a preventive role in equipment protection. Additionally, PLS proactively supports load-following operation in response to fluctuations in electricity generation and process heat demand. It performs supervisory-level power rate limiting and runback functions, conceptually similar to POR. However, PLS does not perform any safety-credited shutdown function. Reactor trips continue to be executed independently by the deterministic logic of the RPS and the Diverse Protection System. Similarly, normal reactor power control remains governed by conventional PID-based control systems without direct reliance on PLS. Therefore, the hierarchical structure introduced by PLS represents an additional operational layer that preserves the independence of safety functions while achieving operational objectives such as load-following capability and cumulative degradation management.

The PLS concept integrates both the investment protection philosophy and the limitation system framework previously proposed for LWRs, thereby providing enhanced operational flexibility and economic protection. It performs a supervisory-level load management function capable of responding to highly dynamic electrical and process heat demands expected in future SMR deployment scenarios. By mitigating unnecessary scram events, PLS helps reduce nonlinear economic losses associated with plant interruptions. Because PLS satisfies the essential design philosophy of a limitation system as emphasized in the EUR—apart from the specific moisture-management function—it is also applicable to advanced LWR designs such as the APR1000.

This study emphasizes cumulative moisture-induced degradation management in HTGRs. Additional aspects of PLS, such as high-fidelity core calculation functions and advanced load-tracking algorithms, will be addressed in future studies. The PLS concept is currently in the design phase, intended for application to the Helium-Cooled Thermal Application Reactor (HECTAR), which is primarily designed for process heat supply in Korea.

4. Conclusions

This study reframes the moisture issue in HTGRs from a cumulative exposure–based, preventive limiting perspective rather than from the conventional threshold-based reactor protection viewpoint. Drawing on the operational experience of the FSV reactor, this study emphasizes the necessity of cumulative degradation management to address long-term functional deterioration mechanisms that are inadequately captured by simple high-moisture trip logic. Accordingly, conceptual indices for cumulative degradation were defined, and PLS was established to integrate the principles of conventional limitation systems with IPS. PLS functions as a complementary operational layer that enhances long-term reliability and economic protection while preserving the independence of safety systems. Further development of PLS requires quantitative validation of the proposed degradation indices, refinement of mechanistic models, and assessment of design feasibility through system-level analysis.

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