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HAZOP-Based Risk Assessment of Pebble Bed Fuel Handling Systems Design

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A B S T R A C T

The High-Temperature Gas-Cooled Reactor (HTGR), a promising candidate for Generation IV nuclear reactors, boasts superior inherent passive safety features and a continuous fuel handling system. This system employs multi-pass cycles, utilizing pneumatic and gravitational mechanisms to feed, circulate, and unload the pebble bed fuel element. This paper presents a descriptive analysis assessing the safety risk of the fuel handling system design in HTR-10. The Hazard and Operability Study (HAZOP) methodology is employed to identify hazard parameters, deviation limitations, causes, impacts, and potential risks to the system's main components. The establishment of probability scales, consequence criteria, risk level ratings, and control activities adheres to the ISO 31000 standard. Primary data were gathered through expert judgment, while secondary data were sourced from design layout documentation, literature reviews, and safety analysis reports. Six main components, namely the elevator, core, singulator, failed fuel separator, burnup measurement, and distributor, were selected as assessment nodes from the piping and instrumentation diagram. The assessment revealed that each node initially presented a moderate to extreme risk potential (risk level rating C to E). However, after assuming the implementation of various control measures outlined in the design, the residual risk for all nodes was reduced to an acceptable limit (risk rating A - very low). Therefore, the fuel handling system design already incorporates adequate control activities to mitigate potential safety risks due to system component failure. Safety risk assessment is a dynamic process; it should be reviewed periodically or whenever there are design changes at any project stage. This ensures the safety risk magnitude is consistently known and managed effectively.

1. INTRODUCTION*

The quest for sustainable and safe energy sources has led to the development of advanced nuclear reactors, among which the High-Temperature Gas-Cooled Reactor (HTGR) stands out [1]. As a promising candidate for Generation IV

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nuclear reactors, the HTGR is characterized by its superior inherent passive safety features and a unique fuel handling system that operates continuously without interrupting the reactor's operation [2].

Despite these advantages, the fuel handling system of the HTGR, specifically in the HTR-10 model, presents certain challenges [3], [4]. These challenges primarily revolve around potential risks and safety concerns that need to be thoroughly assessed to ensure the safe and efficient operation of the reactor [5].

This study aims to address these challenges by conducting a comprehensive safety risk assessment of the fuel handling system design in HTR-10. To achieve this, we employ the Hazard and Operability Study (HAZOP) methodology, a systematic approach to identifying hazard parameters, deviation limitations, causes, impacts, and potential risks to the system's main components [5], [6]. Our approach aligns with the ISO 31000 standard, which provides guidelines for managing risks across various areas [5].

The significance of this study lies in its contribution to enhancing the safety and operational efficiency of HTGRs. By identifying and mitigating potential risks, we aim to facilitate the commercialization of these advanced reactors. Furthermore, our research provides a new perspective on risk assessment, which could be beneficial for future studies in this field.

2. METHODOLOGY

This research employed a descriptive-analytic approach to conduct a safety risk assessment on the fuel handling system design, focusing on potential system failures and their impacts on occupational safety, health, the environment, and finances [7]. It is important to note that this study does not include neutronic analysis.

2.1. Risk Identification

Risk identification in this study was guided by the ISO 31000 standard, which helps establish the probability or likelihood scale, consequence criteria, risk rating, and control activities [5]. The likelihood, representing the probability of an accident, is assessed on a scale of 1 (never) to 5 (must have happened), considering both routine and non-routine work categories.

The consequence value, used to assess the severity of potential accidents, was categorized into three areas: health and safety, dose acceptance, and financial, each rated on a scale of 1 (mild) to 5 (catastrophic) as shown in Table 1. Unlike the standard guideline where the final consequence value is the highest score of the three categories, this study used the accumulated value of all three categories to provide a comprehensive description of the total risk. The overall risk was calculated by multiplying the likelihood value with the combined consequence value by following Eq. 1 [5].

$$R = P \times (K_1 + K_2 + K_3) \qquad (1)$$

where:

- R : risk (A up to E).
- P : probability or likelihood (1 up to 5).
- K_1 : health and safety consequences.
- K_2 : individual dose consequences.
- K_3 : financial consequences.

Table 1. Risk matrixes consist of scale, score, and interpretation used in this study [5].

Scale	Score	Interpretation
A	1 – 15	Accepted
B	16 – 30	Accepted with additional barrier
C	31 – 45	Not accepted yet
D	46 – 60	Rejected
E	61 – 75	Catastrophic

2.2. HAZOP

HAZOP was utilized to identify hazard parameters, deviation limitations, causes, impacts, and potential risks [5], [6]. It is an effective risk assessment method for analyzing and developing safety systems of new designs, focuses on identifying potential hazards at each operational stage. The initial step involves reviewing the system through technical drawings or other relevant information [5], [6], [8].

Table 2. Nodes and parameters utilized in this study [9], [10].

Nodes	Parameters
Elevator	fuel flows, helium pressure, pipe pressure, velocity
Core	pressure, temperature, helium, contamination
Singulator	helium pulse, pressure
Separator	fuel flows
Burn up measurement	burn up value
Distributor	fuel flows

2.3. Data collection

Primary data were collected through expert judgement by qualified experts in nuclear reactor safety design, materials, safety, and risk assessment. The experts consist of five nuclear reactor design experts and two occupational safety experts. All experts were requested to provide a scientific assessment of the likelihood and consequences of each node based on their expertise. Experts were also requested to enclose scientific evidence from related studies to support their assessment. All assessments were carried out on a semi-qualitative basis based on enterprise rise assessment framework [5]. Data triangulation in this assessment was using source triangulation where one topic is questioned to at least three experts to measure the credibility of data. Experimental validation in this study could not be carried out due to the reactor is still at the design stage.

Secondary data were sourced from the HTGR design, Piping and Instrumentation Diagram (P&ID), and literature related to the design, engineering, operation, and safety risk analysis of the pebble bed-type HTGR.

2.4. Node selection

The nodes, representing the main components in the fuel handling system design, are identified from the P&ID of the fuel handling system, as shown in Table 2. Each node was studied in detail to determine the parameters, allowing the deviation parameter study to provide recommendations for design modifications to minimize changes and failure consequences [7], [11], [12].

3. OVERVIEW OF HTR-10 FUEL HANDLING SYSTEMS

3.1. Design principles

Reactor and fuel handling system of HTR-10 referred in this study is shown in Fig. 1 and Table 3 [9], [10], [13].

Table 3. Reactor and fuel handling system of HTR-10 [9], [10].

P*arameter*	Value	Unit
Power	10	MW
Diameter/height	1.8/2	m
Primary system pressure	30	bar
Primary coolant temperature	250/700	ºC
Feed method	Multipass	(MEDUL)
Number of fuel elements	27,000	pcs
Fuel dwell time	230	VLT
Target burn up	80,000	MWd / MTU
Fuel element diameter	60	mm
Matrix density	1.75	g/cm^3

[*] VLT = Voll Last Tagen (Equivalent Full Power Days)

One of the key advantages of a pebble bed reactor lies in its fuel handling system, which operates continuously without necessitating a halt in the reactor's operation [14]. The core of the pebble bed reactor is annular in shape, featuring an outer reflector encircling the core. The helium coolant flows through the gaps between the pebbles, occupying approximately 39% of the core volume. The internal core of the reactor is entirely composed of graphite, with no metal components. Fuel elements are fed into the reactor using a multipass mechanism (MEDUL) [13], [15], and a pneumatic fuel handling system, coupled with gravity [15], [16], is employed to continuously load and unload the fuel elements.

The components of the fuel handling system operate under high-temperature and high-pressure conditions, within a helium atmosphere, and are exposed to high levels of radiation over extended periods. These demanding conditions necessitate high-specification designs for the components. Particular attention must be paid to critical aspects such as the helium seal, bearing lubricants, radioactive shields, and the reliability and maintenance of each component. Any malfunction in a main component of the fuel handling system can impact the operation of the reactor and decrease its reliability [11].

3.2. Fuel handling subsystems

3.2.1. Feed subsystem

Fresh fuel elements are initially housed in a drum, which can accommodate up to 200 pebbles, and stored in a designated area. When the reactor requires fresh fuel elements, these elements are transferred from the drum into a loading box. To prevent direct contact with the external atmosphere during the refueling process, a glove box with a specialized sealing mechanism is employed. This ensures a negative internal pressure, preventing the ingress of outside air. The fuel elements are then transported into the core reactor using pneumatic pressure, generated by a helium gas impulse. In normal daily operation, HTR-10 requires 25 fresh fuel elements [9], [10].

3.2.2. Circulation subsystem

In the reactor core, fuel elements undergo fission reaction. These elements are systematically and continuously unloaded one by one, starting from the bottom via a discharging tube with a diameter of 0.5 meters. To ensure the continuity of this process, the lower end of the discharging tube is fitted with a reducer that is twice the diameter of the fuel element ball. This allows the fuel element to be unloaded from the core and aligned in a singulator.

The unloading of fuel elements is facilitated by gravitational force. These elements are then strained in a separator to remove dirt, fuel fragment, or any fuel that does not meet the specified standards. The fuel elements that pass this quality check are then transferred to an elevator.

Inside the elevator, the burnup value of the fuel elements is measured. If it reaches the targeted burn-up of more than 80 GWd/MTU, the fuel elements are then propelled with a helium gas impulse. The fuel elements remain in this cycle for approximately 1100 days, circulating for five times [9], [10].

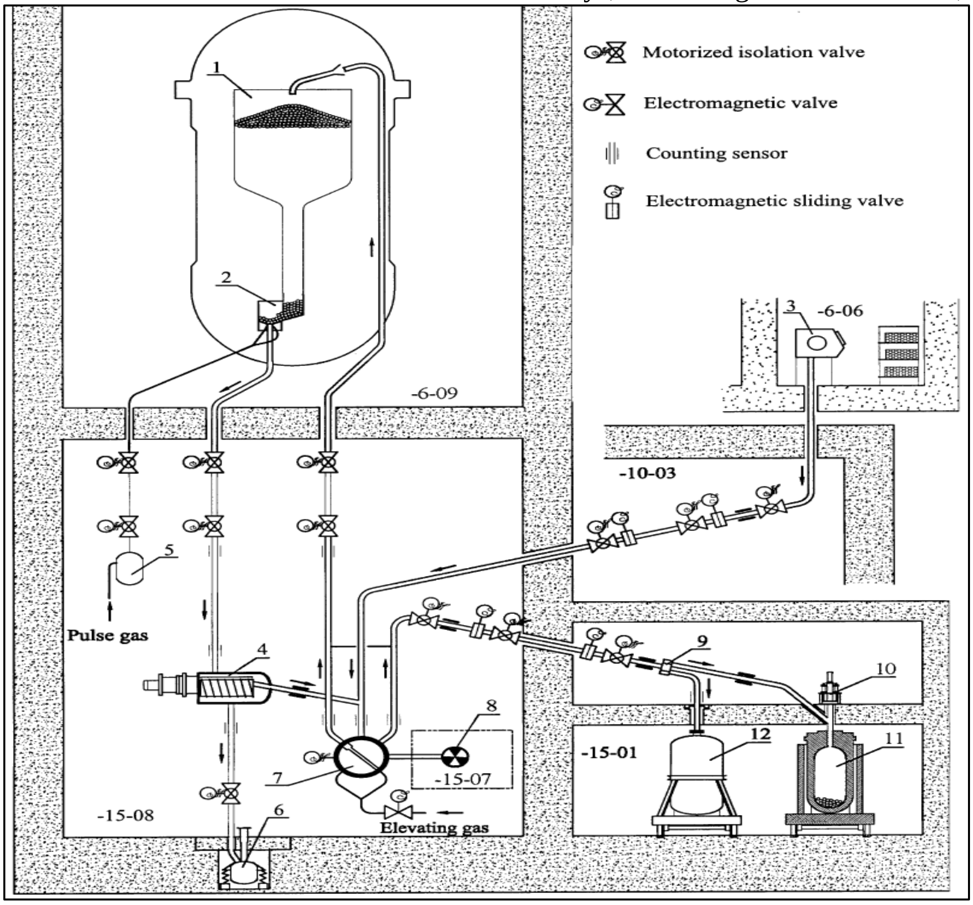

Fig. 1. Pebble bed HTR-10 fuel handing system design [9], [10]

3.2.3. Unloading subsystem

Fuel elements that exceed the targeted burn-up will be directed to spent fuel storage. At the start of the reactor operation, dummy graphite elements are also present in the core. It is necessary for a distributor to segregate these two types of elements and ensure they are sent to their respective storage facilities without being mixed [9], [10].

4. RESULTS AND DISCUSSIONS

Pebble bed reactors operate under various conditions, including initial start-up, normal operation, different power levels, and shutdown [11], [16]. The risk assessment study for the design of the fuel handling system was conducted under the assumption of normal conditions, where power and fuel flow rates are in equilibrium. Initial risk identification at each node was achieved by examining operational parameters, assessing the probability of deviation, and predicting potential impacts. The initial risk assessment was determined without considering control activities in the design [13], which may encompass safety features and fundamental component characteristics. The subsequent step involves identifying control activities in the design. Residual risk was determined by reassessing the initial risk and adjusting it based on the effectiveness of control activities. Effectiveness of control shows the ability of designed safety features to anticipate the initial risk to residual risk. Nodes with unacceptable residual risk necessitate additional control activities in the subsequent design phase. It is important to note that this risk analysis did not consider the competency of the reactor operator [13], [17], [18]. In the end, the summary of this assessment results is shown in Table 4.

Table 4. Summary of HTR-10 fuel handling system using HAZOP analysis.

Node	Deviation	Impact	Initial Risk		Control	Residual Risk	
			Score	**Scale**		**Score**	**Scale**
Elevator	No fuel	Shut down	30	C	Control System (CS), Emergency Power System (EPS), Reactor Protection System (RPS)	8	A
	High gas pressure	Damaging components	40	C	CS, components redundancy, RPS	8	A
	Low gas pressure	Fuel stuck	65	E	CS, components redundancy, SSC, RPS	11	A
	High pipes velocity	Damaged pipes and fuel	65	E	Electromagnetic valve, System Structure Component (SSC), elbow, RPS	11	A
	Low pipe velocity	No fuel	40	C	CS, Electromagnetic valve, RPS	8	A
	High pipe pressure	Damaged pipes	65	E	CS, exhaust system, SSC, RPS	13	A
	High pipe temperature	Damaged pipes	60	D	Velocity adjustment, SSC, RPS	13	A
Core	High pressure	Explosion	75	E	Graphite material, Tri-Structural Isotropic (TRISO), RPS, SSC, Hot duct, CS	11	A
	High-Temperature	Melting	75	E	RPS, CS, Emergency Core Cooling System (ECCS), heat removal, SSC		
	Helium	Melting	75	E	Graphite ceramics, RPS, CS, passive heat removal, SSC	11	A
	Water or air contamination	Neutronic dynamics	45	D	RPS, CS, SSC, Helium purification	10	A
Singulator	Less helium impulse	Less fuel amount	40	C	Component redundancy, CS, RPS	8	A
	Over helium impulse	Over fuel amount	40	C	Component redundancy, CS, RPS	8	A
	High pulse pressure	Bridge sphere error	40	C	Component redundancy, CS, RPS	8	A
	Low pulse pressure	Fuel stuck	40	C	Component redundancy, CS, RPS	8	A
Separator	Error	Spent fuel hoarding	45	C	Redundancy, CS, EPS, RPS, inherent safety separator design	8	A
Burnup Counter	Error burnup value	Invalid fuel burnup value	45	C	CS, redundancy, EPS, Quality Control (QC), RPS	10	A
Distributor	Error flow fuel	Intrusion core dynamics	35	C	Automation, redundancy, CS, EPS	12	A

A: Very Low B: Low C: Medium D: High E: Catastrophic [5]

Table 4 shows the first semi-qualitative analysis of each fuel handling system design node has an initial risk (without considering control) ranging from medium (such as component damage) to catastrophic (such as melting and explosion). The second analysis was carried out to assess the risk on the nodes by assuming the controls in the design are used to anticipate any initial risks that potentially occur. Analysis shows that the residual risk for all nodes is at a very low level (A). So, the fuel handling system design created has sufficient and acceptable safety control features. For example, in the design of core node, the worst initial risk is the occurrence of uncontrolled high pressure which has the potential to cause an uncontrolled fission reaction and lead to an explosion (risk score = 75). However, by implementing various types of safety features such as the use of graphite material, TRISO design, reactor protection system features, use of appropriate materials, hot ducts, and reactor control systems, the potential for explosions can be reduced to very low level (risk score = 11).

4.1. Elevator

The elevator is a mechanically rotating conveyor, operates at a specific direction and rotational speed. Its primary function is to receive fresh fuel elements from the loading box or discharging tube, measure the fuel burnup, and then feed the fuel to the core using a pneumatic gas impulse in a closed-loop system based on the burnup measurement. If the elevator stops or malfunctions, it can disrupt the fuel flow or halt the entire system, leading to an automatic shutdown of the reactor. A situation where fuel becomes jammed within the loop is classified as a level E hazard due to the extreme difficulty and risk associated with manually extracting highly radioactive fuel [11], [19], [20]. Consequently, control activities should be designed to prevent the fuel from becoming jammed or stuck in the loop. Despite the apparent simplicity of elevator mechanism, it plays a crucial role in ensuring the sustainability and reliability of the pebble bed reactor. Deviations that potentially occurred at the elevator node are related to fuel vacancies, temperature, velocity and pressure fluctuations. This deviation has initial risk value of 45 (medium) to 75 (catastrophic). Whereas safety features that designed to anticipate such as various deviations are in the form of control system, reactor protection system, emergency power system, material type, velocity adjustment, and others. The results of the effectiveness of control analysis show that these safety features will be able to anticipate various deviations up to safe limits (very low).

4.2. Core elevator

The core of an HTGR is akin to a furnace, where the heat is generated [13], [17]. The production of heat must be regulated to meet requirements without causing damage to the core. In the core, the fission reaction generates heat, which must not exceed safety limits. Surpassing these limits could result in damage to the core components, or even an explosion that could release highly radioactive fission products [21], [22].

Deviations that potentially occurred at the core node are related to helium, air contamination, temperature, and pressure fluctuations. This deviation has initial risk value of 45 (high) to 75 (catastrophic). Whereas safety features that designed to anticipate such as various deviations are in the use of graphite material, TRISO design, reactor protection system features, use of appropriate materials, hot ducts, and reactor control systems and others. The results of the effectiveness of control analysis show that these safety features will be able to anticipate various deviations up to acceptance criteria (very low).

Any deviations in the core, such as temperature and pressure increase, can be effectively mitigated through engineering solutions and material selection. Graphite, the primary material of the core, is used both as a fuel material and a wall core material. Graphite can withstand temperatures up to 1700°C, well above the maximum temperature in the event of an uncontrolled fission reaction in the HTR-10 core without coolant gas [11], [12], [17], [18]. Additionally, the helium coolant is an inert gas that does not react with other materials [23]. The power settings and reactor shutdown mechanisms are controlled both automatically and manually by gravity. The fail-safe principle is achieved when the reactor is in an emergency condition, as gravity allows the material to fall without additional force.

Moreover, the control of supporting components, such as pipes and the braking system, should be designed to ensure the smooth flow of fuel to the core without damaging the components or the fuel. As indicated in the table, the highest initial risk (E) lies in the fuel dynamics inside the pipes and the fission reaction in the core. Damaged or broken pipes could lead to the large release high radioactivity into the environment [15]. Simultaneously, the initial risk in the core, with high temperature and pressure during the fission reaction, can cause melting and the release of highly radioactive fission products. Therefore, the control activities, primarily the Safety, Systems, and Components (SSC) and reactor protection systems of the pipes, are critical.

4.3. Singulator elevator

The singulator is a component designed to align the fuel elements, allowing them to flow sequentially through the fuel handling loop system. Despite its seemingly simple function, the singulator plays a crucial role in maintaining fuel circulation [9], [10], [17], [21]. If the singulator fails, it could halt fuel circulation, impacting the dynamics of the core and potentially leading to a reactor shutdown. Deviations that potentially occurred at the singulator node are related to helium impulse and pulse pressure fluctuations. This deviation has similar initial risk values at 40 (medium). Whereas safety features that designed to anticipate such as various deviations are in the use redundancy of material, control system, reactor protection system, and others. The results of the effectiveness of control analysis show that these safety features will be able to anticipate various deviations up to tolerable level (very low).

4.4. Separator elevator

After prolonged exposure to the high temperatures in the reactor core or due to high-velocity movement and collisions within the fuel handling loop, fuel elements can sustain damage, resulting in deformation or chipping [24]. Damaged fuel cannot be reintroduced into the core as it could adversely affect the core and other components. Furthermore, chipped fuel contains highly radioactive fission products that lack the protective shielding provided by the graphite layer of fuel pebbles [20]–[22]. Therefore, it is essential that fuel elements are sifted through a separator in each cycle to ensure only undamaged fuel is recycled back into the core.

Deviations that potentially occurred at the separator node are related to error in function. This deviation has initial risk value of 45 (high). Whereas safety features that designed to anticipate such as various deviations are in the use of redundancy, control system, emergency power system, reactor protection system, and others. The results of the effectiveness of control analysis show that these safety features will be able to anticipate various deviations up to acceptance criteria (very low).

4.5. Burnup measurement elevator

The burnup of fuel cannot be physically differentiated. Furthermore, the entire fuel handling system operates remotely [14], [23]. As such, a burnup measurement tool, specifically a gamma detector, is required. This detector can read the 0.6616642 MeV Cesium-137 gamma energy emitted by the fuel as a result of fission reaction in the core [16]. This gamma energy corresponds directly to the burnup value. Once the burnup value is determined, it can provide information on the status of each fuel element, indicating whether it is spent, in good condition, or a dummy graphite. The fuel element is subsequently transported by the elevator to each loop. Therefore, it is crucial that the burnup measurement tool functions correctly to ensure the acquisition of a valid burnup value.

Deviations that potentially occurred at the burn up counter node are related to error in burn up value measure function. This deviation has initial risk value of 45 (high). Whereas safety features that designed to anticipate such as various deviations are in the use of redundancy, control system, emergency power system, reactor protection system, and others. The results of the effectiveness of control analysis show that these safety features will be able to anticipate various deviations up to tolerable level (very low).

4.6. Distributor elevator

At the onset of core loading (prior to the equilibrium phase), the core is loaded with fuel and graphite material that are physically identical, but the graphite materials do not contain uranium. For the HTR-10, the initial fuel-to-dummy pebble ratio is designed at 57:43 [9], [10]. To achieve an equilibrium core, the graphite material must be gradually removed. This process mirrors the mechanism of fuel handling. However, when it is inserted into the storage container, a component, known as a distributor, is required to direct each element to its respective container based on the burnup measurement value. Once the graphite material is removed completely, the core will reach an equilibrium state, and the distributor is deactivated, allowing the fuel to be sent directly to the spent fuel storage as it is no longer a dummy graphite. Although the distributor operates at the end of the loop, if it malfunctions or operates incorrectly in the presence of graphite, it can cause erroneous fuel correspondence, and graphite material may return to the core.

Deviations that potentially occurred at the distributor node are related to error in flow of fuel. This deviation has initial risk value of 35 (medium). Whereas safety features that designed to anticipate such as various deviations are in the use of redundancy, control system, reactor protection system, redundancy system, and others. The results of the effectiveness of control analysis show that these safety features will be able to anticipate various deviations up to tolerable level (very low). Therefore, control activities must be implemented to ensure the proper operation of the distributor.

5. CONCLUSION

The safety risk assessment of the HTR-10 fuels handling system design, conducted using HAZOP, revealed initial risk levels ranging from moderate to extreme (C to E). The most severe initial risks were associated with potential melting, the release of fission products, and pipe ruptures. However, the implementation of various control measures outlined in the design, such as safety features, inherent characteristics, material selection, and general engineering practices, have effectively mitigated these initial risks, bringing the residual risk within acceptable limits. To maintain the relevance and accuracy of the risk value, it is imperative that the risk assessment of the pebble bed reactor system design is reviewed and evaluated periodically, particularly in response to any changes made to the design.

AUTHOR CONTRIBUTION

All authors are equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

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