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Safety and Risk Assessment of Hydrogen Leaks and Ignition in Storage Facility

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Abstract: This study evaluates the safety of hydrogen storage facilities by applying Hazard and Operability (HAZOP) analysis, What-If analysis (WIA), and Fault Tree Analysis (FTA). The HAZOP analysis identifies key deviations such as leakage, overpressure, and valve malfunction, which can lead to hydrogen accumulation, jet fires, and vapor cloud explosions. The What-If analysis considers broader operational scenarios, including relief valve failures, ventilation loss, and external ignition events, which demonstrate the potential for low-frequency but high-consequence accidents. The FTA shows that uncontrolled hydrogen release together with the presence of ignition sources represents the dominant pathway leading to catastrophic events, with electrical sparks, static discharge, and hot surfaces highlighted as significant contributors. The study shows that the combined application of HAZOP, WIA, and FTA offers a comprehensive framework for identifying accident scenarios and supports a deeper understanding of risks in hydrogen storage operations.
Keywords: Hydrogen storage, safety assessment, HAZOP, What-If analysis, Fault Tree Analysis.

I. INTRODUCTION

Hydrogen has gained global attention as a clean energy carrier with applications in transport, heat, industry, and energy storage, supporting deep decarburization objectives. Advances in production technologies and reductions in cost have strengthened its competitiveness, yet safety concerns remain a major barrier to widespread deployment. Hydrogen's wide flammability range, low ignition energy, high burning velocity, and small molecular size increase its propensity for leakage and spontaneous ignition, requiring comprehensive risk assessment in both production and storage facilities. [1, 2].

Risk analysis studies have consistently emphasized the need for structured hazard identification and prevention strategies. Computational fluid dynamics (CFD) simulations of accidental hydrogen releases have demonstrated that large quantities of hydrogen may remain above the lower flammability limit inside warehouses, leading to significant explosion risks with pressure loads dependent on release rates and enclosure sizes [3]. Similarly, experimental analyses of hydrogen jet fires from underground pipelines have identified distinct flame patterns, with pit geometry strongly influencing pulsation frequency, flame length, and heat distribution [4]. Comprehensive frameworks combining HAZOP, preliminary risk analysis, event tree analysis, and quantitative risk assessment have revealed that vapor cloud explosions can generate vulnerability distances up to 280 m, with societal risks partly in as low as reasonably possible (ALARP) and intolerable regions [5].

Literature reviews have highlighted knowledge gaps in spontaneous ignition mechanisms, with electrostatic discharge, diffusion ignition, and adiabatic compression proposed but not fully validated for high-pressure hydrogen releases. Consequence modeling of high-pressure hydrogen storage tanks has further shown that flammable vapor clouds may extend to 301 m, with explosion overpressures capable of causing building damage and injuries at distances near 200 m [6]. Broader assessments of hydrogen and fuel cell applications have confirmed their potential across multiple energy sectors, although infrastructure readiness, safety assurance, and cost reductions remain ongoing challenges [7]. Recent research has placed additional focus on hydrogen production and storage safety. Hazards associated with hydrogen electrolysis and storage have been identified using HAZOP, with critical risk scenarios linked to leaks and equipment failures, and recommendations provided for strengthening preventive and protective barriers [8]. High-intensity, low-probability (HILP) accident scenarios have been analyzed through HAZOP based models, revealing vulnerabilities to catastrophic failures and highlighting the need for early detection and emergency response strategies [9]. Multi-method safety assessments of alkaline water electrolysis systems have confirmed key risks such as hydrogen leaks, oxygen crossover, and operational failures, with consequence modeling demonstrating significant hazard zones [10]. Reviews of hydrogen storage and transportation have outlined persistent uncertainties in high-pressure leakage reactions, liquid hydrogen dispersion, and synergistic material degradation effects.

Beyond safety aspects, evaluations of hydrogen production pathways have demonstrated that renewable and hybrid thermochemical cycles offer promising sustainability advantages, while solar-based processes remain attractive but require further improvements in efficiency and cost for practical deployment such findings underline the dual challenge of advancing hydrogen production for climate goals while ensuring robust safety management in storage and handling [11]. Taken together, these studies establish the foundation for applying systematic safety assessment methodologies—including Hazard and Operability (HAZOP), What-If Analysis, and Fault Tree Analysis—to hydrogen storage facilities. These methods enable structured identification of hazards, evaluation of accident scenarios, and development of mitigation strategies, which are essential for safe and sustainable hydrogen deployment. Despite the growing body of research on hydrogen safety, significant gaps remain in the integrated application of hazard identification and risk assessment methods to storage facilities. Prior studies have addressed hydrogen release dynamics, ignition mechanisms, jet fire behavior, and large-scale accident consequences, while others have focused on production hazards, transport challenges, and sustainability pathways. However, limited attention has been given to the systematic evaluation of hydrogen storage systems using complementary techniques that can identify deviations, anticipate accident scenarios, and quantify failure probabilities.

This study addresses this gap by applying HAZOP analysis, WIA, and FTA to hydrogen storage facilities. The combined use of these methodologies enables structured identification of hazards, evaluation of potential failure modes, and quantitative assessment of critical accident pathways. The main intent is to generate a comprehensive risk profile for hydrogen storage operations and to provide recommendations for mitigation strategies, thereby supporting safer deployment of hydrogen technologies in industrial and energy applications.

This research investigates the safety and risk factors associated with hydrogen storage facilities by systematically applying three complementary assessment methods: HAZOP analysis, WIA, and FTA. The study identifies critical hazards such as leakage, overpressure, and equipment malfunction, evaluates potential accident scenarios including ignition and explosion risks, and quantifies accident pathways leading to catastrophic outcomes. The findings support safer deployment of hydrogen technologies and contribute to advancing safety management practices for sustainable energy applications.

II. METHODOLOGY

The methodology adopted in this study integrates three established risk assessment approaches—HAZOP analysis, WIA, and FTA—to evaluate hazards associated with hydrogen storage facilities. Each method has been applied in a complementary manner to ensure both qualitative and quantitative coverage of potential accident scenarios. The fig.1. illustrates a stepwise approach beginning with system description and data collection, followed by HAZOP analysis to identify deviations and hazards, WIA to explore broader operational scenarios, and FTA to quantify accident probabilities. The final step synthesizes the results for risk evaluation and comparison for supporting the development of mitigation strategies.

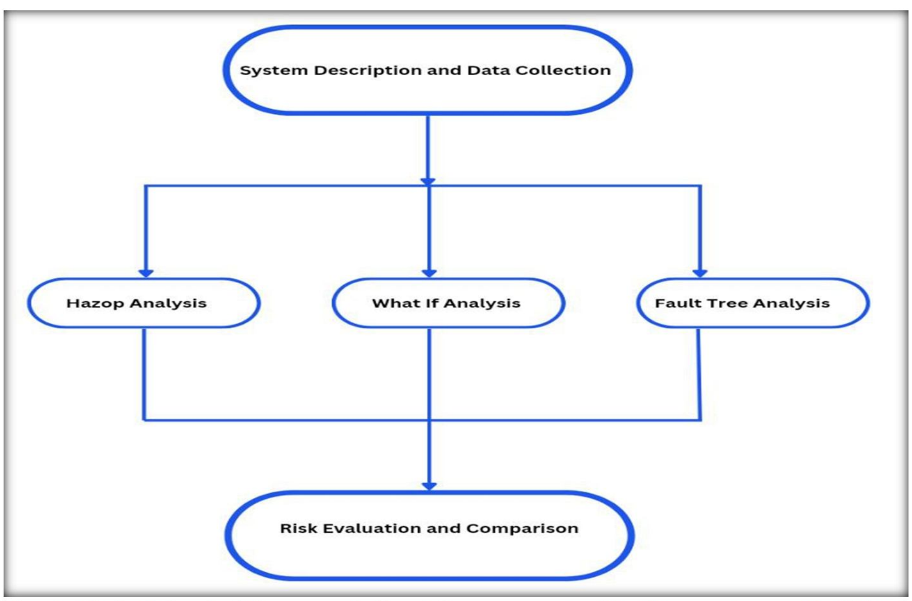

Fig. 1. Methodological framework for risk assessment of hydrogen storage facilities.

A. System Description and Data Collection

The hydrogen storage facility under study has been characterized in terms of storage technology (e.g., high-pressure cylinders, cryogenic tanks, or underground storage), operating conditions, process flow diagrams, and safety systems. Relevant operational parameters, such as design pressure, temperature, storage capacity, and safety barrier specifications, have been compiled from technical documentation, standards, and literature.

Historical accident data, failure rate databases, and experimental findings from prior studies have been incorporated to establish realistic boundary conditions.

B. Hazard and Operability (HAZOP) Analysis on Hydrogen

HAZOP analysis has been conducted by dividing the storage system into functional nodes, including storage vessels, piping, valves, compressors, and safety relief devices.

Standard guidewords such as no, more, less, as well as, and other than have been applied to process parameters like flow, pressure, temperature, and composition.

For each deviation, possible causes, consequences, existing safeguards, and recommendations have been documented. The HAZOP analysis has served as the foundation for identifying credible hazards requiring further evaluation.

C. What-If Analysis

What-If analysis has been performed as a brainstorming technique to complement HAZOP by considering broader operational and external scenarios.

Questions such as "What if a relief valve fails?", "What if hydrogen leaks from a flange connection?", and "What if a fire occurs near the storage vessel?" have been systematically posed. Each scenario has been analyzed for potential consequences, likelihood, and severity. This approach has captured low-frequency, high-consequence events and provided insight into human and organizational factors not fully covered in HAZOP.

D. Fault Tree Analysis (FTA)

FTA has been applied to quantify the probability of critical accident scenarios identified in the previous steps, with hydrogen explosion defined as the top event. The fault tree has been constructed using logical gates to link basic events such as material failure, valve malfunction, operator error, and external ignition sources. Failure rate data from international reliability databases and published hydrogen safety studies have been used as input. Minimal cut sets have been identified, and quantitative calculations have been performed to estimate the top event probability. Sensitivity analysis has been carried out to identify the most influential basic events.

E. Risk Evaluation and Comparison

The outcomes of HAZOP, What-If, and FTA have been synthesized to develop a comprehensive risk profile. Qualitative deviations and scenario-based findings have been compared against the quantitative probabilities from FTA. The combined results have been benchmarked against industry safety criteria such as ALARP (As Low As Reasonably Practicable) and regulatory guidelines. Recommendations for engineering controls, administrative measures, and emergency response planning have been proposed to reduce risks to acceptable levels.

III. RESULTS AND DISCUSSION

A. HAZOP Analysis

The HAZOP study of the hydrogen storage facility has identified critical deviations across key nodes, including storage vessels, piping, valves, and pressure relief systems. Deviations such as No flow, More pressure, Leakage, and Reverse flow have been linked to causes such as valve malfunction, equipment failure, and seal degradation.

Consequences have included hydrogen accumulation, over-pressurization, and potential fire or explosion scenarios. Existing safeguards such as relief valves and leak detection systems have been noted, while additional recommendations have been proposed, including redundant pressure monitoring and improved maintenance protocols. These findings are consistent with prior studies that have emphasized the high flammability and leakage risks of hydrogen facilities.

Table I
Node 1 — Storage vessel (high-pressure gas cylinder / composite tube / vessel)

Guideword	Deviation	Causes	Consequences	Existing safeguards	Likelihood	Severity	Risk	Recommended actions
No / Less (No flow from vessel to downstream)	Unintended isolation or seal blocking preventing expected venting during overpressure	Blocked vent line, stuck valve, frozen actuator	Overpressure buildup → vessel rupture → jet fire / VCE	Pressure gauge, relief valve, periodic inspection	Occasional	Catastrophic	High	E: Redundant PRVs and burst discs; D: high-accuracy pressure monitoring + automated shutdown; A: inspection schedule for vents; ER: emergency isolation plan
More (Excessive flow)	Sudden large release (rupture or large breach)	Mechanical failure, impact damage, embrittlement, overpressuring	Large jet release → immediate ignition risk → jet fire and blast	Relief devices, physical protection, signage	Remote	Catastrophic	High	E: physical shielding, remote isolation valves; D: high-speed flow/pressure detectors; A: exclusion zone around vessels; ER: rapid fire suppression & evacuation plan
Other than (Leak)	Slow or persistent leakage from flange, weld, valve	Seal degradation, gasket failure, hydrogen embrittlement fatigue	Accumulation in enclosed spaces → delayed ignition (VCE risk)	Leak detection (if present), ventilation	Occasional	Major	High	E: use of welded connections where possible; D: fixed H2 detectors at low LFL thresholds + redundant sensors; A: maintenance & torque protocols; ER: immediate ventilation procedures

Table I summarizes deviations identified for hydrogen storage vessels, with a focus on fire and leakage hazards. Causes such as valve malfunction, overpressure, and seal degradation have been linked to consequences including hydrogen accumulation, rupture, and jet fire. Existing safeguards and recommended actions have been detailed to address high-risk scenarios.

Table II
Node 2 — Transfer piping and flanges (between storage and distribution)

Guideword	Deviation	Causes	Consequences	Existing safeguards	Likelihood	Severity	Risk	Recommended actions
Leakage	Permeation or microleak at flange or welded joint	Improper assembly, thermal cycling, vibration	Localized accumulation → ignition (flash fire) or slow buildup → VCE	Torque specs, periodic inspection	Occasional	Major	High	E: use high integrity welds and flange shields; D: localized detectors; A: flange assembly checklist; ER: purge protocols and hot work control

More (unexpected high flow)	Pipe rupture or full bore failure	Third-party strike, mechanical impact, corrosion	Large jet flame → thermal damage, propagation	Pipe supports, fencing	Remote	Catastrophic	High	E: mechanical protection, impact guards; D: high-speed rupture detectors and automatic shutoff; A: third-party work permit systems; ER: remote isolation and firewater supply

Table II presents deviations in hydrogen transfer piping and flanges. Leakage and pipe rupture have been identified as primary hazards, with consequences ranging from localized flash fires to catastrophic jet flames. Recommended actions include impact protection, high-speed rupture detection, and stricter maintenance protocols.

Table III
Node 3 — Pressure relief devices (PRV / burst disc / vents)

Guideword	Deviation	Causes	Consequences	Existing safeguards	Likelihood	Severity	Risk	Recommended actions
No (failure to operate)	PRV stuck or blocked	Corrosion, debris, freeze, actuator failure	Overpressure → vessel rupture → catastrophic release / jet fire	PRV, changeout schedule	Occasional	Catastrophic	High	E: redundant PRVs and remote-actuated backup; D: PRV position monitoring + pressure trend alarm; A: test/maintenance regime with records
More (premature or excessive venting)	PRV lifts unnecessarily	Setpoint drift, instrumentation error	Continuous venting → formation of flammable cloud, increased ignition risk	Vent stack, dispersion design	Remote	Major	Medium	E: stack routing to safe zone; D: monitor vent rate and cause; A: calibration and testing

Table III highlights deviations associated with pressure relief valves (PRVs) and burst discs. Failures to lift during overpressure events and premature venting have been shown to increase risks of catastrophic vessel rupture or formation of flammable clouds. Recommendations include redundant relief systems and PRV monitoring.

Table IV
Node 4 — Fill / transfer operations (loading & unloading)

Guideword	Deviation	Causes	Consequences	Existing safeguards	Likelihood	Severity	Risk	Recommended actions
Other than (overfill)	Overfilling causing overpressure or liquid carryover	Instrument failure, operator error, incorrect procedure	Relief activation or mechanical stress → leak/rupture → jet fire	Level sensors, interlocks	Occasional	Major	High	E: dual independent level sensing + automatic cutoff; D: audible/visual alarms; A: operator training and SOPs; ER: transfer stop & isolate
What-if (wrong connection)	Mis-connection of fill hose (hydrogen → non-compatible system)	Human error, poor labeling	Rapid uncontrolled release, possible ignition	Color coding, labeling	Occasional	Major	High	A: checklists & mating connectors; E: mechanical keyed couplings; D: flow anomaly detection

Table IV shows deviations observed during hydrogen filling and unloading operations. Overfilling and misconnection have been identified as key hazards leading to overpressure, rapid release, or misdirected transfer. Mitigation strategies include dual level sensors, keyed couplings, and operator training.

B. What-If Analysis (WIA)

The What-If analysis has provided complementary insights by considering broader operational and external events. The following are described as:

1) What if a slow leak develops at a buried flange and remains undetected for several hours?

A potential hazard arises when a slow leak develops at a buried flange, which may remain undetected for several hours. Such leaks are typically caused by gasket degradation, the development of micro cracks, or improper installation practices. If left unnoticed, the released hydrogen can accumulate in lower-lying areas, leading to the formation of a flammable cloud. This condition poses a serious risk, as ignition from a distant spark could trigger a vapor cloud explosion (VCE) with widespread vulnerability. Although existing controls such as periodic inspections and a limited number of fixed detectors provide some level of protection, they may not be sufficient to prevent delayed detection. To strengthen safety measures, it is recommended to implement buried-line monitoring techniques, such as pressure decay tests, along with the installation of remote or line-side hydrogen detectors. Additionally, enforcing strict leak-tightness acceptance tests after maintenance activities would help ensure system integrity and minimize the likelihood of hazardous leaks.

2) What if a high-pressure line ruptures during transfer (full-bore break)?

A high-pressure line rupture during transfer, often referred to as a full-bore break, represents a critical hazard in hydrogen storage operations. Such failures can occur due to mechanical impact, third-party excavation near pipelines, or the gradual effects of fatigue and crack growth. The rupture results in an instantaneous release of hydrogen, which, if ignited, can cause an immediate jet fire with severe thermal effects.

These conditions may also trigger domino effects, escalating the incident and endangering surrounding systems and personnel. Existing controls, such as careful pipeline routing and fencing, provide a level of protection but may not be sufficient to fully mitigate the risk. To enhance safety, the implementation of automatic emergency shutdown (ESD) systems with fast-acting shutoff valves is recommended, along with the installation of physical impact shields. Furthermore, rapid isolation logic and site-wide emergency alarms are essential to ensure quick response and containment in the event of such a rupture.

3) What if a relief valve fails to lift during overpressure?

A critical hazard arises if a relief valve fails to lift during an overpressure event in a hydrogen storage system. Such failures may result from corrosion, debris accumulation, incorrect pressure settings, or mechanical blockage of the valve. In this situation, the inability of the relief valve to function properly can lead to uncontrolled overpressure within the vessel, ultimately causing rupture. This rupture may trigger a large-scale hydrogen release with the potential for severe consequences, including a boiling liquid expanding vapor explosion (BLEVE) or a vapor cloud explosion (VCE).

Existing safety measures, such as periodic pressure relief valve (PRV) testing, help reduce the likelihood of such failures but may not fully eliminate the risk. To enhance system reliability, it is recommended to install redundant relief paths that employ diverse technologies, incorporate PRV position feedback with operator alarms, and route PRV blowdown piping to a designated safe zone. Additionally, implementing automated depressurization logic would provide an extra layer of protection, ensuring prompt response to overpressure conditions.

4) What if ventilation fails in an enclosed storage area overnight?

- Causes: fan trip, power outage, blocked intake.
- Consequences: undetected hydrogen build-up → ignition from routine equipment when restarted → explosion.
- Existing controls: natural ventilation, alarms.
- Recommendations: UPS/emergency power for ventilation, automatic ventilation status interlocks preventing restart of electrical equipment until safe, remote H_2 monitoring with failover communications.

5) *What if lightning strikes the facility during a release?*
- Causes: extreme weather, poor grounding.
- Consequences: direct ignition of H_2/air cloud → instantaneous fire/explosion.
- Existing controls: lightning protection for critical equipment.
- Recommendations: ensure bonding/grounding per standards, remote shutoff during storms, sheltering of vulnerable components, update site weather response plan.

C. Fault Tree Analysis (FTA)

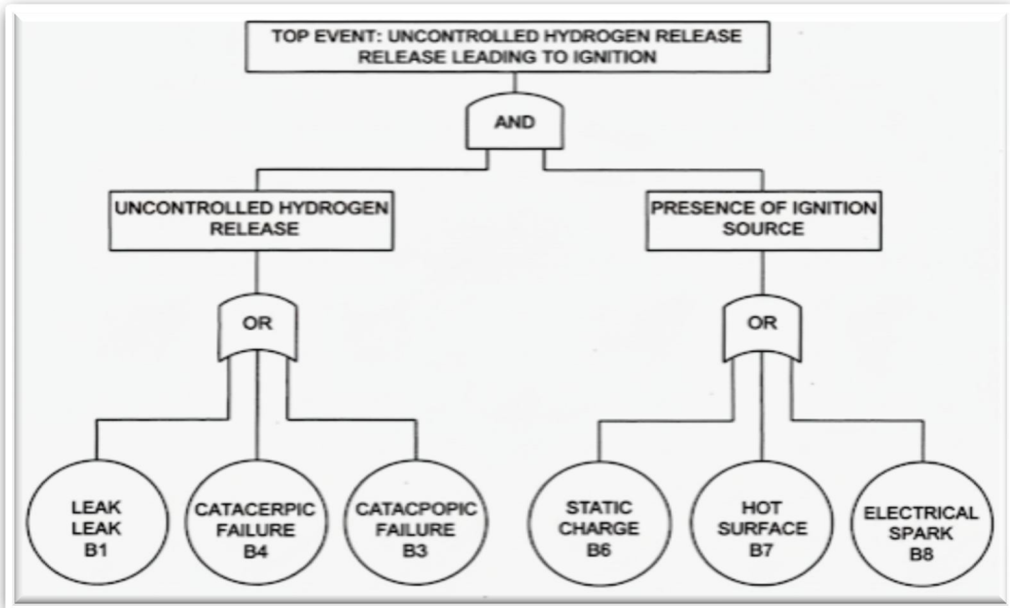

Fig 2. Fault Tree for Hydrogen Storage Facility

Fig 2. shows the logical combination of events that can lead to the top event of “Uncontrolled Hydrogen Release Leading to Ignition.” The OR gate shows that any of the preceding events can cause the next event, while the AND gate shows both “ Uncontrolled Hydrogen Release” and “Presence of Ignition Source” must occur simultaneously for the top event to happen.

The analysis reveals that an "Uncontrolled Hydrogen Release Leading to Ignition" necessitates the simultaneous occurrence of two independent intermediate events: an "Uncontrolled Hydrogen Release" (G1) AND the "Presence of an Ignition Source" (G2). This highlights the importance of controlling both aspects for effective risk mitigation.

The uncontrolled release of hydrogen can stem from various single-point failures or events. The primary pathways identified include such as:

1) Component Integrity Loss (B1, B2, B3, B5): This encompasses small leaks (B1), catastrophic ruptures of vessels or major piping (B2), and failures of specific components like rupture disks (B3) or pipe fittings (B5). These pathways emphasize the need for robust material selection, regular inspection, and maintenance to prevent material degradation or mechanical damage.
2) Operational/Mechanical Failures (B4): Valve failures (B4) represent a critical path, indicating the importance of reliable valve design, proper installation, and scheduled functional testing.

The presence of an ignition source is also multi-faceted, with several independent events capable of providing the necessary energy for ignition:

a) Electrical Sources (B6, B8): Static charge accumulation and discharge (B6), as well as general electrical sparks or arcs from equipment (B8), are significant contributors. This necessitates strict adherence to grounding and bonding protocols, use of intrinsically safe electrical equipment in hazardous zones, and explosion-proof enclosures.
b) Thermal Sources (B7): Hot surfaces (B7) present a direct ignition risk, requiring effective insulation, temperature monitoring, and management of exothermic processes or equipment operating at elevated temperatures.

Minimal Cut Sets: While specific minimal cut sets depend on probabilities, qualitatively, some critical combinations can be inferred:

- {Leak (B1), Static Charge (B6)}
- {Catastrophic Failure (B2), Hot Surface (B7)}
- {Valve Failure (B4), Electrical Spark (B8)}

These cut sets represent the smallest combinations of basic events whose simultaneous occurrence will cause the top event. They are crucial for identifying critical failure pathways and prioritizing safety measures.

IV. CONCLUSION

This study presented a structured risk assessment of hydrogen storage facilities by applying HAZOP, What-If, and Fault Tree Analysis. The HAZOP investigation identified key deviations such as overpressure, leakage, and valve failures across storage vessels, piping, and relief systems, with potential consequences including hydrogen accumulation, jet fires, and vapor cloud explosions. The What-If analysis complemented these findings by capturing broader operational scenarios such as relief valve malfunction, ventilation failure, and external ignition events. Fault Tree Analysis demonstrated that uncontrolled hydrogen release and the presence of ignition sources are the two critical conditions leading to major accidents, with static discharge, electrical sparks, and hot surfaces identified as significant contributors. Collectively, the results underline that hydrogen's inherent properties demand comprehensive risk evaluation, and the integrated application of multiple assessment techniques provides a robust framework for understanding accident pathways in storage operations.

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