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Root Cause Analysis of a Hydrogen Storage Explosion: A Combined BowTie-Tripod Approach Applied to the Gangneung Incident

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Abstract:

Hydrogen storage is critical to the low-carbon transition, yet it introduces distinctive hazards associated with high-pressure vessels, cryogenic media and material degradation. This paper demonstrates a transparent application of an integrated BowTie–Tripod Beta framework, utilising the BowTieXP suite, to translate publicly available incident evidence into structured barrier-based and organisational learning. The 2019 Gangneung buffer-tank explosion was selected as a representative case from the Hydrogen Incident and Accident Database (HIAD). A BowTie diagram was first used to map the complete picture of the incident, highlighting six broad safety barriers that had failed, including the inadequacy or lack of evidence for detecting oxygen (O2) in H2, removal of O2, static controls, and the earthing and bonding system. Tripod Beta then traced each failed barrier back through its immediate causes, preconditions, and underlying causes, revealing systemic weaknesses in design verification, barrier maintenance, and process safety culture. Corrective and Preventive Actions (CAPAs) were formulated to address weaknesses identified in design reviews, barrier integrity monitoring, and competency management, through enhanced training and strict adherence to safety standards. In view of the exclusive reliance on secondary sources, the analysis explicitly grades the evidence strength for each barrier. It frames higher-level organisational contributors as plausible inferences rather than definitive findings. Although conclusions from this single case are not generalisable, the study provides a replicable reporting workflow and traceable CAPA development approach that can be adapted for other high-hazard hydrogen applications. Given the reliance on publicly available secondary sources, evidence-strength tags are used to communicate confidence and to frame the findings as structured hypotheses for verification and barrier design.

Keywords: Hydrogen Storage; Safety; Explosion; Root Cause; BowTie; Tripod Beta.

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1. Introduction

Hydrogen is scaling rapidly as a flexible energy carrier for the net-zero transition. Still, its storage phase introduces unique hazards that demand disciplined incident learning and robust barrier management. Effective accident investigation and identification of root causes of these accidents become central to continuous safety improvement [1], enabling organisations to move beyond the symptoms behind hazards and address deeper systemic weaknesses. Accordingly, investing in accident studies is a proactive approach to building a safer and more reliable hydrogen economy, ensuring its sustainable adoption in the future [2].

Hydrogen possesses unique physicochemical properties that concentrate distinctive hazards, necessitating robust and specialised safety protocols [3], including an extremely low minimum ignition energy and a wide flammability range, which significantly complicate its handling [4]. Hydrogen is also colourless and odourless, making leak detection inherently difficult and exacerbating ignition risks. Under high-pressure storage, improper handling can lead to catastrophic incidents, such as explosions [5]. Furthermore, hydrogen embrittlement poses a long-term material degradation risk [6]. The nearly invisible flame of burning hydrogen further compounds safety risks, negatively affecting rapid incident detection and effective emergency responses [3, 7]. These factors collectively underscore the critical need for systematic safety strategies and a profound understanding of the underlying mechanisms that contribute to hydrogen storage incidents.

Different hydrogen storage methods, broadly classed as physical or material-based, present distinct vulnerabilities [8, 9]. High-pressure systems such as compressed hydrogen gas (CGH_2) are especially prone to leakage and mechanical failure under extreme operating conditions [10, 11]. While physicochemical hazards define the baseline risk landscape, accidents only materialise when the socio-technical defences surrounding them break down. For instance, the embrittlement risk inherent in high-pressure vessels can become critical when maintenance teams lack training in non-destructive testing, allowing micro-cracks to propagate unnoticed. This vulnerability highlights systemic failures, as studies analysing hydrogen incidents have demonstrated that a lack of efficient inspection and maintenance activities commonly causes hydrogen-induced material failures [6, 12].

Consequently, hydrogen incidents are seldom triggered by material factors alone; instead, they emerge from combinations of technical, organisational and environmental weaknesses that align in the causal chain, with human and organisational contributors together accounting for most events [12, 13]. Analyses focusing solely on immediate unsafe acts attribute the event to human error alone in approximately 22% of cases [3]. This discrepancy exists because deeper root cause analysis methods intentionally look beyond blaming the operator to identify the systemic context, management failures, and conditions that made the error possible or inevitable, classifying the ultimate cause as multifaceted [14, 15, 16]. These systemic weaknesses manifest in several recurring ways, ranging from design flaws, gaps in training and awareness that undermine safe operations and maintenance [3, 17], poor or outdated procedures (e.g., miscommunication and unclear instructions were central to the 2019 Santa Clara tube-trailer explosion) and weak management practices [18, 19].

The 2019 Gangneung explosion in the Republic of Korea exemplifies the stakes at hand and serves as an example of a blast from a compressed hydrogen storage facility [20]. This catastrophic event involved a hydrogen buffer tank explosion caused by oxygen contamination from a malfunctioning water electrolyser, which was then ignited by a static spark [18]. Failures of high-pressure hydrogen storage devices, such as the 400 L tank involved, happen frequently and pose significant risks, including mass casualties and property damage [21]. Yet complex incidents of this magnitude are rarely caused by a single, isolated technical failure or inherent physical hazard [22, 23, 24]. Instead, major accidents arise from the failure of multiple layers of protection [22]. Analysing hydrogen-related events has demonstrated that the root causes are often multifaceted, with organisational and human factors contributing significantly [12]. Therefore, the Gangneung incident presents a compelling case from which to extract root causes and demonstrate how a structured investigation, by systematically probing these deep-seated systemic weaknesses and human factors, can inform safer hydrogen storage practices.

Root Cause Analysis (RCA) methodologies are essential because they move beyond proximate technical failures to identify the deeper, system-related reasons why incidents occur [14, 22]. RCA is a systematic process designed to identify fundamental, underlying, system-related reasons why an incident occurred [25, 26]. Recent research evaluating hydrogen storage incidents utilises a range of systematic techniques, including dedicated failure analyses like Tripod Beta for examining pressure relief device (PRD) failures [26], data-driven methods such as business analytics applied to the HIAD 2.0 database to study material failures [6], and overarching systematic reviews advocating frameworks like HEART, HFACS, and Process Safety Management (PSM) principles to address human-managerial factors [14, 27]. However, a single RCA methodology can often limit the breadth or depth of understanding in complex incidents [28, 29]. This limitation is particularly critical in systems as intricate as hydrogen storage, where interactions between materials, equipment, human behaviour, and systemic conditions are multifaceted [30, 31]. These existing studies, while valuable, are often constrained by narrow foci, variable datasets, or the use of a single methodology that fails to comprehensively capture the multifaceted nature of incidents [26]. There is an explicit need for more comprehensive and standardised incident data reporting, the integration of advanced predictive analytics, and an enhanced emphasis on human and organisational factors in these investigations [12, 27, 32].

The effective execution of RCA follows a structured, systematic, and evidence-based investigative approach. This investigative process typically comprises five iterative steps: initiation, establishing facts, analysis, validation, and presentation of results [25]. Ideally, investigators typically combine several RCA methods to more comprehensively address complex incidents [14, 22]. Prevailing RCA techniques remain largely qualitative, and they are often used to identify organisational failure paths [33]. While quantitative tools such as Fault Tree Analysis (FTA) are necessary to provide predictive strength or probabilistic assessments in complex systems [34, 35], reliance on purely data-driven models that use process measurements to diagnose technical disturbances [36] risks overlooking nuanced human and organisational influences [15, 37]; therefore, advanced methods often combine approaches, such as converting qualitative evidence or expert judgment into quantitative metrics (e.g., using fuzzy sets or weighted analysis), to attain a holistic causal view [21, 31, 38].

The overall goal of this research project is to conduct a structured qualitative RCA of the Gangneung hydrogen storage explosion—a critically important case study chosen from the HIAD 2.1 due to its relevance, recency, and the publicly available data that allows for rigorous post-incident reconstruction—using an integrated BowTie and Tripod Beta framework to identify the technical, human, and organisational factors that contributed to the incident. Structured RCA approaches use complementary logic-tree and barrier-based techniques to sequence failure events and interrogate causal pathways (e.g., FTA, Tripod Beta, and BowTie) [14, 31, 37, 39–42]. The BowTie diagram, by visually reconstructing incidents, effectively delineates which specific safety barriers were compromised. The Tripod Beta methodology then complements this by systematically uncovering how and why those failures occurred, tracing failures back through immediate causes, preconditions, and ultimately to the underlying systemic root causes, categorised under Basic Risk Factors (BRFs) [25, 40]. This combined approach is designed to provide a more holistic understanding of multifaceted incidents, moving beyond the limitations of standalone methods and ensuring that a narrow focus does not restrict the analysis [2]. Accordingly, this paper demonstrates a transparent application of an integrated BowTie–Tripod Beta framework, implemented using the BowTieXP suite, to translate publicly available incident evidence from the 2019 Gangneung hydrogen storage explosion into structured barrier-based and organisational learning. The resulting analysis supports the identification of corrective and preventive actions targeting systemic management and operational weaknesses, thereby strengthening the practical utility of post-incident learning for future hydrogen safety improvements [33].

2. Methodology

The framework strategically combines the complementary strengths of BowTie and Tripod Beta methodologies. The analytical process follows established guidelines, using the Centre for Chemical Process Safety (CCPS) for BowTie construction and barrier validation [43], and the Energy Institute (EI) for defining Tripod Beta elements and their causal coding [40].

2.1 Methods and Techniques

The BowTie methodology is a qualitative risk assessment tool that visually represents complex risk scenarios in a clear and easy-to-understand graphic format [44]. It was used in diagnostic (post-incident) mode to reconstruct the accident pathway from threats to consequences and to evaluate the performance of preventive barriers. In line with CCPS guidance, barriers were treated as valid only when they are effective, independent and auditable, and their status was coded as 'Adequate', 'Inadequate', 'Missing', or 'Not evidenced' based on the public record [43].

The status for the preventive barrier is defined as follows:

- Adequate: the incident record provides no indication that the barrier failed to perform its intended function.
- Inadequate: The record indicates partial or complete failure of the intended function (e.g., detection occurred but isolation/purge was not executed).
- Missing: Supported by the records as not incorporated in the design/line-up or absent at the time of the incident.

- Not evidenced: The record is insufficient to confirm whether it was present or absent; treated as unknown and carried forward with lower confidence.

The BowTie method serves as a powerful analytical tool for understanding incidents, providing a clear pictorial representation of events, their causes, and consequences [39, 45] and is crucial for proactive improvements, establishing a baseline that clearly demonstrates where defences were breached and how they can be strengthened [39, 42]. By visualising barrier failures and their influencing factors, BowTie diagrams guide the development of practical recommendations aimed at improving safety systems and management practices to prevent recurrence [14, 27, 46]. The identified influencing factors were mapped to the immediate causes, preconditions, and underlying organisational deficiencies using Tripod Beta—an RCA method that complements the BowTie approach—and applied to failed (or weakly evidenced) preventive barriers to trace each barrier failure to its immediate cause, preconditions, and underlying organisational contributors, coded using the EI Basic Risk Factors (BRFs) to identify systemic vulnerabilities [14, 40]. In Tripod Beta, immediate causes refer to the actions or omissions that directly led to a barrier failure, while preconditions capture the adverse influences that increased the likelihood of those actions; the analysis then links these to deeper, latent weaknesses within organisational systems [40].

2.2 Case Identification and Data Collection

Data collection for this case study follows a documentary approach, focusing on publicly available, traceable sources suitable for a qualitative RCA. The primary dataset is the HIAD version 2.1, maintained by the European Commission's Joint Research Centre (JRC) in Petten, the Netherlands [20]. The case study is selected from this database, which records more than 700 hydrogen events, due to its relevance to hydrogen storage, its recent occurrence, and the considerable volume of publicly accessible information that enables in-depth analysis. HIAD events are validated and classified into eight different categories based on their status and the availability of incident data. The record for this case carries the label 'five', which indicates that the incident is supported by high-quality, traceable sources that may be used to identify root causes [20]. To enhance completeness and verify key facts, the HIAD entry is cross-checked against additional secondary sources, including peer-reviewed publications, official statements, and public news. While the researcher searched for specific technical reports of the incident, none were identified.

2.3 Software and Analytical Tools

The analysis for this research is conducted by using BowTieXP software version 12.0.8.0, which utilises the "BowTieXP Standard + IncidentXP Complete" suite. It is a comprehensive software package from Wolters Kluwer Enablon that facilitates the integrated application of BowTieXP for comprehensive incident visualisation and IncidentXP for Tripod Beta causal analysis. BowTieXP enables organisations to conduct barrier-based incident analysis, learning from barrier failures to improve performance and prevent similar incidents in the future [47].

The integration of BowTie and Tripod Beta is facilitated by the BowTie complete suite (BowTieXP + IncidentXP) software. Figure 1 summarises a seven-stage workflow for integrated incident analysis and continuous improvement: first, comprehensive data from HIAD and other sources are collected to build a chronological understanding of the event and its operational context; second, a BowTie diagram is created to map all relevant threats, potential consequences, and prevention and mitigation barriers; third, this visualisation reveals which preventive barriers failed; fourth, a Tripod Beta core diagram captures the Agent–Object–Event sequence that explains what happened to each failed barrier; fifth, the analysis identifies the immediate human actions or omissions directly responsible for the loss of protection; sixth, these immediate causes are traced through their preconditions to underlying organisational and management-system weaknesses, thereby exposing the root causal pathways; and seventh, the resulting insights inform corrective and preventive actions, using the original BowTie diagram as the baseline for tracking improvement effectiveness.

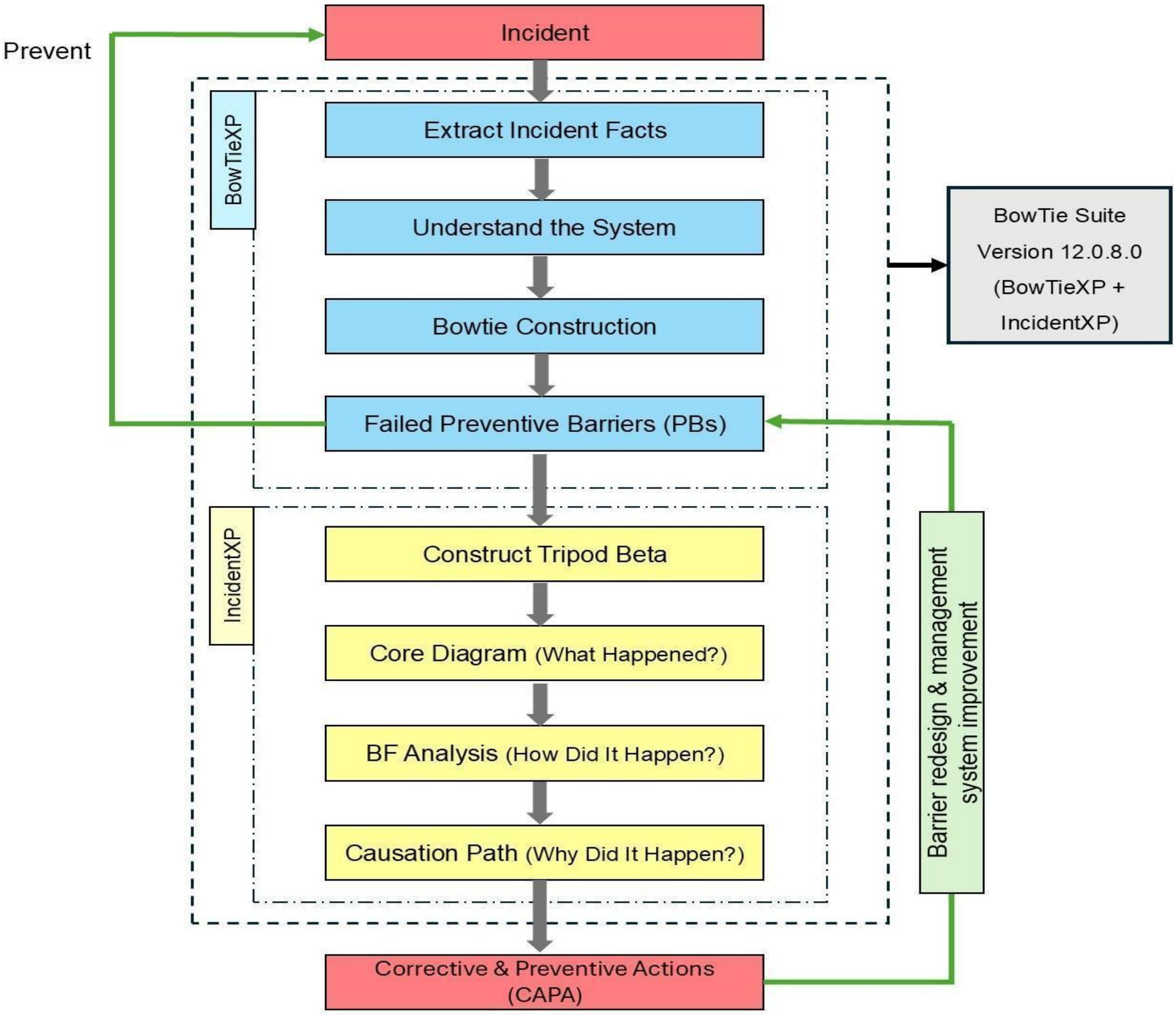

Figure 1: Incident Analysis & Continuous Improvement Flowchart

3. Results

The Gangneung installation was conceived as a small-scale power-to-gas pilot, producing and storing renewable hydrogen. Electrical energy from an on-site photovoltaic (PV) array supplied a 200 kW water electrolyser with a nominal output of ≈ 40 $Nm^3 h^{-1}$ [20, 48]. The produced hydrogen was routed to a storage system comprising one 40 m^3 buffer tank operated at ~1.2 MPa and two additional 40 m^3 storage tanks operated at ~0.7 MPa [20]. On 23 May 2019, an explosion occurred at the Gangneung hydrogen pilot installation in South Korea, resulting in two fatalities and six injuries. The event took place during a trial/validation run of the demonstration facility [46]. Heavy structural damage occurred within ~100 meters, debris was scattered over an area exceeding 3,000 m², fragments of the ruptured tank were projected hundreds of metres (up to ~300 m), and the blast was audible 6–7 km away [20, 49]. The event magnitude is consistently estimated at ~50 kg TNT equivalent, and no post-blast fire was reported [48]. The broader impact extended beyond the site, as 34 companies suffered property damage [46].

3.1 BowTie Analysis

This post-incident (diagnostic) BowTie centres on the internal explosion of the Buffer Tank at the Gangneung pilot installation. Figure 2 illustrates this diagnostic visually: the left-hand side reconstructs the threats that converged on the explosion and the preventive barriers that failed to prevent it. The right-hand side summarises the consequences and any mitigative barriers to limit escalation. To preserve clarity, escalation (degradation) factors that describe the conditions rendering a barrier unavailable or less effective are not depicted on the BowTie. Their causal mechanisms are analysed with Tripod Beta in subsection 3.2. This keeps the BowTie focused on demonstrating all elements that contributed to, or resulted from, the explosion, while subsection 3.2 analyses the causation path of the failed barriers through Tripod Beta.

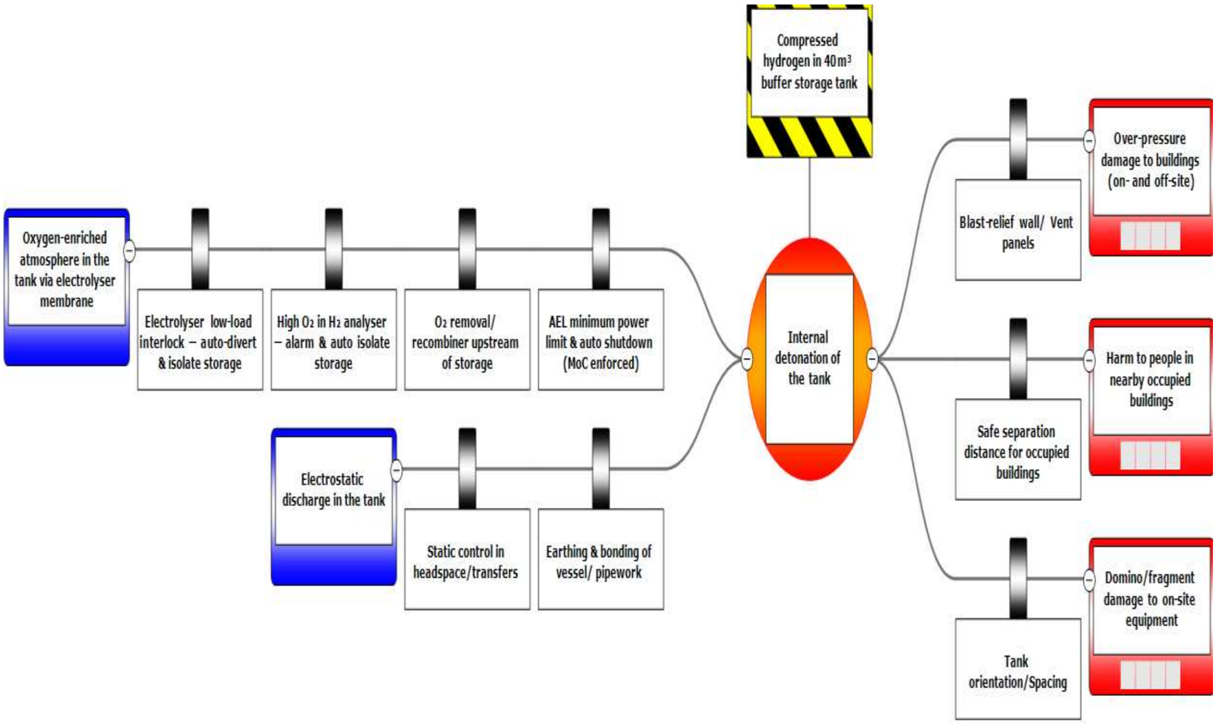

Figure 2: Diagnostic BowTie for the buffer-tank detonation (post-incident reconstruction).

Two immediate threats (T) converged on the top event and are present on the left side of Figure 2.

T1 – Oxygen (O_2) ingress via electrolyser membrane crossover: The tank became oxygen-enriched due to crossover from the electrolyser during low-power operation [20]. The HIAD database reports oxygen concentrations above ~3% during operation and indicates that the buffer-tank oxygen level exceeded ~6% prior to the explosion [20]. These values are treated as secondary evidence: an analyser indication (e.g., ~3% O2) reflects sampling location and time and does not, by itself, confirm that the bulk tank atmosphere was within flammability limits. Under sustained off-spec operation, oxygen can continue to accumulate, and imperfect mixing can create local pockets with a higher oxidiser fraction. Under pressure and confinement, such pockets can support rapid flame acceleration. Accordingly, the reported oxygen indications are used here to support a plausible mixture-formation pathway, while the precise combustion regime (deflagration versus detonation) remains uncertain without primary investigation data.

The following four preventive barriers (PB) are associated with Threat 1:

- PB1 – Low-load auto-divert/isolator on electrolyser off-spec operation (Not evidenced):

The sub-threshold running–the electrolyser was operated at low power, well below its validated load envelope–was documented [20], but no auto-divert/isolation was described.

- PB2 – High-O_2 in H_2 analyser — detector & auto-isolate storage; divert/purge to safe vent (Inadequate):

A concentration of oxygen (≈ 3% O_2 up to ≈ 6%) was detected [20], fulfilling the 'detect' component of an active barrier [43]. However, the critical 'decide' and 'act' components failed, as the operation continued, and neither isolation nor purge was evident.

- PB3 – O_2 removal/recombiner upstream of storage (Missing):

The purification/recombination step is not listed between the electrolyser and the storage buffer, and the option to use an oxygen-removing component was not considered in the final design. This indicates that it was never incorporated into the system [20].

- PB4 – Electrolyser minimum-power limit — auto-shutdown on sub-threshold power (Management of Change (MOC) enforced) (Not evidenced):

Intermittent PV operation normalised low-power running; an enforced minimum-power limit with auto-shutdown was not evidenced [20].

PB1 and PB4 are included as ‘not evidenced’ safeguards because they represent standard engineered controls for electrolyser off-spec operation; their status is treated cautiously due to limited public evidence, and the confidence level is reported in Table 1.

T 2 – Electrostatic discharge in the tank:

The ignition is attributed to a static spark inside the tank [20]. The available records do not document a commissioned earthing and bonding scheme for the vessel and associated pipework. No headspace static-control devices or controlled fill/vent measures are described

[20]. In the diagnostic BowTie, these protections are tagged unknown (not evidenced) rather than confirmed absent:

- PB5 – Static control in headspace/transfers (lining/velocity/charge control) (Not evidenced):

No antistatic linings, charge-relief devices, or controlled fill/vent velocities were described in the available records.

- PB6 – Earthing & bonding of vessel/ pipework (Not evidenced):

A commissioned earthing-and-bonding scheme and pre-start continuity checks were not evidenced.

As for T1, these barriers are related to items not identified rather than those explicitly mentioned as missing in the reports and literature.

The consequences of the explosion are present on the right side of Figure 2. Though the right side was not analysed for root causes, the evaluation of the consequences of an event is crucial for determining the appropriate level and depth of its investigation [43]. The detonation caused two fatalities and six injuries; heavy damage occurred both on- and off-site [49], further highlighting the failure of incident mitigative barriers. Mitigative barriers (MBs) were scarce: MB1—blast-relief wall/vent panels—were absent, offering no over-pressure protection [20]; MB2—safe separation distance to occupied buildings—proved only partly effective when glazing failed ~100 m away and casualties occurred near the site [46]; and MB3—tank orientation/spacing—was undocumented, with adjacent equipment severely damaged [49]. These mitigations are noted solely to contextualise severity and are excluded from the RCA, which focuses instead on preventive layers PB1–PB6.

Overall, the diagnostic BowTie, as shown in Figure 2, visualises a systemic absence or ineffectiveness of critical preventive layers on its left and mitigative barriers on its right. Table 1 further summarises the preventive barriers that failed and led to the explosion.

Table 1: Preventive Barriers (Left Side): Functions & Observed Status

Preventive Barrier	Linked threat	Observed status at event	Evidence Strength	Barrier Criticality	Remark
PB1 – Low-load auto-divert/ isolator on electrolyser off-spec operation.	T1	Not evidenced	Low	Medium	Sub-threshold running occurred; no automatic divert/isolation was described.
PB2 – High-O_2 in H_2 analyser — detector & manual/ auto-isolate storage; divert/ purge to safe vent	T1	Inadequate	High	High	High-O_2 alarm reported; operation continued; no auto-isolation documented.
PB3 – O_2 removal/recombiner upstream of storage	T1	Missing	Medium	High	No O_2-removal / recombiner stage specified in the process line-up.
PB4 – alkaline electrolyser (AEL) minimum-power limit, auto-shutdown on sub-threshold power (MOC-enforced)	T1	Not evidenced	Low	Medium	PV-driven intermittency normalised low-power running; enforced auto-shutdown at the AEL limit not evidenced.
PB5 – Static control in headspace/transfers	T2	Not evidenced	Low	High	No antistatic lining/velocity controls described.
PB6 – Earthing & bonding of vessel/pipework	T2	Not evidenced	Low	High	No earthing and bonding are described.

3.2 Tripod Beta Analysis

For each preventive barrier, the Tripod Beta logic was applied in a stepwise manner: (i) identify an immediate cause (a specific act, decision, or omission) that directly explains how the barrier failed; (ii) identify preconditions that made that act or omission more likely; and (iii) classify the underlying organisational contributors as BRFs using the Tripod Beta taxonomy. To avoid over-interpretation from secondary sources, immediate causes were formulated as close as possible to the observable record (e.g., continued routing of gas to storage after an oxygen indication; omission of an oxygen-removal stage in the published line-up), and each higher-level BRF attribution is treated as a plausible inference rather than a proven fact where direct evidence is not available.

Two immediate threats formed an AND-chain to the top event:

Threat-1: oxygen ingress and mixture formation (PB1–PB4):

During PV-driven operation, the AEL was run below its validated and approved operating conditions (≈ 98 kW for a 200 kW unit), which is associated with oxygen crossover into the hydrogen product stream [20, 46]. There was no oxygen-removal stage upstream of storage, and no automatic isolation/purge was implemented as production continued despite an O_2 level (3%) being detected [20, 50]. Figure 3 depicts the Threat-1 portion of the Tripod.

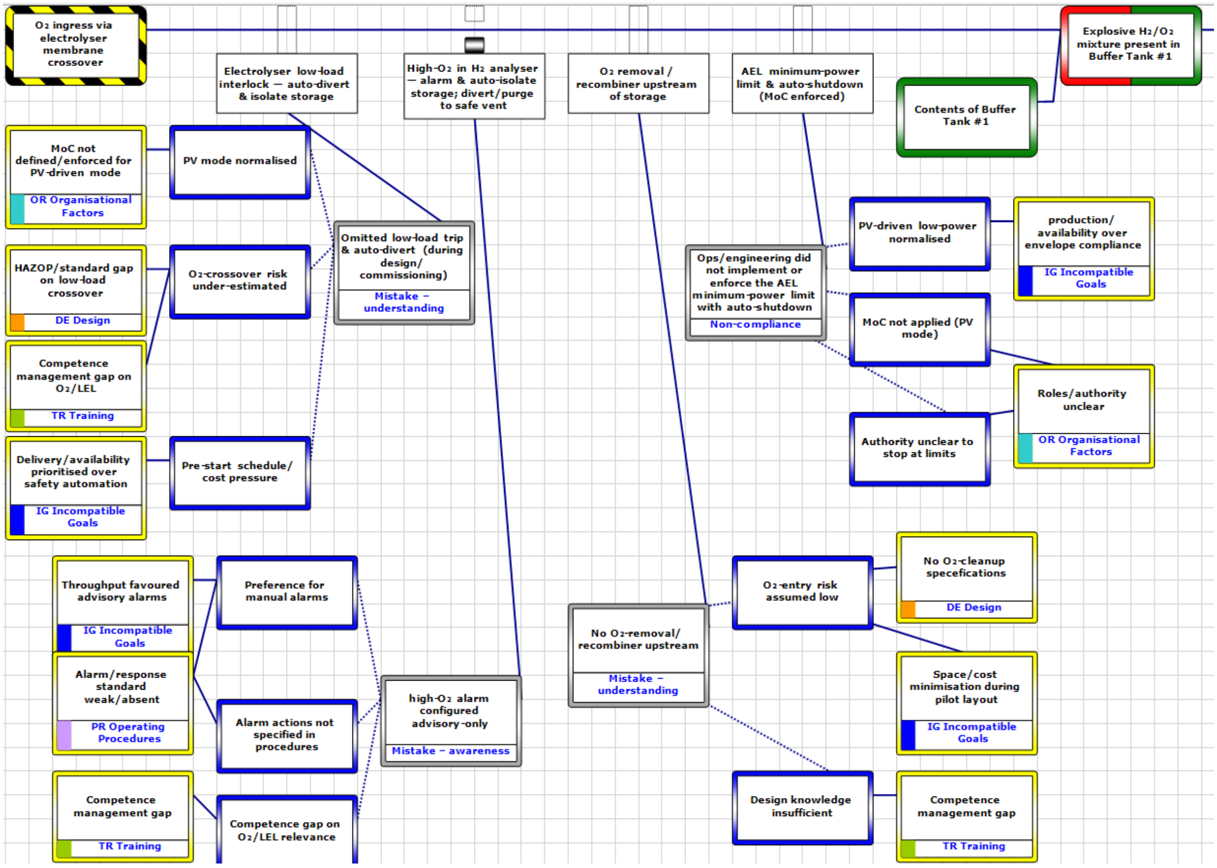

Figure 3: Threat-1 portion of the Tripod Beta

Across the preventive-barrier chain for Threat 1 (oxygen ingress and mixture formation; PB1-PB4), the available evidence points to an electrolyser–storage interface vulnerability under PV-driven, low-load operation. Specifically, operation below the validated power range and the reported oxygen indication suggest that the operating envelope was exceeded and/or not effectively enforced. Where interlocks and automatic diversion/isolation are not evidenced (PB1 and PB4), control of off-spec gas relies disproportionately on detection and human response (PB2). The absence of an explicit oxygen-removal stage in the published line-up (PB3) further reduces defence-in-depth if oxygen crossover persists. Tripod Beta therefore traces the barrier outcomes back to (a) design verification and safeguard specification at the electrolyser–storage boundary, (b) alarm philosophy and response arrangements for oxygen-in-hydrogen, and (c) governance of low-load operating modes (including MOC triggers, decision authority, and acceptance criteria). Where these organisational contributors are inferred rather than directly evidenced in public sources, they are labelled as low-confidence hypotheses and should be validated against primary records (e.g., commissioning documentation, operating procedures, and alarm/event logs).

Threat-2: ignition by electrostatic discharge (B5–B6):

The ignition is attributed to a spark inside the tank headspace [20, 48]. Available records do not document a commissioned earthing and bonding scheme, and no commissioning continuity checks are described. No antistatic linings or transfer-velocity controls are reported for the headspace or fill/vent system. The portion of the Tripod tree is illustrated in Figure 4.

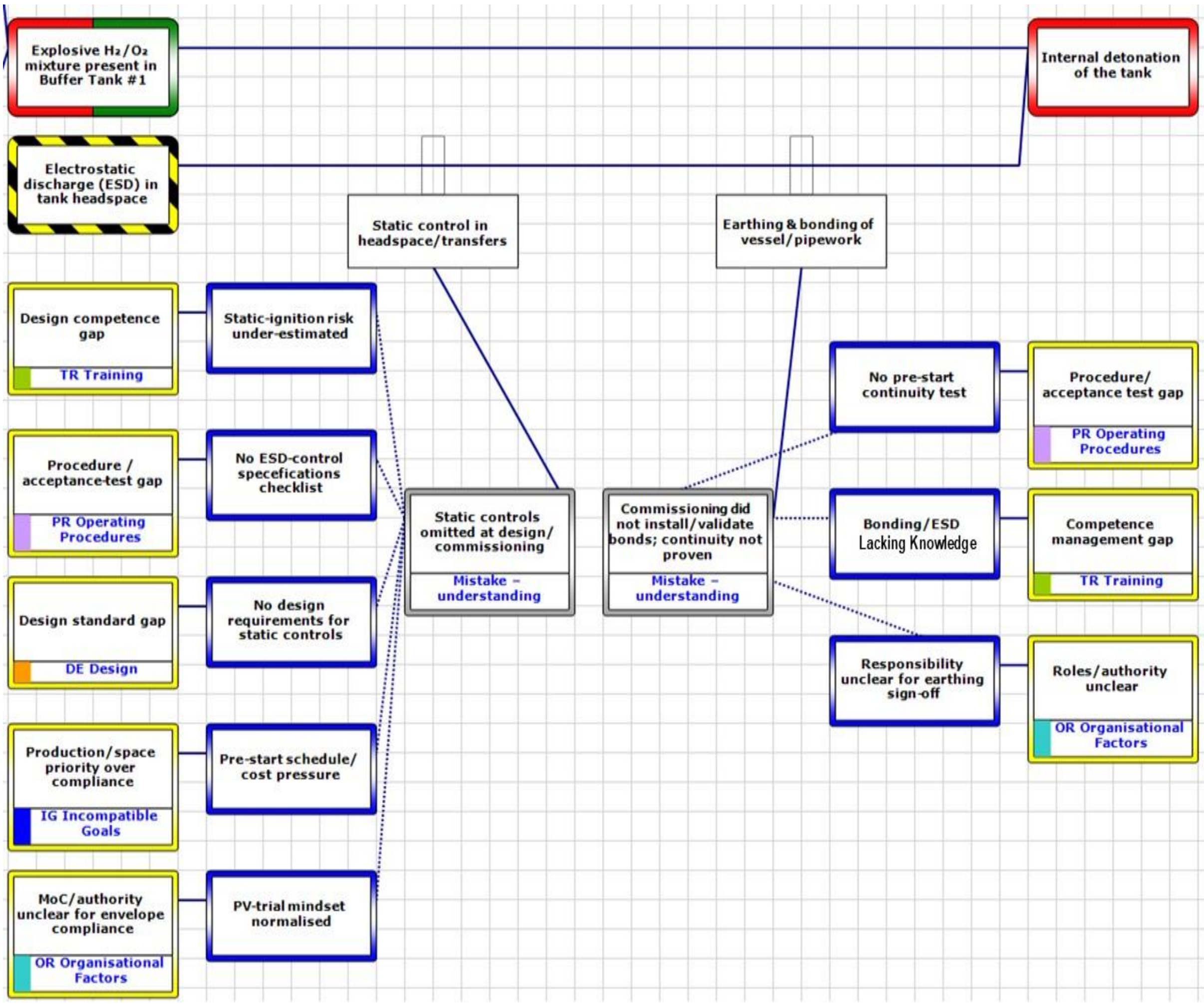

Figure 4: Threat-2 portion of the Tripod Beta

For Threat 2 (ignition by electrostatic discharge; PB5–PB6), the publicly available record does not provide detailed evidence of static-control design features, earthing/bonding specifications, or commissioning verification (e.g., continuity measurements and acceptance criteria). In Tripod Beta terms, the immediate cause is therefore treated as a potential ignition source inside the tank/headspace under conditions where electrostatic charge could accumulate, while the preconditions relate to the absence (or lack of evidence) of engineered and procedural controls that normally prevent charge build-up and ensure effective discharge paths. The underlying contributors are expressed cautiously as possible gaps in design standards/specifications, and Table 2 consolidates the Tripod Beta findings into a smaller set of cross-cutting underlying causal contributors (system-level learning statements), the primary BRF themes they relate to, and the preventive barriers they defeated.

Table 2: Underlying Causal Contributors, BRF Themes and the Defeated Barriers

S.N	Underlying causal contributor	BRF	Barriers primarily affected
1.	MOC triggers and acceptance criteria were not defined/enforced for PV-driven, low-load operating mode at the electrolyser–storage interface.	OR – Organisational Factor	PB1
2.	Decision authority for oxygen-alarm response and operating-envelope compliance was unclear (who can stop/divert/vent, and on what criteria).		PB2, PB4, PB6
3.	Operating-envelope enforcement (minimum load and shutdown criteria) was not governed by a clear decision rule/authority under variable PV supply.		PB5
4.	PHA/design review (e.g., HAZOP) did not explicitly address low-load oxygen crossover and the required safeguards at the electrolyser–storage boundary.	DE – Design	PB1
5.	Design basis did not specify an oxygen management stage (deoxygenation/recombination) upstream of storage, or an equivalent defence-in-depth measure.		PB3
6.	Ignition-control requirements for the storage system (static control, earthing/bonding) were not clearly specified in design standards and acceptance criteria.		PB5
7.	Competence assurance did not ensure recognition of oxygen-crossover risk and the required response to oxygen-in-hydrogen indications.	TR – Training	PB1, PB2
8.	Cross-discipline design knowledge/ verification did not challenge electrolyser–storage interface assumptions (oxygen contamination, clean-up, isolation/divert/purge).		PB3
9.	Competence and verification practices for ignition control (static hazards, bonding/earthing verification) were insufficient or not demonstrated in the public record.		PB5, PB6
10.	Schedule/delivery priorities favoured progress over implementing safety-critical automation for off-spec diversion/isolation.	IG – Incompatible Goals	PB1

11.	Alarm philosophy favoured advisory alarms rather than enforced trip/isolate/divert-and-purge actions for oxygen contamination.		PB2
12.	Cost/space trade-offs contributed to omission of a deoxygenation/recombination stage or equivalent clean-up defence.		PB3
13.	Production objectives encouraged continued operation outside the validated electrolyser envelope (low-load running) rather than enforced shutdown.		PB4
14.	Pre-start schedule/cost pressures reduced the rigour of commissioning verification for ignition controls (static management, bonding/earthing tests).		PB5
15.	Procedures and escalation steps for responding to oxygen-in-hydrogen alarms (isolate, divert, vent/purge, verify) were weak/absent.	PR – Operating Procedures	PB2
16.	Acceptance testing/PSSR did not explicitly verify barrier integrity for bonding/earthing and static control (continuity tests, criteria, records).		PB5, PB6

4. Discussion

The study's main strengths are threefold. First, its integrated BowTie–Tripod Beta framework yields both a clear visual timeline and a rigorous causal probe, revealing not only which barriers failed but also how and why they collapsed. Second, grounding the analysis in the high-impact Gangneung explosion adds immediate industrial relevance, translating safety theory into tangible, practice-oriented insights. Third, grouping root causes into Basic Risk Factors shifts attention from surface-level symptoms to deeper management-system weaknesses and, thus, supports long-term safety improvement [14].

The diagnostic BowTie reconstruction identified two immediate threats, oxygen ingress/mixture formation and electrostatic ignition, and six preventive barriers with varying evidence strength (Table 1). Tripod Beta then linked the key barrier outcomes to a smaller set of cross-cutting organisational contributors (Table 2), supporting CAPAs packages that target design verification at the electrolyser–storage interface, oxygen alarm philosophy/response, commissioning verification of ignition controls, and competence assurance.

Using the Gangneung case as an illustration, a standalone BowTie would have identified PB1–PB6 and the two immediate threats, but it would not, by itself, provide a structured route to the organisational BRFs that explain why those barriers were absent or ineffective. Conversely, a standalone Tripod Beta analysis could be conducted from the event chronology, but without the BowTie barrier lens it risks (i) inconsistent barrier definition across investigators and (ii) weaker traceability from technical threat pathways to organisational causes. The integrated workflow therefore increases transparency by using the BowTie as a completeness check and the Tripod as the causal deep-dive.

However, the analysis relies on publicly available secondary sources; therefore, several barrier assessments are reported as 'not evidenced' and are accompanied by evidence-strength tags (Table 1). Alternative plausible interpretations were considered, such as air ingress during maintenance or ignition from electrical equipment rather than electrostatic discharge, but were not allocated as primary pathways because the available reports most consistently attribute oxygen enrichment to low-load electrolyser crossover and ignition to static discharge [20, 48]. Tripod BRF allocation can also vary between investigators; to mitigate this, we applied explicit coding rules (Section 2.1) and report BRF prominence (IG: 5/16, OR: 3/16, DE: 3/16, TR: 3/16, PR: 2/16) to make the qualitative weighting transparent.

Although official summaries identify oxygen ingress and static ignition, the integrated BowTie–Tripod approach reformulates these conclusions into auditable, hydrogen-storage-specific gaps (electrolyser off-spec governance, oxygen monitoring with automatic isolate/divert-and-purge, absence or non-demonstration of oxygen clean-up, and commissioning/verification of static-control and earthing measures). These gaps are explicitly linked to PB1–PB6 (Table 1) and to the underlying causal contributors in Table 2, improving practical usefulness for design review and operational assurance.

4.1 Industrial and Practical Implications

The root-cause findings, grouped under five BRFs in Table 2, translate into targeted CAPAs primarily for the Gangneung pilot facility; at the same time, they are phrased so that operators of other hydrogen-storage sites can readily adapt them to maintain healthy barriers. Table 3 summarises the CAPA–BRF–PB traceability and flags case-dependent versus transferable elements.

Table 3: CAPA packages mapped to PBs, BRFs, and transferability

CAPA ID / package	Key implementation focus	Mapped PB(s)	Mapped BRF(s)	Transferability
CAPA-C1 – Organisational governance	Define/enforce MOC triggers (incl. PV-driven low-load modes) and clarify authority for off-spec decisions and shutdowns.	PB1, PB2, PB4, PB5, PB6	OR	Transferable (case-dependent trigger: PV-driven operation).
CAPA-C2 – Design engineering	Strengthen electrolyser-storage interface design: specify O2 clean-up where required, define off-spec diversion/isolation logic, and verify safeguards via design review/HAZOP.	PB1, PB3, PB4	DE	Transferable to electrolyser-storage systems (case-dependent: exact PV duty profile).
CAPA-C3 – Training & competence	Assure competence in O2/LEL hazards, alarm response, ignition control (static/earthing), and cross-discipline design intent.	PB1, PB2, PB5, PB6	TR	Transferable.
CAPA-C4 – Managing incompatible goals	Prioritise safety-critical automation over throughput/schedule pressures; adopt conservative alarm philosophy and enforce operating envelope compliance.	PB1, PB2, PB3, PB4	IG	Transferable.
CAPA-C5 – Operating procedures & testing	Formalise alarm response, commissioning/acceptance testing (incl. earthing/bonding continuity checks), and periodic verification of ignition controls.	PB2, PB5, PB6	PR	Transferable.

Therefore, each CAPA presents a concrete instruction for Gangneung, while signalling its broader applicability to comparable installations:

- **CAPA-C1 –** Organisational governance (OR): Institute a robust Management of Change (MOC) system that is explicitly triggered for pressure-variation (PV-driven) operations, and formalise clear lines of authority for both routine tasks and envelope-compliance decisions; such clarity is the "glue" of Process Safety Management (PSM) and underpins safe, efficient operations [14, 15, 22].
- **CAPA-C2 –** Design engineering (DE): Close low-load crossover vulnerabilities by undertaking Hazard and Operability (HAZOP) studies [3, 39]. HAZOP is a crucial Process Hazard Analysis (PHA) tool used to improve a design and identify risks associated with design deviations [14, 39]. Designs must be strictly aligned with up-to-date codes, specifications, and O2 cleanup standards, as these standards embody the lessons learned from past incidents [22]. Rigorous compliance with these guidelines, such as those from the International Organisation for Standardisation (ISO), is essential for hydrogen-materials compatibility and specific design measures necessary to minimise risk. Adhering to these generally accepted engineering practices is required for safe equipment operation.
- **CAPA-C3 –** Training and competence (TR): Embed a competence-management programme that reinforces oxygen/LEL awareness, deepens design knowledge across disciplines, and converts lessons learned into targeted up-skilling initiatives. Such training should prioritise developing practical skills, focusing on training personnel "to do," not simply "to understand," to ensure they have the application competence needed to deal with unforeseen problems [16]. Practical exercises and verified applications must be included to provide adequate training [16, 22].

- **CAPA-C4 –** Incompatible goals (IG): Rebalance production, costs, and space-saving pressures by prioritising safety-critical automation and advisory alarms, integrating alarm-management best practices, and ensuring envelope compliance is never compromised by throughput or schedule demands.
- **CAPA-C5 –** Operating procedures (PR): Strengthen alarm/response standards and embed rigorous acceptance-test protocols so that procedural defences mature in parallel with technical and organisational improvements.

Together, these actions tackle the identified root causes—spanning organisational structure, design rigour, workforce capability, competing objectives, and procedural discipline—and establish a holistic roadmap for barrier integrity and continuous safety improvement.

4.2 Limitations and Future Work

Three main factors constrain this study. First, it's RCAs rely solely on publicly available HIAD data and secondary reports; access to proprietary records, personnel interviews, or site inspections could have revealed finer procedural details. Second, the findings derive from a single qualitative case, the Gangneung explosion, so, although comparable root causes appear in other high-risk industries, the exact failure modes may differ, and no probabilistic insight can be drawn without multi-case statistics [26, 33]. Third, the single-incident focus limits breadth relative to larger database studies [17, 26], even though depth was gained through the iterative application of the integrated BowTie–Tripod Beta method.

Addressing these limitations points directly to future work: (i) apply the framework to a wider spectrum of hydrogen incidents and scales to better generalise root cause patterns and strengthen statistical confidence; (ii) complement qualitative tracing with quantitative risk tools, quantitative risk analysis (QRA) to add probabilistic insight [51], predictive modelling, or database analytics, to estimate the likelihood of Basic Risk Factors leading to barrier failures more broadly; (iii) develop hydrogen-specific RCA taxonomies and standardised reporting to enable consistent multi-organisation analyses, potentially leveraging AI for real-time diagnostics; and (iv) systematically track the field effectiveness of CAPAs derived from such studies to verify their safety impact. Together, these directions would extend the current qualitative insights, broaden their applicability, and create a firmer empirical basis for proactive risk management across the hydrogen value chain.

In particular, a planned next step is to apply the same BowTie–Tripod workflow to a small set of comparable hydrogen storage events (e.g., electrolyser-related oxygen contamination and storage-vessel ignition/rupture cases in HIAD) and to benchmark the outputs against conventional HAZOP/FTA studies. This comparison would help quantify what additional insight the integrated barrier-to-BRF tracing provides when using secondary resources beyond identifying deviations and fault logic alone. As a simple illustration, the BowTie preventive-barrier chain can be converted into a minimal event-tree structure where the probability of the top event is expressed as the joint occurrence of (i) explosive-mixture formation and (ii) ignition, conditioned on barrier failures. For example, mixture formation can be represented as failure of PB1–PB4 (off-spec isolation, O_2 detection/isolation, O_2 removal, and operating-envelope control), while ignition is conditioned on failure of PB5–PB6 (static control and earthing/bonding). Assigning barrier failure probabilities based on equipment data, functional-safety claims, or expert elicitation would allow the present qualitative RCA to inform QRA or a barrier-health digital twin.

5. Conclusion

This research aimed to conduct a structured qualitative RCA of the Gangneung hydrogen buffer-tank explosion using secondary and available resources and to identify interacting technical, human, and organisational contributors. Application of the integrated BowTie–Tripod Beta workflow highlighted two immediate threats and six preventive barriers, and traced the key barrier outcomes to cross-cutting organisational contributors that inform targeted

CAPAs. Limitations arise from the single-case design and the reliance on publicly available secondary evidence; therefore, evidence-strength tagging is used throughout to keep conclusions proportionate to the available record and to distinguish strongly supported findings from plausible inferences. Future studies should validate these findings against primary engineering records and extend the approach across multiple hydrogen storage incidents and contexts to improve transferability and generalisability, including comparative case analysis, integration of quantitative barrier-effectiveness metrics, and coupling with digital-twin technologies for real-time predictive analytics. By addressing these avenues, the proposed framework can evolve into a robust decision-support tool for both regulators and industry, ultimately advancing the safe deployment of hydrogen in the clean-energy economy.

6. References

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