Funded by UK Government

UK Civil Aviation Authority

CAA Hydrogen Challenge
Bowtie Analysis – Aircraft Refuelling

July 2026

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Executive Summary

The development of safe and reliable hydrogen refuelling systems is a critical enabler for achieving Net Zero aviation. While substantial safety research exists in other sectors, aviation specific analysis of hydrogen technologies remains limited due to the industry's early stage of operational experience.

This report presents the outcomes of the CAA's preliminary Bowtie safety assessment for hydrogen aircraft refuelling operations. The analysis identifies key hazards, credible event pathways, and potential consequences linked to hydrogen refuelling activities. It demonstrates that the Bowtie methodology is well suited to evaluating this emerging refuelling process, enabling the early identification of threats, escalation factors, and both preventive and recovery barriers. The assessment provides a structured foundation for proactive safety planning as hydrogen systems begin to integrate into the aviation environment.

Industry engagement through the CAA's Regulatory Sandbox has already identified operational challenges, technology-specific hazards, and areas where mitigation strategies require further validation. In response, the CAA's Technical Strategic Lead for Zero Emissions Flight has commissioned a working group to develop a Bowtie analysis for the hydrogen refuelling of aircraft at aerodromes. These tools provide a structured, visual means of mapping threats, controls, and degradation factors within one of the most safety-critical domains of hydrogen aviation.

Bowtie analysis is particularly valuable in this context due to its ability to integrate complex, multi domain risks into a clear and communicable framework. As Sandbox participants, including ZeroAvia and Cranfield Aerospace Solutions, continue to explore propulsion, storage, and distribution hazards, the Bowtie approach supports consistent risk capture, enhances regulatory alignment, and strengthens the overall evidence base.

The CAA recognises that public confidence in hydrogen remains a challenge. Bowtie diagrams provide a transparent means of demonstrating how risks are controlled and how emerging technologies can be introduced safely into aviation.

In summary, the commissioning of the Bowtie analysis represents a strategic step within the Hydrogen Challenge Programme. It enhances regulatory readiness, supports industry collaboration, strengthens the safety evidence base, and contributes to building public and stakeholder assurance in hydrogen as a future aviation fuel.

1.Introduction

1.1 The transition toward hydrogen powered aviation introduces a new set of technical, operational, and safety considerations for aerodromes. While hydrogen offers significant potential benefits, most notably reduced carbon emissions, and alignment with long term sustainability goals, it also presents hazards that differ substantially from those associated with conventional aviation fuels. These include the unique flammability characteristics of gaseous and liquid hydrogen, rapid dispersion behaviour, cryogenic risks, high pressure storage requirements, and the introduction of novel ground support systems. As the sector explores early deployment pathways for hydrogen fuelled aircraft, it is essential that aerodromes adopt systematic and transparent methods for understanding and managing these emerging risks.

1.2 There are several methods for identifying and assessing risk, including Fault Tree Analysis (FTA), Event Tree Analysis (ETA), HAZOP, Failure Modes and Effects Analysis (FMEA), and system-based approaches such as STPA (Systems-Theoretic Process Analysis). Each offers particular strengths, such as root cause identification, consequence modelling, or detailed component-level analysis. However, the Bowtie methodology was preferred because it integrates causes, consequences, and both preventive and mitigative controls into a single, clear visual framework. This makes it especially effective for communicating risk and barrier effectiveness to both technical specialists and wider stakeholders.

1.3 A Bowtie analysis was therefore undertaken to provide a structured, visual representation of how a hydrogen refuelling system could fail, the threats that might lead to a loss of containment or ignition event, and the potential consequences for people, infrastructure, and operational continuity. This methodology enables aerodrome operators, regulators, and stakeholders to identify the preventive and mitigative barriers required to maintain safety, assess their robustness, and highlight gaps that may require additional controls, procedures, or regulatory guidance.

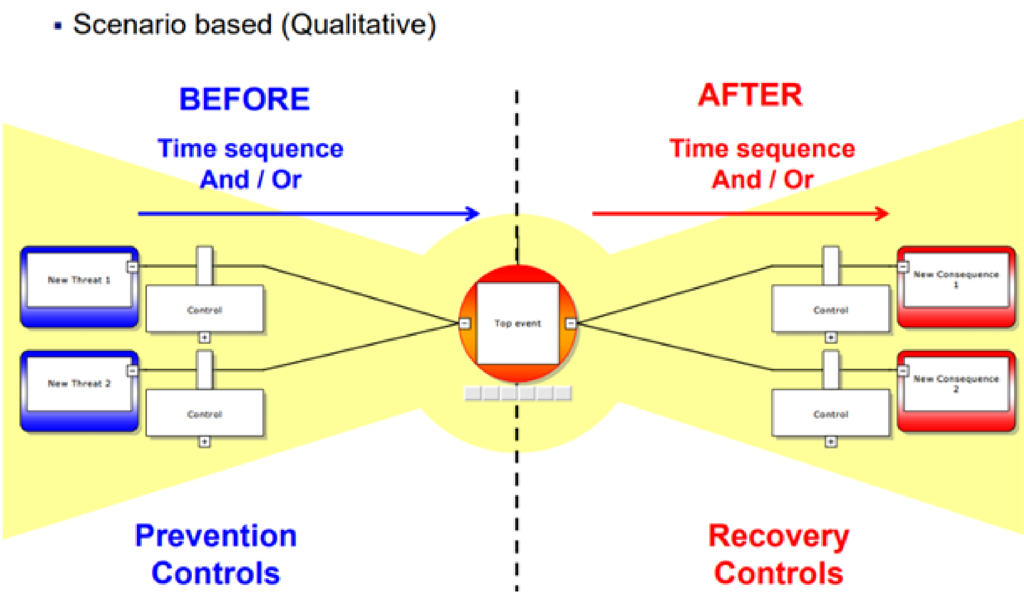
1.4 By mapping the full chain from causes to consequences, the Bowtie framework supports the development of proportionate and evidence-based safety measures during the early adoption of hydrogen technologies. It also promotes a shared understanding across disciplines, including engineering, operations, emergency response, and safety management, which is critical when introducing infrastructure and practices that fall outside established aviation experience.

1.5 This analysis forms a foundational component of the broader hydrogen integration programme, ensuring that aerodromes can plan for safe refuelling operations, support future certification and assurance activities, and prepare emergency response arrangements that reflect the characteristics of hydrogen systems. Ultimately, the Bowtie serves as a practical and communicable tool to underpin decision making and demonstrate that risks associated with hydrogen refuelling are being systematically identified, evaluated, and controlled.

2. History and Development of Bowtie Analysis

2.1 **Concept of Bowties**

2.2 Bowtie Analysis takes its name from the distinctive Bowtie-shaped diagram used to illustrate the assessment. The diagram below (figure 1) provides a visual representation of a hazard, the potential causes that could lead to a hazardous event, the possible consequences if the event occurs, and the controls designed to prevent the causes or mitigate the consequences. This structured layout helps organisations understand how risks are managed and identify potential gaps.



<u>Fig.1 Bowtie Illustration Source: UKCAA Bowtie Training Package</u>

2.3 Methodology of Bowtie Analysis

2.4 Bowtie Analysis follows a series of structured steps to identify and manage risks effectively:

a. **Identify the Hazard:** Define the source of potential harm within the system, activity, or process.

b. **Define the Top Event:** Describe the point at which control of the hazard is lost, creating the potential for adverse outcomes.

c. **Identify Threats:** List all conditions or factors that could cause the top event to occur.

d. **Identify Consequences:** Outline the potential impacts that may result if the top event happens.

e. **Identify Preventive Controls:** Specify the measures in place to prevent each threat from leading to the top event.

f. **Identify Mitigative Controls:** Specify the measures designed to reduce or limit the consequences should the top event occur.

g. **Identify Escalation Factors and Controls:** Determine any conditions that could undermine the effectiveness of the preventive or mitigative controls, along with the actions needed to manage these weaknesses.

h. **Construct the Bowtie Diagram:** Compile all elements into a clear, logical visual representation showing the relationships between hazards, threats, controls, consequences, and escalation factors.

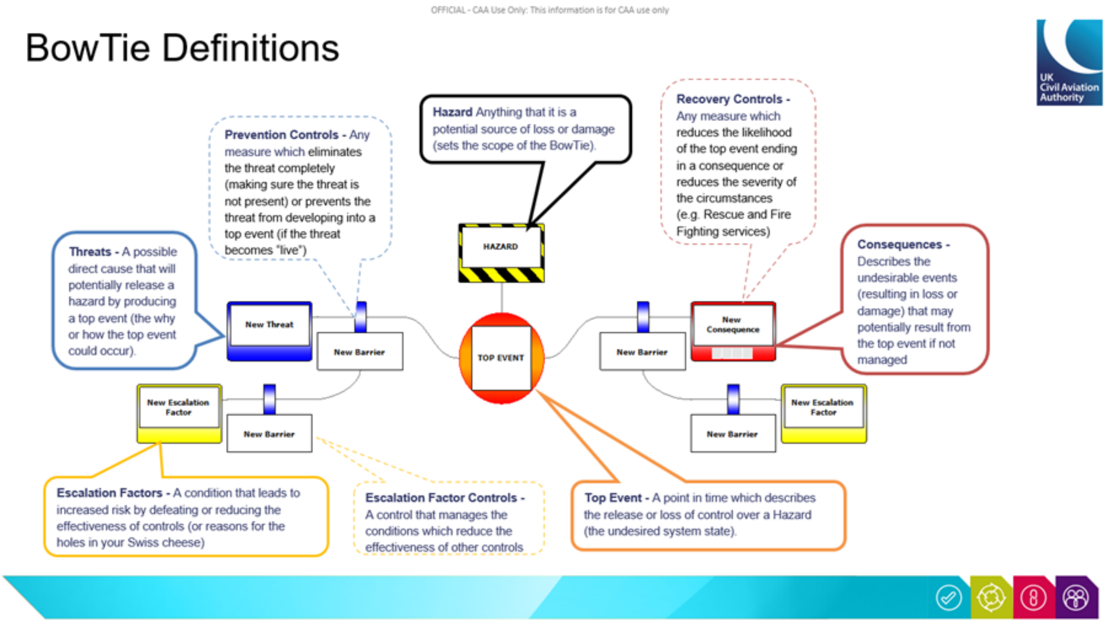


Fig.2 Bowtie Model: Source: UKCAA Bowtie Training Package:

3. Constructing a Hydrogen Bowtie Analysis in Aviation

3.1 Constructing a Bowtie Analysis for hydrogen aircraft refuelling requires a multidisciplinary team and a structured approach. Hydrogen introduces unique properties, such as its low ignition energy, rapid dispersion, cryogenic temperatures when using Liquid Hydrogen (LH_2), and high-pressure storage, which make a thorough and systematic risk assessment essential.

3.2 Bowtie Strategy and Way Forward

3.3 Following an initial in-person meeting, which facilitated the establishment of rapport, the development of trust, and a shared understanding of programme objectives, it was agreed to adopt a structured schedule of subsequent virtual meetings. These meetings provided regular, formalised opportunities to review progress, clarify decisions, validate underlying assumptions, and address emerging risks or issues in a timely manner.

3.4 This combined approach, integrating an initial face-to-face engagement with a planned series of virtual interactions, provided a balanced and effective framework for programme management. The hybrid model supported strong alignment and accountability across stakeholders, while maintaining the flexibility required to respond to evolving programme needs. Additionally, it enabled sustained stakeholder engagement while reducing travel-related costs, thereby contributing to improved efficiency and overall programme

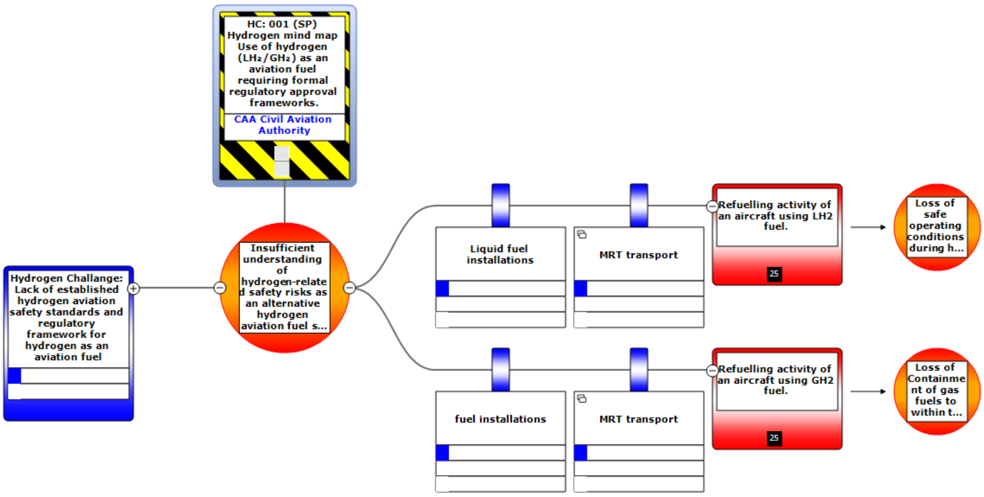
3.5 Scope Definition and Boundaries

3.6 The team agreed to structure the review around defined workstreams, with a primary focus on hydrogen refuelling activities across both landside and airside operations. This workstream was further decomposed into a series of discrete elements and stages, with the Bowtie analysis applied to provide a comprehensive assessment of associated risks and controls.

3.7 The scope of the Bowtie analysis encompassed the following key aspects:

1. **Hydrogen refuelling operations**, including all relevant activities and interfaces.
2. **Hydrogen states**, specifically Liquid Hydrogen (LH_2) and Gaseous Hydrogen (GH_2).
3. **Refuelling infrastructure**, covering both fixed installations and mobile refuelling units.
4. **Operational phases**, including aircraft arrival, connection, fuel transfer, disconnection, storage, and venting processes.
5. **Geographical boundaries**, such as aircraft stands, hydrant areas, and associated storage facilities.
6. **Environmental conditions**, including factors such as wind effects and ambient temperature.

3.8 This structured approach ensured that the analysis was comprehensive, systematic, and aligned with the operational and environmental context in which hydrogen refuelling activities are undertaken.

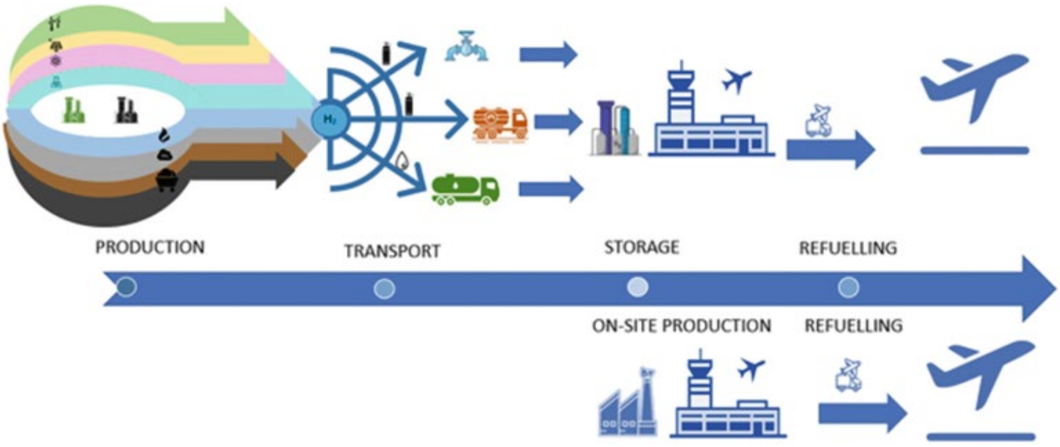


<u>Fig. 4 Bowtie Overview: Source UK CAA Bowtie Server</u>

3.9 It is widely recognised in risk analysis that Bowtie diagrams can become excessively complex, with a tendency to expand to a level that reduces clarity and usability. To mitigate this, it was agreed to structure the assessment into three distinct areas: hydrogen refuelling infrastructure, hydrogen transportation, and aircraft refuelling.

3.10 Following careful consideration, the team determined that the initial focus should be on aircraft refuelling using gaseous hydrogen (GH_2), as this reflects the current approach adopted in operational trials and offers the greatest opportunity for practical learning and insight.

3.11 The methodology developed for the aircraft refuelling Bowtie was intended to serve as a standardised template for subsequent analyses, including those addressing refuelling installations and hydrogen transportation. Accordingly, this report concentrates on the completed Bowtie for aircraft refuelling using gaseous hydrogen (GH_2).



<u>Fig 5. Hydrogen Infrastructure and Logistics in Airports Springer Nature Link</u>

3.12 Hazard Identification

3.13 The Civil Aviation Authority (CAA) requires that all Bowtie analyses relating to hydrogen aircraft refuelling are founded on a clearly defined, succinct, and consistently applied hazard statement. This hazard shall represent the inherent presence and energy potential of hydrogen (in both gaseous and liquid states) under conditions of storage, transfer, and handling, and must remain distinct from the events or outcomes that may arise from it.

3.14 A standardised hazard definition is essential to ensure consistency, comparability, and scalability of Bowtie models across refuelling installations and airside hydrogen operations. It provides a stable analytical basis from which credible top events, threats, consequences, and control measures can be systematically identified and assessed.

3.15 The CAA will maintain this hazard definition as a common reference point within its Bowtie framework, enabling effective governance, periodic review, and incorporation of operational learning. Industry stakeholders are expected to align with this approach to support a shared and coherent understanding of hydrogen-related risks, thereby promoting consistent safety practices across the aviation sector.

3.16 The team agreed on a single, well-defined hazard:

3.17 **Hazard:** HC.LH2 1.3 (SP): Liquid hydrogen (LH_2) aircraft refuelling Liquid hydrogen (LH_2) used for aircraft refuelling operations

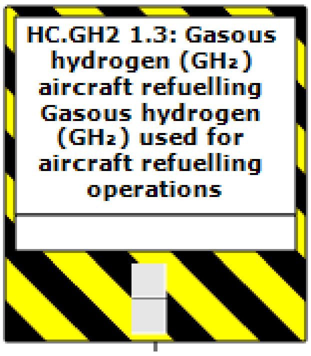


Fig. 7 Hydrogen Refuelling Hazard: Source UK CAA Bowtie Server

3.18 **Define the Top Event**

3.19 Defining the top event as the point of loss of control of hydrogen ensures a structured, consistent, and prevention-focused safety framework, allowing all refuelling scenarios to be assessed against a single, meaningful threshold: the moment hydrogen is no longer contained within the intended system.

a) Uncontrolled release of hydrogen.

b) Loss of containment from hose or coupling.

c) Ignition of released hydrogen.

3.20 With the team agreeing on one primary top event:

3.21 **Top Event:** Loss of safe operating conditions during hydrogen refuelling of the aircraft.

Fig 8. Hydrogen Refuelling top Event: Source UK CAA Bowtie Server

3.22 Identify Threats (Causes of the Top Event)

3.23 Drawing on previous incident reports and identified potential causes, the team undertook a structured threat identification exercise to identify all credible threats, including:

a) Hose, coupling, or connection failure during refuelling.

b) Over pressurisation of refuelling system or aircraft tank.

c) Human error in refuelling operations.

d) Equipment failure (valves, sensors, control system).

e) External impact or damage to refuelling system.

3.24 Threats were placed on the left side of the Bowtie

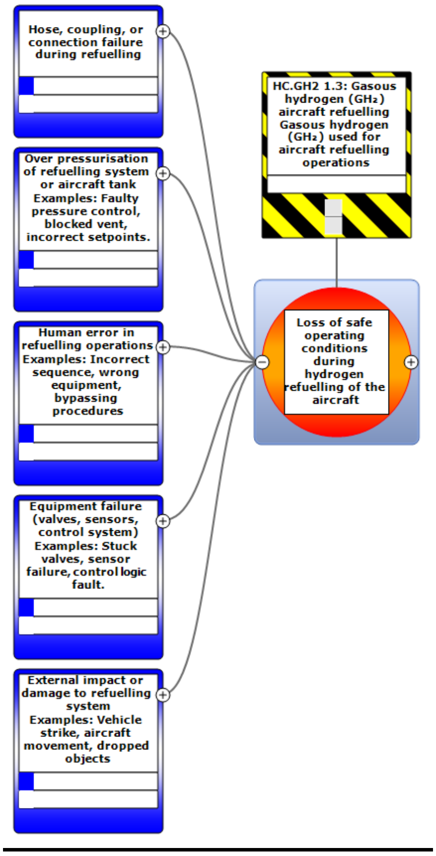


Fig 9 Hydrogen Refuelling Threats: Source UK CAA Bowtie Server

3.25 Identify Preventive Controls (to stop the top event)

3.26 The identification and implementation of effective controls is a fundamental element of the Bowtie methodology, as it directly influences the management and reduction of risk. Controls were therefore defined to be specific, actionable, and explicitly linked to individual threats to ensure clarity of purpose and accountability. This level of precision is essential in avoiding ambiguity and ensuring that each control can be understood, implemented, and maintained effectively within an operational environment.

3.27 Establishing well-defined controls enables the proactive prevention of incidents by interrupting the pathway between threats and the top event. It also provides assurance that appropriate safeguards are in place and functioning as intended. Furthermore, clearly articulated controls support monitoring and verification activities, allowing their effectiveness to be assessed over time and adjusted where necessary.

3.28 By ensuring that controls are robust, targeted, and measurable, the team strengthened the overall integrity of the risk management framework and enhanced confidence that identified risks can be effectively controlled. A selection of illustrative examples is provided below (noting that this is not an exhaustive list).

a) Certified hydrogen rated couplings and pressure relief valves

b) Automatic leak detection sensors

c) Pre refuel equipment inspection protocols

d) Earthing/bonding procedures

e) Interlocks preventing connection under pressure

f) Trained and authorised refuelling operators

g) Ground markings and vehicle exclusion zones

h) Purge verification procedures

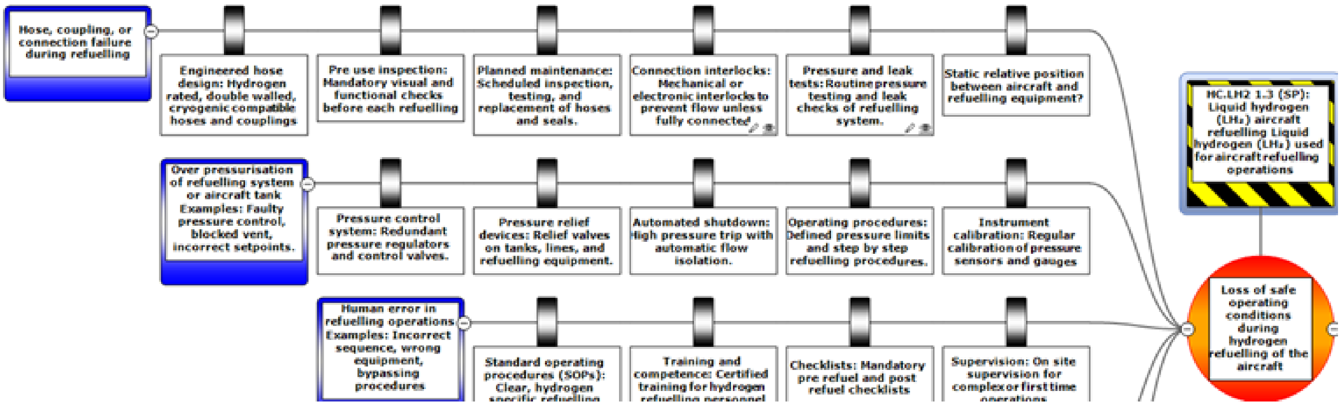


Fig 10 Hydrogen Refuelling Threats Controls: Source UK CAA Bowtie Server

3.29 Identify Consequences (outcomes if the top event occurs)

3.30 On the right-hand side of the diagram, the team identified and documented potential consequences arising from the top event. This step is critical, as a comprehensive understanding of consequences ensures that the full range of potential outcomes—across safety, operational, environmental, and reputational domains, is considered. It also enables the prioritisation of risks based on their potential severity and impact.

3.31 By systematically defining consequences, the team was able to ensure that appropriate mitigative controls and recovery measures were identified and aligned to each outcome. This supports informed decision-making, enhances preparedness, and strengthens overall risk management by ensuring that credible worst-case scenarios are neither overlooked nor underestimated.

3.32 Examples of identified consequences include:

a) Hydrogen fire (jet fire, pool fire, or flash fire)

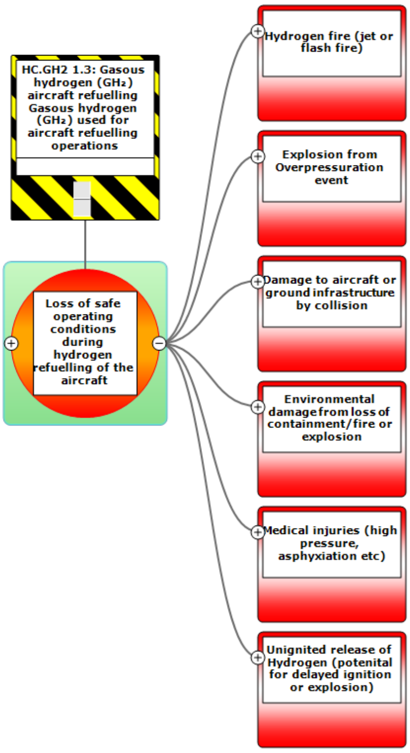
b) Over-pressurisation leading to Explosion

c) Damage to aircraft or ground infrastructure

d) Environmental damage due loss of containment/fire/explosion

e) Cryogenic injury/fatality to personnel (cold burns, frostbite, asphyxiation)

f) Unignited release of Hydrogen (potential for delayed ignition or explosion)



<u>Fig 11 Hydrogen Refuelling Consequences: Source UK CAA Bowtie Server</u>

3.33 Identify Mitigative Controls (to limit consequences)

3.34 Mitigative controls are a critical component of the Bowtie methodology, as they address the management of consequences once the top event has occurred. While preventative controls aim to stop an incident from happening, mitigative controls focus on limiting the severity, spread, and impact of the event, thereby reducing harm to people, assets, the environment, and operations.

3.34 The importance of mitigative controls lies in recognising that not all incidents can be prevented, particularly in complex or innovative systems such as hydrogen operations. As such, a robust risk management framework must account for residual risk and ensure that effective recovery measures are in place. These controls provide resilience within the system, ensuring that, even in the event of failure, outcomes can be contained and managed in a controlled and predictable manner.

3.36 By linking mitigative controls directly to specific consequences, the team ensured that each potential outcome was supported by appropriate response measures. This alignment strengthens emergency preparedness, supports effective incident response, and enables a more targeted allocation of resources. Additionally, clearly defined mitigative controls enhance stakeholder confidence by demonstrating that credible worst-case scenarios have been anticipated and addressed.

3.37 Mitigative controls, by design, activate after the top event occurs and are essential in preventing escalation. A selection of illustrative examples is provided below (noting that this is not an exhaustive list).

a) Gas detection system: Fixed and portable hydrogen detectors with alarms

b) Automatic shutdown: Emergency shutdown (**ESD**) to isolate flow on detection.

c) Flame detection: UV/IR flame detectors suitable for hydrogen’s low visibility flame.

d) Firefighting capability: Trained airport fire service with hydrogen specific procedures.

e) Emergency response plan: Defined roles, communication, and evacuation procedures.

f) Separation distances: Layout to minimise exposure of critical assets.

g) RFFS rapid response procedures: To mobilise immediately upon notification of an incident involving hydrogen.

h) Stand evacuation procedures: For the safe and orderly evacuation of passengers, crew, and ground personnel during a hydrogen related emergency.

i) Remote action emergency stops controls: that enables the immediate shutdown of hydrogen supply systems. These controls must be highly visible, fail safe, and accessible to trained personnel.

j) Protective PPE for operators: All personnel engaged in hydrogen related handling, maintenance, or emergency response activities are equipped with the appropriate level of physical protection.

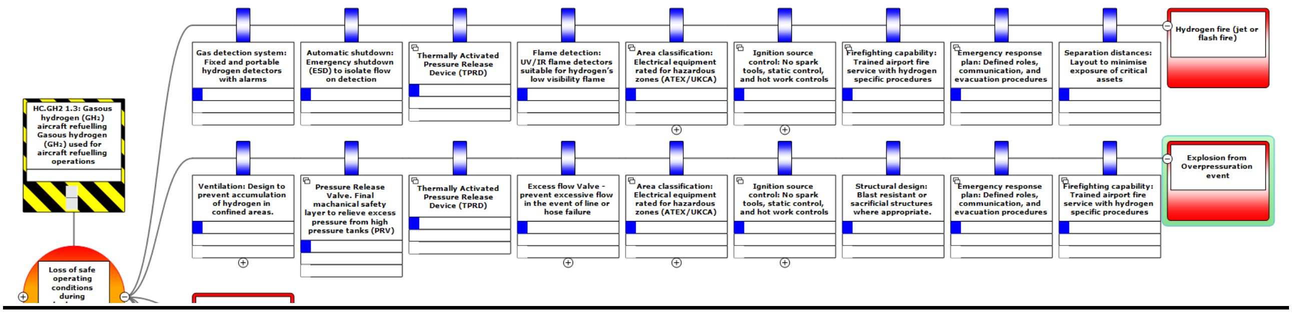


Fig 12 Hydrogen Refuelling Consequences Controls: Source UK CAA Bowtie Server

3.38 Identify Escalation Factors and Escalation Controls

3.39 Escalation factors are an essential element of the Bowtie methodology, as they ensure the analysis reflects real-world conditions and recognises that controls are not infallible. These factors represent conditions or circumstances that can degrade, weaken, or entirely defeat the effectiveness of a control if not properly managed.

3.40 Their inclusion is critical in moving the analysis beyond a purely theoretical model to one that accurately captures system vulnerabilities. Without considering escalation factors, there is a risk of overestimating the reliability of controls and underestimating residual risk. By explicitly identifying these weaknesses, the team is better able to understand where controls may fail and under what conditions.

3.41 Furthermore, escalation factors support the identification of secondary or "control of control" measures, often referred to as escalation factor controls. These are additional safeguards designed to prevent or mitigate the impact of the escalation factor itself, for example, maintenance regimes, competency assurance, supervision, or environmental monitoring. This layered approach strengthens overall system resilience and reduces the likelihood of simultaneous or cascading failures.

3.42 Incorporating escalation factors also enhances operational awareness by highlighting dependencies such as human performance, environmental conditions, equipment reliability, and organisational processes. This enables more informed decision-making, improved contingency planning, and targeted assurance activities.

3.35 Typical examples of escalation factors include conditions such as adverse weather, equipment degradation, human error or fatigue, inadequate training, or failures in inspection and maintenance regimes. By identifying and addressing these factors, the Bowtie model provides a more realistic and robust representation of risk, ensuring that both controls and their potential limitations are fully understood and actively managed.

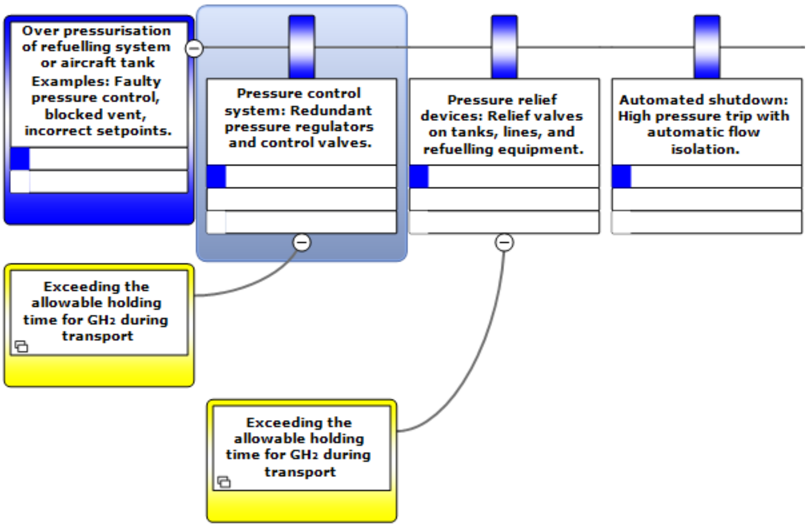


Fig 13 Hydrogen Refuelling Escalating Factors: Source UK CAA Bowtie Server

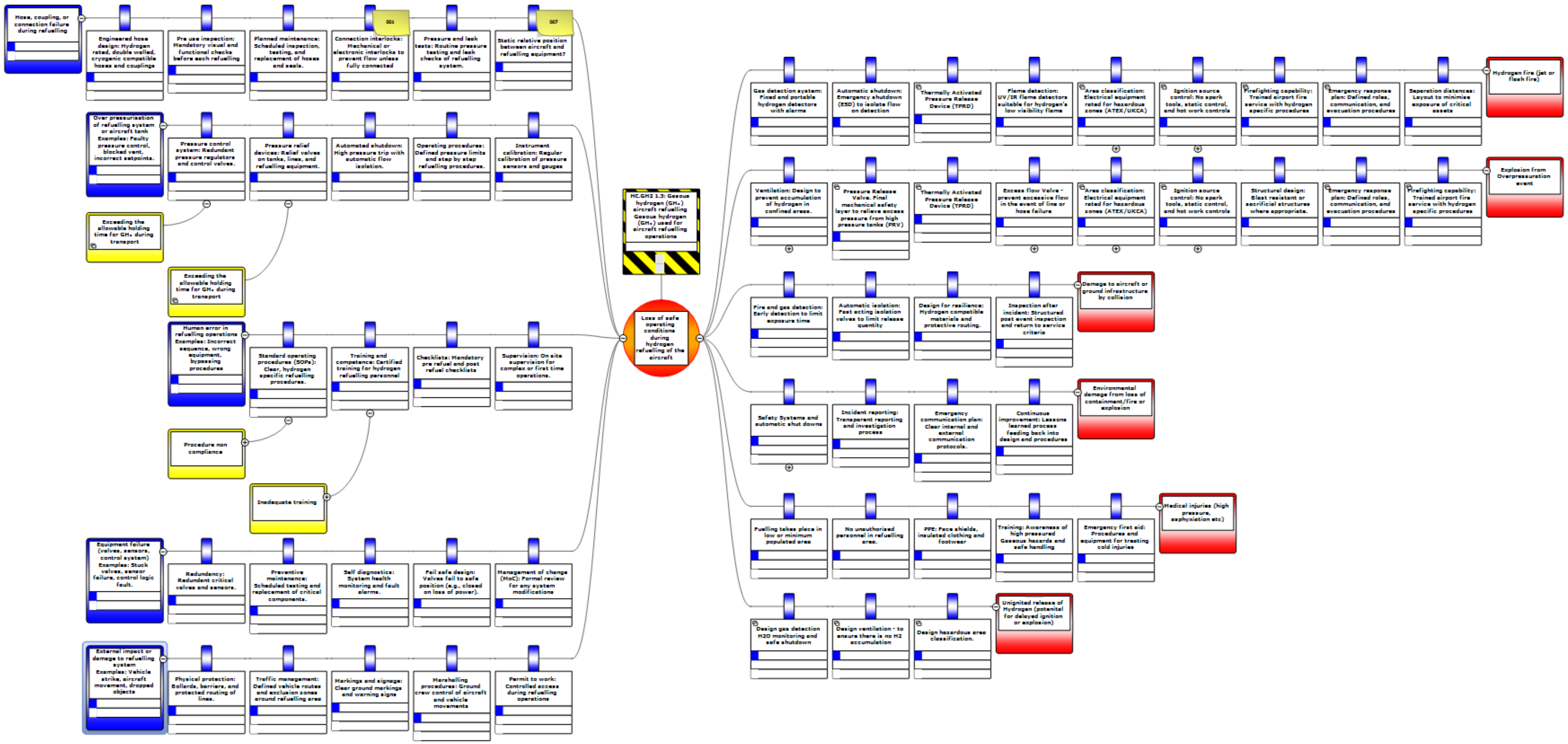
3.36 Build the Bowtie Diagram

3.37 The involvement of a Bowtie specialist from the Performance Based Regulation (PBR) Team was integral to ensuring the quality, consistency, and robustness of the analysis. Their expertise provided assurance that the methodology was applied correctly and in line with established best practice, thereby enhancing the credibility and reliability of the outputs.

3.38 The specialist supported the structured development of the Bowtie by guiding the identification and appropriate placement of threats, consequences, controls, and escalation factors. This ensured that the analysis remained logically coherent, clearly articulated, and aligned with recognised risk assessment principles. In addition, their experience enabled effective challenge and validation of assumptions, helping to identify gaps, inconsistencies, or areas requiring further refinement.

3.39 All elements of the Bowtie were mapped using dedicated Bowtie software, which provided a systematic and standardised platform for developing the analysis. The use of specialist software enhanced clarity and traceability by enabling relationships between threats, controls, escalation factors, and consequences to be clearly visualised and consistently structured. It also supported version control, collaboration, and ease of future updates, ensuring that the Bowtie remains a living tool that can evolve alongside operational and regulatory developments.

3.40 Overall, the combination of specialist expertise and appropriate tooling significantly strengthened the rigour, transparency, and usability of the Bowtie assessment.



<u>**Fig 14 Hydrogen Refuelling Bowtie diagram: Source UK CAA Bowtie Server**</u>

4. Key Observations and Recommendations

4.1 Developing hydrogen Bowtie analyses remains challenging due to the early-stage maturity of hydrogen technologies in aviation. A key limitation is the scarcity of operational experience and incident data, which necessitates a strong reliance on expert judgement and the extrapolation of insights from hydrogen applications outside aviation. Additionally, the rapid evolution of hydrogen-powered aircraft designs, refuelling infrastructure, and emerging regulatory frameworks means that analyses can quickly become outdated, requiring frequent review and revision.

4.2 Hydrogen's unique properties (*rapid dispersion, invisible flames, wide flammability limits, and cryogenic behaviour*) introduce complexities not typically found with conventional fuels. This makes it hard to define an appropriate top event. It also complicates the structuring of credible threat and consequence pathways without making the model too complex. Hydrogen operations span multiple domains: aircraft, ground systems, storage, and emergency response. These domains have significant interdependencies and require input from various stakeholders with differing risk perceptions.

4.3 Emergency response capabilities for hydrogen are still emerging. This makes it harder to quantify barrier effectiveness and human performance. Representing barriers clearly, independently, and verifiably can also be challenging. Finally, many potential failure modes and escalation factors can lead to visually dense Bowties.

5. Key Observations from the Bowtie Analysis

5.1 The hydrogen refuelling Bowtie analysis highlights the following key findings:

a) An elevated risk of hydrogen release during transfer and connection activities.
b) The need for high-integrity detection and isolation systems, reflecting the unique physical properties of hydrogen.
c) Gaps in standardised procedures, training, and emergency response arrangements for hydrogen-related incidents.
d) The requirement for upgraded infrastructure and greater technical harmonisation across aerodromes.
e) Opportunities for the Civil Aviation Authority (CAA) to develop new policy frameworks and regulatory guidance.
f) The necessity to equip all personnel involved in hydrogen handling operations with role-specific personal protective equipment (PPE).

5.2 These observations align with recognised challenges associated with hydrogen aviation and considerations relating to public safety and confidence.

5.3 The completion of the hydrogen Bowtie analysis has informed a series of recommendations aimed at ensuring that identified risks are effectively controlled and reduced to a level that is demonstrably As Low As Reasonably Practicable (ALARP). While the Bowtie framework identifies existing control measures and associated vulnerabilities, the recommendations provide a practical pathway to strengthen these barriers, address identified gaps, and enhance organisational preparedness for hydrogen-related hazards.

5.4 Collectively, these recommendations translate analytical findings into actionable measures, supporting improvements in prevention, detection, mitigation, and emergency response. This approach enables organisations to adapt to the distinct properties of hydrogen, alongside the evolving technologies and operational challenges associated with its use in aviation.

Safety Controls and Barrier Enhancements

a) Strengthen physical safety barriers around storage and refuelling zones

b) Incorporate enhanced separation distances, fire protection systems, controlled access areas and hydrogen specific hazard signage. These are required due to hydrogen's lower ignition energy and cryogenic properties.

Install advanced leak detection and automatic isolation systems

a) Deploy continuous hydrogen monitoring with consideration given to automated shutdown capability to prevent escalation during refuelling activities. Hydrogen safety trials in the Sandbox confirm the need for validated mitigation measures.

Operational Procedures

a) Establish standardised hydrogen refuelling procedures across UK aerodromes

b) Include pre refuelling checks, venting requirements, safe connection methods, and post refuelling confirmation processes. Standardisation supports regulatory readiness and mitigates operational variance.

Enhance emergency response protocols

a) Evaluate potential hydrogen-related incidents, agree inter-agency roles, responsibilities and emergency response procedures

b) Integrate the hydrogen response procedures into the aerodrome emergency response plan (or similar)

c) Validate the emergency response plan by incorporating hydrogen-specific scenarios, including invisible flame detection, cryogenic burn management, and hydrogen release events. Because hydrogen presents unique hazards, aerodrome emergency planning must be tailored to address these distinct risks effectively.

Implement dynamic pre task risk assessments

a) Assess environmental conditions, equipment status, and operator competence before each refuelling activity.

Infrastructure and Technology

a) Upgrade refuelling infrastructure based on identified failure pathways

b) Address vulnerabilities in connectors, hoses, pumps, and tanks. Hydrogen infrastructure modifications are a key focus of Hydrogen Challenge development.

c) Standardise refuelling interfaces across manufacturers

d) Integrate predictive maintenance and monitoring systems

e) Use real time temperature, pressure, and flow monitoring to detect early deterioration.

Regulatory and Assurance Measures

a) Develop CAA endorsed standards and guidance for hydrogen refuelling.

b) Use Bowtie outputs to shape acceptable means of compliance, new regulations, and certification materials.

c) The Hydrogen Challenge explicitly aims to develop hydrogen related policies as indicated below.

d) Establish a national hydrogen refuelling safety case template

e) Ensure consistency in aerodrome submissions and regulatory review processes.

f) Implement hydrogen specific Safety Performance Indicators (SPIs)

g) Examples: frequency of detected leaks, detector reliability, isolation system activation rates.

Competence, Training and Culture

a) Deliver hydrogen specific operator training programmes

b) Focus on hydrogen behaviour, thermodynamics, ignition risk, PPE, and emergency procedures. Training needs are highlighted as a major industry gap.

Develop a certification scheme for hydrogen refuelling operatives

a) Support regulatory consistency and public confidence.

b) Conduct multi agency emergency response exercises

c) Collaborate with RFFS, airport operators, manufacturers, and first responders to validate hydrogen emergency procedures.

Continuous Improvement

a) Integrate Bowtie results into ongoing Safety Management Systems

b) Update the Bowtie as new test data emerges from the Hydrogen Challenge and Sandbox trials.

c) Facilitate cross industry knowledge sharing

d) Support the CAA's aim to improve understanding of hydrogen related challenges across academia, industry, and regulators.

e) Conduct periodic independent assurance reviews

f) Ensure controls remain effective as technologies evolve.

6. Conclusion

6.1 The hydrogen refuelling Bowtie analysis confirms the importance of enhanced safety controls, improved operational consistency, upgraded infrastructure, and strengthened regulatory support. Implementing these recommendations will help ensure safe, consistent, and future-proof hydrogen refuelling operations across UK aerodromes.

6.2 Aligned with the objectives of the Hydrogen Challenge, these actions will contribute to increased regulatory readiness, improved industry collaboration, and greater public confidence as hydrogen moves toward operational deployment in UK aviation.

7. Application of Hydrogen Bowtie Analyses

7.1 Looking ahead, the Civil Aviation Authority (CAA) intends to broaden the scope of its Bowtie analyses to encompass additional hydrogen-related operational scenarios. This will include refuelling installations and the airside transportation of hydrogen in both gaseous (GH_2) and liquid (LH_2) states. Expanding the framework in this way will provide a more comprehensive understanding of risk across the hydrogen aviation ecosystem, ensuring that safety considerations are addressed consistently from fuel delivery through to aircraft operations.

7.2 In parallel, arrangements will be established to ensure that these Bowtie analyses remain living products, capable of evolving alongside technological advances, regulatory developments, and operational experience. The CAA will maintain and govern the Bowties through structured processes, ensuring they are periodically reviewed, updated, and aligned with emerging evidence and recognised best practice.

7.3 Industry stakeholders will be encouraged to adopt these Bowtie models as practical risk management tools. They are intended to support aerodrome operators, fuel providers, ground handlers, and emergency responders in understanding hazard pathways, identifying critical control measures, and aligning local procedures with regulatory expectations. In this way, the Bowties will serve both as a regulatory reference and an operational aid, promoting consistency and a shared understanding of risk across the sector.

7.4 Incident and near-miss investigations will play a central role in identifying weaknesses or failures in existing control measures. Lessons identified from such events will be systematically fed back into the Bowtie framework, enabling controls to be strengthened, refined, or supplemented as necessary.

7.5 Finally, formal review mechanisms, including periodic risk assessments and scheduled updates to the Bowtie analyses, will ensure that control measures remain appropriate in light of operational changes, infrastructure developments, and advances in hydrogen technologies.

7.6 Together, these elements establish a continuous feedback loop in which controls are not only implemented but actively managed, validated, and improved over time. This approach supports a dynamic, evidence-based safety framework, enabling both the CAA and industry to respond effectively to the evolving challenges associated with hydrogen in aviation.