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UK Civil Aviation Authority

CAA Hydrogen Challenge

Hydrogen Fuel Cell Bowtie Analysis Report

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Contents

UK Civil Aviation Authority

Disclaimer

This document does not represent a formal CAA position or decision regarding to any current or future regulatory matters. It provides an overview of the methodology used to construct several selected Bowtie analyses relating to the management of hydrogen as an aviation fuel. The purpose of this material is to support future discussion on whether additional policy development or regulatory intervention may be warranted.

1. Executive Summary

The development of safe and reliable hydrogen Fuel Cell 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 Fuel Cells on aircraft. The analysis identifies key hazards, credible event pathways, and potential consequences linked to hydrogen Fuel Cell installations in aircraft. It demonstrates that the Bowtie methodology is well suited to evaluating this emerging Fuel Cell technology, 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.

The work forms part of the CAA's multi-year Hydrogen Challenge Programme, which aims to ensure the safe introduction of hydrogen as an aviation fuel by addressing safety risks, regulatory gaps, and evidence requirements across aircraft and aerodrome operations. Hydrogen's unique physical and chemical properties, including low ignition energy, cryogenic storage, and novel system behaviours, create a distinct risk landscape that must be systematically understood before large scale deployment.

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 has developed a Bowtie analysis for hydrogen Fuel Cell systems on an aircraft. 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 continue to explore hydrogen 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 is required, the 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 development of the Bowtie analyses 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.

2. Introduction

The transition toward hydrogen powered aircraft introduces a new set of technical, operational, and safety considerations for civil aviation. 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 systematic and transparent methods for understanding and managing these emerging risks are adopted.

A Bowtie analysis was therefore undertaken to provide a structured, visual representation of how a hydrogen Fuel Cell installation in an aircraft 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 aircraft and propulsion system manufacturers, airlines, 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.

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.

This analysis forms a foundational component of the broader hydrogen integration programme, ensuring that manufacturers can plan for safe introduction of Fuel Cell propulsion systems, 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 Fuel Cell are being systematically identified, evaluated, and controlled.

3. History and Development of Bowtie Analysis

3.1 Concept of Bowtie Analysis

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.

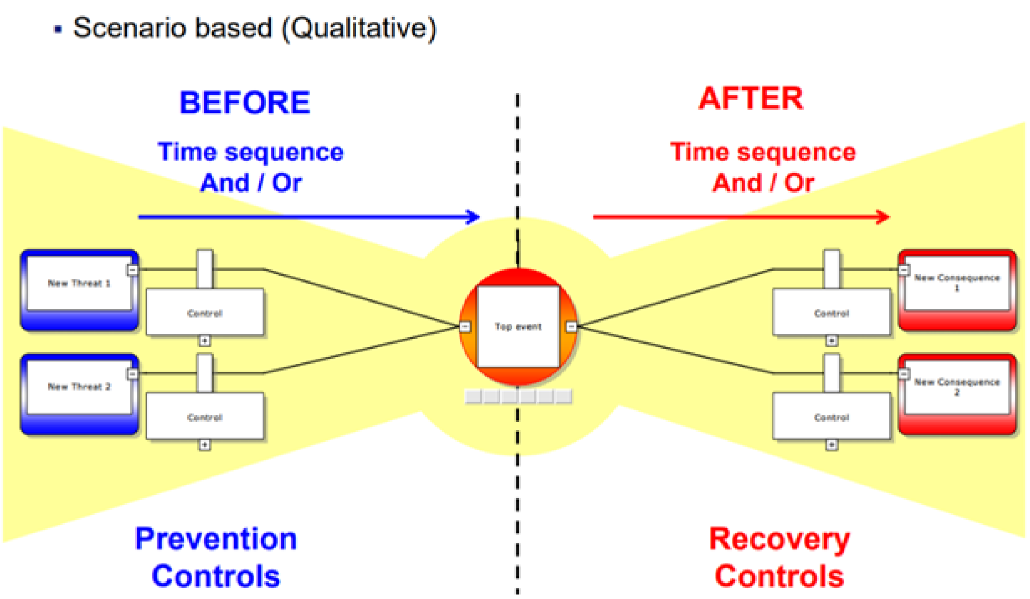

Fig.1 Bowtie Illustration Source: UKCAA Bowtie Training Package

3.2 Methodology of Bowtie Analysis

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

1. Identify the Hazard: Define the source of potential harm within the system, activity, or process.
2. Define the Top Event: Describe the point at which control of the hazard is lost, creating the potential for adverse outcomes.

3. Identify Threats: List all conditions or factors that could cause the top event to occur.
4. Identify Consequences: Outline the potential impacts that may result if the top event happens.
5. Identify Preventive Controls: Specify the measures in place to prevent each threat from leading to the top event.
6. Identify Mitigative Controls: Specify the measures designed to reduce or limit the consequences should the top event occur.
7. 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.
8. Construct the Bowtie Diagram: Compile all elements into a clear, logical visual representation showing the relationships between hazards, threats, controls, consequences, and escalation factors.

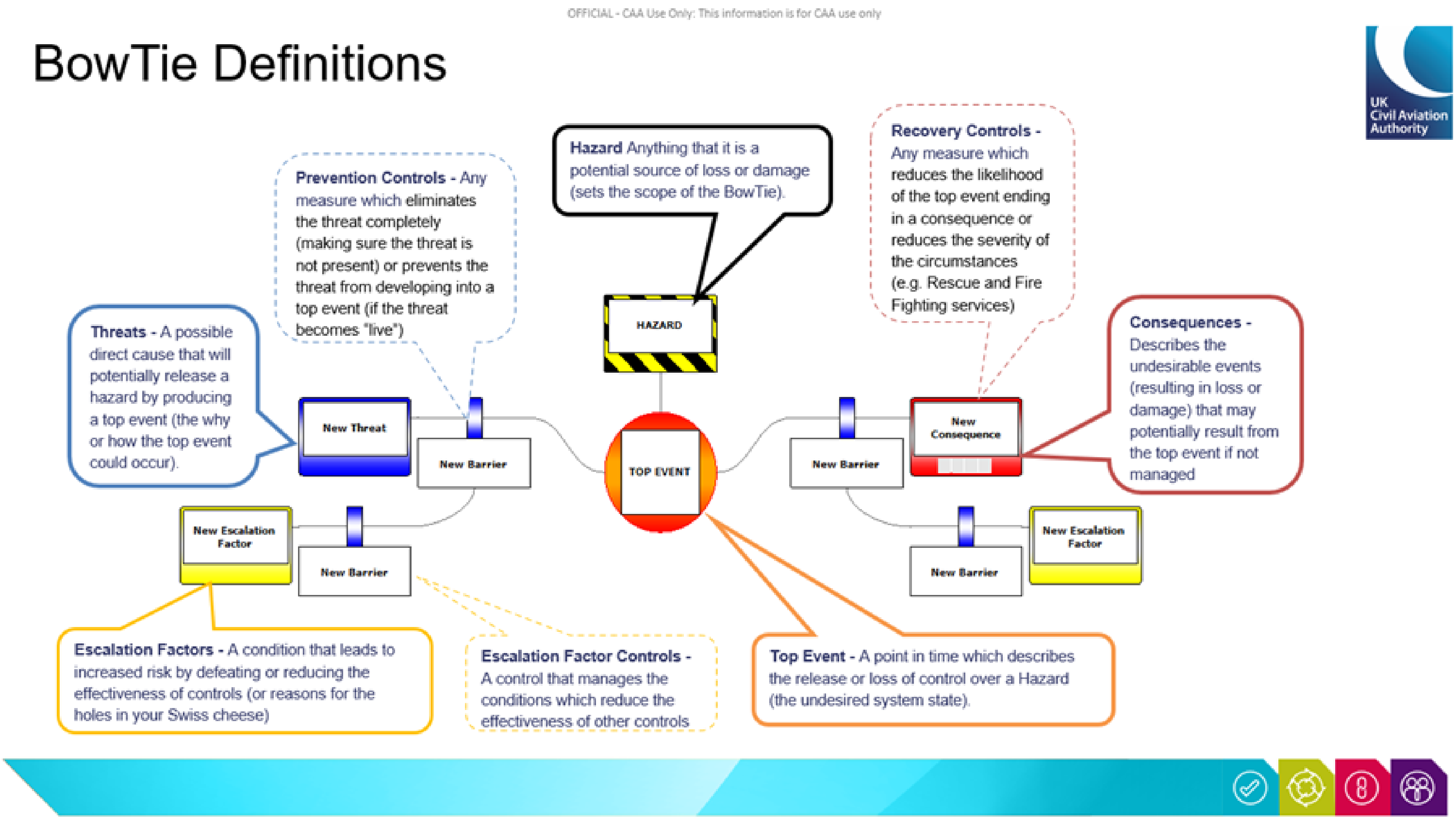

Fig.2 Bowtie Model: Source: UKCAA Bowtie Training Package:

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4. Constructing a Bowtie Analysis for Hydrogen Fuel Cells.

Conducting a Bowtie Analysis for hydrogen Fuel Cells in aircraft 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 (**LH2**), and high-pressure storage when stored in a gaseous form (G350), which make a thorough and systematic risk assessment essential.

4.1 Scope Definition and Boundaries

It was agreed to review through a series of work streams the use of a Hydrogen Fuel Cell system as the primary power source for fixed wing aircraft and examined the failure of the power supply (Fuel Cells) leading to a partial or total loss of propulsion hydrogen Fuel Cells in aircraft and aircraft electric propulsion. This was further broken into multiple stages; the Fuel Cell Bowtie covers:

1. Internal primary materials.
2. External factors
3. Control systems (software/firmware & hardware)
4. Primary Supplies to the Fuel Cell.
5. All Operational phases. (Ground operations, take-off, flight cruise and landing)

The first draft Bowties encapsulated the end-to-end aviation Fuel Cell electrical propulsion architecture; however, it soon became evident that the diagram was becoming overcomplicated as too much detail was added; this is a well-recognised issue in risk analysis and safety management.

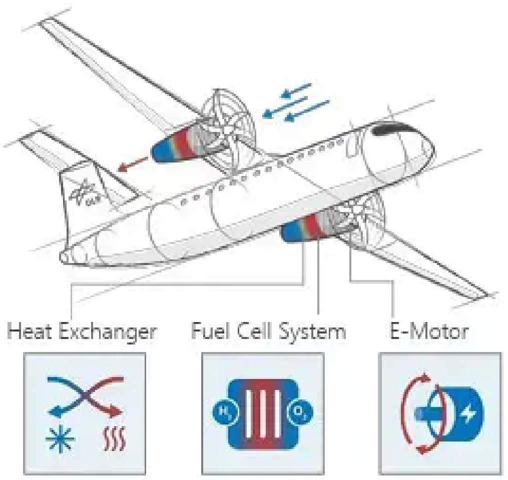


Figure 1. Fuel cell-powered aircraft

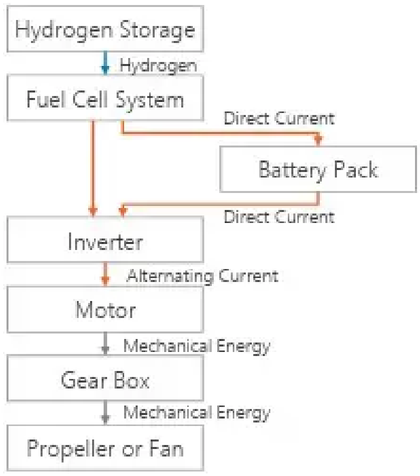


Figure 2. Fuel cell-based propulsion

Fig 3. From 'Functional and Safety Challenges of Hydrogen Fuel Cell Systems for Application in Electrified Regional Aircraft, Stefan Kazula et al 2023 J. Phys.

To maintain clarity, a decision was made to split the assessment into three stages:

1. the Fuel Cell and its primary components
2. the hydrogen on board storage,
3. the electric motor / propulsion system.

All three stages were evaluated using both Liquid Hydrogen (LH2), and a high-pressure gaseous form (G350) of hydrogen resulting in six hydrogen related Bowties. To avoid ambiguity, the remainder of this report focuses exclusively on a Hydrogen Fuel Cell system as the primary power source for fixed wing aircraft and assumes that the hydrogen fuel is conditioned ready for use in the Fuel Cell and that the electric motor / propulsion is out of scope.

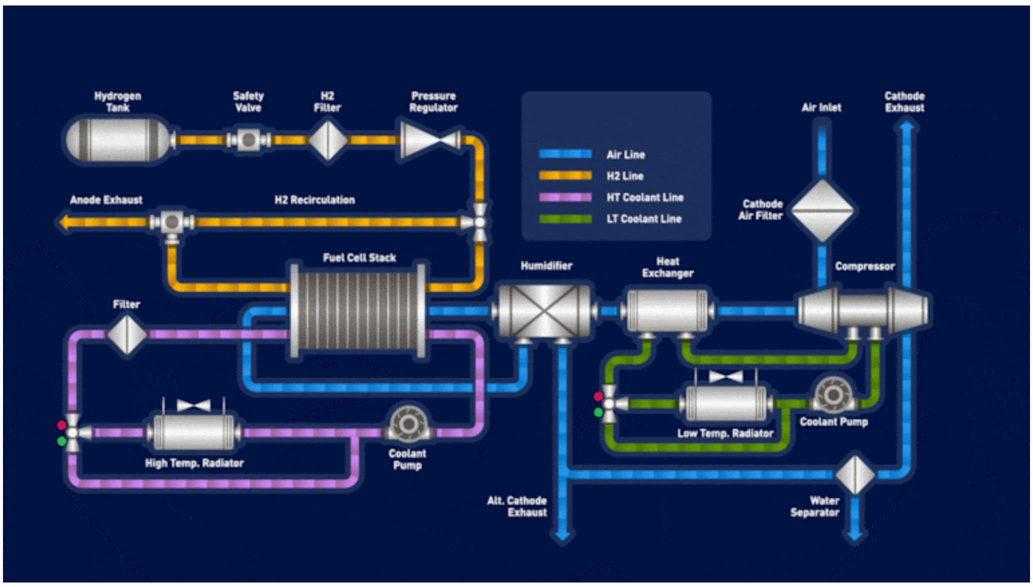


Fig 4. Working schematic of a hydrogen Fuel Cell system / Parker

4.2 Hazard Identification

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

Hazard: HC.FC.1 Use of a Hydrogen Fuel Cell system as the primary power source for fixed wing aircraft.

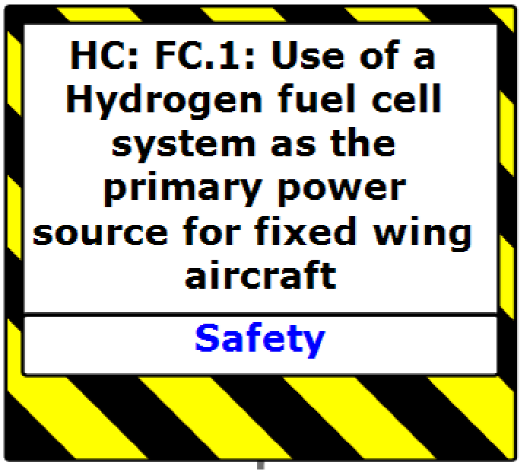


Fig. 5 Hydrogen Fuel Cell Hazard: Source UK CAA Bowtie Server

4.3 Define the Top Event

The top event is the point at which control of the hazard is lost and the following scenarios were discussed:

1. Uncontrolled release of hydrogen.
2. Loss of power from Fuel Cell.
3. Ignition of released hydrogen.

Also, the team agreeing on one primary top event:

Top Event: Failure of power supply (Fuel Cells) leading to partial or total loss of propulsion.

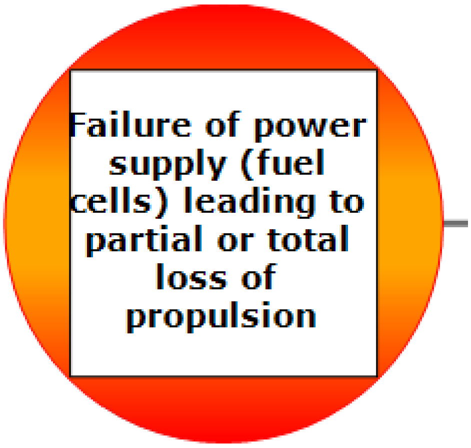


Fig 6. Hydrogen Fuel Cell top Event: Source UK CAA Bowtie Server

4.4 Identify Threats (Causes of the Top Event)

Using previous incident reports and predicated causes the team brainstormed all credible threats, which included:

1. Failure / fatigue of internal Fuel Cell primary materials
2. External factors resulting in Fuel Cell Failure
3. Failure of Fuel Cell control systems (software / firmware) and hardware
    a) Examples: Stuck valves, sensor failure, control logic fault.
4. Loss of Fuel Cell supplies
    a) Examples: insufficient hydrogen, blocked intakes, damaged heat exchanger,

Threats were placed on the left side of the Bowtie

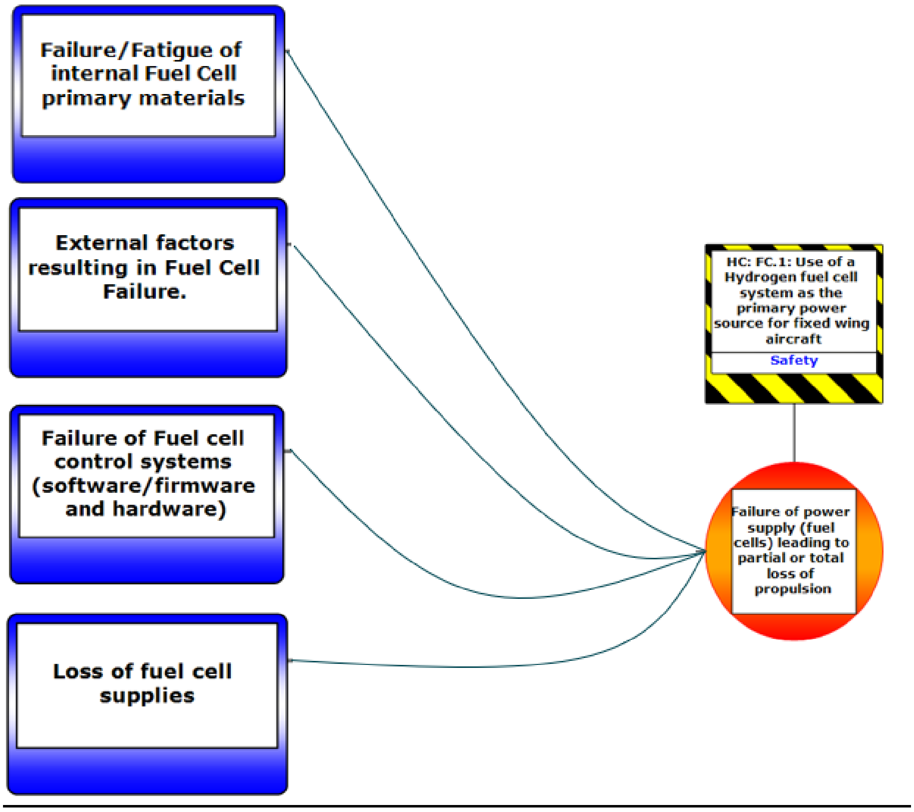


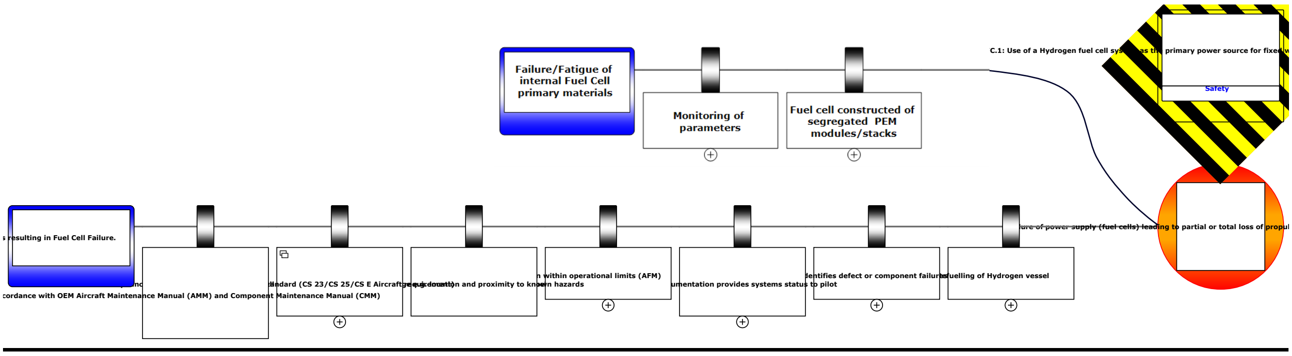
Fig 7 Hydrogen Fuel Cell Threats: Source UK CAA Bowtie Server

4.5 Identify Preventive Controls (to stop the top event)

Controls were specific, actionable and directly linked to individual threats with some examples listed below:

1. Monitoring of Parameters
2. Fuel Cell Constructed of segregated PEM modules / stacks.
3. Regular Fuel Cell / testing in accordance with OEM Aircraft Maintenance Manual (AMM) and Component Maintenance Manual (CMM).
4. Compliance with appropriate certification standard (CS 23/CS 25/CS E Aircraft requirement).
5. Fuel Cell protection against physical damage e.g. location and proximity to known hazards.
6. Fuel Cell Control System (FCCS) instrumentation provides systems status to pilot.
7. Fuel Cell management System provides caution / warning to maintenance team about hardware failure.

8. Divergent software / firmware and operating system (OS voting system)



<u>Fig 8 Hydrogen Fuel Cell Threats Controls: Source UK CAA Bowtie Server</u>

4.6 Identify Consequences (outcomes if the top event occurs)

On the right side of the diagram, the team listed potential consequences, such as:

1. Runway Excursion during take-off or landing leading to fatalities.
2. Loss of Control in-flight leading to terrain and obstacle collision / accident.
3. Forced landing (either on airfield or remote) leading to potential injuries / fatalities.
4. Fire / explosion from Hydrogen / electrical supply leading to fatalities.

Consequences were realistic and relevant to the top event.

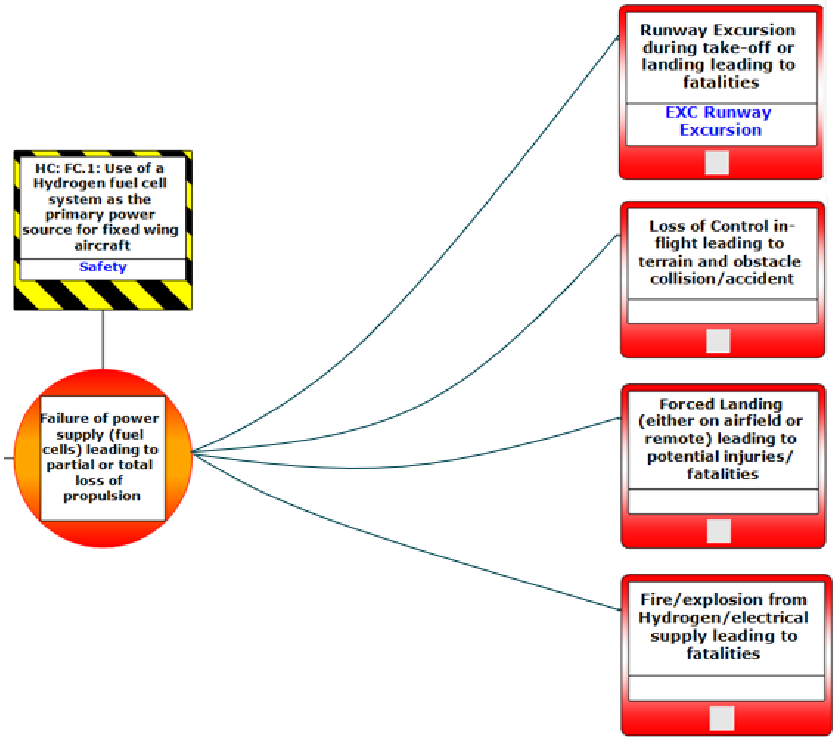


Fig 9 Hydrogen Fuel Cell Consequences: Source UK CAA Bowtie Server

4.7 Identify Mitigative Controls (to limit consequences)

These controls would be activated after the top event occurs. Mitigative controls were tied to specific consequences with some exampled recorded below:

1. Automatic System redundancies.
2. FLT Crew follows emergency procedures.
3. Backup systems (batteries as part of propulsion,) to continue flight, plus APU, Plus RAT.
4. Aerodrome emergency response plan initiated.
5. Manual Override / restart process.

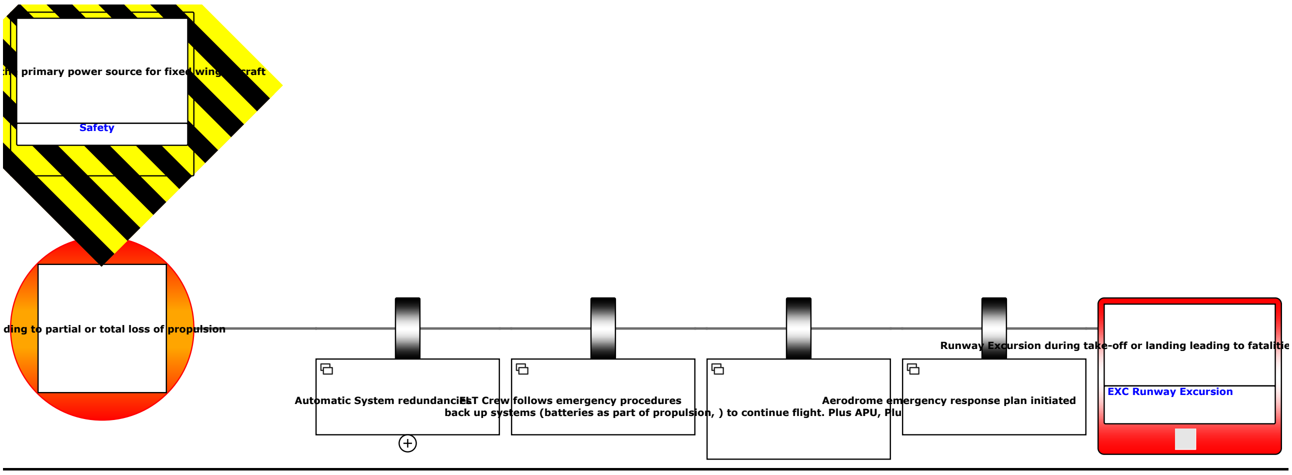


Fig 10 Hydrogen Fuel Cell Consequences Controls: Source UK CAA Bowtie Server

4.8 Identify Escalation Factors and Escalation Controls

These are conditions that can weaken a control, these ensure the Bowtie realistically reflects system vulnerabilities examples include:

4.9 Escalation Factors

1. Catalyst degradation
2. Membrane degradation
3. Water management issues
4. Electrodes
5. GDL
6. Sealing Gasket
7. Mechanical Degradation
8. Thermal Degradation
9. Wear out mechanism.
10. Sensor failure
11. Maintenance overdue

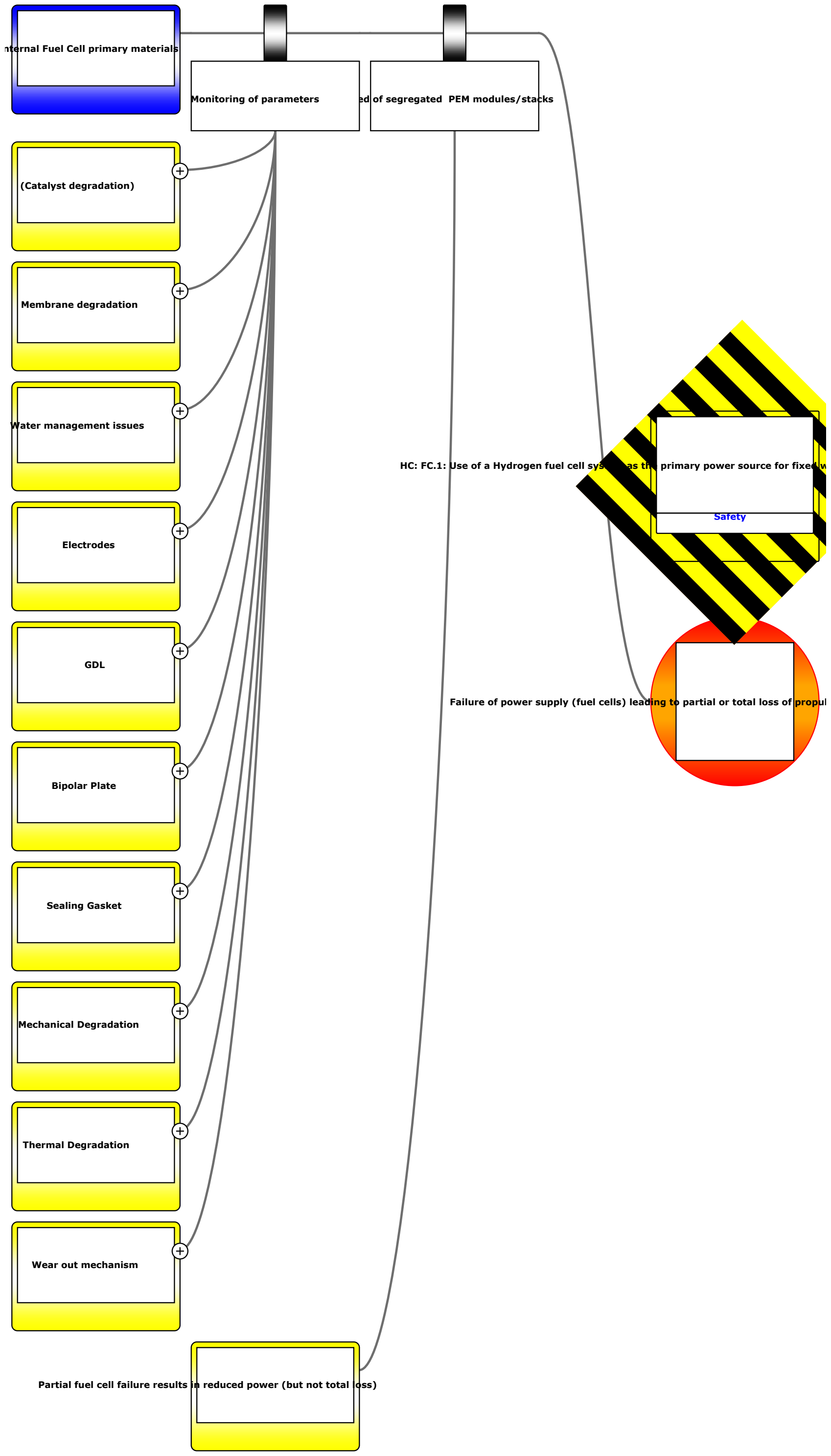


Fig 11 Hydrogen Fuel Cell Escalating Factors: Source UK CAA Bowtie Server

4.10 Escalation Factor Controls

1. Maintenance schedules.
2. Environmental monitoring.
3. Redundancy in detection equipment.

4. Operator training for adverse conditions.
5. Calibration and inspection routines.

4.11 Build the Bowtie Diagram

Using a Bowties specialist from the Performance Based Regulation Team (PBR) the team mapped all elements using Bowtie software:

1. Ensure every threat links to a preventive control.
2. Ensure every consequence has a mitigative control.
3. Avoid duplicated or generic controls.
4. Assign ownership for each barrier.
5. Note any barrier weakness or gaps.

This forms the foundation of the safety case.

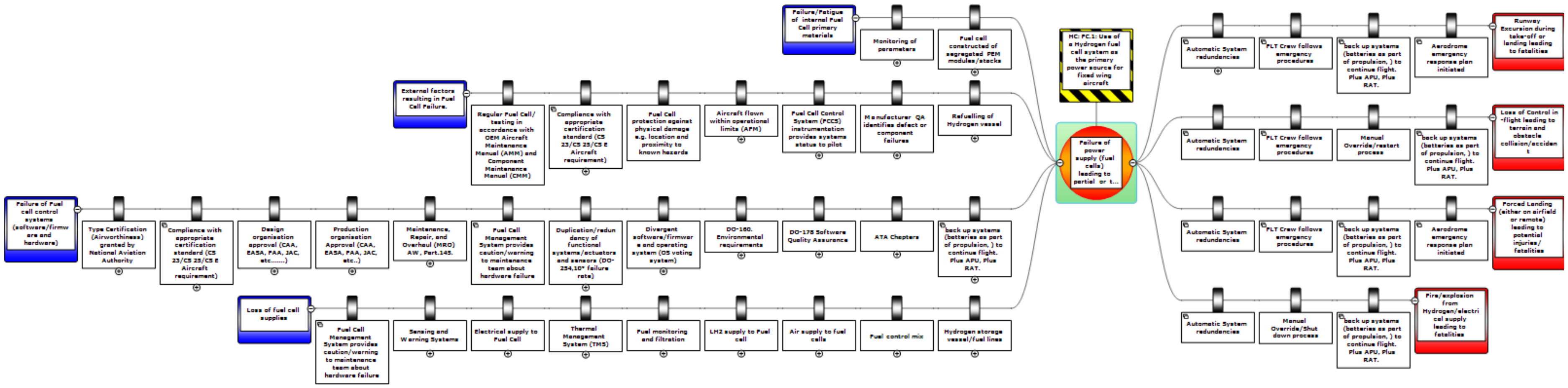


Fig 12 Hydrogen Fuel Cell Bowtie diagram: Source UK CAA Bowtie Server

5. Key Observations and Recommendations

Developing a Hydrogen Bowtie analysis 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, divergent architectures, and emerging regulatory frameworks means that analyses can quickly become outdated, requiring frequent review and revision.

Hydrogen’s unique properties (rapid dispersion, invisible flames, wide flammability limits, and cryogenic behaviour) introduce complexities not typically found with conventional fossil 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.

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.

5.1 Validate the Bowtie

To ensure validity, accuracy and credibility the team will conduct a validation exercise.

Validation involved will consist of methods from:

1. Review by technical experts.
2. Cross checking with hydrogen standards (ISO & SAE)
3. Consultation with emergency services.
4. Alignment with existing non-aviation Fuel Cell risk assessments and procedures.
5. Peer review with aircraft design, aerodrome operators and airline safety teams.

5.2 Key Observations from the Bowtie Analysis

The Hydrogen Fuel Cell Bowtie analysis highlights:

1. The unknown behaviour and characterisation surrounding Fuel Cells operating in aviation.
2. The heightened risk of hydrogen release on-board the aircraft.
3. A need for high integrity detection and isolation systems due to hydrogen's physical behaviour.
4. The need to develop clear and concise hydrogen segregation legislation for future Fuel Cell powered aircraft.
5. Gaps in standardised procedures, training, and emergency response for hydrogen related incidents.
6. The requirement for upgraded infrastructure and technical harmonisation across aircraft platforms.
7. Opportunities for the CAA to develop new policies and regulatory guidance.
8. The requirement to provide all personnel involved in hydrogen handling operations with personal protective equipment (**PPE**) appropriate to their specific role and assigned tasks.

These observations directly align with known hydrogen aviation challenges and public confidence considerations.

5.3 Recommendations

In completing the hydrogen Bowtie analysis, recommendations are proposed to ensure that identified risks are effectively controlled and reduced to a level that is demonstrably as low as reasonably practicable (**ALARP**). While the Bowtie structure highlights existing barriers and their vulnerabilities, recommendations provide a pragmatic route for strengthening those barriers, addressing gaps, and improving organisational preparedness for hydrogen-related hazards. They translate analytical insights into actionable improvement measures, enhancing prevention, detection, mitigation, and emergency response capabilities, so that organisations can continually adapt to the unique properties, technologies, and operational challenges associated with hydrogen systems.

A. Safety Controls and Barrier Enhancements

1. Strengthen physical safety barriers around on-board aircraft systems and establish clear segregation zone control.

2. 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.

B. Install advanced leak detection and automatic isolation systems.

1. Deploy continuous hydrogen monitoring with consideration given to automated shutdown capability to prevent escalation when hydrogen Fuel Cell systems are operating. Hydrogen safety trials in the Sandbox confirm the need for validated mitigation measures.

C. Operational Procedures

1. Establish standardised hydrogen handling procedures across UK aerodromes where hydrogen powered aircraft will be operating.

2. Develop new pre-flight checks for hydrogen. The issue being that fossil fuels may leak and drip and be easily visible, whereas Hydrogen is known to leak at a rate of approx. 4%, so there will be a need to generate standards for safe venting requirements, innovative but failsafe hydrogen leak detection systems,

3. Hydrogen fuel standardisation supporting regulatory readiness and mitigating against operational variance.

D. Enhance emergency response protocols.

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

2. Integrate the hydrogen response procedures into the aircraft and airline emergency response plan (or similar).

3. 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, aircraft and airline emergency planning must be tailored to address these distinct risks effectively.

E. Infrastructure and Technology

1. Upgrade current (automotive) Fuel Cell infrastructure based on identified failure pathways to meet projected aviation requirements.

2. Hydrogen infrastructure modifications are a key focus of Hydrogen Challenge development.

3. Standardise Fuel Cell interfaces across manufacturers / platforms.

4. Integrate predictive maintenance and monitoring systems.

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

F. Regulatory and Assurance Measures

1. Develop CAA endorsed standards and guidance for hydrogen Fuel Cells for aviation.
2. Use Bowtie outputs to shape acceptable means of compliance, new regulations, and certification materials.

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

3. Implement hydrogen specific Safety Performance Indicators (SPIs)

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

G. Competence, Training and Culture

1. Deliver hydrogen specific operator training programme.
2. Focus on hydrogen behaviour, thermodynamics, ignition risk, PPE, and emergency procedures. Training needs are highlighted as a major industry gap.

H. Develop a certification scheme for hydrogen Fuel Cell manufacturers and MRO.

1. Support regulatory consistency and public confidence.
2. Initiate a common Fuel Cell trouble shooting process, and intervention levels.
3. Collaborate with RFFS, airport operators, manufacturers, and first responders to validate hydrogen Fuel Cell aircraft emergency procedures.

I. Continuous Improvement

1. Integrate Bowtie results into ongoing Safety Management Systems
2. Update the Bowtie as new test data emerges from the Hydrogen Challenge and Sandbox trials.
3. Facilitate cross industry knowledge sharing.
4. Support the CAA's aim to improve understanding of hydrogen related challenges across academia, industry, and regulators.
5. Conduct periodic independent assurance reviews.
6. Ensure controls remain effective as technologies evolve.

6. Conclusion

The hydrogen Fuel Cell 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 Fuel Cells systems across future aircraft platforms.

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.