

Assessment of fuel-cell-specific risks

TRA275 Fuel Cell Systems

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Introduction

Since the 1980s, clean energy vehicles have become popular for automotive manufacturers. Compared to traditional fossil fuels, hydrogen is green, somehow clean, and non-polluting.[2] Hydrogen fuel cell systems are being used as an alternative energy source. They offer high energy efficiency compared to combustion engines running on fossil fuels, reduced greenhouse gas emissions, and a sustainable pathway for future energy solutions. However, their widespread adoption also presents safety concerns due to hydrogen's flammability, leakage risks, and explosion hazards. Unlike conventional fuels, hydrogen has a low ignition energy and a wide range of flammability, making it highly susceptible to accidental ignition.[1,2] This study evaluates hydrogen-related risks by analyzing a historical accident, reviewing established risk assessment methodologies, and identifying mitigation strategies to improve safety in hydrogen fuel cell applications.

A notable historical accident occurred during the filling of a hydrogen transportation trailer in Santa Clara, California, in June 2019. During the filling of the tube trailer, a leak occurred. One of the drivers attempted an unauthorised repair of the leaking valve. Hydrogen accumulated in the confined space with inadequate venting, forming a flammable air-hydrogen mixture. This mixture ignited, resulting in an explosion.[5]

Hydrogen Characteristics and Explosion Hazards

Hydrogen has unique chemical and physical properties that make it both a valuable fuel and a potential safety risk:

- **Flammability Range:** Hydrogen ignites within a broad range (4 -74 %) in air, making it more flammable than other fuels like methane and gasoline.
- **Ignition Energy:** Requires 10x less energy to ignite than gasoline, making it susceptible to static electricity or minor sparks.
- **Leakage Risk:** Hydrogen has the smallest molecular size, allowing it to permeate through materials that are typically impermeable to other gases.
- **Accumulation Risk:** Hydrogen is lighter than air, leading to rapid dispersion in open environments but creating explosion risks in enclosed spaces.
- **Embrittlement:** Continuous exposure to hydrogen can degrade metal structures, increasing the risk of pipeline failures and tank leaks.

Mitigation Strategies and Safety Measures

To ensure the safe use of hydrogen fuel cells, several key measures are employed:

- **Explosion Prevention Protocols:** Use of TPRD, automatic shut-off valves, and pressure relief mechanisms to minimize explosion risks in high-pressure hydrogen storage systems.
- **Material Selection:** The Adoption of hydrogen-compatible alloys and composite materials to prevent embrittlement and leakage in the storage tanks.
- **Maintenance and inspection:** Particular attention and efforts should be paid to the inspection, monitoring, and maintenance of the filter and pressure relief devices in a hydrogen forklift's storage and delivery system.[1]
- **Hydrogen Leak Detection Systems:** Implement (Catalytic) Hydrogen detectors and acoustics detectors to detect and mitigate hydrogen leaks before reaching flammable concentrations.
- **Ventilation and Containment Design:** Proper ventilation designs in hydrogen storage and refueling stations to prevent the buildup of combustible gas mixtures.[2]

Interview with FCS Engineer at Volvo Trucks

1. What are the critical components of a fuel cell vehicle in terms of safety?

TPRD, Excess flow valves, Pressure relief valves, Leak detectors are the critical components.

2. What are the correct characteristics of a TPRD in an FC vehicle?

Set point temperature (related to tank material) and orifice size (sufficient venting flow rate to avoid a tank rupture).

3. How is ventilation provided in a compact fuel cell truck design?

Ventilation is provided from the front fan and the passive air flow during driving.

4. How quickly can leak detectors detect the leaks?

Common to use thermal conductive H2 sensors, and standard T90 is 3s.

Case Study

To analyze the consequences of a hydrogen tank failure under extreme conditions, an experiment was conducted by exposing a fuel-cell electric vehicle to fire until the tank ruptured. The hydrogen tank exploded 11 minutes and 12 seconds after the start of the experiment, causing a shockwave, intense fire, and extensive destruction. As a result of the explosion, the rear of the vehicle was lifted about 1.5 meters off the ground, and the front tilted by 15 degrees, while the doors and hood were blown off. The explosion pressure reached 173 kPa near the vehicle and decreased to 136 kPa at a distance of 5 meters, while the protective barrier sustained some damage but prevented the blast from passing through.[3]

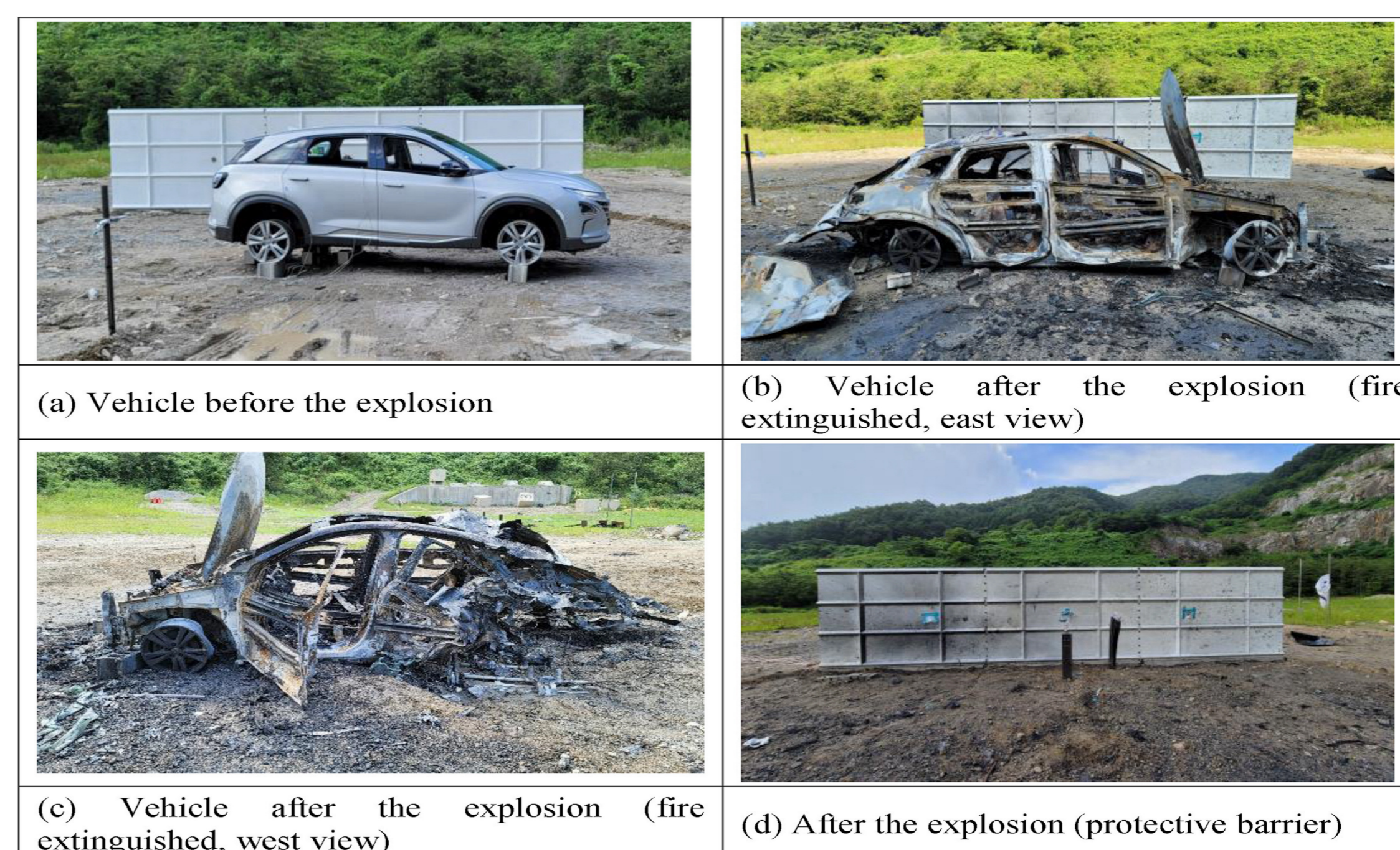


Figure 1: Comparison of vehicle images before and after the explosion.

Risk Assessment Models and Methodologies

To minimize hydrogen-related risks, several analytical models are used:

- **Quantitative Risk Assessment (QRA):** A statistical approach that estimates the likelihood and consequences of hydrogen-related incidents.[1,2]
- **Fault Tree Analysis (FTA):** Identifies critical failure points that could lead to explosions and proposes safety interventions.[1,2]
- **Hazard Analysis and Risk Assessment (HARA):** Applied in the automotive sector to ensure compliance with ISO 26262 for hydrogen fuel cell vehicles.[2]

Lifecycle of functional safety

The below diagram illustrates the Functional Safety Management process based on ISO 26262, covering key stages such as pre-study, risk assessment, product development, and production planning. Although product development and production planning are beyond the scope of our project, we believe that it gives us the whole picture related to the management of hydrogen functional safety.[2]

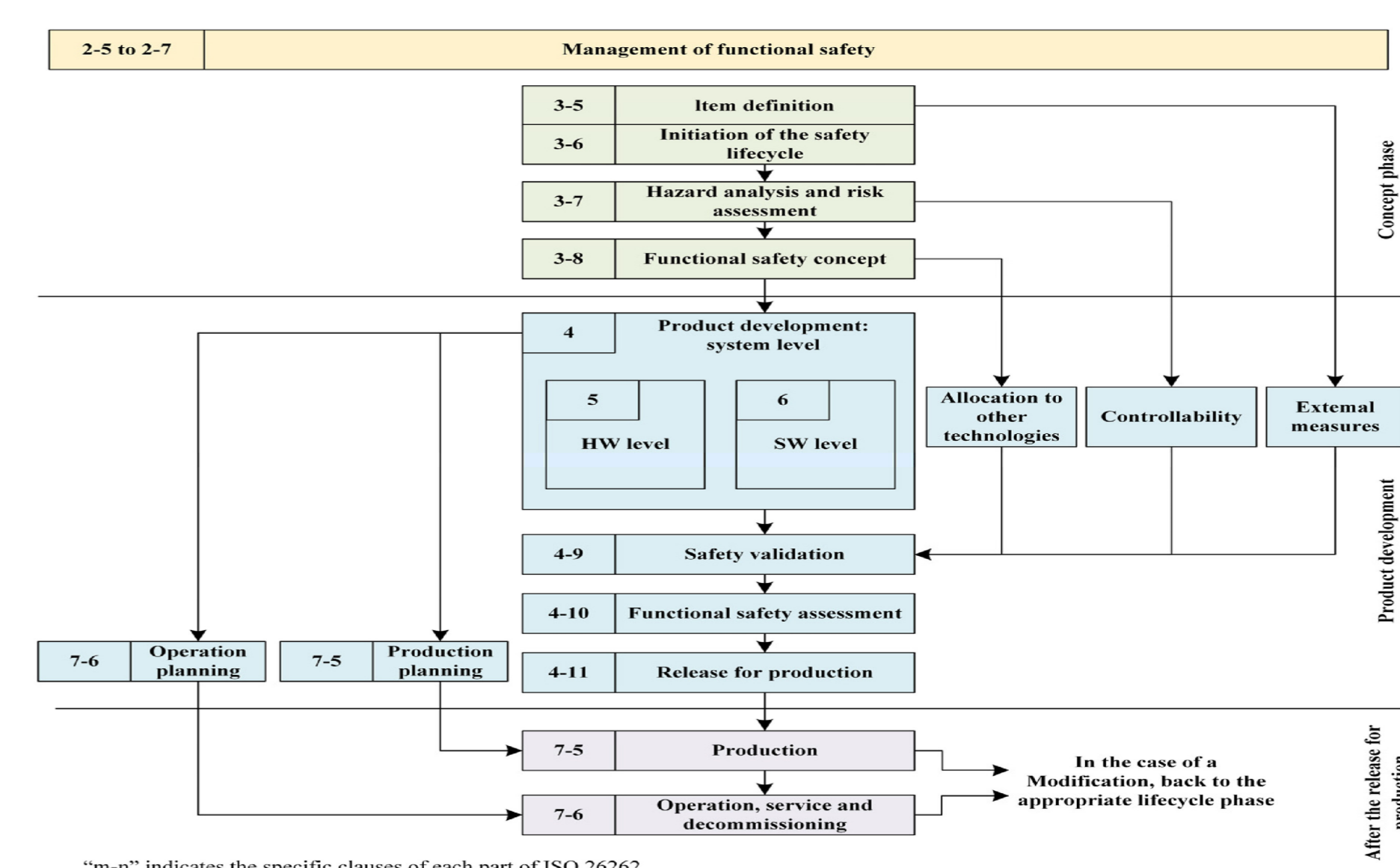


Figure 2: Lifecycle of functional safety

Conclusion

The adoption of hydrogen fuel cells as a clean energy solution necessitates robust safety protocols:

- Hydrogen's high flammability and leakage potential require advanced risk assessment and mitigation strategies.
- Implementing safety standards and monitoring technologies is crucial for large-scale hydrogen adoption.
- Future Research Directions: Development of enhanced leak detection sensors, improved hydrogen storage materials, and next-generation safety frameworks.
- Safety assessments, informed by lessons learnt from previous incidents, play a crucial role in identifying and mitigating risks associated with hydrogen handling, storage, and transportation.[5]

References

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