Position Paper

Explosion free in any fire self-venting (TPRD-less) composite tanks:

fundamentals and manufacturing guidance

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Abstract

The rupture of high-pressure hydrogen storage tanks in fires is a critical safety concern that undermines public confidence and restricts wider deployment of hydrogen technologies. Current safety strategies depend on thermally activated pressure relief devices (TPRDs), which have their disadvantages that can lead to critical consequences, for example failing to react in localised or low-intensity fires and creating additional hazards through high-pressure hydrogen release. This position paper introduces a breakthrough safety concept: explosion-free, self-venting composite tanks that remain safe under any fire scenario. Based on the microleaks-no-burst (μLNB) principle, these tanks eliminate the need for TPRDs by releasing hydrogen through distributed microchannels when exposed to fire. Prototype testing under both realistic and extreme conditions, including impinging hydrogen jet fires with heat release rates well beyond standard protocols, has validated the concept. Results confirm that self-venting tanks prevent rupture, blast waves, fireballs, and pressure peaking, thereby ensuring inherently safer performance across transport and stationary applications. Key challenges remain in advancing this technology, including composite-liner compatibility, thermal degradation, hydrogen permeability, sealing reliability and scaling to larger tanks. Existing test methods lack standardisation and often fail to represent real-world conditions, so underscoring the need for advanced fire testing protocols. Promising results were achieved with different fibre-resin composites and liners, however Type V tanks remain at low TRLs. Further opportunities include the use of thermoplastic materials for circular manufacturing and recycling. Addressing these gaps through coordinated research will accelerate industrial adoption, positioning self-venting tanks as a transformative advancement in hydrogen safety, regulation and sustainability.

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Introduction

Hydrogen incidents can occur at any stage of hydrogen's production, transportation, storage or utilisation[1]. There are known catastrophic incidents with hydrogen tanks, such as Korean tank rupture[2], or incidents of a hydrogen tank rupture on industrial premises in Austria[3], as well as incidents with widely spread around the globe compressed natural gas composite storage tanks, including rupture caused by smouldering fire[4],[5],[6]. These incidents underpin the public concern on the use of hydrogen technologies. The total number of hydrogen-powered vehicles, including passenger cars, commercial transport, and material handling machines [7] is currently about 100,000. In just the first half of 2024, more than 5,500 fuel cell vehicles were sold worldwide[8].

Exclusion of high-pressure hydrogen storage tanks rupture in any fire is crucial for public acceptance for obvious reasons. Indeed, it would eliminate hazards of devastating blast waves, fireballs, and projectiles. The problem is of especial concerns for confined spaces as tunnels, underground parking, hydrogen storage enclosures onboard of road vehicles, rail transport, aircrafts, and maritime vessels. Hydrogen storage tank rupture in the worst-case scenario for hydrogen refuelling stations.

Currently, thermally activated pressure relief devices (TPRDs), represent the standard safety technique to mitigate the probability of compressed hydrogen storage systems (CHSS) rupture in a fire. However, TPRDs have significant unacceptable limitations. It may fail to activate in localised or low-intensity fires, e.g. smouldering fires[9,10]. Releases from TPRDs produce thermal and pressure effects that pose hazards and associated risks to people, property and environment [11]. In case of a TPRD activation inside an enclosure like a garage, it may generate overpressures capable of destroying the enclosure by the pressure peaking phenomenon (PPP)[12] discovered in 2010 and characteristic exclusively for light gases such as hydrogen. The way to public acceptance of hydrogen technologies is elimination of what is precepted as "hydrogen explosions", including storage tanks rupture in a fire of any intensity. One option is the breakthrough safety technology of explosion free in any fire self-venting tanks that does not require TPRD as the whole tank surface is working as a "distributed TPRD"[13,14,15]. The technology is based on the microleaks-no-burst (μLNB) concept and is validated by experiments in several EU projects, e.g. SH2APED, HyTunnel-CS, etc.

The scope of this position paper is to address one of the critical issues of hydrogen safety, particularly fire and explosion safety of composite hydrogen storage systems, by advocating for the development of fundamental understanding of the innovative technology, and manufacturing guidance for adoption of self-venting composite hydrogen storage tanks. It highlights the limitations of current TPRD technique in preventing hydrogen tank rupture, as well as it formulates requirements to components and material performance and compatibility for explosion free in any fire self-venting tanks. The position paper defines fundamental studies and research programme for validation of self-venting tanks. This research shall aid regulatory updates and involve close academia-industry collaboration to support the manufacturing of inherently safer self-venting tanks.

The primary goal is to establish a scientific and regulatory framework for manufacturing and deploying self-venting hydrogen storage tanks by addressing key challenges. These include composite and polymer material science, computational modelling of heat and mass transfer, hydrogen safety, fire interactions with CHSS, and experimental validation of self-venting tank prototypes under various fire conditions.

By eliminating hazards and risks associated with traditional TPRD failures, self-venting tanks present a breakthrough in hydrogen storage technology. They provide a more reliable solution for hydrogen-powered vehicles, infrastructure, and industrial use. Adopting this technology not only enhances hydrogen storage safety but also supports the decarbonisation of transport and energy sectors, reinforcing hydrogen's role in a sustainable future.

Key research challenges in developing and deploying self-venting tanks include material selection, understanding thermal degradation, controlling permeability, and designing advanced fire testing protocols. These protocols must account for real-world conditions to meet the demanding regulatory requirement: "hydrogen storage tanks shall not rupture in any fire".


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Current State of Research

All types of fires, including spill fires, impinging jet fires[16] and smouldering fires, can damage the integrity of onboard hydrogen storage tanks. For example, spill fires can be caused by natural disasters or industrial accidents, such as pipeline leaks, fires, or vehicle collisions. The typical specific heat release rate (HRR divided by the source area, A) for a liquid fuel spill fire is around 1-2 MW/m^2 [17,18,19]. Impinging hydrogen jet fire from nearby storage tank could reach HRR/A=20 MW/m^2 [20]. These values are much higher than the HRR/A levels recommended by the UN Global Technical Regulation No.13 (GTR#13)[21] or the R134[22] fire testing protocol, which suggest values of 0.3 MW/m^2 and 0.7 MW/m^2. The mismatch between the fire intensities in standard test protocols and real fires raises serious safety concerns. The fire resistance rating (FRR) of composite tanks (the time to hydrogen tank rupture in a fire) is highly sensitive to the HRR/A. Research[23] has shown that when the HRR/A is reduced, a hydrogen tank's FRR can increase to tens of minutes, giving enough time to trigger the TPRD and prevent catastrophic rupture. However, this does not rule out the possibility of tank rupture under real fire conditions, where the HRR/A is much higher. The regulated fire test protocol should be revised to account for a full range of real-world fire scenarios, from low-intensity smouldering and spill fires to highly intense fires, such as those involving impinging hydrogen jet flames – a typical incident scenario for CHSS with multiple tanks.

There are known cases of the self-venting behaviour of Type IV tanks. One of such examples is the leak of the composite tanks for LPG [24] in a fire. Such tanks operating at service pressures of 10-20 bar use only a small portion of the critical "load-bearing" composite wall thickness. A similar behaviour was experimentally observed for hydrogen tanks designed for nominal working pressure (NWP) of 700 bar. These tanks are leaking not rupturing in a fire at about 50% state of charge[25]. This behaviour of Type IV tanks was numerically reproduced and explained in study[26]. However, achieving reliable self-venting performance in fully charged standard (conventional) Type IV tanks remains a significant challenge. Explosion free (in any fire) self-venting (TPRD-less) tanks are designed using the innovative microleaks-no-burst (μLNB) concept, which eliminates the need for TPRDs (though their use is not prohibited) by enabling the tank itself to function as a "distributed over surface of tank TPRD" with microchannels for pressure discharge after the liner is melted using the registered invention and know-how.

One of currently used engineering solutions to prevent tank rupture along with TPRD is the use of intumescent paint. Intumescent paint protection can be rapidly eroded by high-pressure hydrogen jet fires resulting from impingement of leaks from adjacent storage sources or pipes.

Key achievements and milestones

The design of self-venting (TPRD-less) Type IV hydrogen tanks has been validated through several European and UK projects[27]. These tanks are designed to prevent explosions during fires by using a specialised structure. They have a double-composite wall with a hydrogen-permeable outer layer and a polymer liner that acts as a barrier. The liner can be made from thermoplastic, thermoset, or other suitable polymer materials, depending on compatibility and safety standards. If the tank is exposed to extreme heat, the polymer liner melts, allowing hydrogen to escape through microleaks before the outer composite wall loses its strength. These microleaks form naturally through tiny microchannels in the composite material, similar in size to the reinforcing fibres, i.e. a few microns wide. The self-venting mechanism offers a critical safety advantage over traditional TPRDs. The size of the flammable envelope, the distance to the lower flammability limit (LFL), is directly linked to the leak diameter. Because microchannels are only a few microns wide, the flammable envelope extends just a few centimetres. This ensures hydrogen disperses rapidly, preventing accumulation in enclosed spaces and requiring only minimal ventilation. The self-venting tanks are characterised by the following achievements distinguished from other safety technologies: no blast wave, no fireball, no projectiles, no long flames, no pressure peaking phenomenon in confines spaces, no flammable cloud formation in naturally ventilated enclosures, no life/property loss in case of hydrogen tank affected by any fire. This technology is proposed as a safer alternative for hydrogen storage in road, rail, aviation, and maritime transport. It is also suitable for hydrogen refuelling stations, marine vessel storage, and underground infrastructure such as tunnels and car parks.

The first designed and manufactured prototypes have undergone successful fire testing under conditions exceeding those specified in GTR#13, with HRR/A=1 MW/m^2. Figure 1 shows sequential snapshots from one of the first fire tests on a self-venting tank prototype. The images capture key stages of the process: localised fire initiation, flame appearance, the onset of an engulfing fire, and the final stage with residual resin combustion. Notably, by the end of the process, the hydrogen pressure drops to 1 bar absolute, and there is no visible increase in flame size at the start of hydrogen release through microleaks or afterward.

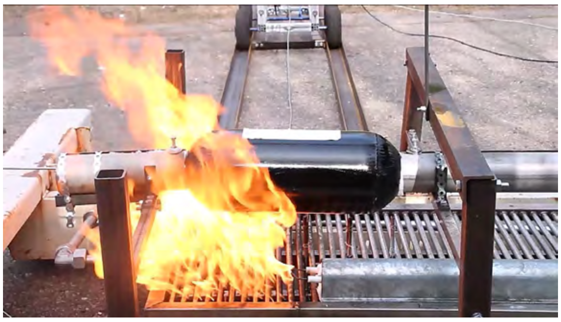
Figure 1. Self-venting NWP=700 bar tank prototype in localised and engulfing fire portions of HRR/A=1 MW/m^2 intensity [28].

Fire test started	First isolated flame	(pressure drops)	Engulfing fire starts	H2-resin combustion
0 s	**3 min**	**10 min 1 s**	**10 min 4 s**	**18 min 10 s**

Experiments were carried out on double-composite overwraps using different fibre-resin materials under realistic fire conditions. Glass and basalt fibres were tested as alternatives to carbon fibre and they offered similar safety performance with lower cost. In all cases, the tanks released hydrogen safely until the pressure dropped to atmospheric level.

Protecting public and first responders is a priority. Firefighting strategies may include moving the vehicle away from the fire (simulated in tests by shutting down the burner) or applying water to suppress the flames. Figure 2 demonstrates the technology validation under fire conditions in case of fire suppression by water jets. Hydrogen release from the tank continued safely even after the fire was extinguished and the sprinkler system suppressed the flames. This demonstrates an advantage over TPRD-based systems, as firefighters can respond as in any conventional fire without the need to cool a TPRD to prevent its activation.

Figure 2. Self-venting tank prototype in a fire with flame extinction [29].



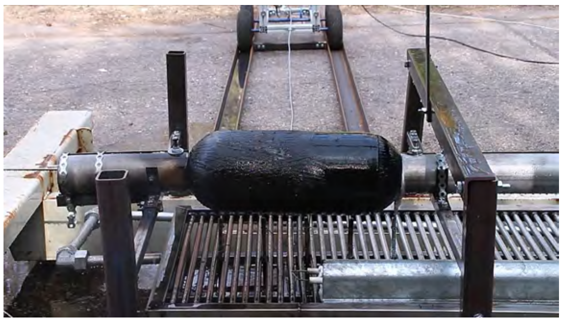
Test start

First sign of resin combusting **01:19**

Burner fuel supply stopped, resin is still burning **05:49**

Water sprinkler started **05:55**

Extinction continues, resin is still burning **06:30**



Seconds after sprinkler stopped, combustion is slightly visible (on video) **13:35**

The key achievement was validating the technology under extreme, yet realistic, CHSS conditions of an impinging hydrogen jet fire from a nearby 700-bar tank (see Figure 3). The experiment showed that the outer composite layers of basalt fibre were eroded by the high-momentum hydrogen jet fire. Intumescent paint could not withstand this intensity and would be destroyed within seconds, failing to protect the tank. A TPRD would also be ineffective In such a scenario, if the jet impacted the tank away from its location.

Figure 3. Self-venting tank prototype under extreme impinging jet fire of highest ever intensity of HRR/A=19.5 MW/m^2 from a 700-bar storage tank: left – during fire test, right – aftermath of the prototype composite of tank test [30].

The findings confirm that this breakthrough safety technology gives a step-change in protection for people, property and the environment. To enable its adoption, standard fire test protocols must be updated to cover the full range of scenarios, from low-intensity smouldering and spill fires to high-intensity hydrogen jet fires affecting adjacent tanks in a CHSS. This safety advancement plays a crucial role in increasing public acceptance of hydrogen.

Notable projects:

- UKRI, EPSRC. UK National Clean Maritime Research Hub (MaRes) (EP/Y024605/1).
- Horizon 2020. H2020-JTI-FCH-2020-1. SH2APED: Storage of hydrogen: alternative pressure enclosure development. GA No.101007182.
- H2020, FCH2JU (now Clean Hydrogen Partnership): HyResponder “European Hydrogen Train the Trainer Programme for Responders” (875089).
- Innovate UK. Clean Maritime Demonstration Competition Round 1 (CMDC1): “Northern Ireland Green Seas” (10009311).
- Interreg Atlantic Area, “HYLANTIC Atlantic Network for Renewable Generation and Supply of Hydrogen to promote High Energy Efficiency” (EAPA_204/2016).

- H2020, FCH2JU. “HyTunnel-CS: PNR for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces”.
- Innovate UK. Clean Maritime Demonstration Competition Round 2 (CMDC2): “Hydrogen Fuel Cell Range Extender” (10041047).
- Invest NI, Centre for Advanced Sustainable Energy (CASE): “Breakthrough safety technologies for hydrogen vessels from Northern Ireland” (PROJECT/A1135).
- Invest NI, Proof of Concept Plus: “Optimisation of explosion-free in fire composite cylinders to industrial requirements” (1703/130130821-1).
- Invest NI, Proof of Concept 629: “Composite tank prototype for onboard compressed hydrogen storage based on novel Ulster’s leak-no-burst safety technology” (1703/130130821).
- EPSRC H2FC SUPERGEN Challenge: “Integrated safety strategies for onboard hydrogen storage systems” (EP/K021109/1).

Current safety technologies have shown effectiveness in fire tests, including scenarios replicating aspects of firefighter interventions and extreme conditions. Prototypes with different fibre-resin composites and liners performed well, but research gaps remain. Materials are still at low TRLs, and their performance and compatibility are uncertain, especially for emerging Type V tanks. Key unknowns include the role of composite porosity, thermal degradation, flame resistance and polymer-liner adhesion. Issues such as liner buckling, delamination and hydrogen permeability also require further study. Existing test methods can give inconsistent results and lack standardisation, but higher pressures and new materials make current protocols less representative of real conditions. Additional work is needed on Joule-Thomson cooling effects, seal reliability and scaling to larger tanks. Addressing these gaps is essential to advance safer composite hydrogen storage systems.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Research Challenges

Further research is needed to understand the fundamental physical processes behind this innovative engineering solution. Validating models for designing self-venting Type V and Type IV tanks across various fire scenarios, ranging from smouldering and liquid spills to impinging jet fires, is essential. Testing these tanks in fires of different intensities will build consumer confidence across sectors of the hydrogen economy. At present, no fire testing protocol covers the full range of scenarios, making its development one of the priorities. Introduction of self-venting tanks also creates an opportunity for regulatory updates. Type V tanks, which are less mature than Type IV, do not use a conventional liner. Instead, the composite wall must act as both the load-bearing structure and the gas barrier. In practice, they often include a barrier from non-reinforced tape winding, which improves barrier properties. Without a discrete liner, strain compatibility issues are reduced, improving fatigue performance. However, the safe operating pressures of Type V tanks are still under investigation. Factors including composite layup sequence, fibre architecture, and manufacturing defects remain critical as they significantly influence burst strength and long-term structural integrity [31].

The performance of self-venting tanks depends on fibre and composite thermal properties, liner melting, resin degradation and the flammability of thermoset and thermoplastic materials. As for Type V polymer-based tanks, the key factors include melting point and heat of fusion. Experimental and numerical studies are needed to define thermal conductivity requirements and confirm the ability to withstand fires of varying intensities without failure. The use of flame-retardant additives should also be assessed. Because hydrogen-liner-composite interactions are complex, close collaboration between academia, industry and research institutions is essential. Future work should focus on thermal stability, degradation, reaction kinetics, pyrolysis and optimised flame-retardancy strategies to advance self-venting tank technology.

Another challenge is the adhesion and structural integrity of liners or inner barriers. In fully thermoplastic structures, cohesive bonding is essential, requiring the liner to form a “true weld” with the reinforced structure. When bonding a thermoplastic liner to a thermoset reinforcement, adhesive bonding is needed – an area that requires further investigation.

The permeability of materials is crucial for safety. Micro-voids and defects in the liner can increase hydrogen permeation [32]. Long-term hydrogen exposure may lead to degradation and embrittlement. Permeation measurements must be conducted on a representative sample from a cylinder, with dimensions tailored for compatibility with bench tests. Ensuring the experimental setup minimises or prevents hydrogen leaks is essential for accurate permeation measurements.

Seals in hydrogen storage systems, particularly elastomeric types, can swell under high-pressure hydrogen. This volumetric expansion weakens their structural integrity and increases the risk of extrusion, tearing, failure and leakage. Swelling also alters barrier properties, potentially raising hydrogen permeation. Seal and connection design must therefore meet strict requirements for durability, environmental resistance, vibration, acceleration, refuelling safety and fire safety. Validation should combine extensive experimental testing with computational modelling using validated tools.

TRL vary from low for Type V tanks to TRL 4-6 for Type IV tanks by the end of the project.

The proposed timeline is medium-term 3-5 years. The suggested estimate of the funding is 9M EUR.

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Rationale for Advancing Research in This Area & Potential Applications

Explosion-free, self-venting hydrogen storage tanks in fires would mark a major step towards public acceptance and sustainability. The use of thermoplastic materials can enable a circular approach to hydrogen tank manufacturing, making production and recycling more efficient. Given the expected increase in hydrogen storage demand, research must prioritise environmentally friendly and cost-effective solutions, covering manufacturing, end-of-life management, and material reuse.

A holistic approach is essential for advancing circular storage systems. While polymers offer recyclability benefits, carbon fibre, being critical for lightweight applications, poses sustainability challenges due to its high CO_2 footprint and limited recyclability. Current carbon fibre composite overwrapped tanks struggle to align with circular economy principles, highlighting the need for innovation in materials and design. A growing demand from sectors such as aerospace and wind energy [33] is driving both price increases and material shortages [34,35]. The fundamental studies aim to investigate the use of alternative fibres for at least the partial replacement of carbon fibres.

This project will strengthen Europe's leadership by enabling breakthrough hydrogen safety technology. It offers unprecedented safety and cost reduction, positioning Europe ahead of competitors. Building a strong technological base, skilled workforce, and manufacturing capability will drive global demand and market adoption.

The scientific impact of this research and its alignment with the technology advancement goals of EC[36] and CHP[37] is indisputable. The team of inventors and researchers working on different projects devoted to the self-venting tanks has demonstrated significant contributions through internationally leading research in hydrogen safety and advanced materials engineering. Key findings have been, and will continue to be, policy influential, which is in line with the goals of Hydrogen Europe Research: “providing evidence-based research”…“to inform European and national policies related to hydrogen development” [38]. The outcomes of the project will impact existing Regulations, Codes and Standards (RCS), including UN ECE GTR#13 (Phase 3), IMO, ISO/TC197, CEN/CLC/JTC6, etc.

Overview of applications

The research will strongly affect safety through the entire range of hydrogen systems and infrastructure. The inherently safer storage systems will be available for hydrogen storage onboard of passenger cars, heavy-duty vehicles, rail, maritime and aviation systems, as well as stationary applications such as hydrogen refuelling stations, domestic storage, etc.

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