Novel Lightweight Insulation for Liquid Hydrogen Fuel Tanks

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1. Executive Summary

A prototype liquid hydrogen (LH_2) tank was designed and assembled by Stratospheric Platforms Ltd (SPL) for future testing with LH_2. The design with its instrumentation enables the creation of LH_2 test data that can be used to further validate SPL's thermal performance models, which have been previously validated with liquid nitrogen.

This report is an account of the development activities to be shared publicly with other hydrogen developers and stakeholders, with the intent to advance the collective maturity of the industry. This demonstration was supported as part of the Hydrogen Innovation Initiative (HII) end to end demonstration programme, with the aim of advancing liquid hydrogen storage for mobile applications.

2. Introduction

As a UK-based SME, based in Cambridge, Stratospheric Platforms Ltd (SPL) is a leading research and technology organisation specialising in High-Altitude Platform Stations (HAPS), with a particular focus on deploying next-generation 5G networking capabilities that bridge the gap between terrestrial and satellite connectivity. The technology will enable maximum 5G coverage for people and the Internet-of-Things.

To achieve its goals, SPL is developing the Stratomast – a high-altitude, remotely-piloted hydrogen-powered aircraft system. The Stratomast system is intended to operate at high altitudes (*c*.18 km or 60,000 feet) to deliver ubiquitous data connectivity that seamlessly integrates terrestrial and satellite-based networks. SPL has developed a unique phased array antenna which, when operating from HAPS, is capable of providing high-capacity network connectivity direct-to-device over a 15,000 km^2 area.

Liquid hydrogen (LH_2) is a candidate fuel for the decarbonisation of the aerospace sector, with the advantages of low mass compared to aviation fuel, ability to be generated with net zero carbon and only emitting water into the atmosphere. Liquid hydrogen is gradually being adopted by the aerospace industry, however there are still some technical aspects which need to be solved to fully unlock the potential of liquid hydrogen. Specifically, one of the heaviest elements of a LH_2 fuel tank is the cryogenic insulation, required for maintaining storage pressures within limits. Aircraft performance and commercial viability is especially sensitive to the mass of onboard systems. Prevailing insulation options are based on either

(i) high vacuum, which necessitates heavy vacuum jackets to resist external pressures and introduces additional failure modes, or
(ii) foam jackets, which are very thick and heavy.

This demonstration addresses the barrier of inherently safer, certifiable, and lightweight LH_2 insulation.

Within its hydrogen programme, SPL has developed a novel insulation system that is ultra-lightweight, compact, and does not rely on vacuum. It is capable of ensuring zero loss of hydrogen during operation and meeting dormancy requirements for when the aircraft is parked for extended periods. Crucially, its inherent safety, simplicity and robustness will dramatically reduce efforts required for development and certification, which is a critical barrier for the commercial operation of LH_2 flights.

SPL has previously validated this concept with successful tests on small-scale prototypes. In this demonstration, SPL has created a new higher fidelity prototype tank to develop manufacturing methods and has tested it using liquid hydrogen to further validate thermal performance models.

This demonstration was supported as part of the Hydrogen Innovation Initiative (HII) end to end demonstration programme, with the aim of advancing liquid hydrogen storage for mobile applications. The overall demonstration objective was to validate thermal performance models of the novel insulation technology by building and testing a representative prototype with LH_2. Another objective was to develop a manufacturing concept for the insulation and to gain experience in building and operating such systems.

The goals during the project were to:

- Design and build a metal pressure vessel to contain pressurised LH_2.
- Design, build and integrate the insulation with the metal tank, complete with sensors and control elements required for testing.
- Integrate the prototype tank with the test facility.
- Publish this report describing the demonstration activities and experience gained in LH_2 technology.

3. Project Description

This demonstration aimed to create a prototype of the insulation of the LH_2 fuel tanks based on technology developed by SPL. The insulation system does not rely on vacuum for its thermal performance and is based on existing commercially available materials. Key advantages of SPL's unique insulation are:

- Highly tuneable performance to optimise weight according to vehicle requirements
- Insensitive to manufacturing features and defects (derating factors for multi-layer insulation (MLI) can vary from 1.5 to 10, *i.e.* heat leaks can be 50% to 1000% higher than ideal[1])
- Robust and damage tolerant
- Less complex, leading to safer, more reliable designs that require less effort for development and certification
- Ultra lightweight
- Improves overall vehicle thermal management

In a previous development project, SPL had built an earlier prototype of the technology and tested it using liquid nitrogen. Good agreement with thermal performance models was obtained, with deviations between predicted and measured performance being < 4%. The current prototype incorporated some key improvements:

- Larger scale
- Spherical shape similar to the flight design
- Improved insulation system materials with aerospace heritage, similar to gravimetric thermal performance of flight design

[1] ASTM International - ASTM C740/C740M-13 Standard Guide for Evacuated Reflective Insulation In Cryogenic Service

- Planned for testing with LH_2, as opposed to LN_2

Testing with LH_2 ensured greater confidence in validation of the thermal performance models, which can then be used for predictions of scaled up performance in aircraft-scale fuel tanks.

During the project, the prototype tank was designed, analysed, and assembled by SPL in Cambridge. A key component was a cryogenic pressure vessel procured from a subcontractor according to SPL's requirements. The completed prototype will be finally tested with LH_2 at Element Digital Engineering's facility in Cirencester.

SPL's project engineering activities followed an Engineering Management Plan (EMP) written within a tailored systems engineering framework. The following gated technical reviews were held:

- Combined Systems Requirements and System Design Review (SRR and SDR)
- Preliminary Design Review (PDR)
- Critical Design Review (CDR)
- Manufacturing Readiness Review (MRR)
- Test Readiness Review (TRR)

This approach ensured a clear set of requirements were communicated between all stakeholders with verification and validation tracked against the design as the project matured. At each review, the maturity of the design was assessed against the review objectives along with a review of the associated project and technical risks.

4. Demonstration Activity

4.1 Prototype test article design

SPL created requirements for and procured a conventional metal tank from a subcontractor with significant experience in cryogenic pressure vessels. Because the purpose of this development was focused on the insulation and not the pressure vessel, conventional design standards were applied to the tank to minimise project risk. The insulation is agnostic of the inner tank and can be applied to any material or shape. The metal tank was spherical with an LH_2 capacity of 4 kg. The design of the prototype enabled two tests to be performed: boil-off calorimetry and self-pressurisation.

In boil-off calorimetry, the mass flow rate out of the tank is measured to determine the total heat leak into the cryogenic contents, under pseudo-steady state conditions. This is a convenient way of gauging the total heat leak for a tank. With the right test design, the test can be designed to isolate only the heat leak from the insulation. Although rigorous test designs, involving thermal guard chambers[2], is required for accurate measurements of material properties, the goal in this project was to measure performance at an assembly level. This would give a more realistic and conservative measure of performance, with effects from installation features, real geometries, and interactions with other parasitic heat leaks.

[2] JE Fesmire *et al* 2015 *IOP Conf. Ser.: Mater. Sci. Eng.* **101** 012056
http://doi.org/10.1088/1757-899X/101/1/012056

The self-pressurisation test measures the rate of pressure rise in a closed tank. This is important to measure experimentally because complex effects strongly influence the pressurisation rate. These effects are often abbreviated as thermal stratification, and includes solid-fluid heat transfer, natural convection, phase change, and turbulence. The result is an accelerated pressurisation rate that is multiples higher than that predicted if a uniform tank temperature was assumed. 3D simulations techniques are capable but current models still require test data for validation[3]. Knowledge of the pressurisation rate is important because this directly influences the hold time of a LH_2 tank, *i.e.* the time that a tank can remain closed until it reaches the set pressure of relief devices. The hold time is potentially a sizing case for the insulation design, and since it could vary by multiples from uniform models, there is potentially a large uncertainty in the insulation mass depending on system requirements.

To perform the tests, the prototype was equipped with sensors and control elements. A total of 40 temperature sensors, a mass flowmeter, a pressure sensor, and a load cell were used. The insulation, piping and instrumentation was designed and assembled by SPL, supported by published guidelines and standards for LH_2[4,5]. Figure 1 shows a schematic diagram of the prototype system.

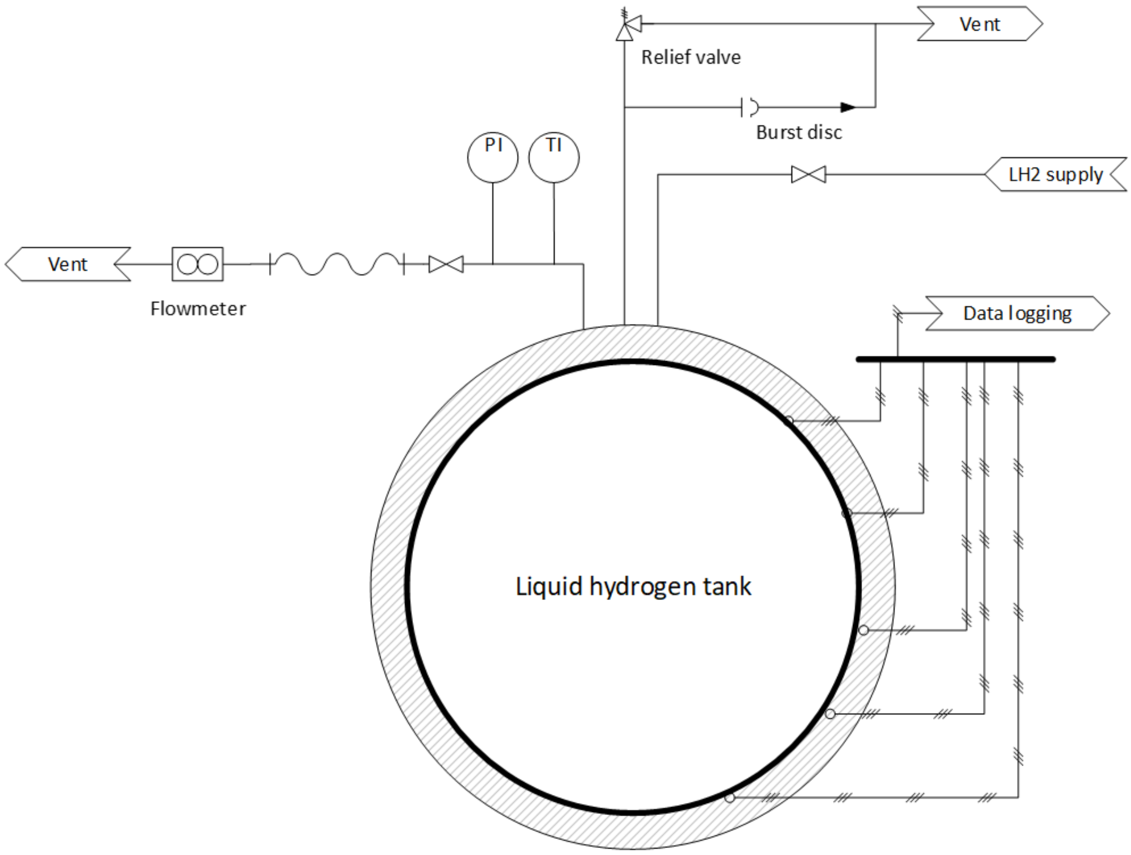

Figure 1. Schematic diagram of prototype liquid hydrogen tank system. Not all the 40 temperature sensors are shown.

[3] O Kartuzova *et al* 2025 NASA document ID: 20240016283 https://ntrs.nasa.gov/citations/20240016283

[4] Guide to Safety of Hydrogen and Hydrogen Systems (ANSI/AIAA G-095A-2017) https://doi.org/10.2514/4.105197.001

[5] National Fire Protection Association, *NFPA 2: Hydrogen Technologies Code*, 2020

Material selection is critical for handling cryogenic hydrogen. Structural elements were generally made of face-centred cubic (FCC) metals, with stainless steel or aluminium being typically recommended. This ensures components remain ductile and does not embrittle and fail prematurely at cryogenic temperatures. These materials are also less susceptible to hydrogen embrittlement and permeation.

The tank was supported by hanging from its neck port at the top of the tank. This provided access around all surfaces of the metal tank during the assembly process. This also ensures all of the outer insulation surface is exposed to ambient air as a boundary condition during the test, in line with the thermal models. The tank weight was carried through a load cell, measuring the overall weight of the system and providing a means to gauge the liquid inventory in the tank.

The LH_2 filling port was a cryogenic bayonet type compatible with the LH_2 supply connection. The lines to the pressure relief devices were rigid piping with tapered thread connections to the burst disc and relief valve. The gas port, which transmits the vapour outflow during the boil-off calorimetry, was attached to a pressure sensor and temperature sensor to measure the cryogenic hydrogen properties. A low pressure drop between the pressure sensor location and the tank internal volume meant that a pressure tapping directly on the tank was not necessary. A flexible vacuum-jacketed hose connects to the mass flowmeter, providing mechanical freedom whilst mitigating cryogenic surface hazards on the line. Fluid connections consisted of twin-ferrule compression fittings, metal gaskets in threaded and flanged joints, and PTFE for tapered threads in accessible locations (*i.e.* not underneath the insulation). Direct connections to the tank were welded.

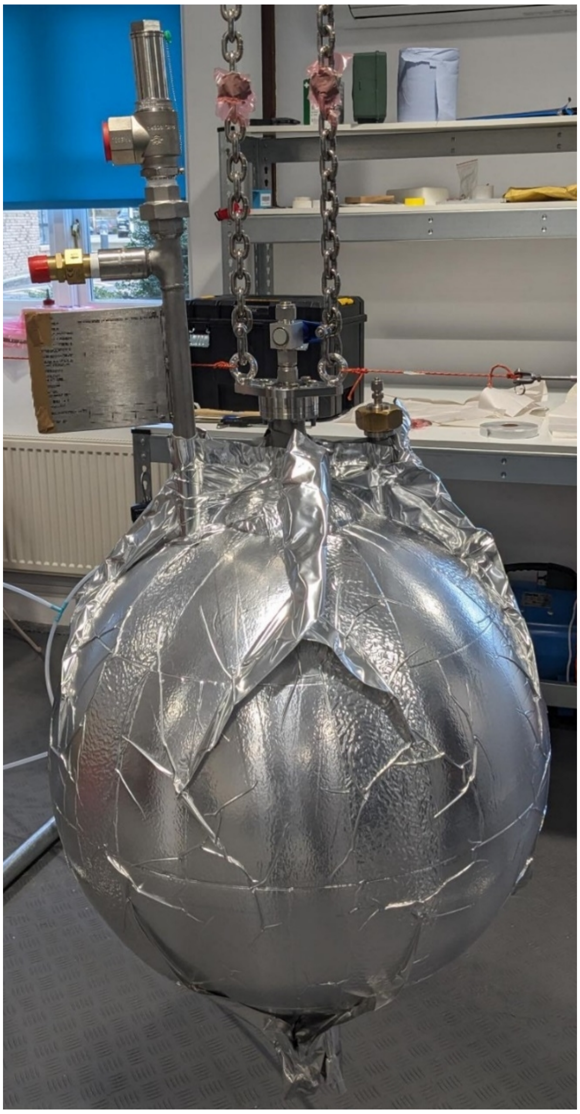

Figure 2. LH_2 tank assembly in progress in SPL facilities.

4.2 Modelling methods

The aim of the modelling was to predict the heat leak of the prototype under the LH_2 test conditions. For the prototype, there are two contributions to the total heat leak: through the insulation and through penetrations such as the fluid lines. These heat leaks were modelled using 1D and 3D techniques. The speed of 1D models is advantageous during design, when rapid iterations are needed. The fidelity of 3D models can be computationally expensive but is useful when more accurate predictions are required, such as for correlation of test data and for modelling of complex geometries. These results will be compared with the test data once the LH_2 tests have been completed.

Aside from predicting performance of a design (*i.e.* a rating calculation), modelling is also used to size the insulation (*i.e.* a design calculation). As an indication of the performance of our insulation relative to conventional vacuum jacketed insulation, approximate mass estimates for LH_2 fuel tanks for passenger aircraft is shown in Figure 3, where potentially 60% to 120% more fuel can be carried for the same full tank mass. SPL's insulation yields greater performances whilst lowering complexity and development effort. Note that actual designs could vary or improve significantly depending on the actual requirements which can differ from those assumed in the calculations shown in Figure 3.

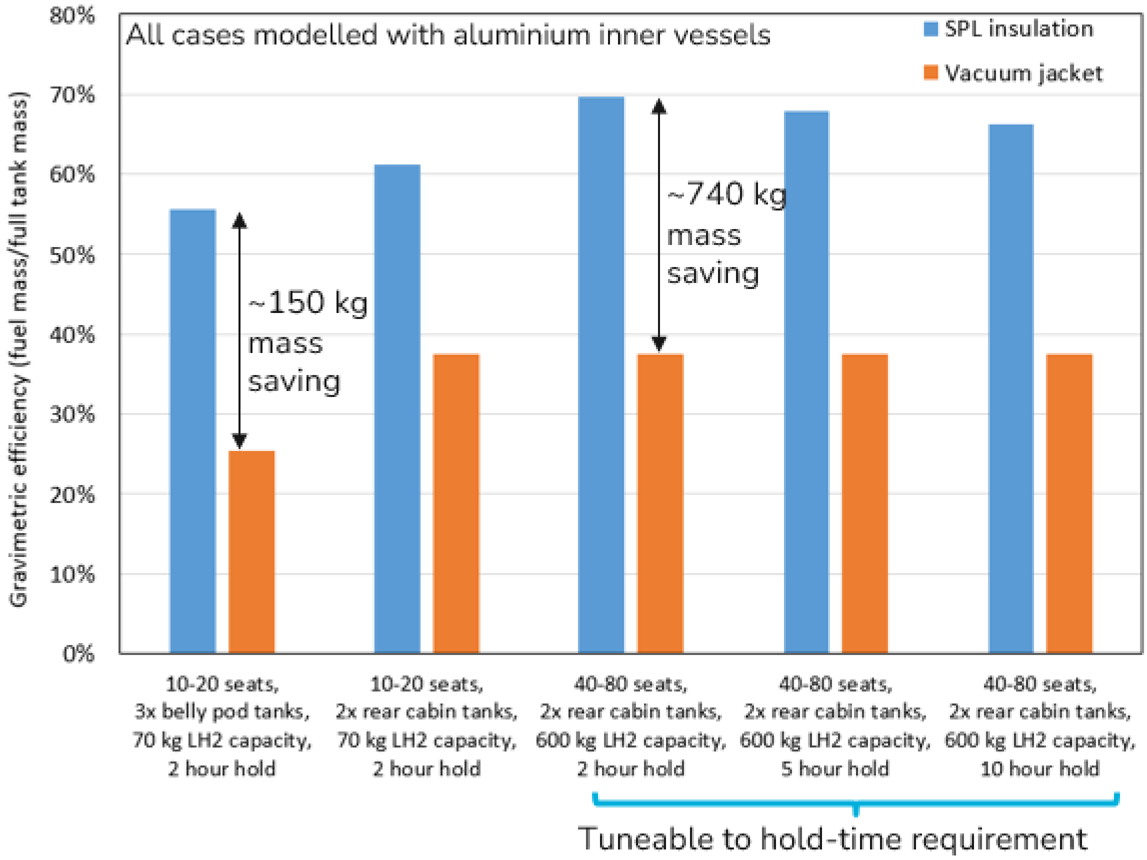

Figure 3. Relative mass comparison between aluminium vacuum jacketed tanks and SPL's novel insulation applied to a variety of different aircraft and configurations.

4.3 Planned test methods

Two main tests will be applied using LH_2, boil-off calorimetry and self-pressurisation. This section describes the planned testing.

4.3.1 Boil-off calorimetry

Boil-off calorimetry is used to gauge the total heat leak into the tank, Q, by the mass flow rate of vapour leaving the tank, w:

$$Q = \frac{\Delta \hat{H}_{\mathrm{vap}}}{1 - \frac{\rho_{\mathrm{V}}}{\rho_{\mathrm{L}}}} w \qquad (1)$$

where:

Q	=	Total heat leak into the tank [W]
w	=	Vapour mass flow rate out of the tank [kg/s]
ρ_{V}	=	Density of GH_2 [kg/m^3]
ρ_{L}	=	Density of LH_2 [kg/m^3]
$\Delta \hat{H}_{\mathrm{vap}}$	=	Specific enthalpy of vaporisation of hydrogen [J/kg]

Note that the factor $1 - \frac{\rho_{\mathrm{V}}}{\rho_{\mathrm{L}}}$ is often neglected but is significant for LH_2 and should be accounted for.

Measurement of Q enables assessment of the insulation performance, with the goal being to keep Q within requirements whilst keeping the weight of insulation low.

The mass flowmeter and load cell will provide independent measurements of the LH_2 boil-off flow rate during the test. The load cell also provides liquid level data. Temperature sensors and a pressure sensor will allow confirmation of pseudo-steady state of the tank. The temperature sensors will also provide further model correlation data to validate thermal modelling. Pt100 resistance temperature detectors (RTDs) were chosen for their ability to measure down to 20 K. Sheathed RTDs, mounted through bored-through compression fittings, enables measurement of the pressurised cryogenic fluid environment.

Once the tank is filled with LH_2, steady measurements of the mass flow rate w then enables total heat leak Q to be calculated using equation (1).

4.3.2 Self-pressurisation

Self-pressurisation will be performed to provide experimental data to validate CFD models. This test measures the rate of increase of pressure in a closed tank. During the test, the tank pressure will be logged, starting from an initial known fill level of LH_2. The heat leak data obtained from the calorimetry test (assuming that the heat leak is constant and equal to the calorimetry scenario during the pressurisation), combined with the pressure evolution data are then compared against model predictions to assess model quality.

4.4 Safety

LH_2 is stored in a pressure vessel which presents potential hazards of flammability, overpressure, air liquefaction, *etc*. Hazard identification was carried out by SPL during the design phase. LH_2 technology standards were used as guidance, such as NFPA 2 and

ANSI/AIAA G-095A-2017. As part of SPL's overall Safety Case for the design, Failure Modes and Effects Analysis (FMEA) studies were also conducted. The Safety Case will be submitted to the testing subcontractor to ensure safety at the facility during the test.

Hydrogen is flammable but this hazard is mitigated as long as it does not mix with air. This was ensured by proper design, assembly, and operation of the prototype. All fluid handling equipment were assessed for suitability for handling cryogenic hydrogen. Helium leak testing was used to ensure fluid connections were correctly assembled. Test procedures will be developed with the test facility to ensure hydrogen and air are never mixed, with typical practice using vacuum or pressure purging. Flammability hazards were also managed by removal of ignition sources near the tank. Electrical equipment was separated. The tank was earthed. Autoignition temperatures of 500 to 585°C for hydrogen will not be present.

The metal tank was equipped with a pressure relief valve and a bursting disc, providing dual redundant protection against overpressure. A bursting disc was deemed necessary because of the residual risk of icing at the outdoor testing facility. The relief devices were sized in accordance with ISO 21013-3 to a scenario corresponding to complete loss of insulation. Although physical causes leading to a complete loss of insulation were difficult to conceive of, this was chosen as a relief sizing scenario to remain conservative and mitigate risk. Fire engulfment was not applied in the relief scenario because the prototype tank will only be used in a controlled test environment. The pressure vessel itself was designed, built and tested in accordance with PD 5500 by an experienced cryogenic vessel supplier. The vessel was helium leak tested and proof pressure tested with margin above its expected maximum pressure during the upcoming LH_2 tests.

Potential reaction of liquid air with organic materials was mitigated either by insulation of cryogenic surfaces or by shielding vulnerable organic surfaces with LOx-compatible materials.

5. Challenges, Solutions, and Key Learnings

5.1 Technical lessons learned

During the design and component selection stage of the project, it was frequently found that cryogenically rated parts and materials were one or more of (i) unavailable, (ii) expensive, or (iii) had long lead times. Whilst options were limited for safety-critical items, low risk items can be more pragmatically selected. Although many off-the-shelf products do not explicitly state suitability for LH_2 temperatures, that does not necessarily mean they are unsuitable. Products were not necessarily discounted because their lower operating temperature was only rated down to 77 K, for example. Careful research, strategic testing where necessary, and collaboration with experienced operators during the project led to identification and selection of more available parts. Familiarity with published guidelines and standards for LH_2 is instrumental in the design and part selection process.

Manufacturing methods had to be developed to achieve the bespoke design. These were concurrently developed during the design process with manufacturing trials. Knowledge gained from the trials enabled feedback and iteration towards a manufacturable design in a cost-effective manner.

5.2 Best practices and recommendations for cryogenic demonstrations

Currently in the UK, sourcing and using LH_2 is a challenge. Only a handful of organisations can offer LH_2 testing with potentially significant lead times. We have learned that early engagement with LH_2 test facilities is essential for successful research and development. Identifying and defining LH_2 quantities, system interfaces, safety requirements, and operating procedures is important to minimise the risk of costly late design and project changes.

Estimates of required LH_2 quantities are important to identify suitable test houses – currently either kilogram-scale or tonnage-scale LH_2 testing services are offered with significantly different lead times. Hand calculations based on approximate thermal masses, filling capacities, boil off, topping up between test points, *etc* give a useful order of a magnitude estimate.

Definition and control of system interfaces, which is fundamental in systems engineering, accelerates LH_2 developers and test houses in developing their respective systems and ensures compatibility on the day of installation at the test facility. Any delays could significantly impact the testing time slot.

Joint definition of safety requirements with the test facility is important especially with a relatively novel fuel like LH_2. Although existing standards are useful in identifying hazards and robust mitigating measures, real operating experience and knowledge of existing protections at the test facility can be useful in developing more practicable requirements, mitigations, and operating procedures.

6. Implications for the Hydrogen Industry

The LH_2 insulation technology developed by this prototype tank is a significant step towards wider adoption of LH_2. One of the barriers against LH_2 storage has been the development of vacuum jackets, which suffers from large mass, high complexity associated with supporting vacuum systems, sensitivity to manufacture and damage, and compatibility with lightweight composite materials which are typically permeable. SPL's insulation technology bypasses these issues and is particularly synergistic with weight-sensitive and safety-critical applications such as aircraft. Originally designed for SPL's Stratomast HAPS, the technology is readily scalable to air taxis and commercial airliners. This technology maximises the benefits of hydrogen as a sustainable transport fuel, unhindered by existing heavier technologies.

The results of the project are highly aligned with the HII end-to-end vision. In terms of the nine key technology areas, this project has advanced (i) lightweight hydrogen fuel storage, which is widely recognised as a key enabling technology for zero carbon flight. SPL has demonstrated its expertise in LH_2 storage, which is recognised as a scarcity in the UK by the ATI[6]. When applied to passenger aircraft, this technology offers significant weight reductions compared to technology options assessed by the ATI's FlyZero programme. The prototype being developed also constitute key elements of (ii) distribution, control and (iii) conditioning of the fuel for on-vehicle downstream systems. The technology also unlocks new architectures for overall vehicle (iv) thermal management – this novel system was in fact originally conceived from a holistic systems design synthesis.

[6] ATI HCN, *UK Cryogenic & Hydrogen Materials Testing Landscape*, 2025 https://www.ati.org.uk/wp-content/uploads/2025/03/UK-Cryogenic-Hydrogen-Material-Testing-Landscape-Final-MAR-25.pdf

In terms of the HII industrial sectors, the utility of this technology for the aerospace sector is by design, because the novel insulation technology is inherently safer, lighter, and provides benefits for overall aircraft thermal management. There is also utility for the energy networks and power generation sectors because of the main target use case – HAPS. SPL's Stratomast HAPS aircraft can achieve up to order-of-magnitude reductions[7] in energy consumption and emissions associated with telecoms operators, which account for 2-3 percent of total global energy demands[8].

As SPL continues to develop the technology, access to additional testing capabilities will be required. It will be advantageous if the UK develops test facilities capable of environmental testing with LH_2, especially in accordance with RTCA DO-160 Environmental Conditions and Test Procedures for Airborne Equipment. These include, amongst others, altitude, shock, vibration, and flammability *etc*. This will be a necessary step towards demonstrating compliance with certification and airworthiness requirements. Access to shared facilities will lower development costs for all LH_2 developers and SPL.

7. Conclusion

A prototype liquid hydrogen (LH_2) tank was designed and assembled by Stratospheric Platforms Ltd (SPL) for future testing with LH_2. The design with its instrumentation enables the creation of LH_2 test data that can be used to further validate SPL's thermal performance models, which have been previously validated with liquid nitrogen.

This report is an account of the development activities to be shared publicly with other hydrogen developers and stakeholders, with the intent to advance the collective maturity of the industry. This demonstration was supported as part of the Hydrogen Innovation Initiative (HII) end to end demonstration programme, with the aim of advancing liquid hydrogen storage for mobile applications.

[7] STL Partners, *Stratospheric Platforms: a faster route to mobile net zero?*, 2021 https://bit.ly/TelecomsDecarbonisationReport

[8] McKinsey & Company, *The case for committing to greener telecom networks*, 2020 https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/the-case-for-committing-to-greener-telecom-networks

8. Abbreviations & Acronyms

Acronym	Description
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ATI	Aerospace Technology Institute
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
EMP	Engineering Management Plan
FCC	Face-centred cubic
FMEA	Failure modes and effects analysis
HAPS	High Altitude Platform Station
HII	Hydrogen Innovation Initiative
ISO	International Organization for Standardization
LH_2	Liquid hydrogen
LOx	Liquid oxygen
MLI	Multilayer insulation
MRR	Manufacturing Readiness Review
NFPA	National Fire Protection Association
PDR	Preliminary Design Review
PTFE	Polytetrafluoroethylene
RTCA	Radio Technical Commission for Aeronautics
RTD	Resistance temperature detector
SDR	System Design Review
SME	Small to medium sized enterprise
SPL	Stratospheric Platforms Ltd
SRR	System Requirements Review
TRR	Test Readiness Review
UK	United Kingdom