Cryogenic Hydrogen Sensors

Technology Landscape

Sensor development for liquid hydrogen fuel systems

July 2025

About

This report is authored by Grazebrook Innovation and Badgerworks, working with the Hydrogen Capability Network to understand the global landscape for **Liquid Hydrogen Sensors.**

Lead Authors

Henry Clarke, Badgerworks – A chartered engineer with 20 years' experience developing aircraft systems, including aircraft fuel systems, air to air refuelling systems, fuel tank vent and inerting systems. Has held many lead engineer roles, in simulation and modelling and R&D; as well as being the airworthiness signature for system performance. The last 5 years focussed on the development of LH_2 systems with experience in modelling and testing with LH_2.

Stella Job, Grazebrook Innovation - An experienced professional in advanced materials and manufacturing, with a focus on sustainability, and an alumna of Oxford University (Engineering Science). Has undertaken environmental assessments for FlyZero, on hydrogen-powered commercial aviation, and Project MONET, looking at low/zero-carbon powertrains for light aircraft. She has authored good practice guides, state-of-the-art reports, articles and book chapters and lectures on sustainable materials at the Universities of Oxford and Loughborough.

Acknowledgements

The authors would like to thank the following for conversations and input to support this report:

- Lui Terry (University of Bristol),
- Peter Wilkins, Jon Chow and Wendy Cheong (Baker Hughes),
- Marcus Walls-Bruck, (National Composites Centre),
- Oscar Brownhill (Airbus),
- Steven Lua (Unitrove),
- Rachael Keslake (Henry Royce Institute),
- Robert Smith and Paul Wilcox (University of Bristol),
- Matthew Day (Dolphitech)
- Laura Cuss, Huw Edwards, Kiran Harish and Rebecca Shaw, (Hydrogen Capability Network / Aerospace Technology Institute).

About the Aerospace Technology Institute

The **Aerospace Technology Institute (ATI)** is an independent organisation that works alongside government and industry to transform UK aerospace through technology and innovation. The ATI is funded equally by the **Department for Business and Trade (DBT)** and by industrial recipients of project grants who pay a small levy. ATI projects are chosen and overseen through close collaboration with DBT and Innovate UK.

As well as running this portfolio of R&T projects, the ATI conducts strategic research projects to help define and answer systemic questions of value to the UK aerospace sector. In 2022 the ATI published the findings of the **FlyZero** project, which concluded that liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft.

The ATI Programme has made several investments in liquid hydrogen technologies to support the next generation of zero-carbon aircraft. The **Hydrogen Capability Network (HCN)** was launched in April 2023 funded by the Department for Business and Trade, to progress key recommendations from FlyZero which will enable the aerospace sector to deliver liquid hydrogen research and development (R&D).

Disclaimer and Funding Acknowledgement

This work was carried out by **Grazebrook Innovation** and **Badgerworks** funded by the **Aerospace Technology Institute's Hydrogen Capability Network**.

The report is based on an analysis of the sensors landscape as of February 2025 and all weblinks are current as of that date. Any data in this report on existing sensor products, condition requirements or work in progress is based on open-source information, company websites, product factsheets and conversations with experts and sensor providers. It is acknowledged that this is an area where there is rapid change and many technologies are in development. Although every effort has been made to ensure it reflects a comprehensive review there may be information contained in this report that may have changed or be incomplete. No evaluation has been undertaken on the stated performance of the products and whether they are fit for purpose, inclusion of products does not guarantee their reliability for the relevant context and users should undertake their own assessments. It is recognised that most commercial sensors listed in this report would need development for aerospace grade liquid hydrogen conditions.

The ATI does not accept liability for any errors, omissions or misleading statements and no warranty is given or responsibility accepted for any actions users may take based on the content of the report. The ATI reserves the right at any time to make changes to the material, or discontinue the report, without notice.

Cryogenic Hydrogen Sensors Summary

The Aerospace Technology Institute's (ATI) Hydrogen Capability Network (HCN) has conducted a number of global landscaping reviews to understand the priorities that will accelerate development of cryogenic hydrogen storage and fuel systems for aircraft. The aerospace industry has highlighted the requirement for reliable and certifiable sensors which can be used on liquid hydrogen (LH_2) powered aircraft, both in flight and during maintenance, as one of its most urgent areas for development in the next few years. Sensors are also needed for research and development testing and certification; these will have different capability and life requirements and potentially lower constraints than those required for operational use on aircraft. This report has mainly focused from the perspective of sensors for on-aircraft use.

The breadth of sensing technologies which will be needed, and the conditions at which the sensors must operate are radically different from those sensors which are used on current aircraft. This document reviews the current state-of-the art sensing technology for LH_2 fuel systems and identifies gaps or areas of opportunity for sensor development.

Commercially available sensors exist for many of the phenomena required, especially temperature, pressure, phase, hydrogen concentration for gas detection and purity, and flame detectors, though work is needed to convert and certify relevant technologies for LH_2 aircraft applications.

For temperature, traditional resistance temperature detectors (RTDs) and thermocouples may be sufficient in some applications, though for cryogenic LH_2 applications thin film zirconium oxynitride sensors are becoming more widely used. Fibre-optic sensors may be important as they remove the risk of an ignition source and reduce the heat leak from sensor electrical connections. There are many pressure sensors that use materials and coatings which allow them to be used with hydrogen, but few which are also designed to work at cryogenic LH_2 temperatures.

If flowmetering is required on-aircraft, it may be limited to single-phase gas flow measurement in the feed system, if liquid flow needs to be measured, then LH_2 flowmeters which are commercially available now for ground-based fuelling could be adapted for aircraft use. Alternatively, electrical capacitance tomography (ECT), could be developed to visually map and measure liquid or multi-phase flow.

Tank gauging is critical and at least two independent solutions will be needed. Several direct level sensing technologies exist, but they may be challenging due to sloshing effects. Work that has been done for space applications in microgravity may provide solutions through radio frequency mass gauging, modal propellant gauging, or ECT. NASA has effectively used silicon diode and Cernox temperature sensors as wet/dry sensors to identify the fluid phase, while Washington State University has demonstrated use of Raman spectroscopy fibre-optic flow cells to measure ortho- and parahydrogen proportions.

Detection of hydrogen leaks is fundamental to aircraft safety, and lightweight, commercial hydrogen gas detectors are available. Ultrasonic leak detection could be effective, subject to understanding acoustic signatures of LH_2 leaks amid background interference. Thermal imaging of the tank structure may also be useful to reveal leaks and insulation failures. If flame detectors are required, there are several commercial options using ultraviolet, infrared or multi-spectrum detection.

Design and development of tanks and pipework should integrate structural monitoring solutions, which may include vibration or acoustic sensing or fibre-Bragg strain measurement. In-situ non-destructive testing (NDT) of twin-walled, vacuum-insulated tanks and pipework is a challenge, exacerbated by limited access, as well as the cryogenic temperature, if cold monitoring is required.

All contaminants except helium will be solid in the LH_2 tank, though some will change phase in the fuel feed system. Build-up of solid contaminants, including solidified air and degraded material particulates, could be measured by the pressure drop across filters. If ECT technology is used in the tank, resolution may be sufficient to identify solids. Vibration monitoring and debris monitors can be used to assess material losses due to friction and wear on moving parts, but will need development for the LH_2 context.

Outputs from a range of sensors, as well as usage and loading data, need to be brought together, applying computational techniques for data analysis and reliable predictive maintenance.

Summary of research priorities

Research and development is needed to address the following priorities:

- Continued development of the LH_2 fuel system so that requirements are more clearly defined is critical.
- Established sensing technologies (e.g. for temperature, pressure, phase, hydrogen gas detection, and flame sensing) need to be developed to work in and be certified for the LH_2 fuel system environment. Facilities for testing in LH_2 are a fundamental requirement for this development work.
- Tank gauging is an essential safety critical measurement for aircraft, where at least two independent techniques are needed for redundancy. Alongside sensor development, a test rig for trialling gauging systems in LH_2 tanks subject to aircraft inertial forces and the resultant sloshing expected from the flight profile and turbulence is essential to enable a CS-23 or CS-25 aircraft to be certified.
- The potential for use of fibre-optics and their durability in LH_2 should be pursued, as they avoid introducing potential ignition sources, reduce heat leaks, and are a cost-effective and lightweight solution which can be used to measure several phenomena.
- Research is needed to assess the extent to which ultrasonic leak detection can work with background acoustic interference from the system.
- NDT of twin-walled vacuum-insulated tanks and pipes is a particular challenge, both for metallic and composites, especially if required while maintaining cryogenic temperatures.
- Advanced debris monitors need to be developed to work in a cryogenic hydrogen environment, identifying and quantifying particles. Lab-based system testing will inform this by establishing what particles need to be identified.
- A holistic approach is needed to develop whole systems with integrated and multi-functional sensing which is lightweight and compatible with materials and processes, resulting in a robust solution.
- Integration of data from avionics and multiple sensor types into onboard maintenance systems, including applying AI/ machine learning, will enable diagnostic and predictive maintenance.

Contents

1. Introduction

The Aerospace Technology Institute's (ATI) FlyZero project concluded that liquid hydrogen (LH_2) is the most viable zero-carbon emission fuel for decarbonising future commercial aircraft. The technological change to a liquid hydrogen architecture is revolutionary with disruptive technology change facing the cryogenic hydrogen fuel storage and delivery system.

The HCN identified through a series of stakeholder workshops the priorities for advancing fundamental science and research for: material behaviour in cryogenic hydrogen environments, cryogenic hydrogen thermofluids behaviour, and cryogenic hydrogen health and safety. Within these workshops the importance of sensors development was also highlighted.

In the Cryogenic Hydrogen Fuel Systems Showcase, an event run jointly with the High Value Manufacturing Catapult (HVMC), focus was given to the critical components of the cryogenic hydrogen fuel storage and delivery system as shown in Figure 1. Within this, sensors were recognised as needing early development due to being fundamental to the performance of the system.

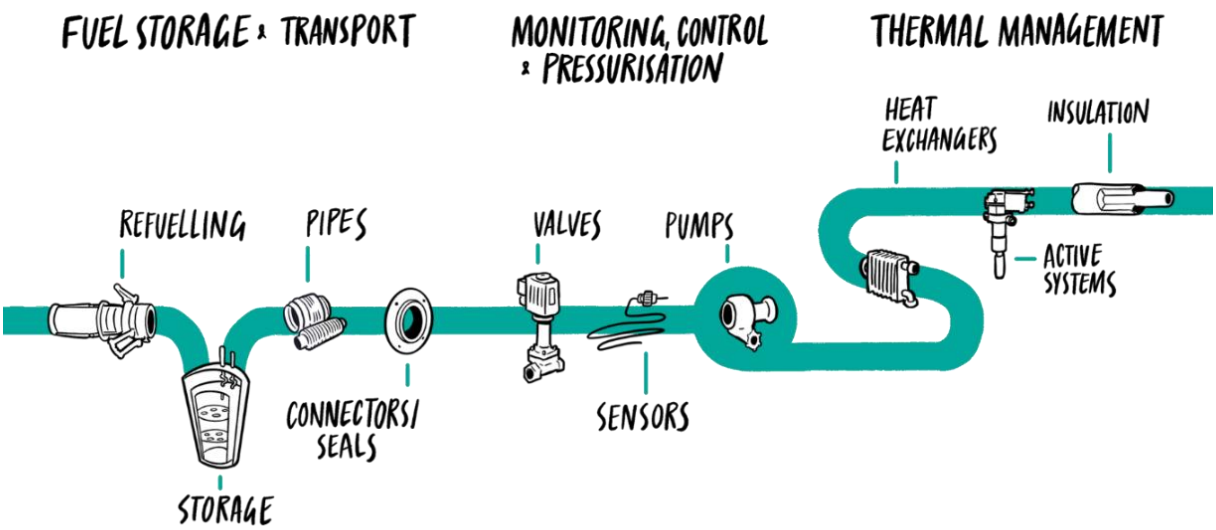

FIGURE 1: FUEL STORAGE AND DELIVERY SYSTEM ON AIRCRAFT SCHEMATIC

This report focuses on Cryogenic Hydrogen Sensors Technology Landscape and summarises the state-of-the-art for sensor technology relevant to LH_2 fuel systems and storage, looking at sensors in several areas which are critical for product / system development and certification for in-flight use. It considers sensors for:

- The on-aircraft fuel system including the tank and to the point of delivery to the propulsion unit (turbine or fuel cell).
- Maintenance of the fuel system.
- Infrastructure and supply.

At the time of analysis there are few sensors qualified for use in LH_2 systems, e.g. for ground-based and space systems, and none for LH_2 in commercial aerospace systems. In some cases, sensors are commercially available which are expected to be suitable for cryogenic hydrogen storage and fuel systems, subject to certification. In other areas the technology to create sensors exists, but in some cases new technology needs to be developed to meet the needs of aerospace LH_2 systems.

Any data in this report on existing sensor products, condition requirements or work in progress is based on open-source information, company websites, product factsheets and conversations with experts and sensor providers. It is acknowledged that this is an area where there is rapid change and many technologies are in development. Therefore, information contained in this report may have changed or be incomplete. No evaluation has been undertaken on the stated performance of the products and whether they are fit for purpose, inclusion of products does not guarantee their reliability for the relevant context and users should undertake their own assessments. It is recognised that most commercial sensors listed in this report would need development for aerospace grade liquid hydrogen conditions.

1.1. General technical considerations

While many cryogenic hydrogen storage and fuel system requirements are still the subject of ongoing development, the following gives an idea of the range of conditions and factors to take into account with developing sensors, or material changes to reduce weight or increase durability for aerospace applications.

A useful general reference in this context is '[Liquid Hydrogen and other Cryogenic Instrumentation Experience at NASA Glenn](https://ntrs.nasa.gov/citations/20230012808)' which gives a clear presentation reviewing methods for temperature, pressure, gauging and flow, with practical application comments from experience[1]. A helpful academic reference describing relevant technologies is Arpaia 2018, 'State of the art and challenges in measurements and transducers for cryogenic monitoring'.[2]

1.1.1. System conditions

The boiling point of hydrogen at atmospheric pressure is 20.28 K (−252.87 °C), though liquid hydrogen may be stored at up to 2 bara at around 26 K, where the hydrogen is in a relatively steady liquid phase. Fuelling is typically in a subcooled state, so that the liquid does not rapidly vaporise as it moves through or contacts warmer parts of the system, reducing the quantity of hydrogen boil-off gas that needs to be recaptured and reliquefied, and enabling faster chill down and shorter refuelling time[3]. Therefore condition requirements in and around the tank and pump would be ~18-30 K, and upper pressure limit between 5 bara and 25 bara.

Through the fuel system the temperature and pressure will change to condition the hydrogen for the propulsion unit (e.g. fuel cell, gas turbine or combustion engine), with expected temperature ranges from 40-500 K for feed to the propulsion system, and pressures up to 70 bara.

For sensors around the tank and pipework, while general operating conditions may be close to ambient, the sensor may need to function in extreme cold or hot conditions for a short time in the case of LH_2 leakage or fire. Ambient humidity in the space should be considered, as some sensors are adversely affected by very high or low relative humidity.

---

[1] Johnson, 'Liquid Hydrogen and other Cryogenic Instrumentation Experience at NASA Glenn', NASA, 2023 https://ntrs.nasa.gov/citations/20230012808

[2] Arpaia et al, 'State of the art and challenges in measurements and transducers for cryogenic monitoring', Measurement, 124 (2018), pp. 1-14, https://doi.org/10.1016/j.measurement.2018.03.080

[3] S. Schäfer and S. Maus, 'Technology Pitch: Subcooled Liquid Hydrogen (sLH_2)' 6 April 2021. [Online]. Available: https://www.now-gmbh.de/wp-content/uploads/2021/05/Heavy-Duty-Event-Subcooled-Liquid-Hydrogen-sLH2-Schaefer-Linde-Maus-Daimler.pdf.

1.1.2. Heat leaks

A challenge with all contact sensors inside the system is that they will introduce a heat leak– they may conduct heat from outside through the sensor's housing enough to raise the temperature a few degrees above the fluid temperature. Careful design of sensors in the LH_2 tank needs to minimise heat leak to prevent excessive boil-off, while for sensors downstream of the tank, in the fuel feed system, a heat leak could be tolerated with careful management of the build-up of ice around sensor insertion points, which may require insulation or active heating.

1.1.3. Materials

Materials used need to be suitable for these conditions, and take into account the effects of hydrogen, such as embrittlement, and the cryogenic temperatures on the sensor materials. For example, adaptations for sensors to resist hydrogen permeation and damage may include passivated chromium (II) oxide or gold plating on the sensor diaphragm.[4] (See also comments under ignition sources in section 1.1.4 below.)

For an extensive review of material properties in cryogenic and hydrogen conditions, see the accompanying report 'Cryogenic Hydrogen Materials Global Research Landscape'.[5]

1.1.4. Ignition sources

Careful consideration of how sensors are powered and materials used is needed to avoid ignition sources in any areas where there is a possibility of hydrogen and oxygen being present. For example, some materials such as titanium are a potential ignition source when subjected to impact or friction, non-conducting coatings may generate an ignition-capable level of electrostatic charge under certain extreme conditions.[6]

Also cold leaks can cause liquefaction or solidification of oxygen from the air. The high concentration of oxygen can increase the potential for ignition in some combustible materials. Potential for heat leaks around sensor connections must be carefully managed. In materials selection for sensors, compatibility and reactivity with LH_2 and liquid oxygen needs to be considered. This area needs further work to understand the risks.

Further information on liquid hydrogen risks can be found in the 'Cryogenic Hydrogen Health & Safety Global Research Landscape' report.[7]

1.1.5. Calibration and drift

Calibration and drift are not addressed directly in this report but are a critical part of sensor maintenance and lifetime expectation. In particular, care in calibration should be taken where sensor outputs become non-linear at very low temperatures. Some sensor materials may be affected by exposure to hydrogen, even at low levels, as well as other environmental conditions, affecting the useful lifetime.

---

[4] Honeywell Smartline Hydrogen Permeation Material Selection Guide, Honeywell https://process.honeywell.com/us/en/services-and-support/support-center/technical-support/technical-solutions/article-detail.ka_000138286

[5] 'Cryogenic Hydrogen Materials Global Research Landscape', ATI, March 2025

[6] 'T5/T5MAX Flare Gas Transducer Installation Guide', Panametrics, April 2024

[7] 'Cryogenic Hydrogen Health & Safety Global Research Landscape' ATI 2025

1.1.6. Installation, maintenance and end of life

Choice of sensor technologies needs to take into account how they can be installed, read and recalibrated, as well as considering repair or replacement throughout the lifetime, and recovery at end-of-life.

Integration of sensors, and in some cases functionality of sensors, may vary with different tank and pipe materials, especially between metallic and composite materials. Integration of sensors in manufacturing processes is the subject of ongoing research and development.

2. Temperature

Cryogenic sensors are well-established and numerous platinum (Pt) resistance temperature detectors (RTDs) and thermocouples are certified and used in aerospace. Germanium RTDs are accurate at liquid hydrogen temperatures (though not at room temperature) and have traditionally been used in the space sector. The sensitivity of Pt RTDs reduces below 30K, but may still be sufficient depending on the accuracy needed. Negative temperature coefficient RTDs are very effective across the range of required temperatures, and are now established technology, especially thin film zirconium oxynitride sensors such as Cernox (Lake Shore Cryotronics) and Zirnox (Scientific Instruments) which have potential to replace germanium RTDs.

A NASA review of instrumentation indicates that thermocouples are lower cost compared to other types listed, but are best for systems above 70-80 K.[1] A challenge with all these sensors is that they introduce a heat leak, so careful design is required - see comments at section 1.1.2.

Fibre-optic sensing has potential to detect temperature and other phenomena, with the advantages that the heat sink associated with electrical sensor connections is much reduced and they are not affected by electromagnetic interference. However more research is needed with respect to hydrogen damage to the glass and methods to improve sensitivity below 30 K, though at least one fibre Bragg grating (FBG) product is in development in relation to LH_2-powered aircraft.

2.1. Condition requirements

Operating temperatures are expected to be in the following ranges:

- Within storage and distribution system: ~18 K – 80 K
- Feed to propulsion system: ~40 K – 500 K

2.2. Measurement methods and applicability

Lake Shore Cryotronics has a useful overview page covering most of the technologies below[8], and a 'Beginners Guide to Cryostats' with more information.[9]

Resistance temperature detectors:

These can use either positive or negative temperature coefficient (PTC / NTC) resistors. PTC sensors include Platinum (Pt) and Germanium RTDs. NTC sensors include thin film zirconium oxynitride and thick film variable ohm (TVO) resistors.

[8] Cryogenic temperature sensors, Lake Shore https://www.lakeshore.com/products/categories/temperature-products/cryogenic-temperature-sensors
[9] 'Beginners Guide to Cryostats', Lake Shore Cryotronics https://www.lakeshorecryotronics.com/beginners-guide-to-cryostats-and-cryocoolers-ty

- **Platinum RTDs**: These are the most common temperature sensors, and are used in aerospace. They are low cost and robust with extensive thermal cycling, but their sensitivity reduces below 30 K and they are sensitive to magnetic fields.[10]
- **Germanium RTDs:** These are more accurate than Pt RTDs for the LH_2 range (0.05 - 100 K) but are not functional at room temperature. They are widely used in space applications and are highly stable but are susceptible to magnetic fields.
- **Thin film zirconium oxynitride (TFZO):** TFZO sensors are highly stable and have a low-drift resistance response over a broad temperature range (0.02 K to 450 K). They have the best accuracy (±0.02 K or better) and precision with minimal sensitivity to magnetic fields or radiation. They are considered by Lake Shore to be the best choice for cryogenics and a better replacement for Ge RTDs (and the older carbon-glass resistors).
- **Thick film ruthenium oxide:** These are useful for high magnetic fields and especially for very low temperatures (25 mK to 20 K).
- **Thick film variable ohm (TVO) resistors:** These sensors use a carbon element in aluminium oxide. They are stable under long-term use, though are sensitive to bending / pressure and to magnetic fields.

TABLE 2.1 SUMMARY OF TEMPERATURE SENSING TECHNOLOGIES

Sensor Type	Accuracy	Temp Sensitivity	EMI Resistance	Durability	Good for LH_2 (18–30 K)?
Platinum RTDs	🟢	🟡 (good down to ~30 K)	🟡	🟢	✗ (low accuracy)
Germanium RTDs	🟢	🟢 (only up to ~100 K)	🔴	🟢	✓
Thin film zirconium oxynitride (Cernox, Zirnox)	🟢	🟢 (full temp range)	🟢	🟢	✓
Thick film ruthenium oxide	🟡	🟢 (esp. 2-100 K)	🟢	🟢	✓
TVO resistors	🟡	🟡 (good below 30 K)	🟡	🟢	✓
Silicon diodes	🟢	🟢 (non-linear below 30 K)	🟡	🟡	✓
Thermocouples	🟡	🟡 (Type E /T best down to 40 K)	🔴	🟢	✗ (low accuracy)

[10] Neumann, 'Low temperature measurement and control technique', Karlsruhe Institute of Technology, from PRESLHY 2nd workshop on Cryo-Measurement Techniques https://www.hysafe.info/wp-content/uploads/sites/3/2018/10/WS_MSR_eng_2017.pdf

Silicon diodes: Silicon diode sensors work over a wide temperature range. They are very accurate, but are sensitive to magnetic fields and radiation, and fragile.

Thermocouples: These have a very wide temperature range and are low cost but at the expense of lower accuracy (±0.5K or worse). They are considered very robust, including with thermal cycling, but are EMI sensitive. Type E (Chromel-Constantan) is the most sensitive down to 40 K and is resistant to corrosion, especially at cryogenic temperatures. Type T is also very stable at cryogenic temperatures.[11] Type K and N are used in aerospace but are not recommended below 100K.

Fibre-optic: FBG sensing for temperature and other phenomena, including level sensing, is being explored for liquid hydrogen environments, and could potentially reduce or eliminate the heat sink problem of other sensors. Below 30 K the temperature sensitivity of FBG diminishes significantly as the thermo-optic effect becomes negligible, but can be enhanced by the use of coatings, such as polymers or copper, which can also protect the fibre from hydrogen damage.[12] [13] Proximion, (Hexatronic group) has a fibre-optic sensor for cryogenic applications which substitutes the thermo-optic effect with the stress-optic effect whereby the thermal expansion of a material attached to or coating the fibre causes measurable changes in strain on the fibre. This may still be in development but is being used in the development of hydrogen-powered aircraft.[14]

2.3. Current offerings

Cryogenic sensors are well-established and several Pt RTD sensors and thermocouples are certified and used in aerospace. Some examples include:

- TC Direct (International) RTD Sensors such as this - Pt100 sensor which is rated down to -200°C have been used for liquid hydrogen [15]
- Lake Shore Cryotronics (USA) Pt RTDs, Cernox, silicon diode, thermocouples [8]
- Scientific Instruments (USA) Zirnox, silicon diode, ruthenium oxide thick film [16]
- Cryotechnics (USA) silicon diode [17]

[11] 'Thermocouple Types', Watlow https://www.watlow.com/resources-and-support/engineering-tools/reference-data/thermocouple-types
[12] Wu et al, 'Effects of coating and diametric load on fiber Bragg gratings as cryogenic temperature sensors', NASA, 2008 https://ntrs.nasa.gov/api/citations/20080014178/downloads/20080014178.pdf
[13] Zhang et al, 'Enhanced strain and temperature sensing in copper-coated fiber Bragg Grating sensors across a wide temperature range from cryogenic to elevated levels', Cryogenics Vol 139, 2024, 103834 https://doi.org/10.1016/j.cryogenics.2024.103834
[14] 'Fiber Optic Temperature Array Sensors for Cryogenic Processes and Storage Monitoring', Proximion, 2024 https://www.hexatronic.com/hubfs/bu-pr/application-note/fiber-optic-sensor-systems/ApplNote_cryogenic_process_and_storage_monitoring.pdf
[15] TC Direct, RTD Sensor - Pt100 Mineral Insulated with Pot Seal 500°C / 600°C Rated https://www.tcdirect.co.uk/product-2-230-16/RTD-Sensor-Pt100-Mineral-Insulated-with-Pot-Seal-500%C2%B0C-%2f-600%C2%B0C-Rated#230_16_2
[16] Cryogenic Temperature Sensors, Scientific Instruments https://www.scientificinstruments.com/cryogenic-temperature-sensors/
[17] Cryogenic Silicon Diode Temperature Sensors, Cryotechnics https://www.cryotechnicsus.com/products/silicon-diode-temperature-sensors

- Hydrotechnik (UK) HT-H2-TPSE combined pressure and temperature sensor designed for use with hydrogen, -40 to +125°C; HT-TH2 low cost sensor for hydrogen, down to -50°C [18].
- Proximion (Sweden) WISTCryo FBG temperature sensor arrays for cryogenic applications, -263°C (10 K) to +50°C, though "remains sensitive below 20K but its performance is untested"; may still be in development. [19]
- Neoptix / Qualitrol (Canada/USA) T1 Fiber Optic Temperature Probe. -270°C (3 K) to +250°C; hydrogen environment not mentioned. [20]

2.4. Gaps or research challenges

It is unclear whether any of these sensors have been tested for a long lifetime in in cryogenic hydrogen conditions, though in most cases they can be hermetically sealed, e.g. in a copper or ceramic shell / glaze. Research is needed to establish effective lifetimes. In addition, the extent to which the sensors introduce a heat sink needs to be considered, along with how to integrate them during manufacturing, and, depending on lifetime, to replace them.

Fibre-optic sensing in the tank for temperature and other phenomena is potentially valuable and further research is needed for functionality and durability.

[18] Hydrogen Temperature Sensors, Hydrotechnik https://www.hydrotechnik.co.uk/hydrogen-temperature-sensors
[19] FBG Sensors, Proximion https://www.proximion.com/products#FBG-sensors
[20] Neoptix, T1 Fiber Optic Temperature Probe https://neoptix.com/t1-sensor.asp

3. Pressure

The pressures considered in a LH_2 fuel system are relatively low compared to a compressed gaseous hydrogen system. Most pressure sensors are based on strain / resistance, but Druck's trench etched resonant pressure sensor (TERPS) technology is interesting in that it is an order of magnitude more accurate than typical strain gauge sensors. There are many pressure sensors (resistance, TERPS and piezoelectric) which use materials and coatings which allow them to be used with hydrogen. Two commercial sensors have been found which are designed both to resist hydrogen and the cryogenic liquid hydrogen temperature range, though some piezoelectric dynamic pressure sensors are available for use down to 33 K. Capacitive pressure sensors exist in literature for pressure sensing, but commercial offerings have not been found.

Vacuum monitoring will also be required for twin-walled pipes and tanks.

3.1. Condition requirements

- ~0 – 25 bara in and around tank / low pressure pump
- 10^{-6} mbara for vacuum insulation
- up to 70 bara high pressure pump to engine feed system

3.2. Measurement methods and applicability

There are numerous methods to measure pressure, though most are force collector types which use a diaphragm or other means to measure strain or deflection caused by the force of the pressurised medium over an area. Another method uses changes in resonant frequency to measure stress. The most relevant types which are used in hydrogen and/or cryogenic applications are listed here.

Piezoresistive: Most pressure sensors are based on this technology, where piezoresistive strain gauges are connected to form a Wheatstone Bridge circuit on a diaphragm which stretches under pressure. The strain affects resistance, leading to an electronic measurement which correlates with pressure. These are simple and robust, stable over time, and very small sensors can be made as MEMS devices. Disadvantages are that the sensor must be powered, and that it is temperature dependent.[21]

Capacitive: Capacitive pressure sensors include two closely spaced, parallel, electrically isolated surfaces, one of which is a diaphragm capable of slight flexing under pressure which alters the gap between them, effectively creating a variable capacitor. The change in capacitance outputs a signal which determines the pressure. These are also simple and robust, inherently low power, and can be used wirelessly with inductive coupling. However, they are non-linear and

[21] 'Capacitive vs piezoresistive vs piezoelectric pressure sensors', Avnet Abacus https://my.avnet.com/abacus/solutions/technologies/sensors/pressure-sensors/core-technologies/capacitive-vs-piezoresistive-vs-piezoelectric/

sensitive to vibration.[21] While capacitive pressure sensors for cryogenic applications appear in older literature[22], a commercial offering has not been found.

Resonant frequency: This uses changes in resonant frequency to measure stress caused by applied pressure. Druck (Baker Hughes) has developed a highly accurate Trench Etched Resonant Pressure Sensor (TERPS) technology platform that provides an order of magnitude greater accuracy and stability than typical pressure measurement technologies. Druck supplies this with a hydrogen barrier coating for gaseous hydrogen applications, with a temperature range down to -40°C.

Piezoelectric: These pressure sensors are typically used to measure dynamic rather than static pressure and have very fast response times. They use the natural properties of piezo-electric materials which produce an electric current when under pressure, though not all piezoelectric materials work at cryogenic temperatures. Sensors are available rated down to around 30 K. Piezoelectric charge output sensors directly output an electrical charge that is generated by the sensing element while integrated electronic piezoelectric (IEPE, or ICP) sensors incorporate an electronic circuit and output voltage. These sensors are good for accelerometry and vibration sensing.

Vacuum monitoring: Vacuum monitoring will also be required for twin-walled pipes and tanks, which should see only trace levels of hydrogen. This may be achieved by pressure monitoring, or using vacuum switches with alarms to indicate if the vacuum system has been compromised. Hydrogen sensors in the vacuum spaces may also be required.

3.3. Current offerings

Commercial – many are available for gaseous hydrogen including protective coatings, etc to resist hydrogen permeation, but only a few, such as the Hydrotechnik sensor below, are rated for liquid hydrogen temperatures.

- Hydrotechnik (UK) [23]
    - HT-CPT-20SD1 Cryogenic Liquid Hydrogen Pressure Sensor accuracy ±0.25% FS, with operating temperature down to -260°C
    - Several others for gaseous hydrogen
- Sino-Inst Cryogenic Pressure Transducer CPT-20SD1 can be customised for hydrogen and down to -260°C [24]
- PCB Piezotronics (USA) Dynamic Cryogenic Pressure Sensors (ICP® Series 102), operating temperature -240°C (33 K) to +100°C, some models are acceleration compensated to minimize vibration sensitivity [25]

---

[22] Echternach, P.M., Hahn, I., Israelsson, U.E. (1996). 'A Novel Silicon Micromachined Cryogenic Capacitive Pressure Transducer', In: Kittel, P. (eds) Advances in Cryogenic Engineering, ACRE vol 41. Springer, Boston, MA. https://doi.org/10.1007/978-1-4613-0373-2_232
[23] Hydrogen Pressure Sensors, Hydrotechnik https://www.hydrotechnik.co.uk/hydrogen-pressure-sensors-0
[24] Sino-Inst Cryogenic Pressure Transducer, https://sino-inst.com/cryogenic-pressure-transducer-model-cpt-20sd1/
[25] Dynamic Cryogenic Pressure Sensors, PCB Piezotronics https://www.pcb.com/sensors-for-test-measurement/pressure-transducers/cryogenic

- Strainsense (UK) S-series piezoelectric pressure transducers, suitable for hydrogen, linearity up to ±0.3% FS, operating temperature down to -55°C
- Druck (UK) [26]
    - RPS/DPS8000H Hydrogen Focused High Accuracy Resonant Pressure Sensor (TERPS), accuracy ±0.01% FS, operating temperature range -40°C to +125°C
    - UNIK5000H Hydrogen Focused Pressure Sensor (MEMS piezoresistive strain gauge), precision ±0.04% FS, operating temperature range –55 to +125°C
- Fuji Electric (France) Pressure transmitter differential for hydrogen - FKC with hydroseal membrane, accuracy ±0.15%, operating temperature -40 to +85°C [27]
- For vacuum, Leybold (UK) COOLVAC e - Cryogenic Vacuum Pumps [28]

3.4. Gaps or research challenges

Few sensors are available specifically approved for LH_2, rather than gaseous hydrogen conditions. - Only the Hydrotechnik HT-CPT-20SD1 and the Sino-Inst CPT-20SD1 have been found that are offered for those conditions commercially, but the technology used is not disclosed in either case. There is scope for developing existing sensor technology, such as piezo-electric or piezo-resistive, or TERPS. These are already hermetically sealed which is promising in terms of function in a hydrogen environment, but the transduction technologies may function differently at such low temperatures and alternative materials may be required. The lifetime of sensors in cryogenic hydrogen conditions will need to be proven for certification in aerospace. Weight reduction will also be important, as many sensor housings are stainless steel.

[26] Druck Hydrogen pressure sensors, Baker Hughes https://www.bakerhughes.com/druck/industrial-pressure-sensors/druck-hydrogen-pressure-sensors

[27] Pressure transmitter differential for hydrogen - FKC with hydroseal membrane, Fuji Electric https://www.fujielectric.fr/en/product/pressure-measurement/hydroseal-differential-pressure-transmitter-fkc/

[28] COOLVAC e - Cryogenic Vacuum Pumps, Leybold https://www.leybold.com/content/leybold/en-uk/products/vacuum-pumps/cryogenic-systems/coolvac-cryo-vacuum-pumps.html

4. Flowrate

It is as yet unclear whether direct flowrate measurement will be required on the aircraft, or if accurate mass gauging is achievable at the tank and ground-based refuelling infrastructure accurately measures LH_2 fuel supply to the aircraft.

Where flow measurement is required for both liquid and gaseous hydrogen, it is likely that the preferred state for flow measurement will be where the fluid is in a stable phase, as either gas or liquid, though it may be necessary to measure multiphase flow in the delivery system from tank to propulsion unit.

Gaseous hydrogen flow metering is well-established, most often using Coriolis or ultrasonic flowmeters, but these are heavy, so may not be suited for adaptation to aircraft. Endress+Hauser supplies a Coriolis flowmeter which is used for LH_2. Chart Industries offers orifice plate meters for both liquid and gaseous hydrogen, though may introduce a greater pressure drop than other flowmeter types. The dependence on pressure measurement is a challenge for multi-phase flow, however Chart may have addressed this with additional sensing. Laminar differential pressure flowmeters for gaseous hydrogen minimise the pressure drop, and measure temperature and pressure at the same time.

Electrical capacitance tomography (ECT) is an established technology which is under development for aircraft-based solutions and can be used to measure multi-phase mass flow rate. An alternative to measuring flowrate directly is to measure the mass in the tank and calculate the change – see section 5.

For LH_2 fuelling stations where mass is not a concern, Coriolis and orifice plate LH_2 flowmeters are commercially available.

4.1. Condition requirements

LH_2 flow measurement is needed for refuelling infrastructure. It is not yet clear whether hydrogen flow measurement will be required on-aircraft, though it may be required in the fuel feed system.

LH_2 supply: ~18-30 K, and potentially up to 25 bara (upper pressure limit)

Delivery to propulsion units: Conditions will vary depending on system parameters, but if required, it is expected that flow measurement will be where the hydrogen is in a stable gaseous phase, likely still cold, but closer to ambient temperature than cryogenic. However, it may be necessary to measure multiphase flow.

No requirements for accuracy have been defined as yet.

4.2. Measurement methods

Ultrasonic flowmeters: This method uses sound waves to measure flow rate by detecting the time delay or Doppler shift in ultrasonic pulses traveling through the fluid, combined with density data. It is non-intrusive, with no moving parts and is suitable for both GH_2 and LH_2 (but not multiphase) with high accuracy. However, it can be affected by density variations in GH_2. Some have been adapted from liquefied natural gas (LNG) applications for LH_2.

Coriolis flowmeters: These flowmeters measure mass flow by detecting the deflection due to the Coriolis force exerted on a U-shaped tube which vibrates at its natural frequency as fluid flows through. It is a direct mass flow measurement, with high accuracy, and also measures density, so is potentially useful for multiphase flow but can be sensitive to vibrations and temperature variations. Commercially available Coriolis meters are heavy, due to the large U-shaped tube, so may not be suitable for adaptation to in-flight applications. Furthermore, in-flight vibrations and transient conditions may interfere with their operation.

Orifice plate: This measures flow by detecting the pressure drop across a plate with a central hole (orifice). It is simple and low-cost, but introduces a pressure drop which may be undesirable in a low pressure system. The pressure change may introduce phase changes with LH_2, and they may be more susceptible to inaccuracies with multiphase flow. However, given that Chart Industries supplies an orifice plate solution for LH_2, these issues may have successfully been addressed. This could be adapted for aircraft if the pressure drop is not a problem.

Laminar differential pressure: These flowmeters convert turbulent flow into smooth laminar flow then measure the pressure drop across a flow channel. From this they can calculate the volumetric flow rate and then a standardised mass flow rate. Also measures temperature and pressure, suitable for GH_2 only. A key advantage is the low pressure drop.[29]

Electrical capacitance tomography: ECT works by measuring the capacitance between multiple pairs of thin, conducting plates and can work with multiphase flow. The capacitance is related to permittivity and therefore to density, which enables mapping of the distribution of fluid in the tank using tomography, which can be used to calculate the mass inside the tank. The ESA funded Atout Smart Tanks for Space (SMARTTS) project with Ariane demonstrated this technology in a LH_2 transfer line at 22K-24K and 1.5 - 2.5 bar, successfully measuring void fraction to +/- 1%.[30]

ECT was originally developed for the oil and gas industry to measure multi-phase mass flow rate in pipes.[31]

Thermal mass gas flow / Thermal anemometry: This technique may be relevant in the research context. It measures fluid velocity by detecting how much heat is lost from a heated wire or film due to fluid flow, but it is not suitable for LH_2. The risk of introducing an ignition source through the heated wire may limit applications.

Ultrasonic, Coriolis and orifice plate flowmeters are commercially available and work for both GH_2 and LH_2 but would be affected by bubble formation / phase changes in LH_2 - which can be managed by keeping the LH_2 subcooled during the flow measurement. Laminar differential pressure and thermal mass flowmeters are limited to GH_2. ECT works effectively with either or both phases of flow. A summary of suitability is given in Several other potential flowrate measurement techniques are described in Friedrich 2019 from the PRESLHY project. Alternatively, or additionally, rather than measuring flowrate, the change in mass left in the tank can be measured – see section 5.

[29] Laminar Differential Pressure (DP) Flow Meter – Operating Principle, Alicat, https://www.alicat.com/support/theory-of-operation-laminar-differential-pressure-flow-measurement/

[30] 'Liquid Hydrogen Void Fraction', Atout Process, 2024 https://www.smarttanksforspace.co.uk/#pressrelease-july

[31] Preliminary results from propellant mass gauging in microgravity with electrical capacitance tomography, NASA 2022 https://ntrs.nasa.gov/api/citations/20220010165/downloads/ECT_TFAWS_rev7.pdf

Table 4.1. Several other potential flowrate measurement techniques are described in Friedrich 2019 from the PRESLHY project.[32] Alternatively, or additionally, rather than measuring flowrate, the change in mass left in the tank can be measured – see section 5.

TABLE 4.1 SUMMARY OF FLOWMETER TECHNOLOGIES

Flowmeter Type	Weight	Suitability GH_2	Suitability LH_2	Suitability multiphase	Pressure drop	Notes
Ultrasonic	🟡	🟢	🟡	🔴	🟢	Non-intrusive, but sensitive to bubbles. Could be lightweight. May struggle with low-density gases.
Coriolis	🔴	🟢	🟢	🟢	🟡	Highly accurate as direct mass flow. Weight is a major drawback on-aircraft, but good for ground-based.
Orifice Plate	🟢	🟢	🟢/🟡	🔴	🟡	Simple and low weight. Good for ground-based, could be adapted for on-aircraft if pressure drop is not a problem.
Laminar differential pressure	🟡	🟢	🔴	🔴	🟢	Very low pressure drop.
Thermal Mass	🟢	🟢	🔴	🔴	🟢	Simple, compact, but struggles with multiphase flow. May introduce ignition source.
ECT	🟢	🟢	🟢	🟢	🟢	Still under development, but promising for aircraft cryo fuel systems.

4.3. Current offerings

Ultrasonic:

- Emerson/ Rosemount (USA) ultrasonic flowmeters for hydrogen gas pipeline applications [33]
- Krohne (Germany) ultrasonic flowmeters for hydrogen gas pipeline applications [34]

[32] Friedrich, 'Flow- (and H2-Concentration) Measurements at Pro-Science/KIT', https://hysafe.info/wp-content/uploads/sites/3/2019/03/01_20190307_PS-FlowWS-new.pdf
[33] Hydrogen Measurement with Ultrasonic Flow Meters https://www.emerson.com/en-gb/automation/measurement-instrumentation/common-applications/hydrogen-measurement-with-ultrasonic-flow-meters
[34] Flow measurement of pure hydrogen as well as hydrogen-natural gas mixtures, Krohne, https://cmp.krohne.com/hydrogen/flow-measurement-of-pure-hydrogen/

- Panametrics (Baker Hughes) (USA) offers ultrasonic flowmeters for flare gas applications, but not specific for hydrogen [35]

Coriolis: These are not listed online as for hydrogen, but are being used (anecdotally) to measure LH2 flow:

- Emerson (USA) Micro Motion ELITE range [36]
- Endress+Hauser (Switzerland) Proline Promass Q [37]

Orifice plate:

- Chart Industries (Flow Instruments & Engineering, Germany) FLOW Flowcom 3000 (GH_2 and LH_2) [38]

Laminar differential pressure: Also measures temperature and pressure

- Hydrotechnik (UK) Hydrogen Flowmeters (GH_2) [39]
- Alicat Scientific (USA) Whisper™ MW Series Meters, can be made specific to hydrogen and have been used in LH_2 system development [40]

ECT:

- Tech4Imaging (Ohio, USA) is developing and testing a new capacitance-based multiphase cryogenic flowmeter, tested with LN_2 and in the process of being tested with LH_2 [41]
- Atout (Southampton, UK) is also active in ECT for cryogenic fuels and can provide real-time imaging of mass distribution and flow rates, demonstrated with LH_2 in SMARTTS project [42]

Thermal mass gas flow:

- Allison (UK) Mass Flow Meters (GH_2) [43]

General:

- Sino-Inst (China) offers cryogenic flowmeters with multiple technologies: differential pressure, turbine, Coriolis and vortex [44]

[35] Panametrics Flare Flow Measurement https://www.bakerhughes.com/panametrics/flow-meters/flare-flowmeters
[36] https://www.emerson.com/en-gb/automation/measurement-instrumentation/flow-measurement/coriolis-flow-meters-for-mass-volume-density-measurement
[37] Endress+Hauser, Proline Promass Q https://www.uk.endress.com/en/press-center/news-and-press-releases/promass-q-news
[38] Chart Industries FLOW https://www.chartindustries.com/Products/Flow-Measurement
[39] Hydrotechnik Hydrogen Flowmeters https://www.hydrotechnik.co.uk/hydrogen-flowmeters
[40] Whisper™ MW Series Meters, Low Pressure Drop Mass Flow Meters with Laminar Differential Pressure Technology https://www.alicat.com/products/gas-flow/mass-flow-meter/low-pressure-drop-mass-flow-meters/
[41] Tech4Imaging https://www.tech4imaging.com/cryogenic-applications/
[42] Atout https://atoutprocess.com/industry-sectors/aviation/
[43] Allison, Hydrogen mass flow https://allison.co.uk/products/hydrogen-mass-flow/
[44] Sino-Inst https://sino-inst.com/flowmeters-for-cryogenic-fluids-flow-measurement/

4.4. Gaps or research challenges

Ensuring accuracy and reliability is critical, though work is needed to clearly define the requirements as thermofluid modelling and demonstrator fuel systems are developed. One key question is whether multiphase flow will need to be measured. While there is proven technology in industrial systems, some would need significant weight reduction to be used on aircraft. In addition systems may need testing to establish whether measurement is affected by vibration and turbulence in a commercial aircraft context.

5. Fuel gauging

Gauging of the mass of hydrogen in the tank is a critical technology for which at least two valid solutions will be needed for redundancy, but it is not yet clear which solutions will work effectively, and it is noted as a particular challenge by both industrial and research communities. The level of accuracy of gauging needed is not yet defined and will affect the choice of solutions.

Techniques which gauge mass or model the fuel level profile in real time may be more relevant than direct level sensing for aircraft due to sloshing, g-forces and turbulence. Pressure differential from the top to the bottom of the tank are typically used to measure fill level in ground-based LH_2 tanks but may be challenging to implement in a moving aircraft. Any flotation devices are not applicable as the density of LH_2 is too low.

Until recently the technologies used for fuel gauging in actual spacecraft using LH_2 were limited to the bookkeeping method (i.e. the fuel filled minus the fuel used), cylindrical capacitance probes, wet/dry resistance / impedance sensors, and pressure differential liquid level sensors.[45] The pressure-volume-temperature method has not typically been used to measure ullage gas volume because hydrogen deviates from ideal gas laws, especially at cryogenic temperatures, and the ullage gas tends to be non-uniform.

Work that has been done for space applications in microgravity is useful for aircraft applications in that it addresses methods that function when the level in the tank is unstable, which is a requirement for aerospace. This has led to research into radio frequency mass gauging (RFMG), modal propellant gauging (MPG) and its variant ultrasound mass gauging (UMG), and electrical capacitance tomography (ECT). RFMG seems to be the most developed of these for space applications and has been tested in spaceflight scenarios. MPG has undergone parabolic flight testing and ECT shows promising preliminary results and is well established for other sectors.

5.1. Condition requirements

- Fractional fill assumed to be 0.0 – 1.0
- Condition accuracy requirements for aviation as yet unknown
- Minimum of two independent methods required on-aircraft

5.2. Measurement methods and applicability

Radio frequency mass gauging (RFMG): RFMG operates by measuring the natural electromagnetic (EM) eigenmode frequencies of a tank. Because the liquid slows the speed of light in a known way, the changes to the EM modes of the tank can be computed and those simulations are used to compare with the measured tank spectrum.[46] The NASA SHIIVER project demonstrated scaling of RFMG up to 4m dia tank scale and an uncertainty around 1-3% has been

[45] Dodge, 'NASA/CR—2008-215281: Propellant Mass Gauging: Database of Vehicle Applications and Research and Development Studies', NASA 2008 https://ntrs.nasa.gov/api/citations/20080034885/downloads/20080034885.pdf

[46] Zimmerli, Gregory, et al. 'Propellant quantity gauging using the radio frequency mass gauge.' 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 2011.

achieved.[47] This has been tested on the ground with LH_2 and on the International Space Station, and is due to be used on a lunar lander with liquid oxygen and liquid methane.[48]

Electrical capacitance tomography: ECT measures changes in capacitance to infer liquid level and distribution - see description in 4.2. It theoretically will work during all phases of flight, regardless of acceleration / g-force, during sloshing or boiling, with variable density fluid.

This method is different from capacitance probes for level sensing, though it uses the same basic technology, measuring the change in capacitance between electrodes to determine whether the fluid is in liquid or gaseous phase. In ECT multiple electrodes around a tank create a cross-sectional image of the contents, providing spatial information on phase distribution and interfaces. It may also be possible to use this technology to identify build-up of solid contaminants in the tank (see section 13).

Atout (Southampton) is working on this technique, and it is a promising potential method with established expertise in other sectors.[49] Atout has worked with Ariane to test ECT for a space application and achieved successful operation in LH_2, with fill level resolution +/-0.5 mm and imaging of bubble and core flow was possible.[50] Tech4Imaging in the USA is also active in this area.[51]

A NASA report on ECT in microgravity gives an extensive assessment of the technology.[52]

Modal propellant gauging (MPG): MPG uses vibration analysis to determine mass by detecting changes in tank resonant frequency. External acoustic excitation causes a modal response in the structure which is affected by the liquid or gas fuel within. The modal response can be used to infer the mass of fuel with high resolution, as well as the mass flow into and out of the tank, and changes in tank pressure.[53] MPG, like ECT, should theoretically work in all phases of flight. However, the low density of the fuel may be a challenge and it is sensitive to external vibrations. This has been researched at Carthage College with Kennedy Space Centre Cryogenics Laboratory for low gravity conditions and has demonstrated gauging resolutions of 1% for settled propellants and 2–3% for unsettled, sloshing propellants.[54]

---

[47] Johnson et al, 'Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER)', NASA 2018 https://ntrs.nasa.gov/api/citations/20180004687/downloads/20180004687.pdf

[48] NASA Tests New Spacecraft Propellant Gauge on Lunar Lander, 2024 https://www.youtube.com/watch?v=OdB_i74H3dc

[49] ECT Research Systems, Atout https://atoutprocess.com/products-and-services/

[50] Philipp Behruzi, Andrew Hunt, Richard Foster-Turner and Alexander Fischer, 'Testing an Electrical Capacitance Tomography sensor in liquid hydrogen' AIAA 2023-1085. AIAA SCITECH 2023 Forum. January 2023

[51] Electrical Capacitance Volume Tomography, Tech4Imaging https://www.tech4imaging.com/electrical-capacitance-volume-tomography/

[52] Storey, et al, 'NASA/TP–20230012805 Propellant Mass Gauging in Microgravity with Electrical Capacitance Tomography', NASA 2023

[53] Crosby, et al, 'Modal Propellant Gauging: High-resolution and non-invasive gauging of both settled and unsettled liquids in reduced gravity', 69th International Astronautical Congress (IAC), Bremen, Germany, 2018 https://ntrs.nasa.gov/api/citations/20200002896/downloads/20200002896.pdf

[54] Krosby et al, 'Modal Propellant Gauging: High-resolution and non-invasive gauging of both settled and unsettled liquids in reduced gravity', Acta Astronaut. 2019 Feb 6;159:499–507. doi: 10.1016/j.actaastro.2019.01.050

Acoustic / ultrasound mass gauging: This a variant of MPG but uses acoustic waves instead of mechanical vibrations. Low-frequency acoustic waves analyse the resonant frequency, which shifts based on the mass of liquid hydrogen inside. A NASA paper has successfully tested it with water[55].

Potential challenges with any acoustic technologies include interference from external noise; the temperature gradient in the tank in use affects the velocity of sound thus limiting precise measurement; the low density of LH_2, combined with surface boiling, could affect how sound waves propagate through the liquid-gas interface.

Fibre-optic rake discrete levels: This concept uses multiple optical fibre sensors on the inside wall of the tank to detect phase, creating a model of tank level, even when sloshing (see section 10, Phase). This could be integrated at manufacture in composite tanks, though if mounted on a probe rather than integrated into tank walls, this could enable use in metallic tanks and facilitate sensor replacements. Advantages are low weight, simplicity, insensitivity to electro-magnetic interference and the ability to detect low levels of fuel. Disadvantages are that the optical fibres may degrade over time in the cryogenic hydrogen environment, though coatings on the optical fibres may help with this (see 2.2). Further work is needed to establish whether the lifetime of sensors could match the lifetime of tanks.

Methods more affected by movement / sloshing

The following options (except flotation) are good for level sensing for tanks on the ground or in a stable environment but represent a challenge for in-flight applications due to movement effects. However, adaptations of these may emerge as useful technologies on-aircraft. For context, current kerosene aircraft most commonly use submersible pressure sensors for level sensing at multiple points across the fuel tanks (which are typically spread across the wings, though may also be in the cargo hold), though some use ultrasonic or capacitance probe level sensors.

- **Load cells:** Load cells or strain gauges measure the total tank weight and the empty tank mass is subtracted. This is unlikely to be useful on aircraft as it is too sensitive to aircraft inertial loads and vibration, and with liquid hydrogen usually the system mass is much greater than differential hydrogen mass. Even on the ground, attachments to pipework and frosting would limit accuracy. However, if used in conjunction with an accelerometer, with allowance for attachments, this could be feasible for tanks on aircraft.
- **Temperature rakes and pressure differentials:** These work well with a stationary tank with well-stratified fuel but are also limited for in-flight applications due to movement and sloshing. Temperature sensors such as Cernox or silcon diodes have been shown to be more effective for gauging when used as wet/dry sensors (see section 10.2.1).[1] A combination of pressure differential measurement and accelerometers may be a solution, though may be low accuracy.
- **Ultrasound, capacitive, radar or superconductive direct level sensing:** Acoustic / ultrasound level sensing is used in newer, high-tech road vehicles for fuel level sensing. This uses ultrasonic level sensors to measure liquid height and infer fuel volume based on tank shape. This has been proposed but only one study has been found in relation to

---

[55] Feller, et al, ‘NASA/TM–2018–219876 Spectral mass gauging of unsettled liquid with acoustic waves’, NASA 2018

LH_2.[56] Capacitive liquid level sensors, where the cryogenic liquid being measured is used as the dielectric material are also good for stable tanks. Superconducting level sensors are used with liquid helium, where the part of the element in the LHe has zero resistance, but in the gas it is not superconducting. However, any direct level sensing is likely to be inaccurate due to sloshing / bubbling.

- **Flotation measurement:** Devices that depend on flotation, such as magnetic level sensors are available for cryogenic liquids such as ammonia and CO_2.[57] However any device that depends on floats cannot work for LH_2 as no solid has low enough density to float, and the voids in any vacuum filled or foam float would likely be filled with hydrogen by permeation over time.

5.3. Current offerings

Direct level sensors - some examples include:

- Endress+Hauser (Switzerland) Liquicap FMI51, capacitance probe, specifically for LH_2, working with Linde [58]
- Rotarex (Germany) C-Stic mobile, capacitance probe, aimed at trucks, LH_2 and LNG [59]
- VEGA (Germany) VEGAPULS 6X, radar level sensor, not specific to hydrogen or cryogenics [60]
- Eptech (China) ultrasonic liquid level sensors, mentions hydrogen [61]
- SMD Fluid Controls (USA) offers capacitive, ultrsasonic and optical level sensors for cryogenic applications, unclear if designed for hydrogen [62]
- Eaton (USA) Levelmaster® Electronic/Optical Sensor – not described as for hydrogen or cryogenic temperatures, but potentially could be modified for this application [63]

Pressure differential sensors: Use pressure sensors – see section 3.3, though some are integrated into systems:

- VEGA (Germany) VEGADIF 85 Differential pressure measurement [64]

---

[56] Nakano, Nishizu, 'Experimental study of liquid level gauge for liquid hydrogen using Helmholtz resonance technique', Cryogenics, Vol 77, p. 43-48, 2016 https://www.sciencedirect.com/science/article/abs/pii/S0011227515300175
[57] Krohne BM26A-6000 Magnetic level indicator for liquefied gas https://krohne.com/en/products/level-measurement/level-indicators-bypass-chambers/magnetic-bypass-level-indicators/bm26a-6000
[58] Endress+Hauser Liquicap FMI51 https://www.de.endress.com/en/endress-hauser-group/Case-studies-application-notes/requirements-hydrogenrefueling
[59] Rotarex C-Stic mobile https://rotarexsrg.com/product/dimes-c-stic-mobile#
[60] VEGAPULS 6X – radar level sensor https://www.vega.com/en-uk/products/product-catalog/level/radar/vegapuls-6x
[61] Eptech - ultrasonic liquid level sensors https://www.eptsensor.com/news/ultrasonic-liquid-level-sensors-in-hydrogen-st-73911594.html
[62] Liquid Level Sensors for Cryogenic Applications, SMD Fluid Controls https://www.fluidswitch.com/2016/01/25/liquid-level-sensors-for-cryogenic-applications/
[63] Levelmaster® Electronic/Optical Sensor, Eaton https://www.eaton.com/content/dam/eaton/products/engine-solutions/sensors/documents/eaton-level-master-electro-optical-sensor-datasheet-en-us.pdf
[64] VEGA VEGADIF 85 Differential pressure measurement https://www.vega.com/en-uk/products/product-catalog/pressure/differential-pressure/vegadif-85

ECT: Tech4Imaging (USA) and Atout (UK) - testing/pre-commercial (see 4.3). Industrial Tomography Systems (ITS) (UK) uses a combination of ECT and electrical resistance tomography in a dual modality system process visualisation for oil and gas applications.[65]

MPG, RFMG and fibre-optic fuel level imaging: In development with research organisations, but it is unclear whether any commercial companies are offering systems at present.

The COCOLIH$_2$T (COmposite COnformal LIquid H$_2$ Tank) project (2023-2026), led by Collins Aerospace, includes development of gauging technology led by Simmonds Precision Products Inc. in Vermont. It is unclear what gauging technology they are working on, but Simmonds has significant expertise in this area.[66]

5.4. Gaps or research challenges

While several direct level sensing techniques exist as commercial offerings, few are designed for cryogenic hydrogen environments and those that are may still need further work to demonstrate accuracy and reliability, as well as weight reduction, for aerospace.

Work in the space sector for microgravity is useful for informing sloshing/unsteady tank conditions that will be experienced in aerospace. However, there will be differences, and systems in development for space (ECT, MPG, RFMG, fibre-optic) will need considerable further testing to demonstrate applicability for long-lifetime commercial aerospace applications.

A test rig for trialling gauging systems in LH$_2$ tanks with movements that are likely to be seen in commercial aircraft – simulating g-forces due to the flight profile and turbulence - would be a useful investment to accelerate development.

[65] Electrical Capacitance Tomography, ITS https://www.itoms.com/technologies/electrical-capacitance-tomography/
[66] COCOLIH2T https://www.cocolih2t.eu/

6. Concentration and leakage

Several experts have commented that it is not "if", but "when" hydrogen will leak,[67] so while detecting individual leaks is critical, constant monitoring of the hydrogen concentration in the region around the fuel system is essential to keep it a safe margin below the lower flammability level (LFL) of 4%, usually 25% LFL, before diluting the air by venting or flushing, as well as avoiding any ignition sources in those areas.

In relation to this and the next section on flame detection, the recently published FAA roadmap states:

Research is needed for rapid, accurate leak source identification methods, e.g., using sensor networks or dispersion models, preferably self-calibrating. Hydrogen leaks may not only result in hydrogen flames; leaks impinging on other surfaces can also affect the combustion characteristics of flammable materials (e.g., faster, stronger heat release). Better information is needed on quantifying such impact and devising appropriate test protocols, as well as fire extinguishing/fireproofing methods.[68]

Many hydrogen gas detection sensors are available, and of particular relevance are those developed for enclosed spaces such as battery rooms. Ideally a low-cost, lightweight hydrogen gas sensor should be aerospace certified so that it can be installed in multiple locations in the aircraft. It may also be appropriate to maintain negative pressure in spaces around fuel systems relative to cabins to minimise any risk of hydrogen gas finding its way into the cabins.

While gas sensors can detect hydrogen in the atmosphere, and flame sensors can detect hydrogen flames (see section 7), detection of points of leakage is also important. Hydrogen leak detector tape is available as a silicone wrap which changes colour on exposure to concentrated hydrogen, though it is not currently certified for cryogenic temperatures. Ultrasound gas leak detection (UGLD) is widely used for high pressure gas, so may be effective at the gaseous end of the fuel system, but further work will be needed to establish whether it can be used in the LH_2 tank region where the low pressure differential combined with background noise may limit applicability. Hydrogen leaked close to the tank will be very cold, so thermal imaging may be an effective way to detect leaks.

In addition to the risk of direct hydrogen fire and explosion, heat leaks can cause liquid or solid oxygen to form, which can increase the potential for ignition in some combustible materials. Hence choice of materials in the regions around fuel systems should be carefully considered, and testing is needed to establish risks.

For more information about safety of liquid hydrogen systems, see the accompanying report 'Cryogenic Hydrogen Health & Safety Global Research Landscape'.[7]

[67] 'Starting Small: Can Hydrogen Propulsion Grow Out Of Its Initial Niche?', Aviation Week Network, August 2024 https://aviationweek.com/aerospace/emerging-technologies/starting-small-can-hydrogen-propulsion-grow-out-its-initial-niche
[68] 'Hydrogen-Fueled Aircraft Safety and Certification Roadmap', FAA, December 2024 https://www.faa.gov/aircraft/air_cert/step/disciplines/propulsion_systems/hydrogen-fueled_aircraft_roadmap

6.1. Condition requirements

Standards such as the National Fire Protection Association (NFPA) typically limit concentrations to 25% LFL, i.e. 1% hydrogen or 10,000 ppm, and have requirements for ventilation.

NFPA 2, Hydrogen Technologies Code shares requirements for hydrogen gas detectors:

- minimum measurement range of 0-4%, recommended 0-10%, hydrogen v/v in air
- trigger a low alarm at 4000 ppm (0.4% v/v, 10% LFL) and a high alarm at 10,000 ppm (1% v/v, 25% LFL)
- minimum lower detection limit (LDL) of 25% of the lower alarm threshold, i.e. 1,000 ppm[69]

Requirements around aircraft fuel systems may be similar to NFPA and other standards. However, factors other than direct flammability may affect limit requirements, such as the effect of a hydrogen rich atmosphere on the combustion characteristics of materials, or potential for hydrogen degrading materials over the aircraft lifetime. While the LFL of hydrogen is 4.1% v/v, tests have shown that hydrogen may burn but is not explosive below 10% v/v. [70] However this can be affected by the presence of catalytic materials, dust, and other environmental conditions, so further research is needed to determine a practical LDL, and/or define requirements for limiting such external conditions.

Any detectable point of leakage should be identified, but requirements are needed to define whether current leak detection methods are adequate. Characterisation of large scale leaks has been carried out by the Health and Safety Executive (HSE) through the Prenormative Research for the Safe Use of Liquid Hydrogen (PRESLHY) programme.[71] The US National Renewable Energy Laboratory (NREL) used information from PRESLHY to develop a hydrogen wide area monitor (HyWAM).[72] The HCN report 'Cryogenic Hydrogen Health & Safety Global Research Landscape' has a section dedicated to leakage considerations and research. [7]

6.2. Measurement methods and applicability

6.2.1. Hydrogen gas detection sensors

There are numerous methods of detecting hydrogen and several useful reviews consider these. Perhaps the most relevant and practical of these is Jia et al 2023, from the China Astronaut Research and Training Center and Beijing University of Technology, which relates to the manned

---

[69] NFPA 2: Hydrogen Technologies Code 2023, NFPA https://www.nfpa.org/codes-and-standards/nfpa-2-standard-development/2

[70] Vogelzang et al, 'The Lower Flammability Limit of Hydrogen', IGRC 2024 https://www.kiwa.com/498e74/globalassets/netherlands/kiwa-technology/downloads/igrc2024-the-lower-flammability-limit-of-hydrogen-oral-presentation-bart-vogelzang.pdf

[71] PRESLHY https://preslhy.eu/

[72] Buttner et al, 'Hydrogen wide area monitoring of LH_2 releases', Int. J. Hydrog. Energy., 46(23):12497-12510 https://doi.org/10.1016/j.ijhydene.2020.08.266

space station environmental control and life support system.[73] Another review with more technical detail of different types is Moussa et al 2024.[74]

The main technologies are summarised below. Most of these technologies require oxygen to function, so would not be suitable if it were decided that the region around the tanks should be in an oxygen-free atmosphere.

Catalytic Bead Sensors (Pellistors): Hydrogen oxidizes (burns) on a heated catalyst bead, and the heat generated changes the resistance of the sensor element.[75] This method is reliable and widely used, but requires oxygen and a high power consumption, and the catalyst is susceptible to humidity and can be poisoned by contaminants, causing drift in the sensor output.

Thermal conductivity: This method measures the change in thermal conductivity of gas when hydrogen is present. It has a quick response and is stable, but is less sensitive at low concentrations, so is best for high-purity hydrogen, though cross-sensitivity with helium is a challenge.

Metal oxide semiconductor: Hydrogen alters the resistance of a metal-oxide semiconductor (e.g., tin oxide, tungsten oxide). These sensors are durable and low cost, with a long lifetime. However, they have relatively high power consumption, and although they can vary ranges of between 30mW and 700mW are seen, they can also be cross-sensitive to other gases. Some require an oxygenated atmosphere to function, but those which are doped with palladium or platinum may not.

Organic semi-conductor: Though not yet commercial, a new hydrogen sensor technology has emerged from the University of Manchester that uses an organic semiconductor as the active layer. It depends on oxygen doping of the semi-conductor, while the presence of hydrogen reverses this doping process. The sensor has a fast response time (less than 1 s), low limit of detection (around 192 ppb) and low power consumption, and is very small and lightweight.[76]

Electrochemical: This method uses a chemical reaction between hydrogen and an electrolyte to generate an electrical current proportional to the gas concentration. It has high sensitivity and low power consumption and is compact, but the lifespan is relatively short as it is affected by temperature and humidity. It also requires oxygen.

Fibre-optic: There are several ways in which fibre-optics can be used to measure low hydrogen concentrations, including coating the fibre with palladium which changes in the presence of hydrogen, affecting the fibre's optical properties, or fibre-Bragg.[77] Fibre-optics have significant

---

[73] Jia et al, 'A Review of Hydrogen Sensors for ECLSS: Fundamentals, Recent Advances, and Challenges', Appl. Sci. 2023, 13(12), 6869; https://doi.org/10.3390/app13126869
[74] Moussa et al, 'Hydrogen Sensing Technologies for the Safe and Reliable Decarbonization of Electric Power: A Review', Energies 2024, 17(18), 4532; https://doi.org/10.3390/en17184532
[75] 'Pellistor Sensor Technology & Applications' SGX, 2007 https://www.sgxsensortech.com/content/uploads/2014/08/AN1-Pellistor-Sensor-Technology-and-Applications1.pdf
[76] 'Scientists develop hydrogen sensor that could pave the way for safer, cleaner energy', University of Manchester, March 2025 https://www.manchester.ac.uk/about/news/scientists-develop-hydrogen-sensor-that-could-pave-the-way-for-safer-cleaner-energy/
[77] Shen et al, 'Review of the Status and Prospects of Fiber Optic Hydrogen Sensing Technology', Chemosensors 2023, 11(9), 473; https://doi.org/10.3390/chemosensors11090473

advantages in that they do not introduce any ignition sources, are lightweight, immune to EM interference and have a fast response time.

Gasochromic: Several compounds change colour with a catalyst in the presence of hydrogen, which has led to commercial hydrogen leak detector tape DetecTape, while other technologies are being researched, such as Pt/WO_3 thin films at Feng Chua University, Taiwan [78], a system using SiO2 nanoparticles, Au-Pd nanoparticles, and indicator-dye at FAU Erlangen-Nürnberg in Germany[79] and vanadium oxide system at London South Bank University.[80] An extension of this gasochromic approach has led to a "nanoplasmonic" optical sensor developed at Chalmers University with around 250 ppb accuracy, using colour changes in palladium nanoparticles when the amount of hydrogen in the surroundings changes. [81] The nanoplasmonic sensor is being commercialised through Insplorion, a spin-out from the TechForH2 team at Chalmers University.

6.2.2. Leak detection

Ultrasonic leak detectors: Several commercial suppliers exist for these, which detect high-frequency sound waves emitted by gas escaping from high-pressure systems with a fast response time. There are several challenges with an acoustic approach:

- Interference from aircraft background noise - though suppliers of ultrasonic systems claim to have good systems for filtering noise and pinpointing the leak.
- The noise from thermoacoustic self-excitation, hydrogen boiling and materials contracting at different rates would also cause interference, though the change in noise due to the effect of a cold leak on materials may have a sufficiently unique acoustic signature to identify leaks.
- The relatively low pressure of LH_2 storage may limit application near the tank, though as the liquid transitions to gas the noise signal may be sufficient.

Several companies supply large, heavy (e.g. 18 kg) ultrasonic gas leak detectors for long-range, outdoor use.[82] However, acoustic cameras, which use a microphone array and an optical camera to overlay the detected ultrasonic signal onto a visual image, make it easier to pinpoint small leaks. These are much lighter and can work with a low pressure differential. [83] Alternatively ultrasonic sensors could be fixed directly to equipment to detect leaks, or high resolution distributed acoustic sensing using optical fibres could be used (see 8.2.2). Research is needed to identify whether an acoustic / ultrasonic approach is realistic at all given the background noise,

---

[78] Chan et al. 'Preparation and characterization of gasochromic Pt/WO3 hydrogen sensor by using the Taguchi design method', Sensors and Actuators B 145 (2010) 691–697 https://doi.org/10.1016/j.snb.2010.01.021
[79] Reichstein et al, 'Supraparticles for Bare-Eye H2 Indication and Monitoring:Design, Working Principle, and Molecular Mobility' Adv. Funct. Mater. 2022, 32, 2112379 https://doi.org/10.1002/adfm.202112379
[80] O'Hara et al, 'Chemochromic Pd-V2O5 Sensors for Passive Hydrogen Detection in Nuclear Containments. 2018 WM Symposia, Nuclear and Industrial Robotics, Remote Systems and Other Emerging Technologies. Phoenix, Arizona, USA 18 - 22 Mar 2018
[81] 'Ultra-sensitive optical sensor can reduce hydrogen's risks', Chalmers University, 2022 https://www.chalmers.se/en/current/news/f-ultra-sensitive-optical-sensor-can-reduce-hydrogen-s-risks/
[82] Rosemount™ Incus Ultrasonic Gas Leak Detector, Emerson https://www.emerson.com/en-us/catalog/rosemount-sku-incus-ultrasonic-gas-leak-detector
[83] 'Ultra Pro – Ultrasonic leak imaging for high-reliability inspections', Distran https://distran.swiss/en/ultra-pro/

and if so, to identify relevant acoustic signatures and the effect of aircraft vibration, hydrogen boiling and self-excitation.

Thermal imaging: Thermal imaging may be a solution for leak detection around the LH_2 tank, as a leak of the cryogenic liquid will be at a much lower temperature than the surroundings. The effect on adjacent materials should be easier to detect optically than the hydrogen itself, and frosting (of water or air) around a leak may be visible to the eye in any case. (See also thermal imaging for structural assessment in section 8).

6.3. Current offerings

Hydrogen gas detection sensors:

There are many hydrogen gas sensors on the market, a selection is included below, focusing on lightweight options (except the pellistor sensor).

- International Gas Detectors (UK) MK8 pellistor gas detector technology with increased reliability due to improved resistance to catalyst poisoning; can be used in several sensor types, including: TOC-750X, 0-40,000 ppm H_2, operating temp: -20 to 55°C, 1.55 kg [84]
- SGX Sensortech (Poland) VQ600 pellistor gas sensor, available as catalytic (range 0 to 100% LEL) or thermal conductivity (0 to 100% volume) type for H_2, operating temp: -20°C to +60°C, 435 g [85]
- Honeywell (USA) HLD Series, thermal conductivity technology, range: 0-4% H_2, 50 ppm H_2 resolution, operating temp: -40°C to 85°C, 50 g [86]
- AST International (Germany) supplies a range of thermal conductivity hydrogen concentration sensors, including 0-5%, 0-10% H_2, ± 0.1vol-% of H_2 in air, operating temp: -40°C to +105°C [87]
- Figaro (USA) TGS 821, tin dioxide (SnO2) semiconductor sensor, for very low concentrations, 50ppm to 4000 ppm (0.4% H_2), operating temp: -10 to 40°C, small and lightweight button sensor [88]
- Crowcon (UK) supplies a range of portable hydrogen gas detectors using different technologies [89]
- City Technology (UK) 3, 4 and 7 series CiTiceLs are electrochemical hydrogen sensors with ranges 0-1000 / 2000 / 10000 / 50000 ppm H_2, operating temp: -20°C to +50°C [90]

[84] 'New Standard in Flammable Gas Detection – MK8 Pellistor Gas Detector', International Gas Detectors https://www.internationalgasdetectors.com/new-standard-in-flammable-gas-detection/
[85] SGX Sensortech, VQ600 Datasheet https://sgx.cdistore.com/datasheets/sgx/ds-0240%20-vq600-v1.pdf
[86] Honeywell HLD Series, range: 0-4% H2 https://automation.honeywell.com/us/en/products/sensing-solutions/sensors/electrification-sensors/hydrogen-safety-sensors/hld-series#resources
[87] AST International, Hydrogen Concentration Sensor https://www.ast-international.com/en.products.hydrogen-concentration-sensor.html
[88] Figaro, TGS 821 - Special Sensor for Hydrogen Gas https://www.figarosensor.com/product/docs/TGS821.pdf
[89] Crowcon Hydrogen gas detectors, https://www.crowcon.com/solutions/gas-hazard/hydrogen/#products
[90] Shaw City, CiTiceL hydrogen sensors https://products.shawcity.co.uk/search?q=citicel%20hydrogen

- Somni (NL) / United Fiber Sensing H_2 2000 T fibre-optic hydrogen sensor, range: 0.1-4% H_2, operating temp: -65 to +80 °C, 100 g [91]
- NevadaNano (USA) MPS™ flammable gas sensor, micromachined silicon, simultaneously detects 0-100% LEL for over a dozen of the most common combustible gases, no field calibration required, operating temp: -40 to +75 °C, 100 g T90 under 20 seconds, ~10g [92]
- Element One (USA) thin film passive RFID hydrogen sensor and Detectape gasochromic H_2 Visual Hydrogen Leak Detector [93]
- Insplorion (Sweden) NPS-P2 nanoplasmonic (optical gasochromic) range: 0-4% H_2, works in low oxygen environments [94]

Ultrasonic leak detection:

- Distran (Switzerland) Ultra Pro X ultrasonic leak detector (acoustic camera); ATEX certified and certified for zone 2 gas for class IIC (USA: div 2 class 1), including hydrogen; filters all noises outside the detection window [83]
- SoundCam (UK) Acoustic cameras [95]
- Infinicon (Switzerland) Whisper ultrasonic leak detector - a small, handheld device where a metal probe is touched onto equipment and ultrasonic noise is converted to audible sound to listen for leaks [96]

6.4. Gaps or research challenges

There are many electrochemical, thermal conductivity and MOS sensors available which are small and lightweight (tens of grams or less). While there is extensive knowledge of gas detection sensors for gaseous hydrogen, and several commercial offerings, there are none certified to operate close to LH_2 temperatures. Failure mechanisms which cause leaks are not yet fully understood, so it is not yet clear whether sensors will need to operate in cryogenic conditions, or whether current offerings are suitable.

The Universities of Bristol and Manchester have recently developed hydrogen sensing technologies which they are aiming to commercialise.[97] [98]

Challenges which need to be addressed include:

- Whether there is a need for hydrogen detection sensors to operate at very low temperatures will depend on the way in which leaks occur and propagate in an enclosed region around a LH_2 fuel system
- Determination the actual lower temperature limit for current sensors of interest

---

[91] Somni, Hydrogen leak detector https://www.somnisolutions.com/somni-hydrogen-leak-detector
[92] NevadaNano, Hydrogen Gas Detection https://nevadanano.com/products/mps-hydrogen-gas-sensor/
[93] 'Hydrogen Detection Solutions', Element One https://elem1.com/hydrogen-detection-solutions/
[94] Insplorion https://www.insplorion.com/en/hydrogen-sensor-p2/
[95] SoundCam https://soundcam.com/
[96] Infinicon Whisper Ultrasonic leak detector https://www.inficon.com/en/products/leak-detectors/whisper
[97] HyTrace (from University of Bristol) https://hytrace.co.uk/
[98] 'Scientists develop hydrogen sensor that could pave the way for safer, cleaner energy', University of Manchester, March 2025 https://www.manchester.ac.uk/about/news/scientists-develop-hydrogen-sensor-that-could-pave-the-way-for-safer-cleaner-energy/

- Whether EM interference needs to be considered
- Ignition risks
- Functionality of sensors in a low-oxygen environment, if that becomes a requirement for the area around fuel systems
- Durability of sensors, especially in an environment which may have low levels of hydrogen over a long period

There are some commercial offerings, and there is significant recent research into fibre-optic sensing, which is of particular interest as it is inherently free from ignition risks and not affected by magnetic interference. This type of sensing is also small, lightweight, and easily integrated, and can detect hydrogen and temperature at the same time. Further research and development is needed to find optimal ways to use fibre-optics in this context.

Ultrasonic leak detectors are used extensively for high pressure systems, but research is needed to identify whether the acoustic signature of escaping liquid as it changes to gas could be the basis of a robust detection system. Likewise the potential for thermal imaging as a leak detection method needs to be investigated, and perhaps could be integrated with UV/IR flame detection cameras. (See section 7.)

7. Flames

Current aircraft do not typically use flame detectors, but they use heat-sensitive loops (helium pneumatic-based continuous element), thermocouple overheat sensors, and photoelectric based smoke detectors for fire safety.[99] The methodology for fire protection around hydrogen systems on aircraft is evolving and it is unclear at this stage whether flame sensors would be required, however, since hydrogen flames emit virtually no visible spectrum radiation, flame sensors could become an important part of fire detection in the case of leakage in the vicinity of hydrogen fuel storage and transmission within the aircraft.

If required, this section assumes that they would be applied to flames from leaks, i.e. not within a pipe or tank, so it is not expected that they would be needed to function in a cryogenic environment. If there are situations where hydrogen is flared, they may also be useful to detect if the flame is extinguished, though temperature monitoring may suffice. Though it is out of scope for this report, they may also be used to ensure the stable and optimised operation of hydrogen gas turbines.

NASA has used UV sensors for hydrogen flame detection.[100] Numerous flame sensors using ultraviolet (UV) and infrared (IR) detection already exist commercially, and could potentially be certified for aerospace, with modifications such as weight reduction if required. UV only sensors tend to have faster response times, multi-spectrum infrared (MIR) are more selective to hydrogen flames. Flame sensors exist with the capability to be used in gas turbines, with a hot end temperature limit up to, e.g. 325 °C.

For more information about safety of liquid hydrogen systems, see the accompanying report 'Cryogenic Hydrogen Health & Safety Global Research Landscape.[7]

7.1. Condition requirements

Flame sensors are line-of-sight sensors which would be deployed around the fuel system, not within it, so their normal working conditions would be around ambient temperature and pressure. However, they may need to work in colder conditions - if affected by a cryogenic hydrogen leak - or hotter, if expected to continue to work once a fire is under way.

It is essential that the sensor is not an ignition source.

7.2. Measurement methods and applicability

Hydrogen flames radiate energy mainly in the UV band, though some IR band radiation also occurs. Flame sensors may use UV detectors, or combined UV/IR, or MIR. UV-only sensors have the fastest response times (~50–500 ms), but can result in false alarms as they are sensitive to arcs, sparks, welding, lightning and other UV-rich sources. This sensitivity may make UV/IR more reliable, though it may not be a problem within the enclosed space around a hydrogen fuel

[99] 'Aerospace Sensors 2019', Counterpoint Market Intelligence Ltd, 2019
[100] 'NSS 1740.16 Safety standard for hydrogen and hydrogen systems', NASA, 1997 https://ntrs.nasa.gov/api/citations/19970033338/downloads/19970033338.pdf

system.[101] MIR can be highly selective for hydrogen, as the technique is designed to detect the unique hot water vapour emission band at ~2.7 µm and OH radical emission near 3.1 µm, which are present in hydrogen combustion, but response times are slower (e.g. ~0.5-3 s).

Traditionally UV sensors have used anode/cathode Geiger-Müller type vacuum tubes, but most now use solid-state photodiodes which are lighter and more compact.

Detectors can be separated from sensitive electronics with an insulated cable between the hot and cool ends. As flame sensors are line of sight detectors, the confined space and complex geometry of spaces may be a challenge.

7.3. Current offerings

Commercial hydrogen flame sensors are available, e.g. in ground-based hydrogen gas turbines.[102] Current offerings focus on pipelines and ground applications, but work at below -40°C and in ATEX conditions. There are numerous commercial examples for gaseous hydrogen at atmospheric or hot conditions, but not cryogenic ones. The following list could be used as a basis for suitable sensors.

For monitoring flame conditions in turbines, i.e. intended to be mounted on a site tube on a combustion chamber:

- Reuter-Stokes (Baker Hughes) Flame Tracker (USA) [103] Rapid response time < 0.175 s, mineral insulated cable linking hot end with flame sensing photodiode to cool end with electronics

Numerous flame detectors are available for detecting hydrogen flames, fireballs or explosions from a distance, e.g. 10m or more. These are based on MIR or UV/IR, e.g.

- Fike (USA) IR3-H2 flame detector, FIK-UV-IR Hydrocarbon and hydrogen flame detector [104]
- Dräger (Germany) Flame 1750 H_2 (IR3) [105]
- Crowcon (UK) FGard H_2 Multi Spectrum IR Hydrogen Flame Detector [106]
- Det-Tronics (USA) X3302 Multispectrum Infrared (IR) Hydrogen Flame Detector [107]

[101] 'Hydrogen and fire safety: Detecting the most flammable element on earth', Det-Tronics white paper, 2019 https://www.det-tronics.com/Content/Documents/Det-Tronics-hydrogen-and-fire-safety-detection-white-paper_74-1014.pdf
[102] 'Hydrogen combustion in turbines: The role of flame sensors in fueling the future', Reuter-Stokes, 2024 https://www.bakerhughes.com/reuter-stokes/flame-sensors-hydrogen-turbines
[103] UV Flame Sensing Solutions for Gas Turbines and Industrial Burners https://www.bakerhughes.com/reuter-stokes/flame
[104] Fike flame detectors https://www.fike.com/fire-protection/solutions/flame-detectors/
[105] Dräger flame detectors https://www.draeger.com/en_uk/Productfinder/fixed-gas-detection/flame-detectors
[106] Crowcon flame detectors https://www.crowcon.com/article/what-you-need-to-know-about-detecting-hydrogen-flames/
[107] Det-Tronics X3302 Multispectrum Infrared (IR) Hydrogen Flame Detector https://www.det-tronics.com/products/x3302-multispectrum-infrared-hydrogen-flame-detector

Some are available with video recording, such as Teledyne's Spyglass™ IR3-H2-V which records video from one minute before a fire event to up to three minutes after[108], which may be particularly useful for developmental work.

7.4. Gaps or research challenges

While several commercial offerings are available, no hydrogen flame detectors have been found specifically for use in aerospace conditions. Existing flame detectors qualified for aerospace (e.g. Kidde OFD) focus on excitation of CO_2 molecules from a hydrocarbon fire. If flame detectors are deemed necessary, some development of existing hydrogen flame detectors would be needed to meet aerospace standards for software and hardware, and to reduce weight.

[108] Teledyne Spyglass™ IR3-H2-V https://www.teledynegasandflamedetection.com/en-us/spyglass-sg50-ir3-h2-optical-flame-detector

8. Structural health and material integrity

Assurance of ongoing reliability of structural parts, especially those that contain hydrogen, needs to be fully addressed in development and certification. This assurance will be under particular scrutiny in the early years of commercial hydrogen-powered aircraft.

This section does not seek to review current aircraft structural health monitoring and non-destructive testing methods, but to identify suitable technologies for issues that differ from traditional aircraft. One way of testing for failure is through leak detection, addressed in section 6, but detection of minor cracks, insulation failures, or conditions that may lead to structural damage, such as excess vibration, need to be in place to predict and avoid failures.

In addition to leak detection, potential methods for identifying material and structural health concerns in a LH_2 fuel system may include:

- Non-destructive testing (NDT) and evaluation (NDE) at maintenance intervals
- In-situ structural health monitoring (SHM) through life, which may include distributed acoustic sensing (DAS) using optical fibres
- Monitoring of wear in moving parts

Condition monitoring through vibration monitoring and/or fibre-optic networks may help identify any material or structural defects or enable predictive maintenance in LH_2 fuel system areas. Thermal imaging of the tank structure can reveal insulation failures. In-situ NDT methods applied to the tank when it is at cryogenic conditions will have significant challenges due to access as well as the temperature. However, ultrasound or radiographic techniques may be realistic, and these and other NDT techniques may be useful at major maintenance checks.

In development, the choice of materials will be very dependent on their properties in the cryogenic hydrogen environment. For an extensive review of material properties in cryogenic and hydrogen conditions, see the accompanying report 'Cryogenic Hydrogen Materials Global Research Landscape'.[5]

8.1. Condition requirements

If it can be achieved within acceptable weight limits, an ideal solution would include on-aircraft monitoring to identify any material or structural defects and enable predictive maintenance on-wing / in-situ, including in LH_2 fuel system areas.

It may be preferred that some non-destructive testing and evaluation (NDT/E) can be carried out whilst material is in contact with LH_2, so tanks can remain cold, limiting the thermal cycling stresses when tanks are allowed to return to ambient temperature. So the key NDT challenges are working on cold (cryogenic) structures, and NDT of twin-walled tanks and pipes.

8.2. Measurement methods and applicability

8.2.1. Non-destructive testing and evaluation

Alongside visual inspection (which may be aided by liquid penetrant testing), a range of NDT/NDE methods are used extensively for flaw detection during aircraft maintenance periods, including ultrasound, eddy current testing (in conductive materials), magnetic particle inspection (in ferro-magnetic materials), radiographic testing (e.g. X-ray / computed tomography (CT)). Any of these may be used where appropriate, but the key challenges here are where the tank is still cold, and for inspection of vacuum-insulated twin-walled tanks and pipes.

Regular ultrasound NDT requires a liquid coupling agent, which would not be possible at LH_2 temperatures, as any fluid would have solidified, though may be possible on the outside wall of the tank depending on the temperature gradient. However, for materials with a conductive surface, transduction without a coupling agent is possible using an electromagnetic acoustic transducer (EMAT). A sensor with a coil and a permanent magnet is moved over the structure and an electromagnetic (EM) field generated by the current through the coil creates eddy currents in the structure. The interaction of the eddy currents and the magnetic field from the permanent magnet cause a Lorentz force which generates an ultrasound wave in the material. This method can work through paint or a layer of insulation.[109] EMAT techniques require a conductive surface, but can be used on composites by adding a metallic layer at or near the surface (foil or mesh).[110]

Another approach that is coupling-free is the Inductosense WAND. In this case a sensor patch is permanently embedded in, or adhesively bonded onto, the surface of the structure. The sensor patch has a piezoelectric element electrically connected to a coil. The coil in the sensor is electromagnetically coupled to another coil the head of the remote reading instrument. The sensors transmit over a large area, so if they are carefully positioned, a complete map of the structure should be possible.[111]

Other non-contact ultrasonic methods are laser ultrasonic or air-coupled piezoelectric transducers in certain configurations, but both are challenging.

Acoustic signals cannot transmit through a vacuum, so ultrasound would not be effective for assessing the far wall of a vacuum-insulated twin-walled tank or fuel pipe. Electric and magnetic fields can travel through a vacuum although there is a decay effect with distance. Depending on the type of defect sought and the conductivity of the material, EM /radiographic NDT methods could be useful on metallics and microwave/terahertz may be useful on non-conductive composites. Computed tomography (CT) scanning can produce a 3D visualisation of the structure.

Thermal imaging has been used effectively for inspection of large, land-based cryogenic tanks [112] and could be used as an ongoing monitoring technique or for assessment at maintenance

---

[109] 'EMAT Technology', Innerspec https://www.innerspec.com/emat-technology
[110] 'Composite Inspection with EMATs', Iowa State University Center for Nondestructive Evaluation, https://www.nde-ed.org/NDETechniques/Ultrasonics/EquipmentTrans/ematcomposite.xhtml
[111] Inductosense WAND sensors https://www.inductosense.com/productsandservices
[112] Arens, 'Thermal Imaging for Inspection of Large Cryogenic Tanks', NASA https://ntrs.nasa.gov/api/citations/20120007653/downloads/20120007653.pdf

intervals, particularly for insulation failures (see section 6.2.2). Cryogenic leak testing can be carried out at maintenance checks.

All NDT technologies have a temperature dependence so it is sometimes important to know the temperature spatial distribution when sensors are in use.

8.2.2. Structural health / condition monitoring

SHM is not routinely included in aircraft structures, but several industrial research activities have been developing systems including sensor networks and AI supported software to analyse data and provide predictive maintenance. Project examples include Cranfield University's AIM, AIM 2, and WINDY projects developing fibre-optic strain and pressure sensor networks[113] and Embraer's Scheduled SHM (S-SHM)[114]. The market is increasing for systems such as Honeywell's Onboard Maintenance Systems (OMS) and Health and Usage Monitoring Systems (HUMS, usually for helicopters), which monitor avionics as well as sensors, including accelerometers and transmission vibration monitors and use the data to drive a model-based diagnostic system.

Fibre Bragg grating: Fibre-optic strain measurement with fibre Bragg grating (FBG) is a potentially useful technique, though FBG is of limited use for small cracks, which will only be detected if fibres are directly over the crack as the change in strain falls off very rapidly to the background level with distance from a crack. Fibre-optic sensors have been used as receivers of guided waves to form a guided wave sensing network, but a means of generating guided waves is required in this case. An example in a cryogenic environment is at Cern: "There is significant effort invested in the development of fibre optic strain measurement using fibre Bragg gratings to measure strain and characterise coefficients of thermal expansion."[115]

Distributed acoustic sensing: Use of optical fibres in high resolution DAS has gained interest recently and is potentially promising for monitoring LH_2 fuel systems. This measures the effect of Rayleigh scattering in optical fibres which essentially become long interferometers, and identifies acoustic signals over long distances. While it's commercial use has predominantly been in long-distance applications in pipeline monitoring or earthquake detection, it is now offered by several companies for monitoring aerospace and other large composite structures.[116]

As noted in section 6.2.2, ultrasonic leak detection and thermal imaging may contribute to SHM of the fuel system. Acoustic emissions monitoring is also an effective technology for monitoring and optimising structures and equipment.

---

[113] 'Developing advanced fibre optic sensors for aircraft and flight test', Cranfield University https://www.cranfield.ac.uk/case-studies/fibre-optic-sensors

[114] dos Santos, 'EMBRAER Perspective on the Challenges for the Introduction of Scheduled SHM (S-SHM) Applications into Commercial Aviation Maintenance Programs', KEM 2013;558:323–30 https://doi.org/10.4028/www.scientific.net/kem.558.323

[115] Giannis et al, 'International landscape on cryogenic and hydrogen materials testing', ATI/NPL 2024 https://www.ati.org.uk/wp-content/uploads/2024/09/International-landscape-on-cryogenic-and-hydrogen-materials-testing-REPRO.pdf

[116] Sensiϕ, Applications https://www.sensiphi.co.uk/application

8.3. Current offerings

The British Institute of Non-destructive Testing (BINDT) has extensive lists of NDT equipment providers, including leak testing [117], and condition monitoring equipment providers, including on-line and off-line debris testing, vibration analysis.[118] See also:

NDT:

- Inductosense (UK) WAND ultrasound system (developed at the University of Bristol) [119]
- Victor Aviation (USA) EMAT for cryogenic NDT [120]
- Helium leak testing is widely used in cryogenics (e.g. in UK: Leybold, Air Products, Ashby)
- Testia (UK/Germany, an Airbus company) Consultancy, installation, support for several NDT and SHM technologies including comparative vacuum monitoring (CVM), ultrasonic testing, FBG [121]

Condition monitoring:

- Honeywell (USA) data gateways for OMS and HUMS [122]
- Collins Aerospace (USA+) ACMS+, Ascentia for aircraft condition / health monitoring and analytics [123]
- Mondaic (Switzerland) fibre-optic DAS, SHM, digital twins [124]
- Luna (USA) solutions and products for monitoring strain, temperature, vibration and acceleration: [125]
    - ODiSI high definition DAS
    - HYPERION high-speed multipoint fibre-optic sensing based on FBG or Fabry-Perot
- Sensiϕ (UK) fibre-optic DAS [116]

8.4. Gaps or research challenges

The primary need for SHM is to understand the requirements better, especially whether NDT will be required on the cold system, and to ensure that testing methods are certifiable. Fundamental material knowledge of how hydrogen embrittlement/attack and the cryogenic temperatures affect materials underpins all aspects of this section.

If work on a cold system is required, understanding how NDT techniques are affected at such low temperatures is needed. Research on NDT techniques for twin-walled, vacuum-insulated

[117] 'NDT Equipment Providers', BINDT https://www.bindt.org/Buyers-Guide/NDT-Equipment-Providers/
[118] 'Condition Monitoring Equipment Providers', BINDT https://www.bindt.org/Buyers-Guide/CM-Equipment-Providers/
[119] Inductosense https://www.inductosense.com/
[120] 'Cryogenic Non Destructive Testing', Victor Aviation http://www.victor-aviation.com/Cryogenic_NDT.php
[121] Testia https://www.testia.com/
[122] 'Data Gateways', Honeywell https://aerospace.honeywell.com/us/en/products-and-services/products/cabin-and-cockpit/data-gateways
[123] Collins Aerospace https://www.collinsaerospace.com/what-we-do/industries/commercial-aviation
[124] Mondaic https://www.mondaic.com/industries/aerospace
[125] Luna Innovations https://lunainc.com/

structures is needed, whether using ultrasound and integrating variants such as EMAT or WAND or radiographic techniques, or a combination of the two.

Fibre-optics have the great advantage of not being subject to EM interference and limiting the heat leak from connections, and DAS could be a very useful tool for monitoring the fuel system health. The different ways in which fibre-optics can be used need to be developed in this context to understand their potential. In the interests of lightweighting, there may be potential for sensing elements which enable gauging and temperature sensing to be in common with elements which inform structural health

Outputs from a range of sensors, as well as usage and loading data, need to be brought together, applying AI-enabled computational techniques for good data analysis and reliable predictive maintenance.

Development of the tank and pipe structures, materials and processing technologies in parallel with understanding the most appropriate sensing and condition monitoring / NDT / maintenance strategies is critical to achieving a robust solution.

9. Tribology and wear

Current aircraft primarily use vibration and debris monitoring to assess material losses due to friction and wear on bearings and other moving parts. Variants of the same monitoring methods are expected to be used in service, though debris monitoring will need to account for the cryogenic hydrogen environment across the system.

Capacitive gap thickness measurements may be more relevant than ultrasonic thin film gap measurement where there is no liquid lubricant. For research and development, some tribometers already exist which are designed for LH_2 and GH_2 conditions.

9.1. Condition requirements

Monitoring and measurement of material losses due to friction and thin film gap measurement will be required at maintenance intervals. In development of materials and products, understanding of wear in bearings and any other moving parts in contact with LH_2 are of particular relevance.

9.2. Measurement methods and applicability

This section only considers requirements beyond usual tribology. In current commercial aircraft, the primary tools to monitor wear on shafts, bearings, and other moving parts in a gas turbine are vibration monitoring and debris monitoring. Numerous debris monitors are available for monitoring friction and wear in bearings. None has been found specifically targeted for cryogenic hydrogen conditions.

For research and development, some tribometers (to measure quantities, such as coefficient of friction, friction force, and wear volume) are available for liquid hydrogen. Roughness and surface measurements can be made using microscopy or stylus measurement.

Ultrasonic sensors can be used for thin film gap measurement between two surfaces, e.g. in bearings. An ultrasonic wave will reflect from the lubricated interface, where the response of the film to the sound wave depends on the acoustic and geometrical properties of the oil layer. The proportion of the wave reflected makes it possible to determine the gap thickness.[126] This technology is primarily used in research rather than commercially, though could be used at maintenance. It would not work in cryogenic hydrogen because a liquid lubricant is not possible.

Capacitive gap thickness measurements are more widely used, and several variants are available commercially. Capacitive air gap sensors are designed to measure the gap between the rotor and stator in power generation applications, but may be more applicable where there is no liquid lubricant.

[126] Harper, et al, 'Journal bearing oil film measurement using ultrasonic reflection', Proceedings of the 29th Leeds-Lyon Symposium on Tribology, vol. 41, pp. 469–476, 2003 https://doi.org/10.1016/S0167-8922(03)80161-X

9.3. Current offerings

- Debris monitoring suppliers - see section 13.3
- I-Tribomat (Europe) Reciprocating/oscillating tribometer, includes LH_2 environment [127]
- TriasRnD (Germany) Cryo-Tribometer from Aerospace & Advanced Composites GmbH (Germany), down to 4 K [128]
- Phoenix Tribology (UK) provides research tribometers including TE 60 High Pressure Hydrogen Reciprocating Tribometer (-50 to +150°C) (not cryogenic) [129]
- Micro-Epsilon (UK) capaNCDT MD6-22 capacitive system for mobile gap measurements [130]
- Sensonics (UK) CS Capacitive Sensor Series - Air gap sensors - designed for the gap between the rotor and stator in power generation applications, but may be more applicable where there is no liquid lubricant. [131]

9.4. Gaps or research challenges

Debris monitors will need development to function in the cryogenic hydrogen context, and without liquid lubricants (see 13.2, 13.4).

Work will be needed to establish the most effective gap measurement technologies.

[127] Reciprocating/Oscillating tribometer, i-Tribomat https://i-tribomat.eu/tribological-characterisation/
[128] Cryo-Tribometer, TriasRnD https://triasrnd.com/en/l/586-cryo-tribometer
[129] TE 60, Phoenix Tribology http://www.phoenix-tribology.com/at2/leaflet/te60
[130] CapaNCDT MD6-22, Micro-Epsilon https://www.micro-epsilon.co.uk/distance-sensors/capacitive-sensors/capancdt-md6-22/
[131] Sensonics https://www.sensonics.co.uk/air-gap-sensors

10. Phase

Several sensor types can be used as wet/dry point sensors in cryogenic hydrogen, to determine whether the hydrogen is liquid or gaseous. Typically a hot wire or electrical resistor method, has been used, though optical, thermal conductivity or metal oxide semi-conductor sensors can be used. NASA has successfully used silicon diode or thin film zirconium oxynitride (TFZO, e.g. Cernox) temperature sensors as wet/dry sensors in hydrogen.

There is strong crossover here with the gauging and level sensing technologies described in section 5.2 which all contribute to an understanding of the phase distribution. All the direct level sensing technologies are measuring the phase interface, and the tomographic techniques (RFMG, ECT) create a detailed visual model of the fuel phase distribution in the tank or pipework.

10.1. Condition requirements

There are no specific requirements defined, but assumptions may include:

- Consistently detect wet/dry conditions
- Maintain accuracy under varying pressure conditions
- Be durable in a long-term hydrogen environment

10.2. Measurement methods and applicability

10.2.1. Wet/dry point sensors and phase interface detection

Point detection is helpfully summarised in Dodge, 2008 [45]:

> Sensors to detect the presence of liquid or gas at a point (i.e., at the sensor location) are usually called wet/dry sensors or point sensors. Common forms include a hot wire or an electrical resistor or some other kind of electrical impedance element through which a small current is passed. These sensors in general determine the presence of liquid or gas at their location by determining the change in their electrical impedance as a function of whether they are immersed in liquid or in gas. The value of the sensor impedance depends on its temperature, which in turn depends on the heat transfer from the sensor that dissipates the ohmic heating of the element caused by the electric current; the heat transfer is greater when the sensor is in liquid.

Temperature sensors as wet/dry sensors: In a stable state in the tank, the gas is typically a little warmer than the liquid, so more accurate temperature sensors can be used directly to detect phase. However, in the case of sloshing, temperature transfer occurs between the liquid and gas, and the temperature across phases becomes more uniform.

Silicon diode and thin film zirconium oxynitride sensors: With minor modifications, some temperature sensors can become more effective as wet/dry sensors. Silicon diode and TFZO sensors have a small excitation current (silicon diode) or voltage (TFZO) across them in normal use. If the voltage or current across the sensor is increased, it causes the sensor to self-heat more. In a liquid that extra heat is easily removed through convection and the measured response does not change, but in a gas the heat causes the sensor to respond as if the gas is warmer and the response changes. The difference allows it to be determined whether the sensor is wet or dry. This method also requires thermal isolation from the temperature rake or any other thermal mass. This is described in detail for silicon diodes in Dempsey 1992[132], and further work at NASA demonstrated that Cernox® has a 6 – 15 x larger response than the silicon diodes. However if the sensors are attached to a heat sink, e.g. a metal structure, the extra heat may be removed and it will not work, as demonstrated in the NASA SHIIVER project.[1]

Fibre-optic wet/dry sensors: Dodge, 2008 also describes optical sensors using a prism and a laser light source. In a gas, light is reflected off the end of the prism back to a photocell, but in liquid, the light is transmitted into the liquid without reflection off the prism, so the phase can be detected. Similar refractometric approaches using fibre-optic sensors have been demonstrated [133] [134] and are now available commercially (e.g. Eaton Levelmaster® [63]). However, another NASA technology, developed for fuel gauging in rockets, uses a resistive heater wire bundled with the optical fibre. The heater is pulsed to induce a local temperature change along the fibre. The length of fibre in the liquid cools more rapidly than that in the gas.[135]

Thermal conductivity sensors: Sensors detect phase changes by measuring variations in thermal conductivity between gaseous and liquid hydrogen.

See also section 5.2 which describes various direct level sensing technologies, including pressure, temperature rake, ultrasound, capacitive, radar or superconductive. Some of these depend on point phase sensing and some on detecting the liquid-gas interface.

10.2.2. Tomographic gauging and simulation

Electrical capacitance tomography: ECT produces a detailed 3D image of the fuel, and so can be used to determine the phase within a tank or pipe. See section 4.2.

Simulation: While not a sensing technology, simulation of thermodynamic coupling characteristics could be very useful in predicting the changing phase distribution during liquid hydrogen sloshing. An interesting example with reference to LH_2 tanks for heavy-duty trucks is described in Zhu 2023, where these observations are made:

> The simulation results show that under the influence of liquid hydrogen large-amplitude sloshing, the convective heat transfer of fluid in the tank is greatly strengthened, resulting in a decrease in the vapor temperature and an increase in the liquid temperature. In particular, the vapor condensation caused by the sloshing promotes a rapid reduction of pressure in the tank. [136]

---

[132] Dempsey & Fabik, 'Using silicon diodes for detecting the liquid-vapor interface in hydrogen', NASA 1992 https://ntrs.nasa.gov/api/citations/19920009214/downloads/19920009214.pdf
[133] Khotiaintsev et al, 'Fiber-Optic Liquid-Interface Sensor for Liquid Hydrogen', Sensors and Materials, Vol. 21, No. 1 (2009) 13–23 https://sensors.myu-group.co.jp/sm_pdf/SM745.pdf
[134] Yang et al, 'Fiber optical liquid level sensor under cryogenic environment', Sensors and Actuators A 94 (2001) 69-75 https://doi.org/10.1016/S0924-4247(01)00663-X
[135] 'Streamlined Liquid Level Sensing Using Fiber Optics (DRC-TOPS-16)', NASA https://technology.nasa.gov/patent/DRC-TOPS-16
[136] Zhu, et al, 'Numerical Study on Thermodynamic Coupling Characteristics of Fluid Sloshing in a Liquid Hydrogen Tank for Heavy-Duty Trucks', Energies 2023, 16(4), 1851; https://doi.org/10.3390/en16041851

10.3. Current offerings

See temperature sensors at section 2.3, gauging technologies / level sensors at section 5.3.

10.4. Gaps or research challenges

While there are several technologies which can detect phase, identifying which of these are most appropriate and developing them for commercial aircraft needs significant research. There is much to be learned from the space sector, and development needs to take into account weight reduction, cost, durability, especially into the effect of hydrogen and the cryogenic environment, and other factors as described in section 1.1.

11. Ortho/para measurement

There are two different nuclear spin isomers of molecular hydrogen, ortho- and parahydrogen, with orthohydrogen having a slightly higher energy due to the parallel spins of its protons. At ambient temperature around 75% is orthohydrogen and 25% parahydrogen. In liquid form, the orthohydrogen slowly converts to parahydrogen over a period of days to weeks, releasing energy. If hydrogen is not converted into parahydrogen before being liquefied, the heat generated by the ortho-para conversion means that extra cooling is required to limit boil-off.

It is not yet clear to what extent this is a concern in commercial aviation systems with rapid fuel throughput. Other properties are also sensitive to proportions of ortho- and parahydrogen including thermal conductivity, speed of sound, viscosity, melting point, boiling point, vapour pressure, and specific heat capacity, though the differences are small. The density of the fluid is not changed by the ortho- and parahydrogen relative amounts.

Ortho- and parahydrogen is considered at more length in the accompanying report, 'Cryogenic Hydrogen Thermofluids Global Research Landscape'.[137]

11.1. Current / recent research

Proportions of ortho and parahydrogen can be measured using Raman spectroscopy. The Cryocatalysis Hydrogen Experiment Facility (CHEF) at Washington State University uses Raman spectroscopy fibre optic flow cells – where the resulting peaks corresponding to ortho- and para-proportions of LH_2 can be measured. [138] A paper from CHEF describes the benefits of Raman spectroscopy over other methods for measuring ortho-parahydrogen compositions such as hot-wire anemometry, nuclear magnetic resonance, and infrared spectroscopy. [139]

A Japanese consortium has developed a measurement system for ortho- and parahydrogen fractions, also using Raman Spectroscopy, for the cryogenic moderator system for the European Spallation Source (ESS)[140]

A study from the Dresden University of Technology about speed-of-sound-based ortho-parahydrogen measurements provides an overview of some ortho-para measurement methods and reported uncertainty-related information (see table 1 in the paper).[141]

---

[137] Cryogenic Hydrogen Thermofluids Global Research Landscape, ATI, March 2025
[138] Cryo-catalysis Hydrogen Experimental Facility, Washington State University https://hydrogen.wsu.edu/3-chef/
[139] Appel and Leachman, 'Uncertainty analysis of Raman spectra for measuring ortho-parahydrogen compositions', IOP Conf. Ser.: Mater. Sci. Eng. 1301 2024 https://doi.org/10.1088/1757-899X/1301/1/012054
[140] Tatsumoto et al, 'Development of an in-situ ortho-to-parahydrogen fraction measurement system for the ESS cryogenic moderator system', Cryogenics, Volume 139, 2024, https://doi.org/10.1016/j.cryogenics.2024.103837
[141] Eisenhut and Haberstroh, 'Speed-of-sound-based ortho-parahydrogen measurements', International Journal of Hydrogen Energy 92 (2024) 312–323 https://doi.org/10.1016/j.ijhydene.2024.10.133

12. Purity (hydrogen supply)

The hydrogen is expected to be delivered to the aircraft in a pure state (according to relevant specifications), so purity sensing would be applied in the upstream supply. As all contaminants except helium will be solid in the LH_2 tank, it is not expected that purity monitoring would be needed on-aircraft, though solid contaminants, including solidified air, need to be managed (see section 13).

Inline monitoring of hydrogen gas in industrial applications is a mature technology, with several companies offering monitors which detect hydrogen content and that of impurities such as oxygen, carbon monoxide, water, hydrogen sulphide, nitrogen, depending on requirements which are related to the feedstock - e.g. whether from natural gas via steam methane reforming or from water via electrolysis.

These analysers are designed for gaseous hydrogen, however the approach taken by Endress+Hauser to use Raman Spectroscopy analysers inline to provide gas composition could potentially be applied for liquid hydrogen (see section 11). However, it may be more cost-effective to take samples and use gas phase analysers after vaporisation.

The HyTrace sensor under development at the University of Bristol is expected to be able to analyse hydrogen purity in liquid phase at cryogenic temperatures, and the technology is inherently low cost, but it is still in the early stages.

12.1. Current offerings

A selection of current offerings includes:

- Cambridge Sensotec (UK) several analysers for hydrogen production [142]
- Weatherall (UK) FI-900 Inline hydrogen gas analyser, optical interferometric gas analyser for combustible gases including hydrogen [143]
- H2scan (USA) HY-OPTIMA® 5030 Series general use inline hydrogen process analyser - 5033 and 5034 measure up to 100% hydrogen and detect contaminants [144]
- Process Sensing Technologies (PST) (international) - dew point and binary gas analysers for electrolyser output, including the HyDetek system which uses multiple sensing technologies for measurement of trace impurities [145]
- Endress+Hauser (Switzerland/UK) supply Raman spectroscopy analysers inline to analyse hydrogen composition (as liquid or gas), as well as optical technologies for moisture and oxygen in electrolyser output [146]

---

[142] Analysis In Hydrogen Production, Cambridge Sensotech https://cambridge-sensotec.co.uk/application/gas-analysis-in-hydrogen-production/

[143] FI-900 Inline hydrogen gas analyser, Weatherall https://www.weatherall-uk.com/products/analysers/FI-900-fuel-gas-analyser-hydrogen/

[144] HY-OPTIMA® 5030 Series General Use Inline Hydrogen Process Analyzer, H2scan https://h2scan.com/product/hy-optima-5000/

[145] Turnkey gas system for H2 quality control and monitoring- HyDetek, PST https://www.processsensing.com/en-us/products/turnkey-system-for-H2-quality-control-and-monitoring-HyDetek.htm#

[146] Hydrogen - key energy carrier to reach decarbonization goals, Endress+Hauser https://www.uk.endress.com/en/industry-expertise/oil-gas-marine/hydrogen-ready

13. Contamination (solids)

Despite stringent controls, regular kerosene aircraft fuel systems can become contaminated with water, particulates, and microbial growth. Microbial growth cannot occur at cryogenic temperatures[147], and the absence of nutrients makes growth of biological contaminants very unlikely even at the warm end of an LH_2 system. However, other contaminants need to be identified and managed.

It is expected that contaminants would be removed as far as possible in the process of purification of the hydrogen at the fuel supply stage, and that positive pressure would eliminate ingress of new contaminants. The possibility remains for build-up of solid particles from breakdown of materials in the system due to degradation caused by hydrogen ingress, friction, etc, or traces of solidified air or other contaminants over time.

Any contaminants except helium will be solid in LH_2 so will tend to collect in the bottom of the tank. Neon has a melting point of 24.6 K at atmospheric pressure, can be gaseous at 20 K at low pressure and has been reported by NASA to cause problems with solidified deposits clogging devices under certain conditions.[148]

Understanding the risk of solid contaminants in the tank reaching the fuel feed system, e.g. in cases of sloshing / turbulence, is needed. Solid contaminants could block valves or affect instrumentation. Any solid oxygen could create an explosive mixture. Even in the absence of ignition sources from sparks due to static electricity or friction, mixtures of solid oxygen and LH_2 are shock sensitive, so a sudden increase in pressure (e.g., collision or blast wave) might have sufficient energy to provoke a detonation.[149] Also oxygen which reaches the fuel feed system will soon change phase and no longer be caught by filters. Hence detection of any oxygen build-up is a priority.

It is possible that further development of electrical capacitance tomography (ECT) will improve resolution sufficiently to identify solid contaminants, and Raman spectroscopy with fibre-optic probes could be used to identify contaminants. In the fuel feed system it is expected that filters will be used, particularly at the inlets of fuel cells, so the magnitude of the pressure drop across the filter would indicate any build-up of contamination.

13.1. Condition requirements

There is a requirement to measure for any contaminants of the following: Frozen air (see below), water ice, oils, and particulates. For fuel cell applications, particular attention is needed for contaminants that poison the catalyst or degrade the fuel cell. Limits of a range of contaminants

[147] Clarke, et al, 'A Low Temperature Limit for Life on Earth', PLOS ONE 8(6): e66207, 2013 https://doi.org/10.1371/journal.pone.0066207
[148] NASA/TM—2009-215495 Jurns and Lekki, 'Clogging of Joule-Thomson Devices in Liquid Hydrogen Handling', NASA 2006, https://ntrs.nasa.gov/api/citations/20090015374/downloads/20090015374.pdf
[149] 'Safety standard for hydrogen and hydrogen systems', NASA 1997 https://ntrs.nasa.gov/citations/19970033338

are defined in the recently updated ISO 14687:2025 for both PEM fuel cells and hydrogen combustion applications.[150]

Condition requirements for sensors will depend on filtering approaches before and after the tank.

- High selectivity to distinguish between different contaminants and avoid cross-sensitivity that could lead to false readings
- Sensitivity and stability in LH_2 environment

The main constituents of air, not including water, are given in Table 13.1 with melting and boiling points at atmospheric pressure. This is provided for reference to give an indication of the phase changes of potential contaminants that are not solid at room temperature.

TABLE 13.1 CONSTITUENTS OF AIR (NOT INCLUDING WATER) WITH MELTING AND BOILING POINTS (AT ATMOSPHERIC PRESSURE) AND COMMENTS ON RISK. HYDROGEN ADDED FOR COMPARISON.

Data from The Engineering Toolbox [151], Air Liquide Gas Encyclopedia [152], NOAA (CO2, CH4 concentration)[153]

Name	Atm. vol. fraction, %	Mass fraction, %	Boiling point, K	Melting point, K	Notes
Nitrogen (N_2)	78.1	75.511	77.4	63.2	
Oxygen (O_2)	20.9	23.14	90.2	54.4	High risk
Argon (Ar)	0.934	1.29	87.3	83.8	
Carbon Dioxide (CO_2)	0.0425 (425 ppm)	0.065 (650 ppm)	(194.7)	216.6	(At ambient / low pressure CO_2 goes straight from solid to gas)
Neon (Ne)	0.00182 (18 ppm)	0.0013 (13 ppm)	27.2	24.6	May cause issues as phase changes close to LH_2 storage temp
Helium (He)	0.000524 (5.2 ppm)	0.00007 (0.7 ppm)	4.2	n/a	
Methane (CH_4)	0.000193 (1.9 ppm)	0.00011 (1.1 ppm)	111.7	90.7	
Krypton (Kr)	0.0001 (1 ppm)	0.00029 (2.9 ppm)	119.8	115.8	
Hydrogen (H_2)			*20.3*	*14.0*	

[150] 'ISO 14687:2025 Hydrogen fuel quality — Product specification' https://www.iso.org/standard/82660.html
[151] 'Air - Composition and Molecular Weight', The Engineering Toolbox, https://www.engineeringtoolbox.com/air-composition-d_212.html
[152] Air Liquide Gas Encyclopedia https://encyclopedia.airliquide.com/
[153] NOAA Global Monitoring Laboratory https://gml.noaa.gov/ccgg/trends/gl_trend.html

13.2. Measurement methods, applicability and current offerings

Hydrogen purity analysis before or after liquefaction is key to ensuring contaminants do not enter the system. See section 12.

Measurement of pressure drop across filters will indicate build-up of solid contaminants. For pressure sensors see section 3.

ECT resolution may be sufficient to detect general build-up of solid contaminants, especially where capacitance is sufficiently different from LH_2. Raman spectroscopy used in conjunction with fibre-optic probes could be used to provide chemical analysis of contaminants.

Quantitative debris monitor (QDM) sensors are passive, magnetic, inductive sensors used to collect, retain and indicate capture of individual ferromagnetic particles in current aircraft turbine lubrication systems. Eaton supplies QDM sensors but, recognising the need for monitoring of more exotic materials, has developed an advanced debris monitoring (ADM) which uses acoustic and optical (fibre-optic) sensing. This can detect ferrous, non-ferrous and non-metallic particles ≥ 250μm. It may be possible to modify such sensors for the cryogenic hydrogen environment.[154]

13.3. Current offerings

For hydrogen purity see section 12, for pressure sensors see section 3, for ECT see sections 4.3, 5.3.

- Eaton Advanced debris monitor, oil debris monitor, chip detector, chip collector [155]
- Gastops MetalSCAN and ChipCHECK debris monitoring [156]

More equipment suppliers of on-line and off-line debris testing are listed on the BINDT website.[118]

13.4. Gaps or research challenges

Research at NREL to identify and quantify system-derived contaminants and to understand the effects of system contaminants on fuel cell performance and durability has led to the development of a material screening data tool for fuel cell contaminants.[157] The context of this research is for LH_2 trucks, so similar work will be needed to account for different materials used aerospace applications and as new catalysts are developed. This will inform the materials used both structurally and in sensors, and sensors with high selectivity for key contaminants will need to be developed.

---

[154] 'Advanced Debris Monitoring System', Eaton (presentation), 2020 https://www.bindt.org/admin/Downloads/3A1%20-%20A.%20Advanced%20Debris%20Monitoring%20ADM%2014%20May%202021.pdf

[155] 'Aerospace Sensors', Eaton (product) https://www.eaton.com/us/en-us/products/engine-solutions/aerospace-sensors.html

[156] Gastops, MetalSCAN https://www.gastops.com/products-services/metalscan/ ChipCHECK https://www.gastops.com/products-services/chipcheck/

[157] 'Fuel Cell System Contaminants Material Screening Data', NREL https://www.nrel.gov/hydrogen/system-contaminants-data

ECT technology needs be developed to see the extent to which this can visualise solids, alongside gauging. Likewise, a system like the Eaton ADM could be developed using optical and / or ultrasonic sensing to detect particles of any material in the LH_2 tank, or to sample from the fuel feed flow and detect, retain and provide information on quantities of particles in the flow.

Debris monitors will need development to function in the cryogenic hydrogen context, and without liquid lubricants. Raman spectroscopy with fibre-optics needs to be considered to chemically identify contaminants in the tank, and possibly at filters and/or in the fuel feed flow, and could be used in developmental systems to identify the likelihood of certain contaminants, whether or not it is deemed necessary on-aircraft.