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Composite Conformal Liquid H_2 Tank

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List of Acronyms

Acronym	Meaning
GA	Grant Agreement
GH2	Gaseous Hydrogen
HLRO	High Level Requirements & Objectives
KPI	Key Performance Indicator
LH2	Liquid Hydrogen
NDI	Non-destructive inspection
PZT	Lead zirconate titanate
SHM	Structural Health Monitoring
FSHM	Fuel System Health Monitoring
TBD	To Be Determined
FMEA	Failure Mode and Effects Analysis
CBM	Conditioned based maintenance
FBG	Fiber Bragg Grating
MEMS	Microelectromechanical systems

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1. Executive Summary

This report describes the development of the structural health monitoring (SHM) and fuel system health monitoring (FSHM) systems for the LH2 storage tank system. The mission of both systems is to monitor the state and identify defects or faults that will develop during the testing phase and the operational life of the LH2 tank storage, and enhance system, safety and reliability. Work package 6 (WP6) of the COCOLIH2T project is tasked with the development of the health monitoring system. Specifically, as it is described in the project grant agreement, the objectives of the work package are:

- Evaluate functional needs and safety requirements of LH2 tank SHM and fuel system monitoring.
- Down-select relevant inspection and monitoring technologies.
- Prove sensor capability and design analysis algorithms to precisely detect, identify, localize and characterize degradations and faults.
- Perform multi-disciplinary optimization of monitoring sensors.
- Validate the technology and algorithms on laboratory-scale demonstrators.
- Integrate health management system to assess overall system health and recommend CBM.

In this work, several concepts for the structural health monitoring and the health monitoring of the fuel system have been developed and evaluated. First, the functional needs and safety requirements, including the list of all failure modes and ways the tank can be monitored have been developed from the HLRO (described in detail in deliverable D2.1) and safety standards for H2. Based on the failure mode and monitoring requirements, innovative sensor technologies for structural health monitoring, were down-selected, and a list of sensors with their technical specifications were proposed for the SHM of the tank, including a concept for an automated non-destructive inspection (NDI) system capable of inspecting the inner tank inside enclosed spaces. Algorithms for the detection of microcracks on the surface of the inner tank and for the fuel system component failure have been developed.

The document is organized as follows. Sections 1 and 2, contain the summary and introduction to the objectives and achievements of this report. Section 3 described the system functional needs and safety requirements related to SHM. Section 4 lists all sensor monitoring technologies description investigated in the project for the structural health monitoring. Sections 5 and 6 presents the framework and algorithms for structural and fuel system health monitoring. Section 7 contains the conclusions of this work and Section 8 presents all relevant references, Annex 9 contains details of inner and outer wall leakage analysis.

2. Introduction

Health monitoring, introduced in this document, includes strategies and methods for monitoring and analysing the reliability, safety and smooth functioning of the hydrogen fuel storage system developed in the COCOLIH2T project, by continuously assessing its operational status and during the test phase. The main structural hazards come from the leakage of the tank itself, the failure of connections between pipelines, the degradation of components such as valves, and the safety or performance related features such as the insulation system. These disruptions should be consistently avoided to ensure safe operationality of liquid hydrogen tanks.

Structural health monitoring is meant to help prevent failures that may hinder the system functionality or, in the worst-case scenarios, could lead to catastrophic events. Preferably all failure modes are covered by the design of the tank, however some of the risks can be mitigated more easily by a SHM solution or extra monitoring maybe required from a safety or maintenance perspective. Given the structural monitoring aspect, this document does not include malfunctions of the control system, failures to follow procedures or accidental damages.

The objective of WP6 is to evaluate the suitability of various SHM capabilities including structural monitoring. The SHM system to be developed would reliably monitor temperature cycles of the cryogenic tank, monitor heat flux over the interfaces and the load cycles of the outer tank. The system would have proven reliable operation of the sensors at cryogenic temperatures for prolonged periods, with proper sealing of sensor cables at interfaces. The Non-Destructive Inspection (NDI) system will be able to inspect tanks with complex geometry and difficult access. In addition, to the SHM, a fuel system health monitoring was developed to assess and analyse the health status of its components (fuelling valves, gauging etc.)

This report describes the development and evaluation of the structural health monitoring system for the H2 fuel storage that has been developed in the COCOLIH2T project. It details the analysis for the down-selection and evaluation of the framework that has been developed for the overall health monitoring for the fuel storage. The framework includes the sensing, inspection and monitoring of all key system and components of the fuel storage including that of the structural health, fuel system components, H2 leakage etc. The key achievements of this work, which will be described in detail in the sections of this report, are briefly summarized below:

1. Definition of the functional and safety requirements for the fuel storage
2. Down-selection of the sensor technologies for inspection and monitoring
3. A framework for structural health monitoring including:
    a. A continuous structural health monitoring framework

   b. An NDI-based interval based structural health monitoring framework, and
4. A fuel system health monitoring framework

Relevant information is provided about the required sensor system, the selected applicable technologies, and the defined framework to assess the structural health and consequent safety of the COCOLIH2T demonstrator during its testing phase. The results from the application of this SHM system will aid the improvement of both the design of the fuel storage structure and the definition of an effective structural health monitoring system itself.

3. Functional needs and safety requirements

The COCOLIH2T fuel storage system concept, represented in Figure 1, is designed to function inside an aircraft to utilize better the available space by using a conformal design, also utilizing composite materials to produce a lightweight solution. Beyond the geometric and material optimization, the storage needs to operate in challenging thermal conditions to maintain LH2 at -253°C. For this reason, the structure is composed of two shells, namely the inner tank and the outer tank, ensuring that a vacuum volume can be maintained for thermal insulation. For the storage system to operate safely and reliably in cryogenic conditions for prolonged periods, it is necessary to monitor and inspect the health status and the timely detection and identification of degradation and failures. The list of the storage sub-systems and their respective failures that may occur during the storage operation are listed in Table 1.

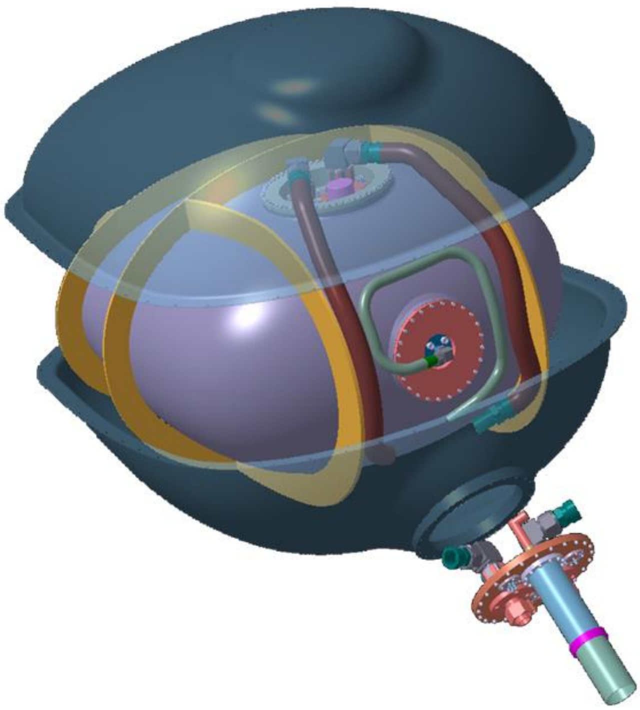

Figure 1 – Representation of conformal LH_2 tank design, as reported in D3.2

A detailed analysis of hazards, safety requirements and failures for the storage system is given in deliverable D8.1 “Safety Analysis Report”, the high-level requirements and FMEA analysis. The failure and high-level requirements analysis is used to define requirements for the health monitoring system which consequently will help define the develop the inspection and health monitoring technologies for this project.

3.1. Applicable HLRO requirement

The following requirements are covered by the design of the tank, but their functionality is maintained with the monitoring activities introduced in this document, and thus they are discussed in the following sections. Other requirements are specifically regarding the development and design of the structural health monitoring system and are thus discussed below.

- HLRO-COCOLIH2T-1-8-1 Vacuum level should be ≤ 10^{-5} mbar
- HLRO-COCOLIH2T-2-7-1 Qualification DO-160G
- HLRO-COCOLIH2T-3-1-1 Fittings load monitoring
- HLRO-COCOLIH2T-3-2-1 Tank pressure and temperature cycles
- HLRO-COCOLIH2T-3-3-1 H_2 leak capture
- HLRO-COCOLIH2T-6-6-1 Inspections
- HLRO-COCOLIH2T-6-7-1 Maintenance on the tank
- HLRO-COCOLIH2T-6-8-1 Tank sensors accessibility, all tank sensors should be accessible directly

DO-160G is a standard for environmental testing of aircraft equipment, published by RTCA (Radio Technical Commission for Aeronautics). It provides guidelines for testing the environmental durability of aircraft systems and equipment. The standard covers various environmental conditions, including:

- Temperature
- Humidity
- Vibration
- Altitude
- Lightning
- Electromagnetic interference (EMI)

These tests ensure that aircraft equipment can withstand the harsh conditions encountered during flight, such as extreme temperatures, turbulence, and humidity. By following DO-160G, manufacturers can verify that their equipment meets the required safety and reliability standards for the aerospace industry. Although not all proposed systems are entirely tested along DO-160G, as is not needed at low TRL levels, there should not be any expected difficulty in complying with the standard in future work. For example, Fibre optic based sensors have already been successfully applied in aircraft environment.

Relevant pressure and temperature data is monitored with reliable sensors in cryogenic conditions as presented in the following chapters. Strategies and sensor to monitor the release of hydrogen and the degradation indicators before this event are the core of this document. The development and validation of the presented concepts will be the result of the COCOLIH2T demonstrator testing.

Inspection of the tank with the automated NDI solution developed in this project requires direct access to the inner tank from the outside through an opening. This opens a series of possibilities, such as development reliable access means or rediscussing the requirement as the design advances. The requirement about direct accessibility of all sensors cannot be met for sensors in the vacuum. Due to resources limitations on the activities regarding the development of the demonstrator design, no maintenance hatch is developed. However, the number of sensors is such that even if a specific sensor would fail, there is still sufficient data on the health of the tank. Also, higher TRL design might eventually allow the accessibility and a lower number of sensors on the inner tank might be needed. Other important sensors like Gas leak sensors, the vacuum pressure and pressure inside the tank are easily accessible outside of the tank.

3.2. Failure modes

During the development of Deliverable 8.1 an extensive analysis had been performed on reported failures in the liquid hydrogen field. Safety guidelines have been derived to be incorporated in design, operational procedures. It is stated that:

"The integration of technologies such as structural health monitoring and vacuum sampling can enhance the early detection of potential failures while a thoughtful design and operation following the principles identified by these safety criteria can ensure the integrity of the system."

In Table 1 an overview of failing components obtained during an analysis of liquid hydrogen failures in a specific context [1] is presented. The reported failure percentages should not be accounted directly, as the designed systems and used materials differs. This list is processed in this context identifying whether the coverage of the failure areas would be monitored by the structural health monitoring (SHM) or the fuel system health monitoring (FSHM), as the first mostly focus on the structure containing the fuel, while the second mostly on components delivering or interacting with the fuel.

Table 1 - Common identified failure modes

Failure	Percentage of total	Covered by
Valve malfunction/Leak	19%	FSHM
Leak from connection	15%	FSHM
Safety disk failure	9%	FSHM
Material issues or embrittlement	9%	SHM
Excessive vent rate	9%	FSHM

Cryo-pumping	9%	SHM
Air enters system	4%	FSHM
Flexible coupling, bellow failure	3%	FSHM
Restricted battery outgassing	3%	Not covered
Tank damage	2%	SHM
Highway traffic accidents	2%	Not covered
Loss of vacuum	1%	SHM
Line rupture	1%	FSHM

Translating the failures to the COCOLIH2T tank, the following failure modes have to be analysed and monitored accordingly:

1. Hydrogen leakage through the inner wall
    a. Due to existing/default permeability of the inner wall material
    b. Increased permeability due to microcracking of the wall material
    c. Due to leakage of specific critical locations of the tanks (i.e. high stressed regions, resin rich areas, ply drop off areas, welds, interface plates and associated pipes or components)
    d. High stressed regions due to the non-conformal shape
    e. Damage due to the combination of:
        i. Thermal cycles (maintenance?)
        ii. Pressure cycles
        iii. Loads introduced by sloshing?
        iv. External loads (vibration, inertia, flight induced loads)
        v. Refuelling? (thermal shock?)
        vi. Excessive displacement of attached components.
2. Air leakage through the outer wall/cryopump
3. Cracks/failure of the inner tank support structure (mounts)
4. Failure of inner pipe connections
5. Cracks/failure of the outer tank pipe connection
6. Leakage along sensor wiring/other connections/feedthroughs
7. Failure, malfunction of valves
8. Failure of the radiative insulation system
9. Failure of the pressure release devices

Failure modes 1, 2, 4, and 6 leads to reduced vacuum insulation performance of the tank and in critical situation to the loss of vacuum itself. Insulation is essential for preventing excessive heat transfer to the inner tank which, if not kept within a certain threshold, would lead to excessive boil-off of the liquid hydrogen resulting in additional pressure which if not managed would lead to tank failure. Insulation is performed by limiting conduction, radiation and convection between a double walled tank. The failure of these systems which prevents these three heat transfer mechanism are detrimental for the performances of the tank, but the reduced vacuum level is the one which deserve more attention. According to HLRO requirement the vacuum level should be always below 10^{-5} mbar for this specific reason. Failure of other type of radiative insulation system, as referenced in point 8 should be monitored accordingly, given its difficult to access location, a relevant method needs to be ensured. The main function of the inner tank support structure is to keep the inner and outer tank separated with an as low as possible thermal leak, thus providing conductive insulation. In the case of Cracks/failure of the inner tank support structure the position of the inner tank with respect to the outer tank cannot be guaranteed for all load cases. During an (extreme) manoeuvre the inner tank then might move thereby damaging the MLI, interface plate, internal pipes, level sensor or in worst case even contact the outer wall resulting in a massive heat leak and boil-off.

If one of the tank walls is damaged, there is no immediate explosion hazard as the other tank wall is still hydrogen or airtight, so an explosive mixture will not develop immediately [1]. Furthermore, as long as the pressure remains below 20 mbar there is no ignition possible. Different approaches are applied following this failure which has to monitored accurately. For instance, when an increased pressure is measured at the appropriate time the vacuum space can be purged with Nitrogen, thus diluting the hydrogen in the vacuum space. In operative conditions, if boil-off reaches unsustainable levels, pressure or fuel would be released through the related fuel safety devices such as PRD and venting channel to avoid unnecessary consequent side effects.

Cracks and failures of the outer tank pipes and connections will lead to hydrogen loss directly outside of the tank into the aircraft. As this is an enclosed environment a dangerous H2 mixture may form. Detection of these failures or the consequence, formation of a H2 mixture, must be detected to ensure safety. For this reason, a proper ventilated environment is required during demonstrator testing. Ventilation in the in-service environment is not covered by the COCOLIH2T design given is low TRL. Failures of fuel system related components, such as valves and pressure release devices result in most of the cases in release of H2 with same results as introduced above. It is thus needed to monitor their behaviour and ensure that their functioning is not impaired.

4. Sensor, inspection and monitoring technologies

Structural health monitoring and fuel system health monitoring rely heavily on the measurement of physical quantities. Several sensor types exist for most quantities each having their advantages and limitations. In the upcoming sections the several sensor options are given.

4.1. Gas composition measurement

The only direct method to determine leakage of hydrogen is to measure the gas composition to detect the presence of its molecules. This can be present for failures of both the fuel containing structure or failures of the fuel system.

How leak detection is implemented depends on the use of these and the other sensors, and this is described in the next chapter. In work package 5 a gas leak detection system is being developed. Details regarding this system are given in deliverable D5.1 - LH2 Tank Subsystems: Detailed Design. Gas leak detection is a task closely related to health monitoring. For completeness the systems are mentioned here as well. The system consists of the following relevant subsystems:

- Optical fibre based gaseous hydrogen detection sensors
- Rest gas analyser (RGA)

The hydrogen detection sensors (see **Error! Reference source not found.**) can p ick up H2 concentrations as low as 0.1 vol% GH2, which is way below the Lower Flammability Limit (LFL) of 4 vol% at standard atmosphere. The sensor should be placed where H2 gas accumulates (e.g., near the ceiling) or leakage is likely (e.g. interface place, feedthroughs etc.).

Figure 2 - H2 leak detection sensor

Leakage into the vacuum space is difficult to measure. During operation of the tank Air content will freeze(/solidify) to the inner wall. Hydrogen will only be present in limited quantities due to the strict requirement on the vacuum pressure. An XT-300 RGA with a range of 1-300 atomic mass units (AMU) will be used. The RGA ionises the gas molecules in a rarefied atmosphere ($<1*10^{-3}$ mbar) and measures the mass of the molecules in a mass spectrometer. The output of the measurements is a spectrum with the partial gas pressures against the selected AMU range. The partial gas pressures can be compared to the known calibration gasses of different H2 concentrations that have been fed to the RGA at different pressures.

4.2. Pressure measurement

Pressure monitoring is a critical aspect of SHM in cryogenic LH2 tanks. It involves tracking changes in pressure and vacuum pressure to detect potential issues with the tank's structure. For the COCOLIH2T tank both the vacuum pressure and the pressure inside the inner tank are important to measure.

4.2.1. Vacuum pressure

The insulation vacuum is specified as $\leq 10^{-5}$ mbar, therefor it falls in the category of deep vacuum. Direct measurement is possible up to approximately 10^{-3} mbar, deep vacuum can only be measured by indirect methods and thus limiting the sensor options. Conventional of the shelve sensors are available, see table. Two main measurement principles are used and sometimes combined:

- Ionization vacuum gauges
- Pirani (thermal conductivity) based gauges

Ionization vacuum gauges are the primary instruments used to measure gas pressures in high and ultrahigh vacuum ranges. Ionization vacuum gauges are a type of vacuum gauge that measures the pressure of a gas by ionizing the gas molecules and measuring the resulting ion current.

Often combined with a form of (filament) Pirani measurement for the "higher" ($\sim 10^{-3}$ mbar and higher) vacuum pressure range. The Filament Pirani gauge works on the principle of thermal conductivity, where the thermal conductivity of a gas is directly proportional to its pressure (in the $\sim 10^{-3}$ mbar – 1mbar range). When an electric current is passed through the filament, it heats up due to resistance. The heat generated by the filament is dissipated through the surrounding gas molecules.

Table 2 - Vacuum pressure measurement technologies

	Coated MEMS, Pirani	Filament Pirani	Filament Pirani, Capacitive	Cold cathode, inverted magnetron	Hot cathode, Pirani
Pressure range [mbar]	$5 \cdot 10^{-5}$ ÷ 1000	$5 \cdot 10^{-4}$ ÷ 1000	$5 \cdot 10^{-5}$ ÷ 2000	$1 \cdot 10^{-8}$ ÷ $5 \cdot 10^{-3}$	$5 \cdot 10^{-10}$ ÷ 1000
Accuracy [mbar]	$5 \cdot 10^{-4}$ to 1·10-3 ±10 % of reading $1 \cdot 10^{-3}$ to 100 ±5 % of reading	$1 \cdot 10^{-3}$ to 100 ±5 % of reading	$5 \cdot 10^{-4}$ to $1 \cdot 10^{-3}$ ±10 % of reading $1 \cdot 10^{-3}$ to 11 ±5 % of reading	±30% at $1 \cdot 10^{-8}$ to $1 \cdot 10^{-3}$ mbar	15% at $1 \cdot 10^{-8}$ - $1 \cdot 10^{-2}$ mbar > 15% at 10^{-1} to 1000 mbar

Based on accuracy, range and past experience the most suitable conventional of the shelve sensor, ITR-90 is available. The principle of measurement is hot cathode ionization vacuum gauges (Bayard-Alpert) for low pressure combined with thermal conductivity (Pirani Measurement). The range covered $5 \cdot 10^{-10}$ to 1000 mbar with a measurement uncertainty of 15% at $1 \cdot 10^{-8}$ - $1 \cdot 10^{-2}$ mbar > 15% at 10^{-1} - 1000 mbar. It covers the required range.

4.2.2. Tank pressure

The pressure inside the tank is an important load on the tank structure. It can be measured in one of the gaseous outlet pipes making the temperature requirements on the sensor to be dictated by the aircraft temperatures. Therefore, the measurement of the tank pressure is important from an SHM point of view. The pressure is also required for the monitoring of the fuelling and de-fuelling of the tank.

A conventional pressure sensor for measuring the GH2 pressure and novel fibre optic based GH2 pressure sensor will be studied further within COCOLIH2T. Fibre optic sensors can be daisy chained which is a huge advantage for combining several sensor types. Furthermore, the optic sensing is advantageous in hazardous environments and therefore, it will be further investigated.

4.3. Strain measurement

One of the challenges for measuring strain up till cryogenic condition lies in the large temperature difference and that most sensors are also sensitive to temperature. Temperature effects can be dealt with in several ways. For conventional strain gauges and FBG strain measurement there are the following options:

- A second dummy strain gauge on an unloaded specimen with same temperature; by subtracting the pure mechanical strain remains
- Zero balancing: if only the strain at a certain (constant) temperature condition is required.
- Full/half Wheatstone bridge configurations; where gauges (or reference resistance) are placed such that temperature effect cancel out
- Active temperature compensation by measuring temperature and using a Temperature compensation curve for the specific gauge to compensate for the thermal effect

Another challenge regarding strain measurement at cryogenic conditions is adhering the strain sensor to the specimen. It was found that for the tested specimens, sensors eventually break off. The adhesive becomes more brittle at cryogenic temperatures. Furthermore, cracks form in the 90-degree layers of the laminate, further worsening the already strained state caused by thermal expansion differences, resulting in harsh conditions.

Experience from previous tests comparing FBG’s and conventional strain gauges showed that proper calibration is an important factor in the successful application of strain gauges. The fast response and sensitivity to temperature of FBG’s should be considered for placing the sensors.

For the COCOLIH_2T project both sensor types will be investigated further.

4.4. Temperature measurement

Temperature measurement is needed for example to measure thermal gradients in the tank, thermal cycles on the tank and for temperature compensation for other sensors. Different available sensor types are shown in Table 3.

Table 3 - Available cryogenic temperature sensors technologies

	Silicone Diode type sensor	Platinum resistance sensor	Carbon resistance sensor	Bare FBG sensors	Coated FBG sensors
Temp. range [K]	1.4 ÷ 500 K	14 ÷ 873 K	2 ÷ 80 K	73.15 ÷ 523.15 K	4.15 ÷ 573.15 K
Accuracy [± K]	2÷30 K: ± 1K 30÷100 K: ± 0.25 K	2÷30 K: ± 1K 30÷100 K: ± 0.25 K	N/A	± 0.8 K	N/A
Notes	Potential source of ignition	Potential source of ignition	N/A	No ignition source	No ignition source

Proper calibration for the FBG based temperature sensors is required. Due to the deep cryogenic temperatures and the temperature dependent properties of FBGs as given in equation below.

$$\frac{\lambda - \lambda_0}{\lambda_0} = \big(\alpha(T) + \xi(T)\big)(T - T_0)$$

In which, λ_0 the nominal wavelength at temperature T_0, α the coefficient of thermal expansion (CTE) (≈ 0.5 με/K) and ξ(T) the temperature dependent thermo-optic coefficient. Both the thermal expansion of the glass and the thermo-optic effect are temperature dependent (especially towards deep cryogenic conditions). Obtaining sensitivity in the deep cryogenic region requires coating or adhering the FBG to a proper material as the sensitivity of a bare FBG is limited in the deep cryogenic range.

4.5. Laminate damage measurement

The complexity of building large-scale composite LH2 tanks, as well as the challenges of the in-service environment may result in various kinds of defects. During the manufacturing process, residual stresses from resin shrinkage and uneven curing can lead to microcracks and matrix cracks, voids and porosity, fibre-matrix debonding, and fibre waviness [1]. After the composite manufacturing process, **inspection** processes are thus required to identify the presence of the defects. Moreover, also during in-service operation, matrix cracks and delamination may appear and grow due to thermal or pressure cyclic loadings, and eventually a network of interconnected matrix cracks, as represented in Figure 3 -, that may lead to reduced permeation capabilities or eventually to the leakage of hydrogen [2]. Therefore, structural health of the laminate needs to be **monitored** also during the service life of the tank, assessing the extension of these damage features.

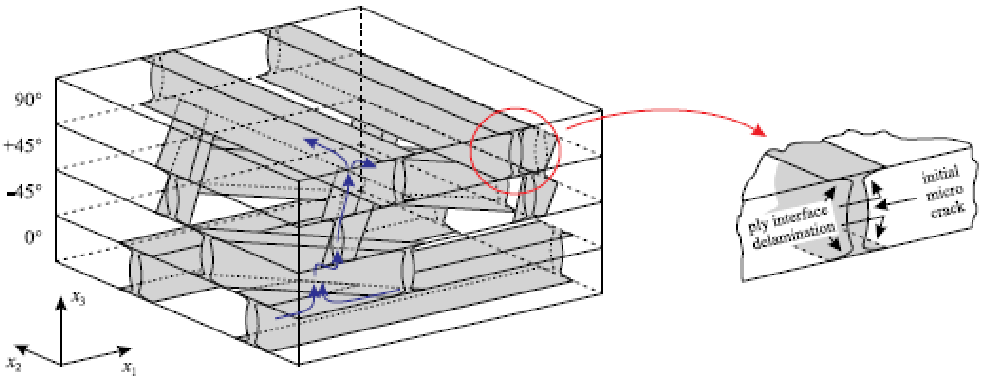

Figure 3 - Damage mode concerning permeation trough laminate [2].

Various technologies have been developed to identify and estimate the damage level of laminate structures. Technical limitation of some of them, limits their usage in environments where the structure is not in operative conditions, those are defined as inspection scenarios or maintenance condition. These approaches typically can provide a broader picture of the damage state of the structure, and the resolution depends on the type of approach adopted. For monitoring the damage in-service conditions, small sensors of different types can be attached to the structure, giving local information about the development of the substrate condition. Common inspection and monitoring approaches for determining the damage condition of composite laminate are:

- Visual inspection
- Ultrasonics
- Thermography
- Shearography
- X-Ray
- Guided waves
- Fibre Bragg gratings
- Acoustic emission

For clarification, visual inspection, ultrasonics, thermography, shearography and X-ray are in this context considered as non-destructive inspection (NDI) techniques as they require device of significant size that cannot be put in cryogenic conditions, while guided waves, fibre Bragg gratings and acoustic emission are considered as structural health monitoring (SHM) for the analysed application.

These techniques are discussed in this section with a focus on their and capabilities in detecting and quantifying laminate damage. In fact, as demonstrated in the Annexes, very small damage in the order of the micrometre size needs to be detected to avoid detrimental effects on the permeation barrier of hydrogen. These defects can be related to an interconnected network of microcracks that thus has to be avoided. A specification is required, as the detection of microcracks on some layer does not necessarily means that an interconnected network of those is present, and this depends on load condition, laminate and tank geometry.

4.5.1. Laminate damage inspection

Ultrasonics ([3], [4]) are one of the most dominant NDI techniques for composites in aerospace industry. By analysing amplitude and time of flight of ultrasonic waves, quantitative characterisation of defect size and depth can be achieved. Detectable defects include delamination, crack, impact damage and so on. Advanced ultrasonic testing methods of phased-array, air-coupled ultrasonics and laser-induced ultrasonics have been developed during the last decades. The frequencies used for ultrasonic NDI are around 0.5-25 MHz. For the detection of small defects (e.g., size of a few mm), high frequency transducers of 5 MHz are normally needed [3], with detectable defect size referenced in Table 4. Main influencing factors of the technique are directionality, attenuation, scattering and multiple reflections of ultrasonics in composite laminates.

Table 4 - Detectable damage sizes in laminate using ultrasonic inspection [5].

Frequency (MHz)	Damage type	Damage size (mm)
5	Delamination	Length: 4.84
5	Side drilled holes	Diameter: 1.5
5	Wrinkles	Amplitude: 0.3

Thermography ([3], [6], [7]) is a common NDI technique that is capable of detecting defects such as delamination, and impact damage. It is a full-field and non-contact optical technique. It can detect defects in composite laminates through the analysis of a sequence of thermal images. A certain type of thermal loading is usually required for thermography NDI, which can be optically or non-optically excited (e.g., using halogen lamps). Non-uniform heating and quick heat loss can create challenges during examination [8].

Shearography ([9], [10], [11]) is another popular laser speckle interferometry NDI technique that has the benefits of being full-field, non-contact, and highly sensitive to surface strain change. Shearography can identify surface strain abnormalities in an object after it has been loaded (for example, thermally or mechanically). It has been utilized for qualitative and quantitative inspection of delamination, debonding, fiber breakage, and impact damage in composite laminates (e.g., thicknesses ranging from 2-5 mm to 50 mm) ([9], [12]). The limitation of this technique is that large rigid-body movements and significant vibrations cause speckle de-correlation which can lead to unsuccessful inspections.

X-ray is an emerging NDI technique for defect detection in composite materials ([3], [6], [7], [8], [13], [9]). It reveals defects by measuring the scattering or absorption of the radiation by composites. Surface and internal defects can be detected. The main disadvantages include the danger associated with X-rays to humans, difficulties with on-site inspection, and high cost.

4.5.2. Laminate damage monitoring

Fibre Bragg Grating (FBG) sensors ([14], [15]) are optical fibre-based sensors that have developed significantly in structural health monitoring applications. Because of the advantages of light weight, small size, high sensitivity, immunity to electromagnetic interferences and harsh environments, they are widely used in aerospace and civil engineering sectors. For hydrogen applications they are very suited also as their optical principle would not provide ignition sources. The principle of FBG relies on Bragg reflection. The length of a FBG sensor is generally in the range of a few millimetres to a few centimetres. Common applications of FBG sensors include point strain and temperature measurements. More recently, FBG sensors have been used to characterise barely visible transverse matrix cracks in composite laminates ([14], [15], [16]), as their high sensitivity can detect the perturbation within their strain field, which should be uniform in the absence of cracks. With this in mind a FBG sensor can only detect damage where the sensor is applied, and a sufficient strain should be applied to magnify this perturbation effect, but their functionality would eventually only need a baseline for no load condition and a calibration for different level of laminate damage condition, with the advantage that these sensors could be queried intermittently.

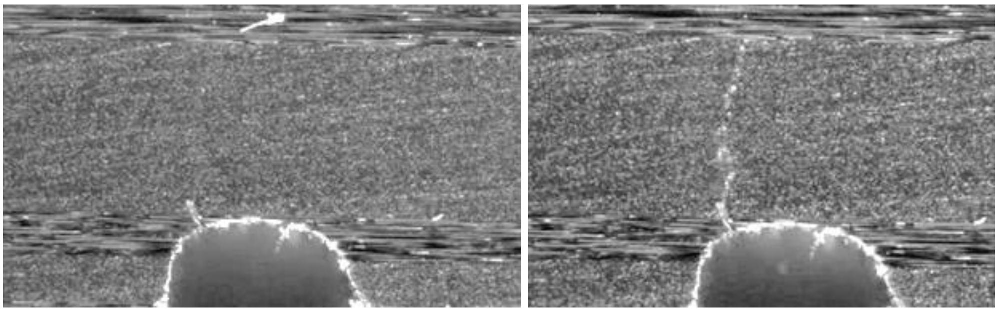

Figure 4 - Crack forming on the transverse layers of a cross-ply laminate.

Sensitive optical acoustic emission (AE) sensors can be used to detect laminate cracking in deep cryogenic conditions. The events recorded by the optical AE sensors correspond with specimens in which microcracks were found. At room temperature, the events detected by the optical AE sensors have been directly correlated with the formation of microcracks using a test bench equipped with a microscope, where a notched specimen was put under tension and the formation of microcracks was observed, Figure 4. The response of a microcrack is very distinctive compared to other events, as shown in Figure 5. This correlation with crack formation means that acoustic emission sensors are suitable to detect microcrack formation. This type of functionality requires a continuous monitoring of the AE signal, which can also be subject to external disturbance. The requirement of continuous measurement may be feasible since an interrogator consumes minimal power. If this requirement is too stringent, measures can be taken to account for the state of the tank after the SHM system was inoperative. For example, a comparison can be made with the microcrack sensor to determine if cracking occurred at critical locations. Alternatively, it can be reasoned that continuous monitoring of the inner tank may not be necessary when the system is on the ground, as the inner tank, being the most critical component for microcracking, is "protected" by the outer tank, thereby reducing the likelihood of damaging events such as tool drops or other impacts.

The exact location of the crack cannot be determined, but it is still a good indicator of the development of laminate damage.

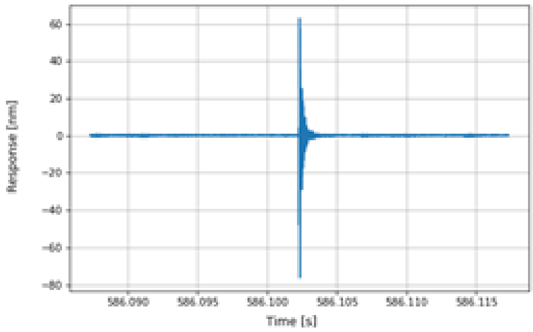

Figure 5 - Typical event corresponding to crack formation shown in the optical image above

Finally, guided waves are excited by piezoelectric actuators attached to the laminate structure that could act also as receiver sensor. These waves are disturbed by the presence of defects but also from geometrical features, thus advanced data processing is needed to determine the damage level. Also, a baseline calibration is at this moment required. Their application within laminate damage is being studied, but at the moment of writing this document, their development level is still low.

Based on the given application and capability of developed algorithms (in terms of identification, localisation and characterisation of structural defects), the availability of the technique in the in-service environmental, potential for automation, safety and costs, phased array based ultrasonics method is selected for the manufacturing and maintenance inspection method of the tank storage system while FBG sensor technology and the acoustic emission methods will be developed for matrix crack monitoring during in-service conditions.

4.6. Monitoring structural health of fuel piping and their fitting connections

Monitoring the structural health of fuel piping systems requires a combination of advanced sensor technologies and proven methods. From detecting microscopic cracks with ultrasonic testing to predicting corrosion with electrochemical sensors, these techniques ensure safety and reliability. By implementing real-time monitoring with integrated systems like SHM, operators can minimize risks and extend the lifespan of critical infrastructure. The following list of was generated with well-known algorithms:

- Ultrasonic Testing for Internal Defects
- Acoustic Emission Monitoring for Dynamic Damage
- Corrosion Monitoring with Electrochemical and Advanced Sensors
- Strain and Stress Analysis for Load Monitoring

4.7. Monitoring of fuel system related components

Monitoring a fuel system typically involves using sensors to track key components like tank fuel level, fuel pressure, fuel flow rate to assess the health condition/state of the fuel system components. The key components in the storage fuel system are the FDV valve that is used to refuel with LH2 the tank and the LH2 gauge that is used to measure the LH2 level.

The key two failures for a refuelling valve are i) loss of valve functionality due to failure of the main valve actuator (degradation, manufacturing faults, jamming in open or closed position etc.), and ii) internal or external leakages that will result to H2 losses and will affect the regular H2 flow (wear, fractures). Cryogenic valves are typically operated by electric or pneumatic actuators that may or may not have feedback systems that can provide position data of the actuator. The position data can be analysed to detect blockages or degradation. In addition, valve blockage or degradation may affect other variables such as pressure drop in the fuel storage, storage LH2 level and H2 flow to the storage. Therefore, additional sensors such as pressure sensors, tank fuel level or flow rate meters, can be used to indirectly detect anomalies in the valve operation. Finally, if feedback does not exist, additional sensors such as ultrasonic transducers can be used to detect integrity defects (blockage, cracks, corrosion etc.).

Defect of the LH2 gauge sensor, include component failures (controller failure, gasket failure, PZT degradation), sensor drift or environment impact (fracture loss, embrittlement). Most of these failures can be detected by continuous monitoring of the actuating and sensing signals of the gauge to detect outliers that can indicate anomalies. Specifically, modelling the gauge nominal response, using signal processing, machine learning etc. can be used to compare the nominal model with real signals of the sensor. Large differences in performance, for which various metrics can be used (such as the error measure mse, rmse etc.), are used as indicators or key performance indexes to identify anomalies.

5. Structural Health Monitoring Framework

In this chapter we present the being-developed framework to ensure that the structural health of the fuel containing system is monitored with a sufficient level of detail, thus ensuring that during the testing phase of the demonstrator failures that compromise the safety are prevented. The application of several different monitoring concepts using sensors on multiple physic domains is significant during this low TRL development phase as functionality and capability of some of the sensors and the structure itself are tested in-service conditions, without extensive subcomponent testing, while relying on virtual testing and analysis of the developed demonstrator system. The result of these campaigns will consent to outline the most reliable sensors and which of them would be required during higher TRL in-service operations. From the tank side, relevant information on critical design aspects of the fuel storage system will be acquired, thus allowing to iterate the developed design.

The structural health monitor system for the fuel containing system wants to prevent the leakage of hydrogen by monitoring the damage state of different key subsystems such as the inner tank structure, the tank support structure and the vacuum insulation. The outer tank structure damage is not monitored within this context as loads are not critical and the design is confident.

The leakage of hydrogen, or a high flow-rate release of hydrogen, is the last event that would be detected in the context of these test and is defined as the first critical event for the safety of the fuel storage system. Different phenomena would eventually appear before this event, and they are used as indirect indicators for hydrogen release. Direct sensing of the presence of hydrogen with gas composition sensors in the vacuum area is thus employed in this context as direct indicator of this critical event. For example, low-flow rate release of hydrogen may be present before that for different reasons such because of an increased permeation of the inner tank due to damage, and this damage would be monitored through secondary indicators. The secondary critical event for the health of the tank would be a loss of insulation as a result of insulation damage or loss of vacuum. Other critical events such as failure of piping connections or malfunction of components such as valves may results in leakage of hydrogen as direct indicator, but their indirect indicators are discussed in the next Chapter as part of the fuel system.

The following paragraphs introduces the process of **measuring** significative physical information, defying indirect **indicators** for the structural health state of the liquid hydrogen fuel containing system and understanding their applicability and their relevance prior the critical events introduced above, thus defying **monitoring** schedules. After this introduction, the framework applied to the demonstrator is presented.

Suitable sensors were selected for structural health monitoring as introduced in the chapter 4 measuring different physics quantities such as temperature, pressure and strain. For quantifying the damage of the structure derivative quantities such as non-uniform strain and wave response of the structure are measured. Sensor placement was planned to identify critical locations within the tank, including stress concentrations, potential damage hotspots such as transition regions and temperature variations areas. Optimization placement algorithms were employed to balance spatial coverage and redundancy, incorporating design boundary conditions and factors like. The sensor coverage layout plan to ensure comprehensive global and local monitoring. Damage inspection is also performed with sensor not attached to the tank, where robotic systems equipped with high-resolution ultrasonic probes are planned to conduct automated NDI for identifying visible or barely visible damage scenarios. Some sensors were acquired off the shelf, while others, such as the microcrack sensor, were developed specifically for this project and required calibration. Sensor calibration was performed at multiple stages, including testing under controlled conditions. Additionally, testing under operational conditions during various stages of demonstrator testing, together with the information of the other sensors, will permit to validate this information.

Indicators of the health state are obtained through understanding and simulating the behaviour of the fuel storage system and the different monitored components such as the wall material. Different health conditions and threshold value are defined for the sensor acquired data at its specific location. Data acquisition from sensors involves signal processing to filter noise and enhance sensor data quality, followed by different operations to output the relevant information. Classification models are employed, with supervised learning predicting local damage from labelled data while unsupervised learning for a more global assessment. Employed tools include models for predicting degradation under stress, local strain field analysis and thermodynamic simulations to assess tank performance and conditions under varying health state and conditions.

Planning a relevant acquisition schedule influences the monitoring performance by determining its precision and efficiency. Continuous monitoring is employed to detect gradual degradations, in the same category event-triggered monitoring focuses on critical events like thermal, pressure surges or acoustic phenomena. Interval-based inspection use external, eventually automated devices for routine analysis to identify structural anomalies, which may also be employed following the detection of an unplanned degradation. High frequency data acquisition systems are required for some signals such as acoustic emissions or wave signals but real-time processing consent to log only relevant information for calibrated sensors. The identified measurement scopes for assessing the health of the tank demonstrator and determining indirect indicator of hydrogen release, along with continuous hydrogen gas concentration measurement at critical locations as the direct indicator, are introduced in the following list:

1. Monitor the vacuum pressure continuously.
2. Monitor strain and temperature at hotspot positions continuously.
3. Monitor the damage state of the inner tank continuously.
4. Count the temperature and pressure cycles of the tank.
5. Monitor the boil-off rate of the liquid hydrogen inside the tank.
6. Analyse the structural state of the inner tank at maintenance intervals.
7. Analyse the H2 gas content of the vacuum at maintenance intervals.

These concepts, their capability and the expected accuracy in determining health indicators are described in detail in the following sections.

5.1. Framework for continuous structural health monitoring

This concerns the continuous monitoring of damage state of the inner tank, vacuum level and temperature trough the appropriate sensors in significant points.

Mechanical and thermodynamic model of the tank system are developed which reliably predict the information provided by the sensors for different health conditions prior critical levels.

The following parameters need to be monitored continuously to ensure a valid health information is provided. Please note that some of this information are relevant stand-alone and valuable to be fed in a digital twin model, while other need the support of a relevant model.

5.1.1. Continuous monitor of the vacuum pressure

Depending on the state of the tank (i.e. filled with LH2, going back to room temperature) increasing pressure readings have different causes.

When the tank is at cryogenic conditions (filled with LH2) any increase in pressure is due to H2 leakage into the vacuum space as all air components would freeze to the inner tank wall and will not be picked up in these conditions. The rate at which H2 enters the vacuum space gives the maximum remaining operation time of the tank (assuming there is no pump restoring the vacuum). At 10E-3 mbar the insulation becomes insufficient and massive boil-off will take place.

When the tank goes from cryogenic conditions back to room temperature solidified air components become liquid and evaporate again at known temperatures. If a pressure increase occurs at the inner tank temperature close to the boiling point of known quantities of air (N2 O2), then air has leaked into the system. Note that during COCOLIH2T testing a rest gas analyser will be installed so that the content of the vacuum pressure can be analysed.

If at no specific temperature the pressure increases. Then it can be assumed that the likely cause is permeation or "sudden" leakage of components.

As long as the pressure remains below 20-25 mbar there is no danger (for any mixture) for explosion. For a tank in operation conditions the allowable vacuum pressure is around 10^{-3} mbar as then the insulation is insufficient and massive boil off would take place.

5.1.2. Continuous monitor of temperature and strain of the inner tank

Health indicators on the state of the inner tank ca be derived by monitoring the strain and temperature in different areas of the tank. This can be done by placing sensor on the external side of the tank, thus avoiding the contact with liquid hydrogen.

The inner tank can be divided in different zones:

- Caps
- Interface plate area
- High loaded areas of the tank

Determining the health state of the tank requires interpretation of the current state (stress/strain and temperature) and the previous loads resulting in a damage state. In Work Package 8 the relation between cyclic loading and temperature on crack density development is studied. The FE-model developed in Work Package 3 is needed to translate the measured strain, temperature(s) and pressure into stress state of the indicated areas.

5.1.3. Continuous monitor of crack damage of the inner tank

As introduced in Section 3.2, repeated loads on the tank structure may degrade the tank wall integrity, which damage shows up as ply cracks arising from highly stressed areas such as manufacturing defects or due to geometric reasons. This degradation, if not monitored properly, may increase the permeation of the laminate in certain areas and lead to leak paths.

A microcrack sensor based on the FBG technology is being developed within this context to measure the crack density in specific areas on the external surface of the inner tank. The operating principle of the FBG-based microcracking sensor relies on the changes observed in the reflected Bragg peak, when a crack transverse to the FBG axis is present, resulting in the non-uniform strain field induced along the sensor itself. A machine learning (ML) approach is being investigated to process this information and classify the damage level, specifically the crack density of the lamina where the sensor is positioned. This has to be optimised to the specific material properties and FBG sensor output, but once ML models have been trained and optimised, they can detect and classify damage in real-time.

This damage information is then used in twofold means. First, for every sensor, given the detected number of cracks and the characterized laminate proprieties, an indication of the residual permeation barrier can be provided. Second, using the damage information of all the sensors, together with a linear elastic model of the tank laminated structure, it is possible to give an overall indication of the residual life of the tank itself. This is possible if relevant location is accounted for application of the sensors. The accuracy and capability of these algorithms will be assessed in the context of their development.

5.1.4. Count of relevant cyclic applied loads

The main relevant parameters related to the lifecycle of the liquid hydrogen pressure vessels are its **temperature** and **pressure** cycles. Loading the tank with fuel involves first its cooling, then the tank gets pressurized after the filling process. Further fuel fillings operations will then introduce pressure cycles to ambient pressure to permit the fuelling procedures, no temperature variation are expected during this process.

These temperature and pressure cycles are significantly relevant for assessing the progress with the fatigue life of the tank itself, with the temperature cycle parameter expected to be more detrimental given the higher stress amplitude involved. In a well-established system these parameters alone can be used to determine the remaining life, while in the context of the COCOLIH2T demonstrator testing, these parameters are acquired to validate structural damage models and capability and sensitivity.

5.1.5. Continuous measurement of boil-off rate

The boil-off rate would be a clear parameter to understand the effect of reduced permeation efficiency, and this might be done with a flow sensor attached to the gas lines. In the Annex, a relationship between air leak and boil-off is presented.

Currently, no flow sensor in the vent channel is provisioned for the demonstrator so the boil-off has to be determined otherwise. The change in mass in the tank can be determined by the level sensor on the aircraft (during the demo tests the mass change can also be determined by the loadcells on the tank). The flow in the

GH2 line is measured. The change in mass measured by the level sensor minus the GH2 flow is the boil-off flow, if there is no filling of the tank. The allowed 2% boil-off per day means that 1.14kg LH2 (57kg LH2 mass in the tank) is allowed to evaporate. This corresponds with 0.0132 g/s or 47.5 g/hour.

It is not possible to distinguish between the causes of a deviating boil-off rate. It is however an important indicator of the tank function.

- How to measure boil-off rate
- How to do it without the influence of external factors
- How to relate the information to structure damage or insulation damage
- What would be the ranges of boil off or the
- It is possible but at a further development level.

5.1.6. Continuous monitor of the acoustic emission of the inner tank

The acoustic emission has currently been used only on coupon level. To count an event as a microcrack event, 2 conditions must be met.

- It was found that all event above a threshold of 5 could be related to microcrack events.
- The shape of the event must mimic the ones that could be related to microcracking. Meaning a high amplitude start of the event that dampens out.

The distance of the sensor to the location of the microcracking will influence its amplitude. An SHM solution will have to account for that. Multiple acoustic sensors can be placed such that the location with respect to the sensor can be determined and thus the severity of the event can be determined.

It is currently unknown what the sensor spacing should be to monitor (part of) the tank. A test program on larger scale specimens has to be performed to find the distance a sensor can still pick up microcracking.

Another important factor is to find out how the actual aircraft environment influences the noise level. It is expected that due to the distinctive signal of a microcrack detection in an aircraft environment might be possible.

5.2. Framework for interval based structural health monitoring.

At the initial stage the composite tank demonstrator is supposed to be inspected after manufacturing, during the assembly phase. After that inspection intervals must be defined giving its measured health degradation behaviour respect to the provisioned one. This will be more frequent during demonstrator activities, reaching an optimal schedule once design and damage phenomena are managed with better accuracy. Still, inspections may be triggered by unexpected variations in the indicators presented above in the context of continuous structural health monitoring.

Inspection intervals are determined by analysing historical data to evaluate potential risks and repercussions, fatigue life models, or environmental factors. Furthermore, the intervals are adjusted based on risk factors, usage trends, and feedback from previous inspections.

5.2.1. Periodic vessel inspection with robotic crawler

The document proposed Robotic crawlers based mobile platforms capable of carrying ultrasonic probe equipment across different surfaces of an LH2 tank for damage assessment. Miniaturize lightweight crawler development for the accessible hole diameter of 300 mm of LH2 CFRP tank. These systems are particularly beneficial for evaluating confined, complex regions, or vertical or overhead structures of storage tanks. Key features of robotic ultrasonic crawlers include adhesion mechanisms for stability, precise positioning-based advanced navigation systems for consistent scanning pathways, and integrated phased-array ultrasonic transducers for high-resolution damage imaging. Initially, the robotic crawler model will evaluate structural integrity by rotating the tank. Further, the system design modified to inspect the tank while tank remains on the aircraft. The following benefits of robotic ultrasonic C-scan testing of the LH2 tank exist.

1. High-resolution damage imaging enables precise defect characterization.
2. Automated systems improve operational efficiency by reducing inspection time and labour needs. Wireless communication based real-time data transfer and remote-control capabilities for enhanced operational flexibility.
3. Robotic systems ensure accessibility to operators to reach locations that are inaccessible for human beings.
4. Robotic systems ensure accurate and consistent scanning of the tank’s structure.

Ultrasonic C-scan probe testing is a mapping technique that yields a two-dimensional image of a material's interior LH2 tank structure. The procedure comprises the generation and reception of ultrasound wave using a transducer that generates high-frequency sound waves that go through the material. The scanning probe transducer captures waves that are reflected from discontinuities or boundaries. The device uses the amplitude and time-of-flight of reflected signals to calculate material thickness, detect damages, and map deteriorated interior structures. The collected data is processed to produce a detailed image intensity representing various material qualities or anomalies. C-scan testing provides high-resolution imaging for detailed analysis, making it ideal for evaluating components of the composite LH2 tanks.

Automatic NDI system must handle the following constraints for the inspection of LH2 composite storage tank:

1. To optimize signal quality and coupling, LH2 tank's surfaces must be clean and smooth.
2. Navigating complex, uneven, or convoluted structures of LH2 tank can be tough.
3. Initial costs for automated robotic systems based ultrasonic damage detection technology can be significant.

Skill requirements for operators require specialized training to operate modern inspection equipment as well as accurately analyse the data of composite LH2 tank. AI-driven machine learning algorithms can be used to enhance defect recognition and reduce interpretation time.

5.2.2. Monitor the vacuum pressure during a maintenance operation at a fixed interval

When sufficient confidence exists in tank design/testing or field experience and loss of vacuum due to leakage or permeation is known to be slow, it is sufficient to monitor vacuum pressure every maintenance interval. For each interval the leak rate and the remaining operation hours can be calculated. If needed the vacuum can be restored.

The acceptable leak rate is small. The upper limit of the allowable leak rate can be calculated by taking the vacuum pressure increase from $p_{initial}= 10^{-5}$ mbar to $p_{final}= 10^{-3}$ mbar in the total operating time till next maintenance. Assuming Δt= 6 months (15811200s) for a maintenance interval and a Vacuum volume of 400 litre the leak rate can be calculated:

$$Q_L = \frac{\Delta(pV)}{\Delta t} = \frac{V_{vacuum} * (p_{final} - p_{initial})}{\Delta t} = \frac{400 * (10^{-3} - 10^{-5})}{15811200}$$

$$Q_L = 2.5 * 10^{-8}\ mbar.l.s^{-1}$$

6. Fuel System Health Monitoring Concepts

The objective of the fuel system health monitoring is to ensure the fuel system remains monitorable and maintainable at all times. It typically utilizes sensors, including fuel levels, pressure, and other related data, to continuously monitor various parameters within the fuel system, and detect/predict potential issues and defects, assessing the overall health. The data collection and data analysis are the key aspects of a fuel system health monitoring where data and parameters from the various sensors are collected and then analysed to identify trends, anomalies and deviations from normal operating parameters which could indicate potential problems.

6.1. Fuel system health monitoring concept

The main objective of the fuel system health monitoring is to detect and identify the critical/high risk failures of the fuel system listed in the FMEA above, by processing and analysing the necessary sensor data. The Failure Mode and Effects Analysis (FMEA) (Deliverable D5.1 "LH2 Tank Subsystems: Detailed Design") and taking into account design and components requirements, the most important and highest impact/risk components are down-selected for health monitoring: the LH2 gauge sensor and Fill and Drain Valve (FDV) and hence the focus of the health monitoring will be on those components. The other high-risk components such as the pressure relieve valve and burst disc are mostly passive safety components with no sensing signals that are not part of the fuel system. However, should a health monitoring system for those components be deemed necessary other sensors from the tank system, such as pressure, gauge sensors etc. could be used to indirectly monitor them. Generally, some components (e.g., relief valve, burst disc, etc.) have no sensors and are triggered in an analogue manner based on some threshold. The temperature, pressure, and fuel level in the inner tank are correlated to failure modes in multiple other subsystems (e.g., MLI, pressure valves, etc.). All these modes will have to be combined into a single monitoring algorithm that includes an automatic root cause analysis to characterise, quantise, and localise these failure modes (if possible).

The health monitoring system development will follow a bottom-up approach. At first the fuel system health monitoring system is designed and optimized considering and using only the existing sensors selected for the H2 tank, i.e. without at the first considering additional dedicated sensors. The purpose is to investigate the fuel system health monitoring design without adding cost to the tank design. Some signals or additional sensor requirements that are nice to have maybe unavailable (e.g. valve state or flowrates not available). From the analysis of the health monitoring system performance, another analysis will follow if additional sensors will be needed to improve further the accuracy and precision of the defect detection and prediction. This investigation will follow towards the end of the fuel system health monitoring design and assessment task. The work will also assess which components in the fuel system can be monitored based on the existing sensors and which will need additional sensors so adequate monitoring can be achieved.

6.2. Health monitoring development and testing

Similarly to the SHM system development in Section 5, the following steps need to be followed (see Figure 5):

Data acquisition: retrieve raw data from the available sensors (LH2 gauge, inner tank pressure, temperature) which can be used to identify performance anomalies such as defects or degradation of the fuel system components. Similarly to SHM, the health monitoring of the fuel system will use data acquisition systems to capture sensor signals and high-resolution data loggers capable of sampling rates suitable for capturing transient signals from the system components. In this step, the data are processed and cleaned to ensure that are properly labelled and time-stamped.

Data Analysis: data analysis is used to process the raw data from the system sensors into features that can provide meaningful insights in the state and performance of the fuel system and detect and identify anomalies in the fuel system. The data analysis consists of the following steps:

1. The raw data are analysed to extract key features, that are descriptive of the anomalies, failures and defects of the fuel system and can identify key patterns that can detect these anomalies. Signal processing methods are used to identify those features. It deploys time and frequency analysis (noise filtering, FFT, wavelets) of the sensor signals to extract features such time-frequency characteristics (time-series values of system variables, power spectrum, spectrogram, scalogram etc.).
2. Anomaly and fault detection methods are used, based on advanced Machine Learning (ML) that process the features from the previous step as inputs and output the classification of anomalies or faults including defect LH2 gauge, blockage in valve, leakage etc. A number of ML methods can be used for anomaly/fault detection depending on the from simple time series analysis and classification methods (Support Vector Machines, Neural Networks) to more advanced Deep Learning (DL) Neural Networks classification and Autoencoders. Autoencoders are tested in this work due to their capability to detect anomalies but also predict them, using the lower dimensional encoder output as an indicator of degradation of the system.

Each component of the fuel system can be monitored in various ways depending on the available sensors following the bottom-up approach described in the previous section. In the following section, the most prominent ways of health monitoring of the fuel system components are described.

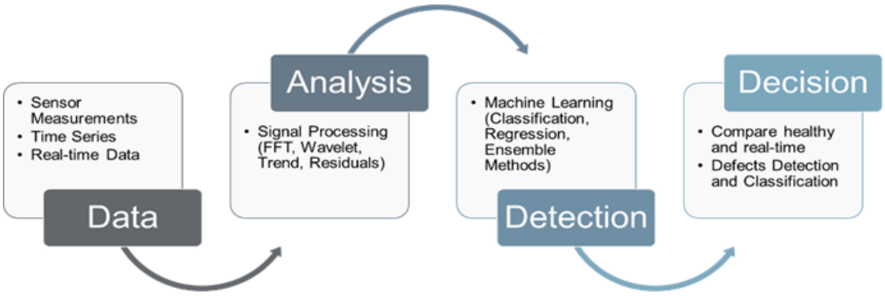

Figure 5 - Fuel system health monitoring framework.

6.2.1. Monitoring of the LH2 gauge

As introduced in Section 4.7, defects of the LH2 gauge are attributed to component failures (controller failure, gasket failure, Piezo-electric Transducer degradation), sensor drift or environment impact (fracture loss, embrittlement). This degradation, if not monitored, will cause performance and accuracy loss of the sensor which in extension will cause wrong readings of the LH2 level in the storage.

A continuous monitoring approach is developed for the LH2 gauge in this project for the defect detection of this sensor, which is shown in Figure 6. The main idea of the method uses continuous measurements of the actuation and sensor values of the gauge to determine the health status of the sensor. A machine learning (ML) modelling method is also investigated, which is used to process the measurement data and classify the damage, following state-of-the-art approaches ([19], [20]). The ML models the nominal operation of the sensor, emulating the time-frequency nominal response (power spectral density, signal amplitude, time response etc.) of the gauge which are used as key features for the ML model training and testing. Since these features describe the state and performance of the system, they are relevant indicators for detecting defects and in general the anomalies in the gauge performance. The ML model features (power spectral density, signal amplitude, time response etc.) are then compared with the ones obtained from the real-time system data during the operation of the gauge to identify key outliers, by using standard KPIs including RMSE/MSE, precision or accuracy.

The ML model can be validated both with synthetic data (generated by fuel system simulations) and real test data from the storage system lab demos. For this purpose, a simulation model of the integrated storage and fuel system, is being developed in the project to provide the training and testing data necessary to develop the continuous monitoring approach for the gauge.

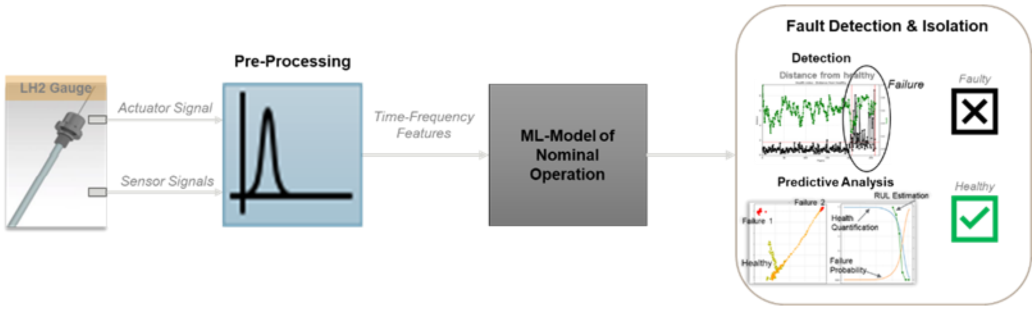

Figure 6 - Continuous monitoring approach for LH2 Gauging.

6.2.2. Continuous Monitoring of the fuel system fill and drain valve

The storage fuel system uses a shut-off valve for managing the flow of LH2 to the tank during fuelling/refuelling, which is mechanically operated when the fuelling takes place. Other valve technologies may also be used, for example solenoid valves that are electromechanically operated, however the key main failures that occur are similar, as the ones described in section 4.7, and therefore similar defect detection and health monitoring approaches can be applied.

The work on fault detection and prognostics health management focuses significantly on the case where valve position, or at least some signal of the valve state, is provided ([20], [21]). Valves with position feedback or position sensors are common in automated systems and can support real-time information that can be used to detect and classify a failure. Other measurements from the overall system have also been used to determine valve failures such as flow meter measurement and pressure drop. These measurements are available in the inner tank of the storage, however additional sensors maybe needed at the valve. Additional methods for valve fault detection include vibration methods, thermal infrared methods, acoustic emission methods ([4], [22]), which require additional specialized sensor such as vibration sensors, cameras and AE sensors, which may add complexity and cost to the system. Signal processing, such as FFT, wavelets and residual analysis, is applied to the data to generate key performance indicators (or features) such as PSD, wavelet coefficients, trends and residual signals that can be used with ML methods to classify the failures.

A simulation-based analysis will be performed in this work to determine the key variables (LH2 level, pressure, mass flow, temperature) that may be affected by the valve failures i.e. the variables in which the failure is observable, by studying the correlations and causality between the failure and the signals. This analysis will provide a report if the current system sensors are adequate to detect failures or additional sensors may be needed, and which signals from the tank sensors to use. The approach in Figure 4 to complete the design of the monitoring system.

6.2.3. Continuous monitoring of leakage in fuel system

Gas leakage in fuel system can take place due to the main fuel system FDV valve malfunction (internal and external leakage), fuel system connections damage (damaged pipping), safety disk failure or line rapture. Leakage detectors have been developed for the project with adequate detection accuracy, that are able to detect H2 concentrations as low as 0,1vol% below the LFL limit. These sensors both apply to the fuel system health and structural health monitoring to detect leakage due to various storage failures that can occur, and that are listed and detailed in section 4.1. close to the places where H2 is likely to accumulate. Other approaches could include indirect detection by measuring other physical values of the fuel system such as reduction in the outlet flow of the fuelling valve and pressure drop in the storage, however these approaches will need additional sensors to be installed. Simulation-based analysis will be followed to evaluate this possibility and if new sensor additions will benefit gas leakage detection.

7. Conclusions

This report presented an SHM concept for a composite hydrogen storage tank, that can identify and prevent structural integrity failures through continuous and interval monitoring utilizing data analytics techniques. Baseline health assessment is used as an initial assessment criterion to establish baseline structural health metrics. Several health indicators are developed in different physics domains such as pressure, temperature, stiffness and structure damage. The capabilities of whose have been discussed. Critical areas were identified as high-stress regions that are vulnerable to failure for focused sensor placement. Regularly update of SHM strategies based on performance of data and emerging failure trends. Analytics and data processing are employed to predict failure and schedule repairs proactively.

The integration of real-time monitoring and predictive maintenance reduces the risk of catastrophic failure, enhances safety, and extends the operational lifespan of the LH2 composite tank structures. In the context of the demonstrator development, it permits to understand which component must be improved and where design changes are needed.

The presented frameworks will be further developed in the project in the remaining work period. They will be evaluated during the demonstration phases of the project where data will be collected from the tank system operation and will be used to evaluate the health monitoring performance. Based on this evaluation changes and adaptations to the SHM and fuel system algorithms will take place to improve accuracy. In addition, the results of this report will be used in the forthcoming work to integrate the proposed health monitoring frameworks presented here in an overall health management system architecture (Task 6.3) that will be detailed in Deliverable D6.2 “Health management system architecture”.

8. References

[1] P. Ordin, "Review of hydrogen accidents and incidents in NASA operations," NASA-TM-X-71565, 1974.

[2] M. Kuznetsov, S. Kobelt, J. Grune and T. Jordan, "Flammability limits and laminar flame speed of hydrogen–air mixtures at sub-atmospheric pressures.," *International Journal of Hydrogen Energy,* vol. 37, no. 22, pp. 17580-17588, 2012.

[3] G. Alleman, The effects of different cure cycles on the mechanical performance of thick-walled composites., TUDelft, 2018.

[4] J. Hohe, A. Neubrand, S. Fliegener, C. Beckmann, M. Schober, K. Weiss and S. Appel, "Performance of fiber reinforced materials under cryogenic conditions—A review.," *Composites Part A: Applied Science and Manufacturing,* vol. 141, p. 106226, 2021.

[5] M. I. Silva, E. Malitckii, T. G. Santos and P. Vilaça, "Review of conventional and advanced non-destructive testing techniques for detection and characterization of small-scale defects.," vol. 138, p. 101155, 2023.

[6] R. Yang and Y. He, "Optically and non-optically excited thermography for composites: A review.," *Infrared Physics & Technology,* vol. 75, p. 26, 2016.

[7] Z. Qin, S. Qu, Z. Wang, W. Yang, S. Li, Z. Liu and Y. Xu, "A fully distributed fiber optic sensor for simultaneous relative humidity and temperature measurement with polyimide-coated polarization maintaining fiber.," *Sensors and Actuators B: Chemical,* vol. 373, p. 132699, 2022.

[8] R. Groves, "Inspection and monitoring of composite aircraft structures.," *In Reference Module in Materials Science and Materials Engineering: Comprehensive Composite Materials II,* p. 300, 2018.

[9] R. Montanini and F. Freni, "Non-destructive evaluation of thick glass fiber-reinforced composites by means of optically excited lock-in thermography.," *Composites Part A: Applied Science and Manufacturing,* vol. 43, no. 11, p. 2075, 2012.

[10] M. Ibrahim, "Nondestructive evaluation of thick-section composites and sandwich structures: A review.," *Composites Part A: Applied Science and Manufacturing,* vol. 64, p. 36, 2014.

[11] N. Tao, A. Anisimov and R. Groves, "Shearography non-destructive testing of thick GFRP laminates: Numerical and experimental study on defect detection with thermal loading.," *Composite Structures,* vol. 282, 115008.

[12] J. Newman, "Shearography nondestructive testing of composites.," *in Comprehensive Composite Materials II,* p. 270, 2018.

[13] N. Tao, A. Anisimov and R. Groves, "FEM-assisted shearography with spatially modulated heating for non-destructive testing of thick composites with deep defects.," *Composite Structures,* vol. 297, p. 115980, 2022.

[14] D. Francis, R. Tatam and R. Groves, "Shearography technology and applications: a review.," *Measurement science and technology,* vol. 21, no. 10, p. 102001, 2010.

[15] H. Yamg, L. Yang, Z. Yang, S. Yinan, H. Gu, J. Ma, X. Zeng, T. T. S. Ma and Z. Wu, "Ultrasonic detection methods for mechanical characterization and damage diagnosis of advanced composite materials: A review.," *Composite Structures,* vol. 324, p. 117554, 2023.

[16] A. Rajabzadeh, R. Heusdens, R. Hendriks and R. Groves, "Calculation of the mean strain of smooth non-uniform strain fields using conventional FBG sensors.," *Journal of Lightwave Technology,* vol. 36, no. 17, p. 3716, 2018.

[17] A. Rajabzadeh, R. Heusdens, R. Hendriks and R. Groves, "Characterisation of transverse matrix cracks in composite materials using fibre Bragg grating sensors.," *Journal of Lightwave Technology,* vol. 37, no. 18, p. 4720, 2019.

[18] A. Rajabzadeh, R. Hendriks, R. Heusdens and R. Groves, "Analysis of FBG reflection spectra under anti-symmetrical strain distributions using the approximated transfer matrix model.," *In Optical Sensing and Detection V,* vol. 10680, p. 134, 2018.

[19] N. Shahid and A. Ghosh, "TrajecNets: Online failure evolution analysis in 2D space.," *IJPHM Special Issue on PHM Applications of Deep Learning & Emerging Analytics,* vol. 10, no. 4, 2019.

[20] M. Rautela, J. Senthilnath, E. Monaco and S. Gopalakrishnan, "Delamination prediction in composite panels using unsupervised-feature learning methods with wavelet-enhanced guided wave representations.," *Composite Structures,* vol. 291, p. 115579, 2022.

[21] S. Liu, T. Zhao and D. Zhang, "Fault Detection of Flow Control Valves Using Online LightGBM and STL Decomposition.," *Actuators,* vol. 13, p. 222, 2024.

[22] E. Ponizovskaya-Devine, D. Luchinsky, A. Kodali, M. Khasin and e. al., "Fault diagnostics and evaluation in cryogenic loading system using optimization algorithm.," *Proceeding of the Annual Conference of the PHM Society,* vol. 7, no. 1, 2015.

[23] X. Wang, X. Sun, Y. Hu and J. Duan, "Temperature-Insensitive Embedded Metal-Packaged Fiber Bragg Grating Inclination Sensor.," *IEEE Sensors Journal,* vol. 24, no. 4, pp. 4472-4479, 2023.

[24] S. Her and W. Lin, "Simultaneous measurement of temperature and mechanical strain using a fiber Bragg grating sensor.," *Sensors,* vol. 20, no. 15, p. 4223, 2020.

[25] B. Piątek, T. Howiacki, M. Kulpa, T. Siwowski, R. Sieńko and Ł. Bednarski, "Strain, crack, stress and shape diagnostics of new and existing post-tensioned structures through distributed fibre optic sensors.," *Measurement,* vol. 221, p. 113480, 2023.

[26] R. Soman, P. Kudela, K. Balasubramaniam, S. K. Singh and P. Malinowski, "A Study of Sensor Placement Optimization Problem for Guided Wave-Based Damage Detection.," *Sensors,* vol. 19, no. 8, p. 1856, 2019.

[27] S. Venkata and S. Rao, "Fault Detection of a Flow Control Valve Using Vibration Analysis and Support Vector Machine.," *Electronics,* vol. 8, no. 10, p. 1062, 2019.

[28] L. Industries, "Fault Detection Technology of Valves," 2022. [Online]. Available: https://www.landee.cn/news/industry-news/fault-detection-technology-of-valves.html.

[29] A. G. Anisimov, M. G. Serikova and R. Groves, "3D shape shearography technique for surface strain measurement of free-form objects.," *Applied Optics,* vol. 58, no. 3, p. 498, 2019.

[30] J. Marr, "Leakage testing handbook.," NASA, NASA-CR-952, 1968.

[31] G. Chi, S. Xu, D. Yu, Z. Wang, Z. He, K. Wang and Q. Zhou, "A brief review of structural health monitoring based on flexible sensing technology for hydrogen storage tank.," *International Journal of Hydrogen Energy,* pp. 980-998, 2024.

9. Annex: Leaks and relevant damages size analysis

At the start of the project an estimate was made of which leak rates can be allowed for the COCOLIH2T inner and outer tank structure accounting on its effect on relevant performance indicators. Allowable damage sizes are then provided, so relevant sensor capabilities to monitor these defects can be developed in this context.

9.1. Inner tank leakage analysis

In a simplified approach the allowed leak rate is then translated to a passing through channel/hole in the inner tank. In reality, a leak path will be formed between different damages through the laminated tank. However, this gives a first estimate the order of magnitude of the damage that needs to be monitored.

In order to be able to register leaks quantitatively, the concept of “leak rate” is used. It is defined as a measure of leakiness and specified in the unit of $mbar.l.s^{-1}$. For systems with leak rates around 10^{-6} to $10^{-3}\ mbar.l.s^{-1}$, the hole size is too small to be considered as an orifice. In this case, a leak path must be considered. To know whether this consideration can be used, it is necessary to obtain an order of magnitude of the leak rate.

The time required to increase the pressure from $10^{-5} mbar$ to $10^{-3}\ mbar$ in the vacuum chamber must be equal to the total operating time. This time has been estimated at: Δt=6 months= 15 811 200s.

The leak rate can be calculated.

$$Q_L = \frac{\Delta(pV)}{\Delta t} = \frac{V_{vacuum} * (p_{final} - p_{initial})}{\Delta t} = \frac{400 * (10^{-3} - 10^{-5})}{15811200}$$

$$Q_L = 2.5 * 10^{-8}\ mbar.l.s^{-1}$$

$Q_L < 10^{-6}\ mbar$, so a leak path approach must be considered in order to simulate a leak in the tank.

The fluid flow depends on the type of flow. Can the hydrogen leaking from the tank into the vacuum space be considered as a laminar or turbulent flow?

To answer this question, the Knudsen number must be calculated. In fact, a laminar flow occurs when this number is low ($Kn < 0.1$), and a turbulent flow when the number is large ($Kn > 10$).

The Knudsen number is defined as:

$$Kn = \frac{\lambda}{L}$$

λ is the mean free path and L is the characteristic length scale.

$$\lambda = \frac{k_B * T}{\sqrt{2} * \pi * d^2 * p}$$

$k_B = Boltzman' s constant$

$T = temperature$

$d = molecular\ diameter$

$$p = pressure$$

where $k_B = 1.380649 * 10^{-23}$, $T = 20K$, $d = 289 * 10^{-9} m$, $p = 4 * 10^5 Pa$, which gives

$$\lambda = 1.86 * 10^{-15}\ m$$

L is the hole diameter which is consider $L = 1 * 10^{-6} m$. Then,

$$\boldsymbol{Kn = 1.86 * 10^{-9}}$$

$Kn \to 0,$ flow is considered a continuum (laminar flow).

9.1.1. Leak on the inner liquid part of the tank

A hole diameter of $1\ \mu m$ is assumed in this section. Remember that the pressure in the vacuum must not exceed $10^{-3}\ mbar$ during the operating phase to ensure an efficient insulation. How does it take for the liquid hydrogen in the tank to build up pressure from $10^{-5}\ mbar$ to $10^{-3}\ mbar$ through a $1\ \mu m$ leak?

The first step to answer this question is the calculation of the mass flow.

$$q_m = \frac{\rho_{avg} * \ \Delta p * \pi * D^4}{128 * \mu * l}$$

ρ_{avg} is the density at average condition ($\rho_{liquid} = 62.949\ kg.m^{-3}$), Δp is the pressure difference ($\Delta p\ \cong 4 * 10^5\ Pa$), D the hole diameter, μ the dynamic viscosity ($\mu_{liquid} = 8.7378 * 10^{-6}\ Pa.s$) and l the length (this is the thickness of the inner wall, $l = 8\ mm$).

$$q_m = \ 8.84 * 10^{-12}\ kg.s^{-1}$$

The formula of the mass flow comes from the Poiseuille equation (incompressible and Newtonian fluid in laminar flow). Flow is caused by pressure difference. The greater the pressure differential between two points, the greater the flow rate [30]:

$$q_m = \rho_{avg} * \frac{\Delta p}{R}$$

where R is the resistance to flow, it includes everything (except pressure) that affects flow rates: $R = \frac{8\mu l}{\pi r^4}$

$$q_m = \rho_{avg} * \frac{\Delta p * \pi * r^4}{8\mu l} = \rho_{avg} * \frac{\Delta p * \pi * D^4}{128\mu l}$$

Then, the leak rate can be determined:

$$Q_L = \frac{R * T}{M} * q_m$$

$$Q_L = 5.82 * 10^{-5} \ mbar.l.s^{-1}$$

Finally, given the just calculated leak rate and the assumption of an upper limit of $10^{-3}\,mbar$ in the vacuum chamber, the time required to increase the pressure is calculated as follow.

$$\Delta t = \frac{\Delta(pV)}{Q_L}$$

$$\boldsymbol{\Delta t = 11766.86\ s = 3.27\ h}$$

This time is very fast. It means that a $1\ \mu m$ hole diameter is not permitted in the inner wall of the tank if effective insulation is to be maintained during the entire operating phase. What would be an acceptable diameter in the inner wall within these limits? Operating time is assumed to be 6 months. Using previous formula:

$$D = \sqrt[4]{\frac{M_{H2} * \frac{\Delta(pV)}{\Delta t} * 128 * \mu_{liquid} * l}{R * T * \rho_{liquid} * \Delta p * \pi}}$$

$$\boldsymbol{D = 1.651 * 10^{-7}\ m = 0.1651\ \mu m}$$

So, to maintain good insulation the pressure in the vacuum must not exceed $10^{-3}\,mbar$. This limit is respected if the leak diameter in the liquid part of the tank is smaller than $0.1651\ \mu m$. This value is very low, it means that the inner wall must not be damaged where the hydrogen is in liquid form.

9.1.2. Leak on the inner gaseous part of the tank

The same reasoning is used as for the liquid part. A hole diameter of $1\ \mu m$ is also assumed in this section.

Hydrogen density: $\rho_{vapor} = 4.8405\ kg.m^{-3}$

Viscosity: $\mu_{vapor} = 1.3496 * 10^{-6}\ Pa.s$

$$q_m = 4.40 * 10^{-12}\ kg.s^{-1}$$

$$Q_L = 2.90 * 10^{-5}\ mbar.l.s^{-1}$$

Finally,

$$\boldsymbol{\Delta t = 23635.36\ s = 6.57\ h}$$

This result is about twice as high as the time obtained in the liquid part of the tank, but it remains very fast. So, a $1\ \mu m$ hole diameter is not permitted in the inner wall of the tank, if effective insulation is to be maintained during the entire operating phase. What would be an acceptable diameter in the inner wall within these limits?

$$D = \sqrt[4]{\frac{M_{H2} * \frac{\Delta(pV)}{\Delta t} * 128 * \mu_{gaseous} * l}{R * T * \rho_{gaseous} * \Delta p * \pi}}$$

$$\boldsymbol{D = 1.966 * 10^{-7}\ m = 0.1966\ \mu m}$$

The limit of $10^{-3} mbar$ is respected if the leak diameter in the gaseous part of the tank is smaller than $0.1966\ \mu m$. This value is very low. It means that the inner wall must not be damaged where the hydrogen is in gaseous form.

9.1.3. Summary of the simplified analysis

It has been demonstrated that the inner wall must not be damaged. In fact, whether in the liquid or gaseous part of the tank, a leak of even a micrometre in diameter has serious consequences for the system and can leads to an extremely rapid loss of vacuum. Only diameters of around $0.1651\ \mu m$ and $0.1966\ \mu m$, respectively for the liquid and the gaseous parts of the tank, are acceptable. These are extremely low limits and can be a problem for the tank. In fact, manufacturing defects can be already present by voids which are the initial point for microcracks. It would then be impossible to respect these limits.

9.2. Outer wall leakage analysis

In this part, the impacts of leak on the outer wall studies. Air leaking into the vacuum area will quickly solidify against the inner wall. Because of the solidification the vacuum pressure remains constant while operating. However, when air solidifies in the inner wall of the tank during the operating phase, heat is released and responsible for hydrogen boil-off. When taking 2% boil-off per day as a limit, the upper bound of the amount of air leaking into the system can be calculated. First, the influence of air solidification on hydrogen will be studied. Then a simplified calculation is made to relate the air leaking into the system assuming a hole size to get an idea of the damage sizes.

9.2.1. Air solidification on the inner wall

During the operating phase, the temperature in the vacuum chamber is around 159.5 K and the temperature of the inner wall around 26 K. The solidification temperatures of oxygen and nitrogen are higher than 26 K. So, the air entering in the vacuum is assumed to solidify immediately on contact with the inner wall.

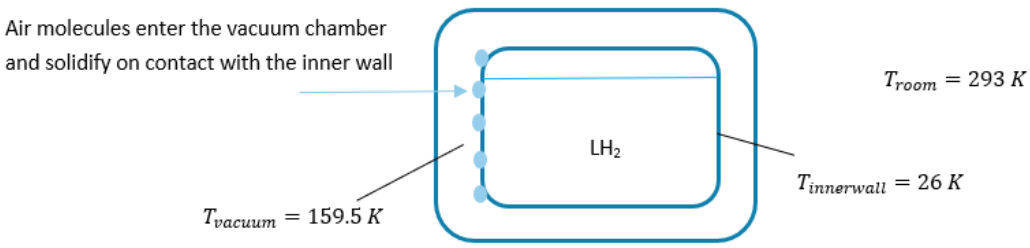

Figure 6 Diagram showing air solidification during the operating phase

Assume 1 mole of air enters the vacuum chamber: $n_{air} = 1\,mol$.

To get an initial approximation, the composition of the air is simplified:

$$n_{N2} = 0.78084\,mol$$

$$n_{O2} = 0.20947\,mol$$

Melting temperature: $T_{meltingN2} = 63.23\ K$

Boiling temperature: $T_{boilingN2} = 77.355\ K$

Heat can be expressed:

$$Q_{N2} = |Q_{293\to77.355} + Q_{boiling} + Q_{77.355\to63.23} + Q_{melting} + Q_{63.23\to20}|$$

$$Q_{N2} = |m_{N2}c_{mN2}(77.355 - 293) - m_{N2}L_{boiling} + m_{N2}c_{mN2}(63.23 - 77.355) - m_{N2}L_{melting} + m_{N2}c_{mN2}(26 - 63.23)|$$

$$\boldsymbol{Q_{N2} = \left|m_{N2}c_{mN2}(26-293) - m_{N2}L_{boiling} - m_{N2}L_{melting}\right|}$$

With:

$c_{mN2} = 1025\, J.K^{-1}.Kg^{-1}$ (weight capacity)

$L_{melting} = 25.7\, kJ.kg^{-1}$ (latent heat)

$L_{boiling} = 200\, kJ.kg^{-1}$

$$Q_{N2} \cong 10.923\, kJ$$

Considering that the boil-off must be less than 2% per day, the maximum mass of liquid hydrogen that can be evaporated in one day can be estimated. (The tank initially contains $57\, kg$ of liquid hydrogen.)

$$m_{H2} = 57 * 0.02 = 1.14\, kg$$

The heat required to convert $1.14\, kg$ mass of hydrogen of LH2 into GH2 must be calculated.

$c_{mH2} = 14300\, J.K^{-1}.kg^{-1}$

$L_{boiling} = 455\, kJ.kg^{-1}$

$$Q_{H2} = m_{H2}c_{mH2}(253 - 252.87) + m_{H2}L_{boiling} + m_{H2}c_{mH2}(252.87 - 247.074)$$

$$\boldsymbol{Q_{H2} = 520.819\, kJ}$$

The maximum quantity of air permitted per day in the vacuum chamber is then calculated.

$$n_{air} = \frac{Q_{LH2}}{Q_{one\ mole\ of\ air}} = \frac{520.818}{14.090} = 36.964\, mol$$

In order to comply with the limit of 2% boil-off per day, the quantity of air entering in the vacuum space during the operating phase must not exceed $\boldsymbol{36.964\, mol}$.

According to the previous part, $36.964\, mol$ of air is assumed to enter in the vacuum chamber in one day. What is the volume of air solidified on the inner wall?

Air contains approximately $78\,\%$ nitrogen and $21\,\%$ oxygen, the masses corresponding to each of these gases is estimated.

$$n_{air} = 36.964\, mol$$

$m_{N2} = 0.8085\, kg$, with $\rho_{N2} = 1026.5\, kg.m^{-3}$

$m_{O2} = 0.2478\, kg$, with $\rho_{O2} = 1426\, kg.m^{-3}$

The volume occupied by air solidified can be calculated.

$$V_{air} = V_{N2} + V_{O2} = 9.614 * 10^{-4}\ m^3$$

$$\boldsymbol{V_{air} = 0.9614\ L}$$

The total volume of the vacuum chamber is: $V_{vacuum} = 691.236\ L$. Thus, the $36.964\ mol$ of air occupy a small volume of the inner wall. In fact, this represents only $0.14\ \%$ of the total volume available.

To define the permissible hole diameter according to the maximum quantity of air that can enter each day, the mass flow must be calculated: ($\Delta t = 1\ day = 86400\ s$)

$$q_m = \frac{\Delta m_{air}}{\Delta t} = 1.2246 * 10^{-5}\ kg.s^{-1}$$

Then, using the other formula of the mass flow used for the leakage of GH2 and LH2, the maximum diameter can be defined.

$$\boldsymbol{D = \left(\frac{128 * \mu * l * q_m}{\rho * \Delta p * \pi}\right)^{\frac{1}{4}}}$$

$$\boldsymbol{D = 156.85\ \mu m}$$

Knowing that the quantity of air entering the vacuum must not exceed 36.528 mol per day, the hole diameter required must be less than $156.85\ \mu m$ in order to comply with this limit.

9.2.2. Summary of the simplified analysis

The allowable outer tank damage is ~1000 times larger than the inner tank. The reason is as follow.

- The pressure difference between vacuum and outer tank wall is lower.
- The air entering into the vacuum solidifies immediately (cryo-pump) on the inner tank wall. Therefore, the allowed amount of air leak is related to the boil-off KPI. As air entering the system and solidifying adds heat to the inner tank.

The reduction in insulation due to loss of vacuum in this case is not accounted as the air solidifies provide a protective layer. Additional heat accumulation needs to be accounted for longer exposures in this environment, or for condition where air does not enter in contact with the inner tank surface. Still the smaller defect size calculated on the inner tank in section 9.1 drives the SHM monitoring of defects.