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LH2 tank wall material permeability: A means of compliance (MoC) approach.

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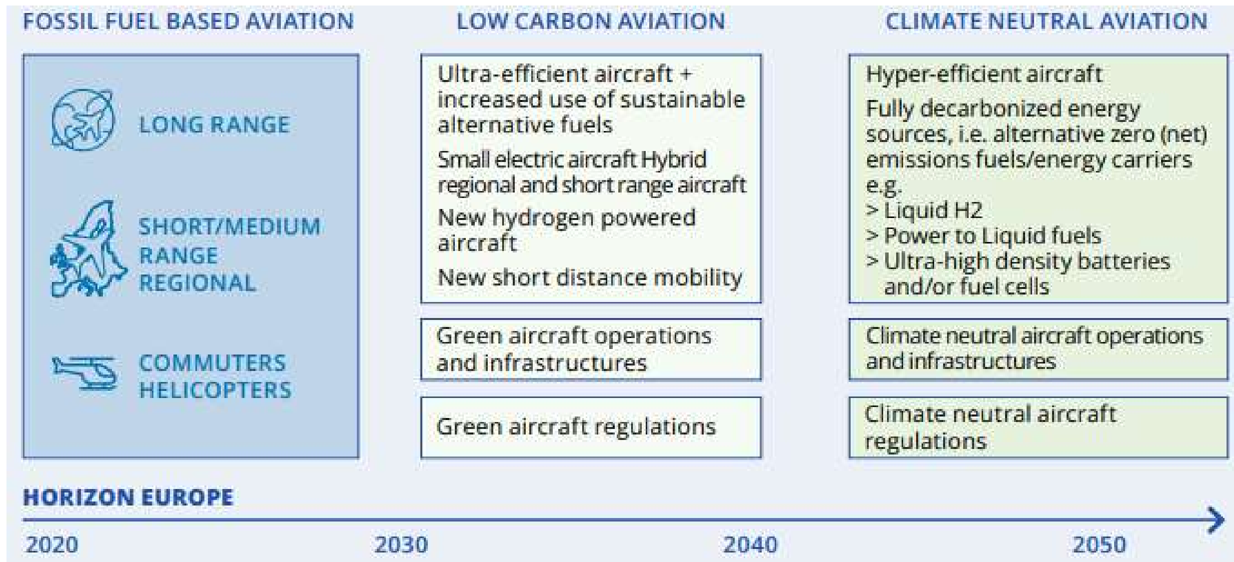
Clean Aviation as part of the EU's SRIA

- to integrate and demonstrate disruptive aircraft technological innovations to decrease net emissions of greenhouse gases by no less than 30 %
- to ensure that the technological and the potential industrial readiness of innovations can support the launch of disruptive new products and services for an entry-into-service by 2035



Clean Aviation SRIA 2024

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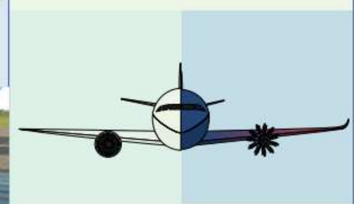
Clean Aviation Phase 2 (2026-2030)

- The second phase of Clean Aviation (2026-2030) will concentrate on integration and demonstration of technologies around aircraft concepts powered either by Sustainable Aviation
- Four aircraft concepts and one validation platform supporting an aircraft concept have been proposed to match Clean Aviation’s main scope: short and medium range and regional market segments

THRUST	ULTRA-EFFICIENT REGIONAL AIRCRAFT	H2 HYDROGEN POWERED AIRCRAFT	ULTRA-EFFICIENT SHORT AND MEDIUM RANGE AIRCRAFT
AIRCRAFT CONCEPTS		 Validation Platform 	
CO_2 Emissions vs 2020 State-of-the-art Non-CO_2 effects not yet quantified	-30% excluding SAF effects up to -86% including SAF effects	-100%	-30% excluding SAF effects up to -86% including SAF effects

Clean Aviation SRIA 2024

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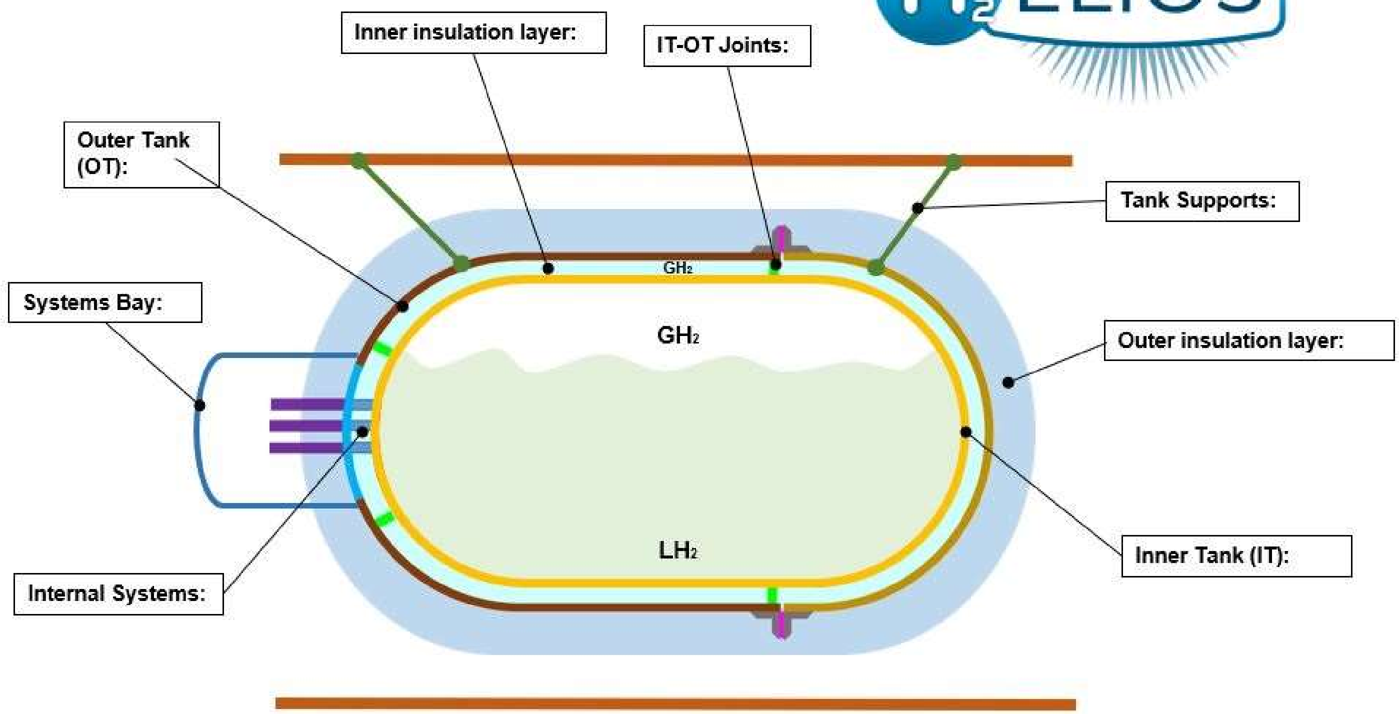
H2ELIOS Hydrogen storage system

- 12-partner consortium run by Aciturri Aerostructures from Spain
- Lightweight, 150 kg load-bearing H2 storage solution
- 35% gravimetric index
- 12+ hours of dormancy time
- Foam insulation, no vacuum insulation



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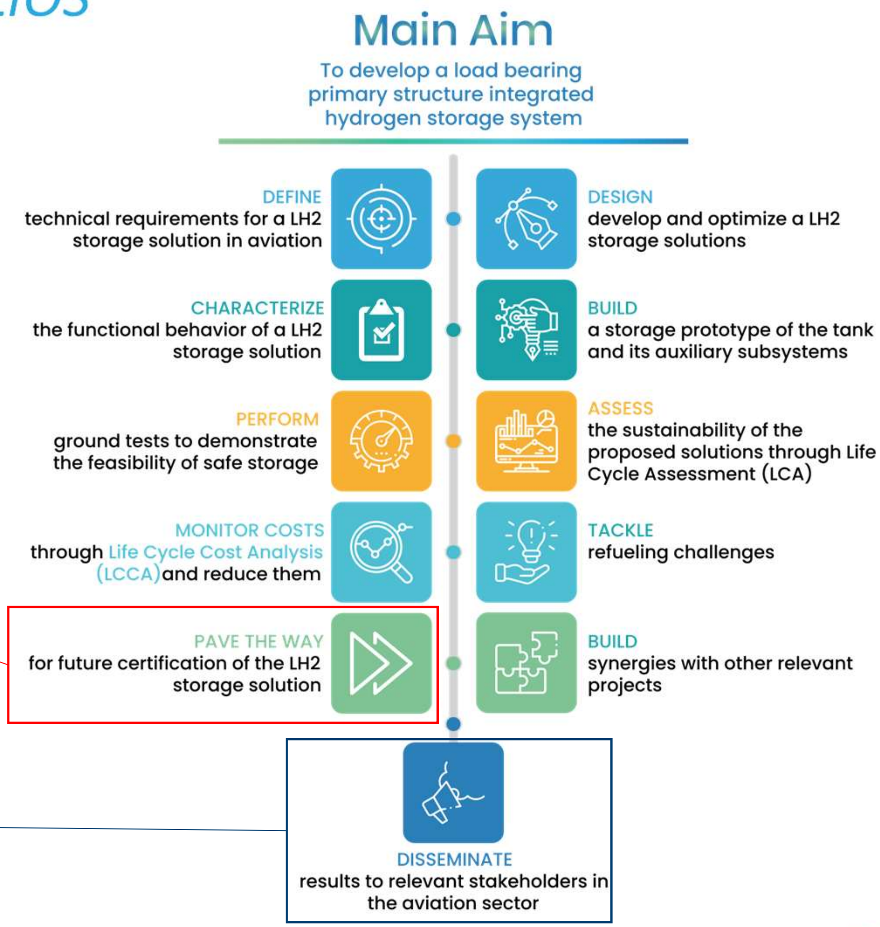
Clean Aviation Phase 1 – H2ELIOS

D1.7 Means of Compliance - tank materials in cryogenic conditions



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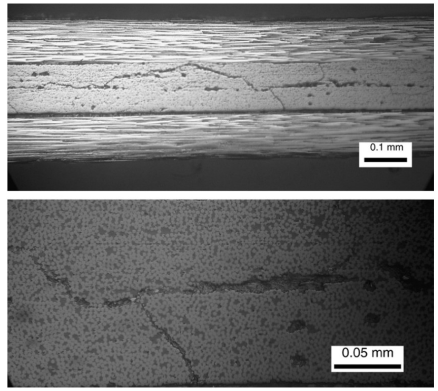
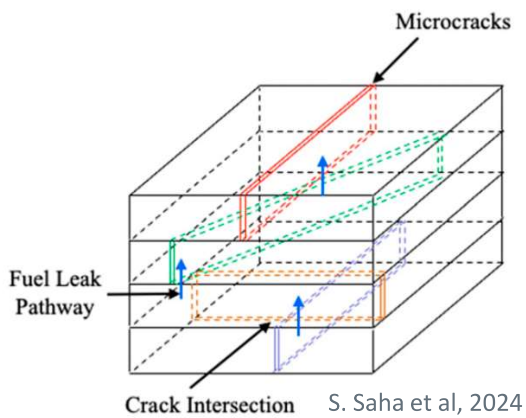
Problem description – H2 permeability/leakage

- Composites are not impermeable
- H2 small molecule that readily permeates
- H2 is a liquid at temps < 20 K
- Thermal cycling due to refueling
- Mechanical cycling due to pressure fluctuations, sloshing and aerodynamic loads
- Different CTE between fiber and matrix
- Microcracking

S. Choi et al, 2007





S. Saha et al, 2024

- Asphyxiation
- Cold burns
- Compromised structural properties
- Liquefaction/Solidification of air components

Formation of a flammable mixture in confined space – between 4 and 75% H_2 at @20°C.

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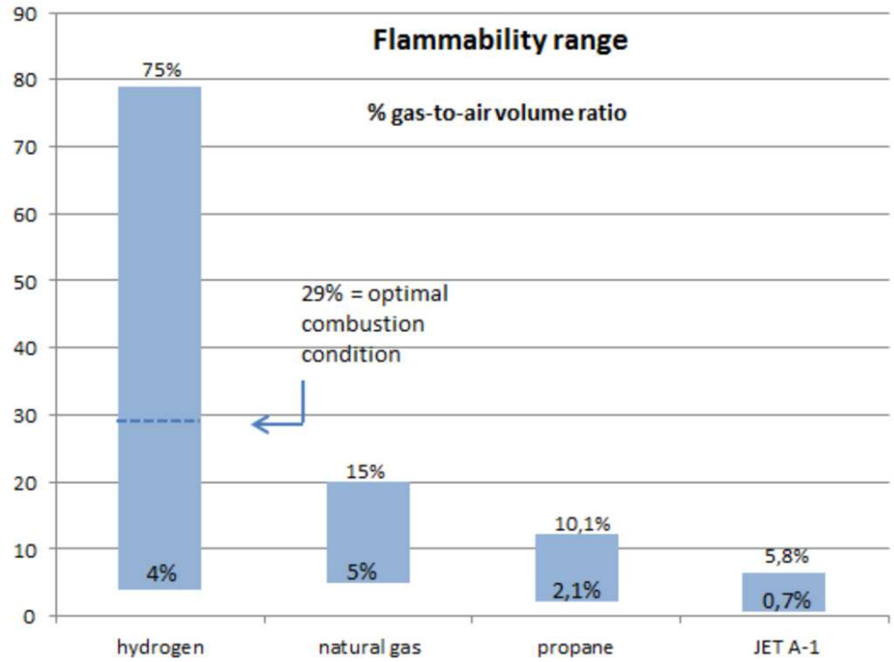
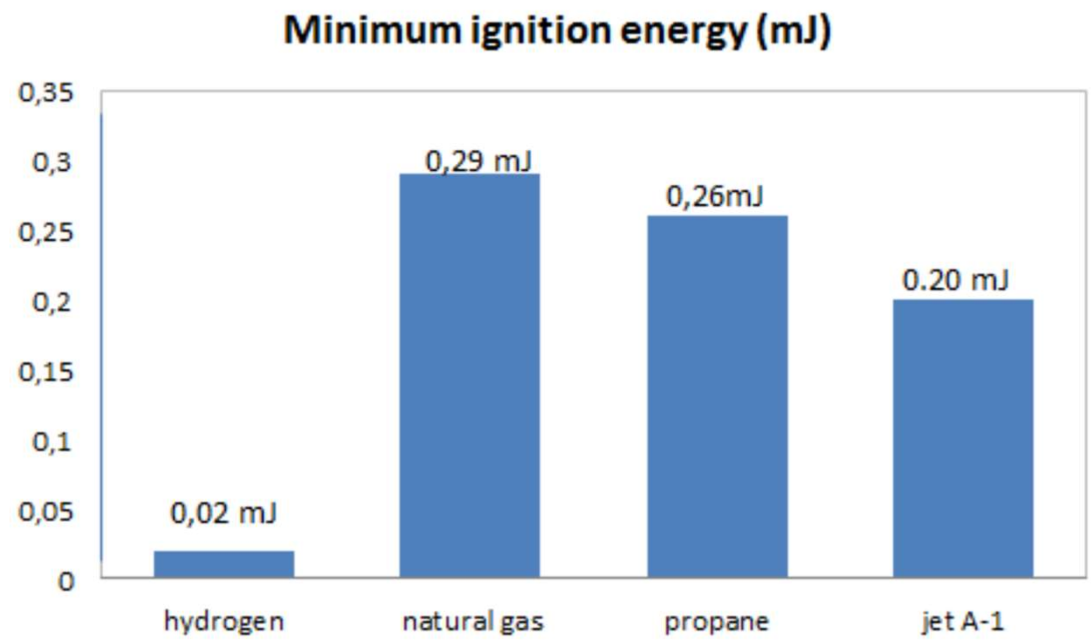
Problem description – H2 permeability/leakage vs Safety





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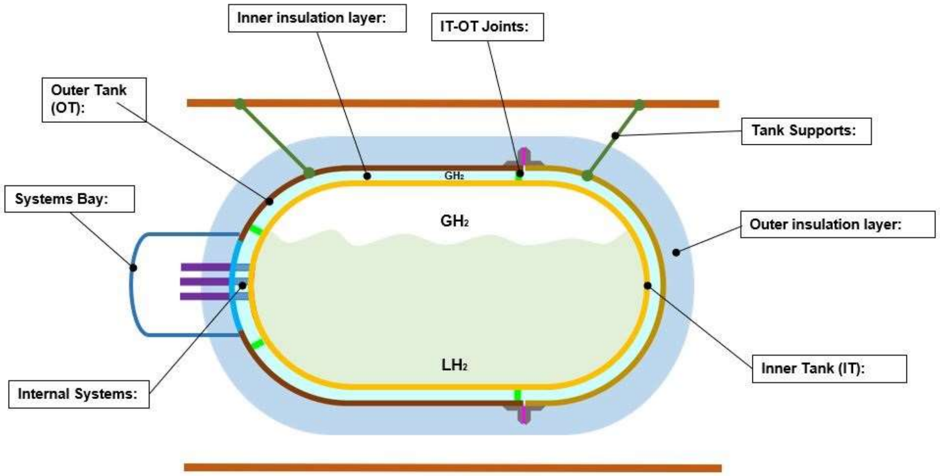
H2ELIOS D1.7 Means of Compliance - Scope

- Only address the suitability of tank materials with respect to permeability/leakage
- Only applies to tank wall materials that are PMCs (Polymer Matrix Composites)
- Need for genericity. It should apply to as many possible H2 storage solution designs as possible



Question at hand: What permeation-related requirements does a material, chosen by an aircraft designer/manufacturer for an LH2 storage solution, have to meet in order to be deemed suitable for the application and how should it go about demonstrating compliance with them?

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Existing/Example regulation

Low leakage - concentration in fuel/air mixture < 25% of LFL (1% volumetric H2 concentration). No safety issues.

Medium leakage – concentration in fuel/air mixture 25% - 50% of LFL (1% to 2% volumetric H2 concentration)

High leakage - concentration > 50% of LFL (>2% volumetric H2 concentration).

A hazardous fuel leak results if debris impact to a fuel tank surface (or resulting pressure wave) causes:

a) a running leak,

b) a dripping leak, or

c) a leak that, 15 minutes after wiping dry, results in a wetted aeroplane surface exceeding 15.2 cm (6 in) in length or diameter.

The leak should be evaluated under maximum fuel pressure (1g on ground with full fuel volume, and also considering any applicable fuel tank pressurization).

Tank pressure test = 1.3 (MAWP + 0.2MPa) – No permanent damage! No leaks!

Tank leak test = He with mass spectrometer leak detector – No detectable leak!

Component leak test after 3 hours of conditioning @ cryo temps and @ MAWP = < 2 cm^3/h @ 20^oC

Component leak test after 24 temp cycles and @ MAWP = < 2 cm^3/h @ 20^oC

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Approach to MoC

EASA
European Union Aviation Safety Agency

Maintain the same level of safety achieved by circa 70 years of fire/explosion regulatory evolutions for large airplane commercial transport: H2 presence shall not degrade this achieved level.

Hydrogen as aviation fuel - Workshop 2023
Aircraft Certification
Fire and Explosion challenges

The facts:

- Attaining 35% GI with metallic solution unlikely
- No impermeable composite "silver bullet" solution yet
- AIAA and EASA have indicated that permeation/leakage will be permissible

The approach:

- Understand/Determine the permeation/leakage behaviour of the material in relevant conditions
- Understand/Determine the associated uncertainties and apply appropriate SFs
- OEM integration solution to manage/mitigate permeation/leakage

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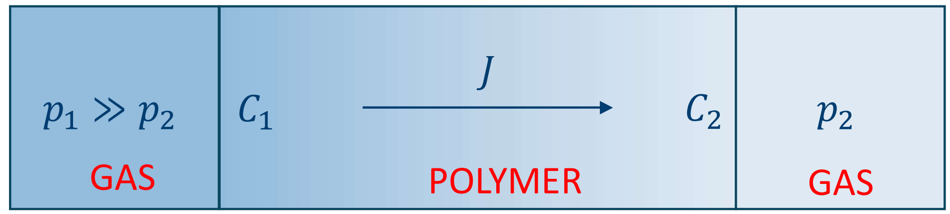
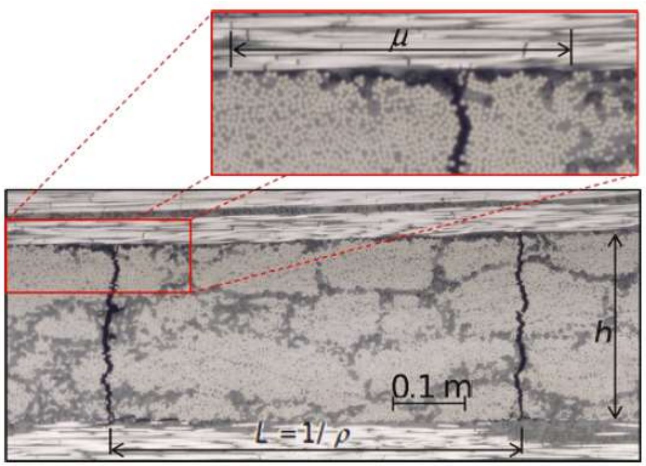
Understanding/Determining the permeation/leakage behaviour: What do we know? What tools do we have?

- Permeation vs Leakage
- Permeation = Diffusion driven by concentration gradient
- Leakage = Flow through leak paths driven by pressure gradient
- Permeation <<<<<<<<< Leakage



Adsorption	Diffusion	Desorption
$C_1 = Sp_1$	$J = -\frac{dC}{dx}$	$p_2 = \frac{C_2}{S}$



H. Laeuffer et al, 2016

- Fick's law $J = -D\frac{d\phi}{dt} = \frac{-D \cdot A \cdot \Delta C}{\Delta x}$
- Darcy's law $q = \frac{Q}{S} = \frac{k}{\mu}\frac{dp}{dx}$

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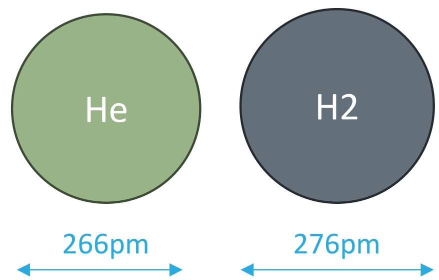
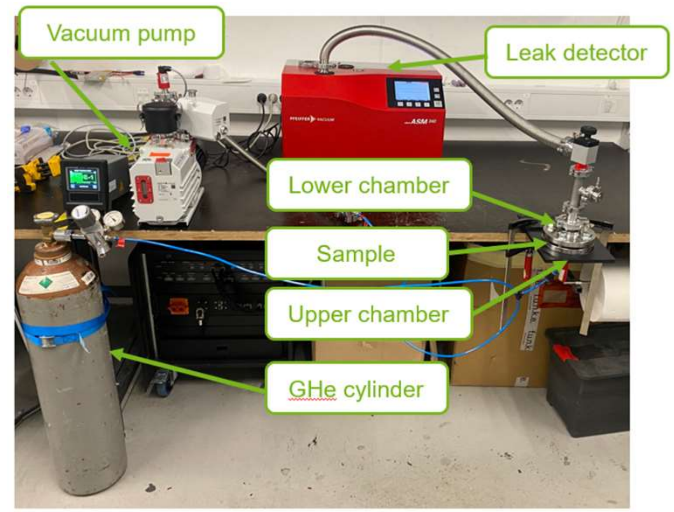
Understanding/Determining the permeation/leakage behaviour: What do we know? What tools do we have?

- ASTM D1434 - Standard Test Method for Determining Gas Permeability Characteristics of Plastic Film and Sheeting
- GHe safer and comparable to GH_2
- Mass spectrometry most common/sensitive

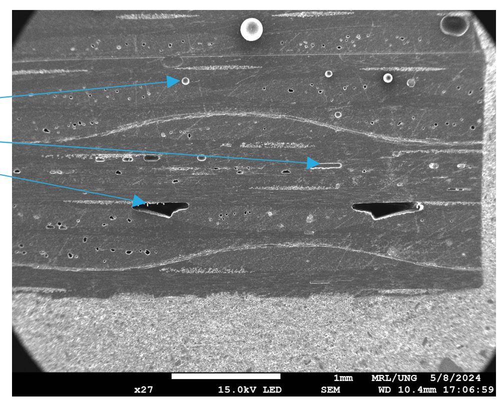


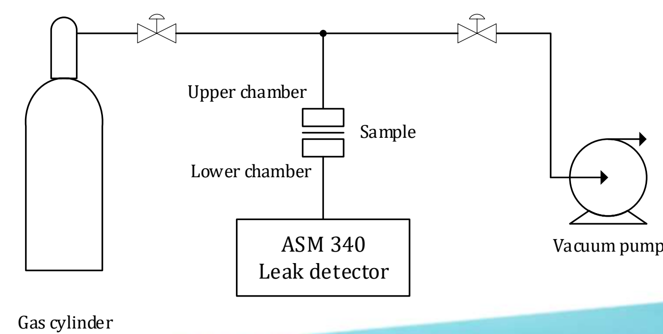


Leakage influenced by:

- Manufacturing defects
- Layup
- Thickness
- Loading

Relevant Conditions





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Understanding/Determining the permeation/leakage behaviour: What DON'T we know? What are we lacking?

- Lacking a way of measuring leakage at cryogenic temperatures
- Lack of consensus about which law, Darcy's or Fick's, best describes leakage in composites in cryogenic conditions
- We lack multiaxial, thermo-mechanical experimental data
- We don't have a multiaxial testing standard
- We lack LN_2 vs LH_2 extrapolation data/confidence
- We have very little real-time leakage data (i.e. while simultaneously exposed to temp/mech loading)
- We lack experimental data using LH_2
- We lack consensus, both from industry and the regulator, about acceptable leak rate

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Initial approach to MoC

- Permeability literature review
- Collected all published leak rate data
- Flanagan's findings (2017) promising

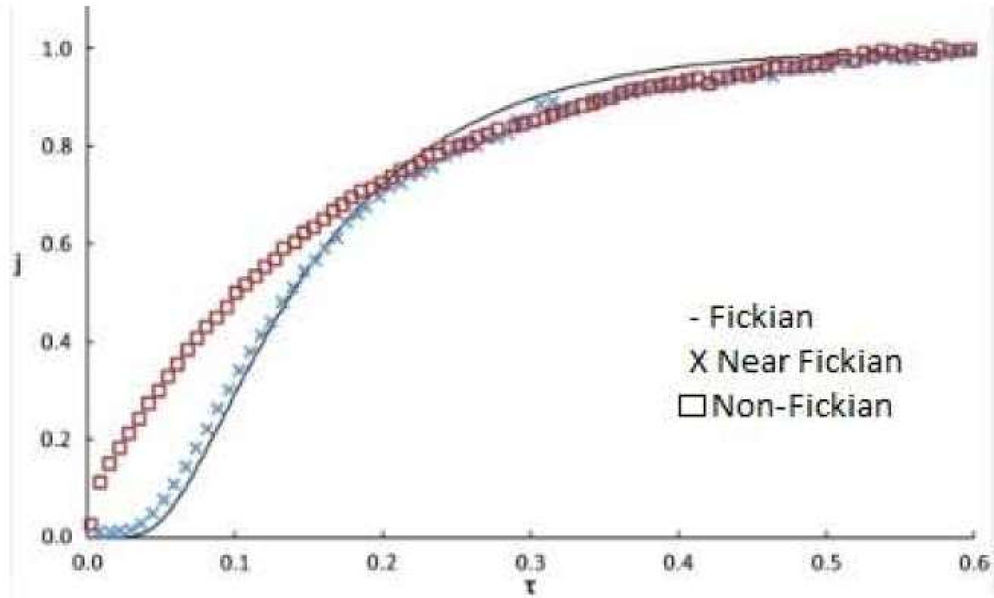
$$P = \frac{J_{ss} l}{A(p_u - p_l)}$$

$$\frac{J}{J_{ss}} = \frac{4}{\sqrt{\pi}} \sqrt{\frac{l^2}{4Dt}} \sum_{n=0}^{n=\infty} \exp\left\{\frac{-(2n+1)^2 L^2}{(4Dt)}\right\}$$

$$j = \frac{J}{J_{SS}} \qquad \tau = \frac{Dt}{l^2}$$

- Samples with different leak rates, thicknesses and test times can be compared to theoretical Fickian behaviour
- Fickian behaviour (time lag) indicative of undamaged sample, Non-Fickian (no time lag) of damaged sample.

Question at hand: What permeation-related requirements does a material, chosen by an aircraft designer/manufacturer for an LH2 storage solution, have to meet in order to be deemed suitable for the application and how should it go about demonstrating compliance with them?



M. Flanagan et al, 2017

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Initial approach to MoC

FEM analysis + Operating temperatures → Choose conditioning scenario and test

- Fickian materials show decrease in leak rate with decreased temperature, Non-Fickian show increase

1	Biaxial thermomechanical loading in relevant permeant	$S_{1\text{-}0}$	0 (reference)	Cycle from HT-CT-HT in relevant permeant, while simultaneously biaxially and cyclically loading the sample to $1.1\varepsilon_{max}$, where ε_{max} is the maximum level of microstrains expected in normal operation. HT is 15°C higher than expected normal operating temperature. Samples to hold at CT for minimum 5 minutes and at HT for minimum 15 minutes. Heating and cooling rates to be representative of the application. Frequency of cyclic loading to be 0.5 Hz.
		$S_{1\text{-}5}$	5	
		$S_{1\text{-}20}$	20	
		$S_{1\text{-}50}$	50	

5	Separate thermal and biaxial mechanical loading in relevant permeant	$S_{5\text{-}0}$	0 (reference)	Cycle from HT-CT-HT in relevant permeant. HT is 15°C higher than expected normal operating temperature. Samples to hold at CT for minimum 5 minutes and at HT for minimum 15 minutes. Heating and cooling rates to be representative of the application. Cyclic biaxial mechanical loading of the same thermally conditioned samples to be performed to $1.3\varepsilon_{max}$, where ε_{max} is the maximum level of microstrains expected in normal operation, and in relevant permeant. Frequency of cyclic loading to be 0.5 Hz.
		$S_{5\text{-}5}$	5	
		$S_{5\text{-}20}$	20	
		$S_{5\text{-}50}$	50	

8	Separate thermal and uniaxial mechanical loading at relevant cryogenic temperatures	$S_{8\text{-}0}$	0 (reference)	Cycle from HT-CT-HT at relevant cryo temps. HT is 15°C higher than expected normal operating temperature. Samples to hold at CT for minimum 5 minutes and at HT for minimum 15 minutes. Heating and cooling rates to be representative of the application. Cyclic uniaxial mechanical loading of the same thermally conditioned samples, in their weaker direction, strength-wise, is to be performed to $1.4\varepsilon_{max}$, if they're anisotropic, where ε_{max} is the maximum level of microstrains expected in normal operation. If they're quasi-isotropic, they shall be tested to $1.5\varepsilon_{max}$. Frequency of cyclic loading to be 0.5 Hz.
		$S_{8\text{-}5}$	5	
		$S_{8\text{-}20}$	20	
		$S_{8\text{-}50}$	50	

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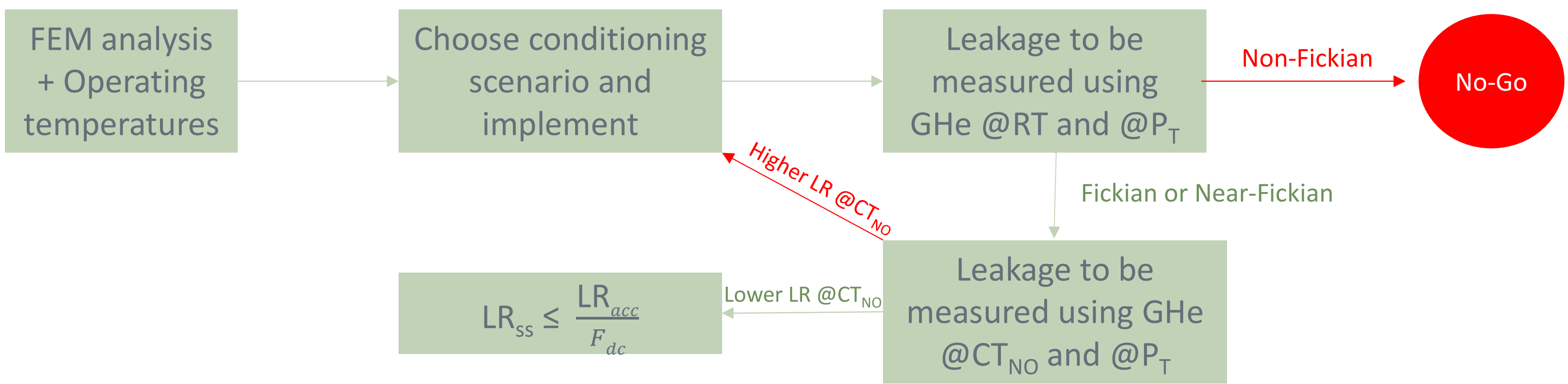
Initial approach to MoC



F_{dc} to be determined via safety assessment and has to reflect:

- H2 compatibility equip./mat. in tank vicinity
- Level of reliab./redund.
- Uncertainties
- …….

- LR_{acc} to be determined as per ANSI/AIAA G-095-2004 and reflect all design features implemented to reduce the chances of LFL being exceeded
- For vacuum insulated solutions permeability < 4.0 x 10^{-23} mol/m.s.Pa → D. Schultheiss, 2007
- Prove LR_{ss} doesn't have detrimental effect on insulation material in vicinity

Note: If measuring leakage @CT_{NO} is not possible or yields inaccurate results, it can be measured at a higher temperature, insomuch as it's at least 80K lower than RT.

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"Go-Around" approach to MoC

- Focus on MEANS of Compliance
- Be prescriptive regarding conditioning

FEM analysis + Operating temperatures

→ Cyclic thermo-conditioning + multiaxial thermo-mechanical conditioning of samples

→ (3x) LR_{ss} to be measured using GHe @RT and @CT, @P_T

→ LR_{ss} @CT < LR_{ss} @RT and Δ LR_{ss} < 10%

No → Cyclic thermo-conditioning + multiaxial thermo-mechanical conditioning of samples

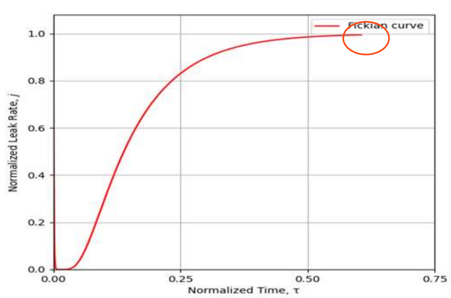
Yes → Compare LR_{ss} measured @CT to LR_{acc}

Thermo-conditioning

- HT-CT-HT, with HT being 15ºC > T_{max}
- # of HT-CT-HT cycles = 20 or 5% fill cycles in lifetime
- Hold CT for min. 5 minutes, HT for 15
- Heating/Cooling rates representative of application

Thermo-Mechanical conditioning

- Multi-axial mechanical loading in relevant cryogen
- Load level = Expected ε @ 1.3MAWP
- # of mech. cycles = 50
- Mech. Loading frequency representative of application



Note: Numbers here are merely initial estimations and are subject to change

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Conclusions

- Finalizing the MoC will be easier once the requirement is finalized.
- Sample conditioning has to incorporate multiaxial thermo-mechanical loading as most representative load case.
- Multiaxial testing standardization required (i.e. crucifix vs bulge vs…….)
- MoC sample conditioning to be made less prescriptive once more experimental data (i.e. LN_2 vs LH_2, permeability @ CT, etc.) and confidence is built up.
- LR_{acc} largely depends on storage solution integration method and the type of insulation incorporated.
- Only the LR_{ss} , that has levelled off after multiple rounds of conditioning, shall be compared to LR_{acc}.
- Comparing leak rates to theoretical Fickian data is potentially a good, non-destructive way of assessing damage level (i.e. leak path development) in conditioned samples.
- MoC is a work in progress. PVS looks forward to finalizing it with its industry partners and EASA.
- MoC will need to address additional items such as material H_2 compatibility (i.e sensitivity to embrittlement, change in flammability properties, loss in crystallinity, molecular weight reduction, etc.) and sections of the tank that are more susceptible to microcracking/leakage (i.e. component interfaces, flanges, bosses, reinforcements, etc.).

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"The H2ELIOS cryogenic tank concept for storing liquid hydrogen is patent protected under a patent owned by Aciturri."

Thank you for your attention!

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