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Parametric Study on Tank Integration for Hydrogen Civil Aviation Propulsion

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1- ABSTRACT

Hydrogen powered gas turbine propulsion will play a central role in the decarbonisation of civil aviation. A key challenge is the integration of large liquid hydrogen tanks into the aircraft, given the low density of liquid hydrogen. Hydrogen offers a quarter of the energy content, per unit volume and one third of the fuel weight, when compared to a conventional fuel. Optimising tank weight is seen as key to aircraft usefulness. A detailed evaluation of tanks for civil aviation is presented here, covering a very wide range of sizes and design solutions.

For passenger air transport, if the choice is made not to vent, dormancy time (the time the tank can be allowed to operate without vapour or important fuel extraction) becomes a key design parameter. This paper highlights the interdependence of Maximum Allowable Operating Pressure and the amount of insulation with heating and venting, considering the influence of dormancy time.

The resulting tank gravimetric efficiency is presented for cylindrical tanks with hemispheric ends (a very likely choice for tank design). Notwithstanding conservative analysis, tank gravimetric efficiencies of 65-70% can be achieved. This permits combined fuel and tank weights that are less than half of those of current aircraft. The issue that then becomes critical is the resulting large tank and aircraft volume.

2- NOMENCLATURE

Variables

E: Young's Modulus
h: Enthalpy
$\dot{m}$: Mass Flow
n: Number of Baffles
l: Length
P: Tank Pressure
$\dot{Q}$: Heat rate
R: Radious
SF: Safety Factor
t_d: Dormancy Time
u: Internal Energy
V: Tank Volume
x: Vapour Quality
w: Thickness
η: Efficiency
ρ: Density
σ: Stress
ν: Poisson's Ratio
Φ: Energy Derivative

Subscripts

b: Buckling
$grav$: Gravimetric
i: Inlet (for $\dot{m}$ and h) or Insulation (for w)
max: Maximum
l: Liquid Phase
o: Outlet
p: Pressure
v: Vapour Phase
w: Wall
ρ: Constant Density

Abbreviations

ERF	Effective Radiating Forcing
LH_2	Liquid Hydrogen
MLI	Multi-Layer Insulation
VC	Vacuum
SAF	Sustainable Aviation Fuel

3- INTRODUCTION

Hydrogen can be a sustainable fuel and a complete solution given the absence of carbon, aromatics, particle emissions and sulphur [1]; there is very high potential for low NOx [2] and contrails can be eliminated by careful rerouting [3] . Attention needs to be devoted to the emissions of large quantities of water vapour in the atmosphere.

Hydrogen aviation and aircraft concepts have been widely studied in a number of comprehensive studies [1,2,4–10]. A challenge that always arises is storing a low energy density fuel and maintain aircraft usefulness. This yields high volume designs although with low take-off weight.

Hydrogen can be stored in a variety of ways, mainly, as a gas; as a liquid; and as part of a chemical compound [11]. In all cases, the challenge arises from its low volumetric density. Compressed hydrogen at 700 bars have a density pf 42 kg/m^3, about half of liquid hydrogen. Liquid hydrogen has a density of 70.8 kg/m^3 with 120MJ/kg LHV, which results in 8.5 GJ/m^3. Kerosene, with 33.6 GJ/m^3 (0.785 kg/m^3 and 42.8 MJ/kg) has approximately four times more energy per unit volume. Current research on hydrides, adsorption or chemical storage could improve the volumetric density, at a great cost in terms of added weight. The automobile industry has opted for gaseous hydrogen at high pressures [12], after carefully examining liquid hydrogen [13] due to the complexity of producing, handling and storing liquid hydrogen for days or weeks inside a car. In aeronautics, liquid hydrogen has been the preferred option of studies to date, although research on how to diminish the high repulsive forces of hydrogen by means of porous carbon material [14], mycelium [15] or others [16], in order to increase the volumetric density is still ongoing. Whatever technology is chosen for aircraft applications, the challenge is the same, integrating very large tanks in the aircraft.

Several studies focus on tank architecture, material and manufacturing technologies [4,11,17–20], aiming to select the lightest solution. The figure of merit commonly accepted is the gravimetric efficiency, or weight of hydrogen per unit of fuel system weight, a similar concept to the weight fraction used in automobile tanks. One of the critical functions of a hydrogen tank is to keep it liquid at a temperature around 20K-30K for the whole mission. Heat leakages will try to increase the temperature while fuel withdrawals will reduce it due to the heat absorbed by a small fraction of the remaining liquid that vaporises and occupy the space that the withdrawal creates. These two phenomena fight against each other during the flight and the design of the tank must balance the overall effect. A large surface to volume ratio, would favour a higher heat leak, but it may be appropriate for short duration tanks with high rates of fuel mass flow. For long range flights, a higher maximum tank temperature (and pressure) can be designed at the cost of a thicker tank wall, or a higher insulation thickness may be placed, yielding to a heavier tank. Or it heat leakage be pursued though a reduction in surface to volume by increasing the tank diameter, reducing the curvature of the hoop stresses, and leading also to thicker walls. There is, however, a wide variety of estimation of tank gravimetric efficiency, ranging from 0.2 [7] to above 0.7 [4,18,21], and many intermediate values [22–24] with no evident explanation on the origin of the differences. The authors could not find a consistent and comprehensive evaluation covering the weight estimation from different sources to define a path for optimum design, considering implications at airport and airline level. A parametric study to understand the effect of tank size, diameter or length, design maximum operating pressure, wall material and tank architecture is performed. This is a central scientific contribution of this paper.

However, even with very heavy tanks, the overall weight of the tanks and fuel for a hydrogen system is lighter than a kerosene one. For example, 1 unit-weight of Kerosene is equivalent to 0.33 unit-weight of hydrogen on an energy basis. Hydrogen tanks can add an extra weight up to 0.66 unit-weight and still be lighter than the kerosene equivalent system. It has been assumed that integral kerosene tanks weight a negligible value compared to the kerosene weight they contain. The kerosene and hydrogen tank system will have equal weight for full tanks at a gravimetric efficiency of 0.33., For higher than this value, hydrogen aircraft will be lighter at take-off than conventional aircraft, but the volume will be much larger. For a gravimetric efficiency of 0.66, a full hydrogen tank weights half of a full kerosene tank with the same energy content. At landing, hydrogen tank adds a relatively small weight. In the very long term, designs capitalising on the careful balance of these two (larger volume lighter weight) conflicting characteristics plus the use of propulsion cycles that could be delivered with hydrogen but not with conventional fuels could yield more efficient aircraft designs.

Central to the design decisions that engender the tank weight are safety considerations, reliability, technology readiness level and venting [25]. Venting is the process of safely releasing hydrogen vapour from the tank once it has reached the maximum allowable pressure due to heat leakage from the atmosphere into the cryogenic tank. Venting design guidelines can vary from venting at most flight segments a controlled amount to no venting at all throughout the flight and for a long time if parked. Venting is common process in all stationary application. However, safety rules and airport specific constrains makes venting in aircraft applications more undesirable. In the long term, safety regulations may find the way to allow venting at or away from the gate, but it is likely that these approvals require time.

Therefore, a novel optimisation process based on the dormancy time (time for the tank pressure to reach venting pressure) as a main design parameter is suggested.. Different tank architectures and insulation technologies are considered to explain the differences in tank gravimetric efficiencies found in previous research. Venting and its implications are analysed. Subsequently, tanks for shorter and longer ranges of different sizes are studied, and limitations of hydrogen tank integration in aircraft are explored.

It is widely accepted that hydrogen have a different hazard behaviour than kerosene, being riskier in some situations and safer in others. For example, its low ignition energy and high volatility makes it more dangerous in confined spaces, while the lower flame emissivity or the higher lower-flammability limit makes it less damaging in open air. Main hazards are broadly represented by hydrogen related injuries, pressure hazard, and combustion hazard [26].

Hydrogen related injuries refer to burns or frostbites under contact with cold fluid or burning fluid. A liquid hydrogen spill will fall down to the floor and air will condense on its surface with an oxygen concentration of around 50%. The rapid evaporation of hydrogen will originate flammable clouds that will travel mostly vertically due to low density of gaseous hydrogen. In order to prevent injuries, hydrogen tanks should be placed separately from the passenger cabin and confined in case of accidental spill.

Pressure hazard relates to the overpressure that could arise under vaporisation of liquid hydrogen in the tank or any closed section of the fuel system. Overpressure may lead to leak of the tank or the component, which represent a combustion hazard. In extreme cases, it may lead to burst of the component, with a massive release of liquid hydrogen. In all designs, the thermal insulation diminish he heat influx, but there is always a boil-off rate inside the tank and system parts that increases the temperature and pressure of the liquid-vapour mixture. After certain period, the pressure would reach the maximum operating pressure, and venting becomes necessary. Since venting at the airport is not recommended at initial stages of hydrogen aviation, then it follows that vacuum insulated tanks, with a much longer dormancy time, will be preferred to first airliners to entry in to service. Vacuum insulated tanks loose most of the thermal insulation if vacuum is lost. Redundancy of the vacuum pumps and system will be required to mitigate this risk.

Combustion – deflagration or detonation – in the aircraft can occur when there are leakages of hydrogen or air through the fuel system parts. This may occur through joints and valves, by a tank or piping wall failure, or by the filling process after an unsatisfactory purging. Deflagration is a minor problem if compared to detonation. Most incidents where ignition of hydrogen in open air has occurred have had limited damages, since hydrogen burns in a vertical buoyant flame. Only under a high ignition energy source or when in total or partial confinement, it has been reported that deflagration turns into detonation. [27,28]

Undesired combustion at the airport may be due to leakages of the fuel system or the refuelling system into the atmosphere or by spontaneous ignition of the venting system, when in operation. Vacuum insulated tanks have a much lower conductivity, and this leads to much longer dormancy times. From this point of view, foam insulated tanks show another disadvantage, particularly, if tanks are designed with a short dormancy time, so that venting becomes a usual procedure. Vented gas can eventually ignite and burn safely at the venting nozzle in stationary applications. Venting stacks up to 0.25kg/s are disposed at least 15 feet above a roof peak. For higher venting mass flows, flare stacks are recommended, but these need to be distanced 60 m from any occupied building [28]. Therefore, venting in an airport environment will need to be avoided in first phases of operations.

Experience from other applications in relation to handling, purging procedures or other health and safety rules can be transfer and constitute a base for safe operation. Still there will be additional aspects that are specific to passenger transport. For example, the cohabitation of liquid hydrogen tanks and passengers in the small space of the fuselage may impose additional safety features; the requirement to have the lightest possible tanks may give rise to new tank architectures that have to demonstrate reliability and durability; a frequency of refilling of several times a day which may imply a higher likelihood of tank and system contamination, to name a few.

Vacuum insulated tanks and pipes offer a preferred short time solution for two reasons: enhanced safe through a double wall, usually with vacuum monitoring and a vast and long experience in ground applications that foam insulated tanks lack. In all cases, fuel system pressure should never be sub-atmospheric, since leakage of air into the tank could lead to a detonation of the mixture. Particular attention must be drawn to hydrogen detection in all confined spaces including the vacuum jacket. An inert gas atmosphere surrounding the tank can provide additional safety feature.

In a longer term, foam insulated tanks, when lighter, could be used, but there need to be enough experience built before then, that must be gained in other applications. Foam insulated tanks present several disadvantages with regards to the combustion hazard: if inner wall is not designed to sustain negative pressure, purging will need to be done by positive pressure purge procedure, typically with Helium. It requires more purging cycles than vacuum purging to reach the same residual concentration of oxygen and therefore will need higher purging gas flows to keep refuelling time acceptable; foam or aerogel must be enclosed and filled with and inert gas to avoid air condensation over the cold wall.

4- INTEGRATION OF HYDROGEN TANKS INTO THE AIRCRAFT

Figure 1 shows a variety of proposed concepts. In all of them, evident is the challenge of integrating very large tanks within the airframe, leading to either an extension of the fuselage or a trade-off between passengers and fuel capacity, or both.

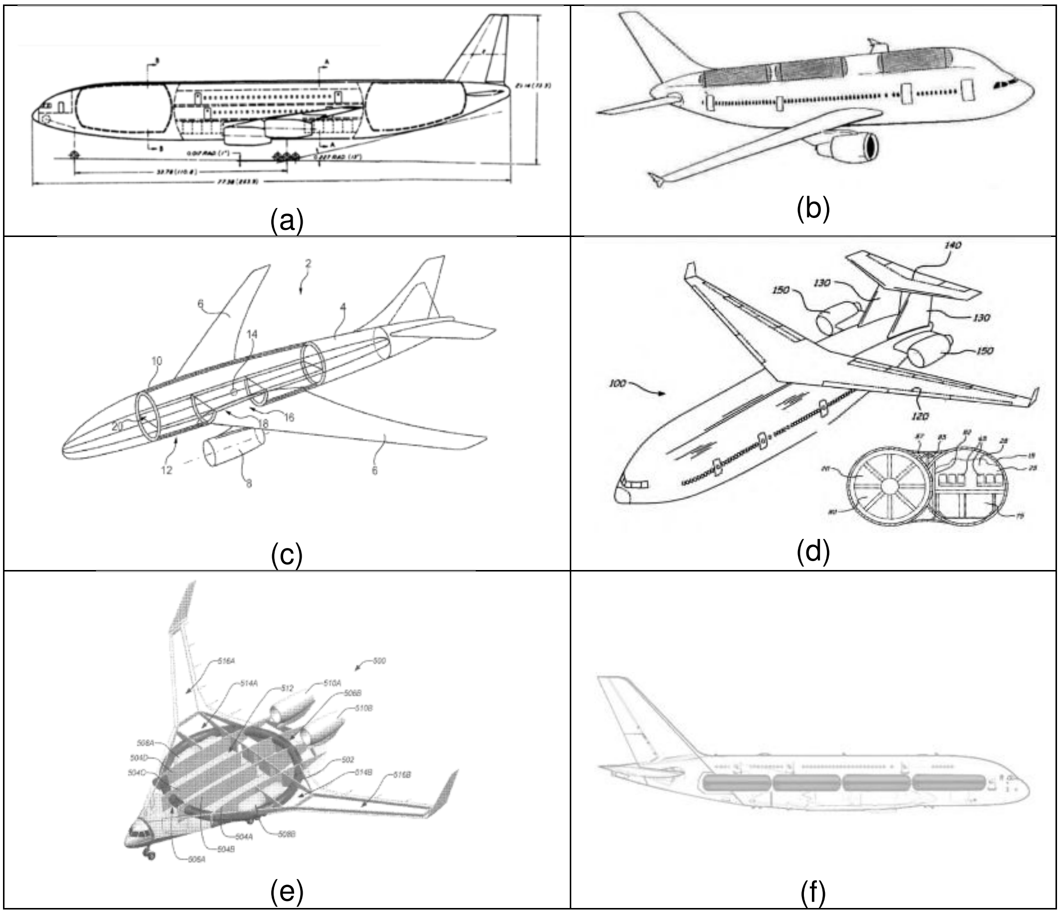


Fig.1 Main concepts of Hydrogen tanks in aircraft applications. (a) Fwd and Aft tank proposed by Brewer [4]*, also adopted Airbus Zero-e concepts* [29] *; (b) Upper tank proposed*

by Cryoplane [30]*, also adopted by ENHABLEH2* [2]*; (c) Other Airbus concept* [31]*; (d) Other Boeing concept* [32]*; (e) Other Boeing concept* [33]*; (f) Two deck Aircraft* [34]*.*

It is widely acknowledged that unconventional designs will ultimately deliver many of the potential benefits of hydrogen [21,35]. BWBs offer a more favourable configuration than the conventional tube and wing design. During the Cryoplane studies several non-conventional configurations were analysed at Cranfield University. A team of researchers and experts from Delft University, Sweden Defence Research Agency, DASA, Dornier and Cranfield University evaluated more than 20 unconventional concepts and concluded that Twin Tail-Boom and Tail-Tank concepts shown in Fig.2 were most appropriate configurations [36].

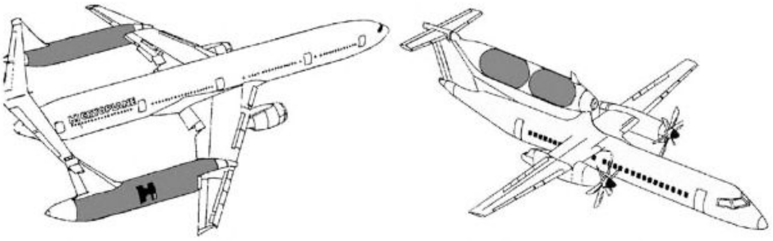


Fig.2 Unconventional concepts explored during the Cryoplane studies.

Recently, in ENHABLEH2, an EU funded consortium led by Cranfield University, 30 conventional and non-conventional configurations have been carefully assessed against 35 criteria for short and long range applications [37] concluding that configurations similar to Fig.1(b) and (e) are the most appropriate for long range aircraft.

The challenge of volume has led to designs with much lower stored energy than comparable conventional fuel aircraft. With a much lower energy onboard and an increased drag, the search for the lightest tanks has been one way to increase the range to acceptable values for airline operation.

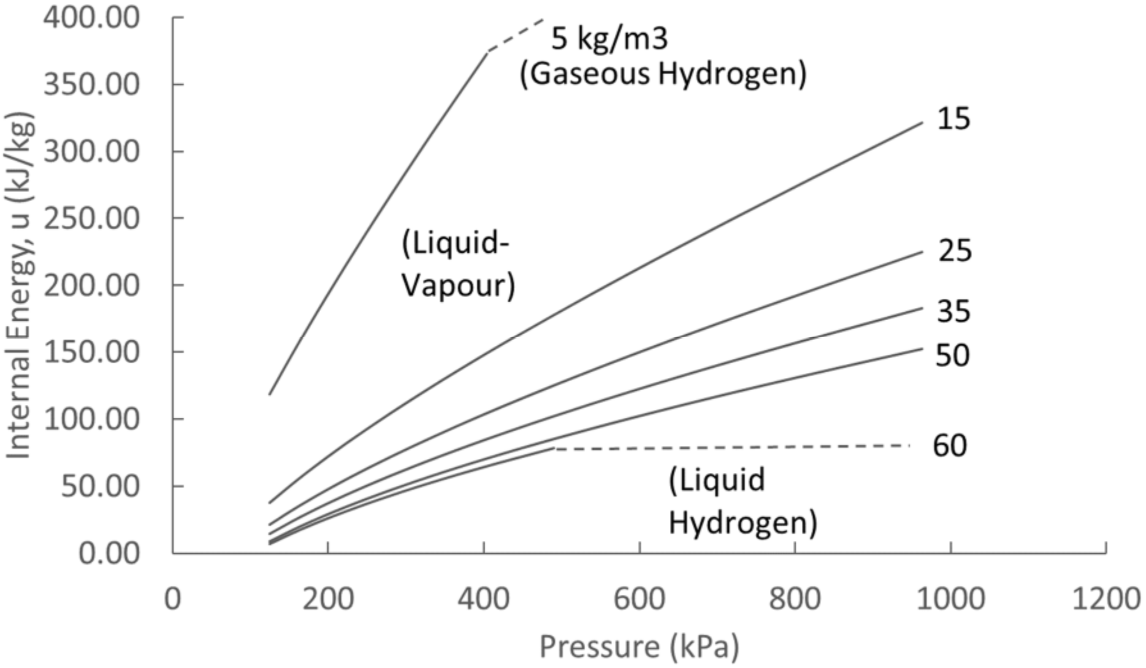
5- DESIGN GUIDELINES AND VENTING IMPLICATIONS

A well stablished method for tank design was introduced by [4,38] an is presented in [11]. The focus is to consider the hydrogen vented during the mission duration as a source of dead weight and minimise the sum of weight of tanks plus vented hydrogen. Usually, the maximum operating pressure of the tanks is chosen arbitrarily, commonly between 200 and 500 kPa. The process leads to an optimum insulation thickness, since for a low insulation thickness, tank weight is low and boil-off gas is high and for a high insulation thickness, the contrary applies. Somewhere in between there is an optimum that minimises the overall dead weight. Such a method is appropriate when the power requirement is low. Not considering the fuel flow to the engines leads to an overestimation of boil-off, because hydrogen withdrawals reduce the pressure of the tank. Pressure variation in the tank is described in Eq.1 [39] :

$$\frac{dP}{dt} = \frac{\Phi}{V}\left\{\dot{Q} + \mathrm{W} + \dot{m}_i\left[h_i - h - \rho\left(\frac{\partial h}{\partial \rho}\right)_P\right] - \dot{m}_o\left[h_o - h - \rho\left(\frac{\partial h}{\partial \rho}\right)_P\right] + \rho^2\left(\frac{\partial h}{\partial \rho}\right)_P\frac{\mathrm{dV}}{\mathrm{dt}}\right\} \quad (1)$$

where the energy derivative, Φ, is shown in Eq.2 and Fig.3 from hydrogen vapour-liquid equilibrium data from [40].

$$\Phi = \frac{1}{\rho\left(\frac{\partial u}{\partial P}\right)_\rho} \quad (2)$$



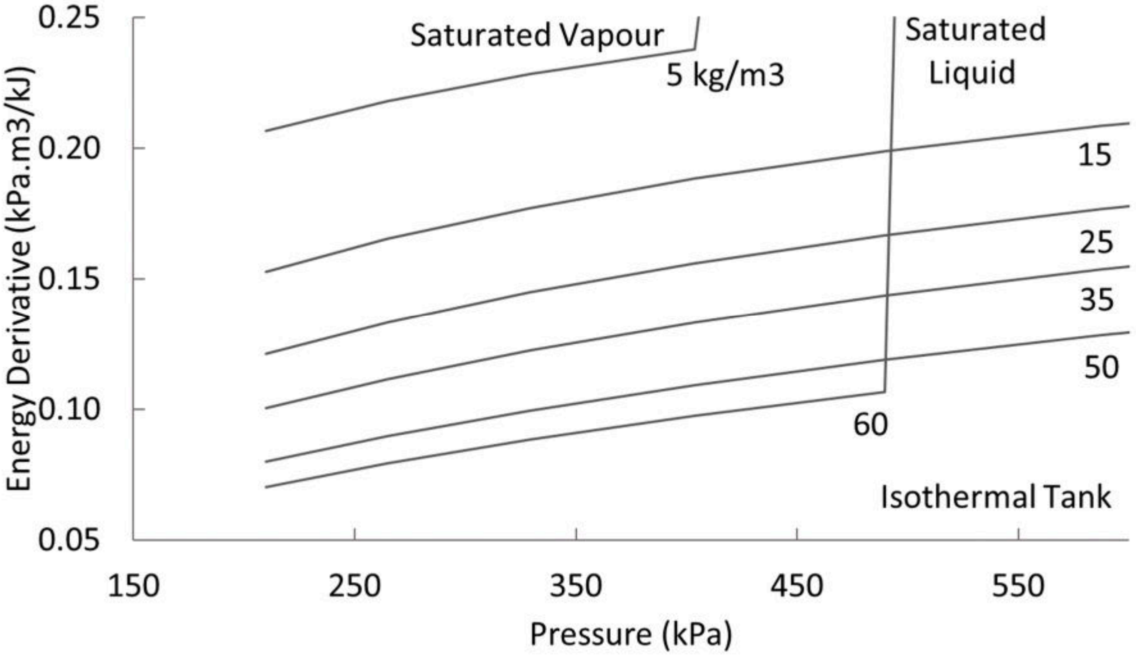


Fig.3 Internal Energy (top) and Energy Derivative (down) of Hydrogen at Liquid-Vapour Equilibrium

Eq.1 can been rewritten, for a fixed volume tank with no inlet flow, as Eq.3:

$$\frac{dP}{dt}=\frac{\Phi}{V}\left\{\dot{Q}+\dot{m}_o\left[h-(h_v-h_l)\left(x+\frac{\rho_v}{\rho_l-\rho_v}\right)\right]-\dot{m}_o h_o\right\}=\frac{\Phi}{V}\left\{\dot{Q}-\dot{m}_o\left[h_o-\left(\frac{h_l\rho_l-h_v\rho_v}{\rho_l-\rho_v}\right)\right]\right\} \quad (3)$$

For a stable steady-state condition to be reached (dP/dt=0) heat input must be balance by an enthalpy removal through an outlet flow – either fuel flow to the engine or venting some vapour flow out of the tank, as determined by Eq.3. Otherwise, pressure would increase or decrease indefinitely. The transient pressure variation rate is also influenced by the energy derivative – with very low values as long as the vapour-liquid equilibrium exists. Pressure variation for a given heat input is damped by the liquid-vapour phase change equilibrium. Energy derivative grows quickly (nearly vertical) as soon as the vapour mixture either fully evaporates (for densities lower than critical point density) or fully condenses (for densities higher than the critical point density), as can be observed in Fig.3.

For a preliminary thermal sizing, Q can be obtained from the steady-state isothermal model of the tank, considering convection and radiation from the surroundings and conduction through the insulation and the wall as described in [11]. For large tanks, consideration of conduction only, with tank external wall temperature equal to that of the surroundings leads to an error in the order of 1%. Further, conduction through the insulation can be approximated for, $w_i < 0.1R$ to:

$$\dot{Q} = kS\frac{dT}{dw_i} \approx kS\frac{\Delta T}{w_i} \quad (4)$$

Substituting Eq.4 into Eq.3 leads to an expression in which pressure variation depends on surface to volume ratio of the tank, insulation properties and tank duration time, t (taken as an approximation to flying time, shown in Eq.5.

$$\frac{dP}{dt} = \Phi\left\{k\frac{S}{V}\frac{\Delta T}{w_i} - \frac{\rho}{t}\left[h_o - \left(\frac{h_l\rho_l - h_v\rho_v}{\rho_l - \rho_v}\right)\right]\right\} \quad (5)$$

Surface to volume ratio is mostly dependant for any cylindrical tank with hemispherical ends on the radius of the tank, *R*. Surface to volume ratio has a minimum value of *2/R* for a very long cylinder and *3/R* for a sphere. For any given cylindrical tank with hemispherical ends, surface to volume ratio has a value between those.

Fig.4 shows Eq.5 for various cases. ‘5hr tank’ shadow area represents any cylindrical tank with hemispheric ends with a liquid withdrawal rate that makes the tank last for 5 hrs, and for a foam insulated thickness of 50 mm and various tank diameters (along horizontal axis). Thermal conductivity of foam has been taken 0.015 W/m.K. ‘2 hr tank’ shadow area shows the equivalent area for a 2 hr lasting tank. The full line at the bottom (Spherical or Cylindrical Vacuum Insulated 2 hr tanks) shows Eq.5 for a MLI vacuum insulated tank with a thermal conductivity of 0.00015 W/m.K. It should be noted that such a low thermal conductivity makes the first term of Eq.5 negligible against the second term.

By assimilating the duration of the tank as the flying time and the liquid withdrawal rate as the cruising hydrogen fuel flow, Fig.4 shows that smaller diameter tanks tend to have a pressure increase during cruise due to a high surface to volume ratio associated with a low diameter, and regardless of the length of the tank. Large diameter tanks and vacuum insulated tanks show pressure reduction during cruise and will need some sort of heat addition in order to limit the minimum pressure in the tank. For a 2 hrs medium haul flights, tanks can be in the 1.5-2 m diameter range for neutral pressure variation and between 3.5m and 5m for a 5 hrs long haul flight. Very small diameter tanks (< 1m) to optimise space use inside wings or in narrow spaces for any range application will require venting at cruise or vacuum insulation with heat addition. For tanks inscribed in current fuselage sizes, at any range, pressure can be design to be more or less constant throughout the flight or slightly reducing. All lines in Fig.4 will shift to the left if a thicker insulation is considered.

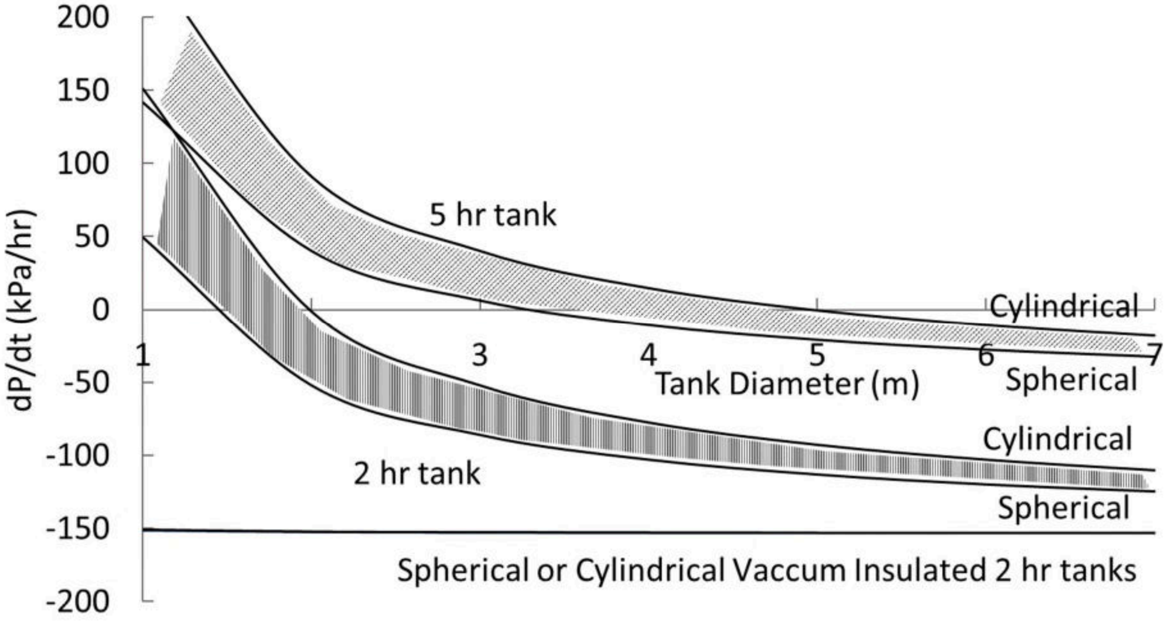


Fig. 4. Effect of tank diameter and geometry on tank pressure variation during liquid withdrawals

When there is fuel withdrawal, the combined effect will be of a pressure decrease whenever the heat leakage is lower than the "corrected" enthalpy of outlet flow. Eq.6 is derived from Eq.3 and Eq.4.

$$\dot{Q} = kS\frac{\Delta T}{w_i} < \dot{m}_o\left[h_o - \left(\frac{h_l\rho_l - h_v\rho_v}{\rho_l - \rho_v}\right)\right] \quad (6)$$

For civil passenger transports, at standard cruise fuel flow, tank pressure would typically fall because the fuel extraction will be much larger than the heat leakage, and heat must be added carefully to avoid decompression below ambient value. At airports, either on a long take-off delay or on a stop-over venting may become eventually necessary. The dormancy time, or time that the tank takes to increase the pressure from re-fill (P_1) to venting (P_2) can be derived from Eq.3 since energy derivative at constant density (closed tank with no outlet flow) is linearly dependant to pressure (see Fig.3). Eq.7 shows the result of the integration after substitution of Eq.4 and the implicit design trade-off between tank wall thickness and insulation thickness since either Q or P_2 can increase the dormancy time.

$$t_d = \frac{V}{\dot{Q}}\int_{P_1}^{P_2}\frac{dP}{\Phi} \cong \frac{V}{S}\frac{w_i}{k\Delta T(d\,\Phi/d\,P)_\rho}ln\left(\frac{\Phi(\mathrm{P}_2)}{\Phi(\mathrm{P}_1)}\right) \quad (7)$$

It should be noted that dormancy time is dependent on the energy derivative “ratio” between initial and final pressure. Such ratio is about double for a full tank than for an empty tank, therefore, it should be expected a shorter time to venting after landing with a nearly empty tank that on a take-off delay.

Once maximum pressure is reached, hydrogen is then removed from the tank for pressure regulation (usually vapour, with a much higher enthalpy). In this case, necessary vented vapour to keep pressure constant is calculated in Eq.8, that also shows a simpler approximated expression, for pressures well below the critical pressure $\rho_l \gg \rho_v$.

$$Q = m_o \left[h_v - \left(\frac{h_l \rho_l - h_v \rho_v}{\rho_l - \rho_v} \right) \right] \cong m_o [h_v - h_l] \quad (8)$$

For a tank with no pressure variation during cruise, it can be deducted from Eq.6, Eq.7, and values of energy derivative in the order of 300 to 500 kPa from Fig.5 that the dormancy time is around 0.6 of the cruising time, taking the cruising time as the duration of the tank at cruise fuel flow. For short and medium haul flights this value would be too low to avoid venting at the airport under a minimum delay. For long haul, it would still be too low for an overnight stop, increasing the insulation thickness requirement over that required to avoid pressure increase during cruise. Therefore, it should be expected that for a non-venting tank at airport, pressure will reduce during cruise.

Figure 5 shows the pressure variation over the different flight segments for a generic case in which pressure reduces during cruise. The starting point in the figure (Refilling) represents the equilibrium of hydrogen mixture inside the tanks after filling. Pressure must be above atmospheric throughout, to avoid accidental air ingestion into the tanks. Since liquid hydrogen density increases with reducing temperature, it is desirable to fill the tank at the lowest possible temperature/pressure. As soon as the tank is closed, the density of the mixture will be fixed, and any variation in conditions will be along the horizontal line marked as “Take-Off Delay”. A small amount of vapour is needed – tank ullage – since any heat leakage before departure will increase the liquid volume fraction. Overfilling of the tank may lead to overpressure if all ullage is taken by the liquid phase expansion. A 5% ullage volume fraction has been considered along the work, offering an allowance for 2K or 150 kPa increase before departure. On departure, pressure starts dropping because of the fuel extraction to the engines, until it reaches a specified lower value above atmospheric. Then heat addition or any other process of heating up the mixture is necessary to prevent a reduction bellow this lower value. Possibly during descent, and certainly after landing when engines are turned off, pressure will start increasing again. Depending on tank pressure at landing and fill level, the tank will eventually reach to venting pressure.

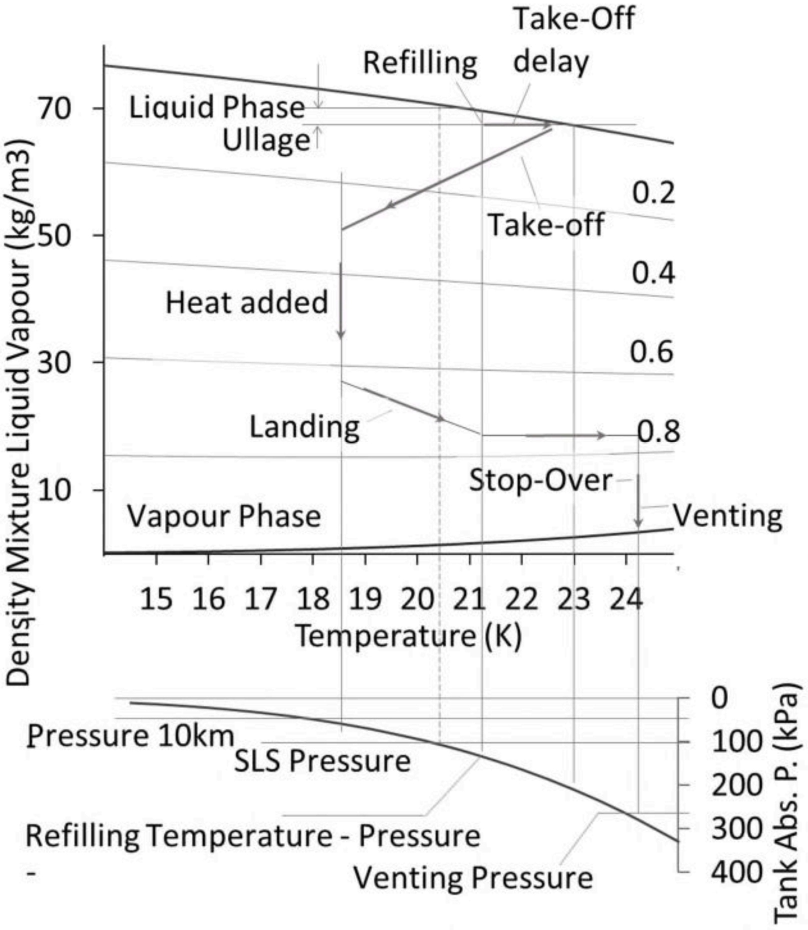


Fig.5. Tank pressure variation over the flight

“Eq.1 provides accurate results for a static, isothermal tank – a tank with homogeneous temperature in all vapour and liquid contained. If the fluid inside the tank is not stirred, a temperature gradient will form due to convection of liquid and vapour in contact with the tank wall and pressure rise will be faster than a homogeneous temperature tank. References [41–43] provide some experimental results that validate this statement.. This is particularly relevant in a low heat efflux long storage tank. The higher the heat efflux, the higher the difference with the homogeneous assumption. Stirring carefully the fluid is an effective way of reducing pressure before venting is necessary at the cost of introducing additional energy to the tank. Mixing power is relatively low compared to heat efflux [39], so for the low dormancy times required for civil aviation it can be assumed that dormancy time with mixing is approximately that of the homogeneous tank.

6- TANK PARAMETRIC STUDY

In this parametric study, tanks are assumed to be cylindrical, with hemispherical ends.. Figure 6 represents a generic tank with three layers: an inner wall (w) sustaining the hydrogen pressure, and intermediate insulation wall (i) reducing the heat leakage into the tank and an outer wall (b) sustaining the negative pressures (buckling) of the vacuum insulation or providing protection of foam insulation. It is assumed that integration of the tanks is possible any location since tanks of all sizes and aspect ratios will be analysed. For any given tank volume, tank shape can vary from a very low radius/long cylindrical tank to a maximum radius spherical tank.

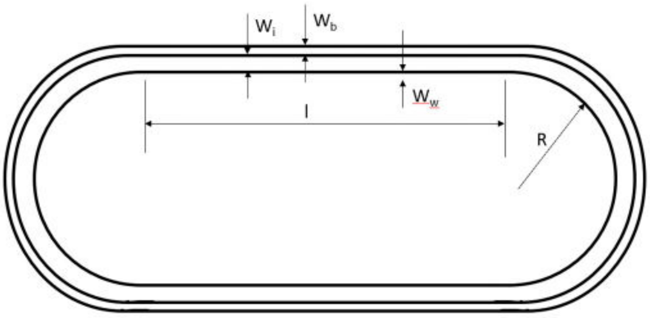


Fig. 6. Tank Dimensions

Tank insulation may be provided by a layer of low conductivity material or by a vacuum jacket. Thermal radiation shields made of low emissivity material can be added to minimise radiation heat transfer. Low conductivity materials, commonly used, are foams and aerogels. Aerogels can improve their thermal conductivity further if operating in a vacuum. Vacuum based insulation has the disadvantage that an accidental loss of vacuum increases the thermal conductivity by several orders of magnitude. Additionally, the jacket external wall must sustain the external negative pressure. Design against buckling of the external wall usually requires a high thickness that ends up representing a high proportion of the weight of the whole tank structure. Wall material can be made of metallic material or composites. In case composites are used, hydrogen diffusion through the wall or air permeation into the vacuum should be avoided or an additional liner should be placed, which will reduce the benefits of a light composite wall. An overview of insulation materials and properties is given in [17].

To compare the different tank architectures and conduct a parametric study and optimisation, three representative technologies will be considered:

1 - polyurethane foam insulation,
2 - MLI vacuum insulation
3 - Stiffened-panel MLI vacuum insulation.

Polyurethane foam has been selected as representative of foams and low density aerogels with a range of thermal conductivities from 0.03 to 0.003 W/m.K and densities between 20 and 60 kg/m^3. MLI insulation technology covers a range of different designs of vacuum multilayer insulated tanks from 0.0003 to 0.00003 W/m.K and densities between 10 and 100 kg/m^3 without considering the outer tank. The density of the MLI insulation is not relevant due to the very low thickness required, being the outer wall the driver of the weight of the tank. Stiffened Panels MLI insulated tank have an outer wall either metallic or composite, but with a bi-grid structure that make the outer wall in the order of three times lighter than a flat panel wall [22]. Table 1 summarises the insulation material properties.

	Thermal Conductivity (W/m.K) (Range Covered)	Density (kg/m^3) (Range Covered)	Construction Material
Polyurethane Foam Insulated	0.015 (0.003 - 0.03)	40 (20-60)	Inner tank: Al Outer Tank: N/A
MLI Vacuum Insulated	$1.5.10^{-4}$ (3.10^{-5}- 3.10^{-4})	40 (10-100)	Inner Tank: Al Outer Tank: Al
Stiffened Panels MLI Vacuum Insulated			Inner Tank: Al Outer Tank: Al or Composite

Table 1. Insulation and tank materials properties considered.

A generic Aluminium allow with a yield strength of 410 MPa and a density of 2,800 kg/m^3 has been used. Preliminary mechanical sizing of the tank is calculated from the maximum operating pressure. Using Von-Misses criteria for radial and axial load of a thin-walled tank yields to Eq.9 for a cylinder and Eq.10 for a sphere.

$$P_{max}SF_P = \frac{w_w \sigma_{max}}{0.86\,R} \quad (9)$$

$$P_{max}SF_P = \frac{w_w \sigma_{max}}{0.5\,R} \quad (10)$$

A safety factor of 2.2 has been used to calculate the tank wall weight. Hemispheric ends are assumed to have the same thickness as the cylindrical section. For foam insulated tanks, an external protective wall of 0.8 mm has been added. This wall provides for mechanical and air contamination protection the foam, preventing air condensation, loss of insulation properties over time or fire hazard under leakage failure.

For vacuum insulated tanks, the outer wall thickness has been dimensioned to prevent curved panel buckling. For a cylindrical tank with non-grid-stiffened wall subjected to uniform external pressure, the maximum allowable pressure, well corelated with experiments is given by Eq.10 [44].

$$P_{atm}SF_B = \frac{E\frac{w_b}{R}}{1+\frac{1}{2}\left(\frac{\pi R}{nl}\right)^2}\left\{\frac{1}{n^2\left[1+\left(\frac{nl}{\pi R}\right)^2\right]^2}+\frac{n^2 {w_b}^2}{12R^2(1-\nu^2)}\left[1+\left(\frac{nl}{\pi R}\right)^2\right]^2\right\} \quad (10)$$

For a better understanding of tank wall dependency on other design parameters as well as for parametric studies, previous formula can be very well approximated by Eq.11 [45].

$$P_{atm}SF_B = 0.807\frac{Ew_b{}^2}{lR}\sqrt[4]{\left(\frac{1}{1-\nu^2}\right)^3\frac{w_b{}^2}{R^2}} \quad (11)$$

For spherical containers, experimental Eq.12 is used [45], which is equivalent to reduction of a factor of 3 to the theoretical value, due to a high sensitivity to manufacturing imperfections [44]. A comparison of results from Eq12 and a finite element analysis of a 2.5 m diameter tank external wall using experimental corelations as performed in [22] shows an error of 12%, Eq.12 being more conservative.

$$P_{atm}SF_B = \frac{2Ew_b{}^2}{R^2\sqrt{3(1-\nu^2)}}\cdot\frac{1}{3} \approx \frac{0.365Ew_b{}^2}{R^2} \quad (12)$$

Equations 4, 7, 9-12 can be used to calculate the weight of the walls and the insulation for different dormancy time requirements and for any insulation technology.

Figures 7(a) and (b) show graphically the trade-off between tank wall thickness and insulation thickness implicit in Eq.7 for a ϕ4m,100m^3 tank and for the technologies considered and described in table 1. Such tank can be representative of a short-range airliner. The tank would have a net capacity (with 5% ullage) of 6128 kg of hydrogen at 329 kPa, with an energy content equivalent to around 20 tons or 25 m^3 of kerosene. The fuselage dimensions for a typical short to medium range airliner are approximately 4 m in diameter and a length of 40 m, the tank being inscribed in the fuselage with a length of 9.3m. Figure 9(a) shows the tank weight and 9(b) shows the gravimetric efficiency of the tank. For a given venting pressure, Eq.9 determines the tank wall thickness, that grows linearly with the maximum operating pressure (line "Internal Tank Weight" in Fig.7(a). Eq.4 and 7 are used to calculate the required insulation thickness for a dormancy time of 24 hrs (empty tank), that reduces with increasing maximum operating pressure (line "Insulation Weight - Foam Insulation"). Total tank weight is the sum the internal and external wall, the insulation, and the accessories (line "Total Weight – Foam Insulation"). If dormancy time requirement is increased to 36 hrs the insulation weight line moves up in the graph to higher values (line "Insulation Weight – Higher Foam Insulation"), and the total weight curve shifts accordingly with its minimum at a higher maximum operating pressure (line "Total Weight – Higher Foam Insulation". This same trade off, is used later, not only for maximum operating pressure, but for tank diameter and volume. Consideration of the variation of wall and insulation thickness separately, and the shift in the curves is key to understanding the optimisation process. For vacuum insulated tanks, Eq.11 and 12 are used to calculate the external wall thickness, which is not dependant on internal pressure (line "External Wall Weight – MLI VC Insulation"). Vacuum insulated tanks offer more dormancy time than usually required at a minimum insulation thickness, so insulation weight is a horizontal line (line "MLI Insulation Weight"). Total weight for MLI VC insulated tanks is, therefore, a growing line parallel to the internal wall weight. (line "Total Weight – MLI VC Insulation").

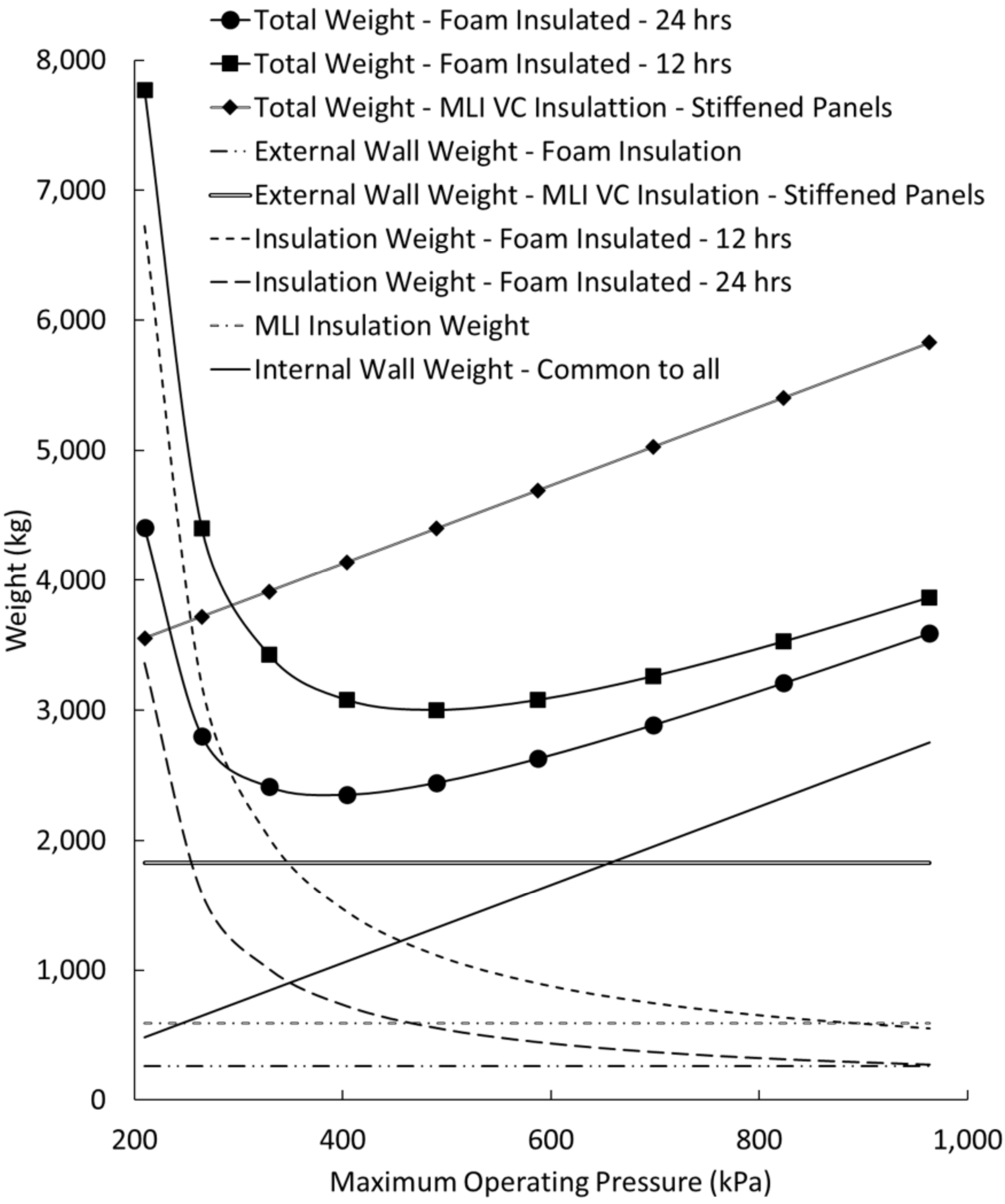


Figure 7(a). Tank Weight Trade-off for different architectures and technologies for a 100m^3 cylindrical tank with hemispheric ends.

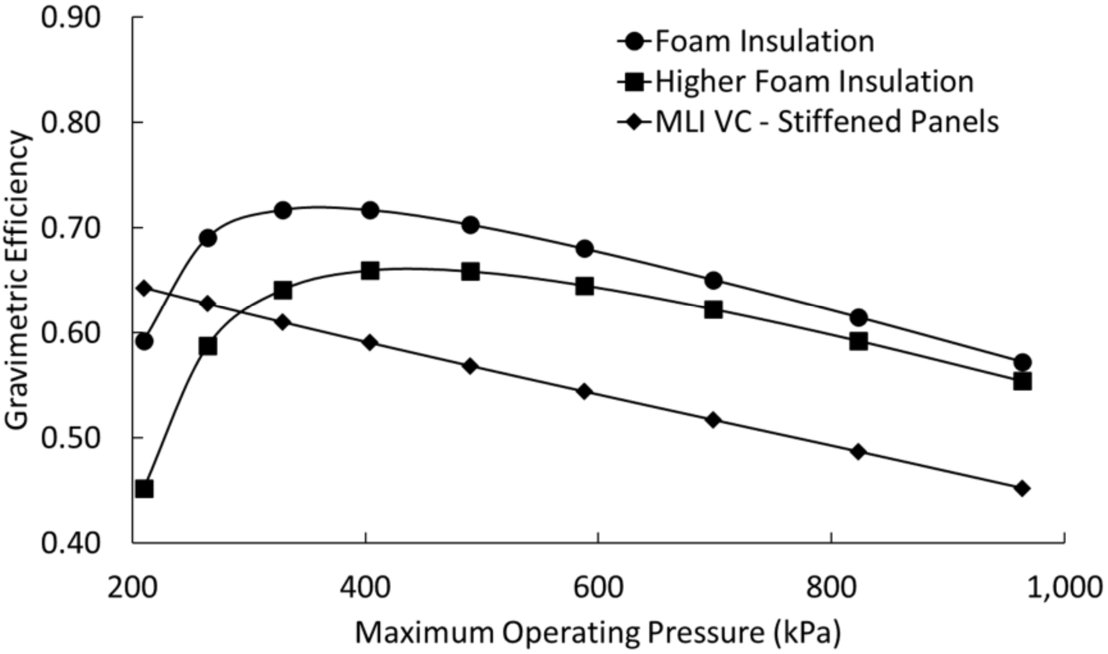


Fig.7(b) Tank Gravimetric Efficiency for different architectures and technologies.

Optimum radius

For a given volume, tank shape can vary between a long cylinder of small radius and hemispherical ends and a sphere. The surface of this shape will decrease asymptotically to that of the sphere with increasing radius. For a required dormancy time, Eqs.9 and 7 show that with increasing radius (decreasing surface to volume ratio), internal wall thickness will increase, and insulation thickness will decrease. For foam insulated tanks, it is expected therefore that there is an optimum radius in which tank weight is minimum. For vacuum insulated tanks, the external wall is subject to buckling and Eq.11 can be used to deduct that thickness decreases with increasing radius. External wall weight is one order of magnitude higher than the internal wall weight, so that the sum of both walls weight decreases, leaving no optimum radius other than the sphere. Vacuum insulation is so efficient that lower than practical values are calculated for minimum insulation thickness, so it has been assumed a minimum MLI vacuum thickness safe value of 127 mm (5 in.) without any relevant incidence in weight. Figure 8 shows the gravimetric efficiency of the tank as a function of the radius (radius) of the tank. Gravimetric efficiency has been calculated as the mass of stored hydrogen at the maximum allowable pressure or venting pressure divided by the mass of the tank plus the stored hydrogen. An additional 300 kg of accessories to make an allowance for buffers, instrumentation and fuel feed manifolds has been added. Other design parameters are as follow: Maximum allowable pressure: 329 kPa (equivalent to 25K vapour liquid equilibrium), Pressure at fill: 163.5 kPa (22K), Safety Factor Mechanical Design: 2.2, Minimum thickness of Al wall: 0.8 mm.

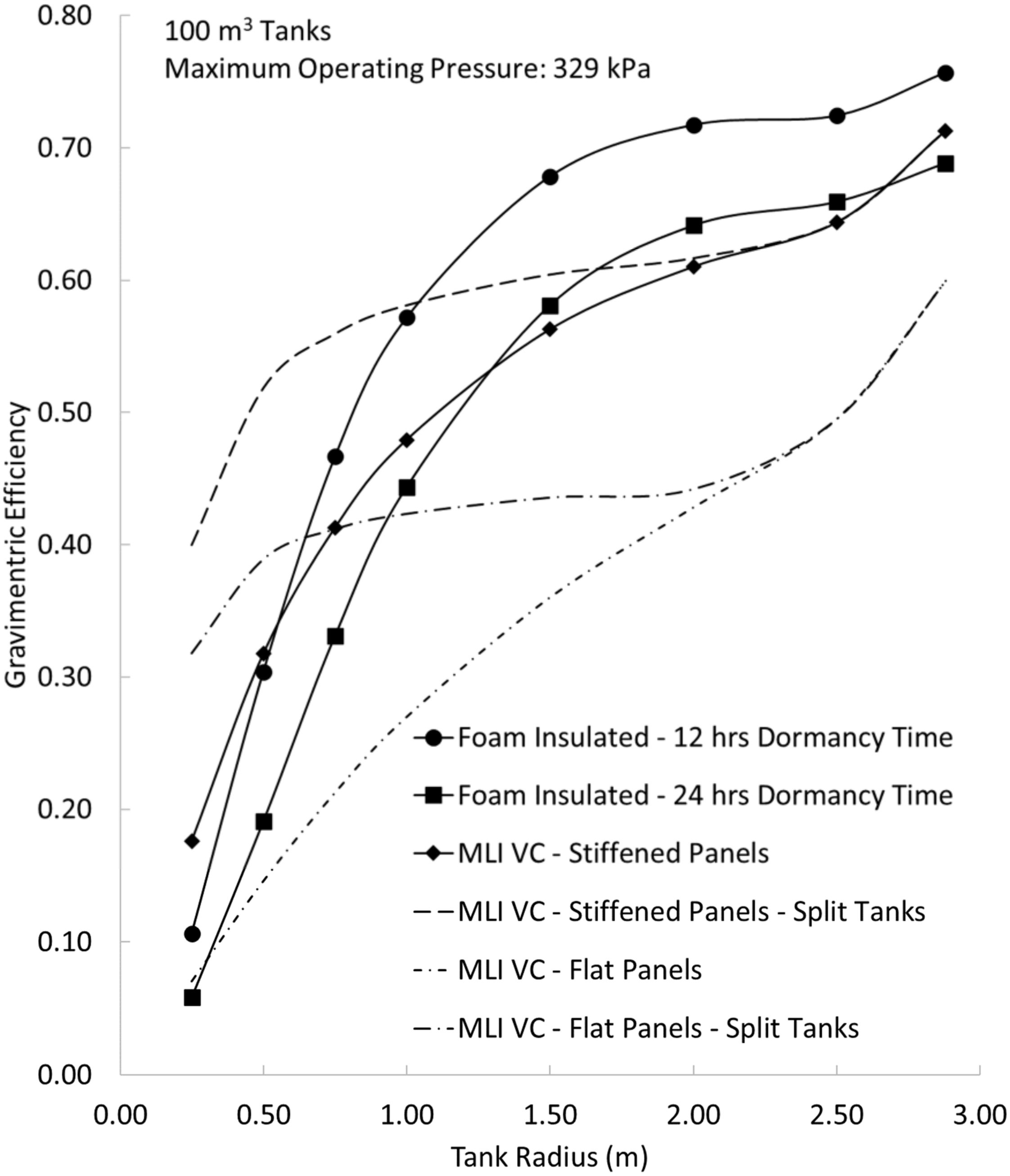


Fig.8 Effect of tank radius on gravimetric efficiency.

It should be noted the large difference in gravimetric efficiency obtained at different tank radius. This effect was also recognised by [18] for foam insulated tanks. This fact underpins the large variation in gravimetric efficiencies found in the literature and explains the different optimum designs depending on range of the application and maximum fuselage size. The existence of an optimum radius for foam insulated tanks is also visible in [18] and in [23], although it is not discussed there. Optimum radius for a 100 m^3 foam insulated cylindrical tank is between 2 and 2.5m, higher for longer dormancy times with thicker insulation. As the tank approaches a sphere (radius 2.88 m), there is a discontinuity since mechanical performance of the sphere is superior and gravimetric efficiency reaches an absolute maximum. Vacuum insulated tanks have a dormancy time in the order of hundreds of hours and therefore, only one line has been drawn for each type. In terms of weight, except for very low radius, they behave worse for dormancy time requirements lower than 24 hrs.

“The effect of having multiple tanks rather than one for the same fuel capacity is now considered, as in Fig.1(f). Long tanks may be split into several tanks, each of them having the same diameter as the single tank but reduced length.” Foam insulated tanks weight more when split into several tanks of the same radius, since wall thickness would not vary, and total surface would increase [23]. Vacuum insulated tanks, on the contrary, can improve the weight, since buckling stress limit is dependent on length. This option also increases the tank volume compared to fuel volume since the cap envelope of large diameter cylinders or spheres is unusable. Figure 8 also shows the improvement with multiple vacuum insulated tanks in the lines with the text ‘Split Tanks’. These lines represent the trend line of multiple tanks with a length to radius ratio of 4. For small diameter tanks, gain is larger. This trend is observed for all tank volumes. Longer length to radius ratio gives intermediate values between both cases.

Consideration of elliptical tanks yield to same trends, but at a higher weight and lower gravimetric efficiency, due to a higher radius of curvature at the minor axis points. A study on the sensitivity of elliptical foam insulated tank to longitudinal and cross section aspect ratios can be found in [23].

Optimum Length

To understand the effect of length, a 2m radius tank and varying volumes has been studied. Results are plotted in Fig.9. The effects of tank size can be explained through the surface to volume ratio of the tank. For any given volume, the lowest surface to volume ratio corresponds to a sphere (*3/R*). For any given diameter, the longer the tank, the smaller the surface to volume ratio, with a rapid trend towards that of the cylinder (*2/R*). This asymptotic behaviour of the S/V ratio explains the small variation in gravimetric efficiency.

For foam insulated tanks, because the tank wall thickness depends only on diameter, it will not vary with tank length. Insulation thickness depends on S/V ratio, so the impact of volume variation in gravimetric efficiency is only that of the S/V ratio. Vacuum insulated tanks show the effect of increased external wall thickness with length. Splitting vacuum insulated tanks into multiple tanks improves the gravimetric efficiency and may ideally keep it constant for any tank volume, providing the same length to diameter ratio is kept constant.

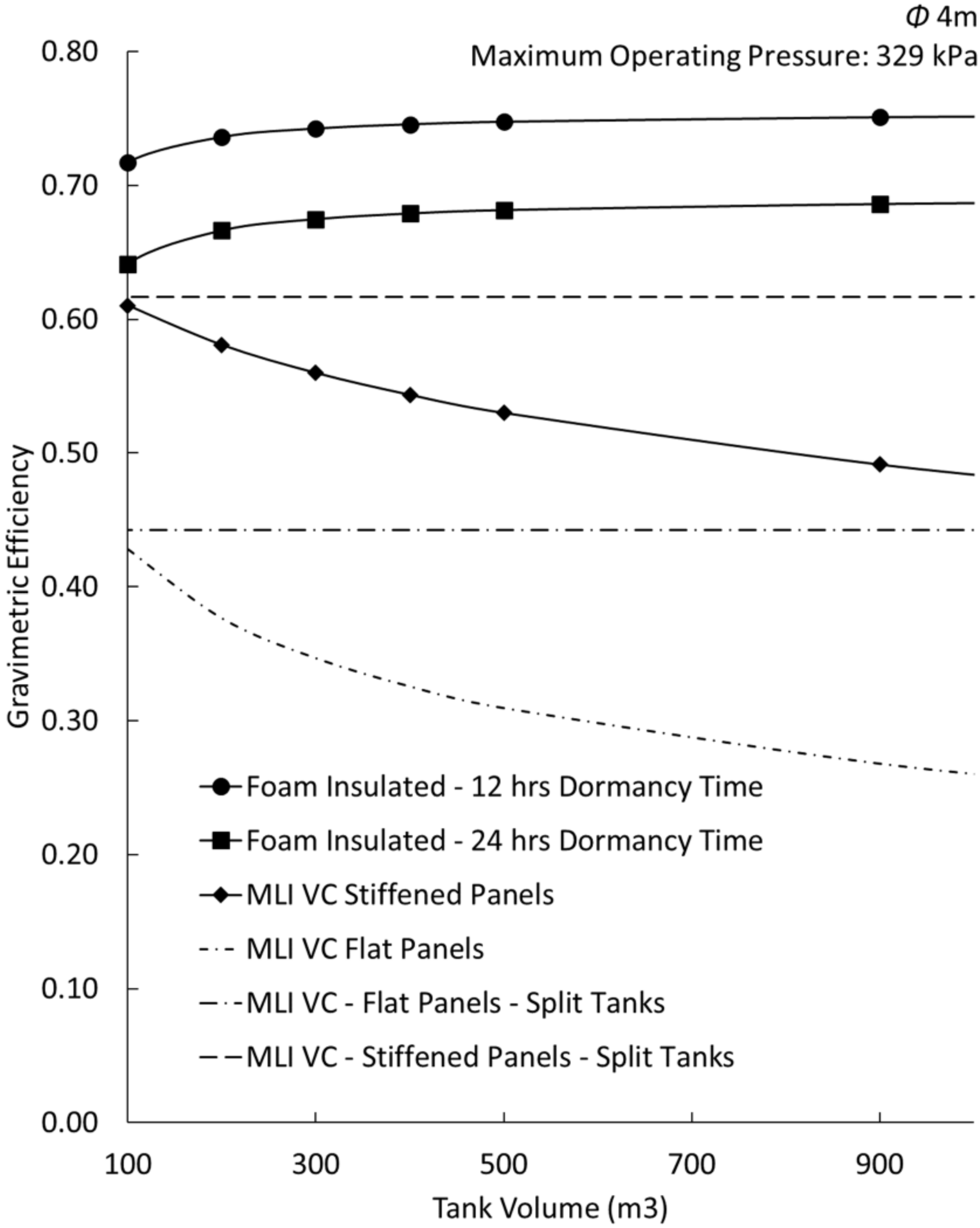


Fig.9 Effect of tank length on gravimetric efficiency for constant diameter tanks.

The most important conclusion is that for large tanks, gravimetric efficiency is mostly affected by the radius of the tank, rather than by the length or the volume.

Optimum pressure

For any given tank size, tank wall thickness increases with maximum allowable pressure, as per Eq.9. Heat leakage increases with increasing maximum allowable pressure as per Eq.7 for a required dormancy time, and hence, insulation thickness requirement reduces. It is then expected that a trade-off exists, that shows a minimum value of tank weight at a certain pressure. Vacuum insulated tanks have a very low insulation weight and a very high external wall weight, neither of which depend on maximum operating pressure. Therefore, there minimum value occurs at the minimum pressure. Fig.10 shows the gravimetric efficiency of a 100 m^3, both for a 2 m radius cylindrical, and for a 2.88 m radius spherical tank.

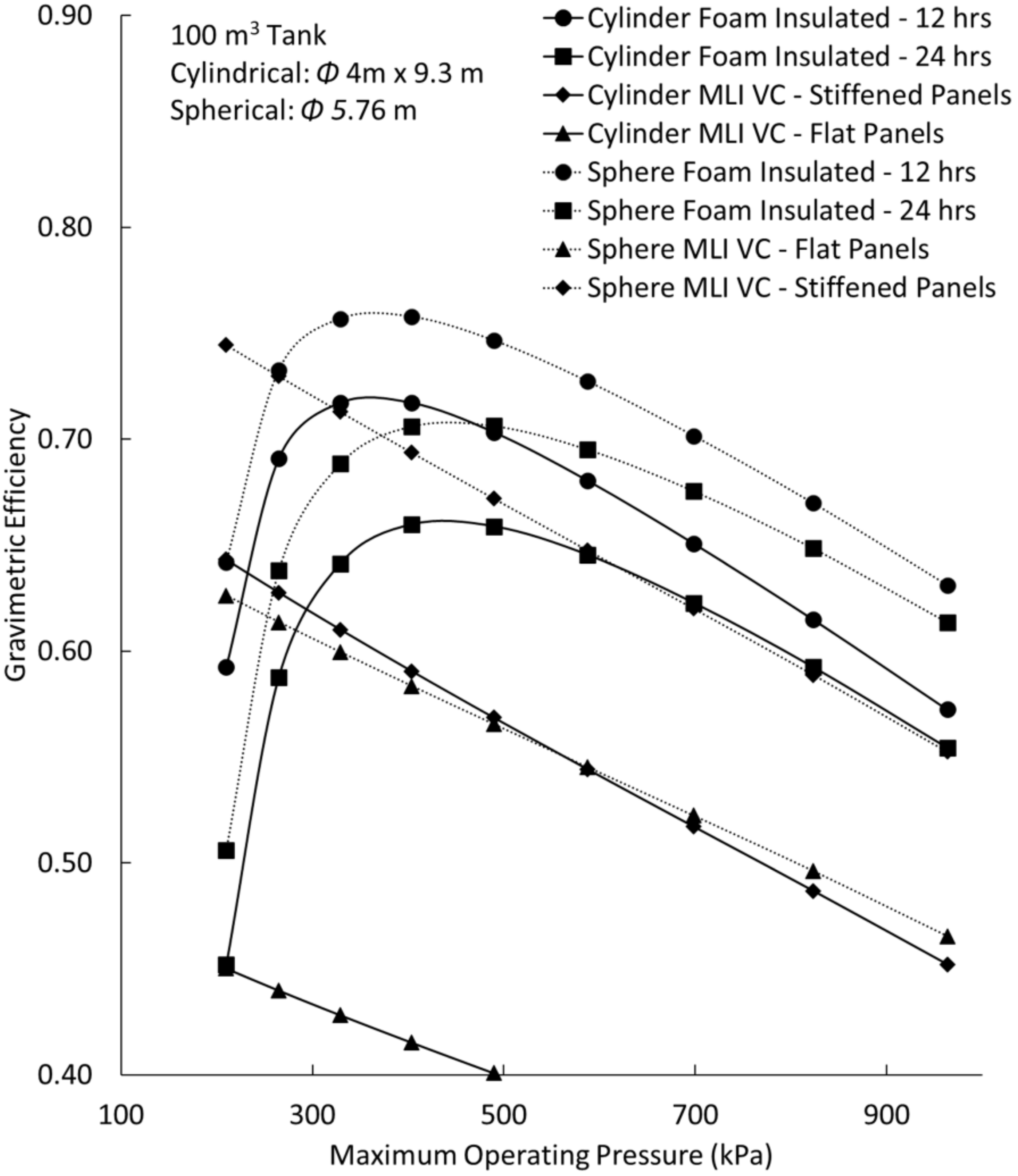


Fig.10 Effect of Maximum Operating Pressure on Tank Gravimetric Efficiency

Optimum pressure varies from 300 to 500 kPa, higher for longer dormancy times since insulation thickness is higher. Optimum pressure is slightly higher for the spherical tank as wall weight reduces compared to a cylinder.

Optimum architecture

In this section, a comparison of optimum tanks for the different architectures described previously is performed. A 100 m^3 tank is taken as an example but general conclusions for larger tanks are also given.

An optimum 100 m^3 foam insulated tank will be spherical or cylindrical with radius above 2 m, with a small loss of gravimetric efficiency between 2 and 2.5m. A 24 hrs dormancy time (full tank condition) has been used leading to an optimum Maximum Operating Pressure around 400 kPa. Optimum vacuum insulated tanks have also the largest possible radius, with diminishing returns as the tank approached a sphere, and a discontinuity at the spherical shape due to the double curvature. Since the optimum Maximum operating pressure is the lowest possible, 200 kPa has been considered as a safe value above atmospheric. Table 2 summarises optimum tank designs. Two options for cylindrical tanks with a radius of 2 m with optimum insulation based on foam and vacuum, and a 2.88m radius optimum spherical tank are compared.

100 m^3 Tank	Cylinder	Cylinder	Sphere
	Foam	Stiffened Panels MLI Vacuum	Stiffened Panels MLI Vacuum
Diameter (m)	4	4	5.76
Dormancy Time (hrs)	24	200	240
Total Length (m)	9.29	9.29	
Maximum Operating Pressure (kPa)	404	210	210
Useful LH2 Capacity (kg)	5969	6405	6405
Inner Wall			
Material	Aluminium		
Thickness (mm)	3.27	1.94	1.62
Weight (kg)	1,068	633	473
Insulation			
Material	Foam	MLI Vacuum	MLI Vacuum
Thickness (mm)	310	127	127
Weight (kg)	1450	593	529
Outer Wall			
Material	Al	Al (bi-grid panel)	
Weight (kg)	262	1,828	696
Accessories (kg)	300	500	500
Total Weight (kg)	**3,079**	**3,554**	**2,199**
Gravimetric Efficiency	0.660	0.643	0.744

Table2. Short/Medium Haul Transport Aircraft Optimum Tanks

Both cylindrical options have a very similar result. The spherical option is superior, but difficult to integrate in common short to medium range aircraft designs, with a fuselage diameter of around 4 m.

For larger tanks, physical limitations for fuselage integration restrict the maximum radius to that of the fuselage. As per Fig.8 and 9, optimum tanks will have the largest possible radius and gravimetric efficiency will not very significantly with tank length. Due to thicker required walls, optimum Maximum Operating Pressure will be lower than the 100m^3 tank given as an example, but to give an order of magnitude, still in the range of 300 kPa for a 1.000 m^3 tank. As it can be observed in Fig.9, the farther from a spherical shape the tank is (or the higher the length to radius ratio), the larger the difference in gravimetric efficiency between foam and vacuum insulated tanks. Since large tanks with limited maximum radius will have a higher length to radius ratio, the larger the tank, the more favourable will be the foam insulated construction. This fact is observed in Fig.11 (a) for a 6m diameter 300m^3 tank and Fig.11(b) for a 7 m diameter 900 m^3 tank. For medium and large size tanks foam insulation is the preferable option. As expected from Fig.8 and 9, foam insulated tanks behave better for long haul capacity. As it also can be deducted from figure 9, vacuum insulated tanks for long haul can be improved by splitting the volume into 3 tanks, leading to maximum values similar to the 300 m^3 tank, but still lower than foam insulation.

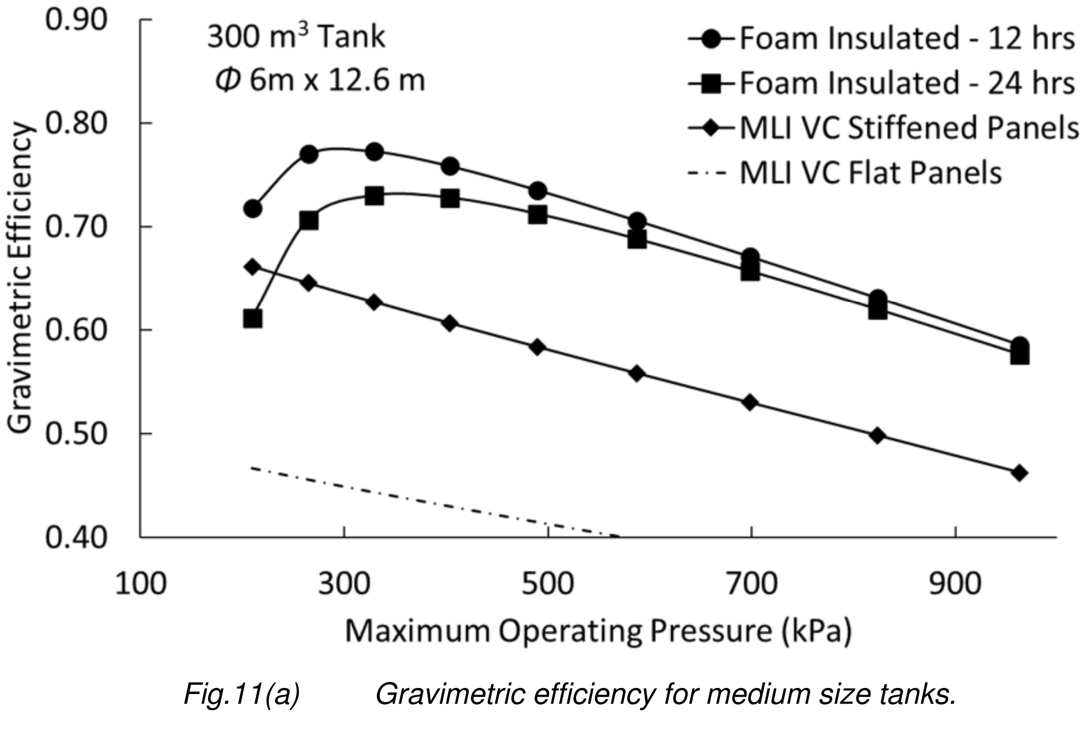


Fig.11(a) Gravimetric efficiency for medium size tanks.

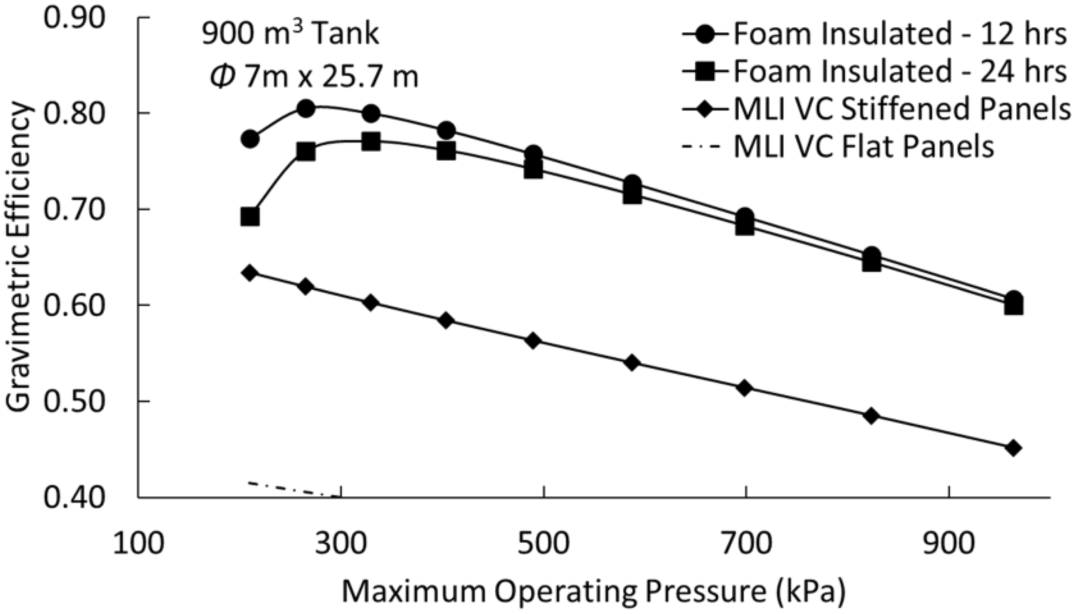


Fig.11(b) Gravimetric efficiency for large tanks.

7- CONCLUSIONS

A comprehensive review of tank design criteria provides an explanation for the large variety of quoted gravimetric efficiency of tanks in previous literature.

The gravimetric efficiency of liquid hydrogen tanks shows a wide variation, mainly, with tank diameter, yielding values as low as 0.1 for 0.5m tanks, up to nearly 0.8 for very large tanks. Increasing the length of the cylindrical tank at any given diameter, does not significantly affect the gravimetric efficiency. Optimum tanks are, therefore, those with maximum diameter that can be inscribed into the aircraft fuselage. Tanks designed to be fit into the wings or in smaller compartments will be heavier or require venting at cruise. For tanks bellow 2-3m diameter, MLI vacuum insulated tanks with an external wall with stiffened panels offer the lowest weight. For larger diameters, foam insulated tanks are lighter.

The low density of liquid Hydrogen requires aircraft tanks with four times the volume of those used in an equivalent conventional aircraft. For existing aircraft fuselage diameters, and for all ranges above regional aircraft, tank gravimetric efficiency calculated is higher than 66% w. hydrogen, meaning that weight of tank is half the weight of hydrogen stored or lower. Being hydrogen tree times lighter per unit of energy content, the weight of the full tank will be lower for a hydrogen aircraft than for a kerosene equivalent aircraft. This conclusion suggests that the main challenge to the design of a hydrogen fuelled aircraft is the volume of the tank rather the weight.

Large capacity insulated tanks required for hydrogen aviation show increasing gravimetric efficiency with growing diameters. Regardless of the technology used for insulation, an increase in diameter results in a reduction of surface to volume ratio that makes the tank weight in relation to stored hydrogen to drop. Being the tank diameter limited by aerodynamic design of aircraft, lightest tanks will be the largest that can be inscribed into the airframe.

Foam insulated tanks are generally superior to MLI Vacuum Insulated tanks, even if stiffened panels are used for the external wall subject to negative pressure. Vacuum insulated tank weight can be reduced if tank is split into several tanks of same diameter and a smaller length to diameter ratio is used. On the contrary, splitting foam insulated tanks deteriorate the total weight. Only for very small tanks, such as automobile applications or long endurance missions, vacuum insulated tanks offer a better solution. Optimum maximum operating pressure is between 3 and 5 bar for foam insulated tanks and around 2 bar for vacuum insulated.

Optimum tank size and architecture will depend on the mission and should be evaluated in each case. However, there are some trends observed in this research. Short range aircraft will be less affected by the gravimetric efficiency of the tanks, since the amount of store hydrogen and hence the weight of the tanks are a minor fraction of the aircraft weight. MLI vacuum insulated tanks, even at low diameter could provide a compromise solution. Long range aircraft, on the contrary, will be heavily penalised by low gravimetric efficiency tank. For those, large diameter foam insulated tanks, such as those depicted in Fig.1 (a) and (d) could lead to lightest tanks. Still, the impact of reduced aerodynamic efficiency of these may balance the optimum towards a compromise solution such as Fig1.(b), (c), (f) or any of the unconventional concepts depicted in Fig.2. Optimum tank configuration cannot be determined but at a system level.

A novel method was developed to enable to optimise lightweight tanks for hydrogen fuelled airliners. This method considers the dormancy time as a principal design parameter and considers the evolution of mass, pressure, temperature, and phase change of hydrogen during a flight. It is also shown that the type of aircraft and its mission will have a profound influence on tank design. One of the key conclusions of the study is that there is a very large design space to be explored. When the considerations of heating, stirring, and venting are added this offers many opportunities for optimisation that comprise the aircraft and airport systems and includes aircraft performance and economic dimensions. It is the expectation of the authors that, as successive innovation waves are implemented, these opportunities will give rise to very efficient hydrogen aircraft and propulsion systems.

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Parametric study on tank integration for hydrogen civil aviation propulsion

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