



**HAL**  
open science

# Hydrogen tank configuration optimisation for a tube and wing aircraft

Romain Parello, Sebastien Defoort, Emmanuel Benard, Yves Gourinat

► **To cite this version:**

Romain Parello, Sebastien Defoort, Emmanuel Benard, Yves Gourinat. Hydrogen tank configuration optimisation for a tube and wing aircraft. ICAS 2024, Sep 2024, Florence, Italy. hal-04779895

**HAL Id: hal-04779895**

**<https://hal.science/hal-04779895v1>**

Submitted on 13 Nov 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



# HYDROGEN TANK CONFIGURATION OPTIMIZATION FOR A TUBE AND WING AIRCRAFT

R. Parello<sup>1,2</sup>, S. Defoort<sup>1</sup>, E. Benard<sup>2</sup> & Y. Gourinat<sup>2</sup>

<sup>1</sup>ONERA, 2 Av. Edouard Belin, Toulouse, France

<sup>2</sup>ISAE-SUPAERO, 10 Av. Edouard Belin, Toulouse, France

## Abstract

In response to the climate crisis, the aviation industry pledged through ICAO to become climate neutral by 2050. One of the most promising solutions to achieve this goal is the introduction of hydrogen-fueled aircraft. Using hydrogen as fuel on an aircraft presents however huge challenges, especially due to its complex storage, as it must be stored in pressurized cryogenic tank. This study focuses on the integration of a medium-fidelity cryogenic hydrogen tank model into an overall aircraft design tool (FAST-OAD) and its exploitation to optimize a hydrogen aircraft. This integration allows the comparison of different tank configurations at the aircraft level and the search of the optimum ones, depending on the high-level requirements or optimization criteria.

**Keywords:** Aircraft Design, Hydrogen Tank, Conceptual design, MDAO

## 1. Introduction

In its sixth assessment report [1] the Intergovernmental Panel on Climate Change clearly states that human activities emitting greenhouse gases are the main cause of current global warming. To limit the negative impact that climate change will have on human society, countries around the globe signed the Paris Agreement in 2015, promising to cut their greenhouse gas emissions to stay below a 2°C increase on earth by 2100 and even below 1.5°C if they can. The aviation industry is part of these activities emitting greenhouse gas, its  $CO_2$  emissions being responsible for around 3% of the current radiative forcing on earth. But if non- $CO_2$  effects are included (mainly  $NO_x$  emissions and contrails formation), this share rises to approximately 5-6% of the radiative forcing, although a big uncertainty margin remains on that second part [2]. This situation pushed the International Civil Aviation Organization (ICAO) to declare that the aviation industry will pursue the objective of becoming climate neutral by 2050 to stay aligned with the Paris Agreement. One of the most promising solutions to reach climate neutrality in aviation is the use of new carbon-free fuels on aircraft, like hydrogen. Hydrogen doesn't emit  $CO_2$  indeed when burned in a gas turbine or consumed in a fuel cell to produce electricity, so hydrogen aircraft would indeed emit no  $CO_2$  if hydrogen was produced in a sustainable way. Concerning non- $CO_2$  effects, fuel cells simply don't produce any, while studies have shown promising possibilities to reduce  $NO_x$  emissions and contrail impact of hydrogen turbine [3].

Designing a hydrogen aircraft for commercial use remains however a technological and economic challenge. If some prototypes have already flown in the past, none have already been fully designed, built, and certified. It is a very disruptive concept compared to kerosene aircraft that requires a profound revision of classical design methods. The cryoplane study [4] demonstrated nevertheless in 2003 already that this solution is technically feasible with lots of further research and development. If hydrogen aircraft are so difficult to design, it is mainly due to the storage of hydrogen onboard. Hydrogen has indeed a very low energy density at standard temperature and pressure. Except maybe for regional flight, which is not the focus of this study, it must so be stored in liquid form to reach an acceptable storage volume. But even so it requires roughly four times the volume of

kerosene to store the same amount of energy. Hydrogen is moreover liquid at 20K, so a hydrogen tank must be cryogenic and able to hold the pressure of hydrogen boiling off inside. The tank design becomes consequently much more complex and heavy, necessitating its inclusion in the conceptual design phase of the aircraft, as it will have a major influence on the aircraft's performance. This impact is closely related to the tank gravimetric efficiency or gravimetric index (GI), defined as:

$$\eta_{grav} = \frac{m_{H2}}{m_{H2} + m_{tank}} \quad (1)$$

The dependency of hydrogen aircraft energy consumption to their tank gravimetric index was illustrated by Adler and Martins in [5]. What should be noticed in their work is that the energy consumption of hydrogen aircraft increases exponentially when their tank gravimetric index deteriorates, and even more so for longer ranges. At 5000 nm range for example, a hydrogen aircraft with a GI of 0.55 consumes approximately as much energy as a kerosene aircraft, but it consumes 15% more at a GI of 0.4, 50% at GI of 0.3 and more than 100% at a GI of 0.2. Adler and Martins found however in their review of liquid hydrogen aircraft design studies that this index varies from 20% to 85% depending on technology and modeling choices. In regards to the high sensitivity of a hydrogen aircraft to its tank characteristics, it is necessary to use a cryogenic tank model of relatively high fidelity at the conceptual level of the aircraft. This model must be generic and have a sufficient parametric degree of freedom to explore different design configurations. To fully explore all the designs, it must also remain lightweight enough to be run in an iterative optimization process.

Designing a cryogenic tank for an aircraft is indeed a trade-off between the thermal and structural performance of the tank. More insulation reduces hydrogen loss due to boil-off, but also increases the weight of the insulation, which increases fuel consumption. The second option, increasing the maximum tank design pressure, delays the need for venting but requires a heavier structure too. A complete tank model must then be able to determine the quantity of hydrogen lost due to boil-off by estimating how much heat is entering the tank during the mission while also sizing the structure of the tank. But in order to optimize this trade-off, the tank model must be integrated into a complete tank overall design analysis. The tank mass will indeed affect the aircraft design in multiple ways, like its volume or integration, and these impacts can only be fully assessed in an overall design multidisciplinary analysis. Once this integration is completed, it becomes possible to determine which tank insulation technologies or configurations would be best suited and what the benefits and drawbacks of the different tank integration possibilities are. Several studies have tried to design hydrogen aircraft. Most authors use a thermal model derived from the one initially developed by Verstraete in [6] with the help of previous work made by Brewer in [7]. For structure sizing, two different possibilities arise: an integral tank where the structure is part of the fuselage or a non-integral tank, where the tank is simply placed inside the fuselage. Brewer [7] prefers the integral concept because it should save on mass and facilitate inspections. Verstraete [8] chooses this configuration for the same reasons, whereas Winnefeld et al. [9] only consider non-integral tanks. Onarato and al. [10] tried to model both concepts. But none of those studies compared both concepts at the aircraft level within a multidisciplinary design analysis and optimization (MDAO), as their choice was based on expert judgment.

The purpose of the present study is to use a new model for an aircraft's hydrogen tank integrated into FAST-OAD [11], which is an overall aircraft design tool, in order to optimize a full hydrogen aircraft. This will determine which tank configurations or technologies are best suited for each aircraft design mission. The tank model used for this will also be of higher fidelity than the previous studies. The structure of this paper will first describes this new model and how it was implemented in FAST-OAD. Then several aircraft design analyses will be presented to explore the different hydrogen aircraft configuration and optimization cases will be performed to determine the best design choices and the feasibility or performance of such aircraft

## 2. Methodology

### 2.1 FAST-OAD : an Aircraft Design Tool

Aircraft design is a complex process as it involves multiple disciplines (aerodynamics, structure, controls, etc.) that are coupled because they depend on each other. For example the aerodynamic loads

## Hydrogen Tank Configuration Optimization for a Tube and Wing Aircraft

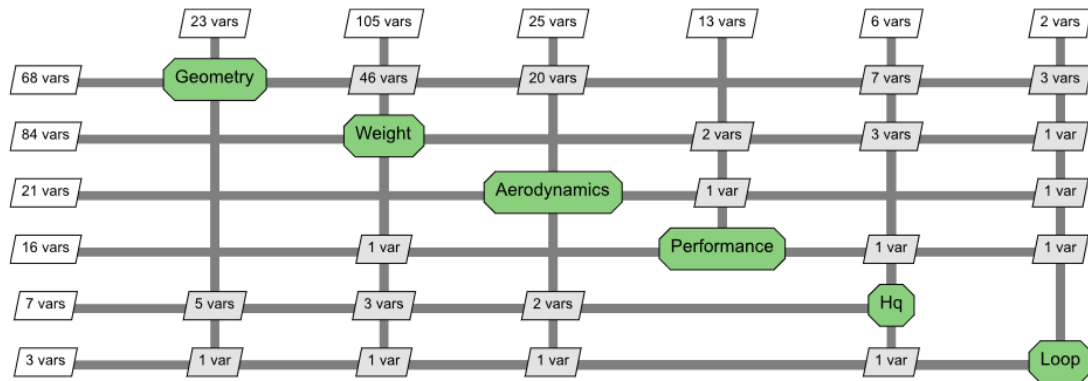


Figure 1 – FAST-OAD multidisciplinary Analysis process [11]

on the wing depend on its shape, but these loads deform the shape of the wing. These are the basic inter-coupled disciplines of aircraft design but there are lots of others. To solve this problem, the multidisciplinary design analysis and optimization paradigm have emerged recently. The idea with MDAO is to solve an analysis with multiple coupled disciplines in an iterative and automated process. This was implemented by ONERA and ISAE-SUPAERO in FAST-OAD (Future Aircraft Sizing Tool Overall Aircraft Design) [11]. In his current version, FAST-OAD loops the multidisciplinary analysis around the fuel mass. It computes indeed the fuel mass required for the mission based on an initial maximum take off mass (MTOW) guess and sizes the structure based on this fuel mass and the Top Level Aircraft Requirements (TLARs). It can then determine the updated MTOW of this aircraft as it knows the structure mass. It can finally recompute the updated fuel mass with a time-step integration of the mission profile and restart the process until the fuel mass and aircraft mass converges on a feasible aircraft design. The MDA process is represented on figure 1.

To ease the MDA process, FAST-OAD was implemented in Python under the OpenMDAO format developed by the NASA [12] which specifically address this type of problem.

FAST-OAD was developed originally for conventional Tube and Wing (T&W) small to medium range aircraft. To be able to design hydrogen aircraft some module of the program had to be modified:

- Propulsion module: Several conventional aircraft has already been converted to hydrogen (for example the US successfully modified a B-57 to fly on liquid hydrogen [13] in the 1960's). This suggest that an hydrogen turbine won't differ that much from a conventional gas turbine. At the conceptual design level and for a first approach, it was considered acceptable to represent in FAST-OAD hydrogen turbines with the same rubber engine as for conventional one. The consumed fuel flow was just reduced by the ratio of specific energy between hydrogen and kerosene (so by approximately 3).
- Geometry module: The geometry module define the geometry of each aircraft component based on their masses and a few empiric rules. It was also modified to compute the tank geometry depending on block fuel. The choice was made to always place the tank(s) behind the cabin. The tank modeled are cylindrical tank with hemispherical or elliptical bulkhead. The method to size the tank use the diameter of the fuselage and the fuel mass to determine the tank length, taking into account the insulation and wall thickness, the bulkhead shape and the number of tank as well as the distribution of the fuel if there are multiple tanks. The tank length is then added to the fuselage length.
- Weight module: In this discipline the structural model presented in section 2.2s added to size the tank and determine its mass based on its geometry, its materials and its specific constraints.
- Handling quality module (HQ): while defining the tank geometry, the center of gravity of the tank are also computed to be considered when assessing the stability and control of the aircraft
- Performance module: that is where the time-step integration of the mission occurs. There the

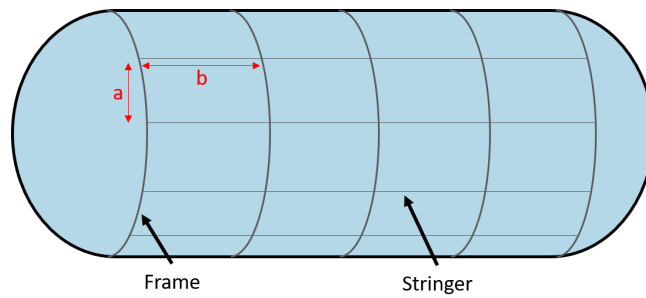


Figure 2 – Tank structure [14]

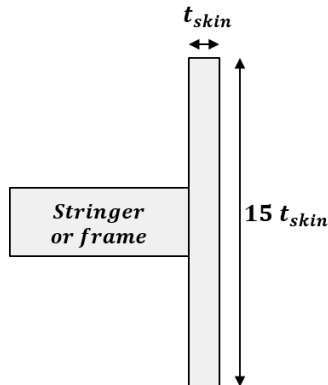


Figure 3 – Super stiffener representation [14]

thermal model present in section 2.3s past-processing the mission to determine the boil-off at each time-step. The amount of hydrogen boil off is then added to the total block fuel.

## 2.2 Tank structure sizing

The structural model of the tank is an important part of tank design process, as the majority of the tank weight is indeed due to its structure. The tank structure must be able to hold a pressure differential between the interior and exterior of the tank. As the liquid hydrogen is stored at 20K, the tank internal pressure should always stay above the external pressure to avoid air or water leaking inside and freezing, clogging the fuel system. With hydrogen boiling-off the internal pressure will also rise, so a maximum pressure differential with the exterior environment must also be set in the design constraints. As the tank is placed in an aircraft, most probably in a non-pressurized section of the fuselage, this fixed pressure differential will lead to a maximum and minimum acceptable pressure in the tank evolving during the flight with the atmospheric pressure. In the case of an integral tank concept, the structure is part of the fuselage and must as a consequence also support the different bending and shear loads of the fuselage. The methodology used to design the structure of the tank is the same as the one presented by the authors in [14] and it will be briefly summarized.

The structure of a cylindrical-shaped tank is composed of the tank wall and the stiffening frames and stringers, as represented in figure 2. The frames are longitudinal stiffeners, while the frames are circular ones. Like the skin, they must respect specific requirement as the current CS-25 states[15] : the skin must withstand the operational load alone, which is the bending, shear, torsion, and pressure load encountered during a nominal mission. This means that it must be thick enough to not suffer plastic deformation under those loads. The skin should also not buckle up to the operational load. As the skin buckling depends on the stringers and frames pitches (respectively a and b on figure 2), this criteria determines how many frames and stringers are needed on the tank.

Above the operational load up to the ultimate load, defined as two times the operational load, the super stiffening structure must bear all the load as the skin is assumed to have buckled. Super stiffeners are the frames and stringers augmented with a part of the tank's skin around their attach point that hasn't buckled [16] as represented on figure 3. The superstiffening structure is then sized to stay

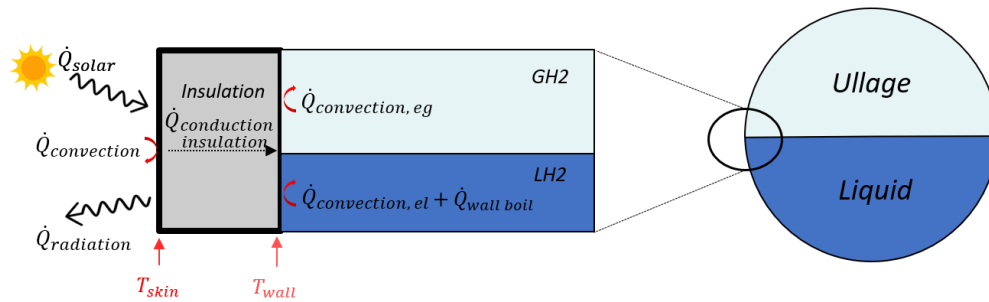


Figure 4 – Heat flows impacting a cryogenic hydrogen tank

below the break stress at the ultimate load but also to remain in elastic deformation at the limit load, defined as the ultimate load divided by 1.5 (approximately 1.33 times the operational load). Once the skin thickness and stiffeners sections are determined, it becomes possible to compute their volume and so their masses.

### 2.3 Tank thermal analysis

A liquid hydrogen tank is said to be cryogenic because it must keep the fuel at around 20K. Designing such a tank requires a detailed thermodynamic analysis to know what insulation is needed and how the liquid hydrogen will evolve during the mission. The tank will indeed not stay at a constant temperature or pressure during the whole mission. The heat leaking inside the tank will cause hydrogen to boil off, which will increase the interior pressure. The tank is therefore in a periodic cycle of self-pressurization and venting, where hydrogen is released in order to stay below the maximum design pressure. The adopted thermodynamic model for both the self-pressurization and venting phases is detailed in a previous paper of the authors [17] but will be summarized in the following paragraphs.

In the entire thermal model, thermodynamic properties of chemical species are computed using the CoolProp Python library [18] or using the thermodynamic properties interpolation created by Ramos in [19].

#### 2.3.1 Thermal circuit model

The thermodynamic model of the tank is divided into three parts: the thermal circuit, which estimates of much heat is entering the tank, the boil-off model, which describes the evolution of the fuel in the tank in response to this heat inflow; and the venting phase, which occurs when the pressure reaches its maximum.

The first part is called the thermal circuit model because it uses an analogy with electrical resistance to determine the incoming heat flow. With this approach, different heat flows associated with different physical phenomena are computed and then added. The model considers two surfaces that are assumed to always be in thermal equilibrium: the tank internal surface, called the tank wall, and the tank external surface, or the tank skin, which can also be the aircraft skin if the tank is integral.

For the tank skin, four heat flows represented on figure 4 can be considered [6], [20]:

- Convective heat flow :  $\dot{Q}_{ext,conv}$
- Conductive heat flow through the insulation:  $\dot{Q}_{cond}$
- Radiative heat flow towards the exterior environment:  $\dot{Q}_{rad}$
- Solar irradiation:  $\dot{Q}_{solar}$

For the internal wall of the tank, three phenomena should be taken into account:

- Natural convection on the internal wall:  $\dot{Q}_{int,conv}$
- Conductive heat flow through the insulation:  $\dot{Q}_{cond}$
- Hydrogen boiling on the wall :  $\dot{Q}_{boil}$

The heat flow entering tank is equal to the sum of the convective heat flow and the flow associated with hydrogen boiling on the wall (which is zero if the wall is in contact with gaseous hydrogen), both of which depends on the wall temperature. With the thermal equilibrium assumption,  $T_{wall}$  can be obtained by solving the following system:

$$\begin{cases} \dot{Q}_{ext,conv} + \dot{Q}_{rad} - \dot{Q}_{solar} - \dot{Q}_{cond} = 0 \\ \dot{Q}_{int,conv} - \dot{Q}_{boil} - \dot{Q}_{cond} = 0 \end{cases} \quad (2)$$

The system 2 is in fact solved several times, one for each "region" of the tank which are determined by the internal environment (gaseous or liquid hydrogen) and the external environment (aircraft interior or atmosphere, lit or not by the sun) in contact with the tank. This yields multiple heat flows entering the gaseous or liquid hydrogen volumes. Those heat flows are then summed up to determine the total flow arriving in each phase.

### 2.3.2 Boil off model

Once the heat transfer to the liquid and gaseous hydrogen is known, it becomes possible to determine the evolution of both hydrogen phase. Unlike most previous studies, the model used here doesn't make the homogeneous tank assumption but considers three separate control volumes: bulk liquid hydrogen, gaseous hydrogen, also called the ullage, and the interface between both, which is an infinitely thin layer with a definite temperature but no mass, like Ramos in [19]. The state of these control volumes is fully described with only four variables:  $T_g, T_l, m_g$  and  $V_g$ . By applying the conservation of energy the system 3 is obtained.

$$\begin{cases} \dot{m}_g = \frac{\dot{Q}_{gs} - \dot{Q}_{sl}}{h_{vap} + c_{p,l}(T_s - T_l) + (h_g - h_{sat})} + \dot{m}_{boil} + \dot{m}_{pressurization} \\ \dot{T}_g = \frac{\dot{Q}_{eg} - \dot{Q}_{gs} - P_g \dot{V}_g + \dot{m}_g h_g + h_l \dot{m}_{boil} - \dot{m}_g u_g}{m_g c_{v,g}} \\ \dot{V}_g = \frac{\dot{m}_g + \dot{m}_f}{\rho_l} \\ \dot{T}_l = \frac{\dot{Q}_{el} + \dot{Q}_{sl} + P_l \dot{V}_l - \dot{m}_g h_l + h_l \dot{m}_f - \dot{m}_l u_l}{m_l c_{p,l}} \end{cases} \quad (3)$$

A representation of the model can be seen in figure 5[ht]

### 2.3.3 Venting

By providing an initial tank state and a mission profile where the fuel flow, the altitude and the mach are given as a function of time, it becomes possible to solve both systems ?? and 3 and estimate the evolution of the tank state during the mission. During the mission, hydrogen boil-off will increase the pressure in the tank and once the maximum pressure is reached, hydrogen will be vented. The venting is considered to be instantaneous and immediately after, the pressure is equal to the minimum pressure admissible in the the tank. The temperature of the ullage is also reset to the saturation temperature at this minimum pressure. The ideal gas law allows then to determine how much hydrogen has been vented [19]:

$$m_{vent} = m_{g,1} - m_{g,2} = \frac{P_2 m_{g,1} T_{g,1}}{P_1 T_2} \quad (4)$$

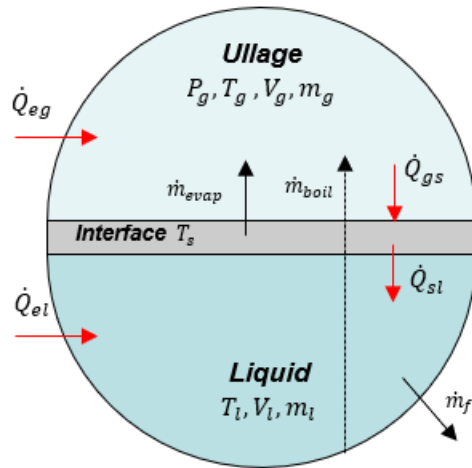


Figure 5 – Self-pressurizing hydrogen tank model [17]

### 3. Expected results

With the tank model now fully integrated into FAST-OAD, it becomes possible to realize sensibility analysis or optimization of tank design parameters at the entire aircraft level. Multiple parameters will be studied. One of the most interesting is for example the impact of an integral or non-integral tank on the aircraft’s performance. The impact of this choice is already visible at the tank level, as shown in figure 6. This graph shows how a non-integral tank mass would evolve in response to the percentage of the fuselage load that is transmitted to it at two maximum pressures. An integral tank corresponds then to the 100% load transmission factor. The behavior of the tank is obviously quite complex and more analysis will be needed to better understand the reasons for it. Other studies that will be realized include the assessment of the penalty of having two hydrogen tanks for safety reasons, the optimization at the aircraft level of the insulation thickness and the maximum tank pressure, the sensitivity of the aircraft’s performance to the insulation and tank wall material, or to its design mission TLARS. Mixed-variable optimization, where the variable to optimize isn’t always a continuous variable but can also be a categorical or integral variable, is also considered to determine at the aircraft level the optimum number of tank, their best integration configuration or even the best fuselage diameter depending on seat layout.

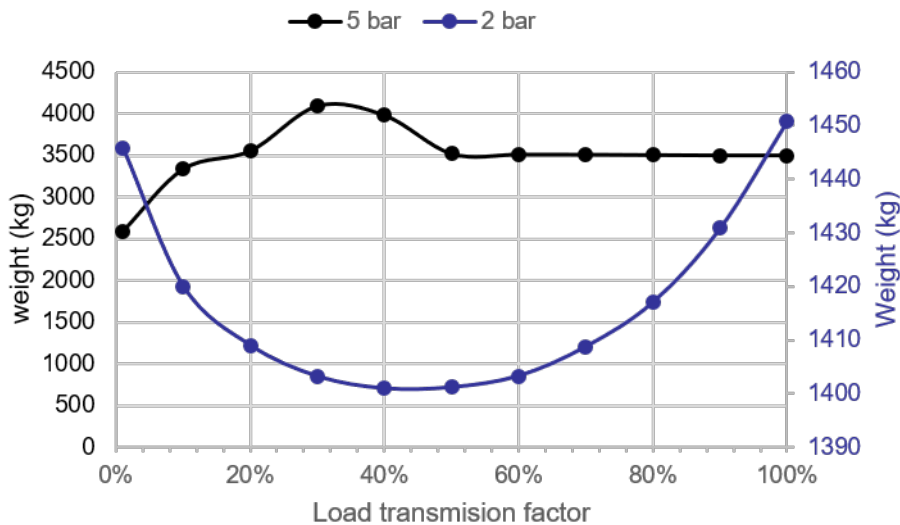


Figure 6 – Impact of tank integration in the fuselage on weight



#### 4. Contact Author Email Address

mailto:romain.parello@onera.fr

#### 5. Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

#### References

- [1] V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Technical report, Cambridge University Press, 2021.
- [2] D. S. Lee, D. W. Fahey, A. Skowron, M. R. Allen, U. Burkhardt, Q. Chen, S. J. Doherty, S. Freeman, P. M. Forster, J. Fuglestedt, A. Gettelman, R. R. De León, L. L. Lim, M. T. Lund, R. J. Millar, B. Owen, J. E. Penner, G. Pitari, M. J. Prather, R. Sausen, and L. J. Wilcox. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 244:117834, January 2021.
- [3] Joseph Brand, Sam Sampath, Frank Shum, Robert Bayt, and Jeffrey Cohen. Potential Use of Hydrogen In Air Propulsion. In *AIAA International Air and Space Symposium and Exposition: The Next 100 Years*, Dayton, Ohio, July 2003. American Institute of Aeronautics and Astronautics.
- [4] A. Westenberger. *Liquid Hydrogen Fuelled Aircraft – System Analysis (CRYOPLANE)*. Technical, Airbus Deutschland GmbH, September 2003.
- [5] Eytan J Adler and Joaquim R. R. A. Martins. Hydrogen-Powered Aircraft: Fundamental Concepts, Key Technologies, and Environmental Impacts. *Progress in Aerospace Sciences*, 2023.
- [6] Dries Verstraete. *The Potential of Liquid Hydrogen for long range aircraft propulsion*. PhD thesis, Cranfield, April 2009.
- [7] G. Daniel Brewer. *Hydrogen Aircraft Technology*. Routledge, New York, 1 edition, 1991.
- [8] D. Verstraete, P. Hendrick, P. Pilidis, and K. Ramsden. Hydrogen fuel tanks for subsonic transport aircraft. *International Journal of Hydrogen Energy*, 35(20):11085–11098, October 2010.
- [9] Christopher Winnefeld, Thomas Kadyk, Boris Bensmann, Ulrike Krewer, and Richard Hanke-Rauschenbach. Modelling and Designing Cryogenic Hydrogen Tanks for Future Aircraft Applications. *Energies*, 11(1):105, January 2018. Number: 1 Publisher: Multidisciplinary Digital Publishing Institute.
- [10] G. Onorato, P. Proesmans, and M. F. M. Hoogreef. Assessment of hydrogen transport aircraft. *CEAS Aeronautical Journal*, 13(4):813–845, October 2022.
- [11] Christophe David, Scott Delbecq, Sebastien Defoort, Peter Schmollgruber, Emmanuel Benard, and Valerie Pommier-Budinger. From FAST to FAST-OAD: An open source framework for rapid Overall Aircraft Design. *IOP Conference Series: Materials Science and Engineering*, 1024(1):012062, January 2021.
- [12] Justin S. Gray, John T. Hwang, Joaquim R. R. A. Martins, Kenneth T. Moore, and Bret A. Naylor. OpenM-DAO: an open-source framework for multidisciplinary design, analysis, and optimization. *Structural and Multidisciplinary Optimization*, 59(4):1075–1104, April 2019.
- [13] David B. Fenn, Loren W. Acker, and Joseph S. Algranti. Flight Operation of a Pump-Fed Liquid-Hydrogen Fuel System. Technical Report NASA-TM-X-252, April 1960. NTRS Author Affiliations: NASA Lewis Research Center NTRS Document ID: 19680068699 NTRS Research Center: Glenn Research Center (GRC).
- [14] R Parello, Y Gourinat, E Benard, and S Defoort. Structural sizing of a hydrogen tank for a commercial aircraft. *Journal of Physics: Conference Series*, 2023.
- [15] Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (CS-25), November 2021.
- [16] Yves GOURINAT. Charges structurales en vol Dimensionnement de panneaux fuselage. *Techniques de l'ingénieur: Systèmes aéronautiques et spatiaux*, (TRP 4033 V1), August 2017. Editions T.I.
- [17] Romain C Parello, Yves Gourinat, Emmanuel Benard, and Sebastien Defoort. Design and Integration of a Liquid Hydrogen Tank on an Aircraft. Orlando, Florida USA, January 2024. AIAA.

- [18] Ian H. Bell, Jorrit Wronski, Sylvain Quoilin, and Vincent Lemort. Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp. *Industrial & Engineering Chemistry Research*, 53(6):2498–2508, February 2014. Publisher: American Chemical Society.
- [19] Eugina Mendez Ramos. *Enabling Conceptual Design and Analysis of Cryogenic In-Space Vehicles through the Development of an Extensible Boil-Off Model*. PhD thesis, Georgia Institute of Technology, ATLANTA, US, May 2021.
- [20] Mingxuan Shi, Imon Chakraborty, Jimmy C. Tai, and Dimitri N. Mavris. Integrated Gas Turbine and Environmental Control System Pack Sizing and Analysis. In *2018 AIAA Aerospace Sciences Meeting*, Kissimmee, Florida, January 2018. American Institute of Aeronautics and Astronautics.