LH2-TANK PERFORMANCE ANALYSIS

Master Thesis 2013

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Introduction

This report presents the Master Thesis carried out at ASTRIUM ST Bremen.

In the frame of Ariane 5 performance improvement plan, several ideas have arisen. One of them affects the Cryogenic Upper Stage (ESC-A). Indeed since the Ariane 5 flight V 157, the loading level of liquid hydrogen has been raised in order to improve the performance of the launcher, enabling to increase the payload mass or the altitude of the delivery orbit. However, this change raises safety problems.

Optimal safety should be guaranteed both on ground and during flight. However, this study focuses only on the flight preparation phase, that is to say the ground phase starting from tank loading until lift-off (H0).

After a short presentation of the company, the subject and problematic of this analysis are defined. The fourth part describes the methodology followed and the different steps to reach the objectives of this project. The theory on which rely all the calculations is explained in parts five to seven. Finally, the results obtained are gathered and interpreted in the eighth part.

This study was conducted using MatLab.
I. ASTRIUM Space Transportation

Along with AIRBUS, EUROCOPTER and CASSIDIAN, ASTRIUM is a subsidiary of the European Aeronautic Defence and Space Company (EADS). With around 133 000 employees spread over more than 170 sites, the EADS Group is a global leader in aerospace, defence and related services. Resulting from the merger of Aérospatiale-Matra, DaimlerChrysler Aerospace AG (DASA) and Construcciones Aeronáuticas SA (CASA), EADS was formed in July 2000. In order to increase its visibility within an always more competitive environment, the EADS Group has recently announced its restructuration plan. Tom Enders, Chief Executive Officer, has indeed expressed his wish to change the names of the different members of the Group. ASTRIUM will thus become member of the entity called “Airbus Defence and Space”. Even though such a project will take a while before being completed, it shows how dynamic the Group is and its will to keep an active role within the aerospace environment.

ASTRIUM is the European leader and number three worldwide in space transportation, satellite systems and services. With 18 000 employees worldwide, ASTRIUM guarantees Europe’s access to space thanks to its wholly known products: the Ariane rocket family, the International Space Station (ISS), the Automated Transfer Vehicle (ATV) among many others. Since space has become essential for our daily lives, ASTRIUM has got together the most efficient and high-skilled teams in order to offer the best products to its clients. The company’s actions expand across all sectors of the space business. For that matter, ASTRIUM is divided into three branches: ASTRIUM Space Transportation (ST), ASTRIUM Satellites and ASTRIUM Services.

The first branch is the European prime contractor for civil and military space transportation and manned space activities. Indeed, it is responsible for the design, development and production of launchers and ballistic missiles. Moreover, ASTRIUM ST is the industrial prime contractor for the Columbus laboratory (which is part of the ISS) as well as the ATV and has become a specialist in re-entry vehicles, propulsion systems and space equipment.

ASTRIUM Satellites focuses on the design and manufacture of satellite systems, while ASTRIUM Services handles everything that comes along with the use of satellites: Earth observation, navigation and secure communications.

This project was carried out at ASTRIUM ST Bremen in Germany. This particular site has its own field of expertise: manned spaceflight, launch vehicles and space robotics. With around 1000 employees, the company makes a key contribution to the International Space Station via the Columbus space lab and the ATV. The upper stage of the Ariane 5 launcher is also developed and built in Bremen.

More specifically, this analysis was made within the department TEB 43. Here is an organization chart to understand better:
There are four teams, which amount to thirty people inside the department TEB 43:
- Advanced projects
- A5ME development
- MPCV development
- Production & ARTA

This project was conducted within the latter, which is responsible for the upper stage from the time it is produced and during all its life time.
II. Presentation of the ESC-A

The Ariane rocket family is the symbol and pride of Europe’s enrolment in the Space Race. The latest version, Ariane 5, is divided into three stages: the main cryogenic stage (EPC), the two side boosters and the cryogenic upper stage ESC-A. This part aims at giving an overview of the object of this analysis: the ESC-A.

Below is the synoptic of this stage, in order to have a better idea of how it is organized:
The ESC-A was historically derived from the H10 stage that was used on the previous version Ariane 4. Some arrangements and improvements were made to reuse as many existing features as possible, while others are completely new. Among the unchanged items are the engine called HM7B, the Fluid Control Equipment (FCE), the LOX tank and the Engine Frame (Bâti Moteur BM). The biggest change between the H10 and the ESC-A is the LH2 tank: to fit with the increased diameter of Ariane 5, the idea was to reuse the LOX tank and to put the LH2 tank on top of it.

The aim of the cryogenic upper stage is to place the payload onto its predefined orbit, using the engine. To supply any engine, one needs propellant, a combustion chamber and a means to drive the propellant from the tank into the combustion chamber. Thanks to the turbopump, the propellants get to the combustion chamber under high pressure with the correct flow rate. Since liquid hydrogen is used to cool down the chamber and the nozzle extension, it vaporizes before reaching the combustion chamber. Oxygen however is directly injected at liquid state. The propellants are then mixed inside the chamber and ignited creating the thrust that will propel the whole stage.

The crucial problem when using liquid hydrogen and liquid oxygen as propellants is their storage. Indeed, their vaporisation temperatures are extremely low: 90 K for oxygen and 20 K for hydrogen. Moreover, one litre of liquid hydrogen amounts to roughly 700 litres of gaseous hydrogen. The LH2 tank is thus one of the most hazardous items inside the ESC-A.
III. Problematic

Space has become essential for our daily lives: from telecommunications to weather forecast and from scientific advances to security and defence. In this context, new challenges have arisen: achieving better performance, increased efficiency but at lower costs. A company such as ASTRIUM needs to find solutions to ensure its leadership within an increasingly competitive environment.

Since the Ariane 5 flight V157 in 2002, the loading level of liquid hydrogen inside the LH2 tank has been raised, enabling to increase the payload mass or the altitude of the delivery orbit. However, the rocket was first designed and certified for a lower liquid level. As a consequence, such a change questions the safety of the launcher.

Moreover, the LH2 tank is one of the most hazardous items inside the ESC-A. Indeed, with a vaporization temperature of 20 K, liquid hydrogen is hard to store. Besides, one litre of liquid hydrogen amounts to roughly 700 litres of gaseous hydrogen, making it even more difficult to handle as a propellant. The design and the use of the LH2 tank are thus very challenging.

For these reasons, **the purpose of this study is to assess whether the LH2 tank has a safety level still high enough when overloaded.**

**Objectives**

The safety of the overloaded LH2 tank should be guaranteed both on ground and during flight. However, this study focuses only on the flight preparation phase, that is to say, the ground phase starting from tank loading until lift-off (H0).

The objectives of this internship are:

- To define the key parameters that are relevant when assessing the safety of the LH2 tank
- To develop a code using MatLab, that would enable to calculate the evolution of these key parameters during ground phase
- To conclude on the safety of the overloaded launcher
IV. Methodology

To reach the objectives presented above, the first step was to define the notion of safety. The definition of safety relies on the respect of constraints: for a given phase, if this parameter respects this constraint, then the tank is guaranteed to be safe enough. These constraints are gathered in the official documents written by ASTRIUM called Spécifications de Mise en Oeuvre de l’ESC-A (SMO) [1].

The second step was to consider the most dimensioning case. Indeed, if the launcher is safe in the worst situation possible, it will be safe in any other less dangerous case. Once this was done, the SMO furnished exactly which parameters to study and what requirements they had to fulfill.

Finally, to develop the MatLab code, every physical effect occurring during the ground phase had to be taken into account. For that matter, a previous study [2] was used. Moreover, the model was refined step by step. Starting from rough assumptions leading to coherent results, the code was then changed so that it would get closer and closer to what happened in reality.
V. Ground phase operations

This analysis focuses on the safety on ground, meaning from tank filling until lift-off (H0). The following part describes the different operations occurring during flight preparation phase.

Tank cooling

This first phase consists in cleaning up the tank and ensuring a certain gas temperature. The tank is flushed with helium by operating several cycles of opening and closing relevant valves in order to first clean up the tank and then cool it down. This step continues until the end of the “chasse-bulle” phase (see next paragraph).

Tank chilling down and LH2 feed line flushing (or “chasse-bulle” phase)

The objective here is to prepare the tank for the filling phase. The relevant valve is opened so that hydrogen enters the tank; then the ground valve is activated to start the tank chilling down. During the whole process, the pressure must be regulated. Moreover, the LH2 feed line is flushed with gaseous hydrogen in order to make sure that there is no helium left in the U-turn forming the start of the feed line; this operation is called “chasse-bulle”:

Tank filling phase

The aim is now to fill in the LH2 tank. The flow rate through the ground valve is first increased to an intermediate value and then set to maximum to accelerate the filling. The LH2 tank is then depressurized. This phase ends when M7NV103 or M7NV203 sensor indicates a certain threshold. As soon as this value is reached, the flow rate is set back to its previous intermediate value.
**Tank topping up phase**

The topping up phase consists in keeping the liquid level in the LH2 tank close to the target level using predefined margins. At the end of this phase, the ground valve is closed and the tank pressurization can start.

**Pressurization**

During the pressurization phase, the aim is to reach a tank pressure which is compliant with flight requirements. The pressurization duration is in the range of one minute. The ground valves are then closed and their umbilicals are purged. The gas pressure inside the LH2 tank must remain under the specified higher pressure threshold.

During all these phases, the temperature and pressure vary causing some changes in the LH2 tank volume as well. These phenomena are the focus of next part.
VI. LH2 behaviour during ground phase

This part focuses on the behaviour and phenomena occurring during the ground phase operations described above.
The following graph shows the evolution of the liquid level during ground phase:

Three parts can be deduced from ground valve closure until lift-off (H0).

At ground valve closure and before start of pressurization, the liquid level decreases. During pressurization, the level drops. Finally, between end of pressurization and lift-off, the liquid level increases linearly.

This evolution can be explained by several physical phenomena occurring on ground:

- Tank contraction due to temperature decrease
- Tank dilatation due to pressure increase
- Evaporation of liquid hydrogen
- Out gassing
- Heat fluxes into LH2 tank

These physical effects are explained in the following sections.
**Tank contraction due to temperature decrease**

When filling the tank with liquid hydrogen, this substance being at 20 K, the tank volume reduces due to a change in the properties of the tank material. The volume at a given temperature $T$ can be calculated as follows: [2]

$$V(T) = V_{293K} \left[1 - \alpha_T \frac{293 - T}{293 - 20}\right]^3$$

(1)

Where

- $V_{293K}$ is the tank volume at 293 K [m$^3$]
- $\alpha_T$ is the dimensionless “thermal contraction coefficient”
- $T$ is the temperature at which the volume is calculated [K]

**Tank dilatation due to pressure increase**

The differential pressure increase between inside and outside the tank leads to a rise in the real LH2 tank volume. The liquid level will thus change. For a given delta pressure $\Delta P$, the volume is expressed by:

$$V(P) = V(T)[1 + \alpha_P \Delta P]$$

(2)

Where $\alpha_P$ is the dimensionless “dilatation under pressure coefficient”

**Evaporation of LH2**

At ground valve closure, the saturation pressure is equal to the loading pressure. Additional evaporation occurs at the contact surface between liquid and gaseous hydrogen. Though specific models to quantify this phenomenon are needed, few kilograms of liquid hydrogen will be assumed to evaporate between ground valve closure and start of pressurization in order to remain as simple as possible. Since there is no additional evaporation until upper stage engine ignition, the mass of liquid hydrogen remains constant from start of pressurization until after lift-off.

**Out gassing**

During tank filling, the saturated conditions cause gaseous hydrogen to be absorbed into the liquid hydrogen phase. This gas is released during tank pressurization with helium. This phenomenon has an impact on the liquid level of hydrogen and is described by the boiling rate $f$.

**Temperature increase due to tank compression**

During tank pressurization, the temperature of liquid hydrogen increases due to compression.
Heat fluxes on ground

On ground, after pressurization, entering heat fluxes lead to a liquid hydrogen temperature increase expressed as follows:

\[ \dot{Q} = \frac{m \cdot c_p \cdot \Delta T}{\Delta t} \]  \hspace{1cm} (3)

Where
\( \dot{Q} \) are the entering ground heat fluxes [W]
\( m \) is the mass of liquid hydrogen [kg]
\( c_p \) is the specific heat capacity under constant pressure [J.kg\(^{-1}\).K\(^{-1}\)]
\( \Delta T \) is the delta temperature [K]
\( \Delta t \) is the time step [s]

The density is thus decreased meaning that the volume directly linked to the liquid level increases (the mass of liquid hydrogen remains constant).
No additional evaporation is assumed although the liquid temperature rises.

From thermal studies [3], we get three different cases of ground heat fluxes:

- Cold case
- Mean case
- Hot case
VII. Tank Performance Analysis

This part explains the theory that was used to reach the objectives of the project.

1) Context

Since the Ariane 5 flight V 157, the loading level of liquid hydrogen inside the LH2 tank has been raised, questioning the safety of the launcher. The purpose of this study is thus to assess whether the LH2 tank still respects the constraints set by the SMO [1] when overloaded. For that matter, the first step is to determine the most dimensioning case. Knowing this, key parameters must be identified. Finally, using a simplified model, the aim is to calculate the evolution of these parameters so that a conclusion can be drawn concerning the safety problem.

2) Worst case scenario

When studying the safety of the LH2 tank, the most important thing is to consider the most dimensioning case. A risk analysis reveals that the worst case scenario is as follows:
- Nominal pressurization of the LH2 tank
- Launch abort at H0, meaning that the cryogenic arms are no longer connected to the launcher
- LH2-Tank depressurization within 3 minutes starting from H0 if the liquid level enables it: in order to take the worst possible situation, depressurization will occur at the latest, i.e. after three minutes isolation from launch abort on.
- Tank emergency de-loading

Knowing this, the criteria that should be respected for the different variables can be defined with reference to the SMO [1]:

**Tank Pressure:** from a structural point of view, the SMO [1] specifies that the tank pressure should not get higher than $P_{damage}$.

**Liquid level:** because of the geometry of the diffuser, a maximum liquid level has been set by the SMO [1] to $x_{ingestion}$. A higher level would cause ingestion into the diffuser.

The first objective is now reached: key parameters have been defined and all the tools needed to describe their evolution on ground have been presented. The second objective now is to develop a MatLab code in order to simulate the evolution of key parameters, so that a conclusion on the safety of the overloaded tank can be drawn. The theory on which rely all the calculations is explained in the following part.
3) Simplified model

Assumptions

- The heat fluxes are assumed to be constant during the whole ground phase. The liquid temperature rises thus linearly (equation (3)).
- Even though the liquid temperature rises and the tank pressure changes, no additional evaporation is assumed apart from a few kilograms between ground valve closure and start of pressurization.
- The boiling rate \( f \) is set to a precise value using [4].
- Gaseous hydrogen and helium are assumed to be ideal gases.
- The gas temperature is set to a constant value (average value).

These assumptions are valid for the whole simplified model.

1) Tank isolation

As mentioned before, the worst case scenario starts with an isolation phase: from launch abort announcement occurring at H0 until start of tank depressurization (at the latest three minutes later).

Liquid level

Additional assumptions

Valve S37 ensures the tank pressure regulation. It opens when the tank pressure gets higher than the upper threshold \( P_{\text{max}} \) and closes when it drops to the lower threshold \( P_{\text{min}} \) [5]. In a first approximation, a constant tank pressure can be assumed from launch abort at H0 until start of tank depressurization through SCAR 16 and/or SCAR 14 (three minutes after H0).

The purpose here is to evaluate the liquid level after three minutes isolation starting from launch abort in order to ensure that the depressurization is allowed with reference to the SMO file 133 [1].

Calculation process

Knowing the pressure at ground valve closure \( (P_{\text{cp}}) \), the mass of LH2 inside the tank \( (\text{mass}) \), the liquid temperature \( (T_{\text{liq}}) \) and the tank pressure \( (\text{tankpressure}) \); the gas volume, liquid volume and liquid level are calculated using a function defined in MatLab:

\[
\text{tankLh2}(P_{\text{cp}}, \text{mass}, \text{pressurized}, \text{tankpressure}, T_{\text{liq}}, \text{bubblingfac}, p_{\text{atm}})
\]

When the parameter called pressurized is set to “true”, this function takes into account the thermal contraction due to the temperature of liquid hydrogen, as well as the tank dilatation due to the pressure difference between inside and outside the tank.
Besides, the liquid temperature can be calculated with equation (3), using the fact that the heat fluxes on ground are constant:

$$
\Delta T = \frac{\Delta t \cdot \dot{Q}}{m \cdot c_p}
$$

(4)

Where

$\Delta t$ is the time step [s]
$m$ is the mass of liquid hydrogen [kg]
$c_p$ is the specific heat capacity at constant pressure [J.kg$^{-1}$.K$^{-1}$]
$\dot{Q}$ are the entering ground heat fluxes [W]

**Tank Pressure**

**Additional assumptions**

To calculate the pressure evolution from H0 and during the three minutes preceding tank depressurization, no regulation through S37 is assumed. The purpose is to see if the pressure would get higher than the upper limit $P_{damage}$ if the pressure regulation did not work.

**Calculation process**

The pressure is calculated using the ideal gas equation:

$$
P_{tank} = \frac{m_{Gas}RT_{Gas}}{V_{Gas}}
$$

(5)

Where

$m_{Gas}$ is the total mass of gas, i.e. helium and gaseous hydrogen [kg]
$R$ is the specific gas constant [J.kg$^{-1}$.K$^{-1}$]
$T_{Gas}$ is the gas mixture temperature [K]
$V_{Gas}$ is the volume occupied by the gas mixture [m$^3$]
One of the unknowns in equation (5) is the mass of gas inside the tank. Hereafter is an explanation of how it is calculated:

**Before Tank Pressurization**

Before the tank is pressurized, it is assumed that the pressure inside the tank $P_{loading}$, which is also the pressure at ground valve closure ($P_{cp}$) is equal to the saturation pressure $P_{sat}$:

$$P_{loading} = P_{sat} \text{ meaning that } T_{sat} = T_{LH_2}$$

Moreover, the liquid temperature is assumed to be equal to the gas temperature. Since before pressurization, there is only hydrogen inside the tank:

$$T_{LH_2} = T_{GH_2} = T_{sat}$$

The only remaining unknown in equation (5) is the gas volume, which can be deduced from the tank volume and liquid volume:

$$V_{Gas} = V_{Tank} - V_{liquid}$$

With all these assumptions, the mass of gaseous hydrogen can be deduced:

$$m_{GH_2} = \frac{P_{loading} \cdot V_{Gas}}{R_{GH_2} T_{GH_2}} \quad (6)$$
After pressurization

The aim of the pressurization is to set the tank pressure to a predefined value: $P_{\text{new}}$
For that matter, a certain mass of helium is injected inside the tank. This mass can be calculated as follows:

From the ideal gas equation (5), the tank pressure at H0 can be expressed by:

$$p_{\text{tank}} = P_{\text{new}} = \frac{(m_{\text{GH}_2} + m_{\text{He}})RT_{\text{gas}}}{V_{\text{gas},H0}} \quad (7)$$

Where $m_{\text{GH}_2}$ is the mass of gaseous hydrogen, $m_{\text{He}}$ is the mass of helium, $T_{\text{gas}}$ is the gas temperature, $V_{\text{gas},H0}$ is the gas volume at H0 and $R$ is the specific gas constant that depends on the nature of the considered gas:

$$R = \frac{m_{\text{GH}_2}}{m_{\text{GH}_2} + m_{\text{He}}}R_{\text{GH}_2} + \frac{m_{\text{He}}}{m_{\text{GH}_2} + m_{\text{He}}}R_{\text{He}} \quad (8)$$

The two unknowns in equation (7) are the helium mass $m_{\text{He}}$ and the gas mixture temperature $T_{\text{gas}}$. A second equation is thus needed in order to solve the problem. From (6), the gas mixture temperature is equal to:

$$T_{\text{gas}} = \frac{m_{\text{GH}_2}c_{v,\text{GH}_2}T_{\text{GH}_2} + m_{\text{He}}c_{v,\text{He}}T_{\text{He}}}{m_{\text{GH}_2}c_{v,\text{GH}_2} + m_{\text{He}}c_{v,\text{He}}} \quad (9)$$

By injecting the temperature expression (9) into equation (7), a second degree equation is obtained:

$$a \cdot m_{\text{He}}^2 + b \cdot m_{\text{He}} + c = 0 \quad (10)$$

Where

$$\begin{align*}
    a &= R_{\text{He}}c_{v,\text{He}}T_{\text{He}} \\
    b &= R_{\text{He}}m_{\text{GH}_2}c_{v,\text{GH}_2}T_{\text{GH}_2} + R_{\text{GH}_2}m_{\text{GH}_2}c_{v,\text{He}}T_{\text{He}} - P_{\text{new}}V_{\text{gas},H0}c_{v,\text{He}} \\
    c &= R_{\text{GH}_2}m_{\text{GH}_2}^2c_{v,\text{GH}_2}T_{\text{GH}_2} - P_{\text{new}}V_{\text{gas},H0}m_{\text{GH}_2}c_{v,\text{GH}_2}
\end{align*}$$
The helium mass can be calculated solving equation (10) and the gas mixture temperature is then deduced using equation (9):

\[
\begin{align*}
    m_{He} &= \frac{-b + \sqrt{b^2 - 4ac}}{2a} \\
    T_{Gas} &= \frac{m_{GH_2} \cdot c_{v,GH_2} \cdot T_{GH_2} + m_{He} \cdot c_{v,He} \cdot T_{He}}{m_{GH_2} \cdot c_{v,GH_2} + m_{He} \cdot c_{v,He}}
\end{align*}
\]

The purpose of the calculations is to determine the pressure and liquid level evolutions inside the LH2 tank from launch abort at H0 until H0 + 3 minutes.

Since the liquid volume and gas volume depend on the liquid temperature and tank pressure, these calculations use a loop. The principle is as follows:

1) Define a time step
2) During this time laps, the liquid temperature increases linearly according to equation (4)
3) Having calculated the new liquid temperature, the liquid level as well as the gas volume can be deduced using the MatLab function `tankLh2`.
4) Since the gas mass is constant as well as the gas temperature, the tank pressure can be deduced using the ideal gas equation (5):

\[
p_{tank} = \frac{m_{Gas}RT_{Gas}}{V_{Gas}}
\]

This loop returns the tank pressure, the liquid level (and corresponding volume), the liquid temperature and the gas volume at the end of tank isolation (H0 + 3 minutes).
2) Pressure regulation

As said before, when the tank is isolated, the pressure is regulated thanks to valve S37. This valve opens automatically when the tank pressure reaches the upper threshold $P_{\text{max}}$ and closes again when the pressure has dropped to the lower threshold $P_{\text{min}}$ [5]:

![Diagram of pressure regulation](image)

In a first approximation, a constant pressure was assumed (VII. 3) 1) Tank isolation). To be closer to reality, the aim is now to develop a model that takes into account the pressure regulation and assess the evolution of the different tank parameters during isolation from H0 until H0 + 3 minutes.

Calculation process

At H0, the tank pressure is set to its nominal value. At this point, the launch is aborted and the tank remains isolated under pressure for maximum three minutes before depressurization. The model should thus consider three minutes pressure regulation by S37 from launch abort on.

The principle is based on a loop since the mass flow rate through S37 depends on the nozzle inlet pressure. Indeed, due to ground heat fluxes, the liquid temperature increases leading to a liquid level increase. As a consequence, the gas volume decreases changing the tank pressure and thus the S37 inlet pressure.

The loop consists in the following calculation process:

1) Define a time step
2) All parameters are initialized at their value at H0. Being isolated, the tank pressure increases continuously. First, the liquid temperature increases linearly driven by the following equation (4):
\[ \Delta T = \frac{\Delta t \cdot Q}{m \cdot c_p} \]  \hfill (4)

The liquid level is then recalculated using the function `tankLh2` with this new liquid temperature. From that, the gas volume is deduced (with `tankLh2` again) and finally, considering that the gas mass is constant, the pressure inside the tank is calculated using the ideal gas equation (5):

\[ p_{tank} = \frac{m_{gas}RT_{gas}}{v_{gas}} \]  \hfill (5)

3) When the pressure gets higher than the upper threshold \( p_{max} \), valve S37 opens. This is reflected by a mass flow rate going through the purge nozzle.

Another loop enables to calculate the pressure evolution while S37 is open. At each step in this second loop, the liquid temperature continues to increase with the same equation (4). At the same time, the mass flow rate through S37 is calculated. Considering the pressure difference between nozzle inlet and outlet, the nozzle can be assumed to be choked. The mass flow rate can thus be expressed as follows:

\[ \dot{m} = C \cdot A \sqrt{\gamma \rho_0 p_0 \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}} \]  \hfill (11)

Where:
- \( C \) is the discharge coefficient set to 1 [\(-\)]
- \( A \) is the cross section area of the purge nozzle [\( m^2 \)]
- \( \gamma \) is the heat capacity ratio of the gas going through the nozzle [\(-\)]
- \( \rho_0 \) is the gas density at pressure \( p_0 \) and temperature \( T_0 \) [\( kg/m^3 \)]
\( p_0 \) is the upstream total pressure of the gas [Pa]

Or using the ideal gas equation (5), the density can be expressed by:

\[
\rho_0 = \frac{p_0}{RT_0}
\]

The mass flow rate can also be given by the expression:

\[
\dot{m} = C \cdot A \cdot p_0 \left( \frac{\gamma}{RT_0} \right)^{\frac{\gamma+1}{2(\gamma-1)}}
\]

(12)

Where:
- \( C \) is the discharge coefficient set to 1 [-]
- \( A \) is the cross section area of the purge nozzle [m²]
- \( \gamma \) is the heat capacity ratio of the gas going through the nozzle [-]
- \( p_0 \) is the upstream total pressure of the gas [Pa]
- \( T_0 \) is the upstream total temperature of the gas [K]

Furthermore, the LH2 tank is assumed to be filled with a gaseous mixture of helium and gaseous hydrogen. These two gases do not mix when inside the tank as can be seen on the following representation:

This means that the gas going through S37 is pure helium. The following assumption on the helium mass fraction is thus made:

\[
MassFraction_{He} = \begin{cases} 
1 & \text{if } m_{He,\text{tank}} > \frac{m_{He,Ho}}{10} \\
0 & \text{if } m_{He,\text{tank}} \leq 5.10^{-2}kg \\
\frac{m_{He}}{m_{He} + m_{GH2}} & \text{if } 5.10^{-2}kg < m_{He,\text{tank}} < \frac{m_{He,Ho}}{10}
\end{cases}
\]
The helium mass decreases as well as the gaseous hydrogen mass, so the total mass of gas can be expressed as follows:

\[ m_{\text{He,new}} = m_{\text{He,initial}} - \text{MassFraction}_{\text{He}} \cdot \dot{m} \cdot \Delta t \]
\[ m_{\text{GH}_2,\text{new}} = m_{\text{GH}_2,\text{initial}} - \text{MassFraction}_{\text{GH}_2} \cdot \dot{m} \cdot \Delta t \]

Where \( \text{MassFraction}_{\text{GH}_2} = 1 - \text{MassFraction}_{\text{He}} \)

Leading to the total mass of gas:

\[ m_{\text{Gas}} = m_{\text{GH}_2} + m_{\text{He}} \]

The mass fractions can then be recalculated and the new value of the specific gas constant \( R \) deduced (equation (8)).

Finally, the pressure inside the tank is equal to:

\[ p_{\text{tank}} = \frac{m_{\text{Gas}} RT_{\text{Gas}}}{V_{\text{Gas}}} \]  
(5)

4) The valve remains open as long as the pressure inside the tank is higher than the lower threshold \( p_{\text{min}} \). When the pressure gets low enough, the valve is closed meaning that the mass flow rate is equal to zero and the pressure is calculated using the first loop.

Limits:

Since the gas goes through lines before being expelled by the purge nozzle, the pressure at the nozzle inlet should actually be less than the tank pressure because of the losses in the lines. From equation (12),

\[ \dot{m} = C \cdot A \cdot p_0 \left( \frac{\gamma}{RT_0} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}} \right) \]  
(12)

the mass flow rate is proportional to the inlet pressure \( p_0 \). If the pressure \( p_0 \) is higher than in reality, the mass flow rate is over evaluated as well, meaning that the depressurization time is under estimated.

Moreover, the model does not consider the additional evaporation of liquid hydrogen even though the temperature inside the liquid phase increases.
3) **Depressurization**

After three minutes isolation starting from launch abort (H0), the tank needs to be depressurized. However, this can only be done if the liquid level is below a certain value \( x_{\text{threshold}} \) given by the SMO [1]. From the previous calculations, it can be concluded on the level value at H0 + 3 minutes. If the level respects the constraint, the tank can be depressurized until three minutes after launch abort announcement. The following calculations aim at evaluating the time duration of this depressurization.

**Additional assumptions**

The initial system is set to the system at H0 + 3 minutes (end of the three minutes following launch abort announcement calculated above), with or without pressure regulation.

According to the SMO [1], the depressurization should be done by opening SCAR 16 (see scheme) and/or SCAR 14 if needed.
Calculation process

The purpose of these calculations is to estimate the time to depressurize the LH2 tank through SCAR 16 and SCAR 14 if needed. For that matter, the mass flow rate needs to be calculated. Since the mass flow rate depends on the inlet pressure which varies with the gas volume and thus the liquid level, the same problem as in the previous part arises. The calculation process uses a loop to recalculate the different parameters that vary at each time step. The iteration is explained below:

1) Define a time step
2) Initialize the tank parameters to the values at \( H_0 + 3 \) minutes: tank pressure, tank temperature, liquid level, mass of helium and gaseous hydrogen, liquid temperature, helium and gaseous hydrogen mass fractions
3) Knowing the tank pressure, the nozzle inlet pressure is deduced by introducing loss coefficients [7]
4) During the time step and knowing the nozzle inlet and outlet pressures, the mass flow rate through the SCAR can be calculated. This mass flow rate depends however on the pressure ratio between nozzle inlet and nozzle outlet. If the pressure ratio is higher than a critical ratio, the nozzle is choked. This critical value can be expressed through the dimensionless ratio:

\[
\frac{p^*}{p_0} = \left( \frac{2}{\gamma + 1} \right)^{\frac{y-1}{y + 1}}
\]  

(13)

The mass flow rate can then be expressed by the previous equation (11):

\[
\dot{m} = C \cdot A \cdot \sqrt{\gamma \rho_0 p_0 \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}}}
\]  

(11)

Or the modified expression (12):

\[
\dot{m} = C \cdot A \cdot p_0 \sqrt{\frac{\gamma}{RT_0} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}}}
\]  

(12)

If the pressure ratio is less than the critical ratio, the nozzle is unchoked and the mass flow rate is then equal to:

\[
\dot{m} = C \cdot A \sqrt{2 \rho_1 p_1 \left( \frac{\gamma}{\gamma - 1} \right) \left[ \left( \frac{p_2}{p_1} \right)^{\frac{\gamma}{\gamma - 1}} - \left( \frac{p_2}{p_1} \right)^{\frac{\gamma + 1}{\gamma}} \right]}
\]  

(14)

Where the index 1 corresponds to the nozzle inlet and the index 2 corresponds to the nozzle outlet.
Using the ideal gas law (5), the mass flow rate becomes:

\[
\dot{m} = C \cdot A \cdot p_1 \sqrt{\frac{2}{RT_1} \left( \frac{\gamma}{\gamma - 1} \right) \left[ \left( \frac{p_2}{p_1} \right)^{\frac{\gamma}{\gamma - 1}} - \left( \frac{p_2}{p_1} \right)^{\frac{\gamma + 1}{\gamma}} \right]}
\]  

(15)

5) Knowing the mass of gas going through the nozzle during the time step, the remaining mass of gas mix can be deduced:

\[
m_{He,\text{new}} = m_{He,\text{initial}} - \text{MassFraction}_{He} \cdot \dot{m} \cdot \Delta t
\]

\[
m_{GH,\text{new}} = m_{GH,\text{initial}} - \text{MassFraction}_{GH} \cdot \dot{m} \cdot \Delta t
\]

6) The total mass of gas inside the LH2 tank is thus:

\[
m_{\text{Gas}} = m_{GH} + m_{He}
\]

7) With these new mass values, the new mass fractions can be calculated leading to a new value of the specific gas constant \( R \):

\[
R = \frac{m_{GH}}{m_{GH} + m_{He}} R_{GH} + \frac{m_{He}}{m_{GH} + m_{He}} R_{He}
\]  

(8)

8) On the other hand, the ground heat fluxes increase the liquid temperature (equation (4)):

\[
T = T_{\text{initial}} + \frac{Q \Delta t}{m \cdot c_p}
\]

9) With this new liquid temperature, the liquid level changes and is calculated using the function `tanklh2` in MatLab. The same function furnishes the new gas volume.

10) Knowing the total mass of gas inside the tank, the helium mass fraction, the gas temperature as well as the gas volume, the tank pressure can now be calculated using the ideal gas equation (5):

\[
p_{\text{tank}} = \frac{m_{\text{Gas}} R T_{\text{Gas}}}{V_{\text{Gas}}}
\]  

(5)

This iteration is done until the tank pressure reaches a value of 1.3 bar.

Limits:

The gas mass is roughly estimated since no additional evaporation is considered even though the liquid temperature rises.

When considering the tank depressurization, the pressure was assumed to fall down to a threshold of 1.3 bar (higher than the atmospheric pressure) to avoid a divergence of the model. This threshold has been chosen to counter the fact that under certain pressure and temperature conditions, liquid hydrogen evaporates. The use of refprop does not allow to consider these temperatures and pressures. The same
reason leads to a shorter time of simulation when studying the tank isolation with high ground heat fluxes (hot case).

4) Tank isolation before deloading

The tank is isolated again between end of depressurization and start of deloading. The key parameter here is again the liquid level which must not overspend $x_{\text{ingestion}}$. The calculations conducted here aim at determining the time it takes to reach this limit. For that matter, the principle used is the same as in the first section (VII.3)1) Tank Isolation). The initial system is set to the system at end of depressurization.

5) Tank isolation during ten minutes

In the worst case, the tank can be isolated without being depressurized nor deloaded for ten minutes from launch abort announcement on. The isolated tank model was used to assess the evolution of the tank parameters in this case.
VIII. Results

This part focuses on the results obtained with the simulations that have just been presented above.

1) Gas temperature

When solving the system of equations (9) and (10), the following gas temperatures are obtained depending on the ground heat fluxes and the pressure at H0 (launch abort):

<table>
<thead>
<tr>
<th>Pressure at H0</th>
<th>3.25 bar</th>
<th>3.3 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat flux</td>
<td>cold</td>
<td>mean</td>
</tr>
<tr>
<td>Gas Temperature (K)</td>
<td>49.2</td>
<td>48.8</td>
</tr>
</tbody>
</table>

From [8], the average gas temperature was found to be equal to 47.3 K. The values here above are not far from this reference and can thus be considered as valid.

2) Tank isolation before depressurization

1) Under constant pressure

In a first approximation, the tank pressure was set to a constant at H0, either 3.25 bar or 3.3 bar. The constraint set by the SMO [1] was to not overspend $x_{threshold}$ to be able to depressurize. The following table gives the liquid level three minutes after H0 under this assumption:

<table>
<thead>
<tr>
<th>Pressure at H0</th>
<th>3.25 bar</th>
<th>3.3 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat flux</td>
<td>cold</td>
<td>mean</td>
</tr>
<tr>
<td>Liquid Level at H0 + 3 minutes</td>
<td>$&lt; x_{threshold}$</td>
<td>$&lt; x_{threshold}$</td>
</tr>
</tbody>
</table>
The evolution of liquid level can be drawn from ground valve closure until three minutes after launch abort (H0 + 3 minutes):

![Liquid Level Evolution under Constant Pressure 3.25 bar](image1)

![Liquid Level Evolution under Constant Pressure 3.3 bar](image2)

From the values obtained, one can notice that:
- The higher the heat fluxes, the higher the liquid level. The temperature of liquid hydrogen increases even more when the heat fluxes are higher, leading to a stronger decrease in the density and thus a stronger liquid volume increase. The liquid level is indeed higher.
- Comparing the liquid level under equal heat fluxes:

The liquid level is lower if the tank pressure is higher. Indeed, if the pressure increases, the tank volume increases as well due to the dilatation caused by the pressure difference between inside and outside the tank (see VI). The liquid level is thus lower.

In the worst case, the liquid level is well under the maximal threshold \( x_{\text{threshold}} \) to be able to depressurize the tank. So, in case of a launch abort, the LH2 tank can be depressurized at any time point within the first three minutes. The requirements stated by the SMO [1] are thus fulfilled.

2) With pressure regulation through S37

To refine these calculations, the idea was to develop a model to simulate the tank pressure regulation through S37. The results are gathered in the following table:

<table>
<thead>
<tr>
<th>Pressure at H0</th>
<th>Regulated Pressure through S37</th>
<th>3.25 bar</th>
<th>3.3 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat flux</td>
<td></td>
<td>cold</td>
<td>mean</td>
</tr>
<tr>
<td>Liquid Level at H0 + 3 minutes</td>
<td>( &lt; x_{\text{threshold}} )</td>
<td>( &lt; x_{\text{threshold}} )</td>
<td>( &lt; x_{\text{threshold}} )</td>
</tr>
</tbody>
</table>

The evolution of the liquid level can be drawn for the different heat fluxes and starting with a pressure at H0 of 3.25 bar or 3.3 bar:
In this case, the results depend on the computation time. Indeed, the regulation was assumed to last for three minutes starting from launch abort at H0. Here again, one can notice that:
- The higher the heat fluxes, the higher the liquid level.
- Under equal heat fluxes, the liquid level is lower if the tank pressure is higher. This is true for both cold and hot cases but not for the mean case as can be seen on the graph hereafter. This is due to the computation time.
Once more, the levels do not overspend the maximum threshold. This could be awaited since the calculations with a rough model showed the same result. However, there could have been some unexpected values due to the consecutive openings and closings of valve S37.

Concerning the pressure evolution, the following table gives the pressure three minutes after H0:

<table>
<thead>
<tr>
<th>Regulated Pressure through S37</th>
<th>3.25 bar</th>
<th>3.3 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressure at H0</strong></td>
<td>cold</td>
<td>mean</td>
</tr>
<tr>
<td><strong>Heat flux</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cold</td>
<td>$&lt; P_{\text{damage}}$</td>
<td>$&lt; P_{\text{damage}}$</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hot</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thanks to the S37, the pressure inside the tank never gets higher than $P_{\text{damage}}$. Actually, it does not overspend the upper threshold $P_{\text{max}}$. The graphs here under show the evolution of this tank pressure during three minutes starting from H0:
Since the results depend on the computation time, the tank pressure in the mean case in terms of heat fluxes happens to be lower than in the two other cases.

Looking closely at the mean heat flux case, the liquid level evolution if the pressure is regulated through S37 can be compared to its evolution under constant pressure. The following graph shows the liquid level evolution in the two cases in question:
The results for these two cases are not far from each other, which validates the refined model simulating the pressure regulation through S37.

Conclusion:

Thanks to the regulation through S37, the pressure does not overspend the structural limit $P_{\text{damage}}$. Moreover, the liquid level remains under $x_{\text{threshold}}$ stated by the SMO [1]: the constraints are thus fulfilled and the LH2 tank can be depressurized at any time point within three minutes following launch abort announcement.

3) Isolated tank

Another scenario was to imagine that there was no pressure regulation meaning that the tank would be completely isolated during three minutes starting from H0. The following table shows the results on the liquid level in this case:

<table>
<thead>
<tr>
<th>Pressure at H0</th>
<th>3.25 bar</th>
<th>3.3 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Level at H0 + 3 minutes</td>
<td>$&lt; x_{\text{threshold}}$</td>
<td>$&lt; x_{\text{threshold}}$</td>
</tr>
</tbody>
</table>
The following graphs show the liquid level evolution during isolation:

Here as well, the liquid levels are below $x_{\text{threshold}}$ that must not be overspent to be able to depressurize the tank.

The same phenomena can be noticed in this case as well:
- The higher the heat fluxes, the higher the liquid level.
- Under equal heat fluxes, the liquid level is lower if the tank pressure is higher:

Moreover, comparing this case with the regulated tank:

Under equal heat fluxes, the liquid level in the isolated tank is much lower than in the regulated tank. This can be explained by the dilatation of the tank. When the pressure inside the tank is higher, its volume increases leading to a decrease in the liquid level (see VI).

In terms of liquid level, the isolated tank appears to be a less critical case because of the tank dilatation.

However, in this particular case, the tank pressure must be calculated carefully. Indeed, with the heat fluxes on ground, the absence of pressure regulation can lead to a dramatic increase in this parameter. The evolution of the tank pressure can be drawn:
Even though the pressure increases continuously during three minutes tank isolation starting from H0, the structural limit of $P_{\text{damage}}$ is not reached whatever the heat fluxes. In this degraded case (no pressure regulation) of an already degraded case (launch abort), the constraints are fulfilled.

**Conclusion:**

With this first part of calculations, it has been established that in case of a launch abort occurring at H0, the tank depressurization at any time point within three minutes following launch abort announcement is possible according to the constraints set by the SMO [1].

The next part will thus focus on the depressurization phase, and study the evolution of key parameters inside the LH2 tank.
3) Depressurization

This part focuses on the results of the LH2 tank depressurization. Depending on the previous phase, the initial state of the system differs.

1) Initial System

Regulated Tank

If the tank is regulated in pressure, the consecutive openings and closings of the S37 lead to a change in the helium mass (pure helium is assumed to go through the valve). The tank parameters at depressurization start is also dependent on the ground heat fluxes.

The following graphs give the evolution of the helium mass during the regulation:
The total gas mass will thus be lower in the regulated tank than in the isolated tank.

**Isolated Tank**

In the isolated tank case, the gas masses remain constant from launch abort announcement until start of depressurization.

2) **Time to depressurize**

The aim of the calculations is to assess the depressurization time duration. Here again, the worst case scenario is studied meaning that only one nozzle is activated: the depressurization is done by opening SCAR 16 only.

From the results obtained, the time to depressurize is longer in the isolated case. Since the initial system is not the same in both cases, the tank parameters need to be studied more carefully in order to determine why the isolated tank takes less time to be depressurized. This will be the aim of next part as well as ensuring that the safety of the launcher is guaranteed with regard to the SMO [1].

3) **Evolution of the tank parameters during depressurization**

**Regulated tank**

If the tank pressure was regulated before starting the depressurization, the initial liquid level, the initial pressure and the gas masses are different than in the isolated case. In terms of safety, the liquid level and the tank pressure are the two most important parameters. The liquid level being higher in the regulated case, its evolution needs to be calculated precisely.
Furthermore, the evolution of the different parameters inside the tank can be drawn:

<table>
<thead>
<tr>
<th>Liquid Level (mm)</th>
<th>Liquid Level Evolution during Depressurization</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{\text{ingestion}}$</td>
<td>![Graph of liquid level evolution]</td>
</tr>
</tbody>
</table>

The liquid levels do not get over $x_{\text{ingestion}}$ that would lead to diffuser ingestion.
The same graphs can be drawn for the tank pressure:

As expected, the tank pressure decreases gradually when opening SCAR 16. One can notice that this evolution is smooth, except for one change in the slope. To understand this discontinuity, the evolution of the mass flow rate going through the nozzle can be drawn:
One can notice on the graphs above a discontinuity in the mass flow rate. If both tank pressure and mass flow rate are drawn on the same graph, the result shows that their discontinuity occurs at the same time point:
This can be explained by the assumption made on the nature of the gas going through the SCAR: pure helium first and a mixture of gaseous hydrogen and helium when the mass of helium gets lower than a certain value. The evolution of the helium mass fraction compared to the mass flow rate and the tank pressure are as follows:
The change in gas nature going through the nozzle is thus the reason of the observed discontinuity in the mass flow rate. This has then the same consequence on the tank pressure and liquid level evolutions. Another interesting thing to notice is the absence of discontinuity in the mass flow rate when the nozzle goes from choked to unchoked. The equations used are thus correct.

Conclusion:

In terms of safety, the liquid level does not reach the maximum limit $x_{ingestion}$ that would lead to diffuser ingestion. The regulated tank fulfils the requirements whatever the ground heat fluxes.
**Isolated tank**

The following graphs show the evolution of the liquid level during tank depressurization if no pressure regulation is assumed:

Here again, these levels are not getting over $x_{\text{ingestion}}$, the maximum requested by the SMO [1].
The second key parameter being the tank pressure, its evolution during depressurization can be drawn:

The discontinuity that was noticed in the previous part appears again in this case and is due to the same reason: the assumption made on the gas nature.
The following graphs can attest it:

**Conclusion:**

The isolated tank satisfies the constraints set by the SMO [1] since the liquid level remains under $x_{ingestion}$ at the end of the depressurization phase.
Comparison between Isolated and Regulated Tank

Having studied both regulated and isolated tanks, the aim now is to compare these two models.

- **Liquid Level**

The liquid levels in the isolated case are not very far from those found with the regulated tank. An explanation could be that the initial level is lower in the isolated case but the time to depressurize is longer.
- **Time to depressurize**

Moreover, the depressurization time does not vary too much between the two models. This can be explained by the fact that the mass flow rate through SCAR 16 decreases by 30% in the regulated case compared to the isolated case.

![Mass Flow Rate Graph](image)

This difference must be due to the pressure value. Indeed, the mass flow rate depends on the nozzle inlet pressure (equation (12)), which is directly related to the tank pressure.

![Tank Pressure Evolution Graph](image)

In the isolated case, the tank pressure is much higher than in the regulated case, leading to this difference between the two values.
Conclusion:

The calculations for the tank depressurization show a low time to depressurize. However, the model does not enable to go to a tank pressure equal to the atmospheric pressure but only to a value of 1.3 bar, leading to an underestimation of the depressurization time.

Now that the tank has been depressurized, more than three minutes have passed since launch abort announcement at H0. However, it is not sure that the deloading will start immediately after this phase. Since liquid hydrogen must not get into the diffuser, the next part gives the time it would take before the liquid level reaches the value \( x_{\text{ingestion}} \).

4) Tank isolation before deloading

The following graphs give the complete evolution from launch abort announcement at H0 until diffuser ingestion for both regulated and isolated tanks.

*Regulated Tank*
The total duration from launch abort announcement at H0 until diffuser ingestion can thus be deduced and the conclusions are gathered in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Regulated Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressure at H0</strong></td>
<td>3.25 bar</td>
</tr>
<tr>
<td><strong>Heat flux</strong></td>
<td>cold</td>
</tr>
<tr>
<td></td>
<td>cold</td>
</tr>
<tr>
<td><strong>Total duration</strong></td>
<td>&lt;requirement</td>
</tr>
<tr>
<td>from H0 until</td>
<td></td>
</tr>
<tr>
<td>ingestion</td>
<td></td>
</tr>
</tbody>
</table>
**Isolated Tank**

The same can be done for the isolated tank:
Leading to the following table:

<table>
<thead>
<tr>
<th></th>
<th>Isolated Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure at H0</td>
<td>3.25 bar</td>
</tr>
<tr>
<td></td>
<td>3.3 bar</td>
</tr>
<tr>
<td>Heat flux</td>
<td>cold</td>
</tr>
<tr>
<td></td>
<td>mean</td>
</tr>
<tr>
<td></td>
<td>hot</td>
</tr>
<tr>
<td></td>
<td>cold</td>
</tr>
<tr>
<td></td>
<td>mean</td>
</tr>
<tr>
<td></td>
<td>hot</td>
</tr>
<tr>
<td>Total duration</td>
<td>&lt;requirement</td>
</tr>
<tr>
<td>from H0 until ingestion</td>
<td>&lt;requirement</td>
</tr>
<tr>
<td></td>
<td>&gt;requirement</td>
</tr>
<tr>
<td></td>
<td>&lt;requirement</td>
</tr>
<tr>
<td></td>
<td>&lt;requirement</td>
</tr>
<tr>
<td></td>
<td>&gt;requirement</td>
</tr>
</tbody>
</table>

**Conclusion:**

From the tables above, with the highest ground heat fluxes (hot case), the time laps from launch abort announcement (at H0) until the liquid level reaches $x_{\text{ingestion}}$ (limit requested by the SMO [1] to avoid diffuser ingestion) is less than the requirement. This is true for both regulated and isolated tanks; the regulated tank being the closest to reality. In the hot case, the tank deloading must occur earlier if liquid ingestion shall be avoided.
5) Tank isolation during ten minutes

As explained before, the tank can remain isolated for ten minutes without being depressurized nor deloaded. This part gives the result obtained in this case for both regulated and isolated tanks.

**Regulated Tank**

The following table gathers the liquid level values ten minutes after H0 (launch abort announcement):

<table>
<thead>
<tr>
<th>Heat flux</th>
<th>Regulated Pressure through S37</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure at H0</td>
<td>3.25 bar</td>
</tr>
<tr>
<td>Liquid Level at H0 + 10 minutes</td>
<td>$&lt; x_{\text{max}}$</td>
</tr>
</tbody>
</table>

In the hot case, the model does not converge because of the use of refprop. Indeed, under certain pressure and temperature conditions, liquid hydrogen vaporizes leading to an error when using refprop. To avoid this problem, the iteration was conducted until H0 + 500 seconds:

<table>
<thead>
<tr>
<th>Heat flux</th>
<th>Regulated Pressure through S37</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure at H0</td>
<td>3.25 bar</td>
</tr>
<tr>
<td>Liquid Level at H0 + 500 s</td>
<td>$&lt; x_{\text{max}}$</td>
</tr>
</tbody>
</table>

These liquid levels are high after 8 minutes but still under the maximum threshold. After ten minutes, these levels could get dangerous and a liquid ingestion could be possible. The tank pressure being regulated, there is no concern since valve S37 ensures that it remains under the upper threshold pressure $P_{\text{max}}$. 
**Isolated Tank**

The same simulation was conducted with the isolated tank. The results are gathered in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Isolated Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressure at H0</strong></td>
<td>3.25 bar</td>
</tr>
<tr>
<td><strong>Heat flux</strong></td>
<td>cold, mean, hot</td>
</tr>
<tr>
<td><strong>Liquid Level at H0 + 10 minutes</strong></td>
<td>$&lt; x_{\text{max}}$, $&lt; x_{\text{max}}$, $\emptyset$, $&lt; x_{\text{max}}$, $&lt; x_{\text{max}}$, $\emptyset$</td>
</tr>
</tbody>
</table>

In the hot case again, the model does not converge because of the use of refprop. To avoid this problem, the iteration was conducted until H0 + 500 seconds:

<table>
<thead>
<tr>
<th></th>
<th>Isolated Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressure at H0</strong></td>
<td>3.25 bar</td>
</tr>
<tr>
<td><strong>Heat flux</strong></td>
<td>hot</td>
</tr>
<tr>
<td><strong>Liquid Level at H0 + 500 s</strong></td>
<td>$&lt; x_{\text{max}}$, $&lt; x_{\text{max}}$</td>
</tr>
</tbody>
</table>

If the tank is left ten minutes after launch abort with or without pressure regulation through S37, **the liquid level does not reach the ingestion level**. However, without pressure regulation, the tank pressure is really a key parameter. Here are the values of the tank pressure after ten minutes isolation starting from H0:

<table>
<thead>
<tr>
<th></th>
<th>Isolated Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressure at H0</strong></td>
<td>3.25 bar</td>
</tr>
<tr>
<td><strong>Heat flux</strong></td>
<td>cold, mean, hot</td>
</tr>
<tr>
<td><strong>Tank Pressure at H0 + 10 minutes</strong></td>
<td>$&lt; P_{\text{damage}}$, $&gt; P_{\text{damage}}$, $\emptyset$, $&gt; P_{\text{damage}}$, $&gt; P_{\text{damage}}$, $\emptyset$</td>
</tr>
</tbody>
</table>

In the hot case again, the model does not converge because of the use of refprop. To avoid this problem, the iteration was conducted until H0 + 500 seconds:

<table>
<thead>
<tr>
<th></th>
<th>Isolated Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressure at H0</strong></td>
<td>3.25 bar</td>
</tr>
<tr>
<td><strong>Heat flux</strong></td>
<td>hot</td>
</tr>
<tr>
<td><strong>Tank Pressure at H0 + 500 s</strong></td>
<td>$&gt; P_{\text{damage}}$, $&gt; P_{\text{damage}}$</td>
</tr>
</tbody>
</table>

In the isolated case, liquid hydrogen does not get to high levels (because of the higher pressure value). However, the tank pressure becomes extremely high and overspends the structural limit of $P_{\text{damage}}$ in both mean and hot cases. But this case is a degraded case of a degraded case.
Conclusion:

If the tank remains isolated during ten minutes starting from launch abort announcement without being depressurized nor deloaded, the liquid level does not get higher than $x_{\text{ingestion}}$. If the tank is regulated, the pressure remains under $P_{\text{damage}}$. In the regulated tank, the constraints are thus fulfilled.
Conclusion

The aim of this study was to assess the overloading of the LH2 tank inside the ESC-A stage in terms of safety on ground.

From the simulations made using MatLab, the following results were deduced:

With the new loading level of liquid hydrogen, the LH2 tank can sustain a launch abort occurring at any time point until lift-off (H0).

The constraints set by the SMO [1] are indeed respected:

- The liquid level does not overspend $x_{threshold}$ after three minutes tank isolation starting from launch abort announcement (H0).
- The tank can thus be depressurized at any time point within three minutes following launch abort announcement (H0).
- The liquid level does not overspend $x_{ingestion}$ (diffuser ingestion) after ten minutes tank isolation starting from launch abort announcement (H0).
- The pressure regulation through S37 ensures that the pressure does not get higher than the upper threshold pressure. The structural limit of $P_{damage}$ is thus not reached.

However, in case of high ground heat fluxes (hot case), the tank must be deloaded within three minutes following the tank depressurization in order to avoid diffuser ingestion.
Personal conclusion

On a more personal point of view, I have spent a wonderful time at ASTRUM ST Bremen. This internship was for me the first occasion to step into the industrial world and I consider it as a success. I really learnt a lot during the past six months.

First, I had the opportunity to discover how a company actually works. Moreover, I chose to do my final internship abroad so that I could get to know a new culture. It also enabled me to be part of a multicultural team, which was a very enriching experience. ASTRUM resulting from the merger between a German and a French company, the employees are mainly coming from these two countries. Even though France and Germany are neighbors, both cultures are not the same and I enjoyed discovering these differences. Mixing the nationalities brings richness in terms of ideas but alongside come all the cultural divergences, which I could witness while working in Bremen.

Besides, since the launch site is located in Kourou (French Guyana), most of the official documents are written in French, making the communication and comprehension between countries sometimes difficult. The language barrier is a real difficulty; I personally take it as a challenge to be able to communicate with the people I am surrounded with. I thus took the opportunity to work in Germany to practice my language skills.

Finally, and most importantly, I worked on a subject that really interested me. Not only did I get to study a concrete and very impressive product: the Ariane 5 upper stage, but I could also see the importance of the project I was treating. Rockets are very delicate to handle, I knew that in theory thanks to my studies. But it is another thing to see it for oneself. I had the chance to take part in the calculations, to understand how difficulties are handled and problems are solved.

In a word, working within a high-performance environment such as ASTRUM enabled me to become more autonomous, to extend my knowledge on space systems and it gave me the conviction that I would like to continue working within the Space Industry.
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