

ZBO system concepts adapted for European Long Term Cryogenic Propulsion

Jerome Lacapere, Julien Tanchon*, Tomaso Misuri** and Thierry Tirolien****

**Absolut System*

5 Rue de Champlars, 28240 Meylan, France

***Alta Space Spa*

Via A. Gherardesca 5 - 56121 Ospedaletto, Pisa, Italy

****ESA/ESTEC*

2200 Noordwijk, , The Netherlands

Abstract

Cryogenic propulsion is now considered as mature to be used as a possible alternative to storable propellant for interplanetary missions. Some efforts should be yet provided on the different concept to master Boil-Off Masses on passive and active solutions (with cryocooler). Zero Boil-Off systems adapted to LOX / LCH₄ propulsion systems are presented in this paper. These Zero Boil-Off systems dedicated to several months duration missions include some solutions to reduce conductive and radiative heat transfer thanks to structural materials. These passive solutions reducing heat fluxes received are not detailed in this paper. This paper is focused on some interesting solutions to integrate a cryocooler with efficient heat transfer solutions through different cooling loops strategy. A thermal model has been created to analyse different configurations and to propose the best one (or the preferred one).

1. Introduction

LOX / LCH₄ propulsion system has been identified by ESA as an interesting solution for interplanetary missions like Mars Moon (Deimos) Sample Return (DSR) [1]. Even with a lower ISP (about 350 s) compared to 450 s for a LOX/LH₂ propulsion system, this LOX/methane propulsion system is interesting because of the size of the propellant tank and the relative facility to achieve complete ZBO (compared to a LH₂ tank). In fact, the storage temperatures from 94 K to 115 K allow the use of already developed cryocoolers with high TRL. Thus, ZBO systems could be reached for such cryogenic propulsion systems. This paper presents the different configurations to reach ZBO. Some passive solutions are the first step to reduce conductive and radiative heat fluxes. These solutions are presented but not analyzed in detail in this paper. Starting from the calculated heat fluxes received by the two cryogenic tanks, some active solutions are presented to reach complete ZBO using different cooling loops strategy. The interest of our preferred solution is the integration simplicity : the cryocooler is integrated with a TVS solution and might be switch off for a simple pressure regulation in low gravity.

2. Reference configuration

2.1 Geometric considerations

The propulsion system is composed of a LOX tank containing 5 m³ of cryogenic liquid and a LCH₄ tank of 3.6 m³. The methane tank is considered as spherical, the LOX tank is considered as cylindro-spherical with a diameter equal to LCH₄ tank for a simpler integration of the upper stage. The calculated diameter is then 1.93 m. The figure 1 represents the reference configuration of the 2 cryogenic tanks with the supporting structure. In this reference configuration, all the supporting structure considered are struts made with low conductivity materials.

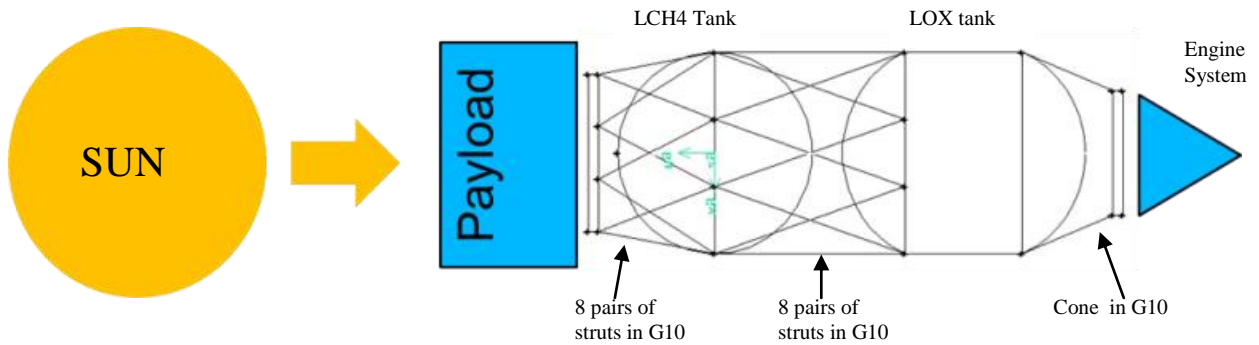


Figure 1: Reference configuration of the LOX/LCH4 stage

2.2 Mission and environment

The mission considered for this study is the DSR mission presented in [1]. This mission is composed of 1 week in LEO Orbit with a high fill ratio followed by 6 months of cruise to planet with a low fill ratio (due to the boost performed to go to the cruise orbit). During the cruise orbit, planet IR and planet albedo are not taken into account, only Solar fluxes are considered with a decreasing value from 1425 W/m^2 at the beginning of the cruise and 600 W/m^2 at the end of the cruise. In order to limit the received heat fluxes, attitude control is required to point the payload to the sun. Thus, a small shield located between the payload and the LCH4 tank will reduce dramatically radiation heat fluxes received by the tanks. The dimension of this shield shall be adapted following the possibilities of the RCS : a precise RCS shall allow to use a shield with a limited diameter. Remaining radiation heat fluxes shall take place between this shield and the LCH4 Upper Bulkhead :

2.3 Propellant management and TVS

After the boost to leave LEO, liquid fill ratio shall be low and a PMD shall be used in order to limit liquid wetting of all surfaces and to ensure engine re-ignition after the 6 months of cruise without gravity. However, even with an efficient PMD able to maintain liquid phase at the tank bottom, tank venting might be a difficult task. In fact, if a low pressure needs to be reached or maintained during or after transient phases, tank venting has to be performed with pure vapour. This venting can be an efficient and rapid way to regulate the pressure even with an efficient cryocooler : the cryocooler effect shall have a delay in time and the venting effect is immediate.

Thus, in order to be sure to vent only vapour in low gravity environment, an additional system named TVS (Thermodynamic Venting System) [6] is needed (even with the use of PMD, which cannot guarantee some liquid droplet escaping through the ullage).

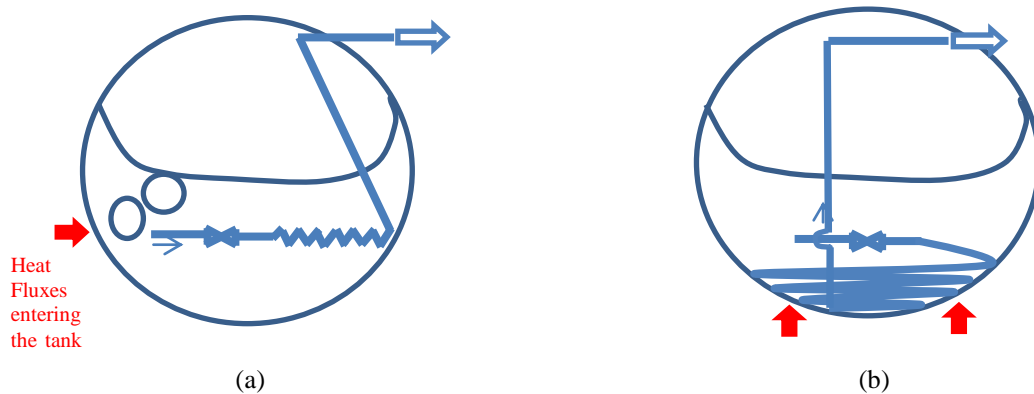


Figure 2: Schematization of TVS in a cryogenic tank with 2 alternatives : (a) Heat Exchange with Liquid (b) Heat Exchange with tank wall

3. Reduction of heat fluxes received by cryogenic tank

3.1 Use of Multi-Layer Insulation

MLI blankets are used in order to reduce radiative heat fluxes. An external layer with specific coating is also used in addition in order to reflect solar heat fluxes. This external layer has a low absorptivity index (around 0.1). Empirical relations [5] can help to find the adequate number of layers with the adequate layer density. Thus, in our case, a MLI blanket of 60 layers with a layer density of 15 layers/cm gives a low radiative heat flux around 0.13 W/m^2 between 115 K and 300 K. This value is quite coherent with the common value considered of 0.22 W/m^2 between 20 K and 300 K [4]. However, in order to be conservative in our analysis (taking into account possible settling of layers during propulsive phases and all singularities), this value is multiplied by a factor 10 for the rest of our analysis.

3.2 Reduction of conductive heat fluxes

In order to reduce conductive heat fluxes, composite materials with low conductivity at low temperatures are used. In our configuration, fiberglass epoxy is chosen for the struts between LOX and LCH₄ tanks and between LCH₄ tank and the payload. Fiberglass epoxy is also chosen for the structural cone between LOX tank and the propulsive system. The struts are designed through flexion loads and the LOX cone is designed through buckling loads. For the temperature considered, the mean thermal conductivity of fiber-glass is around 0.7 W/m.K .

3.3 Heat fluxes balance

Considering use of MLI to reduce radiative heat fluxes and use of fiberglass epoxy materials for the struts and the LOX cone, the following thermal balance is calculated :

LOX side : 10 W

- Conductive heat fluxes : 2 W
- Radiative heat fluxes : 8 W

LCH₄ side : 8 W

- Conductive heat fluxes 1 W
- Radiative heat fluxes : 7 W

4 Active cooling solutions

The storage temperatures of the two cryogenic tanks considered in this paper are respectively around 95 K for LOX and 115 K for LCH₄ (storage pressure of 1.5 bar). For these temperatures and the considered heat fluxes (more than 18 W), cryocooler technologies has high TRL and could use different thermodynamic processes. The main question is how to integrate the cryocooler in an efficient way.

For this LOX/LCH₄ system, this cryocooling can be integrated through different configurations.

A direct interception with cryocoolers directly plugged in the tank wall could be a simple solution. In that case, two cryocoolers are used with capacities adapted to each tank :

- 10 W @ 90 K for LOX tank
- 8 W @ 110 K for LCH₄ tank

However, this solution implies some constraints from a propellant management point of view. In fact, with a cryocooler (or precisely the cold finger) directly plugged to the tank wall, the heat exchange surface is quite limited and the cryogenic propellant must remain in contact with this heat exchange surface. Furthermore, fluid mixing must be performed in order to increase heat transfer inside the tank and to have a temperature homogenisation. Thus, it becomes difficult in low gravity to ensure the presence of liquid in the right location (heat exchange surface) and at the same time to mix this liquid to avoid stratification and improve heat exchange. Even with an efficient PMD, free surface can be destroyed easily and it should be difficult to find the right working point.

This direct solution is thus not analysed further.

Cooling pipes are then considered in a second step directly connected with the tank walls.

Considering this general concept of cooling pipe around the tank walls (externally), different solutions can be set-up for the cryocooler integration.

A first solution consists in using liquid methane stored in the tanks to intercept heat fluxes. With this first solution, the liquid methane has to be reconditioned in order to be re-injected in the tank.

A second solution consists in using an external cooling loop. Within this second solution, two alternatives might be highlighted :

- One alternative using a boiling liquid (at a temperature around 90 K) in a closed circuit. The liquid is vaporized at contact of hotter tank walls. A cryocooler is used to re-liquefy this vaporized liquid.
- Another alternative using a non-condensable gas to cool down the tank walls. This cooling circuit is part of a reverse Brayton cycle.

4.1 Solution 1 using stored liquid methane

For this solution 1, Liquid Methane stored in the LCH₄ tank is directly used. For that purpose, a PMD is used in order to feed the pipe with liquid. In case of vapour feeding, the mission is not jeopardized but the ZBO efficiency will be reduced. After injection in the pipe, liquid methane goes through a JT valve and is submitted to a large expansion. In fact, two JT valves are used with downstream pressure adapted to each tank. Thanks to this expansion through the JT valve, the saturation temperature is reduced. The downstream pressure is chosen in order to get boiling at walls of each tank. For liquid methane tank, this saturation temperature is reached for a pressure of 0.7 bar. For LOX tank, the pressure is lower (0.14 bar) in order to get boiling at the LOX tank walls. Special care has to be taken regarding this downstream pressure in order to have always a pressure larger than 0.12 bar (to avoid methane freezing) and lower than 0.16 bar to allow boiling around LOX tank walls (even if the storage pressure can also be adapted to fit with this downstream pressure). After these expansions associated not only to a pressure decrease (linked to a saturation temperature decrease) but also to the creation of vapour methane, the remaining liquid boils around the tank walls with energy exchange with LOX and LCH₄ tanks. The calculated mass flow rates has also to take into account the liquid mass flashed through the JT valve.

After heat exchange with LOX and LCH₄ tanks, vapour methane at low pressure is then compressed (thanks to hot compressor), and re-liquefy thanks to the cryocooler. An alternative might be set up with a liquid compressor instead of the hot vapour compressor.

Total mass flow rate in the cooling pipes is calculated starting from the total heat fluxes to intercept, ie. 18 W in our case. Taking into account the liquid losses through the JT with margins, the liquid methane mass flow rate to be considered is around 48 mg/s.

The specified cryocooler has to reliquefy this last mass flow rate. It means that he cryocooler has to produce 30 W @ 110 K (taking into account heat exchanger and compressor efficiencies).

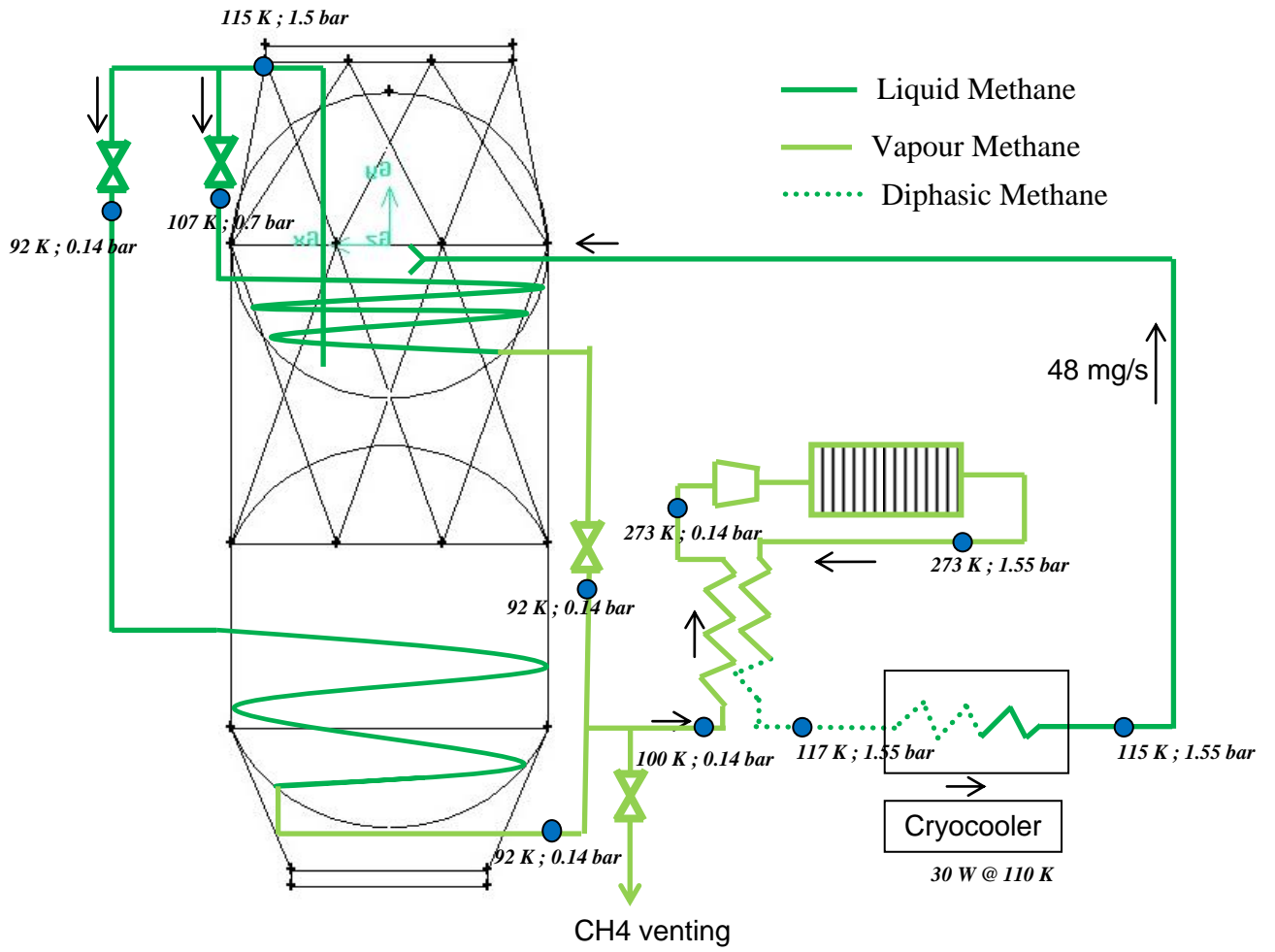


Figure 3 : Illustration of a ZBO solution using stored liquid methane

4.2 Solution 2 using external diphasic cooling pipe with boiling liquid

With this configuration, the cooling pipes have to intercept directly 22 W (corresponding to the 18 W of calculated external heat fluxes including 20 % of margins).

The interception temperature corresponds to the minimum boiling temperature of the 2 cryogenic liquids which is 94 K (for LOX side).

In order to have a clear interception of remaining heat fluxes at constant temperature, the cooling pipes must use a diphasic fluid with a boiling temperature around 89 K to get boiling with high efficiency between liquid in the pipe and cryogenic liquids (pressure in the pipes must be adapted in consequence).

During cooling process around LOX tank, a part of cooling liquid vaporizes. The LCH4 tank is then cooled by a diphasic mixture.

A heat exchanger with a cryocooler is then used to recondense the vapor of this fluid. After the heat exchanger, a circulator is used in liquid phase to get the right mass flow rate. This mass flow rate is adapted following the heat of vaporization of the selected fluid.

Thus, the cryocooler has a cooling capacity of 25 W (including 0.9 of heat exchanger efficiency) at 84 K (5 K lower than the temperature of the cooling pipe).

The liquid used could be Argon at 2.1 bar (saturation temperature = 95 K)

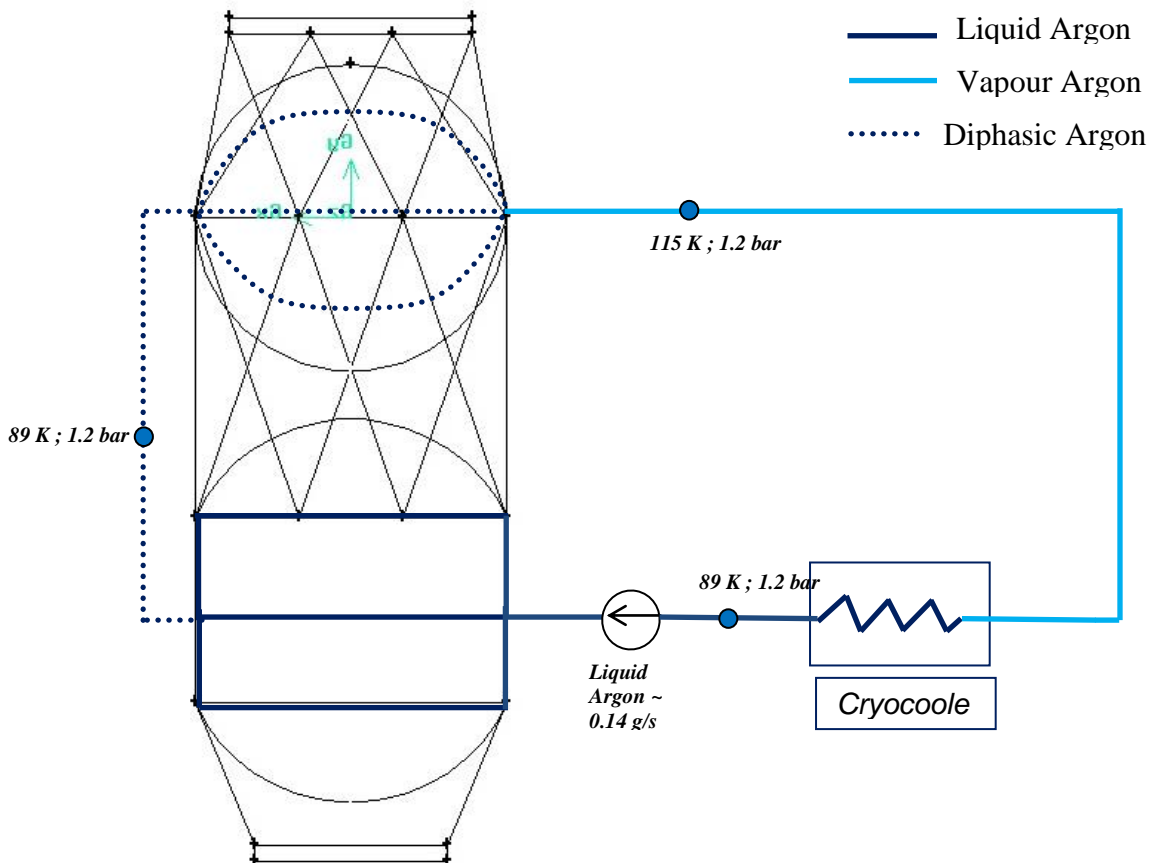


Figure 4 : Illustration of a ZBO solution using external cooling pipe and boiling liquid

4.3 Solution 2 using external gaseous cooling pipe

An alternative could be to use non-condensable gas in the cooling pipes and to create a reverse Brayton cycle. In that case, the inlet temperature around LOX tank should be calculated in order to get 94 K at the LOX tank piping outlet. Thus, an inlet temperature around 89 K should be sufficient. The working fluid can be Helium or Neon to avoid condensation in the cooling pipe.

Thus, the process must have a cooling capacity of 22 W at 89 K.
This solution is already under consideration in Broad Area Cooling studies [2]

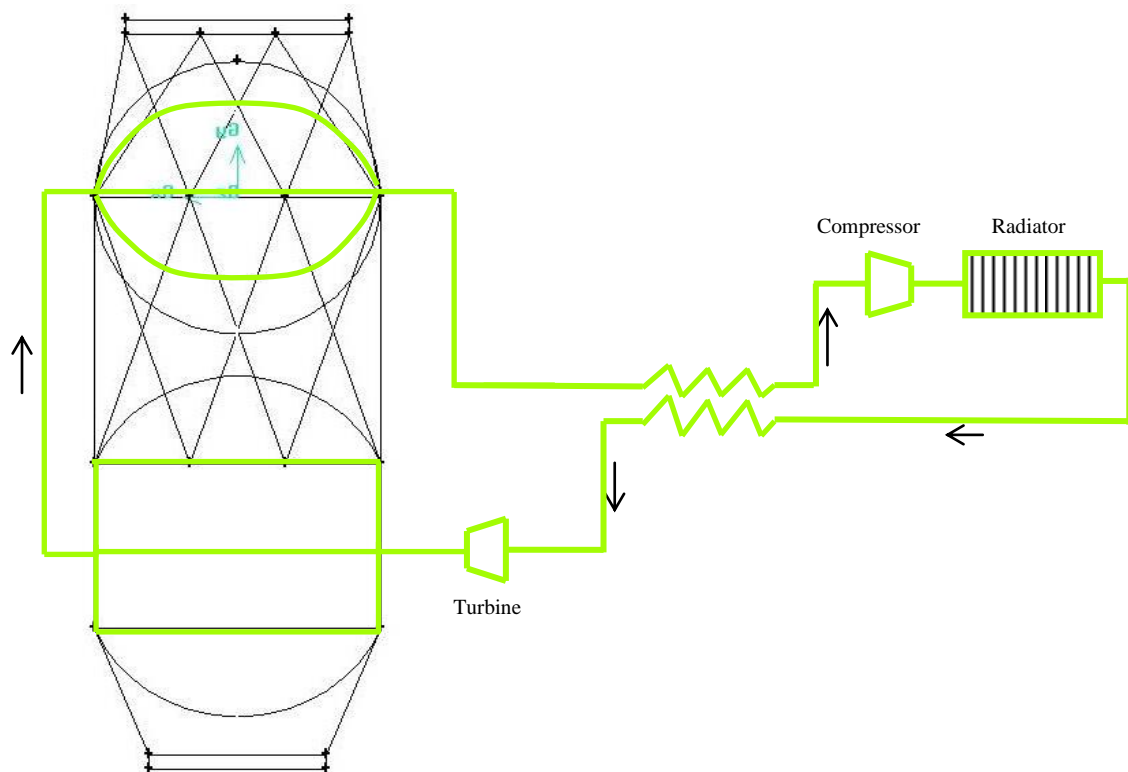


Figure 5 : Illustration of a ZBO solution using external cooling pipe with non-condensable gas

5 Synthesis

The following table gives a synthesis of the solutions detailed previously. These solutions consist in using a cryocooler to deliver about 25 W @ 90 K (exact values can vary depending on the configuration used). For such values, space cryocoolers exist and relevant technologies have a high TRL.

	1st configuration Tank cooling with internal methane liquid	2nd configuration Alternative 1 using boiling liquid (Argon)	2nd configuration Alternative 2 – Reverse Brayton Cycle
Heat transfer to tank	Boiling	Boiling	Convective
PMD needs and objectives	To be able to feed cooling pipe with liquid methane	No explicit needs of PMD	No explicit needs of PMD
TVS needs	TVS included in the system	TVS needed in addition	TVS needed in addition
Total Mass	50 kg (including 20 kg of piping)	62 kg (including 20 kg of piping)	55 kg (including 20 kg of piping)
Advantages	- TVS included - Constant tank wall temperature	- Independent System - Constant tank wall temperature	- Independent system - Only 1 compressor and 1 heat Exchange
Drawbacks	- Specific care to the pipe pressure losses and additional compressor capacities - Need of compressor in addition to the cryocooler - Need of PMD	- Additional TVS needed - Need of circulator in addition to cryocooler	- Additional TVS needed - Temperature differences at tank walls
Cryocooler specifications	30 W @ 110 K Several cryocoolers can be used for this range of values Stirling Cooler can be selected	25 W @ 84 K Several cryocoolers can be used for this range of values Stirling Cooler can be selected	22 W @ 89 K Reverse Brayton Cycle

Even if it needs an additional compressor, the solution using liquid methane (from the storage tank) is quite attractive for the following reasons :

- It allows heat fluxes interception at constant temperature
- TVS is already part of this solution. It can be seen as a TVS with an active cooler.
- It seems to be the lightest solution (TBC by further studies)

However, this solution needs also an efficient PMD to guarantee liquid feeding.

The solution using the reverse Brayton process is a robust solution which is already under consideration in lots of studies [2][3]. It could be considered as a back-up solution.

This study has been funded by ESA.

References

- [1] F.Caramelli, M.Van Pelt, A.Fesidis, G.Chirulli, A.Sirbi and A.Atzei. 2006. Long Term Cryogenic Propulsion for Interplanetary Missions. AIAA 2006-5129
- [2] M.C.Guzik and T.M.Tomsik. 2011. An active Broad area cooling model of a cryogenic propellant tank with a single stage reverse turbo-Brayton cycle cryocooler. TFAWS 2011.
- [3] J.F.LeBar and E.C.Cady. 2006. The advanced cryogenic evolved stage (ACES) – A low cost, low risk approach to space exploration launch. AIAA-2006-7454

- [4] A.Hedayat, T.M.Brown, L.J.Hastings, and J.Martin. 2000. Variable density Multilayer Insulation for cryogenic storage. 36th Joint Propulsion Conference; 36th; 17-19 Jul. 2000; Huntsville, AL; United States
- [5] G.R.Cunnington, C.W.Keller and G.A.Bell. 1967. Thermal Performance of Multilayer Insulations. NASA CR-1274
- [6] L.J.Hastings, R.H.Flachbart, J.J. Martin, A.Hedayat, M.Fazah, T.Lak, H.Nguyen and J.W.Bailey. 2003. Spray Bar Zero-Gravity Vent System for On-Orbit Liquid Hydrogen Storage. NASA/TM—2003–212926