IMPROVED XENON LOADING EQUIPMENT WITH LOADING CAPACITY UP TO 1200 KG FOR ALPHABUS

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Abstract

Plasmic propulsion systems on board space-crafts require filling, draining and tests with Xenon during on-ground operations. Taking into account specific thermodynamic characteristics of Xenon and the high storage pressure in the spacecraft's tanks, a Ground Support Equipment has been developed by AIR LIQUIDE DTA in 1999. Up to now, three GSE have been built for ALCATEL SPACE INDUSTRIES (1999), SPACE SYSTEM LORAL (2001) and ASTRIUM (2002).
The Xe GSE includes thermal compressors, heat exchanger, weighing system for measurement of transferred mass and a Personal Computer with the Labview software for command / control of the process.
This paper describes first the existing equipment designed to load up to between 200 and 300 kg of Xenon and then the possible modifications to load up to 1200 kg of Xenon.

Introduction

The use of electric propulsion systems on board space-crafts is growing up as the benefits are attractive and as this technology is today extensively tested and made available.
To load the STENTOR spacecraft it was decided in 1998 to develop a specific Ground Support Equipment for management of the Xenon propellant needed for optimized performances of the thrusters. This development was decided because in addition to generic requirements of leak-tightness and no-pollution, it was also required to fill the storage tank at the optimized storage pressure of about 150 bar as fast as possible without overheating the tank. In addition, recovery of Xenon during draining is strongly required as Xenon is a rare and expensive gas. AIR LIQUIDE DTA has proposed and developed a solution for an automatic Xenon transfer with 'thermal' cryogenic compressors.

The Xe GSE provides the following functions :

- Loading of the spacecraft tanks with Xenon propellant up to a specified pressure and within a specified temperature range
- Draining of the spacecraft tanks
- Conditioning of the system with Argon or Helium gas
- Pressure and temperature control of the delivered propellant
- Measurement of loaded Xenon mass
- Control of Xenon purity
- Storage of the Xenon to be transferred to the spacecraft tanks
- Evacuation of the propellant tanks and of the XeGSE itself.

Moreover, the XeGSE :

- Allows easy interfaces with the operator
- Guarantee security of personnel and of spacecraft components through passive and active security devices.

Since the spacecraft tank operating pressure is higher than the pressure of the gas cylinders provided by the Xenon suppliers, the XeGSE must include a compression system.
Two solutions have been considered by AIR LIQUIDE DTA :

- the first solution used static so-called "thermal" compressors
- the second solution used a 2 stage - mechanical compressor with membranes.

Solutions with other compressor types have been rejected from the beginning due to the high purity level and reliability requirements.
The solution with the thermal compressors presents several significant advantages :

- a lower mass (< 50 % of the second solution) for the Xenon loading equipment and its container,
- less noise during operation (no motor),
- a full redundancy since 2 "thermal" compressors are used in a parallel layout,
- a lower procurement cost (at least for the second and following units),
- lower maintenance cost (no membrane and no oil replacement),
- more industrial flexibility since thermal compressor spares can be manufactured by many sub-contractors,
- no pollution risk because the compressor is static (no moving part).

After a trade-off taking into account procurement cost, transportation cost of the equipment and its container, flow performances and reliability, the mechanical solution has been rejected. The Xenon GSE developed by AIR LIQUIDE DTA is equipped with thermal compressors.

Description of the existing XeGSE

The Xe GSE is constituted by a cart, a ground storage and insulated hoses.
The hoses are used to connect the cart to the satellite and the cart to the ground storage.
The ground storage is a rack carrying B50 cylinders out of aluminium filled with Xe. The cylinders are located above a 1500 kg weighing system.
The standard cart includes mainly :

- 2 « thermal compressors », each equipped with a cold source (LN2), a hot source (electrical heater) and a weighing system,
- Xenon valves (of the membrane or bellow type) used to by-pass either one of the compressors,
- a LN2 circuit with valves, check valves, relief valves, pressure and temperature sensors,
- a Coriolis mass flow meter to measure instantaneous mass flow delivered to the spacecraft tanks,
- an heat exchanger using LN2 as a cold source and electrical energy as a heat source, to control the temperature of the Xenon at the outlet of the XeGSE,
- pressure/temperature sensors to control the process,
- inlet/outlet ports for gas conditioning, vacuum pumping, purity analysis,
- electrical equipment,
- I/O SCXI electronic cards/connections,
- a protective housing structure equipped with pivoting and blocking wheels,
- a 6 bg air supplying circuit to control the piloted valves,
- a PC with the LABVIEW software used for the manual or remote control of the process,
- a vacuum pump with its equipment (valve, controller, gauge…),
- analyzers for O_2 and H_2O content.

A container, designed for air/road/rail/boat shipments is provided for the transportation of the cart.

The control command of the Xe GSE is carried out through a Personal Computer with the LABVIEW software supplied by National Instrument. All the I/O cards (SCXI type) are supplied by National Instrument to preclude compatibility problems between hardware and software. The LABVIEW software allows to :

- control the process by :
  . opening/closing the on/off valves on the Xenon line
  . adjusting the regulation valve position on the Xenon line through a 4-20 mA convertor
  . opening/closing the on/off valves on the LN2 lines for the compressors and the heat exchanger
  . adjusting the power of the heaters inside the compressors and the heat-exchanger,
- have a log file of the past commands performed by the operator or the automatic process
- give the status of the cart (valves position and instantaneous measurements)
- have real time visualization of the measurements
- perform the calibration of the sensors

Existing Xe GSE Characteristics :

- Maximum pressure : 150 bar standard
- Loading flow rate : 10 g/s for 70 bar in the S/C tank(s) and 7 g/s for 150 bar in the S/C tank(s)
- Mass of the cart < 700 kg (without the 350 kg container)
- Volume of the cart : 1200 mm (high) x 1500 mm (wide) x 1800 mm (long)
- Operating power : 10 kW (220, 380 or 460 Vdc, 50 or 60 Hz, 3 phases electrical transformer)
- Movable : equipped with 4 wheels, fork lift pockets and capable to be lifted by a crane/hoist
- Aluminium transportation container : designed for a 100 mm drop and 3 g ‘static’ or vibration levels according to MIL-STD
- Instrumentation accuracy :
  . loaded mass : 200 g for 300 kg loaded
  . pressure : 0,2 bar in the 0-180 bar range
  . temperature : 1°C in the 0-40°C range
  . mass flow : 0,2 % in the 0-30 g/s range
  . contaminant : 0.5 ppm O_2 and H_2O
- Vacuum pumping capacity : between 1000 and 10^{-4} mbar
- Operated with the LABVIEW @ software

Figure 1 : photo of the AIR LIQUIDE Xenon Ground Supply Equipment

Description of the need for ALPHABUS

ALPHABUS platforms designed by CNES, ALCATEL SPACE INDUSTRIES and ASTRIUM may need up to 1200 kg of Xenon to provide up to 18 kW during 15 years (possible loads of 1500 kg have been envisaged at the beginning of the design process but the maximum value has been reduced later).
For these platforms, the Xenon could be stored in 2 or 3 big tanks of 400 or 600 kg each. Such large Xenon tanks are under pre-design by AEROSPATIALE Aquitaine.
It will be impossible to load large tanks with Xenon in S/C's constructor premises as it could be done with small tanks designed with high safety factor. The tanks will have to be loaded on the launch pad during the launch campaign. Furthermore for contingency operations, it could be necessary to unload the tanks. It is thus necessary to reduce the duration of the loading operations and for that to increase the loading capacity (average flow rate) of the Xe GSE.
However, such large tanks have low thermal inertia and the loading capacity may be limited by thermal constraints. In order to avoid to design a loading cart with a too large loading capacity, some calculations of the thermal behavior of the Xe tank during the loading process have been performed with a simplified model.

The simplified model is a transient nodal model considering 5 nodes : 1 node for the fluid inside the tank, 1 node for the fluid entering the tank (at imposed temperature), 1 node for the liner, 1 node for the over-wrapping layer and 1 node for the external environment. Heat exchange between the Xenon inside the tank and the liner is done by natural convection (in that case the heat exchange coefficient is computed with standard relationship using the Rayleigh number) excepted at the beginning of the loading process. In fact, at low pressure and thus low density of the Xenon, the forced convection due to the low flow section of the inlet port is higher than the free convection. The heat transfer inside the liner and the over-wrapping layer is done by conduction only. The heat transfer between the tank and the external environment is done by conduction through the supports of the tank and by natural convection. Some details of this model and comparison with experimental results can be found in reference [R1].

<u>Loading phase</u>

The figures n°2 and n°3 show the results of the loading of two 360 l tanks with a liner made out of Titanium (18 kg) and an over-wrapping layer out made of Carbon T1000 (24 kg). Two computations have been done :

- the first computation corresponds to a maximum Xe GSE flow rate of 30 g/s during the loading phase without the compressors (P<50 bar) and also 30 g/s during the loading phase with the compressors,
- the second computation corresponds to a maximum Xe GSE flow rate of 30 g/s during the loading phase without the compressors (P<50 bar) and only 15 g/s during the loading phase with the compressors.

Flow rates given here-above are flow rates of the Xe GSE. Flow rates entering each tank are half these values.

By experience, the thermal gradient between the average fluid temperature and the maximum temperature located at the top of the tank (with the loading through an entrance port located at the bottom of the tank) is around 8°C. Thus a maximal temperature of 50°C has been considered in the computation for the node corresponding to the liner.
With a loading capacity of 30 g/s during the loading phase with the compressors, the loading of the 1200 kg (600 kg/tank) is achieved for a pressure of 150 bar and can be performed within 16 hours. For a pressure higher than 120 bar, the flow rate is limited by the maximal temperature allowed for the S/C tank. At 150 bar the flow rate is limited to 6 g/s per tank, that is 12 g/s for the 2 tanks.
With a loading capacity of 14 g/s during the loading phase with the compressors, the loading of the 1200 kg (600 kg/tank) is achieved for a pressure of 150 bar and can be performed within 23 hours. For a pressure higher than 145 bar, the flow rate is limited by the maximal temperature allowed for the S/C tank. At 150 bar the flow rate is limited to 6 g/s per tank, that is 12 g/s for the 2 tanks.

These results show that it is not necessary to increase too much the loading capacity of the Xe GSE since the loading rate will be limited by the maximum allowed temperature of the S/C tanks (for a temperature of Xenon of 20°C at the inlet of the tank).

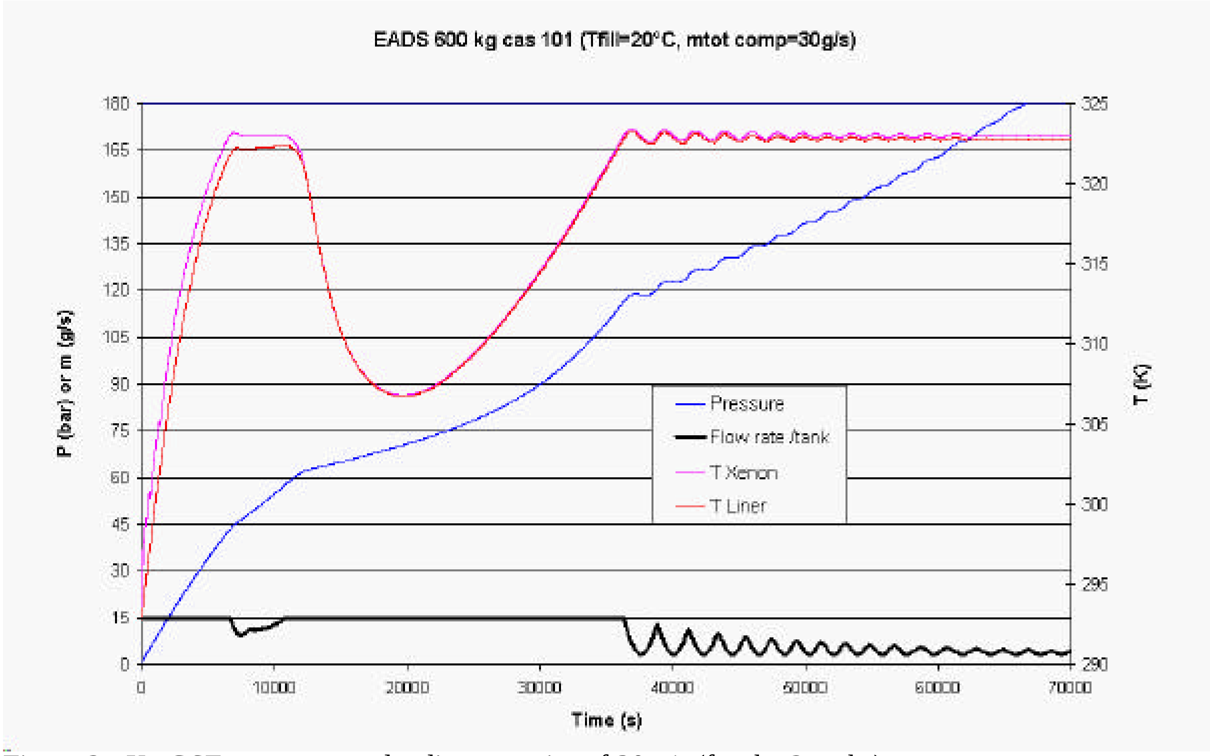

Figure 2 : Xe GSE compressors loading capacity of 30 g/s (for the 2 tanks)

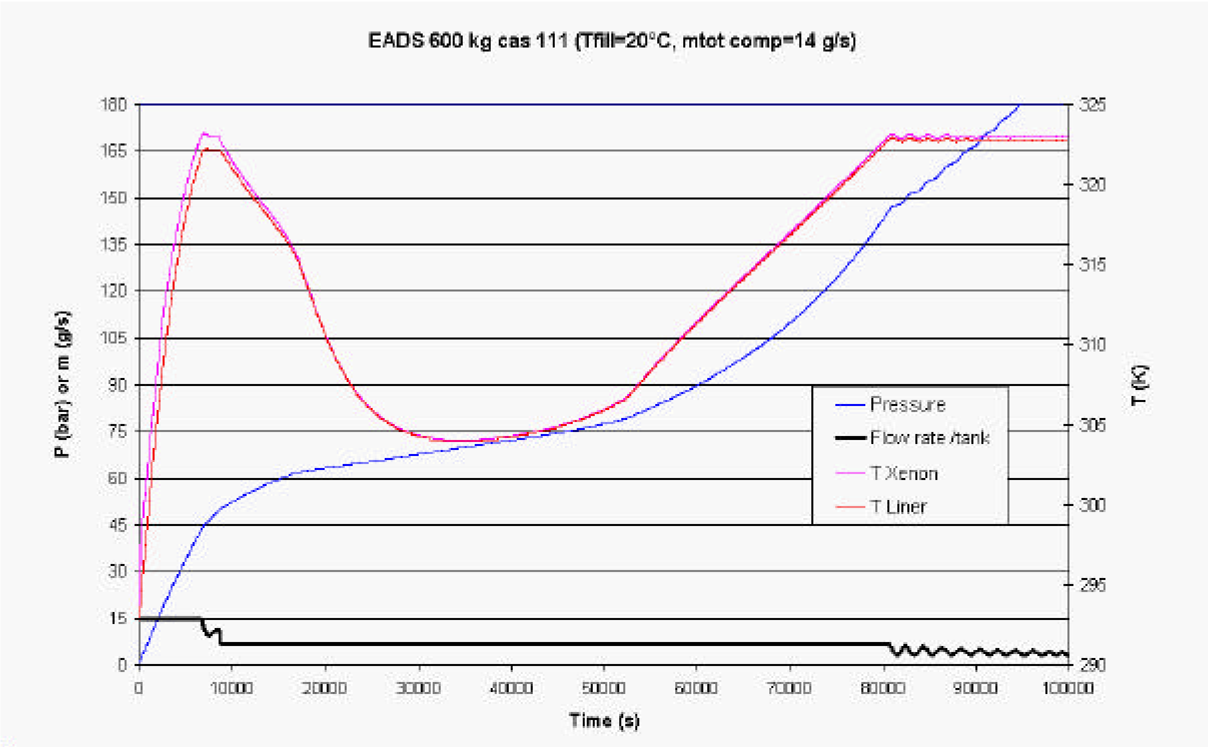

Figure 3 : Xe GSE compressors loading capacity of 14 g/s (for the 2 tanks)

Draining phase

During the draining phase, the pressure expansion inside the tanks lead to a temperature drop. This temperature drop can be limited by heating the tanks. This heating can be performed either by an external flushing of the tank with air at temperature around 35°C or with electrical heaters attached onto the external wall of the tanks. When equipped with MLI for in-orbit temperature control, the cooling method using air may be not very efficient due to the thermal resistance of the MLI. Furthermore, the velocity of the flushed air may be limited to prevent damage to the MLI or due to geometrical restriction of the flow section (according to the location of the tank and other equipment installed onto the Spacecraft).

The AIR LIQUIDE Xenon GSE allows the user to supply two heaters of 100 W each (in 24 VDC). The heaters can be switched on/off by the user or automatically by the control/command software according to the temperature given by temperature sensors (up to 3) attached onto the tank(s). Fenwall temperature sensors have been used for 2 of the 3 carts already built.

For this study we have considered that each tank can be heated with a 100 W heater. The minimum temperature allowed to avoid condensation has been considered to 13°C. The initial temperature of the Xenon and the tank is 25°C (the corresponding pressure is 90 bar).

The figures n°4 and 5 show the results of the draining of the same two 360 l tanks considered for the loading phase. Two computations have been done :

- the first computation corresponds to a maximum Xe GSE flow rate of 40 g/s during the unloading phase without the compressors (P>58 bar) and 36 g/s during the unloading phase with the 2 compressors,
- the second computation corresponds to a maximum Xe GSE flow rate of 40 g/s during the unloading phase without the compressors (P>58 bar) and only 18 g/s during the loading phase with the 2 compressors.

Flow rates given here-above are flow rates of the Xe GSE. Flow rates entering each tank are half of these values. These flow rates are larger than those considered for the loading phase (30 g/s and 14 g/s respectively) because the pressure in the B50 cylinders in which the Xenon would be unloaded would stay under 70 bar during the draining of the S/C tanks.

With a capacity of 36 g/s during the unloading phase with the compressors, the loading of the 1200 kg (600 kg/tank) can be performed within 12 hours. For a pressure lower than 55 bar, the flow rate is slightly limited (at 14 g/s per tank) by the minimum temperature allowed for the S/C tanks.

With a capacity of 17 g/s during the unloading phase with the compressors, the loading of the 1200 kg (600 kg/tank) can be performed within 19 hours. The flow rate is never limited by the minimum temperature allowed for the S/C tanks.

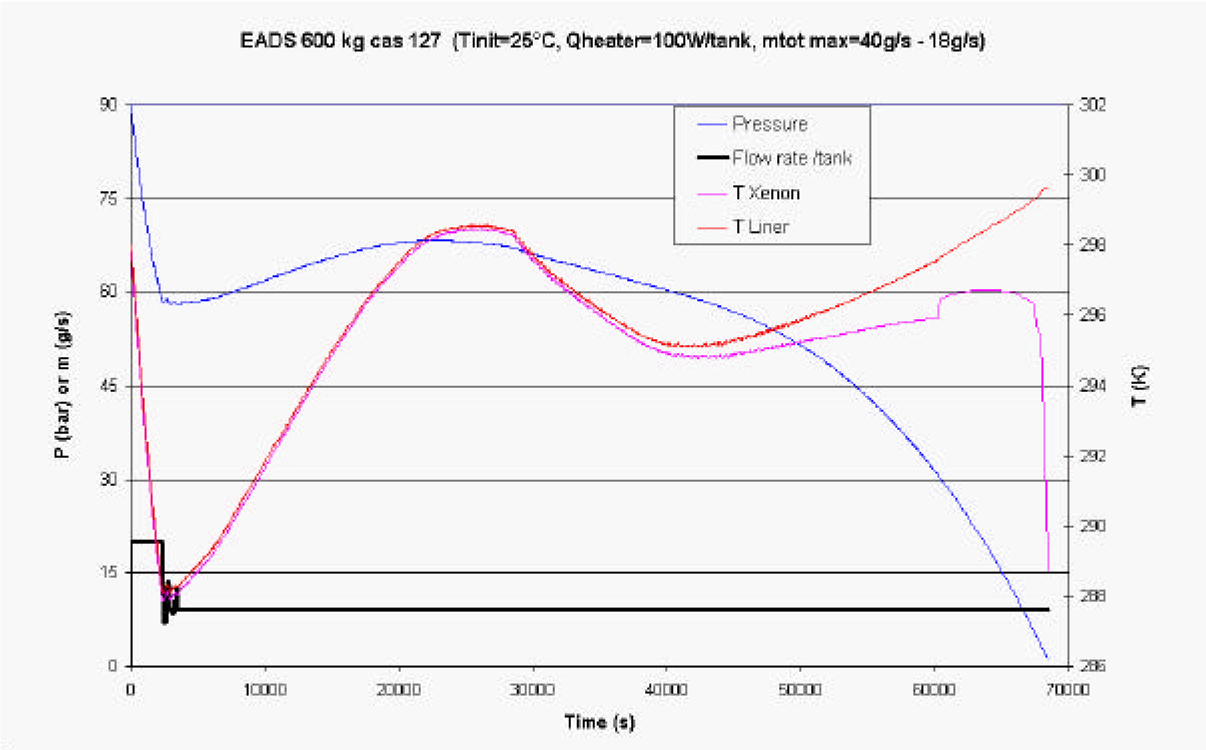

Figure 4 : Xe GSE compressors unloading capacity of 18 g/s (for the 2 tanks)

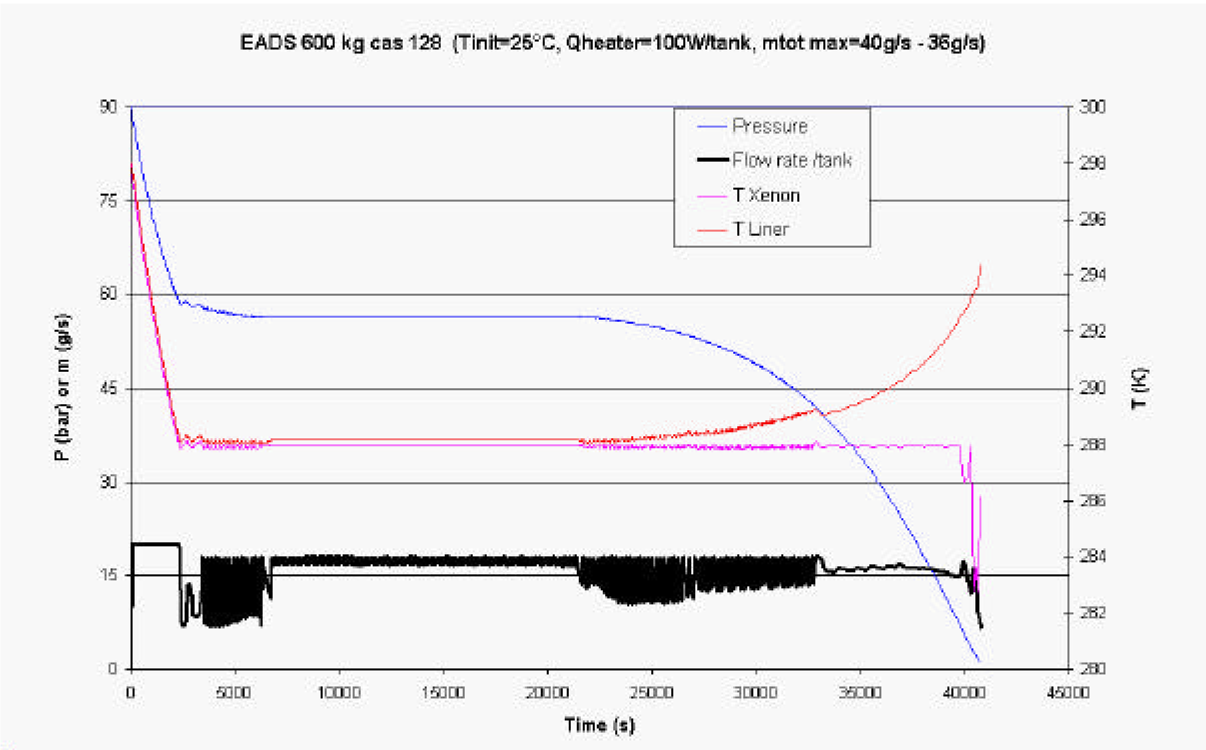

Figure 5 : Xe GSE compressors unloading capacity of 36 g/s (for the 2 tanks)

Description of the possible Xe GSE modifications to comply with ALPHABUS need

Two kind of modifications have been studied for the Xe GSE to comply with the ALPHABUS need :
. a major upgrade of the loading capacity that would allow to reach approximately 30 g/s during both the loading and unloading phase,
. a minor upgrade of the loading capacity that would allow to reach approximately 14 g/s during the loading and 18 g/s during the unloading phase.

The major upgrade would lead to increase to much the electrical power of the XeGSE (more than 16 kW) and the design of the cart would have to be changed completely because of the limited available size.

Thus, only the minor upgrade of the XLE has been studied in more details.

To increase the flow rate of the 2 compressor from 8 to 14 g/s the following modifications can be done quite easily :
. to increase the installed electrical power from 2.3 to 3.5 kW per compressor
. to slightly increase the height (and thus the internal volume) of the compressors without changing their thickness,
. to increase the diameter and thus the heat exchange surface of the LN2 heat exchanger in the compressors (12/14 mm tube instead of 10/12 mm tube)
. to increase the diameter and thus the heat exchange surface of the Xenon pipe in the heat exchanger located downstream the compressors (6/8 mm tube instead of 4.4/6.5 mm tube)
. to delete a manual flow control valve FCV001 located at the inlet of the LN2 circuit in order to decrease pressure drop and thus to increase the LN2 flow (tests done of the previous carts show that the LN2 flow rate can be easily controlled with the LN2 supply tank pressure, without this valve).
. to reduce from 8 m to 6 m the length of the flexible hose between the XeGSE and both the cylinder rack and the S/C (to be confirmed)
. to modify the control/command software to allow to work with 2 compressors during the draining (for the Xe GSE already built, 1 compressor is enough during the draining of the S/C tank taking into account the limitation of the flow rate to avoid condensation on the tank wall)

Furthermore the other envisaged modifications are :
. the location of (existing) temperature sensors to improve the temperature control of the Xenon by the heat exchanger located downstream the compressors,
. to increase slightly the length of the LN2 hoses between the LN2 valves and the compressors to reduce stiffness of these hoses.

Conclusions

The development of the Xenon Ground Support Equipment as needed for use of Xenon propellant was successfully achieved by AIR LIQUIDE. Three carts have been built for major S/C manufacturers, with a loading capacity around 8 g/s (mean value between 70 and 150 bar).

For the Alphabus program, up to 1200 kg may have to be loaded on board the S/C tanks. Such a large capacity may be loaded within 22 hours with a slightly modified cart. The unloading could be performed within 19 hours if the 2 thermal compressors are used during the unloading phase.

The modifications needed to reach such performances would not require to perform a new PDR phase . The low mass/volume and the transportability of the cart would not be changed by these modifications.

This paper is dedicated to the two co-authors, Cécile GELAS and Roland SALOME from CNES, who both died recently. Their competence had equal only their sympathy.

References

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