Solid storage of H2 for propulsion and energetic modules

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ABSTRACT

SNPE Matériaux Energétiques develops new advanced formulations in order to provide innovative solutions for advanced propulsion and for energetic modules. One of these energetic materials is the NFH2® composition (New Formulation H2) which allows storing hydrogen in a solid way and displays a high gravimetric hydrogen yield. The presentation will give a description of how the formulation is working. A state of the art of current SNPE development will also be provided. An overview of advanced applications for propulsion and energetic modules that might use this technology will be given. To illustrate in more details possible applications, two of the advanced modules were selected and will be presented, in particular how these technologies can be used and what are their advantages. The first one is a new advanced stage architecture for space transportation systems in order to use the NFH2® to pressurize storable fuels (in house funded study in cooperation with ASTRIUM ST). The second one relates to the fuel cell technology for aircraft applications in substitution of the Ram Air Turbine (common study with Airbus France).

INTRODUCTION

SNPE Matériaux Energétiques develops solid hydrogen storage systems in order to be able to furnish alternative solutions, completing existing technologies for hydrogen storage systems (hydrogen pressure vessels, storage in complex hydrides or in porous materials – reversible systems).

Hydrides are a good basis to develop these solid hydrogen storage solutions. They can be used by thermolysis to deliver pure hydrogen. The hydrogen yield of these components is one of the main advantages of these raw materials. The hydrogen yield of some of these hydrides, as $LiBH_4$ (18.4 %), $Al(BH_4)_3$ (16.8 %) and NH_3BH_3 (19.6 %), is very high.

For this reason they must be considered for this kind of solution, plus the fact that the synthesis is well documented in the literature [1]. SNPE Matériaux Energétiques has been working on these potential solutions, and has developed a technology based on the reaction of two solid reactants. The first one is a specific hydrogen-rich hydride which is a specific SNPE Matériaux Energétiques product still under development, and the second one is a classic oxidizer which is available and already used in pyrotechnics.

The composition that has been formulated has been characterized in gas generators. To ensure the complete decomposition of the mixture during the combustion, the reactant proportion had to be scaled. Some agents are added in order to produce and to use the materials in good safety conditions. The mixture was shaped to obtain pellets by pressing the mix of hydrogen-rich hydride and the solid reactant together. The manufacturing process is well known from the automotive safety industry. This technology avoids binders which would introduce pollutants for fuel cell applications.

Once the mixture initiated, the pyrolysis releases pure gaseous hydrogen and generates solid residues which stay by mechanical filtration in the combustion chamber.

However, a lot of hydrides are not easy to handle from an industrial point of view: hygroscopicity, thermal stability and safety behavior have to be conclusive for a future use and an industrial manufacturing process.

Most of the commercial available hydrides were evaluated and at least SNPE developed an in house product with better characteristics than the commercial ones.

As already mentioned, most of the commercial hydrides are hygroscopic at room temperature such as lithium borohydride as we can see in Figure 1.

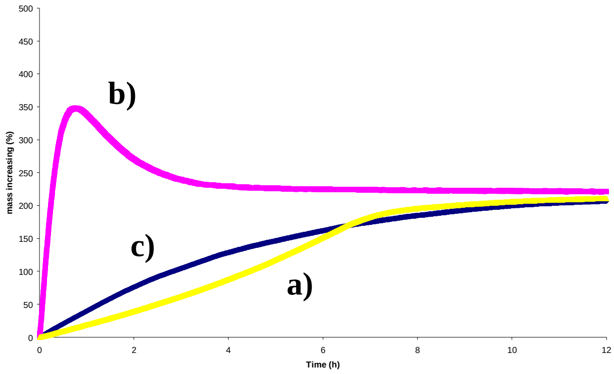

Figure 1: Mass increasing for three different shapes of lithium borohydride versus time (T=20°C and HR=65%); a) Pellet, b) Powder bed, c) Powder's heap.

This figure shows the mass increasing of the hydride due to hydrolyze with the ambient air.

It is important to underscore that the mass increasing of a material depends on the hygrometry rate and the temperature.

What's more the thermal stability is very low for a large scale of commercial hydrides such as lithium borohydride as shown in Figure 2 .

The results shown in this graph make's it evident that the lithium borohydride for example is finally not a good candidate for an industrial application in order to develop a solid hydrogen storage solution.

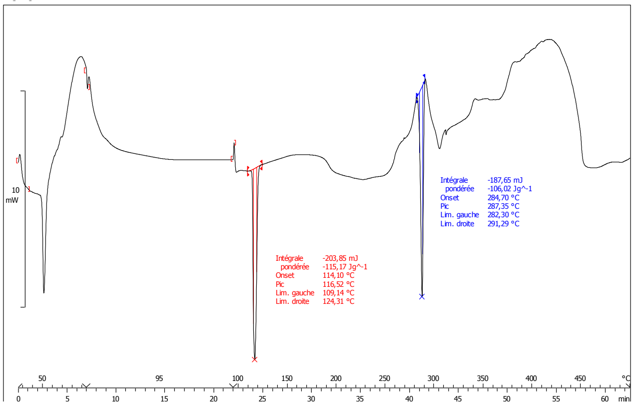

Figure 2: Differential scanning calorimetry of typical commercial lithium borohydride (Heating rate 5°C/min under nitrogen flow).

After identification or development of a hydride which can be used for industrial mass production at acceptable production costs, a suitable oxidizer has to be determined.

Improved industrial oxidizers have to be chosen to reduce development cost, for instance oxidizers already used in pyrotechnics or in the automotive airbag safety industry are considered.

Once this study level reached, classical formulations have to satisfy to the following safety tests:

- Friction sensitivity
- Shock sensitivity
- Sensitivity to electrostatic discharge

Finally, the formulation has also to be improved to obtain hydrogen-rich gases compliant with the performances required by the advanced applications. For example, most of the fuel cells are very intolerant to gas species like carbon monoxide or ammoniac in the range of compatibility of some ppm up to less than 1 %.

The purpose of this paper is to present results obtained up to now by SNPE Matériaux Energétiques in the development of a solid hydrogen storage solution for specific on board applications. When development is fully completed, hydrogen mass yield of this formulation has to be higher than 10%. At least 2 potential applications will be illustrated.

SOLID HYDROGEN STORAGE

HYDROGEN STORAGE TECHNOLOGY

The technology developed by SNPE Matériaux Energétiques concerns the reaction of two solid reactants. The first one is a specific hydrogen-rich hydride which is a specific SNPE Matériaux Energétiques product still being developed and the second one is a classic oxidizer which is already available and already used in industry.

The reactant proportion must be scaled to ensure the complete decomposition of the mixture in order to optimize also the mass fraction of released hydrogen. Some agents are added in order to produce and to use the materials in good safety conditions.

The mixture of hydrogen-rich compound and the solid reactant are pressed together to obtain a pellet shape from two powders. Pellets of 1 g and more were formed.

The manufacturing process is well known from the automotive safety industry. This technology avoids binders which would introduce pollutants in order to take in account the purity requirements for fuel cell applications. The pellet dimension can be adjusted to the hydrogen mass flow need to feed the fuel cell.

Once the mixture initiated the pyrolysis will release pure gaseous hydrogen and generate solid residues which stay by mechanical filtration in the combustion chamber. The temperature of this hydrogen inside the combustion chamber will be about 600 K. The temperature can be mastered in function of some additives which are added to the NFH2® formulation.

MAIN ADVANTAGES

This technology is compliant to other existing hydrogen storage solutions.

The main advantages are the following:

- **A fair energetic density.**
  The final energetic material will have a hydrogen mass yield higher than 10 %. Taking in account this parameter, it will be possible to obtain hydrogen storage systems with a total hydrogen yield of about 7 %.

- **Hydrogen is only released when required.**
  The hydrogen of the hydride will only be delivered on demand. There will be no risk of leaking hydrogen during the long term storage phases.

- **Does not need to be stored under pressure.**
  This technology does not need pressure vessels during the sleeping storage phase. Hence, it is possible to reduce maintenance and monitoring costs by increasing safety level.

- **Durable product**
  The hydrogen producing energetic material will have a similar aging behavior than current energetic materials from civil and military applications.

- **Temperature range.**
  The solid hydrogen storage technology allows hydrogen to be delivered on demand at a large temperature range and especially at very low temperatures down to -45 °C. The upper limit is given by the thermal stability of the hydrogen-rich hydride.

HYDROGEN GAS GENERATOR

A lab scale gas generator has been developed for the combustion of small quantities of products (few grams) as shown in Figure 3. It is composed of a combustion chamber (14 mm of diameter) equipped with a hot wire to avoid generating impure gas phases. Generally 3 pellets of 1 g are placed in combustion chamber. The initial gaseous volume is filled up with helium in order to allow reliable gas analysis on the combustion gases. After ignition, the solid-solid reaction occurs. At the end of the combustion, gases are collected in a storage system of 150 ml. Pressure and temperature are both measured, respectively, by a pressure and temperature transducer in the combustion chamber and in the plenum.

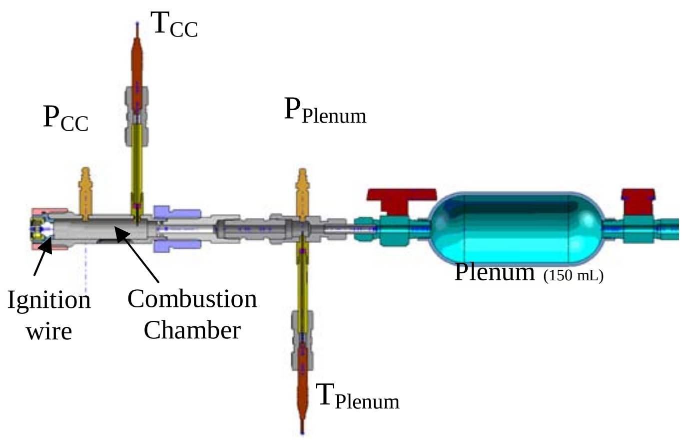

Figure 3: Experimental lab scale gas generator design.

The latest gas generator evolution allows the combustion of about 50g of the NFH2® formulation.

BALLISTIC PROPERTIES

In order to evaluate the ballistic performances and the combustion parameters of the composition developed by SNPE Matériaux Energétiques, tests on manometric vessel were carried out as shown in Figure 5. The burning rate can be correlated to the burning law defined by the equation $v=aP^n$ with a=0.32 mm/s/MPa and n=0.96 according to the following pressure range 24 MPa < P < 71 MPa. Pellets burn in parallel layer.

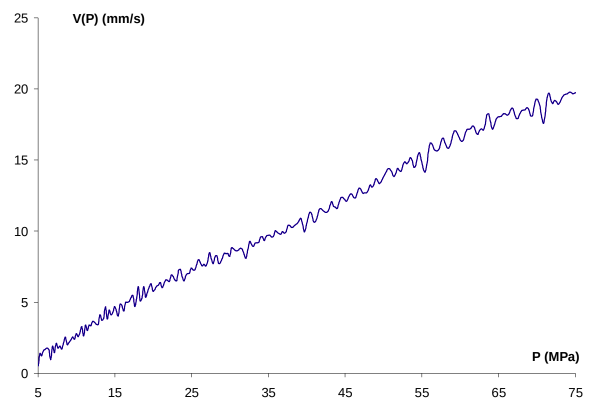

Figure 4: Burning rate of SNPE Matériaux Energétiques composition versus pressure.

Taking in account this result (pressure exponent), gas generators were equipped with ball valves to obtain repeatable operation pressure. The improvement of the pressure exponent is one subject of the current studies conducted at SNPE Matériaux Energétiques.

TEST RESULTS

Experiments were performed in lab scale gas generator systems used for the combustion of small quantities to evaluate the hydrogen mass yield of the newest formulation NFH2®[1]. Results of hydrogen mass yield are given in the following Table 1.

	NFH2®[1]
Ambient temperature 25 °C	10,1 %
Cold temperature -45 °C	5.8 %

Table 1: Hydrogen mass yield for NFH2® formulation tested at room and cold temperature.

Note: The formulation used for the ambient temperature combustion tests was the latest evolution and gives already very good results. The result can be improved in a near future by an more advanced optimized formulation.
The result given for -45°C was obtained with an older formulation which gave 7.0% of hydrogen mass yield at ambient temperature. With the latest evolution of NFH2® this result would be much better.

Gas analyses were performed after each combustion test. The results show that the hydrogen purity versus fuel cell poisons is quite good. The volumetric concentration of hydrogen is about 90 %, the residual gases are composed of nitrogen (9 %) and some traces of oxygen (0.001 %) and ammoniac (0.003 %).

Figure 5 shows the encouraging thermal stability of the hydride developed by SNPE Matériaux Energétiques for its NFH2®[1] formulation.

[1] SNPE Matériaux Energétiques patent

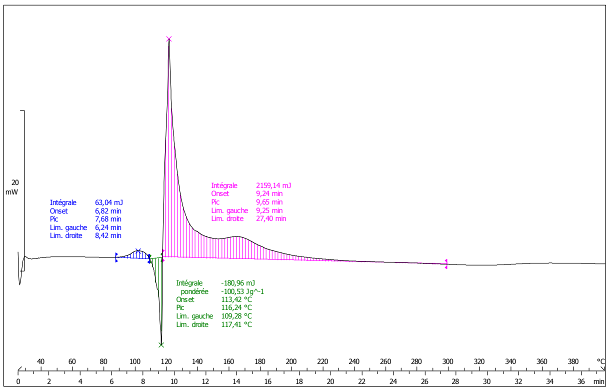

Figure 5: Differential scanning calorimetry of hydride synthesized by SNPE Matériaux Energétiques. (Heating rate 5°C/min under nitrogen flow).

Combustion residues obtained are white, hard, and crumbly. The morphology and physical aspect are showed in Figure 6. In addition, residues are very stable at ambient temperature and represent no particularly healthy risk.

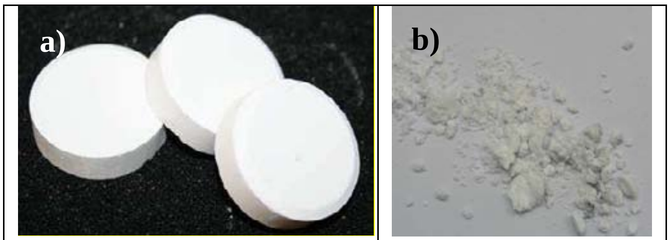

Figure 6: Physicals aspects of the composition before and after combustion. a) Products are formulated with a pellet shape initially, b) Residues of combustion after the combustion process in gas generator.

Before testing combustion on new formulations, this one has to be tested in terms of safety. Results concerning the composition developed by SNPE Matériaux Energétiques are presented in Table 2. No major problem appears, the product can be handled safely.

Safety tests	Friction sensitivity	Shock sensitivity	Sensitivity to static electricity
NFH2®[1]	Non sensitive	Non sensitive	Sensitive*

*(can be improved by adjunction of non pollutant additives)

Table 2: Safety tests results NFH2®[1] formulation.

POTENTIAL APPLICATIONS

The solid hydrogen storage technology is complementary to other already existing solutions. This technology addresses issues concerning safety or long duration storage requirements, like:

- Gas generators to feed Turbo-Pumps (TP) in order to pressurize propellants (space and missile applications),
- Hydrogen storage for on board emergency systems, as fuel cell systems in substitution of Ram Air Turbines (RAT),
- Hydrogen for military fuel cell systems which have also to operate at very low temperatures with good safety characteristics,
- Fuel cells for unmanned submarines for long time missions,
- Solid Hydrogen source for Pulse Detonation Engines.

For the two first applications some more details are given below :

TURBO PUMP APPLICATION

ASTRIUM ST and SNPE Matériaux Energétiques have joined resources in the frame of a collaborative R&T agreement to conduct an analysis combining both launcher system needs knowledge (Astrium-ST) and technological solutions expertise (SNPE and Astrium-TP). Purpose of this joint study was to investigate feasibility and interest of new energetic formulations for gas generators to feed low temperature turbopumps.

The hydrogen gas generators under ongoing development by SNPE Matériaux Energétiques is suitable for this kind of application and enable to improve the performance of propulsion system.

The purpose of this chapter is to present the potential application that it offers, in particular in the pressurization of propulsion system of Ariane 5G launcher upper stage.

GAS GENERATOR TECHNOLOGY FOR TURBOPUMPS

GAS GENERATOR CONCEPT

SNPE Matériaux Energétiques works on a concept of gas generator equivalent to a gas bottle with other assets described above. The functional analysis and the most important work directions are described on Figure 7.

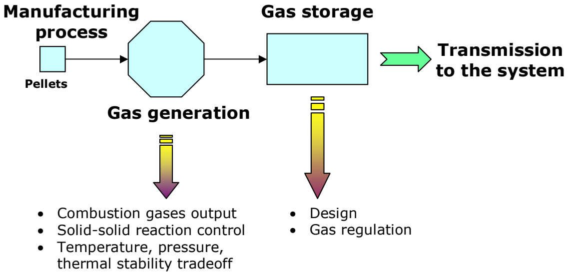

Figure 7: Functional analysis

POTENTIAL SPACE APPLICATIONS

PRESSURIZATION OF PROPULSION SYSTEM OF ARIANE 5G LAUNCHER UPPER STAGE

In the space industry there are two major ways of supplying the engine with propellants. The Pressure Fed system (PF) involves high pressure gas which pushes the propellants in the combustion chamber. It is simple and reliable but heavy.

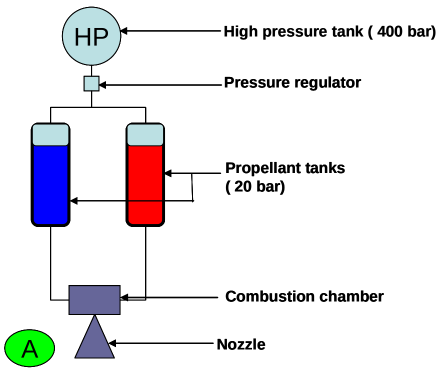

Figure 8: Pressure fed system

On the other hand, Turbo-Pump (TP) system involves pumps and turbines powered by a small part of the propellants. The propellant tanks are pressurized with a little amount of high pressure gas. It is light, but complex and costly.

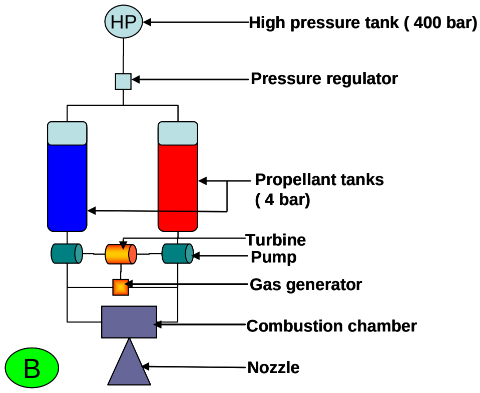

Figure 9: Turbo-pump system

As a general rule, pressure fed systems is not competitive with pump-fed systems for large scale engines and large amount of propellant.

Parameters	Pressure Fed	Turbo-pump
Reliability	+	-
Cost	+	-
Development	+	-
Volume	-	+
Performances	-	+

Table 3: TP vs PF comparison

The lowest reliability of TP system is linked to:

- coupling between propellant used both for engine feeding and for turbine feeding via gas generator,
- high speed rotating system combined with high pressure and temperature levels,

The high cost of TP system is coming from:

- heavy development cost due to more complex studies and tests to define and to tune feeding system,
- high recurrent cost due to TP cost (around 30% of engine cost)

These complex TP studies and tests involve a more risky program and a longer development phase.

Higher volume of PF system is due to high pressure tank required for gaseous helium storage.

Higher performance got on TP system is mainly linked to:

- mass saving on propellant tank (low pressure level) and pressurant tank,
- and higher specific impulse (high pressure level of TP engine allows larger expansion nozzle in the same layout).

This performance increase has been validated both for cryogenic and storable propulsion systems.

The goal of this paragraph is to present the interest of an intermediate solution between these both systems and based on the gas generator technology under development by SNPE.

It consists in using this gas source to power a small TP and so to pressurize the propellants.

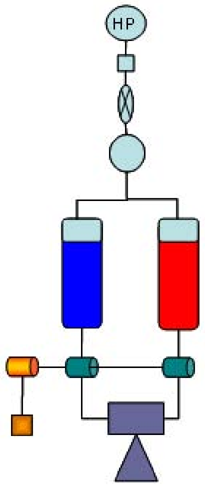

Figure 10: Principle of TP fed by warm gas generator

With regards to present "classical" turbo-pump used in space industry, external turbine feeding source simplify strongly synoptic and avoid complex and not reliable system. Moreover, usual development cost necessary to calibrate global feeding system will be highly decreased.

In the suggested concept, two gases are required. Warm gas, generated by solid generator, is used to power turbine power and a cold gas, helium stored in high pressure tank, is required for propellant tank pressurization.

Helium is used, instead of warm gas, in propellant tank thanks its neutrality and lack of propellant heating risk.

The first approach is applied hereafter to an existing pressure fed system to show its potential impact especially in a performance of view (mass reduction).

Pressure Fed S/S: the A5 EPS case

The "Etage à Propergols Stockables" (EPS) stage of Ariane 5 was taken as a reference.

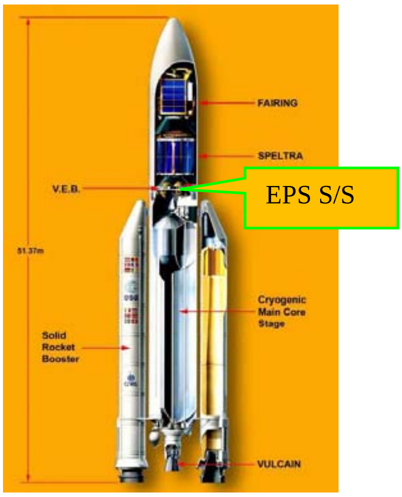

Figure 11: Ariane 5G launcher

The propulsion system of EPS is re-ignitable and containing 10 tons of storable propellants (MMH and N_2O_4). It has been developed by Astrium ST in Bremen, Germany. This stage is used since 1996 (first launch) and has now been replaced by the more powerful ESC-A. Nevertheless, its re-ignition capability led EADS Astrium to use it again for the ATV mission (three boosts were necessary).

Figure 12: Upper stage of A5G

The hereafter synoptic is a simplified schematic of the system currently used in the EPS stage of Ariane 5.

The system is composed with four main components:

- A **high pressure gas container**. In the present version of the EPS, there are two Helium tanks of 300 L each. They contain Helium at 400 bar initial pressure.

- A **pressure regulator** which takes high and variant pressure at inlet and generates a constant pressure of 20 bar in the propellant tanks.

- **The propellant tanks**. In the present version of the EPS there are four propellant tanks (two for MMH and two for NTO). They are sized to withstand the high pressure coming from the pressure regulator and necessary to push the propellants in the combustion chamber.

- **The engine** constituted of the combustion chamber and the nozzle (the Aestus engine in the EPS).

Sizing of the new pressuring system

When possible, components of EPS are kept to facilitate the comparison and reduce cost development.

Modified and new components are:

- gas generator
- turbine
- propellant pumps
- propellant tanks are modified to integrate pressure level reduction
- pressuring tanks are also modified (volume reduction) to integrate GHe mass reduction

Gas generator

One of the gas generators which could be potentially used for this application is the hydrogen gas generator with the following characteristics:

Hydrogen gas generator:

- >50 mol/kg
- temperature range : 600 to 900 K
- hydrogen mass yield > 10 %
- 75 to 90 % of hydrogen in the generated gases

Taken into account present low TRL of the hydrogen gas generator technology, several assumptions have been made for the structural index. This sensitivity analysis has shown the sizing robustness with regards to this parameter.

Turbine

Classical space TP are not adapted for the needs: the required turbine power and volume flow rate is out of range by at least a factor of ten.

Another kind of turbines, called the Mini Gas Turbines (MGT), is compatible with the needs. These turbines have small diameters, high rotation speed and deliver power from 1 to 100 kW.

Mini-turbines are used in electricity generators for various systems. The sizing performed had given the following results:

Inlet/outlet pressure	20 / 0.1 (bar)
Inlet temperature	800 K
Gas supplying the turbine	NFH2®
Maximal efficiency	0.7 (-)
Max/Min speed N_{max}	334/42 (1E3 rpm)
Outlet Ø (mm) for N_{max} /N_{min}	70.6/210.4

Table 4: Characteristics of ideal turbines

The pump

The current space pump is in the [10 – 3800] L/min range, so a factor higher than 3 with regards to our present needs. Like for turbine a specific design is suggested with a lower diameter and higher rotation speed.

The turbo-pump assembly (TP)

Turbine and pump suggested have different rotation speeds. Required gearbox generates some losses and also decreases reliability level. However, if mission involves a higher level of confidence, this component could be avoided with slight design modifications and non significant performance degradation.

As turbine and pump required for the present application have very specific characteristics, the mass has been evaluated using a cross check method. First evaluation is an extrapolation based on an empirical law defined from OTS turbo-pumps. Second approach is based on summation of turbine mass and pump mass calculated from OTS commercial components. The consistency between both results gives a good level of confidence on the global result.

Global feeding system efficiency using this TP is mainly linked to pressure level in propellant tank. Maximal value, around 12 bar, is got with an intermediate value between EPS value (20 bar) and minimal thickness value (4 bar).

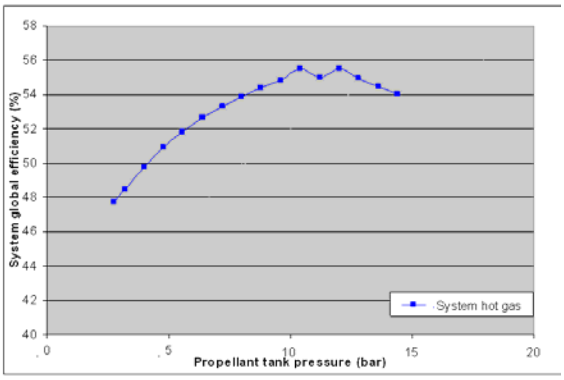

Figure 13: Feeding efficiency versus tank pressure

However global mass, and not the efficiency, is the major driver for design point definition. This global mass value is a combination of TP, gas, gas storage S/S and tank masses.

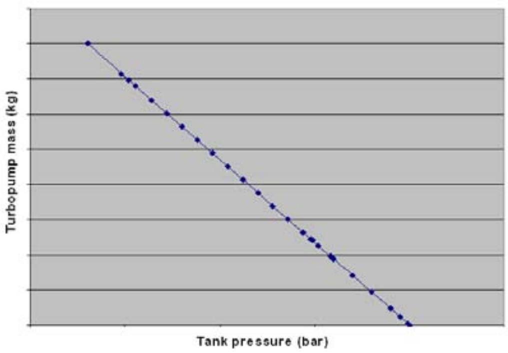

Figure 14: Turbo-pump mass versus tank pressure

Propellant tank

Propellant tank of EPS is sized to withstand the Maximum Expected Operating Pressure (MEOP) seen in the tank.

Its mass is assumed to be proportional to the pressure value taken into account a safety factor of 1.25 and internal additional equipments for propellant acquisition. The reference mass is the EPS value defined for 20.7 bar.

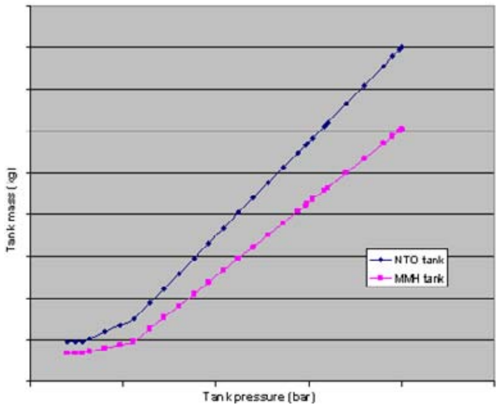

Figure 15: Tank mass versus tank pressure level

Curves are non linear and are explained by industrial constraint: a minimal thickness is assumed to integrate manufacturing limit (th ≥ 0.8 mm) and taken into account wall location (spherical or cylinder part).

Gas and gas storage system

Helium amount need is decreasing with propellant tank pressure level.

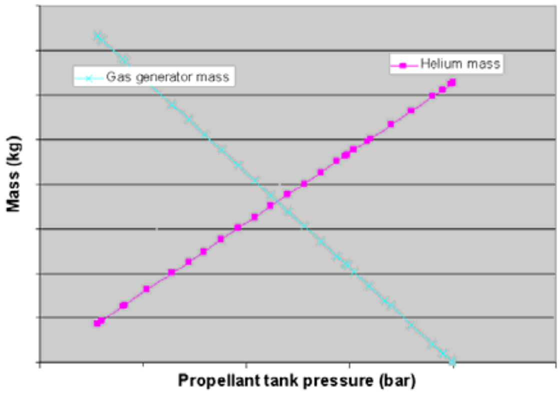

Figure 16: Gas masses versus tank pressure

According our evaluation, warm gas mass required to power the turbine is decreasing linearly versus propellant tank pressure. So globally total mass needs of gas is nearly constant whatever tank pressure is.

However storage gas system mass is very sensitive to tank pressure. Mass budget of Helium storage increases strongly with pressure level. At the opposite storage mass of warm gas decreases slowly. The consequence is that the minimal mass is reached at low pressure.

Propulsion system mass and sensitivity analysis

Mass budget provided hereafter is related on subsystems impacted with regards to present EPS.

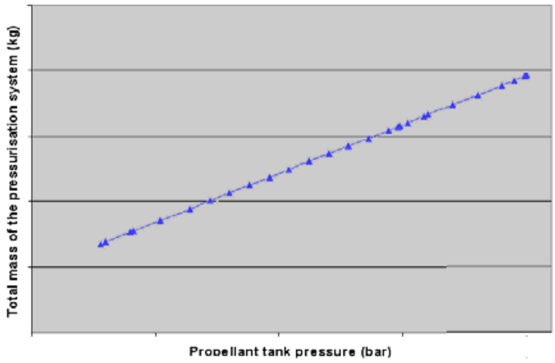

Figure 17: Pressuring system mass versus tank pressure

Taking into propellant tank pressure level as major driver, the potential mass saving is higher than 60 % for the pressuring system.

Additional potential criterion is pressuring volume. Analysis shows that pressuring is directly function of helium mass (high pressure tank) and so best option is also got for low pressure value.

As global mass is a combination TP, gas and gas storage system masses, global sensitivity is linked to robustness of subcomponent masses.

According to TRL level of warm gas generator (GG), a big uncertainty exists about gas generator mass. However, sensitivity analysis shows a positive gain even with pessimistic constructive index. This result is explained by the low mass fraction of gas generator sub-system.

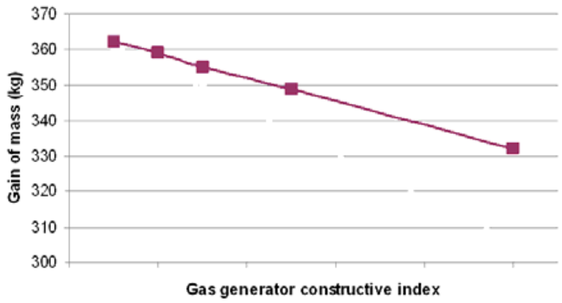

Figure 18: Mass saving versus GG structural index

The other major uncertainty is linked to the TP performance. The sensitivity shows the following result: efficiency higher than 40 % brings low gain. At the opposite, mass saving is decreasing rapidly when efficiency is lower than 20 %.

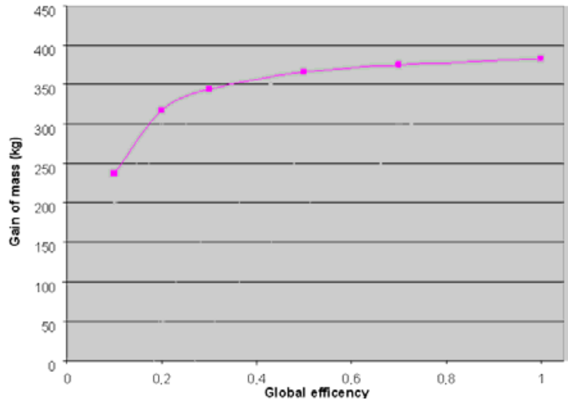

Figure 19: Mass saving versus TP efficiency

Conclusion for Turbopump application

First evaluation of NFH2® applied to an existing propulsion system, the A5G EPS, shows a mass saving around 60 % on propellant pressuring system.

Result is a performing compromise between a heavy, reliable and low expansive pressure fed system and a light, complex and costly classical turbo-pump system.

Over-cost with regards to pressure fed is limited due low additional development: low coupling level between components allows separated tests.

Propulsion systems with a TP fed by solid hydrogen gas generator are a good candidate for interplanetary applications where reliable, light and low volume systems are required and where classical complex turbo-pump systems are usually prohibited.

<u>EMERGENCY FUEL CELL SYSTEM IN SUBSTITUTION OF RAM AIR TURBINES</u>

Ram Air Turbine (RAT)

Modern aircrafts generate the electrical power required by the aircraft in flight through the main engines. During failure of all main engines, the aircraft has to be powered by an auxiliary emergency power source in order to power vital systems, as flight controls, linked hydraulics and also flight critical instruments.

Most of modern aircrafts are fitted with Ram Air Turbines (RAT). The RAT generates power from the airstream due to the speed of the aircraft. In normal conditions the RAT is retracted into the fuselage, deploying automatically in emergency case.

One example of such a Ram Air Turbine is given here below, in figure 20:

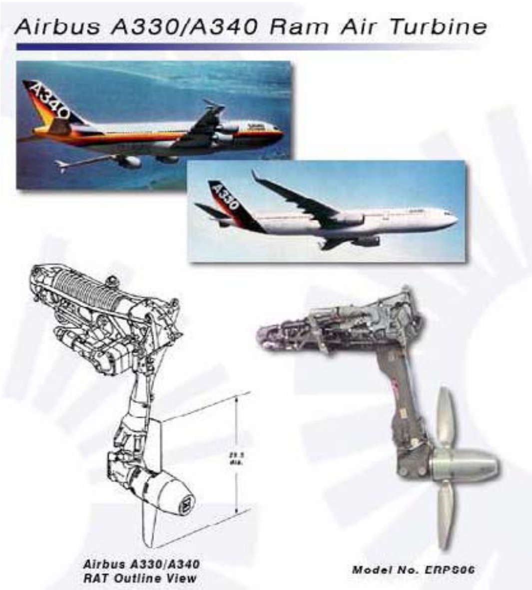

Figure 20: Ram Air Turbine

Currently AIRBUS and DLR [2] are studying the interest and feasibility to substitute the RAT by fuel cell systems. The main reasons for this interest are the following:

- High maintenance cost for Ram Air Turbines. Fuel cell systems should be less expensive from this point of view.

- At lower aircraft speeds and during the landing approach the RAT is working less effective. Fuel Cell Systems will work undependably of the aircraft speed and flight angle with constant efficiency.

- The starting delay of the fuel cell system should be reduced comparing to the starting delay of the RAT.

In 2008 AIRBUS in cooperation with DLR tested in flight successfully a 20kW fuel cell provided by MICHELIN on an Airbus A320 [2].

This flight tests validated the feasibility to operate a fuel cell in flight conditions.

Solid Hydrogen Storage Technology for on board emergency fuel cell systems

In 2006/2007 AIRBUS France contracted SNPE Matériaux Energétiques in order to evaluate the feasibility and the mass budget of his solid hydrogen storage technology for on board fuel cell applications.

In the frame of the RAT substitution by a fuel cell system, a trade off was conducted in order to feed hydrogen to a 50kW fuel cell during 1 hour.

Using the solid hydrogen storage technology from SNPE Matériaux Energétiques the following gas generator architecture was proposed:

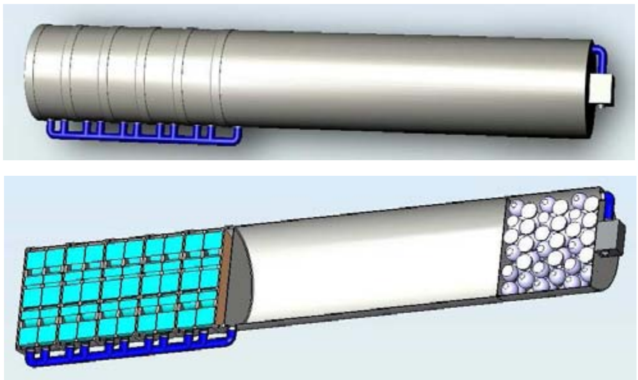

Figure 21: Hydrogen gas generator for on board 50kW fuel cell system

The gas generator is composed of 10 separated combustion chambers linked to a medium pressure plenum. Downstream to pressure plenum we have a metallic membrane, purifying the hydrogen in order to eliminate the small among of Nitrogen and Ammoniac. The filtration system is linked to a cooling device in order to reduce temperature of the hydrogen. The hydrogen mass flow is driven by a mass flow regulator on the outlet connection of the gas generator.

With the latest evolution of hydrogen generation formulation NFH2® the cooling device is no longer necessary.

Due to the use of pellet shapes for the generation of hydrogen, it is not possible to initiate a constant pyrolyse during the entire functioning time of the fuel cell. The generated hydrogen mass flow by the combustion of the pellets is higher than the hydrogen consumption of the fuel cell. For this reason the generated hydrogen is stored in an intermediate medium pressure plenum. The combustion chambers are designed in order to pressurize the medium pressure plenum with hydrogen rich gases up to 130 bar. Each combustion chamber is sequentially initiated on a low pressure level measured in the pressure plenum. In this way, the pressure level in the gas generator during functioning of the fuel cell can be limited to medium pressure level by reducing volume and mass of the hydrogen storage system.

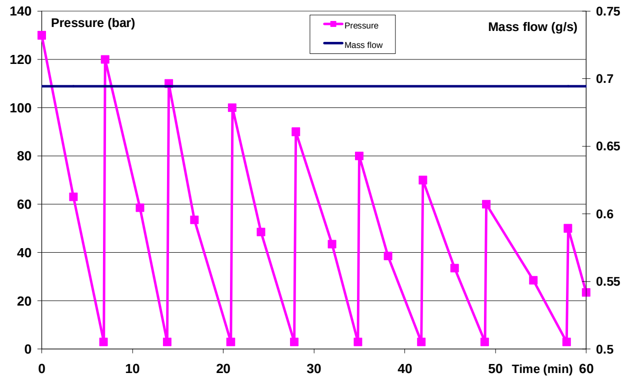

Figure 22: Pressure evolution in the plenum of the hydrogen gas generator during fuel cell functioning

The maximum pressure level decreases after each sequential combustion because the volume of the plenum is increasing by integrating the volume of the used combustion chambers.

For the latest evolution of the NFH2® formulation the cooling stage is no longer required. In this case the hydrogen yield of this architecture of hydrogen gas generator could be higher than 5% with the NFH2® technology.

Conclusion for on board fuel cell applications

The solid hydrogen storage technology under development at SNPE Matériaux Energétiques allows the long time storage of an hydrogen source without any pressure. The hydrogen is delivered on demand, when required. The hydrogen yield of this technology is more performing than for classical pressure vessels.

For one shot emergency fuel cell applications the SNPE technology allows to reduce mass budget by increasing safety and maintenance cost.

CONCLUSIONS

SNPE Matériaux Energétiques has already demonstrated that his solid hydrogen storage system is able to release pure hydrogen at low and room temperature. The experimental hydrogen yields of the energetic material NFH2® from SNPE is very performing (>10%). With advanced architecture design for some applications the hydrogen yield of the storage system should exceed 7%.

The release of hydrogen at high temperature is not really a problem. Nevertheless, the upper temperature limit for thermal stability has to be improved in order to obtain a good aging behavior. The SNPE Matériaux Energétiques in house product has very promising characteristics, which have to be completed by test results and further development studies.

For a several number of fuel cells applications, the hydrogen storage system will be a real issue. The fuel cell alone will not be a performing solution without a performing hydrogen storage technology. The safety requirements for some of these applications would be also a real issue.

For emergency systems with very long storage and inoperative durations a solid hydrogen storage technology, as the SNPE Matériaux Energétiques solution, will be a very good alternative in order to reduce monitoring and maintenance costs. With very competitive hydrogen yields this technology will also allow to reduce mass budget.

For military applications the hydrogen pressure vessels are for obvious reasons proscribed. To be operational at any meteorological condition you also need a storage system which is able to release hydrogen at any temperature and especially at low temperatures which is one of the main technical issues.

For propulsion applications the hydrogen gas generator technology based on NFH2® should also be a very interesting technology in order to replace pressure fed systems by turbo-pump fed systems for explorations missions. This technology will allow the use of new propulsion architectures for interplanetary missions with reliable, reduced mass and low volume components, where classical complex turbo-pump architectures are usually prohibited.

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