Low cost and green small storable propulsion system

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Abstract

It becomes obvious that now main criterion used to build an access to space is not "best performances" but "performances combined to best cost". In addition to that, new challenging parameters must be taken into account as safety rules combined with environmental impact.

Since several years, all these points have been introduced at AIRBUS DS level to define future storable propulsion systems especially to replace current hydrazine based propulsion system.

This paper discusses about environmental and cost criteria used and presents different identified alternatives according weight associated to each criterion.

For environmental criteria, drivers and main objectives of the on-going Eco-Space project are presented. As more and more technologies are claimed to be "green" without effective assessment or by only avoiding the use of REACh impacted substances, this R&T Airbus DS project aims to create a methodology to assess the environmental impacts of new emerging technologies. This is performed by the use of Life Cycle Assessment methodology and the implementation of an Eco-efficiency label for sustainable technologies. Both propellants and manufacturing processes are covered by this project. The way to proceed is explained.
For cost criteria, an economical comparison is drawn, based on material used and manufacturing process. In particular the interest of an Additive Layer Manufacturing approach is compared to a classical process. Impact of propellant toxicity on operations is also mentioned.

For propellant, several options have been identified. Inventory covers all kind of propellant starting from new energetic propellants based on ADN and HAN, until "old propellant" as H2O2. For manufacturing phase, alternatives are ranked from cost point of view but also with regards to associated TRL and by taking into account the used material.

Finally a "launcher RACS Class" thruster demonstrator project is presented. This thruster, developed at AIRBUS DS, combines both "Low cost" and "Environment friendly" characteristics. Firing tests, done end of 2014, are shown.

Introduction

Green propellants are less toxic than classical propellants such as nitrogen tetra-oxide (N2O4) or hydrazine currently used in launchers and satellites. The use of such propellants could reduce the high cost linked to operation, transportation and storage. Moreover they could be sent by plane and transfer from tank to tank quickly and efficiently. Operators don't need heavy Scape suits as for traditional propellants. Moreover some of these green propellants deliver now a similar or higher level of performances.

1. H2O2 thruster demonstrator

1.1 Program overview

The H2O2 thruster demonstrator development is an R&T Airbus DS project. It is part of Alternative Propellant Program which aims mainly to identify best monopropellant(s) to replace hydrazine in propulsion systems.

Initial main goals of this project were:

1. to demonstrate capability to perform, from scratch, in a short duration and with a limited budget, a hot firing test with H2O2 as monopropellant on a new thruster of launcher RACS class range,
2. to get data to be able to initiate a complete thruster development.

   An additional objective was added during first exchange: this program was an opportunity to demonstrate than a fully ALM manufactured thruster works with acceptable performance.

Logic defined end of 2013, to achieve this project, including manufacturing phase, led to following steps. First points were to build requirements then to perform sizing. After material was chosen based on decomposition characteristics (from thermal and chemical point of views) and also based on manufacturing process specificities. A validation of hydraulic performances was performed thanks to pre-manufacturing of injector parts. Two loops were needed to reach the requirement goals then freeze of design, taking into account some ALM constraints, was done before final MAIT process.

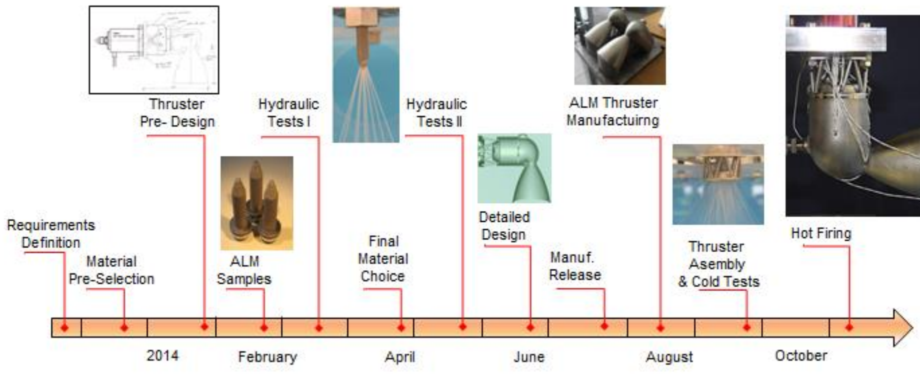

Figure 1: H2O2 thruster demonstrator planning

In parallel hot firing test preparation (test plan definition, test jig design and manufacturing, and test bench adaptation) was managed including some exchanges with DLR, and that until Hot Firing Tests end of 2014.

Presented activities were performed in less than one year in a cooperative French-German team with the support of DLR for HFT preparation and test facilities and Heraeus the for catalyst material providing.

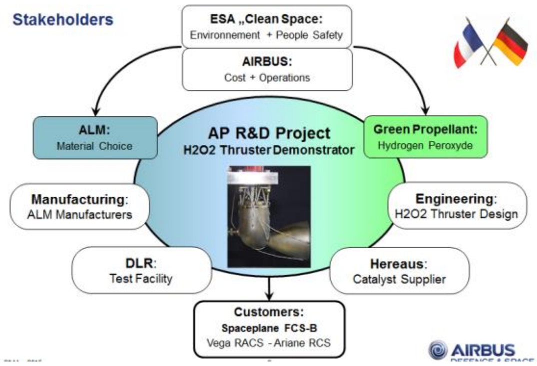

Figure 2: project actors and inputs

1.2 Thruster demonstrator requirements

Thruster specifications were based on a launcher reaction control engine needs but with specific relaxations and constraints to be consistent with the demonstrator approach. Major specificities are issued from short development duration and limited budget and have led to

1. derive design from a robust and proof design hydrazine thruster,
2. choose manufacturing process well adapted to low cost and quick change,
3. relax performance box size and
4. remove long life duration test in this early development step.

In addition support of DLR and Hereaus were also key factors to reach the programmatic targets.

1.3 Additive Layer Manufacturing

ALM approach was selected (with classical method as back-up) because it is really adapted to fast prototyping: nearly direct chaining between CAD phase and manufacturing and short manufacturing duration. Only some very limited additional machining (surfacing) were added at thruster parts interfaces.

Figure 3: Chamber/nozzle part just after ALM phase

In addition the use of ALM in a thruster demonstrator became a contributor of ALM R&T logic. The use of ALM is interesting not only for demonstrator but also well adapted to space applications when a low quantity of a components is needed.

It shall be noticed that limitations appear during development on injector pressure drop linked to roughness level brought by ALM process. This roughness level is due both to material and to powder size used. Several loops were needed to reach, through the change of some shape design parameters and hydraulic test check, correct pressure drop and homogeneous spray at injector. .

1.4 Thruster design

For programmatic reason, it was decided, to limit the development risk, to privilege a robust design was chosen. Potential optimization offered by ALM approach through a wide range of possible shape was not yet used for this demonstrator.

Chamber/throat/nozzle geometry was based on a well-mastered monopropellant AIRBUS thruster with only some adaptations to be compliant with propellant characteristics and catalyst specificities. Always for robustness reason, wall thickness was not optimized. A large safety factor was used to avoid heavy 3D thermomechanical analysis.

1.5 Material choice

A trade off was performed to choose the best materials compliant both with functional thruster constraints (propellant compatibility and thermomechanical loads) and with ALM manufacturing specificities and ALM sample tests.

2. Environment:

2.1 Eco-design & Life Cycle Assessment

ESA has recently launched the Cleanspace initiative focusing on 4 main topics:
- Eco-Design
- Green Technologies
- Space Debris Mitigation
- Technologies for Space Debris Remediation

Following the ESA Cleanspace initiative, Airbus DS Space Systems has launched in 2013 the Eco-Space project. This project especially supports the Eco-Design and Green Technologies branch of the Cleanspace program.

Main objectives of the project are:

- Developing eco-design rules, processes and tools on new products
- Giving consistency to “Airbus DS Space Systems green initiatives”
  - inventory of intended green technologies
  - giving cost and environmental arguments for new technologies development
  - applying Life Cycle Assessment (LCA) methodology on products and new technologies development
  - providing consistency and control for customers

Life Cycle Assessment is a driver for decision making which allows quantifying products’ environmental impact from raw materials phase until end of life.
This methodology is based on the analysis of every aspect and phase of a product or program through its overall life cycle, from design or acquisition to disposal or recycling.

LCA is a structured and standardized method and management tool through ISO 14040 & ISO 14044.
Life Cycle Assessment plays a key role in the future product development by taking care of all the current environmental impacts on earth affecting Human Health, Ecosystems and Resources Depletion.

Efficient products and technologies contribute also to reduce costs by decreasing material inputs, energy consumption and waste.
This approach meets two of the major objectives of all futures Space Program: costs control and environmental impacts.

2.2 Assessment of intended ''Green'' technologies

As more and more technologies are claimed to be "green" without effective assessment or by only avoiding the use of REACh impacted substances, Eco-Space project aims to create a methodology to assess the environmental impacts of new emerging technologies.

In this context, intended green propellants like H2O2 or ADN based propellants have to be assessed.

- ➔ As Hydrazine is a highly toxic propellant targeted by REACh regulations, H2O2 and ADN based propellants are investigated to replace Hydrazine propellants for specific applications.

Even if these propellants are well known as less toxic than Hydrazine for human health, indirect environmental impacts on their overall life cycle had never been studied or never used as main criteria to justify their "green" aspect (except for LMP-103S ECAPS with a LCA analysis) . This is an argument which cannot be scientifically proven by only focusing on one environmental criterion or by focusing on one phase of the propellant life cycle.

This topic is under study within Airbus DS Space Systems in order to assess the environmental impacts of H2O2 and LMP-103S (ADN based propellant) compared to Hydrazine propellant.
The methodology of LCA has been chosen for this study as it is a multi-criteria assessment approach covering the full life cycle phases of propellants.

2.3 Development logic for propellant comparison

Whilst it is generally considered in the rocket and atmospheric communities that propellant released (plume) is the source of major environmental impact, this is neglecting the upstream phases like propellant synthesis or storage which can be very energy intensive.

The LCA under study on H2O2, LMP-103S and Hydrazine is taking into account the overall life cycle of propellants, from the propellant synthesis until propellant released during use phase of launchers.

At every step of the life cycle, inputs and outputs interacting with the propellants are collected. Main attention is devoted to the materials and chemicals which are taking part of the propellant synthesis, to the energy consumption of every process or transport and to the global rate of waste.

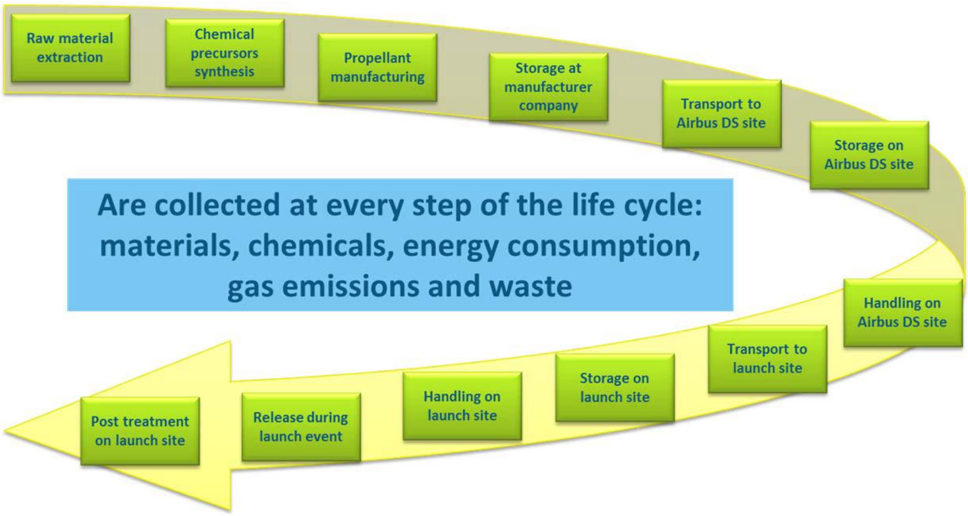

Figure 4: LCA perimeter of propellants study

All these inputs and outputs flows are then linked to environmental impacts using common LCA calculation methods and tools. To cover a large range of environmental concerns, the following environmental impact indicators are taken into account:

- Global Warming
- Ozone Layer Depletion
- Human Toxicity
- Air Acidification
- Freshwater Aquatic Eco-toxicity
- Abiotic Resources Depletion

Comparison of the three propellants is made regarding these six environmental indicators. In order to confirm the green aspect of H2O2 or LMP-103S, reduction of the environmental impact on the majority of these indicators must be noticed (compared to Hydrazine).

2.4 Next steps

Even if some specific trends can be pointed out on the three propellants (high toxicity of Hydrazine, specific storage tank for H2O2, high pre-heating power for LMP-103S thruster), this has not quantitatively been assessed yet.

When it has been supplied at Airbus DS site, propellants have to be followed in order to gather quantitative data on storage, transport and handling processes.

Meetings with propellant manufacturers will be arranged in order to collect quantitative data on propellant synthesis phase.

2.5 ALM as a green technology

Additive Layer Manufacturing (ALM) is an emerging, innovative and disruptive technology which intends to replace conventional manufacturing for specific applications within space sector. Several studies have been performed within Airbus DS in order to evaluate the environmental and cost benefits of this technology. On specific high value metallic parts, savings up to 30%, 40% and 50% have been noticed respectively on weight, cost and environment.

- ➔ Weight saving by new design options: functionalization, optimization of thickness and shape, topology optimization, removal of non-functional matter.
- ➔ Cost saving by improving the buy-to-fly ratio for complex and high value parts.
- ➔ Environmental impact benefits due to less energy consumption, improvement of buy-to-fly ratio conducting to reduce material use and waste production.

3. Low cost propulsion system:

Monopropellant system offers lower level of performance than bipropellant system except when total impulse level needed is reduced as on launcher RCS thanks to a lower dry mass. In addition it offers a better reliability and is less expensive.

Major part of past and current launcher RCS use hydrazine based propulsion system. However impact of toxicity on programmatic and potential future REACh restriction has led space industry to develop propellant alternatives. Favorites candidates are ionic products as ADN (Ammonium DiNitramide**)** and HAN (Hydroxyl Ammonium Nitrate**)** derivate, more simple products as Nitrous Oxide blend and also “old one” Hydrogen Peroxide (H2O2).

Two possible approaches are suggested for RACS propulsion systems development. First one focuses on high performance level criteria. Second one brings best “performance / cost” ratio. Indeed if performance level and reliability could be a killing parameter on space activity, more and more, economical model produces major criteria. High performance to cost ratio becomes the correct target.

<u>Cost parameters</u>
Identified ways to reduce recurring cost but without or with limited impact on performances are, for a low thrust storable chemical propulsion system, are:

a. to reduce components,
b. to simplify subsystems and interface,
c. to limit ground operations cost (production, assembly, transport and test)
d. to use a low cost propellant.

3.1 Component cost

Cost of component is reduced thanks to large removal of machining processes possible with the use of ALM process. In our project, as 2 separated ALM parts are mandatory to allow catalyst bed implementation, a single welding phase is required to join the thruster parts (nozzle-chamber assembly with injector head). That’s, with I/F surfacing, the lonely operations done before final with the valve.

From a cost point of view, a factor 2 is seen between ALM and classical approaches to get thruster body. If valve, final integration and test are included, saving is 25%.

Tableau 1: Figure 4: ALM vs classical costs for demonstrator thruster case

Manufacturing	Thruster parts cost (w/o valve and catalyst)	Thruster parts cost (with valve and catalyst)
Classical process	50%	100%
ALM manufacturing	25%	75%

The new engine, a reaction control thruster for launcher was made out of two parts only incorporating in one part the injector, heat barrier and mounting interface ad in the second part the chamber and the canted nozzle. These parts were printed in one day. A comparable classical engine would need more than 10 times more parts with subsequent effort in joining these parts together.

Interest of green propellants

Use of green propellant has several impacts with regards to cost. Architecture complexity, weight of operations and potentially cost of propellant are impacted by choice of a toxic or a non-toxic propellant.

3.2 Subsystem and I/F simplification

Use of a non-toxic propellant allows reduces complexity through architecture simplification. Indeed toxic propellant leads to specific requirement as additional safety barrier. In a practical point of view, to secure operations, additional valves are added to withstand failure without risk of operator injury. Globally saving is double: first during development, non-toxic propellant avoids heavy safety analysis mandatory to get and demonstrate a safe design. Secondly, from a recurring point of views, lack of additional safety barriers reduces both number of valves, lines for recurring cost and specific sensors to monitor sub-system and also specific interfaces with electrical system and OBS to manage health monitoring for during operations.

3.3 Ground operations cost (production, assembly, transport and test)

Indeed operations process could be simplified at ground level for green propellant.
Current processes for classical hydrazine based monopropellant system are well mastered and fully safe but are complex and expensive. For example for propellant loading phase in propulsion system, toxic hydrazine involves use of scape suits for operators. During this phase it is also mandatory to follow additional specific steps to check that system is propellant leak-free.
Another example in favor to green propellant is linked to transportation rules: propellant distribution from providers towards test(s) and flight center areas are eased for a non-toxic product with regards to a toxic product.

3.4 Propellant cost

All these additional costs lead to choose non-toxic propellant for low cost propulsion system. Among these propellants several options are possible:

- Hydrazine offers good performances and large heritage but is toxic and costly with regards to operations and presents a risk with regards REACh next limitations,

- Hydroxyl-ammonium Nitrate (HAN) and Ammonium DiNitramide (ADN) based liquid propellant: these two products are younger propellant candidates. Oxidizer rich salts are mixed with liquid fuels and blend result offer similar or better performances than monopropellant hydrazine system (specific impulse and density). Level of maturity is intermediate: some propulsion systems have been developed and have flown. These chemical products are more expensive than N2H4 and have some specificity as high combustion temperature that involves use of exotic chamber materials and a preheated catalyst bed for example. In addition procurement is not secured linked to lack of current large-scale applications (Space and Industry).

- Nitrous Oxides blend: this propellant is older than HAN and ADN. N2O alone is used as oxidizer in hybrid system but could be used also as monopropellant when mixed with a fuel (Nitrous Oxide Fuel Blend). NASA promotes this option [Ref. 10]. Specific impulse is close to bipropellant system one's. However high vapor pressure, at ambient temperature, involves specific component as propellants tank with a high MEOP leading to a high structural index compared to other monopropellant systems and also a potential high propellant residual value. This vapor pressure level allows keeping a nearly constant thrust level (no blowdown effect as on other monopropellant systems).

- Last main candidate is oldest one. Hydrogen peroxide has been used successfully since 2nd world war. Main application is gas generator, but it covers also monopropellant and bipropellant propulsion system. Level of performances (Isp and RhoxIsp) is lower than hydrazine, HAN and ADN. Contrary, level of cost is lower and with possible provider alternatives.

For our application, as programmatic constraints were high, non-toxic H2O2 was the preferred solution. More specifically it was decided to use a standard H2O2 concentration which offers both to ease providing (European), storage (better compatibility), transport (simplified rules and constraints) and a lower cost. In addition low concentration level eases material choice at propulsion system mainly for the decomposition chamber.

Table 1: mono-propellants table

	Hydrazine (N2H4)	AF-M315E (HAN basis)	LMP103S (ADN basis)	NOFBX	H2O2 (HTP) (87.5%)
Isp / Isp ref	100%	113% [Ref 3]	108% [Ref 3]	139% [Ref 5]	62% [Ref6]
Rho x Isp	100%	162% [Ref 3]	133% [Ref 3]	> 100%	112% [Ref 1] (TBC)
Tc	>1000°C (link. to dissoc. level)	1860°C [Ref 3]	1608°C [Ref 3]	1642°C [Ref 4]	800°C
Preheating (w)		350°C [Ref 7]	350°C [Ref 7]	Ignition needed	
Cost (propel.)	100%		>> 100%		1.6% [Ref 1]
Cost (loading)	+ 100k$ [Ref 2]	-	-	-	-
Remarks	Large heritage Highly toxic (programmatic impacts) REACh risk	Low heritage (GPIM) – Dvpt needed Catalyst bed heating needed ITAR constraint for AF-M315E LMP-103S is in Qualification phase (CNES mission)		Heavy tanks (Pv: 60 bar [Ref 4]) and high residual)	Heritage mainly on GG Decomposition # 1% / year

4. Component tests and HFT preparation:

4.1 Engineering tests

Before hot firing test, some specific tests were mandatory:

- Water test at injector level to validate mass flow and spray shape. Linked to “ALM + machining-less” approach for complete feeding line, hydraulic test was done to tune “injector design + ALM manufacturing”, several loops were done until reaching correct hydraulic behavior (spray shape and pressure drop/mass flow).
- Water tests were also done on “valve to injection head” part to validate full hydraulic pressure loss.
- Chemical reactivity: this test shows, qualitatively, high kinetic of reaction when HTP is putted in contact with propellant.

  These tests were done at Lampoldshausen.

For Hot firing test two variant of chamber/catalyst were manufactured:

- Taking into account benefit of ALM fats and low cost prototyping approach, two kinds of thruster chamber (2 lengths) have been manufactured to get sensitivity of catalyst bed length on thruster performances.

4.2 Hot Firing Test bench preparation

- Trauen DLR facilities have been used for test. Previously adapted for a hybrid propulsion test, some changes were done to be compliant with low thrust level thruster. Test plan defined covers nominal box with margins to show robustness of the thruster. Pulse mode firing and steady state firing have been performed with some long duration firing tests were done. Full life demonstration was not performed due to un-compatibility with demonstrator budget.

- After integration on test bench, thruster was tested for leak tightness and the complete measurement chain including video and infrared recording

4.3 Hot Firing Tests:

Firing tests were done on November at DLR Trauen test site in Germany. Steady State Mode firing and Pulse Mode were tested. As the tests of thruster were done without problems, a second thruster with longer thruster chamber/catalyst was tested to compare performances.

Figure 5: firing tests at DLR Tauen test center

Sensitivity with regards to feeding pressure and temperature levels were also measured. First rough analysis demonstrates consistency with performances requirements on thrust level, specific impulse and operating box in steady state mode.

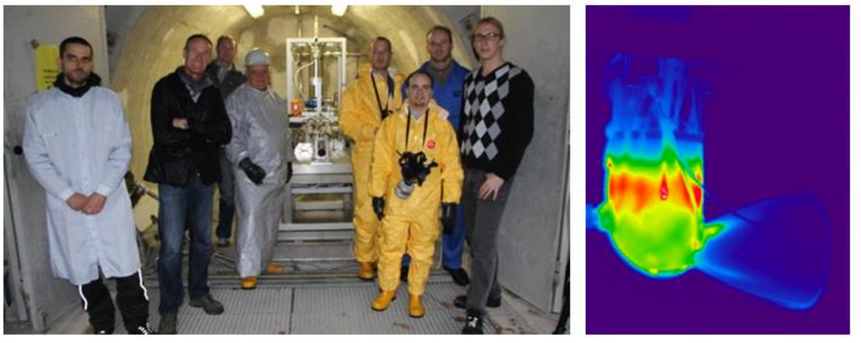

Figure 6: Test team and thermal view of thruster during firing

Last analysis about detailed transients phase and sensitivity with regards to inlet propellant pressure and temperature level are, today, not completed but cold start capability, rise and decay times and repeatability were, in a rough approach, coherent with expectations.

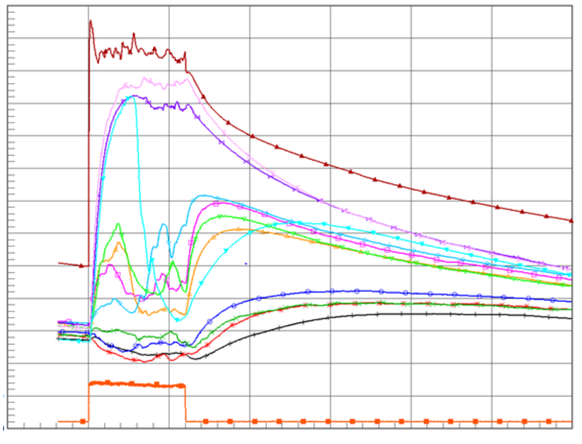

Figure 7 : Typical thermal and pressure evolution during long duration

Sensor measurements were recorded and results are now a valuable contributor to introduce this technology into a real mission.

☑ No safety critical condition occurred

☑ 36 kg total throughput for thruster #1 and 25 kg for thruster #2

☑ Full Operation Box including margin demonstrated (nominal: 8 - 24 bar: margin: 5 - 26 bar)

☑ Cold start capabilities demonstrated (7°C going directly into SSF at max inlet pressure) without pressure spike

☑ Pulse mode (re-ignitability, reactivity level) demonstrated

☑ Chamber temperatures and Chamber pressure within expected range – smooth decomposition behaviour

☑ HD Video recording (5 cameras including IR camera)

Figure 8: Performance criteria success of Hot Firing Test

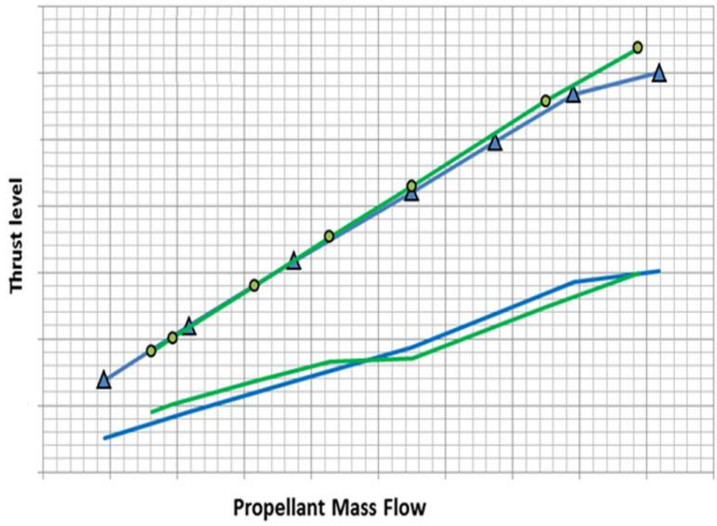

Figure 9: Thrust level versus mass flow for 2 catalyst bed lengths

5. Synthesis and next step

H2O2 thruster demonstrator program has allowed reaching the following objectives:

- To demonstrate capability to perform, with a limited budget, in a short duration, with involvement of different sites from Germany and France, a complete design, manufacturing and firing test of a green propulsion thruster.
- To get data to be able to initiate a complete thruster development.

An additional objective was achieved: a complete ALM thruster (except valve and catalyst) is compliant with level of performance expected for a launcher RCS thruster. Only full life duration was not demonstrated but long duration firing was done with no significant loss of performances.

This program was successful thanks to

- A good cooperation spirit between all German and French areas,
- Choose of a robust approach:
  - low performance but green propellant,
  - Use of ALM manufacturing process well adapt to reactive and low cost process (fast prototyping: one day to remanufacture thruster bodies),
- Support of DLR and Hereaus for test bench and catalyst material.

Next steps, partially already initiated are:

- Detailed HFT report especially for transient phases,
- Identify, in addition to long firing test, which new tests has to be done to have complete mastering of thruster performances,
- Perform a new and more optimized design focusing on 1 or 2 specific program thanks to 1st HFT analysis background.

6. Conclusion

In Nov. 2014 Airbus Defense & Space completed a fully successful test series with newly developed rocket engines. These engines incorporated two innovative technologies: a fully 3D printed thruster and the use of nontoxic ("green") propellant.

The use of 3D printing or Additive Layer Manufacturing (ALM) significantly reduced development time and development cost

Acknowledgments

The author thanks H2O2 demonstrator French/German AIRBUS team which has shown a building sprit and has demonstrated capability:

- to perform relevant choices,
- to be efficient between different phases,

and finally allows reaching both technical and programmatic requirements.

In addition, DLR and Hereaus have also contributed to this success this collaboration through a win-win approach.

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