ESA FUTURE LAUNCHERS PREPARATORY PROGRAM (FLPP): EXPANDER-CYCLE UPPER STAGE ENGINE DEMONSTRATION PROJECT ACHIEVEMENTS AND PERSPECTIVES

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ABSTRACT

Demonstrator projects are designed to significantly reduce the risks of subsequent developments. They are particularly meaningful in the field of liquid rocket propulsion. In 2006, the Vinci engine entered a 3-year expander-cycle demonstrator project in the ESA Future Launchers Preparatory Programme. By performing a large amount of hot-fire testing in vacuum conditions and making progress on the most challenging modelling issues, the demonstration has increased and harmonised the technology readiness level of the cryogenic expander-cycle engine in Europe. The results achieved are a sound base for the studies of future applications, such as the Next Generation Launcher.

Introduction

Liquid rocket propulsion is a specific and demanding area of the launcher sector. As liquid-propellant engines shape to a large extent the performance and reliability of the launchers they thrust, they are the object of long and test-intensive developments. Adding to the difficulty, the development timeline of a liquid-propellant engine does not synchronise easily with those of launcher or stage systems. Therefore, the logic and contents of an engine development plan must provide robustness with regard to unexpected technical results or specification changes. In such a case, an engine demonstrator project is in a position to bring valuable advantages in terms of overall risk reduction and development synchronicity. By focusing at an early stage on the technologies with the lowest readiness levels, the demonstrator significantly reduces the risk of costly and time consuming trial and error loops in a subsequent development.

Launcher system studies in the frame of the Future Launchers Preparatory Programme (FLPP) have identified the cryogenic expander-cycle engine as a common application for the different upper stage propulsion cases, such as the Next Generation Launcher. In 2006, the Vinci engine entered a 3-year expander-cycle demonstrator project in FLPP. The demonstrator was able to rapidly reach intensive engine hot-fire testing and achieve a comprehensive technical evaluation of the cryogenic expander-cycle. Improvement and harmonisation of the technology readiness level has been pursued.

The cryogenic expander-cycle engine demonstrator project was supported by eleven ESA Member States [1]. The programmatic and technical management were under the direct responsibility of ESA. The French space agency CNES, being at the inception of the Vinci engine, provided technical assistance to the project.

The industrial team was organised around the engine Prime contractor Snecma of Vernon, France [2]. The expander-cycle engine is the result of a wide European cooperation, giving way to a close international teamwork. The expander-cycle demonstrator has contributed to the safeguarding and progress of the cryogenic propulsion teams of the contractors.

Functional description

The propulsion of an upper stage induces specificities linked to the launcher mission profile and to the outer environment. The engine is ignited in vacuum conditions, after the boost phase of the lower composite. It must have been properly chilled down and conditioned before its ignition. It must also have withheld the dynamic environment of the previous boost phases. On a performance standpoint, for upper stage propulsion, a high specific impulse, low mass and efficient pump suction characteristics are the key specifications.

The expander-cycle offers two main comparative advantages, namely an integrated cycle, efficiently using the entire propellant flow, and the simplicity and robustness of the start-up transient, due to a limited number of subsystems. The turbines of the propellant pumps are powered by the main hydrogen flow after it has been expanded in the combustion chamber regenerative channels. Therefore, there is no need to derive a fraction of the propellants into a secondary combustion device to power the turbines with hot gas. Devices such as gas generator, gas generator valves, starter, igniter or exhaust pipe are not part of an expander-cycle engine design.

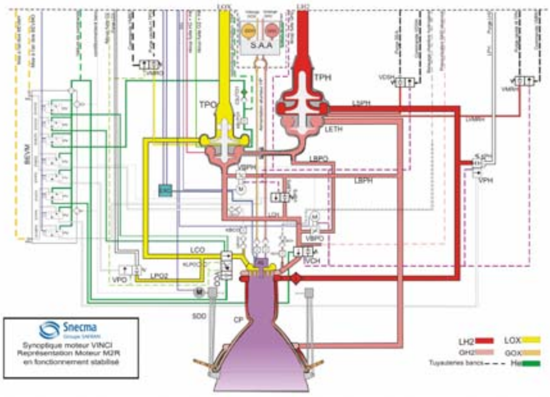

Fig. 1 – Expander-cycle engine flow schematic

The fuel side is the most specific in the expander-cycle. The hydrogen is pumped through the cooling channels of the combustion chamber, where it is charged with enthalpy. The gaseous hydrogen then powers in series the turbines of the propellant pumps, before being injected into the combustion chamber. The oxidiser side is more simple and classical, with liquid oxygen pumped directly toward the injectors of the combustion chamber. The operating point of the engine is trimmed by two valves controlling the flow of gaseous hydrogen by-passing the turbines. One valve controls the by-pass of both turbines, hence monitoring the engine thrust level. The other valve controls the by-pass of the turbine on oxidiser side only, thereby monitoring the engine propellant mixture ratio.

The temperature of the gaseous hydrogen injected into the combustion chamber is higher than in the case of gas generator engines. This leads to a smoother and more stable injection process on fuel side. As a confirmation, the bomb tests performed in winter 2009 in Germany have shown an extremely stable combustion chamber. The relatively higher hydrogen temperature is also helpful to the smoothness of the ignition process.

A radiating self-cooled composite nozzle is mounted on the regenerative combustion chamber. With this design, no dumped hydrogen cooling is necessary, and the integrated cycle does not require any exhaust pipe; therefore a high specific impulse is expected.

As of today, the ignition process in the combustion chamber has been kept similar to the experience of other European cryogenic engines, i.e. with a gaseous hydrogen lead. As re-ignition capability was part of the Vinci specification, the engine is equipped with a bi-propellant torch igniter. This has allowed to test the re-ignition in the demonstrator project, and to get precious technical results if the re-ignition requirement is confirmed in the future. The torch igniter is also extremely useful to increase the engine test cadence, avoiding the need to replace the igniter after every firing, as it is the case with a pyrotechnic one.

Technology Readiness progress

In line with the demonstration objective to maximise the technological content and readiness level increase, a list of all the technologies specific to the cryogenic re-ignitable expander-cycle engine has been drawn up at the beginning of the project. For each item, the technology readiness level (TRL) was assessed and the road map defined. The different road maps were integrated into the overall engine demonstrator logic, with a goal to increase and harmonise the different TRLs.

The cryogenic expander cycle is in itself a central topic. The main issues were organised around the start up, the steady state and the shut down phases. The start up transient of an expander-cycle engine has strong specificities, essentially linked to the direct coupling between regenerative flow and turbine power. The ramp up of the engine regime has to be monitored amid several functional limits pertaining to turbopump speeds or combustion mixture ratio. In engine testing, the ignitions have always been very smooth. The start-up transient has been tested in a wide range of regenerative circuit temperatures, with no impact on the steady state level. The steady state has always been observed stable, in a large domain of thrust and mixture ratio. It was not destabilised by strong gaseous hydrogen tap-off sequences simulating the pressurisation needs of an upper stage fuel tank. The scattering in propellant mixture ratio is very low, which is a valuable asset for an upper stage engine. This is explained by the turbines-in-series lay-out. For the shut down, the power in the turbines is reduced by opening the by-pass valves, inducing a decrease of the propellant flow rates and of the combustion pressure. The chamber valves are closed at the end of the transient. The hydrogen chamber valve being placed downstream the regenerative circuit, the expansion of the hydrogen after its closure induces a temporary reverse flow.

The combustion pressure is relatively high (60 bar), allowing for a compact engine design. This answers favourably the important requirement of an upper stage engine to be mounted in a limited space between two stages. The combustion chamber is designed after the same technology as the other European cryogenic engines HM7 and Vulcain, i.e.

a copper body with milled cooling channels, surrounded by a nickel shell. In order to achieve the high heat pick-up requirement of an expander-cycle, the cooling channels are thinner and longer than those of the gas generator engines. The heat pick-up has been fully in its specification at the first design. This is a remarkable performance, keeping in mind the specific shape of the cooling channels and the difficult physical phenomena considered in the models. The same is true for the pressure drop in the cooling channels, which is lower than specified. Important progress has been achieved by the demonstrator project on models coupling combustion and regenerative circuitry. In particular, the models can now accurately predict the inner wall temperature map. It is an important parameter to position the design with regard to hot gas water condensation, the occurrence of which is more likely on an expander-cycle engine, and which can have impacts on a hot composite nozzle.

The composite nozzle has been the object of continued progress on material characterisation and thermo-mechanical model. It has been successfully tested on four engine hot-firing tests in 2006 and 2008. These tests gave the opportunity to observe the heat soak back after engine shut down.

The hydrogen turbopump has a high pressure head requirement on an expander-cycle engine, in order to ensure the propellant flow through the cooling channels, the two turbines and the combustion chamber injectors. To this end, it is equipped with a double-stage pump. The impellers use the metal powder compaction technology, and ceramic bearings have been chosen to sustain the loads. The hydrogen turbopump reached 97100 rpm in engine hot-fire test.
The main specificity induced by the expander-cycle on the oxygen turbopump design is the separation of liquid oxygen on pump side and high pressure gaseous hydrogen on turbine side. Due to the fact that the turbines are upstream the combustion chamber, the pressure in the expander-cycle turbines can be in a higher range than what is experienced in the gas generator engine turbines. This leads to demanding requirements for the dynamic seals on turbine side.
Both turbopumps are equipped with blisk mono-stage turbines. The aero-elastic modes of the blades have been successfully measured with a laser tip timing technology during engine hot-firing tests.
Both turbopumps have fleet leaders accumulating more than 2550 seconds and 17 starts on the engine tested in 2007.

The cryogenic expander-cycle leads to high pressure levels in the hydrogen circuits. As an illustration, the pressure at pump outlet has trespassed 250 bar in engine hot-fire testing. The high hydrogen pressure increases the criticality of the metal embrittlement phenomenon, where the contact with gaseous hydrogen may reduce the mechanical properties of certain metals. The demonstrator project has carried out dedicated material tests and improved the knowledge database in this field. The material choices of the engine can be soundly justified on this point.

Beyond the hardware, the modelling and design tools have been considered as technology issues as well in the demonstrator project. The functional models of the first European closed-cycle engine have given fairly good results right from the start. The transient model of the expander-cycle engine is now in close agreement with the test observations, becoming an efficient tool to optimise the start up and shut down sequences. The steady state engine model is operational, but needs more engines in testing to perfect the identification process. The mechanical model has been designed to be able to sort out the internal and external loads, and their consequences on the margins. More than ever, emphasis has been given to the engine thermal model, in particular to simulate the effects of the radiating nozzle during the boost and coast phases.

Overall, the expander demonstrator project has achieved important TRL improvements, both at engine and subsystem level. The high pressure cryogenic expander-cycle engine is mastered. The re-ignition capability was conveniently assessed. Of course, not all technology items have reached the same TRL. Further steps remain to be achieved, for instance on particular aspects of the combustion chamber, or the transient sequences. But the demonstrated package is overall very positive.

The testing activities

The FLPP has started the Expander Demonstrator project with the Vinci engine at a very early stage of testing, namely 92 seconds of hot fire tests and 3 start-ups reaching steady state. It was a central and defying task of the demonstrator project to run the engine further in hot-fire testing. This turned out to be a primordial source of information on the performances and limitations of the Vinci engine, and a very representative and valuable activity for the cryogenic expander demonstration. In an intensive period of 18 months, the Expander Demonstrator project has added 23 boosts and 4580 seconds of hot-firing time to the engine experience. As a comparison, the RD-0146 is at 1680 seconds after a similar number of tests.

The tests were performed at the P4.1 test stand in Germany. This test stand has a vacuum capability of a size unique in Europe, which allows the engine firing tests in fully-fledged altitude simulation. Scale one engine hot-fire tests are among the most complex operational activities in the launcher sector. They were successfully led by the DLR teams, under the leadership of the prime contractor Snecma, sometimes reaching a testing rate of four ignitions per month.

Fig. 2 – Outer view of the P4.1 test stand

Three different engines have been tested in the frame of the demonstrator project. The tests have validated a shorter start up transient sequence, ensuring a regular rise of the combustion pressure up to the steady state. As a cautionary approach, the very first starts of the engine were performed with a two-step regime. Some fine tuning remains to be done in order to limit the amount of propellants dumped during the start up transient. Similar progress has been achieved on the shut down sequence, but here also with remaining work to reduce hydrogen back flow and propellant dumping.

As mentioned above, 4580 seconds of steady state have been added to the engine test log during the demonstration, revealing no major functional issue. The engine could be accurately monitored and trimmed in thrust and mixture ratio during the hot-firing tests with the help of proportional electric actuators mounted on the turbine by-pass valves. This closed-loop engine monitoring system was untested on a European expander-cycle engine, and worked correctly right from the start. It is a powerful development tool, which allows to accurately test a large number of operating points on a same firing sequence. It brings also valuable results to model engineers, who can reach faster and more accurate engine and subsystem identifications. Different engines were compared on the exact same operating point.

Fig. 3 – View of firing engine in test cell

Still, the longest test duration to day has been 565 seconds, lower than an upper stage boost duration which lies typically in a range between 750 and more than a thousand seconds. Reaching such durations is foreseen in the near future, without any showstopper identified.

The thrust delivered by the engine was measured at each test, yielding results in line with the predictions. Four tests have been performed with a composite nozzle installed under the engine. They have confirmed the severe thermal environment induced, giving important data to the engine thermal model and to the heat shield and subsystem specifications.

As often in operational activities, the demonstrator project had to cope with contingencies during the hot-firing test campaigns. Some issues were raised around the vacuum cell thermal environment, the altitude simulation operations or the control / command system. However, all of them were conveniently solved and none impeded seriously the performance of the engine tests. The appearance of such glitches is not abnormal on such a complex test bench at an early stage of its operational life. On the engine standpoint, the most noticeable issues have been linked to an external crack on the combustion chamber, a wear of the oxygen turbopump dynamic seals, and transducers used in redline logics.

Nonetheless, no major mechanical failure or fire event occurred during the engine hot-firing tests, which is an important achievement for the first tests of a closed-cycle cryogenic engine in Europe. The observed failure rate of the engine is comparatively low at this stage of experience. After 4672 seconds of hot fire testing, the level of risk is better known and mastered enough to go on with the test campaigns. However, extreme attention shall be dedicated to the execution of every future test.

During the expander demonstrator project, hot-fire testing has also been performed at the level of the combustion chamber. From the very beginning of the project, the improvement and validation of the combustion chamber modelling tools has been identified as a major objective. This was justified by the fact that the combustion chamber has more demanding requirements on an expander-cycle engine than on a gas-generator one. Sixteen firing tests of a well instrumented subscale chamber have been carried out in 2008 at the P8 test stand in DLR Germany. They brought important results to the design engineers of Astrium GmbH, in particular in the field of the mastering of hot gas water condensation on the chamber inner wall.

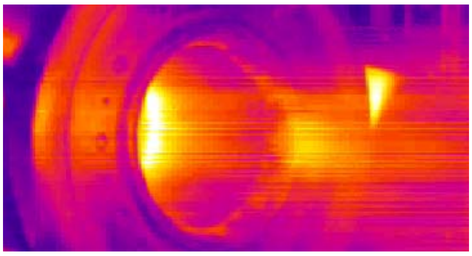

Fig. 4 – Thermo-graphic view of subscale chamber firing test

As for the full scale combustion chamber, a whole campaign of bomb tests was performed in 2009 at the P3.2 test stand in DLR Germany. These tests, done on a water cooled chamber, have all shown extremely stable results. The P3.2 is now undergoing an important adaptation in order to enable extensive hot-firing tests of the hydrogen cooled chamber. The enhanced P3.2 bench will feature such complex devices as an altitude simulation system, and a hydrogen mixing loop to simulate the missing turbines.

In 2008, mechanical dynamic tests have been performed by the engine prime contractor Snecma on a complete engine after its firing test campaign. For the first time, a deployable nozzle was installed on this engine, for low level dynamic characterisation and actual deployment sequences.

<u>Manufacturing aspects</u>

Overall, manufacturing and assembly activities went on smoothly, with a reduced number of anomalies. For economic and calendar reasons, refurbishment of hardware was privileged whenever possible. The crack on a combustion chamber has been the occasion of a full-blown demonstration of the capability of the prime contractor to dismount the engine from the bench, dismount the engine for replacement of the combustion chamber, remount and re-install on the bench, all this within a few weeks.

Sharp control and repair techniques of the combustion chamber have been supported by the demonstration project (e.g. laser welding repair)

At the end of the demonstration project, the hardware is in good shape, still offering large residual potential use for the next steps.

Upper stage functions

The expander-cycle demonstrator project, leaning on the engine hot-firing test results, provides a large array of results which are as many inputs for the Future Launcher Preparatory Programme. By identifying the validated areas and the limitations, it grounds a sound optimisation process in connection with upper stage and launcher system studies, in view of possible future applications such as the Next Generation Launcher (NGL).

NGLHH 3 / 5 / 8t GTO & 24t LEO configuration

Fig.5 – NGL views

For a development application, the engine must match the well known performance and functional requirements of a cryogenic upper stage, i.e.:

- a high in-flight reliability
- a high specific impulse
- a light mass
- good propellant pump suction capabilities
- a good mixture ratio accuracy
- to provide gaseous hydrogen for hydrogen tank pressurisation
- to provide heat to helium for oxygen tank pressurisation

All these topics were addressed in the demonstrator project, logging sound statements on each of them.

In the frame of the project, a wide range of thrust and mixture ratio have been considered, as well as the re-ignition capability, which is a potential requirement of future missions. Several re-ignitions were performed, all successful, meaning that the engine per se is able of re-ignition. However, re-ignition of a cryogenic upper stage induces technical complications which have to be carefully traded at launcher system level.

A similar careful trade has to be done on the engine thrust and mass. As a matter of fact, the thrust level is the main driver of the engine mass, even more so for an expander-cycle engine, where the requested fuel pump outlet pressure increases very fast with the thrust. On a system standpoint, the dry mass of an upper stage is in direct competition with the payload, and a heavy propulsion is likely to induce snowball effects on the mass of the upper stage structure. These are strong arguments to limit the upper stage thrust level to what is strictly necessary.

Preliminary assessments of the engine integration onto an upper stage and launcher have been performed. Some questions were raised about its on-site maintainability, regarding in particular the igniter and the deployable nozzle around the engine. Addressing the tolerance to foreign particles, which is a concrete issue of upper stages in operation, it has to be noted that the engine is equipped with a filter upstream the chamber regenerative circuit, thus protecting the cooling channels, the turbines, the by-pass valves and the hydrogen chamber valve.

Conclusion & Perspectives

The 3-year expander demonstrator project in the FLPP represents a successful step in the direction of a next generation of cryogenic upper stage engine in Europe. It has achieved the first cryogenic re-ignitions and closed-loop regulation in European rocket propulsion, and demonstrated the mastering of the high pressure hydrogen expander cycle, with a highest tested point at 63 bar of combustion pressure and 180 kN of equivalent thrust.

The demonstration results prepare for a wide range of future potential specifications. The overall Technology Readiness Level of the technical roadmap was harmonised toward TRL 6, with some remaining axis of progress in the fields of combustion chamber design, pump suction demonstration, endurance demonstration, sequence optimisation, mass, composite nozzle thermal effects or turbine dynamic seals.

Out of the expander demonstrator project, the contractors' teams end up with considerably enlarged experimental knowledge, sharpened modelling tools in functional, fluidic, thermo-mechanical fields, and more practice in engine assembly.

The cryogenic expander-cycle engine is at the crossroads of several preparatory programmes. To start with, the Vinci engine has been chosen in its current design as the baseline propulsion for the A5 mid-life evolution project. This project benefits directly from the engine test experience and the overall engine documentation update. The demonstrator project, performed in the frame of the FLPP, has also achieved the exhaustive and detailed technology readiness mapping of the cryogenic expander-cycle engine, making it an important input for the task of defining the specifications of future launchers.

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[1] Austria, Belgium, France, Germany, Ireland, Italy, Norway, Spain, Sweden, Switzerland, The Netherlands

[2] Engine hot-fire testing to DLR Germany, Combustion chamber to Astrium GmbH Germany, Hydrogen turbopump to Snecma Moteurs France, Oxygen turbopump to Avio SpA Italy, Turbines to Volvo Aero Corp. Sweden, Nozzle to Snecma Propulsion Solide France, Igniter to APP The Netherlands, Valves to Techspace Aero Belgium, Nozzle Deployment Device to Kongsberg DA Norway, Transducers to Vibrometer Switzerland, Struts to Ampac Ireland