

Results of the Vulcain X technological demonstration

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ABSTRACT

The intent of this paper is to provide an overview of the VULCAIN X technological demonstration roadmap progress at mid 2011, i.e. at the time of near completion of the program.

The VULCAIN X demonstration program, based on the LOX/LH2 VULCAIN 2 engine, encompasses various systems and sub-systems demonstrations of new propulsion technologies. The main targets are cost reduction, robustness, increased reliability, all of them focused on VULCAIN 2 engine evolutions.

The different "Demos X" that were performed are the Hydrogen turbo-pump TPX, the gas generator GGPX, high bandwidth regulation valves VRR, the electrical hot gas valve VGCE and the sandwich nozzle extension NEX. At system level, the main subjects which are being explored are the simplification of the chill-down procedure, immediate tests diagnosis (health monitoring system), mechanical integration evolutions and exploration of smooth transients.

The testing rationale of this program is :

- Sub-systems demonstration alone or on a power-pack combining GPX and TPX in order to characterize and validate the behavior of the different sub-systems
- System demonstration on a VULCAIN 2 engine in the frame of an ARTA test campaign, ARTA being a program dedicated to perform production follow-up tests in order to demonstrate that the flight worthiness of production hardware is maintained.

The VULCAIN X program is managed by the Centre National d'Etudes Spatiales (CNES) and involves different partners in Europe.

The publication will focus on the major achievements up to 2011, i.e. the results of the sub-system test either alone or in a powerpack configuration, the results of the demonstration performed at system level, i.e essentially the ARTA 7 and 8 tests.

The kick-off of the program took place at the end of September 2005. The first system passenger tests took place on the production follow-up ARTA 7 campaign during the summer of 2006. The sub-system tests were performed in 2010.

Introduction

The VULCAIN X demonstration program was initiated in September 2005 by the Centre National d'Etudes Spatiales (CNES).

The overall objective of this program is to test various new technologies related to rocket engine sub-systems and system in a fully representative environment and therefore to demonstrate that they have achieved a TRL (Technological Readiness Level) which allows them to be included in future development.

The overall system design and integration of the different technologies proposed on this program is under the responsibility of SNECMA (SAFRAN group) in Vernon, France. The major industrial partners, sustained by national agencies such as the Swedish Agency SNSB, which are involved on this program are VOLVO Aero Corporation (VAC) for the hydrogen turbopump turbine (TPX), VAC and ASTRIUM GmbH for the sandwich nozzle extension, Techspace Aero (Liège, Belgium) for the valves in cooperation with ESTEC, Vibrometer (Switzerland) for Health Monitoring System hardware

Context and major objectives of the program

The technical objectives of the different technological demonstrations which are part of the VULCAIN X program are focused on the reduction of the recurring cost, in parallel with an increase of robustness and reliability. The development of system skills, i.e. improving the performance of analysis and design tools, and the increase of life duration of hardware were also goals of the program.

The programmatic objectives of the VULCAIN X demonstration program can be summarized as follow:

- to demonstrate - through fully representative testing - readiness of new technologies and sub-systems architecture for their introduction in future development programs at stage or engine level,
- to ease future engine development programs by reducing risks, cost and lead-time,
- to develop and maintain training of highly-skilled design teams,
- to act as a leading vector for the development of new generation engine and subsystems.

Content of the demonstration

The modified sub-systems, on which new technologies are being introduced are the following :

- The Hydrogen Turbo-pump TPX
- The Gas Generator GGPX
- The Electric Hot Gas Valve VGCE
- The High Bandwidth regulation Valves VRRH and VRRO (gas generator injection)
- The Sandwich Nozzle Extension

There is no demonstration planned on the LOX turbo-pump or the Combustion Chamber in the frame of the VULCAIN X program.

These modified sub-systems are designed to be compatible with the VULCAIN 2 architecture. This allows an easy integration on any ongoing Vulcain engine test campaign. Consequently they could be easily integrated in an improved version of Vulcain 2. They can also be applied to the preparation of a next generation high thrust rocket engine such as a 200 to 300 tons thrust first stage engine, either gaz generator of staged combustion engine.

Test facilities

Since the main objective of this project is to obtain as soon as possible a demonstration of the different demo X sub-systems throughout full representative tests, all tests facilities that can possibly be used were considered :

The ARTA production follow-up campaigns are used for the VULCAIN X objectives which are system related, such as the soaking chill down characterization, the health monitoring or the regulation. They are also used for integration of modified sub-systems such as the sandwich nozzle extension.

The turbo-pump, the gas generator GGPX alone and the Powerpack GPX (composed of TPX + GGPX + VGC) are tested on the PF52 test bench, at the Snecma facility in Vernon, France. These tests are representative of the operating conditions of the Vulcain 2 engine.

A component test bench at the Vernon facility is used for testing the VRR actuator with a specific tool simulating the hydraulic torque and thermal environnement.

The Hydrogen Turbo-pump TPX

Developing a new Hydrogen turbo-pump presenting high economical and reliability performance is a challenging task and requires introducing technologies departing from the current existing ones. Over the past years, CNES and Snecma have been committed to this goal through joint research & technology activities and demonstrators such as the TP Tech project. These activities comprise fundamental research with university laboratories, reduced scale turbo-pump testing and development of simulation tools.

Relying on this experience, the innovative architectural choices made for the hydrogen turbo-pump TPX were:

- the stage pump, its impeller and inducer,

- the Hydrostatic fluid film bearings giving stiffness and damping to the rotating shaft and authorizing an overhang turbine developed by VOLVO AERO (Sweden).

Un-shrouded impellers provide a higher head rise per stage because they can reach higher tip speed than shrouded impellers. Hydro-static bearing provides stiffer supports of the rotor. Consequently, both these technologies allow to design high head rise and large flow rate turbo-pumps required for new engines for future launchers.

The demonstration objectives of the turbo-pump TPX are of two different kinds:

- Main objectives of cost reduction, with an increase in robustness, reliability and without reducing the turbo-pump performance, compared to VULCAIN 2 Hydrogen turbo-pump
- Exploratory objectives such as increased life duration, throttling capacity, i.e. operating over a large functional domain,

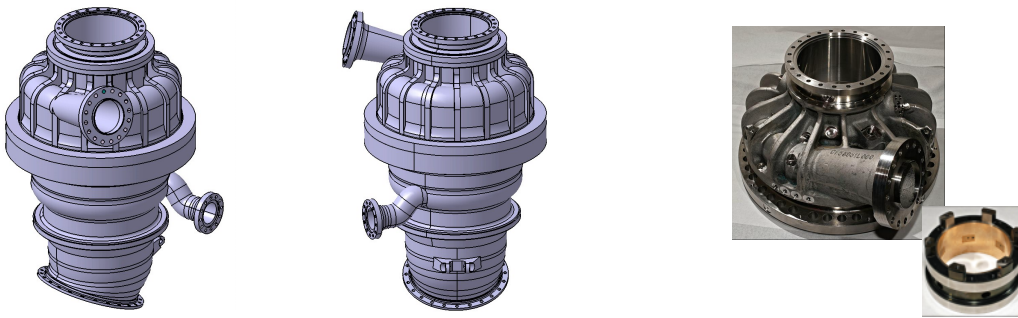


Figure 1 : LH2 turbo-pump TPX Demonstrator

The main design issues which had to be taken into account for establishing the test objectives and the instrumentation plan were:

- The TPX thermo-mechanical behavior,
- The dynamic behavior of the rotor with hydrostatic fluid film bearings,
- The axial equilibrium of the impeller.

The test campaign was planned in progressive steps:

- a first series of cold gas tests to determine the main turbo-pump operating characteristics
- hot gas tests together with the gas generator GGFX to characterize its thermo-mechanical behavior. Hot gas temperature will be increased step by step, as rotational speed, first in the nominal design domain and secondly in the exploratory domain for margins characterization (high and low rotational speed, high and low flow coefficient).
- Additional tests either in cold gas tests or with a Vulcain 2 gas generator for specific objectives such as for pump cavitation characterization

A total of 10 effective tests were performed with the TPX demonstrator.

The TPX was tested:

- (1) With the turbine fed by cold pressurized hydrogen
- (2) With the turbine fed by the hot gaz coming from the GGFX gas generator
- (3) With the turbine fed by the hot gaz coming from a regular VULCAIN 2 gas generator

Two tests were performed in configuration (1) prior to performing two tests in configuration (2) then 6 tests in configuration (3). The following results were obtained:

- A behavior of the open impeller and of the hydrostatic bearing fulfilling all expected objectives
- A satisfactory and reproducible rotor dynamic behavior
- A pump performance matching prediction (within 1 %)

- A stable operation of the active axial balancing system over the entire domain

Two cavitation tests were performed down to a loss of head rise reaching -5 and -7 %.



Figure 2 : TPX on the test stand

Gas generator GGPX

One of the main goals of the GGPX gas generator demonstration is to increase the maturity of the tricoax injector. Compared to a “classical” shear injection element in which a core of liquid oxygen is enveloped by a layer of hydrogen, in a tricoax injector a layer of liquid oxygen flows in between two layers of hydrogen leading to the possibility of injecting a higher mass flow per injection element. The use of the tricoax injector simplifies the architecture of the injection head and optimizes its manufacturing process.

Similarly to the turbo-pump TPX, the demonstration objectives of the gas generator GGPX are of twofold :

- A main objective of cost reduction, with an increase in robustness for a performance equivalent to the VULCAIN 2 gas generator performance,
- Exploratory objectives associated with life duration, throttling capacity, i.e. operating in a large functional domain, high pressure capacity.

The life duration objective led to the choice of a main pressure vessel made of powder metallurgy Hastelloy X in order to increase its low cycle fatigue potential considering that the vessel is un-cooled.

The design choices for the gas generator GGPX are:

- Tricoax injectors on an injection head with a cold flange, Hydrogen injection chamber closed by counter bore and a lateral igniter,

- A combustion chamber grouping all the non axi-symmetries (whereas the injection head is axisymmetric) and integrating the hot gas distributor and the turbo pumps starter interface,
- An additional starter interface implemented in the upper part of the combustion chamber to let the possibility of an ignition with only the starter .

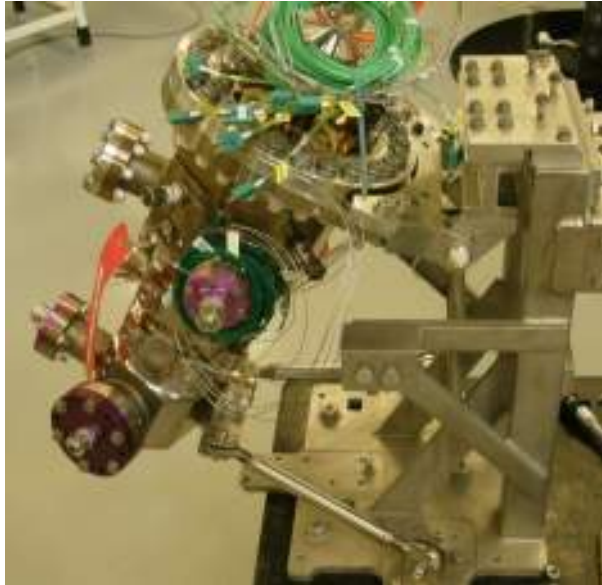


Figure 3 : GGPX Gas Generator Demonstrator

The gas generator GGPX design benefits from the experience gained with previous demonstrations of tricoax injectors, the BUE injector element and gas generator GGP8 test campaigns at test facility P8 in Lampoldhausen, Germany in the frame of CNES/SNECMA joint Research and Development activities. It provides key information on the behavior of the GGPX on a large operating domain, operating at low mixture ratio, and on gas generator ignition with a lateral igniter.

The GGPX tests were performed at the PF52 test facility, with tests of the GGPX alone and tests of GGPX coupled to TPX.

The GGPX demonstration test plan includes:

- Tests to define the gas generator transient sequences,
- Tests to verify the behavior of the gas generator at full power in the nominal design envelope in order to be able to use this gas generator for the hot gas turbo-pump TPX tests in a Powerpack configuration.
- Tests to characterize the margins (low pressure, low mixture ratio)

A total of 8 tests were performed.

The following results were obtained:

- The combustion efficiency and the injection pressure drop fulfil their expected requirements
- The demonstration that the gas generator design can provide a stratification level of the hot gas and a pressure fluctuation level acceptable for the down-stream turbine.
- A satisfactory thermo-mechanical behavior with respect to leak tightness of the main flange and low cycle fatigue behavior. The post-test examination of the pressure vessel did not any evidence of deterioration.

The electrical VGC

On the Vulcain 2 engine, the hot gas valve, named VGC, is located down stream of the gas generator on the oxygen turbine side and is essentially the mixture ratio adjustment valve.

A hot gas valve VGC with a new electrical actuator was tested with the GGPX.

In order to obtain a consistent electrically actuated regulation system, Techspace Aero (Belgium) developed an electrical brush DC actuator for the hot gas valve. This actuator is based on a high ratio gear box concept and its technology is similar to the VINCI engine by-pass valve actuator.

The main requirements are the following:

- to be sufficiently slow to avoid generating pressure drops during operating point switch,
- to be compatible of the on board switching box command in order to avoid flight electronic cost,
- to have limited impact on the hydraulic characteristic of the existing VULCAIN 2 VGC valve.

Thanks to an electrical VGC, the entire engine regulation system could be electric, opening opportunities in terms of adjustment and acceptance tests simplification and allowing a wider range of operating modes.

The valve and its electrical actuator were tested with the gas generator GGPX and the turbopump TPX on the turbine line. These tests provided a full characterization (hydraulic and mechanical torques, accuracy and repeatability of the angular positioning in the different modes) in a realistic environment.

High bandwidth electrical actuation system for regulation valves VRR

The VRR is a high band width actuator to be used on a regulation valve. The order of magnitude of the bandwidth is 10 Hz.

High bandwidth regulation valves are required to ensure control loop stability for fast valve actuation with electrical actuators. This requirement is part of the demonstration objective in order to optimize the transient and introduce power level regulation while ensuring engine safety and reliability.

In addition, mastering the high bandwidth electrical actuation system technology for regulation valves during steady state and transient phases is also contributing to the objective of optimizing the development process by:

- reducing the valves actuation time scattering, and therefore limiting the experience plan needed in development to cover those dispersions,
- providing the opportunity to simplify the adjustment and acceptance tests process taking advantage of the increased adjustment precision and possibly the same actuator on ground and in flight.

This technology will also contribute, in the long term, to the objective of an all electric engine for cost reduction by suppressing the pneumatic system for valves actuation (and replacing it by an electrical supply).

The VRR valves use the hydraulic part of VINCI upper stage engine by-pass valve. The actuator, developed by ARTUS (FRANCE), is based on a synchronous brushless motor driven through resolver position transducers. The controller is developed by SAGEM Valence (FRANCE). The design is focused on reliability including risk analysis and redundancy management, BUS coupling and position control loop. These valves answer the function of regulation for transients, adjustment of the operating point or stability control in steady state operation. Tightness/shut down function is insured by a second valve. As opposed to the VGC which was tested with the GGPX and TPX, the VRR actuator was tested separately on a dedicated test bench.

These valves recently performed component level tests to verify actuation performances. Their behavior was in line with the foreseen performances.



Figure 4 : Hot gas VGC valve and VRR actuator

Sandwich Nozzle Extension

The sandwich nozzle extension is a full-length dump cooled sandwich nozzle whose principal demonstration objectives are focused on:

- Robustness and reliability of the manufacturing process on sandwich manufacturing, forming in contour, closure of channels, external shell and interfaces (cone joint, inlet and outlet Manifold, stiffeners),
- Cost reduction,
- Robustness of the thermo-mechanical concept.

The nozzle extension demonstration takes also into account the constraint to be able to operate on the VULCAIN 2 engine, therefore to keep the same interfaces with the combustion chamber and the same engine performance in terms of specific impulse.

The Sandwich wall is manufactured in an upper and a lower cone of half the Nozzle Extension length in each, with a welded cone joint at the junction. A Thermal Barrier Coating (TBC) can be applied on 250 mm at the upper and lower end of the nozzle extension if needed regarding life potential with the thermal loads. The design of the demonstrator is however done without TBC and the characterization of its effect on thermal margins will be obtained in tests with the proper instrumentation.

The upper stiffening structure is a jacket design of Metal Deposition. The exhaust turbine lines LEH and LEO are upgraded (based on VULCAIN 1 technology), since there is no re-injection gas system like on the VULCAIN 2 engine.

The manufacturing took place at Volvo premises in Sweden with the contribution of Force Technology in Denmark, where the laser welding technology for the sandwich technology has been developed .

The demonstration nozzle is heavily instrumented (temperature, pressure, vibration and strain).

The first two demonstration tests were performed at the end of the ARTA 8 production follow-up campaign.

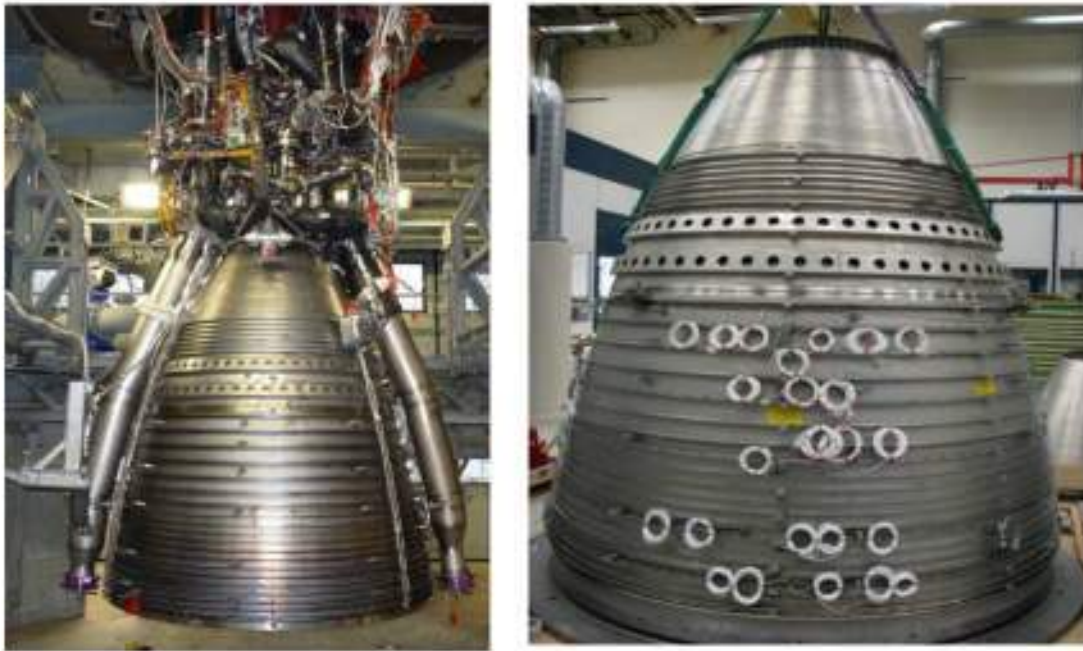


Figure 5: Sandwich Nozzle Extension with VOLVO AERO CORPORATION Courtesy

Health Monitoring System

The Health Monitoring System HMS activities are a major element on the road to development process optimization. Indeed, the HMS gives the opportunity to dispose of redlines and diagnosis methods that can be very helpful to optimize the objectives display, the duration and the rate of tests campaigns. The aim of the demonstration is to have a first experience of the use of this type of system during the power-pack hot firing tests and to validate this system in parallel with the control command system of the test facility.

The demonstrator hardware was developed and manufactured by Vibrometer. This demonstrator is now implemented on PF52 bench.

The Applicative Software will be implemented in an initial version for the first tests of the GGPX demonstrator and will evolve during the overall test campaign.

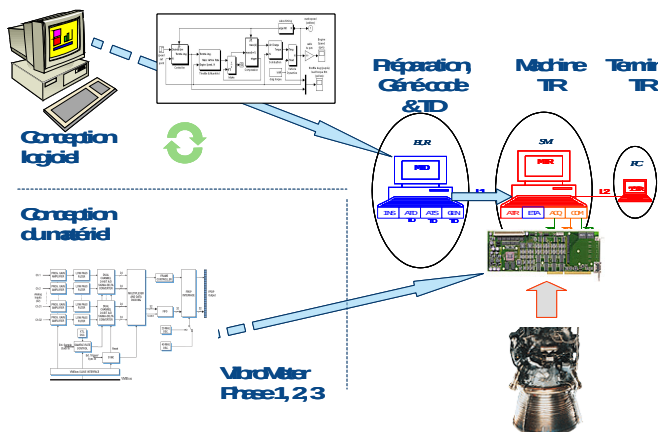


Figure 6 : HMS concept schematic

The Vulcain X program history and prospect

The past major phases of the VULCAIN X program were:

- Phase 1 (2006 – 2009)
 - System analysis of demonstration objective to be performed at engine level on ARTA production follow-up hardware
 - Sub-system DEMOs X definition, manufacturing
- Phase 2 (2009-2010)
 - Demonstration of gas generator GGPX, LH2 turbo-pump TPX, and electrical hot gas valve VGC at the PF52. The high bandwidth regulation actuator VRR is tested on a specific test bench

A future step of the program could be the integration and demonstration at engine level of all the “demos X” sub-systems in a single demonstration combining all the elements of the program together.

Conclusion

Capitalizing on past Research & Development results, the subsystem and system demonstrations conducted in the frame of the Vulcain X program bring significant innovation with respect to the current rocket engine European state of the art. The technologies which they contribute to consolidate will find application to various type of engines such as improved version of the current Vulcain 2 engine or a future first stage engine.

The most significant demonstration are the fuel turbopump TPX, the sandwich nozzle extension NEX, the gas generator GGPX, the electrical hot gas valve actuator, the health monitoring system HMS. In 2010 the Vulcain X program came to near completion with all the tests of all the elements of the program being successfully achieved: the nozzle extension NEX test on the ARTA 8 engine, the Powerpack tests on the test bench PF52 in Vernon (France) with the LH2 turbopump TPX, the gas generator GGPX, the hot gas electrical valve VGCE and Health Monitoring System HMS device.

The VULCAIN X demonstration program is a major step in improving the current ARIANE launcher and preparing the development of its future versions with a focus on robustness, reliability and cost efficiency.

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