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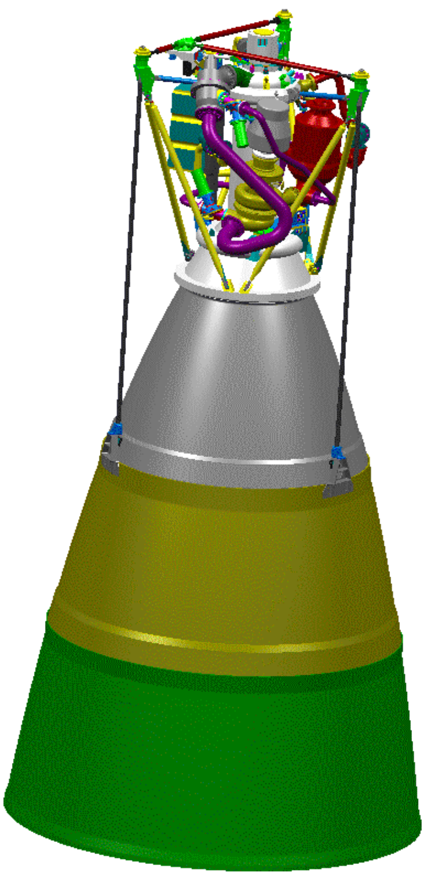

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OVERVIEW OF THE DEVELOPMENT PROGRESS OF THE ARIANE 5 UPPER STAGE VINCI ENGINE

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Abstract

This paper presents the status of the VINCI engine development program as of mid-2002. The VINCI engine will power the Ariane 5 ESC-B upper stage and contributes to provide a 12-ton payload capability in geo-stationary transfer orbit to the Ariane 5 launch system. The multiple firing capability also broadens the array of possible missions. The VINCI engine is a cryogenic expander cycle engine combining the required features of this cycle, i.e. high performance chamber cooling and high performance hydrogen turbopump, with proven design concepts based on the accumulated experience from previous European cryogenic engines from HM7 to Vulcain 2. High performance along with a constant focus on reliability, low cost and simplicity of architecture are the design goals of the VINCI program. The paper recalls the engine design rationale using design-to-cost methods. The paper highlights the major achievements of the program over the 2001 - 2002 period, i.e. the completion of the engine detailed design, the manufacturing of the first subsystems, the first component and subsystem tests. The ESC-B and VINCI developments are programs of the European Space Agency (ESA) whose management has been delegated to Centre National d'Etudes Spatiales (CNES), the French Space Agency.

Introduction

In June 1998, the European Space Agency (ESA) took the decision to develop a new cryogenic upper stage, named ESC-B, powered by a new cryogenic engine, the VINCI. CNES, the French Space Agency, obtained the delegation for the management of this development program from ESA.

From the beginning of the project, the requirements for low cost, high performance, multiple ignitions and high reliability have led to the choice of an expander cycle for the VINCI.

In November 2001, a European Government Conference approved of the funding for the ARIANE 5 Plus program including the VINCI engine and the ESC-B stage up to the completion of the program. At the end of 2001, a concept review of the ARIANE 5 Plus configuration with the ESC-B upper stage confirmed the performance goal of 12 tons in geostationary orbit and the need for multi-boost missions.

The engine overall system design and integration is under the responsibility of Snecma Moteurs in Vernon, France. The major subsystem contractors are Astrium (Munich, Germany) for the combustion chamber, FiatAvio (Turin, Italy) for the oxygen turbopump and Snecma Moteurs for the hydrogen turbopump.

From early 2001 to the first quarter of 2002, calls for tender have been issued for all the remaining components of the engine, such as the nozzle extension and nozzle deployment system, the solenoid valves, the gimbal, the ignition system. By May 2002 the industrial organization pertaining to all engine component was finalized and concept key points or preliminary design review had been held for all engine components.

Engine architecture

The engine architecture is designed to meet the goal of reliability, simplicity and low recurring cost. The engine flow schematic is shown on figure 1.

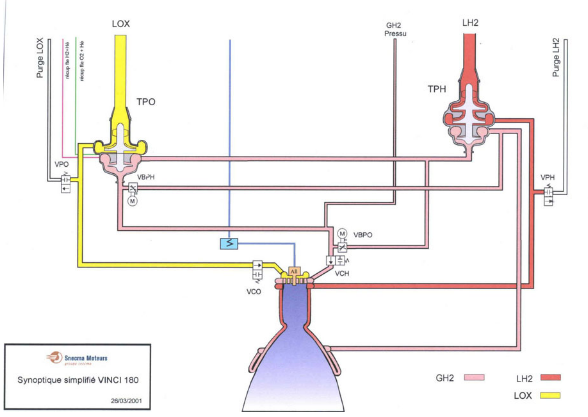

Figure 1: VINCI flow schematic

The engine is characterized by a high performance hydrogen turbopump (TPH) shown on figure 2, an optimized combustion chamber cooling circuit, the use of advanced manufacturing processes (powder metallurgy impellers, cooling channel high speed milling) and a constant use of a design-to-cost approach.

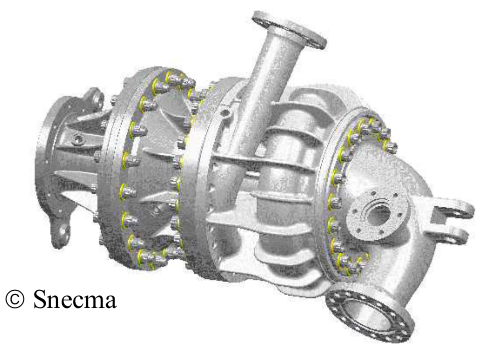

Figure 2: CAD view of the TPH

The chamber body is a "smooth wall" chamber using the same technology as the HM7B and VULCAIN, but significantly longer (see figure 3) in order to meet the thermodynamic performance needed by the expander cycle: the hydrogen must gain enough energy to drive the turbines while cooling the chamber wall. The use of a regenerative nozzle extension was avoided in order to reduce cost and number of interfaces.

Figure 3: View of a combustion chamber body during a manufacturing operation

The engine has two separate turbopumps mounted close together in a "power pack" kit. Turbines are set "in series", and a set of two by-pass valves adjust the flow rate through the turbines, and consequently are used for tuning the engine operating point, in terms of thrust and mixture ratio. Both turbopumps have integral inducers which lead to low NPSP, thus eliminating the need for boost pumps whereas keeping acceptable tank pressure level.

A H2/O2 gas fed torch, electrically initiated by a spark system is used for engine ignition. Fuel and oxidizer for the igniter are stored in high-pressure vessels.

The description of the major subsystems was presented in references 3, 4, 5 and 6.

System engineering

An optimization of the ESC-B upper stage tank volume and VINCI operating point led to the thrust and mixture ratio design range : trim point set at 180 kN with adjustable mixture ratio between 5.7 and 5.9 (see table 1). Similarly to previous Ariane upper stages, the ESC-B will be operated at a fixed mixture ratio setting during the whole flight duration. Since propellant depletion is prohibited and the probability of depletion is mostly a function of mixture ratio scatter, the proper prediction of the mixture ratio is essential to maximize the payload. As for the HM7 for which flight analysis shows very little scatter between obtained and predicted values, much attention will be paid to propellant flow measurements during acceptance tests and transposition from acceptance test conditions to flight conditions using engine functional modeling. A set of two turbine by-pass valves is devoted to the adjustment of the engine thrust and mixture ratio.

Thrust in vacuum	180 kN
ISP in vacuum	464 s
Mixture ratio	5,8
Chamber pressure	61 bar
LOX mass flow rate	33,69 kg/s
TPO rotational speed	18015 rpm
LOX pump discharge pressure	81 bar
LH2 mass flow rate	5,81 kg/s
TPH rotational speed	90127 rpm
LH2 pump discharge pressure	224 bar

Table 1: Vinci reference configuration

The system engineering activities over the 2001 - 2002 period have focused on the definition of a reference chilldown sequence and consolidation of reference start-up and shutdown sequences. The optimization and robustness analysis of the start and shutdown sequences has been performed by varying a large number of functional parameters in the form of an analysis case matrix. It provided knowledge of the key parameters of the sequence and paved the way for the preparation of the engine overall test plan. The engine has a set of poppet chilldown valves with calibrated orifices, which are sized in order to allow a sufficient discharge flow during start-up and shutdown transients. The duration during which these valves are opened during the chilldown phase has to be minimized since their full opening may lead to a more than required propellant consumption for chilldown purpose. The completion of the chilldown sequence in confined areas can be obtained using pulsed flow, percolation chilldown or an auxiliary chilldown circuit in order to force the chilldown while maintaining the main chilldown valves closed.

The goal of maintaining the mixture ratio in a controlled range during the start-up transient immediately after ignition is a prime concern when establishing the start-up sequence and specifying the valve design, especially the oxygen chamber valve. The engineering effort dedicated to the consolidation of reference transients and reference valve actuation sequences as well as the sensitivity analysis of these transients have led to the consolidation of the valve and control specifications.

The low recurring cost objective has led to the choice of slow actuation rate by-pass valves. The large gearing ratio between actuation electric motor and valve shaft ensures stability of the valve, therefore eliminates the need for an electronic control. The by-pass valve (VBP) development is significantly advanced with the completion of valve flow tests and actuator component tests (figures 4 and 5).

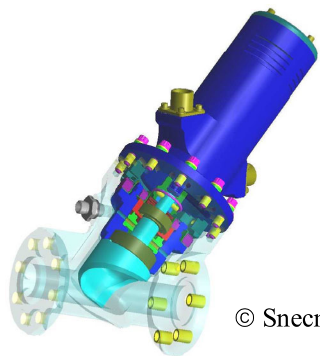

Figure 4: CAD view of a VBP

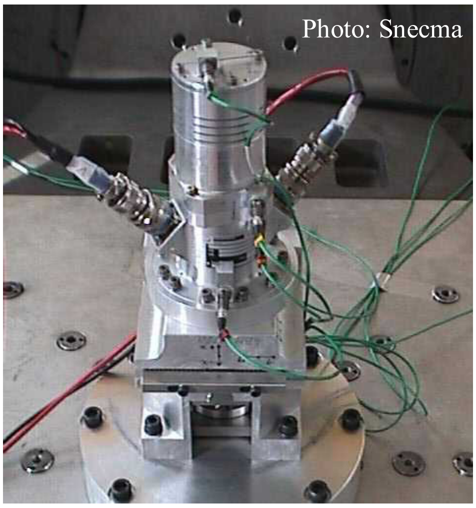

Figure 5: VBP actuator on vibration test rig

The oxygen chamber valve (VCO) is a pneumatic valve (figure 6, left). This choice reflects the priority given to simplicity of architecture and low recurring cost. An electric control valve is considered as a back-up option during development tests in order to reduce the amount of testing and the development time which may be necessary to define the proper opening profile required to monitor the mixture ratio during transient.

The fuel chamber valve (VCH) is a pneumatic poppet valve (figure 6, right). Since the VCH rapid closing may create a pressure peak upstream of the poppet during the shut down transient, a detailed modeling of the valve including actuator mechanical characteristics has been introduced in the engine transient model and an iterative process has been established with the valve supplier in order to optimize the valve characteristics, spring stiffness and helium inlet calibration.

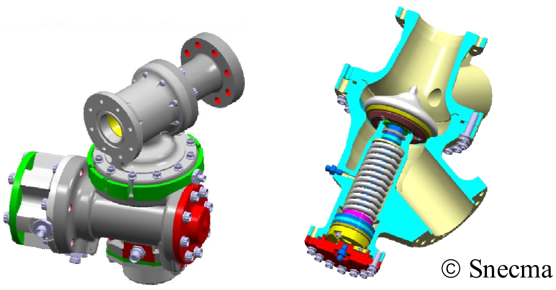

Figure 6: VCO (left) and VCH (right) CAD views

An extensive effort of reliability and safety analysis has been performed in order to consolidate the engine system architecture. This analysis covers all phases of flight including the ground phase prior to launch.

The development activities related to engine ignition and start-up after a ballistic phase for multiple boost missions accounts for a significant part of the development plan. They encompass three domains of activity: the use of Ariane 5 ESC-A flight for ballistic flight investigation, a strong focus on thermal engineering activities, and specific activities aimed at investigating the effect of a low gravity environment on heat transfer and two-phase flow. Concerning this latest item, a review of engine functions which are potentially affected by low gravity was performed. The two major areas of concern are the start-up transient and the heat transfer phenomena during engine chill-down. The heat transfer coefficients in low velocity areas or closed cavities, the heat transfer processes involving bubble detachment from walls are potentially affected by low gravity. A test plan using the available tools of low gravity testing in Europe (drop tower and Zero-G plane) is established.

Detailed design and mechanical engineering

The major features of the mechanical development of the engine are the following:

- a significant effort of analytical modeling relying on mechanical and thermal models;

- extensive use of computer aided design with much emphasis on the data transfers which are required to solve interface problems between numerous subcontractors all over Europe;

- the early involvement of manufacturing engineers in the design process.

The benefit brought by computer aided simulations as well as close coordination between design and manufacturing teams could be seen through the assembly of the

first hydrogen turbopump which took place in April 2002 as a relatively smooth process, free of major non conformances.

An engine mechanical model, established at the beginning of the development, is regularly updated. It is a finite element model, which includes condensed models of the engine major subsystems. It provides the engine dynamic mode shapes, the response of the engine to dynamic environmental spectra and loads at all engine interfaces. Two dynamic testing campaigns, on a development engine first, and on a qualification engine later will be used for comparison between experimental and analytical results concerning mode shapes, damping coefficients and areas sensitive to the dynamic environment.

An engine thermal model (figure 7) is also being established using the finite volume method. It provides the thermal status of the engine during operation, which is strongly dominated by the heat flux originating from the radiative nozzle and the thermal status of the engine during ballistic phases, which is an essential input for prediction of the engine restart condition.

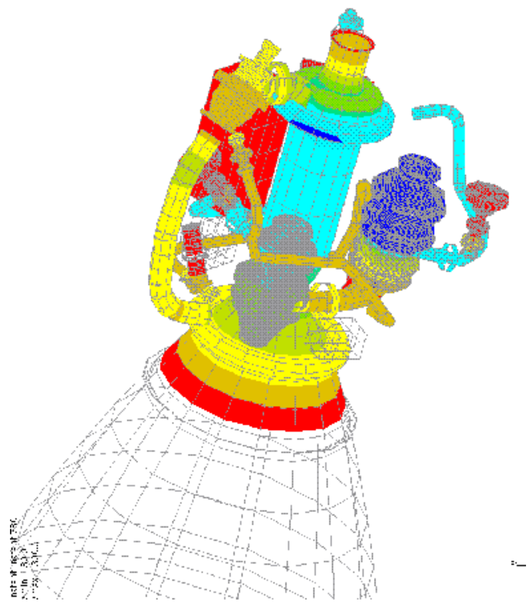
Figure 7: Engine thermal model

Besides a priority requirement for reliability, the engine design must comply with a goal of low recurring cost. In order to reach this goal, formalized design and decision methods are used as often as possible. Formalized trade-off with weighted criteria and ratings have been used for the selection of processes and suppliers. For the major parts of the hydrogen turbopump for instance, design and manufacturing engineers are quantifying the contribution of dimensional tolerances and control methods as regard the fulfillment of the part major functions, for a given manufacturing process. This is formalized through the use of grids expressing part function, function criticality, and available margins for each process. The format of these grids is based on the one proposed by the Quality Function Deployment methods.

The priority given to the goal of low recurring cost may lead to conflicting situations considering that performance is also a major requirement of an upper stage engine. In order to arbitrate these potential conflicts a careful monitoring of the performance parameters and systematic trade-off analysis are conducted on a regular basis. A performance indicator was established in the form of a formula combining the major performance parameters (Isp, Net Positive Suction Pressure, mass) expressed as equivalent geostationary payload using sensitivity coefficients. This performance indicator must not fall below a threshold based on engine specified values. The relevance of any modification affecting the performance can also be evaluated using recurring cost versus payload and development cost versus payload sensitivity coefficients.

As an example of cost oriented trade-off, the fluid lines are rigid hyper-static lines. Lines equipped with flexible joints would have allowed easier component installation and replacement. However, rigid lines were selected in order to avoid higher development and recurring costs associated with high pressure elbows and gimbals.

The completion of the engine detailed design necessitates a large number of activities which must converge to the goal of final engine assembly and meet the first

engine delivery deadline : piping lay-out, harness and wiring lay-out, component support design, etc… In order to speed up this process and to obtain a timely convergence of these activities without one of them clearly being on the critical path, they have been broken into subsets of tasks; each with its own design review and each being conducted with an early involvement of manufacturing entities.

A side view of the engine showing its mechanical layout is presented on figure 8.

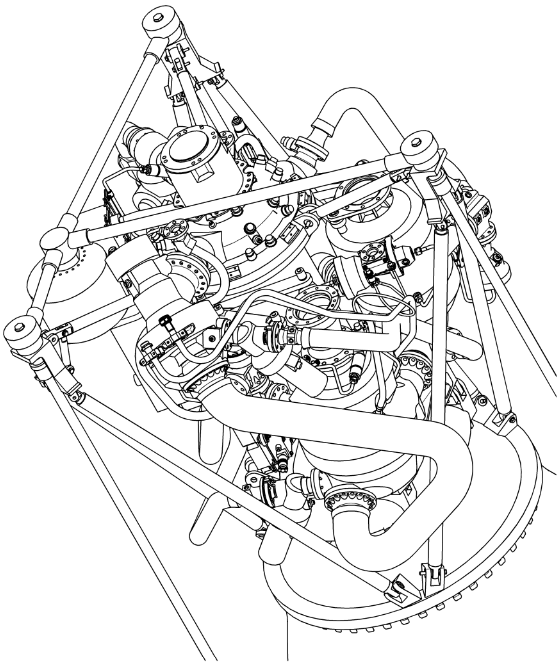

Figure 8: Side view of the engine

Manufacturing and component test status

As regards the **thrust chamber**, manufacturing and assembly of the first injection head (figure 9) and the first chamber body were complete in April 2002. Over the summer, a number of chamber pre-runners (figure 10) have been manufactured by Astrium before the development hardware in order to validate the manufacturing processes and to conduct component tests. The benefits of this "Full Development" approach is threefold: it provides a knowledge of key manufacturing processes; it consolidates manufacturing reproducibility; and it enables to use fully qualified processes when it comes to development engines manufacturing.

Figure 9: Thrust chamber injection head

Figure 10: Chamber manufacturing

Spray tests have been conducted at the P3.2 test facility in Lampoldshausen, Germany, for use in models verification and anchoring. They consist in filling the injector dome with LN_2 and investigating the igniter interaction (figure 11). The results are in line with the 3D-CFD calculations.

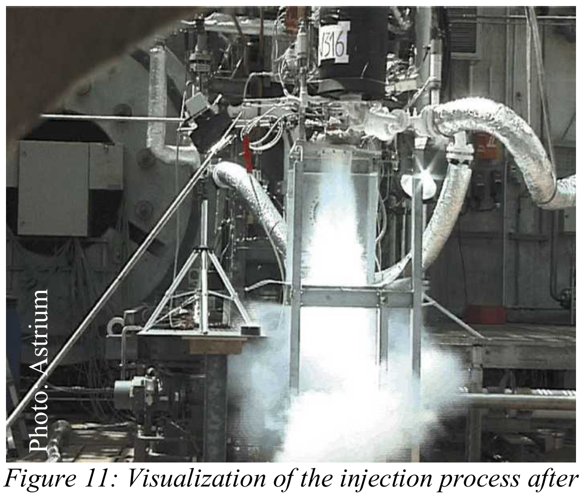

Figure 11: Visualization of the injection process after chamber valve opening

Upcoming tests include transient cool-down flowchecks with the original regenerative chamber, ignition hot tests with a capacitively cooled chamber and original injector, and combined ignition and start-up hot tests for combustion stability demonstration.

As for the first **hydrogen turbopump (TPH)**, the assembly is complete (figures 12 and 13) and manufacturing of the TPH for the first engine (M1) is under way.

Figure 12 : Rotor of the first hydrogen turbopump

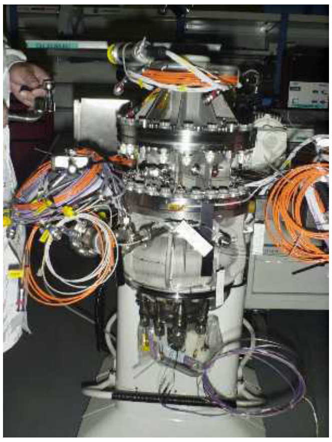
Figure 13 : First VINCI hydrogen turbopump

Component tests are in progress:

- The bearing test campaign started in March on the BCLH2 bench in Vernon, France. In one of the first long duration tests of the campaign, the successful behavior of one set of bearings was demonstrated at the maximum engine operating speed over more than twice the flight duration. More than 23000 s of tests have been conducted in order to check the behavior of the bearings under various axial and radial loads.

- Turbine aerodynamic tests performed by Volvo Aero characterized the performance of the turbine on a wide range of operating conditions.

- Inducer hydraulic tests were completed in March for the hydrogen turbopump (figure 14) on the CREMHyG bench, Grenoble, France. They showed that specified requirements for suction performance will be met. The test results also demonstrated robustness as regards manufacturing scatter.

Figure 14: Cavitation pattern of the hydrogen turbopump inducer in water

- Cryogenic spin tests are being conducted on the titanium powder metallurgy impellers. Since these impellers are products of an innovative technology, the tests provide a demonstration of reproducibility and a knowledge of failure modes. Figure 15 shows an impeller on the test rig. On the same bench, a margin of at least 50% over the maximum operating speed has been demonstrated for the turbine rotor burst limit.

Figure 15: Impeller on cryogenic spin test rig

The hydrogen turbopump test campaign (figure 16) is in progress on the PF52 test bench in Vernon, France. The TPH1 is equipped with approximately 120 measurement channels providing an exhaustive knowledge of its behavior : temperature probes, pressure sensors, strain gages, accelerometers. Displacement transducers are used to monitor the rotor dynamic, and miniaturized transducers have been specifically developed for the Vinci turbopump, with respect to the reduced size of the machine compared to Vulcain hardware.

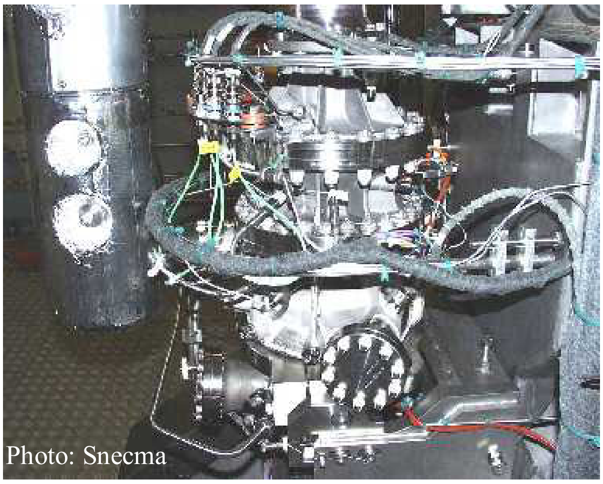

Figure 16: TPH on the PF52 test bench

The test plan focuses on the following objectives :

- A series of childown tests: this was done in June 2002;

- A step-by-step exploration of the operating domain: tests have been conducted at 30000 and 65000 rpm so far and the TPH behaved as expected. The critical speeds were passed without excessive vibrations and the axial balance system was active very early in the start-up transient;

- Specific objectives related to performance (including suction performance, rotor dynamics, behavior over a wide range of pump mass flow rate conditions…).

As of today the test campaign shows a satisfactory and fast progress compared to the Vulcain TPH tests: the cumulative testing time on the TPH is plotted versus the campaign duration on figure 17.

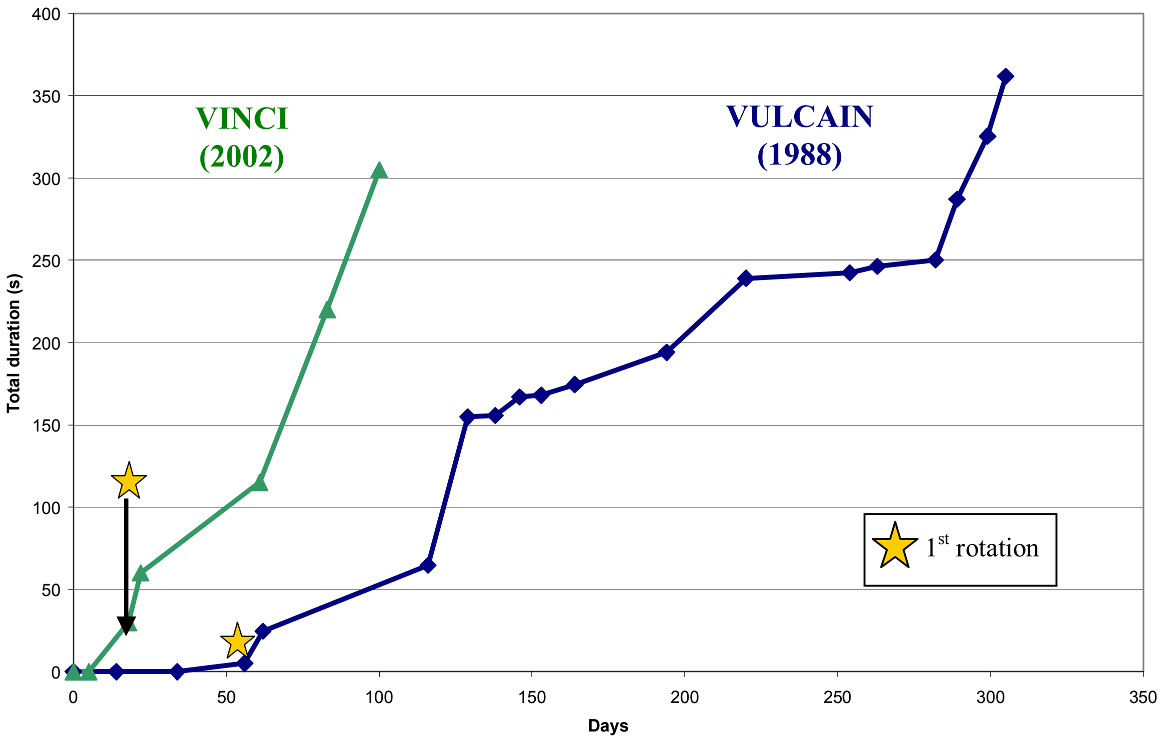

Figure 17: Compared history of VINCI and VULCAIN first TPH test campaigns

On the **oxygen turbopump (TPO)** side, the first turbopump is to be delivered by FiatAvio in Vernon for installation on the PF52 test bench. The configuration of this test with 3 test cells (TPH, TPO, engine) offers attractive operational flexibility to conduct TPH tests while preparing TPO tests or vice-versa.

Component tests are also ongoing: inducer and impeller hydraulic tests, bearing tests, DSP (Dynamic Seal Package) tests… Last of all, manufacturing of the TPO for the first engine has also started.

Test facilities and engine test plan

Two test facilities are used for the development of the VINCI engine, the P4.1 at DLR in Lampoldshausen and the PF52 at Snecma Moteurs in Vernon. Significant progress of the design and construction of these two test benches were achieved over the 2001-2002 period.

The engine test cell of the PF52 is designed for long duration endurance testing throughout the VINCI development and will be used for acceptance tests of production engines in the future. The layout of the PF52 test cell and the engine to test bench integration procedure are designed with the goal of minimizing the duration of acceptance tests in the production phase. It is also designed in order to minimize the duration of the required operation for return to flight configuration performed on the test bench after acceptance test. The engine will be operated without the nozzle extension in horizontal position (figure 18).

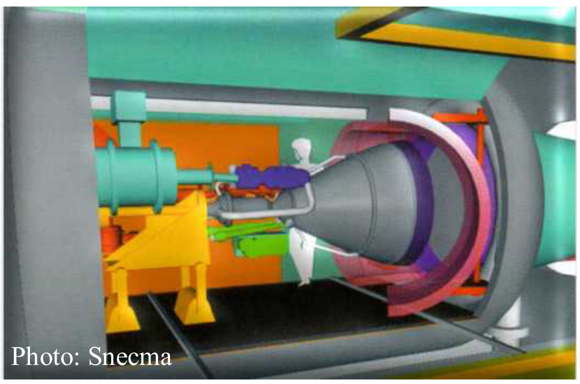

Figure 18: CAD view of the Vinci engine on the PF52

The engine ignition is performed in vacuum conditions (60 mbar) and the steady state operation occurs in ambient conditions. This sequence is obtained with an exhaust duct equipped with a door which opens when the thrust chamber pressure exceeds the ambient pressure.

As seen above, the PF52 also has turbopumps test cells that are already operating. The engine test cell is under completion: the test cell walls and the propellant tanks have been built (figure 19).

Figure 19: Building site of the PF52

The second VINCI test bench is the P4.1 at DLR in Lampoldshausen, Germany (figures 20 and 21). It is a versatile test bench offering the capability of testing the engine at ambient pressure or in vacuum conditions, without the nozzle, with the fixed part of the nozzle or with the fully deployed nozzle. The engine can be run in full vacuum conditions during the whole duration of a test. The P4.1 is equipped with a thrust measurement load cell. These test bench characteristics make it the primary development tool to study transient robustness and restart conditions. The line flow resistance will closely approximate the real stage line impedance through the use of

an auxiliary tank during the start-up transient on both the hydrogen an oxygen side. The chilldown line flow resistance and downstream pressure boundary conditions will also be representative of stage lines.

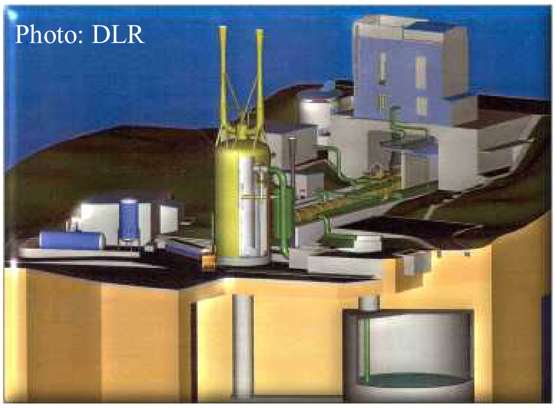

Figure 20: CAD view of the P4.1

Figure 21: Building site of the P4.1 H_2 tank

The capability of simulating various thermal environments, which may occur during the ballistic phase of multiple boost missions, is one of the P4.1 key features. This will be achieved through radiative heating or local conditioning and through the simulation of hot and cold restart cases. This will consolidate the demonstration of the engine restart capability.

On the P4.1 the vacuum chamber was recently integrated in the building. The condenser (in light green on figure 20), used to collect the water steam from the engine exhaust, and the propellant tanks are also well under way.

The engine test plan is established on the basis of at least 150 tests and 45000 s of accumulated time distributed over the two engine test benches P4.1 and PF52. Seven development engines and two qualification engines will be used. P4.1 tests have objectives pertaining to the behavior of the engine with the nozzle extension, the engine thermal status and its restart capability. PF52 tests have objectives related to endurance at various points of the operating domain, steady-state mixture ratio trimming procedure and preparation of the acceptance test of flight engines.

Conclusion

After ESA decision to initiate the development of a new cryogenic engine for Ariane 5 in June 1998, a significant milestone was the ESA commitment to provide funding for the development of the VINCI engine up to its qualification in 2005, which was obtained at the end of 2001.

Over the mid 2001 - mid 2002 period, the first major subsystems, combustion chamber and turbopumps, have been manufactured and assembled, and testing is in progress. The test facilities construction is also well on track. Snecma Moteurs and its European industrial partners are ready for the tests of the first development engine in 2003.

References

1. AIAA 2000-3786
   Development status of the VINCI engine for Ariane 5 upper stage
   F. Jean - E. Dalbies (Snecma Moteurs)

2. AIAA 2001-3553
   Development status of the VINCI engine for Ariane 5 upper stage
   F. Jean - P. Alliot (Snecma Moteurs)

3. AIAA 2000-3156
   VINCI hydrogen turbopump : a new step in safe, faster and cheaper developments
   B. Goirand - J.F. Gallardo - R. Bosson (Snecma Moteurs)

4. AIAA 2000-3167
Status of cryogenic chamber development for Ariane 5 at Astrium GmbH
R. Nikolay - T. Mattstedt - D. Theleman

5. AIAA 99-2346
High Performance Cryogenic Ball Bearing Demonstration
R. Bosson - E. Edeline - L. Collongeat

6. AIAA 2002-4007
The VINCI hydrogen turbopump development status
P.Alliot - N. Marchal - B. Goirand (Snecma Moteurs)
C. Bernard-Lépine (CNES)

7. AIAA 2002-4006
Development status of the VINCI engine for the Ariane 5 upper stage
P. Alliot - E. Dalbies (Snecma Moteurs)
J.-M. Ruault (CNES)

8. IAA - 01 - IAA - 3.2.05
VINCI: A new Step for European Cooperation in Liquid Rocket Propulsion
F. Jean (Snecma Moteurs)
J.-M. Ruault (CNES)