Progress of the VINCI engine system development

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ABSTRACT

The intent of this publication is to provide an overview of the progress of the VINCI development over the 2010-2011 period.

The VINCI is a cryogenic expander cycle engine combining the required features of this cycle, i.e. high performance chamber cooling and high performance hydrogen turbo-pump, with proven design concepts based on the accumulated experience from previous European cryogenic engines such as the HM7 and the Vulcain. The Vinci engine has been selected as the base of the future Ariane 5 evolution (so called A5ME) powering a new cryogenic upper stage. Additionally, the high performance of this engine and its restart capability offer potential applications on various future launcher upper stages as well as orbital spacecrafts.

This publication represents the continuation of a series publications which showed how the first four engine test campaigns relying on two engines, M1 and M2 and their refurbishments, led to a reference system configuration with reliable transients and steady state operation.

The current phase of the VINCI development is focused on confirming the system design maturity through additional engine test campaigns with the M3 and M4 engines.

The main objectives of the M3 campaign which took place in 2010 and early 2011 were the following:

- to complete a more extensive coverage of the operating domain with margin tests beyond the flight domain
- to operate with inlet thermodynamic conditions representative of the future upper stage
- to test design modifications of the sub-systems (fuel turbo-pump, turbine by-pass valves, thrust chamber,…) which provide increased performance and reliability
- to perform tests with the complete deployed nozzle

In 2011, the M4 engine test campaign is implemented with the objective to test the engine improvements necessary to comply with the requirements of the new A5ME launcher, preparing the extensive test program to be performed in a second phase of development aiming at qualifying the engine for flight.

Along with the M3 and M4 campaign, a dedicated combustion chamber test campaign is performed in 2010 at the P3.2 test bench in Lampoldshausen (Germany). It provided detailed knowledge of the regenerative circuit temperature, heat flux and flow conditions, wall temperature.

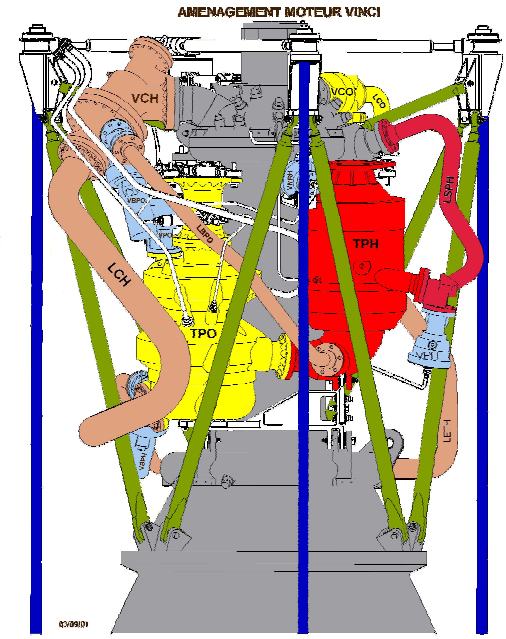


Figure 1 : Side view of the engine showing the hydrogen turbopump (TPH), the oxygen turbopump (TPO), the hydrogen chamber valve (VCH)

Introduction

The VINCI engine is a 180 kN re-startable upper stage cryogenic engine. Its preliminary design was initiated in the frame of the Ariane 5+ program managed by CNES under delegation of ESA. Between 2006 and 2008, its engineering and testing were conducted under the ESA Future Launcher Preparatory Program (FLPP). VINCI is currently the basis for the next evolution of the ARIANE 5 launcher developed by Astrium as launcher prime contractor in the frame of ESA A5 Mid life Evolution (A5ME) program.

The VINCI is a cryogenic expander cycle engine. This cycle was found to be the most promising option to achieve the overall objectives of higher reliability, higher performance, multiple ignition capability and low recurring cost.

The engine overall system design and integration is under responsibility of Snecma (Vernon, France). The major subsystem contractors are ASTRIUM GmbH (Ottobrunn, Germany) for the thrust chamber, Volvo AC (Trollhättan, Sweden) for the turbines of the turbopumps, AVIO (Turin, Italy) for the oxygen turbopump, Snecma for the hydrogen turbopump, Snecma Propulsion Solide (Bordeaux, France) for the composite nozzle and. Techspace Aero (Liège, Belgium) for the valves. The engine hot fire testing is performed at DLR P4.1 test facility (Lampoldshausen, Germany)



Figure 2 : View of the second and third assembled engine

Engine architecture and system engineering

The engine is characterized by a high performance hydrogen turbopump, 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.

The engine architecture, which was already presented in numerous previous publications (see references 1,4 and 5) is designed to meet the goal of reliability, simplicity and low recurring cost. The engine flow schematic is shown on figure 3.

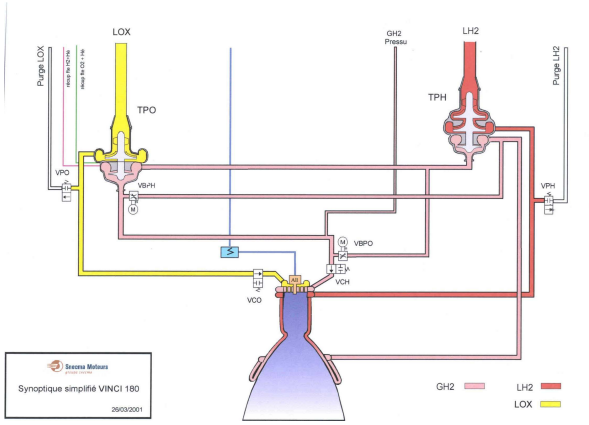


Figure 3 : VINCI flow schematic

The combustion chamber body is a "smooth wall" chamber using the same technology as the HM7B and VULCAIN, but significantly longer in order to meet the thermodynamic performance needed by the expander cycle. The use of a regenerative nozzle extension was avoided in order to reduce cost and number of fluid interfaces. The chamber is shown on figure 4 during engine assembly prior to power pack installation.

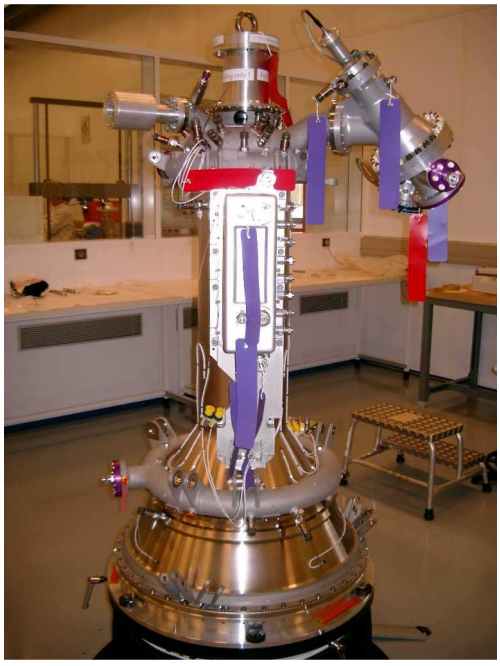


Figure 4: Thrust chamber of the first development engine with the fuel chamber valve and the solenoid valve box

The engine has two separate turbopumps mounted close to one another in a "power pack" kit as shown on figure 6. Turbines are set "in serial", and a set of two by-pass valves adjusts their flow rates. This set allows to tune the engine operating point, in terms of thrust and mixture ratio.

Both turbopumps have integral inducers, which lead to low NPSP with the objective to avoid the use of boost pump.

A H2/O2 gas fed torch, electrically initiated by a spark system, is used for engine ignition. This igniter is fed by gaseous oxygen and hydrogen contained in high-pressure bottles operating in a blow down mode. The igniter is developed by APP (Netherlands) under contract from ASTRIUM GmbH.

The description of the major subsystems was presented in reference 2 and 3.

The VINCI is designed to operate in a domain centered around a nominal thrust equal to 180 kN and the mixture range 5.7 / 5.9.
The oxygen chamber valve is a pneumatic ball valve. This choice is based on the priority given to simplicity of architecture and low recurring cost. The fuel chamber valve (VCH) is a pneumatic poppet valve.
The low recurring cost objective has led to the choice of slow actuation rate by-pass valves. The large multiplication rate between actuation electric motor and valve shaft ensures stability of the valve, therefore eliminating the need for an electronic control.
The engine has a set of poppet chill-down valves with calibrated orifices, which are sized in order to allow a sufficient discharge flow during start-up and shutdown transients.

One of the major new features of the engine is a large area ratio deployable composite nozzle.. The nozzle, shown on figure 5, is composed of a fixed part attached to the combustion chamber and a deployable part stored around the upper part of the engine during the first stage flight.

The nozzle deployment system is designed by Kongsberg (Norway).
One major axis of the current development period is the assessment of the re-start capability. This function leads to place a strong focus on the thermal control of the engine and the thermodynamic conditions of the propellant at engine inlet.



Figure 5 : Vinci Nozzle Extension after testing

Summary of the engine system engineering

The development of the engine strongly relies on the use of analytical models, computational tools and the comparison between test and simulation results. The following major simulation models can be mentioned:
- the engine functional steady state model
- the engine functional transient model
- the chill-down model
- the engine overall mechanical model to simulate the engine dynamic behaviour, including a mode shape characterization, and to provide loads at subsystem interfaces
- the engine thermal model, to provide the engine thermal map in all flight phases (among them the coast phases) or in test bench conditions.

Over the 2010 – 2011 period, the engine technical specification, the sub-system specifications and the justification files were updated in order to take into account the requirements issued from the A5ME launch vehicle and its new upper stage. The justification files are organized into functional, mechanical and thermal ones. They express how the results of the analytical simulations combined with the results of the test campaigns contribute to show that the engine meets its

upper level launch vehicle requirements. A Complementary Preliminary Design review was organised in early 2011 to confirm the adequacy of these documents as the basis of the up-coming phase of development.

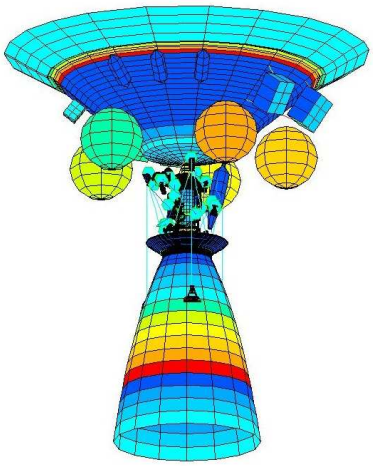


Figure 6 : Thermal model of the engine

Chamber tests

Following a combustion chamber test campaign dedicated to the knowledge of high frequency margin in the start-up transient which took place in 2008, a test campaign dedicated to the detailed knowledge of the regenerative circuit (temperature, heat flux and flow conditions, wall temperature) started in 2010 and extended over 2011.

The Chamber tests are performed at the P3.2 test bench in Lampoldshausen. The current phase of the chamber tests dedicated to the regenerative circuit relies on an extensive instrumentation (thermo-couple, static and rapid variation pressure gages,...) in order to establish detailed distribution of temperature and pressure over the injector and regenerative circuit during transient and steady state operation. The chamber operates in vacuum and is equipped with a part of the first section of the nozzle. Operating duration at high mixture ratio was performed as part of the objective of life demonstration. Low thrust operating points were also tested.

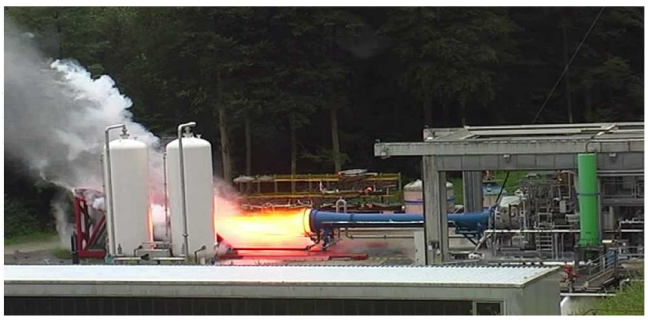


Figure 7 : Test rig for chamber tests (source EADS-Astrium)

The engine test facility

The engine hot-firing tests are performed on the P4.1 test stand at DLR in Lampoldshausen, Germany.

The P4.1 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 operated in full vacuum conditions during the whole duration of a test.

The P4.1 is equipped with a thrust measurement load cell. Its characteristics make it the primary tool to study transient robustness and restart conditions.

The bench propellant feed-lines closely approximate the impedance of real upper stage lines through the use of a buffer tank during the start-up transient on both the hydrogen and oxygen side.
The chill-down line flow resistance and downstream pressure boundary conditions are also representative of real stage lines.
The capability of simulating various thermal environments, which may occur during the coast phases of multiple boost missions, is one of the P4.1 key features. This will be essential for the demonstration of the engine restart capability.
Figure 8 shows a view of the test cell and exhaust duct. During the operation of the engine, vacuum (approximately 10 mbar) is maintained using steam ejectors.



Figure 8 : View of the P4.1 test stand and exhaust duct (source DLR)

Engine first test campaigns

From 2005 to 2008, the engine testing was based on the availability of 2 engines, M1 and M2, and components available for a back-up engine if necessary. After changes of components, M1 was refurbished into M1B and M1C; M2 was refurbished into M2R. The first two engines M1 and M2 were tested from mi-2005 to early 2006. After these campaigns, M1 and M2 were refurbished respectively into M1B/C and M2R with modifications or changes of components.

After the completion of the M1C and M2R test campaigns, a total of four test campaigns (M1, M2, M1B/M1C, M2R) comprising 31 tests, which means 37 individual firings considering dual firing tests and 4672 sec of accumulated operating duration, had been achieved.

The main objectives of the M1C and M2R test campaign were:
- to demonstrate the restart capability of the engine,
- to accumulate testing time and number of firings at various operating points of the flight domain,
- to confirm the robustness of the start-up and shut-down transients,
- to test various types of chill down.

The majors lessons learned from these campaigns are summarized in the following paragraphs.

(1) Transient and steady state operation
The first and second test campaigns showed that a reference system configuration with reliable steady state and transient behaviour had been obtained. A reference start-up and shutdown sequence was successfully established and tested. This sequence led to a reproducible behavior of the engine during the start and shutdown transients with two different hardware M1 and M2. These test campaigns also showed a very stable behavior of the engine during steady-state operation.

In addition, the results of the M1C and M2R test campaigns provided the validation of stable behavior of the engine and its ability to be operated in a close loop regulation mode

(2) Restart capability

The engine restart capability was tested during the M1C and M2R test campaigns. Several tests of the M1C and M2R test campaigns included a main boost and a restart boost; consequently the restart transient could be analyzed for various engine status resulting from the first boost stop transient.
Testing a significant number of start, re-start and shutdown transients gave the opportunity to confirm the robustness of the transient and its tolerance to valve actuation scatter.

(3) Nozzle extension

The fixed part of the deployable nozzle designated as the A cone was tested during the M2 and M2R test campaign.
Thermal cameras and thermocouples provided an extensive knowledge of the thermal behavior of the radiative nozzle and allowed an evaluation of the hot gas heat flux.

(4) Life demonstration

A significant amount of duration and number of transients were cumulated on two Vinci engine with one of them being tested for more than one design life. The Vinci design life is defined as the addition of acceptance tests to a flight comprising up to five individual burns, the first burn being based on the duration of the upper stage burn of an Ariane 5 GTO mission.
Post test examination performed on engines M1C and M2R did not show evidence of life related damage.



Figure 9 : View of the engine in operation with the fixed part of the nozzle

Vini Engine test campaign rationale

The overall development of the Vinci Engine aims at an Engine qualification in 2015, and previously an Engine CDR in 2013.
The Engine test rationale is the following:

- Two engines M3 and M4 designated as “design adjustment engine”, will serve as a bridge between the early “debugging” engines and the final development and qualification engine. They will contribute to establish the engine maturity with respect to Ariane5ME requirements. Their test campaign extends over the 2010 and 2011 period.
- M5 and M6 will be “failure mode testing engine” with a focus on determination of design margin and response to failure cases or extreme situations.. The results of their test campaign will be the basis of the engine Critical Design Review and make possible finalizing the definition of the qualification engine.
- The Qualification will rely on four engines:
    - M7 and M8 for subsystem qualification with operation covering the sub-system flight domain and beyond,
    - M9 and M10 for engine qualification with endurance demonstration in the flight domain.

M3 test campaigns

The M3 test campaign took place over the last semester of 2010 and the first quarter of 2011.
The major objective of the M3 campaign, which is the first of the two campaigns designated as an engine adjustment phase were:

- to test the complete deployable nozzle,
- to operate at operating points covering the entire flight domain and increase the accumulated testing duration at operating points covering the complete flight and extreme domain
- to perform thermal measurement which will be essential for predicting the thermal status of the engine before a restart,
- to study the sensitivity of the start-up transient and first few second of operation to the thermodynamic condition at engine inlet,
- to continue the optimization of the chill-down in order to decrease the propellant consumption and the duration required to reach chill-down completion.
- to validate a first set of engine modifications required for adaptation to A5ME requirement and to test the engine at very low thrust in order to demonstrate its throttling capability

As part of this adjustment phase, the following modifications were also tested:

- improvement of LH2 turbo-pump and the by-pass valve, in order to increase Engine performance ,
- mass reduction modifications

Performing tests with the fully deployed nozzle was one of the highlight of the M3 test campaign.
The risk analysis of this test showed that the stop transient in a test bench environment may be more severe than in flight and jeopardize both the structural integrity of the nozzle and of the engine. Consequently, assessing the structural integrity of the nozzle was the subject of extensive mechanical analysis which took place in early 2010. Three tests with the complete nozzle were performed cumulating a total duration of 1930 sec on the same nozzle. The post test examination confirmed the good behaviour of the nozzle. The main benefit of these tests were:

- The knowledge of the thermal behavior of the nozzle and of the nozzle to chamber interface
- The dynamic characterization of the engine with its nozzle

Exploring first start and re-start thermodynamic conditions at engine inlet representative of real flight ones is an essential part of the campaign. Testing was be performed with pump inlet condition representative of the future upper stage: inlet pressure equal to 2.7 bar on the oxygen side and 3.3 bar on the hydrogen side, with excursions further down. Additionally, sub-cooled liquid oxygen was tested for some duration and helium injection on both propellant side was performed, enlarging the knowledge of the engine response to various operating conditions.

Operation at a higher and much lower thrust than nominal was also a major achievement of the campaign. Steady state operation at 206 KN (compared to the 180 KN nominal) was achieved with the hydrogen turbopump rotating speed and exit pressure reaching 103000 rpm, 300 bar. The introduction of a new set of turbine by-pass with very low leakage in close position was an essential element for reaching this thrust level. Throttling at very low thrust level was performed with successive operation at 100 KN, 61 KN, 43 KN, 27 KN. (see figure 10). This result is essential to demonstrate the capability of the engine to fulfil multiple versatile missions which include a second firing at a low thrust level such as a de-orbitation boost.

A very long duration test with a single firing of 714 s, compared to the nominal 700 s for a mission into geo-stationary transfer orbit, was also performed.

One ball screw rod from the nozzle deployment system was present in the M3 test campaign along with its attachment device to the nozzle. This was aimed at characterizing its behaviour when exposed to the thermal flux of the nozzle and verifying that the ball screw keeps its structural integrity during engine firing.

For most of tests, the chill-down sequence was the reference sequence established as a result of the optimization effort started in previous test campaigns: most the chill-down duration is performed at a trickle flow through the turbo-pump bearing chill-down circuit with fluid vaporization used to extract thermal energy, the end of the chill-down is performed with the full opening of the chill-down valve (which main function is also a power shedding function during transients).

The overall M3 campaign represents 11 tests, 13 firings accounting for tests with successive firings, and 6287 s of cumulated duration.

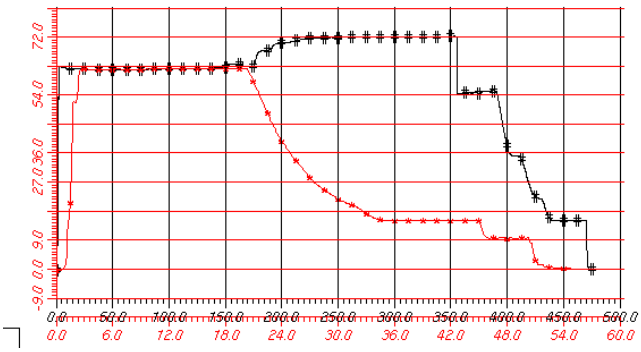


Figure 10 : Chamber pressure during the first (black curve) and second boost (red curve) of test M3-11 with operating points from 206 KN (first boost) down to 27 KN.

M4 test campaigns

Further design improvements are implemented on the M4 engine with the following goals:

- To maturate the engine definition by incorporating modifications aimed at improving the subsystem robustness
- To introduce modifications with the objective of engine mass reduction
- To obtain an easier and faster engine production

Conclusion

The VINCI, as a high-performance cryogenic re-ignitable upper stage engine using the expander cycle, is a key element for the future developments of European launchers.

From 2005 to 2008, the first engine test campaigns relying on engine M1, M2, M2R showed that a reference system configuration with reliable transient and steady state behavior had been obtained. They demonstrated the engine restart capability, the reproducibility of the transient behavior and initiated the endurance demonstration.

In 2010 and 2011, the M3 campaign completes this demonstration with the following achievements:

- Several tests of the fully deployed nozzle
- Tests covering the compete flight operating domain and beyond into the extreme domain
- Operation at a very low thrust level showing the adaptability of the engine to multiple ARIANE 5ME mission requirement.

Tests with similar objectives are repeated in 2011 with the M4 engine.
When completed the M3 and M4 test campaign will provide the assurance that a final development phase with margin test campaigns and qualification test campaigns can confidently be initiated.
The future key milestone of the VINCI development will be the engine Critical Design Review in 2013 and the engine qualification in 2015.

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