3rd EUCASS
JULY 6-9th 2009, Versailles, France

EUCASS 2009
Progress of the VINCI engine system engineering

P. Alliot – Ph. James – C. Fiorentino – E.Edeline,
Snecma Space Engines Division - Vernon, France

ABSTRACT

This paper provides an overview of the progress of the VINCI engine system engineering over the 2008-2009 period.

The VINCI engine is a 18 ton-thrust upper-stage cryogenic expander cycle engine tested under ESA Future Launcher Preparatory Programme. It combines high performance chamber cooling and hydrogen turbopump, with proven design concepts based on accumulated experience from previous European cryogenic engines such as HM7 and Vulcain.
The high performance of this engine and its restart capability offer potential applications on various future launcher upper stages as well as orbital spacecrafts.

The system engineering activities aimed at improving the design maturity are essentially focused on the consolidation of the engine steady-state operational domain, engine ignition and start-up after a ballistic phase for multiple boost missions.
Mechanical engineering activities mainly concern the ability of the engine to sustain the dynamic environment of the booster and first stage flight. They also concern the deployment of the nozzle. They rely on engine dynamic tests, component tests and deployment tests.
Re-start oriented activities encompass the following domains : thermal engineering analysis aimed at assessing the thermal status of the engine prior to a re-start, specific activities aimed at investigating the effect of a low gravity environment on heat transfer and two phase flow.

Introduction

The VINCI engine was developed as an 180 kN reignitable upper stage cryogenic engine. Its features were investigated in the frame of the ESA Future Launcher Preparatory Program (FLPP) between 2006 and 2008. VINCI is now the basis for the next evolution of the ARIANE 5 launcher.

The cryogenic expander 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)

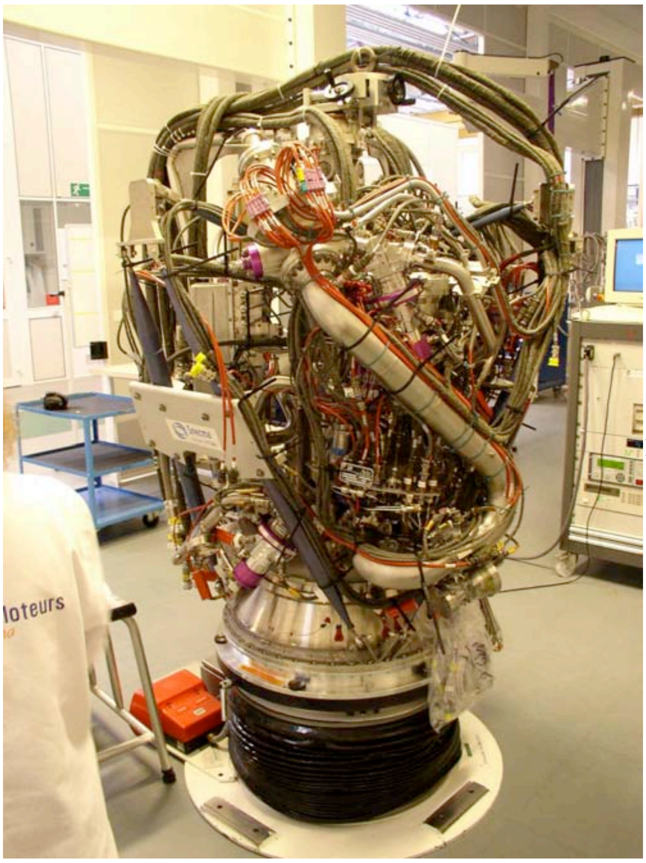

Figure 2 : View of the second assembled engine

Engine architecture

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 reference 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.

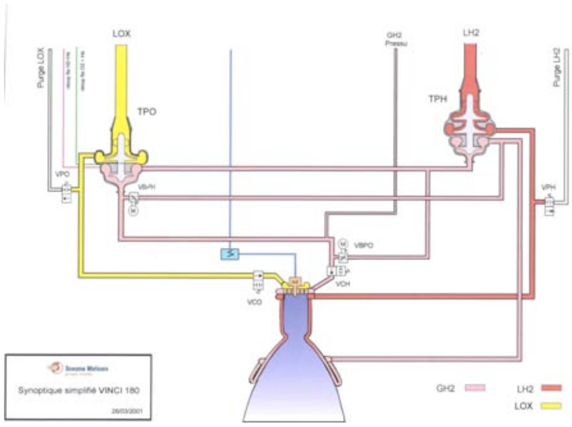

Figure 3 : VINCI flow schematic

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 of the first development engine is shown on figure 4.

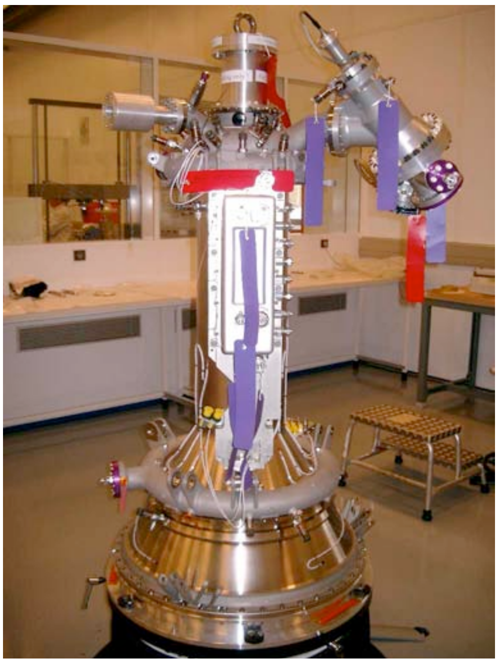

Figure 4: Thrust chamber of the first development engine with the fuel chamber valve and the solenoid valve box

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 H_2/O_2 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.

One of the major new features of the engine is a large area ratio deployable composite nozzle.. The nozzle 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 particular axis of the demonstration program is the re-start capability. This function leads to place a strong focus on the thermal control of the engine and the behaviour of propellants in microgravity.

Overview 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.

The engine steady state functional model serves as the basis for establishing the component and sub-system functional specifications. In the production phase, this model will be used for engine tuning, i.e. thrust adjustment and mixture ratio trimming.

The engine transient model is an essential tool for test preparation and analysis.
Its necessary features are :
- enough flexibility in order to quickly introduce system modification (the current engine model relies on a library of functional components which provide this flexibility)
- an accurate representation of hydrogen two phase flow regime (heat transfer correlation and pressure drop) for the low power early condition of the start-up transient and accurate representation of real gas behaviour at high power.

The engine mechanical model was established early in the development and is constantly 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.

The engine thermal model is established for steady state, transient and coast phases. It provides the thermal status of the engine during operation, which is strongly dominated by the heat flux originating from the radiative nozzle. It also provides the thermal status of the engine during coast phases, which is an essential input for prediction of the engine restart condition. A view of this model is shown on figure 9.

Steady-state and performance analysis

The method used to derive the operational envelop of an engine is usually the following:
- Determination of a flight operational envelop around the engine reference points taking into account scatter in engine component performance and engine inlet conditions,
- Determination of engine qualification points where the engine shall be tested in order to demonstrate its reliability with respect to future production scatter.

The results of four test campaigns comprising 31 firings and 4672 sec of accumulated operating duration with 2 engines are used to obtain a first evaluation of component scatter, for instance the scatter associated with a turbine efficiency or an injection pressure drop, and confirm the size of the flight operational envelop and the position of the qualification points (see figure 5).

The operational envelops are established using a proven reference method based on the linearization of the response of the engine steady-state functional model around given operating points. The robustness of this approach is also verified by Monte-Carlo simulations (see figure 6).

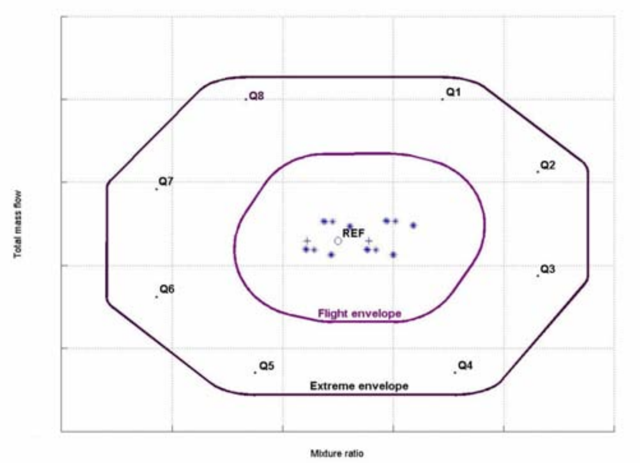

Figure 5 : Engine operating envelops in the Thrust (or total flow) vs mixture ration axis

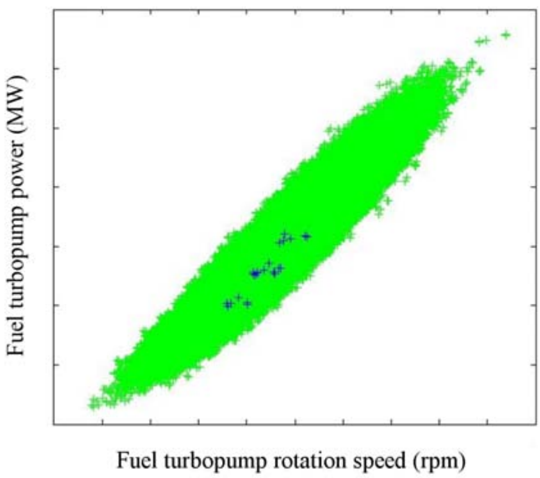

Figure 6 : Fuel turbopump operating domain obtained by Monte-Carlo analysis

Local 3-D flow analysis were performed in location where a precise determination of flow velocity distribution and pressure drops is necessary to consolidate the engine performance evaluation.

Chill-down and micro-gravity

A chill-down sequence involves a combination of convective phase (i.e. heat removal by convection with opened chill-down valves) and soaking phases (i.e. heat removal in pool boiling with closed chill-down valves). Parametric investigation of various chill-down sequences were performed in the first four test campaigns and will be continued in the M3 test campaign. Test results are compared to prediction by simulation models which are developed with a focus on the relationship between two phase flow regimes and heat transfer prediction. Additionally, since the complementary chill-down phase required for re-starting the engine after a ballistic phase may be affected by micro-gravity, theoretical investigations of micro-gravity on heat transfer regimes will be performed in order to support the engineering activities related to the engine re-start capability. They rely on research experiments performed in the frame of Research and Technology programme supported by CNES.

Dynamic testing

An upper stage engine is submitted to the dynamic environment imposed by the first stage during the first part of the launcher ascent. Therefore dynamic analysis and testing account for a significant part of the engine mechanical development.

A complete engine experimental modal analysis was performed at the end of 2008. It provides the knowledge of the overall dynamic behaviour of the engine and leads to the identification of locations of the structure where an excessive dissipation of vibratory energy may result fatigue damage or local fretting. The modal analysis is performed with the engine hanging from a support frame in a free configuration using dynamic actuators in several excitation points. In addition to the modal characterization based on low level sine sweeps, higher excitation levels are applied at specific frequencies in order to observe possible non-linearities. Special attention was paid to the support structure of the nozzle deployment mechanism which is a large low frequency structure prone to be excited by the dynamic environment of the booster ascent phase. As an example of a design consolidation activity, stiffening rods were added to the nozzle deployment support frame in order to increase its level of robustness and increase its natural frequencies.

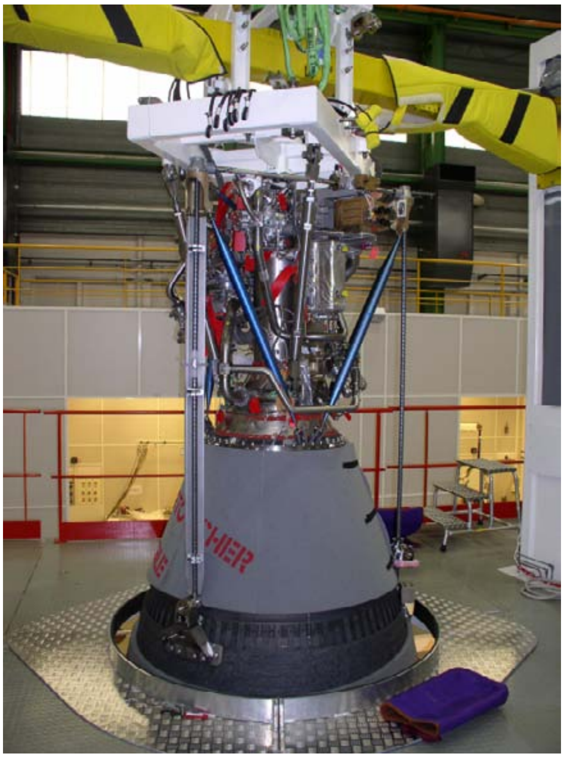

Figure 7 : Engine dynamic testing

Engine thermal analysis

A number of tests of the latest M2R campaign involved tests with the simulation of a ballistic phase after the main boost, a complementary chill-down and a restart boost. The thermal behavior of the engine during the simulated ballistic phase is compared to the results of a thermal model of the engine in test bench conditions. Using this model to represent the engine coupled to the future upper stage in the flight environment will be an essential task of the future re-start engineering activities.

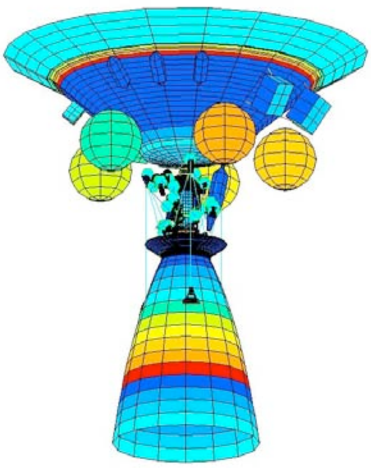

Figure 8 : Thermal model of the engine

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 11 shows a view of the test cell and exhaust duct. During the operation of the engine, vacuum (approximately 20 mbar) is maintained using steam ejectors.

Figure 9 : View of the P4.1 test stand and exhaust duct

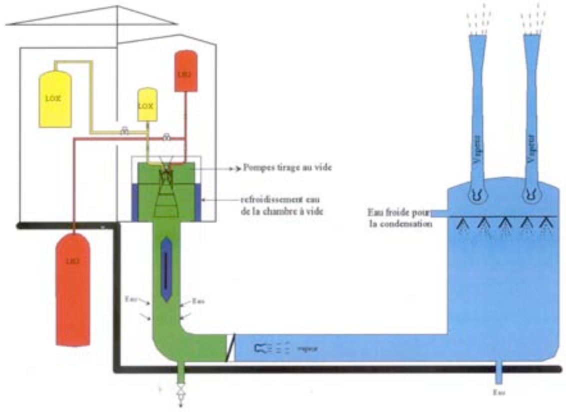

Figure 10 : P4.1 test bench general arrangement

Engine first four test campaigns

From 2005 to 2008, the engine testing was based on the availability of 2 engines, M1 and M2, which were refurbished during this period into M1B and M1C and M2R respectively.

The first two engines M1 and M2 were tested from mid-2005 to early 2006 and M1C and M2R on the period 2007-2008.
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.

Figure 11 : View of the engine in operation

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.

<u>(1) Transient and steady state operation</u>

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.
The results of the M1C and M2R test campaigns provided :
- the confirmation of the robustness of the start-up and shut down transients,
- the validation of stable behavior of the engine and its ability to be operated in a close loop regulation mode.

<u>(2) Restart capability</u>

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.

<u>(3) Nozzle extension</u>

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.

<u>(4) Life demonstration</u>

Accumulating testing duration and number of firings has served the goal of demonstrating margins with respect to life related failure mode: high cycle fatigue (HCF), low cycle fatigue (LCF).

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 these two engines did not show evidence of life related damage.

Preparation of the next test campaign

In the frame of the new Ariane 5 post ECA ESA programme, Vinci has been selected to powered the new cryogenic reignitable upper stage of the new Ariane 5 evolution (so called A5ME).
The first phase of this programme (2009-2011) will include 2 additional engine test campaigns on M3 and M4 engines.

The next test campaign will be performed with engine M3, starting during the last quarter of 2009. The main objective of this campaign is to perform test with the complete deployed nozzle. It is also to complete a more extensive coverage of the operating domain and to operate with inlet thermodynamic conditions more representative of the future upper stage.
The preparation of the engine test with its complete nozzle involves activities related to the installation and deployment of the nozzle in the test bench environment as well as a risk analysis of operating the nozzle in test bench condition with the vacuum extraction facility. A detailed analysis of the response of the nozzle to dissymmetrical pressure field during the start transient and external over pressure during the stop transient are an essential part of the risk analysis of this test.

The M4 engine test campaign is planned to be performed in 2011 with the objective to test the engine improvements necessary to cope with the requirement of the new launcher, preparing the extensive test programme of the development second phase aiming to qualify the engine for flight.

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.
The expander demonstration program, based on Vinci engine, was launched in the frame of the ESA Future Launcher Preparatory Program (FLPP).

The first four engine test campaigns which took place from 2005 to 2008 showed that a reference system configuration with reliable steady state and transient behavior had been obtained. They demonstrated the engine restart capability, the reproducibility of the transient behavior and initiated the endurance demonstration.

In parallel, system engineering activities are implemented with the objective of improving the design maturity, capitalizing on the results of these four test campaigns.

After these four test campaigns which have shown the robustness of the engine overall design and which have also shown the areas where a consolidation effort had to be focused. Vinci engine has been selected as the base of the future Ariane 5 evolution (so called A5ME) powering a new cryogenic reignitable upper stage. A first phase of this programme has been launch beginning of 2009 which will lead, for Vinci engine, to confirm the design configuration to be extensively tested and qualified in a future development phase, leading to the engine qualification.

References

1. AIAA 2003-4484
   Development status of the VINCI engine for the Ariane 5 upper stage
   P. Alliot - E.Dalbies - J-F. Delange (Snecma Moteurs)
   J-M. Ruault (CNES)

2. AIAA-2002-4009
   Development,Manufacturing and test status of the VINCI Expander Thrust Chamber Assembly
   T. Mattstedt, F. Haidinger, P. Luger and H. Linner, Astrium Gmbh Space Infrastrure Propulsion Division, Munich, Germany

3. AIAA 2002-4007 : The VINCI hydrogen turbopump development status
   P. Alliot - N. Marchal - B. Goirand, Snecma Moteurs - C. Bernard-Lépine, CNES

4. AIAA 2004-3530

Development Status of the VINCI engine for the Ariane 5 upper stage
P.Alliot – F. Lassoudière - J-F. Delange (Snecma Moteurs) - J-M. Ruault (CNES)

5. AIAA 2005-3755
Development Status of the VINCI engine for the Ariane 5 upper stage
P.Alliot – F. Lassoudière – C.Fiorentino (Snecma Moteurs) - J-M. Ruault (CNES)

6. AIAA 2006-4901
Results of the VINCI engine first test campaign.
P.Alliot – F. Lassoudière – C.Fiorentino (Snecma Moteurs) - J-M. Bahu (CNES)

7. IAC-08-C4.1.9 Technological readiness of the VINCI expander engine - Ph. James, C. Fiorentino, P. Caisso (Snecma, Vernon, France) - J.N. Caruana (ESA HQ, France) - J.M. Bahu (CNES Launchers Directorate, Evry, France)