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VINCI®, THE EUROPEAN REFERENCE FOR ARIANE 6 UPPER STAGE CRYOGENIC PROPULSIVE SYSTEM

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The intent of this publication is to provide an overview of the development of the VINCI® engine over the period 2014–2015. The VINCI® engine is an upper stage, cryogenic expander cycle engine. It combines 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 such as the HM7 and the VULCAIN®. In addition, its high performance and reliability, its restart and throttle capability offer potential applications on various future launcher upper stages as well as orbital spacecraft. At the end of 2014, the VINCI® successfully passed the Critical Design Review that was held after the major subsystem (combustion chamber, fuel and oxygen turbopump) had passed their own Critical Design Review all along the second half of 2014. In December, a Ministerial Conference at government level gave priority to the Ariane 6 program as Europe future launcher. In the framework of this decision, VINCI® was confirmed as the engine to equip Ariane 6 cryogenic upper stage engine. This publication shows how the VINCI development is progressing toward qualification, and also how the requirements of the new Ariane 6 configuration taken into account, i. e., offering new opportunities to the launch system and managing the new constraints. Moreover, the authors capitalize on the development already achieved for the evolution of Ariane 5. In parallel to completing the engine development and qualification, the configuration and the equipment of the propulsive system for Ariane 6 such as the components of the pressurization and helium command systems, board to ground coupling equipment, are being defined.

1 INTRODUCTION

The VINCI® engine is a 180-kilonewton restartable upper stage cryogenic engine using the expander cycle (Fig. 1). 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 VINCI® 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). From 2009 until 2014, VINCI® was developed as the upper stage propulsion system for the next evolution of the Ariane 5 launcher developed by Airbus Defence & Space as launcher prime contractor. VINCI® is currently the reference engine of the Ariane 6 launcher family upper stage (Fig. 2).

Besides offering the flexibility required to comply with a large array of missions, the restart capability of the VINCI® is also an answer to the need of the new legal requirements concerning avoidance and reduction of space debris.

The engine hot fire tests are currently performed at DLR P4.1 test facility (Lampoldshausen, Germany) and will be conducted both in DLR and Snecma (PF52 engine test cell under finalization) starting in the fall of 2015 in order to shorten the development schedule and to qualify the future production phase test stand for engine acceptance.

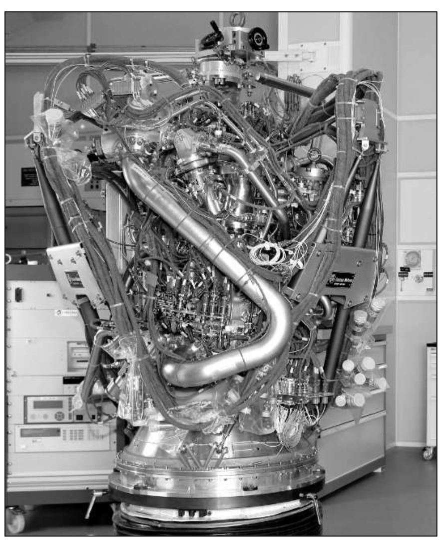

Figure 1 Side view of the engine in the assembly hall

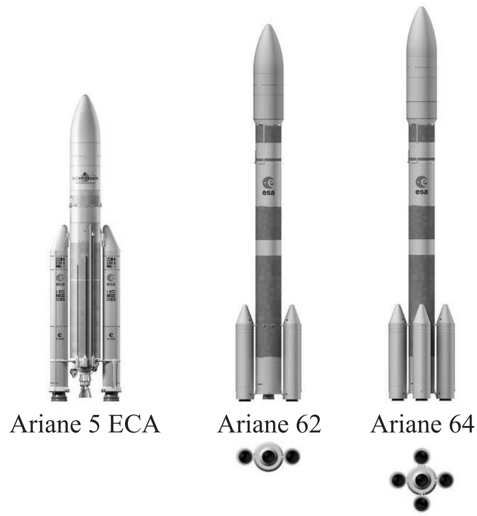

Figure 2 The two configurations of the Ariane 6 launcher

2 ENGINE ARCHITECTURE AND SPECIFICATION

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, is designed to meet the goal of reliability, simplicity, and low recurring cost. The engine flow schematic is shown in Fig. 3.

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 (NE) was avoided in order to reduce cost and number of fluid interfaces. In Fig. 4, the chamber is shown during engine assembly prior to power pack assembly

The engine has two separate turbopumps mounted close to one another in a "power pack" kit as shown in Fig. 5. Turbines are set "in series" and a set of two by-pass valves are used to adjust their flow rates. This set allows tuning the engine operating point in terms of thrust and mixture ratio.

Both turbopumps have integral inducers which lead to low net positive suction pressure (NPSP) with the objective to avoid the use of boost pump.

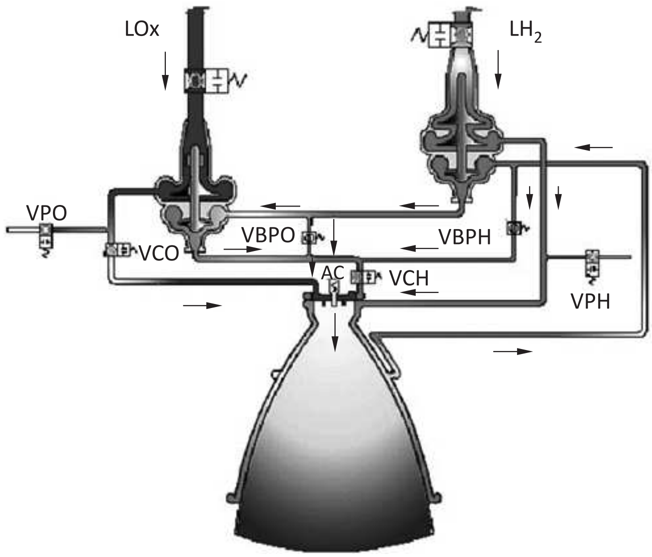

Figure 3 VINCI® flow schematic: VPO — oxygen purge valve; VCO — oxygen chamber valve; VBPO — oxygen bypass valve; VBPH — hydrogen bypass valve; VCH — hydrogen chamber valve; VPH — hydrogen purge valve; and AC — combustion chamber igniter

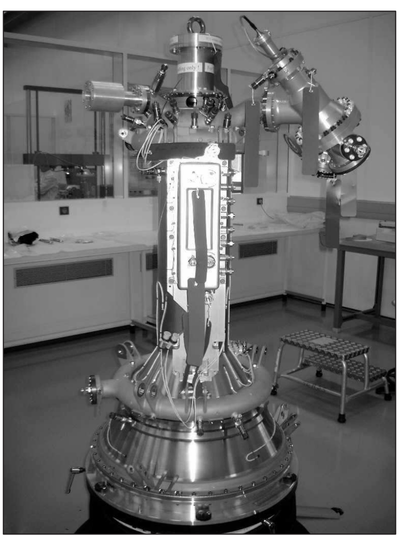

Figure 4 Thrust chamber of the first development engine with the fuel chamber valve and the solenoid valve box

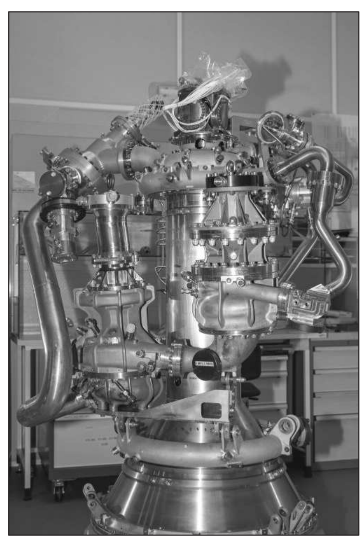

Figure 5 Liquid oxygen and liquid hydrogen turbopumps "power pack" layout

Figure 6 VINCI® NE as tested in the A5ME configuration, seen after testing

An 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 blowdown mode. Starting with engine M5, a dual spark plug ignition system was implemented to ensure complete redundancy of the system. The igniter is developed by APP (Netherlands).

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 chilldown valves with calibrated orifices, which are sized in order to allow a sufficient discharge flow during startup and shutdown transients.

In its Ariane 6 configuration, the VINCI® engine is equipped with a fixed radiative composite nozzle derived from the deployable nozzle previously tested for the Ariane 5ME configuration (Fig. 6).

At full thrust, the VINCI® is designed to operate in a domain centered around a nominal thrust equal to 180 kN and a large range of mixture ratio, typically MR = 5.7/6.2. It is also designed to operate at a low thrust level equal to 130 kN. This dual operating mode was selected in order to optimize performance. In a typical mission, the first main boost is performed in two successive steps of 180 kN first, then 130 kN. The subsequent restart boosts are performed at 130 kN.

3 SUMMARY OF THE ENGINE DEVELOPMENT RATIONALE

The VINCI® engine development up to Engine qualification is organized in three main phases:

(1) the Preliminary Definition Phase, concluded by a Preliminary Design Review (PDR) that authorized entering the Detailed Definition Phase and freezing the Engine specification; this phase was successfully passed with a complementary PDR held in November 2010;

(2) the Detailed Definition and design adjustment Phase, concluded by the critical design review (CDR) that took place in November 2014 after completion of the subsystem critical design reviews in the second half of 2014. This CDR was based on a complete verification of the design definition be used for the qualification engines; and

(3) the Ground Qualification Phase, corresponding to the qualification tests of the equipments and engine to be concluded by the qualification review.

The overall development of the VINCI® engine aims at an Engine qualification in 2017.

In conjunction with the engine development, the propulsive system functions and hardware such as propellant feed lines, tank pressurization, and helium command system are developed by Snecma with the goal of ensuring optimized interfaces between the engine and the propulsive system.

The VINCI® engine development relies on multiple test campaigns and engineering justification loops.

M1 and its refurbished configuration, M1B and M1C, M2, and M2R were the first engines to be tested. These test campaigns demonstrated a reliable steady state and transient behavior of the engine and contributed to evaluate different types of chilldown.

Two engines M3 and M4 designated as "design adjustment engines" served as a bridge between the early development engines and the final engine design configuration. They demonstrated the engine maturity through several tests campaigns in 2010 and 2011.

Later on, the detailed definition and design adjustment phase was supported by the M4R and M5 test campaigns focused on the determination of design margins. They served as the basis for the CDR and allowed freezing the configuration for the qualification. The M4–M4R campaigns took place over the period 2012–2013 and the M5 campaign started in 2014.

One major axis of this development phase is the assessment of the restart capability. The implementation of 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.

The main objectives of CDR that was held at the end of 2014 were to validate the detailed design of the engine and its industrialization, i. e., its adaptation to production requirements and to agree on the qualification plan. The results of the M4 and M5 test campaigns were the basis of this review.

The Qualification test plan incorporates objectives related to margin demonstration based on operation within and beyond the flight domain and objectives related to endurance in the flight domain.

The content of the functional and mechanical justification files was also examined at the CDR.

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 engine simulation models can be mentioned:

– Functional steady state model;
– Functional transient model;
– Chill-down model;
– Mechanical model to simulate the engine dynamic behavior, including a mode shape characterization, and to provide loads at subsystem interfaces; and
– Thermal model to provide the engine thermal map in all flight phases (among them, the coast phases) or in test bench conditions.

A comparison between tests results and analytical prediction leading to possible model adjustment and consolidation was performed prior to the CDR in each area, functional, mechanical, and thermal engineering.

In 2015, additional development tests will be performed on refurbished versions of engine M4 and M5 in order to test late subsystem modification, to incorporate Ariane 6 objectives, to operate the engine at the modified P4.1 test cell configuration and the new PF52 test cell.

Finally, VINCI® engine qualification phase will rely on 4 engines test campaigns:

– M6 and M7 dedicated to Subsystem qualification with operation around the subsystem flight domains; and
– Q1 and Q2 dedicated to Engine qualification with endurance demonstration in the flight domain.

These test campaigns will be performed simultaneously at DLR P4.1 test facility (Lampoldshausen, Germany) and Snecma PF52 test facility (Vernon, France).

4 ENGINE TEST FACILITIES

The engine hot-firing tests are currently 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, with or without NE. 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 feedlines closely approximate the impedance of real upper stage lines through the use of a buffer tank during the startup transient on both the hydrogen and oxygen side. The chilldown line flow resistance and downstream pressure boundary conditions are also representative of real stage lines.

Modifications of the test bench with the objective of better representing the flight configuration are being implemented in 2015. They include the representation of real stage feedlines.

Figures 7 and 8 show a view of engine M5 in the test cell and M2 hot fired.

Over the period 2013–2014, the design and construction of the test cell devoted to future production acceptance tests were continued at the PF52 test bench. The test bench is designed with the goal of reducing the duration of the acceptance process without compromising the quality of the engine tuning and the contribution to reliability brought by the acceptance test. The PF52 test

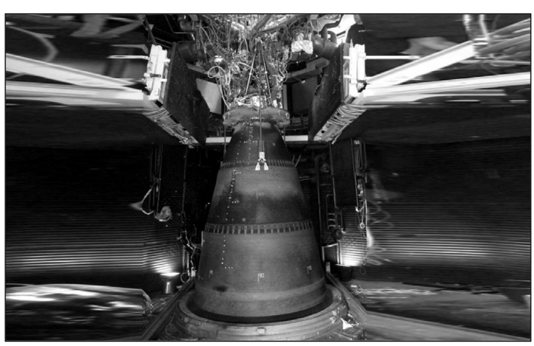

Figure 7 View of the M5 engine in P4.1 test cell

Figure 8 View of the engine in operation with the upper part of the nozzle

cell is also used for the qualification test campaign and will start being operated with a VINCI® engine in 2015.

5 HIGHLIGHTS OF THE ENGINE FIRST FOUR TEST CAMPAIGNS

From 2005 to 2011, three engines, M1, M2, and M3, were tested. These test campaigns 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. The M3 test campaign was the longest one with a total of 6287-second cumulated duration and 13 ignitions. During the M3 campaign, throttling at very low thrust level was successfully performed with successive operation at 100, 61, 43, and 27 kN. The M4 and M4R test campaigns took place in 2011 and 2012. Their main objectives were the following:

- to maturate the engine definition by incorporating modifications aimed at improving the subsystem robustness;
- to consolidate the knowledge of the engine operation at full and reduced thrust level; and
- to incorporate modifications with the goal of obtaining an easier and faster engine production.

The detailed description of the results obtained with these first four engines is contained in previous publications [1–3].

6 THE M5 TEST CAMPAIGN

The M5 engine is the last "development" engine before entering the qualification phase and, therefore, the M5 test campaign is focused on:

- identifying engine margins such as NPSP margins. Similarly to the M4 test campaign, several sequences of ramping down the inlet propellant pressure on both sides are performed in order to confirm the engine suction performance;
- characterizing design margins with the use of a liquid hydrogen (LH_2) turbopump with geometrical parameters at the limit of the manufacturing tolerance interval;
- demonstrating robustness of the startup and shutdown sequences with respect to different thermal environment;
- incorporating latest modifications to further improve the engine reliability and the design robustness such as a fully redundant ignition system with dual spark plugs; and
- simplifying engine manufacturing and assembly. One example is the design of the fluid circuit between the exit of the fuel turbopump and the inlet of the regenerative circuit. The branching toward the purge/exhaust line and the regenerative circuit upstream filter were merged in a single "additive manufacturing" part.

Prior to being fire tested, engine M5 had been submitted to the environmental tests described in order to characterize its dynamic behavior. The M5 test campaign started in October 2013 and was completed by summer 2014.

During the first 10 tests of this campaign, the engine future acceptance testing and flight reference profile were tested. The limit (i. e., flight operational) domain and extreme domain of the engine were largely explored.

The thrust was varied within the flight domain, below and above the nominal values of 180 and 130 kN.

As part of the M5 campaign, the M5 engine was equipped with the latest design of the deployable NE corresponding to the Ariane 5ME configuration and three repeated nozzle deployments in vacuum were successfully performed. Similarly to the M4–M4R tests, most of the M5 tests were multiple boosts. For instance, as shown in Fig. 9, 4 boosts were achieved on test M5-9 and M5-10, representing a nominal flight comprising the first 200-second boost, followed by three 15-second boosts, thus confirming VINCI® engine capability of performing multiple ignition missions.

A "design of experiment" approach on transient sequence was implemented to freeze the sequence for the first and subsequent boosts with "hot" and "cold" transient testing.

Several tests with Helium injection to simulate the Pogo Suppression Device effect were performed.

At the completion of the M5 test campaign extension, the VINCI® engine had cumulated 21 534 s of operating duration through 91 tests performed at P4.1 which included multiboost tests. The contribution of the latest major test campaigns in terms of duration and number of tests was:

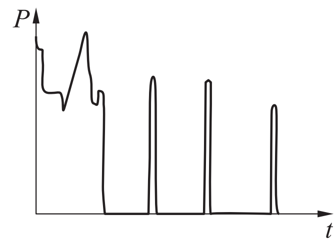

Figure 9 Chamber pressure illustrating the 4 boosts performed on M5-10

M3: 6286 s of operation in 13 boosts including 2 reboosts and 3 tests with full NE and one test with maximum duration of 730 s;

M4: 2747 s of operation in 9 boost including 3 reboosts;

M4R: 1840 s of operation in 11 boost including 3 reboosts; and

M5: 5987 s of operation in 23 tests representing a total of 33 individual boosts.

Two additional test campaigns with refurbished versions of M4 and M5 (designated M4R2 and M5R) are planned for the last quarter of 2015. They will allow testing new thermodynamic conditions at engine inlet as a result of the Ariane 6 requirements.

The M4R2 firing test campaign will take place at the new VINCI® test cell PF52 in Vernon (France).

This campaign will contribute to the new bench acceptance phase and also to PF52 characterization with respect to bench configuration impacts on engine operation: characterization of the operation at atmospheric pressure, impact of the engine horizontal position compared to the vertical position at P4.1 (Fig. 10).

The PF52 will be used in the production phase for VINCI® acceptance tests; therefore, the M4R2 tests will contribute to adjust the acceptance test profile and process. Operation in the flight domain and the extreme domain are also foreseen during M4R2, as well as the exploration of Ariane 6 interface conditions between stage and engine and their effect on engine operation with warmer propellant tested on both the liquid oxygen (LOx) and LH_2 sides.

The M5R campaign will start in October 2015 at P4.1 (Germany), the engine operating in vacuum conditions. Similarly to M4R2, it will allow to test new thermodynamic conditions at engine inlet as results of Ariane 6 requirements. Multiboosts operations are also foreseen, and one of the major objectives is to

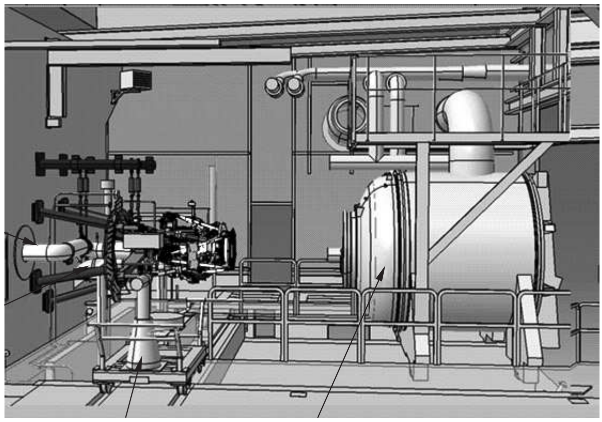

Figure 10 View of the PF52 test cell

confirm the robustness of the reference transient sequence for various Ariane 6 conditions. Another major objective of the M5R campaign is to test the new oxygen turbopump Dynamic Seal Package (DSP) developed by AVIO with modifications improving the DSP endurance capability and tolerance to accidental pollution.

7 MAIN ENGINE ARCHITECTURE EVOLUTION FOR ARIANE 6

The main engine architecture evolution for the VINCI® engine in the Ariane 6 new context concerns NE. As the foreseen Ariane 6 facilities should not be constrained any more for the upper stage integration, it is proposed to suppress the NE Deployment Device to gain in robustness and global operating cost. In the same way, it is proposed to remove the third part of the NE (C Cone, see Fig. 11) so as:

- to allow a significant engine mass and cost reduction;
- to keep the resulting loss of specific impulse compatible with Ariane 6 expected performance; and
- to increase the engine robustness with regards to NE deployment and dynamic loads of Solid Rocket Motor (SRM) and Main Cryogenic Stage (MCS) boosted phases.

Figure 11 Engine configuration artist view for A5ME and for Ariane 6

8 OTHER PROPULSIVE FUNCTIONS

The engineering of the propulsive functions, i.e., pressurization, helium command, and ground-launcher interface relies on the developments of equipments initiated with the Ariane 5 evolution program. They are updated in compliance with the Ariane 6 requirements.

One of the major modifications to be implemented in the Ariane 6 framework will be the introduction of new board to ground coupling equipments.

9 CONCLUDING REMARKS

The VINCI®, as a high-performance cryogenic reignitable upper stage engine using the expander cycle, is a key element for the future Ariane 6 European launcher.

From 2005 to 2012, the first engine test campaigns relying on four engines and their refurbishments, M1, M2, M2R, M3, and M4, 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.

Later on, the M4R and M5 test campaigns have shown the maturity of the VINCI® engine design and served as a basis for the CDR that was successfully completed at the end of 2014.

After implementing test bench modification at P4.1 with the objective of better representing the flight configuration, starting operating the VINCI® engine at the PF52 test cell and performing some additional development tests on these two benches, the test campaigns of the qualification phase will be initiated aiming at a qualification review planned for 2017.

As a summary, for Ariane 6, the reference for the upper stage is VINCI® engine "as it is already developed for A5ME," except:

- higher boost duration (due to higher propellant loading, especially for A64 configuration);
- "warm LOx" behavior (due to separated tanks stage layout instead of A5ME "common tank bulkhead" cold LOx behavior);
- NE without Deployment System / NE without C Cone (cost reduction, mechanical margin);
- new ground board interfaces (Cost reduction and launcher availability); and
- improved chilling down, lower duration and consumption (performance increase for multiboost missions).

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