VINCI Engine Composite Nozzle Extension Full Scale Altitude Simulation Testing Achievements

Thierry PICHON[1], Hervé COPERET[2] and Xavier ZORRILLA[3]
Snecma Propulsion Solide, Safran Group, Le Haillan, France
thierry.pichon@snecma.fr
herve.coperet@snecma.fr
xavier.zorrilla@snecma.fr

Abstract

A high Isp cryogenic upper stage engine with a thrust of 180 kN and restart capability, named Vinci is being developed in Europe, first managed by the Centre National d'Etudes Spatiales (CNES), the French space agency, by delegation of the European Space Agency, until 2005, and then as a demonstrator phase from 2006 to 2008, under ESA responsibility in the frame of the Future Launcher Preparatory Programme (FLPP).

Today, as a result of the decisions taken during the Ministerial Conference held in late 2008, the Vinci cryogenic re-ignitable upper stage engine development and qualification activities have been re-initiated, with a scheduled split in 2 phases and covering the period from 2009 up to 2015:

- a development phase 1 from early 2009 up to late 2011, reaching a status where sub-system CDRs should be ready to be held,
- a development phase 2 from early 2012 up to late 2015 from the CDR up to the qualification and first flight of the engine.
-

Among the main components developed for the engine is a large C-C/SiC and C-C radiative nozzle extension (NE) which channels the combustion gas flow, sustains the thrust and provides the highest possible Isp. To lower the mass and the height of the launcher a deployable radiative Nozzle Extension has been designed, which reduces the inter-stage height and efficiently uses the available space. This deployable extension is to be deployed before ignition of the engine.

The first ground firing tests have been undertaken during the demonstrator phase, during which full scale altitude simulation firing of the fixed forward NE1A cone has been successfully performed at the DLR test bench P4.1. During these tests nearly three life durations have been demonstrated, and the main achievements will be described in the first section of this paper.

The complete NE1 nozzle extension, refurbished following the previous tests, has been delivered to the DLR P4.1 test facility for integration onto the M3 engine, where the first firing tests with the complete deployed nozzle extension were performed late in 2010. A description of the NE1 test firing configurations, the performed test conditions, and preliminary nozzle extension related test results of this European first time achievement, will be provided in the second section of this paper.

[1] Programme Manager, High Temperature Composites for Space Applications
[2] Project Manager, Vinci Nozzle Extension Development
[3] Design Lead Engineer, Composite Nozzle Extensions

1 Vinci Nozzle Extension Development Logic

The Vinci Nozzle Extension Development restarted after a three year period in 2006-2008 during which Demonstrations activates were performed after the initial development phase from 2001 to 2005. During the 2006-2008 demonstrator phase, a first complete full scale nozzle extension called NE1 was manufactured. This nozzle extension was also the first one to be tested both in dynamic environment, and in simulated altitude firing. After these first tests, NE1 remained available for further testing in the frame of the development phase re-start.

The overall logic followed in this new development phase is depicted in Figure 1 hereunder. In this logic, NE1 is to be tested during the M3 test campaign for further assessment of the ability of the NE to survive a full limit life cycle mission, and also to verify the thermal specification. Additional secondary objectives of the M3 test campaign related to the NE are to demonstrate the four lifetimes requested in the specification with the fixed cone, to verify the new oxidation protection coating on the extendible section, and to verify the compliance of the design with start-up and shutdown transient loads. Additional testing in more severe conditions will also be performed in the frame of the following M4 test campaign on the same nozzle extension. In parallel, updated load specifications will be analysed in order to prepare a complimentary preliminary design review in the end of 2011 timeframe.

At the same time a second nozzle extension NE2 is manufactured which will be delivered and used in following test campaigns, including flight level dynamic testing, followed by a third nozzle extension NE3. A second set of updated load specifications will then be available and will be used for the final design and justification of the nozzle extension to be validated at the CDR in end 2013. For the final qualification step after the CDR, two qualification nozzle extensions NE4 and NEQ will be used in qualification level testing, both in dynamic environment and simulated altitude testing.

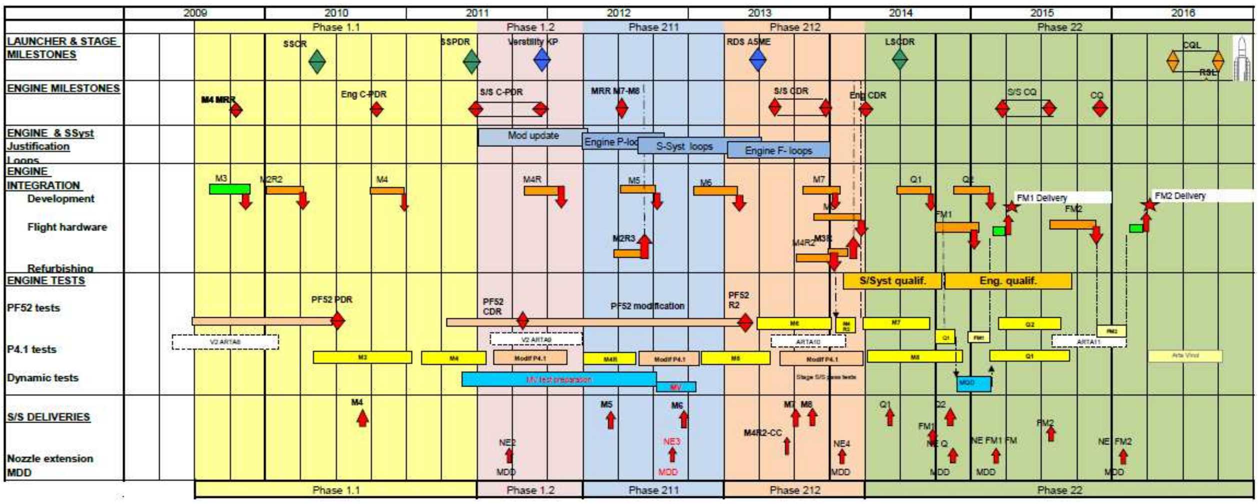


Figure 1 : Vinci engine overall logic

2 Vinci Nozzle Extension Design

The Vinci Nozzle Extension is composed of a set of three cones, each one made essentially of high temperature composite materials:

- one cone is the fixed part which is connected during on-ground assembly operations by a bolted flange to the metallic combustion chamber on one hand and with metallic fasteners to the Deployment Mechanism on the other hand,
- the two other cones are assembled also on ground (field joint) to form the extendible part of the nozzle extension that is latched to the end of the static part during flight (flight joint) before engine ignition.

The following Table 1 lists the different items constituting the Nozzle Extension:

	Items
Fixed part	Bare C/C - SiC A cone
	Latching system to connect A cone to the extendible part. C/C fingers, ceramic bonding and screws
	Fixed brackets assemblies: Three fixed metallic brackets , Bonding and screws
	Deployment shock reduction device: bumper
Extendible part	Oxidation protection coated C/C B and C cones
	Latching system to assemble B and C cones in one part. C/C fingers, ceramic bonding, screws and elastic spring
	Translating brackets assemblies: Three translating brackets, Bonding and screws

Table 1: Nozzle Extension Constituting Items

The following Figure 2 shows the location of each item:

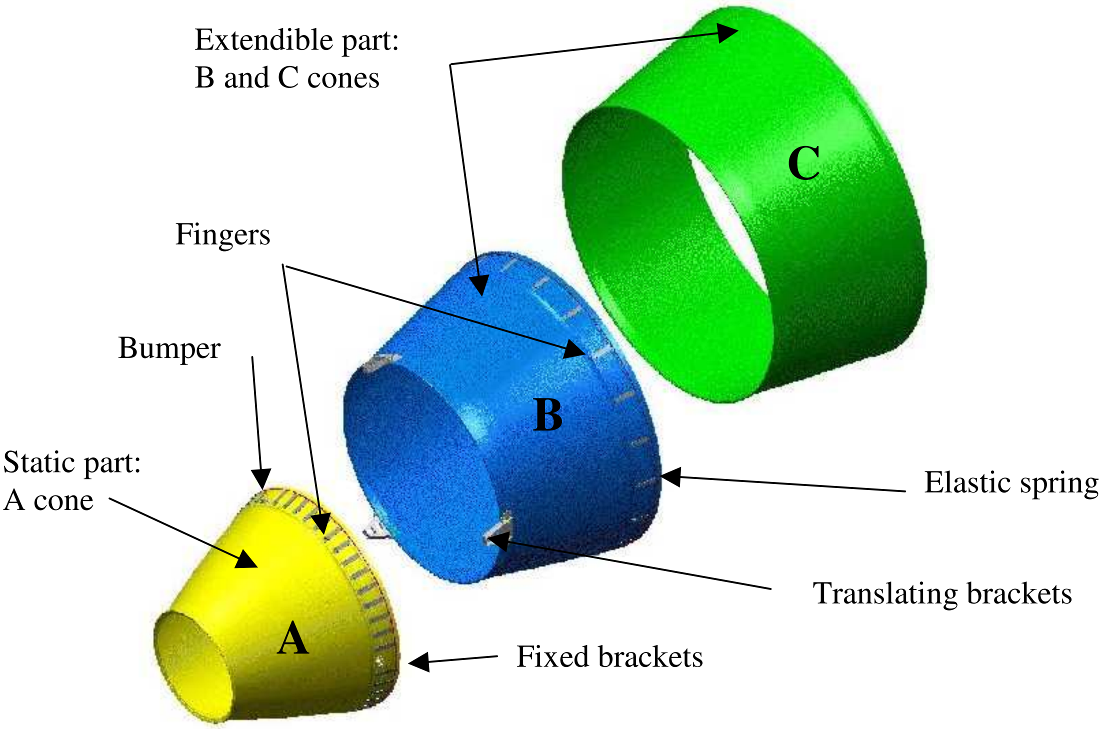


Figure 2: Nozzle Extension Exploded View

The main dimensions of the nozzle extension in deployed configuration are presented in Figure 3 hereunder.

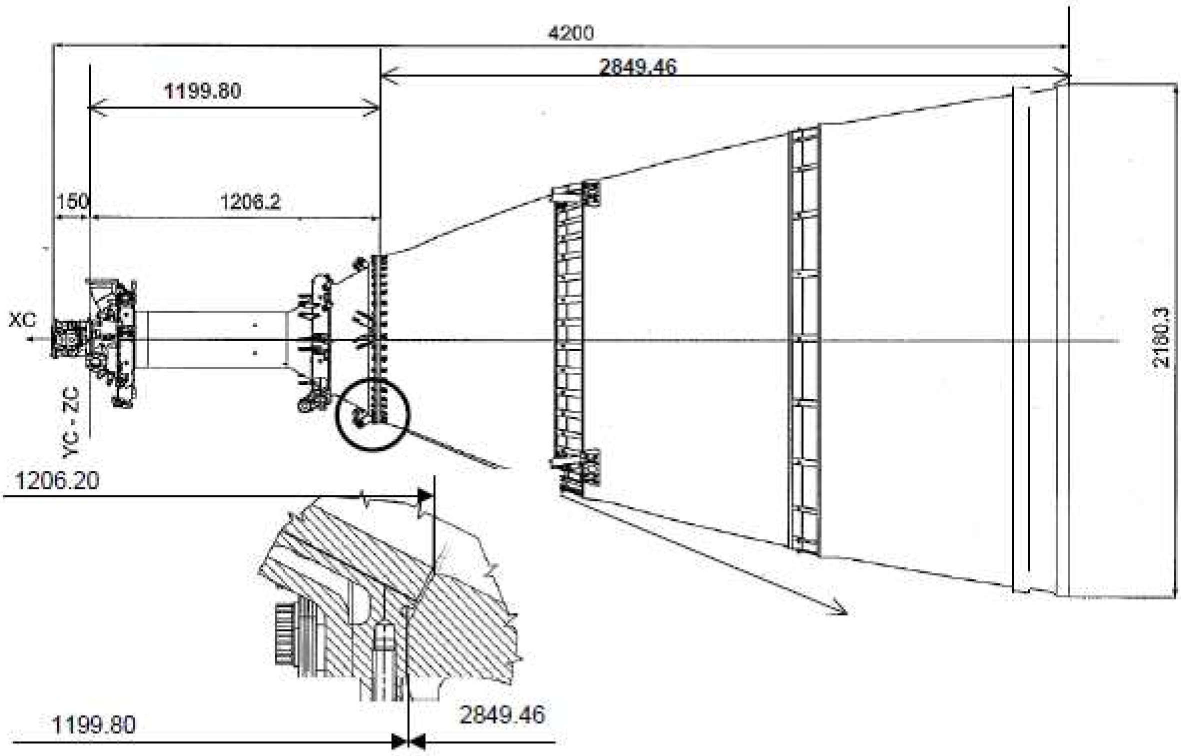


Figure 3 : Vinci nozzle extension overall dimensions

The latching system allows to connect the cones together in a manner which allows to transfer the loads from one cone to the other and up to the thrust chamber, in particular the thrust of the engine during firing operations. It is worth noting that this attachment system is reversible, by simply pressing simultaneously on all the fingers to unlatch the cones. The advantage of this system is that it allows easy access to the engine for eventual in-stage operations, and also allow multiple checks of the deployment system. A bumper or spring between the cones allow to dampen the shocks during first stage operation and during the final steps of the deployment itself. Figure 4 below details the principle of the latching system.

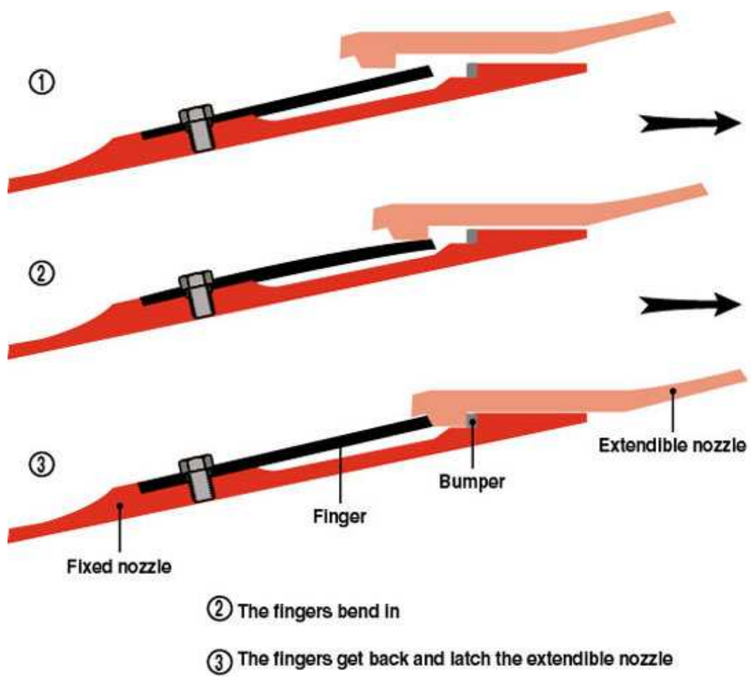


Figure 4 : Latching System Principle

3 Vinci Nozzle Extension Test Bench Loads Justification

3.1 Test bench configuration

The test bench that is used for altitude simulation testing is the P4.1 installed in DLR Lampoldshausen. It is a new test bench that has been designed and built specifically for the Vinci engine development tests. The general configuration of the test bench is described in Figure 5 hereunder.

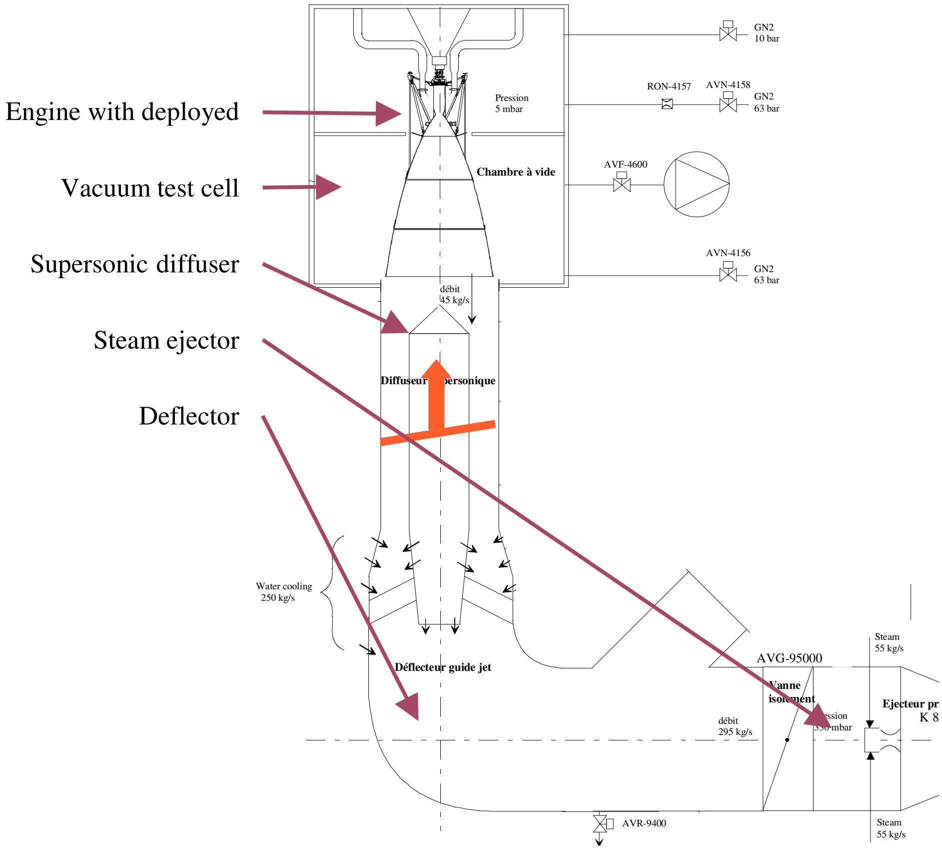


Figure 5 : P4.1 test bench configuration

During the shutdown phase, the blow back pressure that moves back up the supersonic diffuser leads to asymmetrical loads on the nozzle extension due to differences in pressure between the inside and the outside of the nozzle, combined with differences in pressure between two opposite sides of the part. To limit the resulting loads and displacements which can be very severe, a Displacement Limitation Device (DLD) is implemented at the aft end of the nozzle extension

This Displacement Limitation Device consists in a floating ring, placed around the aft ground stiffener of C cone, and which can slide on a support fixed to the cell floor of the test bench. This floating ring allows limited nozzle/engine movement while at the same time preventing excessive loads through the means of radial stoppers. In addition, the system also provides dynamic damping to the reaction of these highly transient loads. A conceptual view of this DLD placed around the nozzle extension is depicted in Figure 6 below.

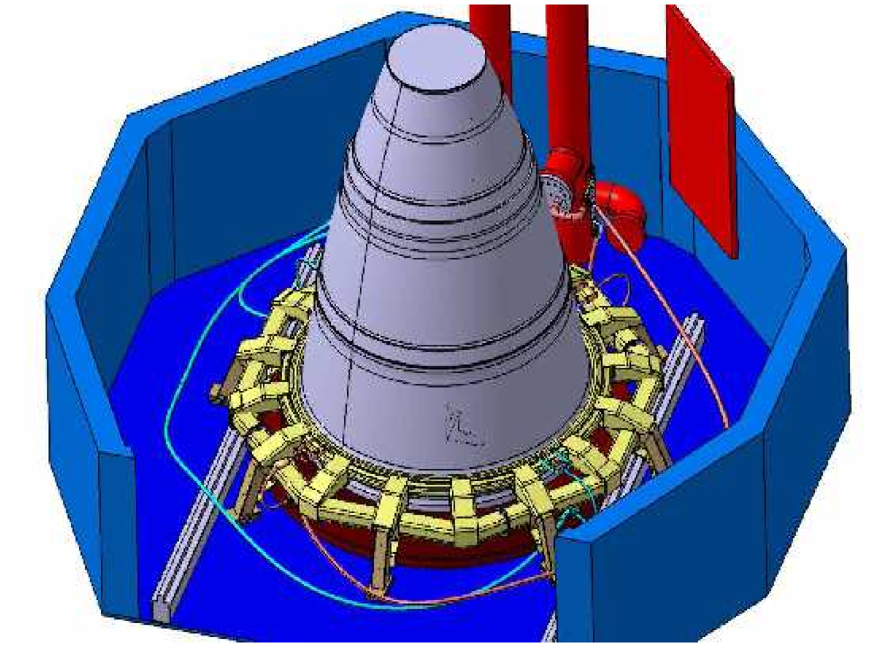


Figure 6 : Displacement Limitation Device

3.2 Transient shut-down load cases

In addition to the flight loads, the nozzle extension has to sustain altitude simulation test bench transient start-up and shut-down loads. These transient loads have been modelled in two configurations of side-loads that represent the most severe shut-down cases : a nominal shutdown dissymmetric load-case and an emergency shutdown dissymmetric load-case.

The pressure applied for the nominal dissymmetric load-case is presented on Figure 7 hereunder. The wall pressure Pw is the one resulting from an intermediate chamber pressure during the shut-down sequence. The counter pressure Pcounter includes a safety factor of 1.25 and the additional dynamical amplification factor of 1.2.

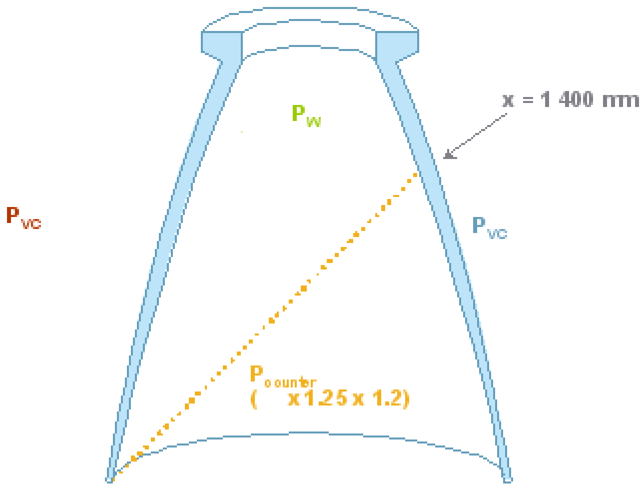


Figure 7 : Nominal shut-down dissymmetrical load case

The pressure loading for the emergency dissymmetric load-case is very similar to the nominal one, but with higher pressure levels in the chamber and the counter pressure area. The same safety factors as for the nominal load-case are applied on the counter pressure.

3.3 Model Description

The model used for this analysis is a 3D shell model, with the exception of the rigid ring of the DLD which is composed of volumetric brick elements. The overall finite elements model is composed of 58 038 nodes and 55 280 elements. It is shown on Figure 8 below. The combustion chamber is simplified in this analysis as are the actuators which are represented as springs. On the other hand, the fingers and the DLD are detailed to ensure a correct representativity of their complex behaviour.

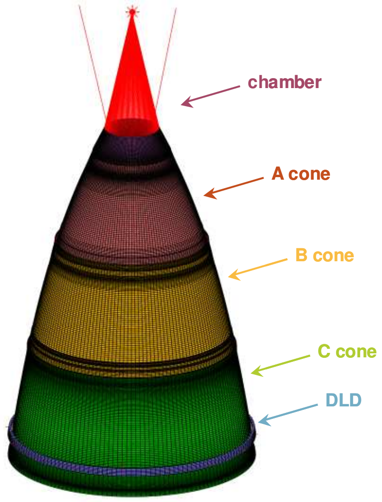


Figure 8 : Overall view of the finite element model of the nozzle extension

The temperature map issued form the thermal analysis is applied on the thermo-mechanical model, and on top of this, the pressure is applied on the model as described for the nominal load-case and for the emergency load-case. By using the characteristics of the materials at the temperatures reached at shut-down, the combined thermo-mechanical and mechanical strains are computed, from which the related margins are derived.

An example of the results obtained for the nominal dissymmetric shut-down load case is presented in the Figure 9 hereunder. The impact of the contact with the shock-absorbers is clearly noticeable as a change of slope.

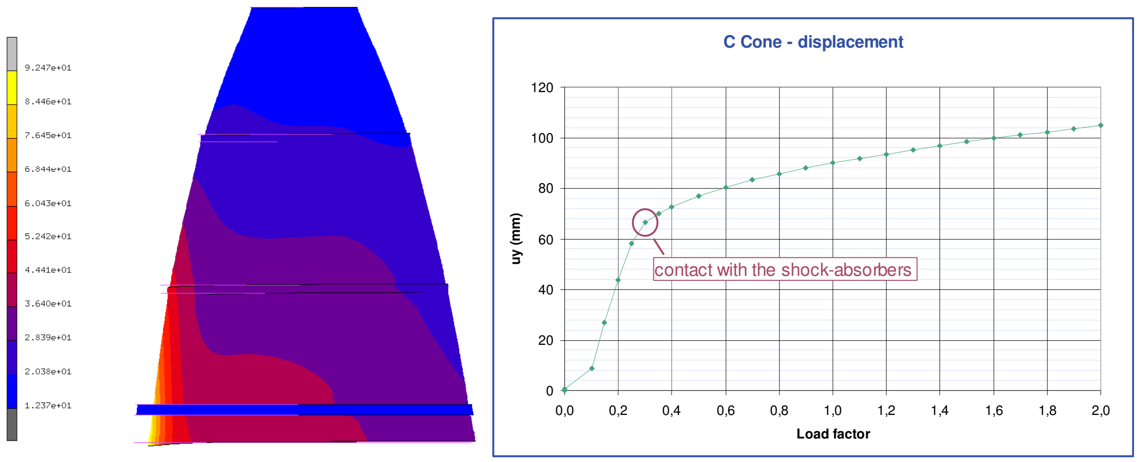


Figure 9 : Aft cone radial displacement - nominal dissymmetric load case

The analysis performed shows that the nominal load-case leads to positive margins on each part of the nozzle extension, while the emergency load-case shows a low probability of negative margin on the B/C fingers. However, this is not considered critical as the fingers can be easily exchanged, and as the risk analysis performed showed that no critical failure could occur. As such, the results confirmed that the test could be performed without risk to either the nozzle extension, the engine, or the test bench.

4 Vinci Nozzle Extension Test results

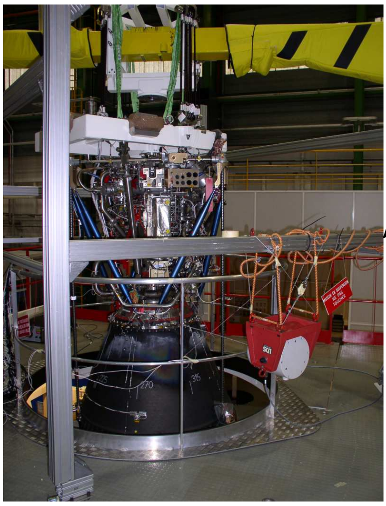
The A cone, also called NE1A, was tested at DLR Lampoldshausen during the M2R campaign in the May – June 2008 timeframe. The A cone sustained 2 fire tests of 140s and 565s, which corresponds to a complete lifetime duration. The maximum external temperature reached was approximately 1710K, measured by IR camera. This occurred during an engine operating point with a mixture ratio of roughly 6.5,and a chamber pressure in the range of 60 bar. It is worth noting that the maximum reached temperature is well below the demonstrated capability of the NE1A material, which is 2010K for 4 lifetimes, demonstrated on sample tests. The Figure 10below shows the NE1A cone during firing in the P4.1 test bench.

Figure 10 : NE1 A cone in P4.1 during firing (left) and after firing (right)

Post test visual inspections showed that it did not present any damage whatsoever, and NE1A was declared fit for following tests. The cone was refurbished to remove thermocouples and bond deployment brackets, in order to be configured for dynamic testing, in both stowed and deployed configuration. The objective of this M1D test campaign were to validate the dynamic model of the Vinci engine used to calculate and define the dimensioning loads (cf Figure 11hereunder) :

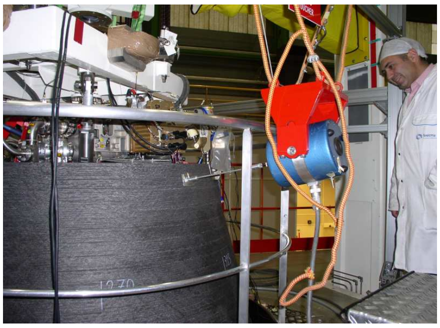
- in stowed position, representative of the configuration inside the inter-stage during Ariane 5 first stage operation,
- in deployed position, representative of the configuration during Vinci engine firing.

In addition a second objective was to test the Nozzle Extension deployment system (MDD), for different levels of efforts, ranging from 3 to 100 N applied on the NE, 30 to 150 N applied on the MDD. Finally, a hammer shock test was carried out to evaluate the evolution of the dynamic characteristics due to material ageing during test firings.



Courtesy Snecma

- Tests in the two configurations:
  - stowed (2 excitation points)
  - deployed (4 excitation points)
- Modal analysis in the frequency range [2 - 130 Hz] with 176 measurement channels
- 4 levels of force for each excitation point.



Courtesy Snecma

Figure 11 : Dynamic testing performed in Snecma Vernon

The complete NE1 nozzle extension, refurbished following the previous tests, has been delivered to the DLR P4.1 test facility for integration onto the M3 engine, where two addition tests were performed with the NE1 cone only, followed by the first firing tests with the complete deployed nozzle extension late in 2010 and early in 2011. The Figure 12 hereunder shows the complete nozzle extension in the test bench, with the three cones unlatched for assembly and accessibility purposes. They are manually deployed and latched prior to test firing.

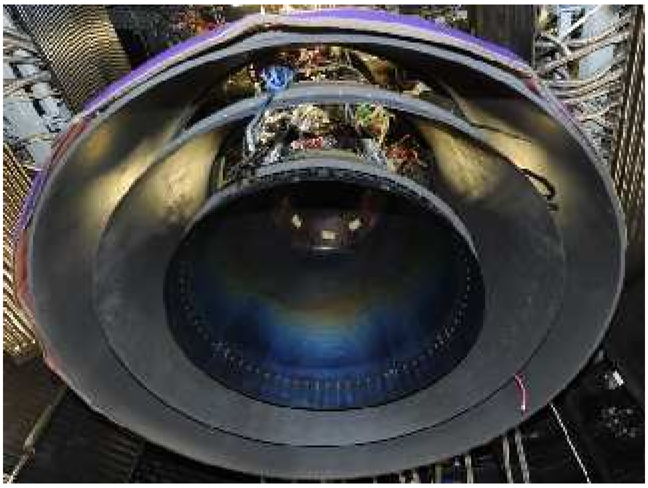


Figure 12 : Complete nozzle extension being installed in the P 4.1 test cell

Three complete test runs in simulated altitude with the full nozzle extension deployed. The engine operating points were varied during the test runs and between different runs to explore the normal operating envelope of the thrust chamber pressure and mixture ratio. The

Figure 13below shows the nozzle extension prior to testing, with its protection, and during one of the firings, as seen through one of the visualization windows.

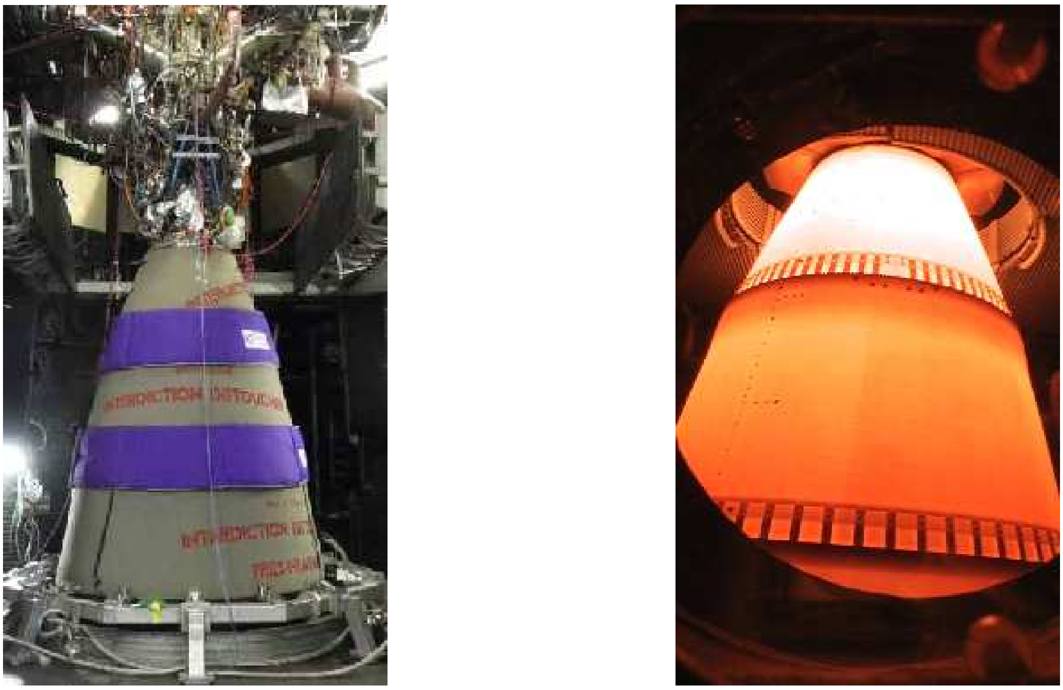


Figure 13 : Complete nozzle extension in P4.1 before firing (left) and during firing (right)

The Table 2 hereunder presents the details of each test run in terms of test duration. As can be seen, the A cone made of C/C-SiC material has sustained a total of 4075 seconds of cumulated firing, which is nearly 6 times the nominal life cycle, whereas the requirement is only 4 times the nominal life cycle. This demonstrates the robustness of the material and design of this A cone.

Date	Bench	Firing	Cone / material		
			NE1A Naxeco/SiC	NE1B Naxeco/C/A280/A210	NE1C Naxeco/C/A280/A210
14/05/2008	P4.1	M2R-03	140		
04/06/2008	P4.1	M2R-04b	565		
25/06/2010	P4.1	M3-02C	620		
29/07/2010	P4.1	M3-03	620		
09/11/2010	P4.1	M3-07B	620	620	620
23/11/2010	P4.1	M3-08	620	620	620
21/12/2010	P4.1	M3-09	690	690	690
28/01/2011	P4.1	M3-10	200		
	Cumulated duration (s)		**4075**	**1930**	**1930**
	Number of life cycles		**5.82**	**2.76**	**2.76**

Table 2 : Cumulated firing durations on NE1 nozzle extension

As for the B and C cones, made from C/C material with an oxidation protection system, it has already sustained nearly 3 times the nominal life cycle, for the same requirement of 4 times the nominal life cycle. This is quite remarkable for a component which never been tested before in such conditions.

A careful visual inspection was performed after each test, to ensure that no damage was occurring. This inspection allowed to confirm that the A cone is in excellent condition, with no noticeable wear except for a normal bluish iridescence due to the formation of atomic silica on the surfaces. The B and C cones internal surface is protected by two different types of oxidation protection systems, for experimental purposes. Both completely fulfilled their function to full satisfaction. Normal local traces of wear at the interface with the composite screws of the fingers can be observed, which are due to the step at the interface between cone and screw, but this was expected. The outside surfaces of the B and C cones are in perfect conditions, and in particular in the Displacement Limitation Device (DLD) contact area. This shows that the DLD fulfilled its role, limiting excessive displacements of the nozzle extension during the shut-down transients, while avoiding any damage to the parts.

5 Conclusion

The Vinci Nozzle Extension is now well into its development phase, with numerous successful full scale tests. The first nozzle extension that has been produced for this application has already sustained a significant number of firings, and for the A cone already has already exceeded the requirement of 4 times the nominal life cycle. Following these tests, a careful inspection has shown that the nozzle had no noticeable damage, and it is now being prepared for some additional full scale testing within the M4 test campaign, where it will be tested for the first time with the deployment mechanism attached. The successful tests already performed demonstrate the interest and robustness of the design solutions selected for the highly demanding operating conditions, and confirm the deployable nozzle extension's contribution to the overall performance of the Vinci engine.

6 References

[1] VINCI Composite Nozzle Extension Development Status
ESA – 3AF - Space Propulsion 2010
San Sebastian, 03 – 06 May 2010
T. Pichon, H. Copéret, X. Zorrilla,,
Snecma Propulsion Solide, Safran Group, Le Haillan, France