VINCI Engine Composite Nozzle Extension For Ariane 6

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ABSTRACT
The thermo-structural composite Nozzle Extension of the Ariane 6 VINCI engine is designed and manufactured by the ArianeGroup on its Le Haillan site in France. The development started in the early 2000s for Ariane 5 Mid-Life Evolution.
The Nozzle Extension is composed of two thermo-structural cones, one in Carbon/Carbon-Silicon Carbide and one in Carbon/Carbon with an oxidation protection.
The full-scale altitude simulation test qualification campaign M6 at P4.1 with the first Qualification Nozzle Extension NE3 for Ariane 6 was held successfully in 2017.
The dynamic qualification campaign EDQ at IABG with the second Qualification Nozzle Extension NEQ was held successfully mid-2017.
The second altitude simulation test qualification campaign Q1 at P4.1 with the second Qualification Nozzle Extension NEQ will span from April to June 2018, for a qualification review end of 2018.

KEYWORDS: Vinci, Ariane 6, Nozzle Extension, thermo-structural, Sepcarb-inox, Sepcarb

ABBREVIATIONS AND ACRONYMS/
A5ME Ariane 5 Mid-life Evolution
A6 Ariane 6
AOC Anti Oxidation Coating
C/C Carbon fibre and Carbon Matrix
C/C-SiC Carbon fibre and Carbon and Silicon Carbide Matrix
CDR Critical Design Review
DLR Deutsches Zentrum für Luft- und Raumfahrt
MDD Mécanisme De Déploiement (Deployment Mechanism)
NE Nozzle Extension
NE1 Nozzle Extension hw number 1
NE2 Nozzle Extension hw number 2
NE3 Nozzle Extension hw number 3
NEQ Nozzle Extension for qualification
QR Qualification Review
SRM Solid Rocket Motor
TZM Titanium Zirconium Molybdenum

1. INTRODUCTION: VINCI NOZZLE EXTENSION DEVELOPMENT LOGIC

The Vinci Nozzle Extension Development for Ariane 6 inherits from the A5ME development and was re-oriented for Ariane 6 at the end of year 2014.

The initial A5ME development phase lasted from 2001 to 2005. It was followed by the 2006-2008 demonstrator phase and by a re-start of the A5ME development phase from 2009 to 2014. The current development phase for A6 started at the end of 2014 and will continue until the first flight in 2020.
During the A5ME and the demonstrator phases, two A cones called S1 and NE3A in C/C+AOC and two full Nozzle Extensions called NE1 and NE2 were manufactured. Those Nozzle Extensions were tested in seven full-scale altitude simulation test campaigns (M2, M1C, M2R, M3, M4, M4R, M5) at the DLR test bench P4.1 and in two Engine Dynamic test campaigns (M1D and MV) in the ArianeGroup Vernon site and IABG.

The full-scale altitude simulation test campaigns allowed assessing the ability of the NE to endure the four lifetimes requested in the specification, equally verifying the thermal specification, verifying the anti-oxidation coating behaviour on the B cone, and verifying the compliance of the design with start-up and shutdown transient loads.

In early 2015, the Nozzle Extension design was adapted to the A6 configuration (fix NE with 2 cones) based on a Design To Cost approach. This allowed starting the manufacturing of the NE3 Nozzle Extension, the first one with the A6 design.
NE3 was delivered in March 2017 and successfully underwent the first hot test qualification campaign M6 at P4.1 from March to July 2017.
NEQ was delivered in June 2017 and successfully underwent the first dynamic qualification campaign EDQ at IABG from June to July 2017.
A full qualification justification loop will be performed in 2018 and the Qualification Review will be held at the end of 2018.
For the final qualification step, NEQ will be hot tested in the second hot test qualification campaign Q1.

2. A6 VINCI NOZZLE EXTENSION DESIGN

The Nozzle Extension is composed of a 2 cones set, each cone made of thermo-structural composite materials. Additional parts make the inter-cone junction and an elastomer component (spring) localized between the two cones fills the assembly gap and improves the dynamic response during the Solid Rocket Motor (SRM) flight phase. The A cone is connected to the Combustion Chamber by metallic bolts. The A cone is made of a high temperature C/C-SiC material named Naxeco® Sepcarb-inox L3.

The B cone is assembled on the A cone to constitute the fix NE. The B cone is made of a high temperature C/C material named Naxeco® Sepcarb L2 protected with AOC on the inner wall. The AOC protects the NE from oxidation due to the C/C material chemical reaction with the combustion gases at high temperature.

The two cones are held together by C/C axial stoppers that are fixed on the A cone by TZM bolts. The axial stopper C/C material is the same as the B cone material.

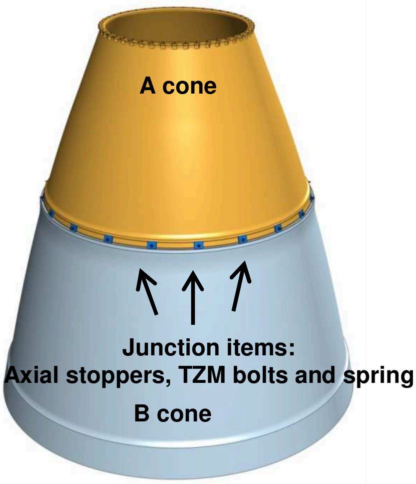

Figure 1: A6 Vinci Nozzle Extension overall view

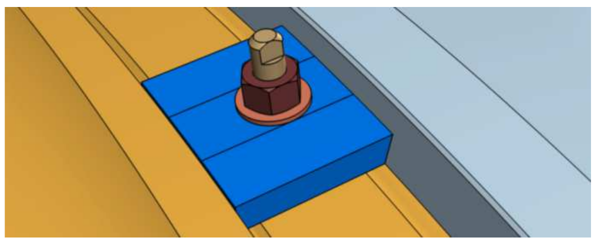

Figure 2: Axial stoppers principle

Table 1: A6 Vinci Nozzle Extension mass budget

Item	**Mass (kg)**
A cone	28
B cone+ AOC	42
Junction items: Axial stoppers, TZM bolts and spring	<1
Nozzle Extension assembled	**≈70**

3. DIFFERENCES BETWEEN THE A5ME AND THE A6 VINCI NOZZLE EXTENSIONS

On the A6 Vinci Nozzle Extension, the C cone has been removed; the NE Nozzle Extension is fixed and is no longer deployable in flight. The main differences are listed below:

Table 2: Main differences between the A5ME and the A6 vinci Nozzle Extensions

Item	**A5ME**	**A6**
Number of cones	3 (A, B, C)	2 (A, B)
Concept	A fix, B+C deployable in flight	A+B fix
Cone junction	C/C fingers and bolts	C/C axial stoppers and anti-rotation devices and TZM bolts
IF with engine	holes on the A cone flange, holes on the A cone bottom, holes on the B cone top	holes on the A cone flange
Mass	≈110 kg	≈70 kg

The A cone and B cone designs are very similar, the only difference is in the A cone thickness, the A cone to B cone junction and in the bottom part of the B cone, where there is a stiffener on the A6 design. The figure below shows the differences:

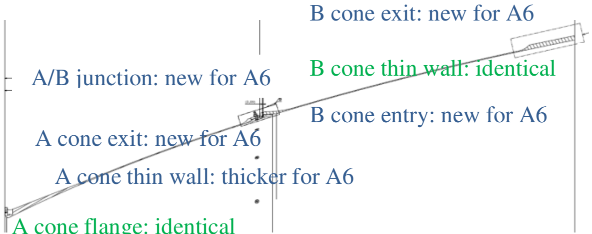

Figure 3: A and B cone comparison between A5ME and A6 Vinci Nozzle Extensions

4. VINCI NOZZLE EXTENSION TEST BENCH LOADS JUSTIFICATION

4.1. Test bench configuration

The test bench that is used for altitude simulation testing is the P4.1 installed in DLR Lampoldshausen. This test bench has been designed and built specifically for the Vinci engine development and qualification tests. The general configuration of the test bench is described in Figure 4.

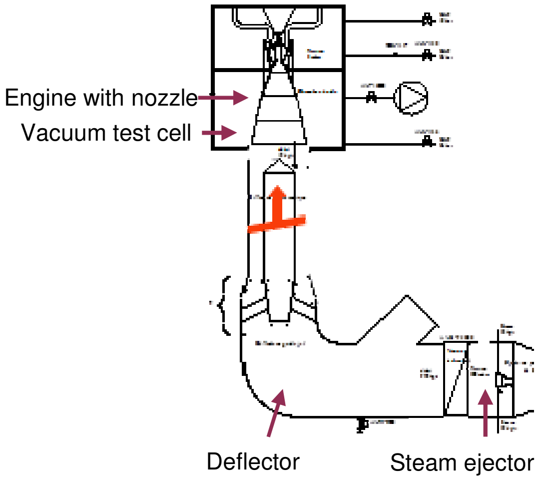

Figure 4: P4.1 test bench configuration

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 the two opposite sides of the part. To limit the resulting loads and displacements which can be very severe, a displacement limitation device was implemented at the aft end of the Nozzle Extension during the A5ME tests with full nozzle.

4.2. Transient shut-down load cases

The transient loads for the A6 configuration with only 2 cones were established and the justification of these loads was performed in 2016 for the M5R test campaign. Thanks to the removal of the C cone, the A6 side loads are less severe than the A5ME loads, which were successfully tolerated by the full A5ME Nozzle Extension.

5. VINCI NOZZLE EXTENSION TEST CAMPAIGNS

Since 2006, the A5ME configuration with 3 cones has been tested with S1, NE1 and NE2 and has successfully participated in a total of seven full-scale altitude simulation test campaigns (M2, M1C, M2R, M3, M4, M4R, M5) at the DLR test bench P4.1 in Lampoldshausen and in two Engine Dynamic test campaigns (M1D and MV) on the ArianeGroup Vernon site and at IABG Munich.

The A6 configuration with 2 cones was tested successfully in a full-scale altitude simulation test

- Firstly during the M5R campaign at P4.1 in 2016, with the retrofitted NE2 Nozzle Extension from A5ME
- Secondly during the M6 qualification campaign at P4.1 in 2017 with NE3, the first NE in A6 definition
- Thirdly at the end of the M6 qualification campaign at P4.1 in 2018 with NEQ, the second NE in A6 definition

It will also be tested for a fourth time during the Q1 campaign at P4.1 in 2018 with the NEQ, the second NE in A6 definition.

The NEQ Nozzle Extension also successfully participated in the Engine Dynamic test campaign EDQ in 2017.

5.1. M2 2006 - Full scale hot tests

The S1 cone test M2-06 was the first test of the Vinci Nozzle Extension in P4.1.
S1 was in C/C-Sic material, with a Novoltex® preform manufactured from a carbon precursor fibre.

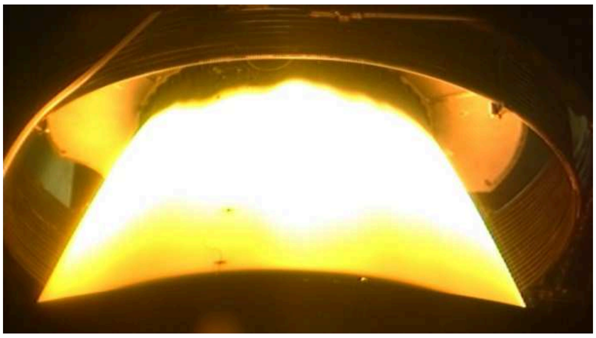

Figure 5: S1 A cone in P4.1 during M2 campaign firing - Heating phase

The test lasted 350s. Post-test inspection showed that the nozzle had several cracks around the circumference. The detailed analyses conducted after the test showed that the cracks were caused by thermo-mechanical strains above the material allowables. It was decided to use a material with higher ultimate strain allowables, from a preform manufactured from a carbon fibre, named Naxeco®.

5.2. M1C 2008 - Full scale hot tests

The cracked S1 cone was re-tested for 70s during this campaign. This allowed demonstrating that the thermo-structural material is not sensitive to crack propagation and to prepare the next test campaign with NE1A, the first A cone in Naxeco® C/C-SiC material.

5.3. M2R 2008 - Full scale hot tests

Only the NE1 A cone was tested during this altitude simulation test campaign. It withstood 2 fire tests of 140s and 565s. The maximum external temperature reached was approximately 1710K, measured by an Infra-Red (IR) camera. This temperature was reached during an engine operating point with a mixture ratio of roughly 6.5 and a chamber pressure in the range of 60 bars. 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 below shows the NE1A cone during firing in the P4.1 test bench.

Figure 6: NE1 A cone in P4.1 during M2R campaign firing - Stabilized phase

Figure 7: NE1 A cone in P4.1 after firing

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.

5.4. M1D campaign 2008 - Dynamic & Deployment

The objective of this M1D test campaign was to validate the dynamic model of the Vinci engine used to calculate and define the dimensioning loads:
- in stowed position, representative of the configuration inside the inter-stage during A5ME first stage operation (cf. Figure 8 hereunder),
- in deployed position, representative of the configuration during Vinci engine firing (cf. Figure 12 hereunder).

The modal analysis was performed in the frequency range [2-130 Hz] with 176 measurement channels, and 4 levels of force for each excitation point.

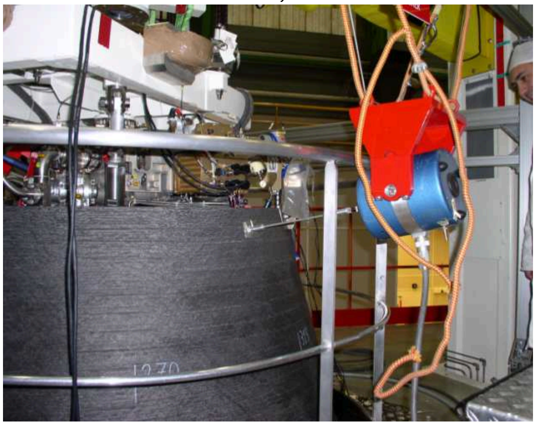

Figure 8: Dynamic testing performed in stowed condition (2 excitation points)

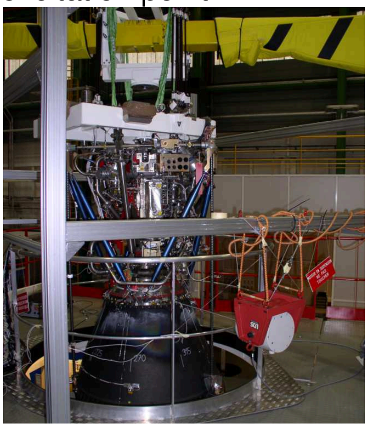

Figure 9: Dynamic testing performed in deployed configuration (4 excitation points)

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.

5.5. M3 campaign 2010/2011 - Full scale hot tests

The full NE1 Nozzle Extension, refurbished following the previous tests, was delivered to the DLR P4.1 test facility for integration onto the M3 engine, where two additional tests were performed with the NE1 A cone only, followed by the firing tests with the full deployed Nozzle Extension. The Figure 10 shows the full Nozzle Extension in the test bench, with the three cones unlatched for assembly and accessibility purposes.

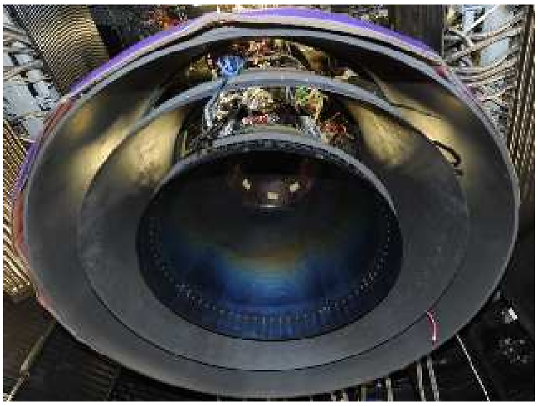

Figure 10: Full Nozzle Extension NE1 unlatched in the P 4.1 test cell

Five complete test runs were performed in simulated altitude conditions with the full Nozzle Extension manually deployed. The deployment mechanism was not installed for this campaign.

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 11 below shows the Nozzle Extension prior to testing, with its protection, and Figure 12 shows the Nozzle Extension during one of the firings.

Figure 11: Full Nozzle Extension NE1 in P4.1 before firing

Figure 12: Full Nozzle Extension NE1 in P4.1 during M3 campaign firing

5.6. M4 campaign 2011 - Full scale hot tests

The main objective of this campaign for the NE was to test it with the deployment mechanism and to perform multiple boosts. Hence, the full NE1 was submitted to 3 deployments in vacuum and cold conditions at the start of the M4 campaign followed by two complete test runs in simulated altitude, with the deployment mechanism in place, see Figure 13 below, with deployment mechanism bracket in green, blue and yellow on the image.

M4-04 test included 2 boosts.

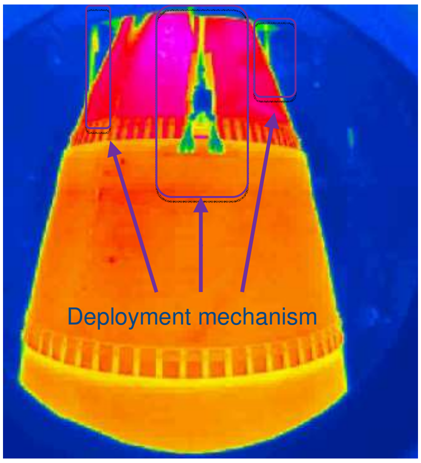

Figure 13: Full Nozzle Extension NE1 in P4.1 during M4 campaign firing

The NE1A cone made of C/C-SiC material withstood a total of 4973 seconds of cumulated firing and 11 boosts, which is more than 5 times that of the nominal A6 lifetime, while the NE1 B and C cones in C/C+AOC material withstood 2828 seconds of cumulated firing and 6 boosts.

A careful visual inspection was performed after each test, to ensure that no damages had occurred. This inspection allowed confirming that the NE1 A cone was in excellent condition, with no noticeable wear except for a normal bluish iridescence due to the formation of atomic silica on the surfaces. The NE1 B and C cones internal surface anti-oxidation protection completely fulfilled their function.

5.7. M4R campaign 2012 - Full scale hot tests

The main objectives of this campaign for the NE were to test the second development Nozzle Extension NE2, to perform emergency shut-downs, to run multiple boosts and to test the 130 kN domain. The AOC on the B and C cone was intentionally damaged (stains, scratches...), in order to start a catalogue of acceptable defects for the serial production. NE2 was tested successfully on 4 tests, including two tests with three boosts.

5.8. MV campaign 2013 – Dynamic & Deployment

The NE1 Nozzle Extension was successfully submitted to a dynamic test campaign in stowed and deployed conditions on the engine. The campaign was done at IABG in Ottobrunn, Germany.

5.9. M5 campaign 2013/2014 - Full scale hot tests

The main objectives of this campaign for the NE were to perform deployments in vacuum and cold conditions, to accumulate lifetime and boosts, and to test a demonstrator A cone in C/C+AOC instead of C/C-SiC (for Recurring Cost reduction objectives) with a new carbon fibre.

14 hot tests and 22 boosts were performed on the Nozzle Extension.

During this campaign, the NE2 A cone made of C/C-SiC material withstood a total of 2125 seconds of cumulated firing, while the B and C cones in C/C+AOC material withstood 3541 seconds of cumulated firing.

Unfortunately, the demonstrator A cone NE3A in C/C and AOC became eroded after its fourth test in the upper part of the NE, thus confirming the strong thermal solicitations of the NE and the necessity to use C/C-SiC material to withstand the thermal loads.

A careful visual inspection was performed after each test, to ensure that no damage had occurred. This inspection allowed confirming that the NE2 A cone was in excellent condition after 4 lifetimes, with no noticeable wear except for a normal bluish iridescence. The NE2 B and C cones were in very good conditions after 4430 seconds of cumulated firing duration, including in the area of intentional AOC defects. On the B cone, traces of erosion at the interface with the composite screws of the deployment system could be observed, as expected, which were due to the interface step between cone and screws.

5.10. M5R campaign 2016 - Full scale hot tests

This campaign at P4.1 used the retrofitted NE2M Nozzle Extension from A5ME, in a 2 cone configuration. The small eroded areas on the B cone were protected with AOC.
The main objectives of this campaign for the NE were to validate the hot point E2V in the extreme domain with high mixture ratio and high chamber pressure (for thermal specification anchoring), to tests the TZM bolts for the A6 junction and to prepare the following qualification campaigns in the A6 configuration.

The NE2 A cone made of C/C-SiC material withstood a total of 7945 seconds of cumulated firing and 41 boosts while the NE2 B cone in C/C+AOC material withstood 7513 seconds in 35 boosts. This is more than 8 times the nominal A6 lifetime.

5.11. M6 campaign 2017 - Full scale hot tests

This first qualification campaign from March to July 2017 had the objective to qualify the Nozzle Extension in the limit envelope, on the first A6 NE hardware NE3, including gimballing during hot firing. Tests in the extreme envelope were also performed. During this qualification campaign, NEQ underwent 7 hot tests, 12 boosts and 4390s of cumulated firing time.

Figure 14: Full Nozzle Extension NE3 in P4.1 during M6 campaign firing

The Nozzle Extension was in a very good state after this campaign.

The NE3 nozzle withstood a total of 4390 seconds of cumulated firing and 12 boosts. This is more than 4 times the nominal A6 lifetime.

5.12. EDQ campaign 2017 - Dynamic

This dynamic qualification campaign was done at IABG at engine level with the objective to qualify the engine with its Nozzle Extension wrt to the dynamic loadings, on the NE hardware NEQ. The campaign was completed in July 2017 and was successful.

Figure 15: Nozzle Extension NEQ at IABG during EDQ dynamic test campaign

5.13. Q1 campaign 2017-018 - Full scale hot tests

NEQ that has already undergone the dynamic qualification tests EDQ was equipped with thermocouples and will be submitted in this hot test campaign to a full nominal life cycle. This will be followed by tests in the extreme envelope. The campaign will be done in 2018.

6. CONCLUSION

The A6 Vinci Nozzle Extension has finished its development phase and is now in its qualification phase.

The numerous full scale hot tests (31) on the A5ME version of the NE allowed to well exceed the requirement of 4 times the A6 nominal life cycle (900 s) and 4 times the number of boosts (3) on both the A cone in C/C-SiC and the B cone in C/C+AOC.

One of the two hot test qualification campaigns has now been successfully completed for the A6 Nozzle Extension and allowed exceeding the requirement of 4 lifetimes.

The engine dynamic qualification campaign has also been successfully completed with the A6 Nozzle Extension.

The last hot test qualification campaign is still to be performed with the Nozzle Extension NEQ that has already been submitted to the engine dynamic qualification campaign.

The Qualification Review is planned at the end of 2018.