Thermostructural Composite Nozzles :Off the Shelves Breakthrough Technology to Improve Upper Stage Liquid Rocket Engine Performance

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Abstract

The need to increase the payload capacity of the current launchers drives rocket engine manufacturers to seek higher thrust level, specific impulse and thrust to weight ratio. A particularly efficient way to do this is the use of increased expansion ratio nozzle extensions for upper stage engines, and using high temperature composite materials in order to allow higher temperature material limitations, take benefit of the outstanding thermal mechanical and fatigue resistance of these materials and to decrease mass. The Carbon-Carbon composites (C-C) or the Ceramic Matrix Composites (CMC) do not require any active cooling (i.e. film cooling or dump cooling) for applications up to very high temperature (i.e. 2000 K or higher) and keep remarkable high mechanical load bearing capability although their densities remains as low as 1.4 to 2.2. This makes nozzle extensions and extendible nozzle extensions a predilection domain of application in either solid rocket motor or liquid rocket engine areas.

Up to the mid 90s, the use of composite nozzles has been limited to solid rocket motors, but recent developments led to flight qualification on the RL10 B-2 engine of the DELTA 4 upper stage and, are on the track to prepare the next ARIANE 5 ECB upper stage generation powered with the VINCI engine. Both engines are equipped with very large extendible composite nozzles developed and produced by Snecma Propulsion Solide, SAFRAN Group.

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The paper will report the significant investment Snecma has done along over 30 years in this area inherited from solid rocket motors and later on extended to liquid rocket engines. This will include material and process improvements with regard to key drivers such as reliability, reusability and cost, technological demonstrations and operational experience. It provides an up-to-date status of the demonstrations already performed on different liquid rocket engines and details all of the recent progress on technical and manufacturing performance. The manufacturing process has also been improved and simplified in order to allow the manufacturing of larger scale nozzles , at lower cost.

Finally, this paper evidences that this high temperature composite technology of Snecma Propulsion Solide is today mature, efficient and available on an industrial basis for implementation on existing or future liquid rocket engines being developed.

Introduction

For more than 35 years, Snecma Propulsion Solide has developed very advanced high temperature composite materials. At first, C-C was developed to satisfy the very demanding strategic missiles propulsion performance requirements. Then, these materials appeared very well suited for many other applications to bring advantages in performance, efficiency and affordability.

In particular, patented industrial 3D C-Cs developed allow constructions of light, robust and reliable huge nozzle extensions which, in turn, offer a terrific improvement in the Isp performance of LREs.

In the following paper a history of SPS's background in the field of high temperature composites is presented, then 3D industrial Novoltex and Naxeco® textile preform constructions are described, and finally, interest of the C-Cs using these preforms for design and manufacture of very high performance nozzle extension is presented.

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1. Snecma Propulsion Solide high temperature composites background

In the early seventies, Snecma Propulsion Solide developed Carbon-Carbon materials to improve performance of strategic ballistic missile Solid Rocket Motor applications.
Lighter than Tungsten, more resistant and less brittle than Graphite, Carbon-Carbon appeared as a promising material providing more reliability and improving performance of Solid Rocket Motor (SRM) nozzles.

An evaluation of different densification process methods for 2D carbon fabric stack up preforms was done: pitch high pressure infiltration; polymeric resin carbon precursor impregnation; Chemical Vapor Infiltration (CVI); or combination of these densification process routes. The results showed that:

- 2D Carbon-Carbon manufacturing is sensitive to delaminations and attendant high scrap rates ,
- 2D Carbon-Carbon is not adequate to sustain very high thermal and mechanical loads in the nozzle throat area because of its interlaminar shear and cross ply tensile weakness,
- Pitch densification under high pressure (up to 1000 atmospheres) and high temperature (above 700°C) allows high density and graphitizable Carbon-Carbon materials, characteristics needed for nozzle throat erosion resistance,
- Among various polymeric resin carbon precursors, Phenolic resin seems well adapted to carbon fabric impregnation and carbon fabric ply stack up construction, using similar processes for current polyester or epoxy composite materials, leading after carbonization to an hardened Carbon-Carbon billet of low density but suitable for further densification processing,
- Because of the well organized carbon microstructure deposition around the fibers, CVI densification leads to Carbon-Carbon with the highest mechanical properties. Moreover, microstructure deposition can be managed to obtain very specific thermal characteristics in connection with nature of deposited carbon microstructure: rough laminar; smooth laminar; isotopic; etc….

These results oriented the material development choices towards:

- Multidirectional performs to eradicate the delaminating weakness of 2D materials. This resulted in 4D performs which is made of carbon rods put in the diagonal directions of a cube (figure 1).
- Pitch densification combined with 4D performs to produce high performance nozzle throat components for SRM.
- 2D Involute phenolic-resin-impregnated carbon fabric followed by hardening carbonization before CVI densification to manufacture larger components as SRM exit cones (figure 1).

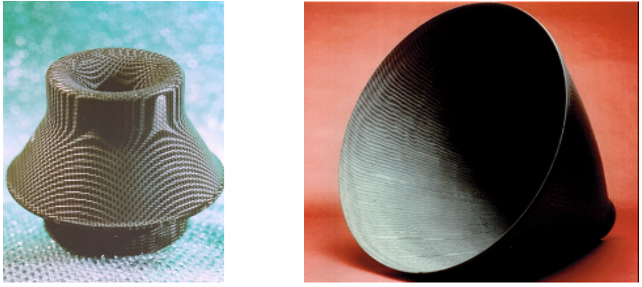


Figure 1: 4D carbon-carbon nozzle throat and 2D involute carbon-carbon exit cone

At the same time, industrial capacities were set up at Snecma Propulsion Solide to produce SRM nozzle components and satisfy the needs of Strategic Ballistic Missiles.

At the end of the seventies, aiming at the aircraft brake application (a large volume and low cost product compared to Snecma Propulsion Solide's SRM core business), an innovative 3D carbon textile perform was developed to increase the producibility, reduce manufacturing scraps, enhance production efficiency, and increase operational reliability while making an affordable Carbon-Carbon for brake discs. This innovative textile perform is dubbed Novoltex®.

Combined with CVI process, the resulting Novoltex® Carbon-Carbon quickly appeared as an industrial product using needling machines specifically developed to automatically produce Novoltex® and batched furnace loading for CVI densification managed by an automatic control system.
This material was qualified for Airbus airplane Carbon-Carbon brakes in October 1984. Production facilities were implemented in Lyon in 1985 to satisfy the large demand of Novoltex® Carbon-Carbon brake discs to be delivered to Airbus.

As part of the SAFRAN Group industrial organization within branches of activities, Novoltex® Carbon-Carbon brake disc production capacities merged within the Messier Bugatti brake and wheel manufacturer division in 1997, and another Carbon-Carbon brake disk plant was set up in Kentucky, USA, in 1999 to provide the US DoD with a domestic source. Now Messier-Bugatti USA is the US hub to satisfy US and Asian airlines customers. Now Carbon discs, wheels and brake assemblies for Airbus, Boeing and USAF are either manufactured by Messier Bugatti USA or Messier-Bugatti in France (figure 2).

Figure 2: Novoltex® carbon-carbon brake disks

In the time Novoltex® Carbon-Carbon was developed for brake applications, the performance of the material appeared of interest for SRMs, not only for large nozzle throats for which erosion is less sensitive on motor performance, but also for lightweight advanced exit cones.

First Novoltex® Carbon-Carbon exit cone was test fired successfully on a SRM in 1984, via R & T funding. Moreover, the strength and robustness of Novoltex® Carbon-Carbon allowed breakthrough in nozzle advanced design, in particular high performance extendible exit cones.

Also Novoltex® Carbon-Carbon was selected in the late eighties for the Ariane 5 SRM nozzle throat, which is of huge dimensions, around 0.9 m (3 feet) internal diameter and 100 mm (4 inches) thickness. First ground test firing was successfully performed in 1993 (figure 3).

Since 1985, a very large number of SRM test firings have been performed, all successfully, proving the remarkable adaptation of the Novoltex® C-C material for SRM nozzle applications (in particular for throats and exit cones) (figure 4).

Figure 3: Novoltex® carbon-carbon nozzle throat of Ariane 5 SRM

Figure 4: Novoltex® carbon-carbon extendible nozzle extension (two translating cones) equipping a SRM.

In the late eighties, Novoltex® Carbon-Carbon as well as Novoltex® Carbon-Silicon Carbide nozzle extensions were evaluated for the first time for LOx - LH_2 cryogenic Liquid Rocket Engine applications. A scale one Ariane upper stage HM7 engine with a Novoltex® Carbon-Silicon Carbide nozzle extension was successfully tested at simulated altitude, twice, cumulating 1650 sec of firing time, in 1989 (figure 5).

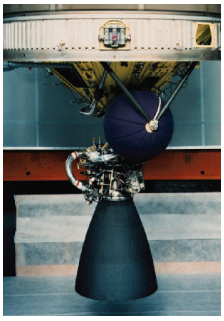


Figure 5: Novoltex® carbon-silicon carbide nozzle extension equipping a HM7 cryogenic engine

In 1995, the largest-ever designed and built Carbon-Carbon extendible nozzle, made of Novoltex® , was mated to the Pratt & Whitney Rocketdyne RL10 B-2 LOx – LH_2 Liquid Rocket Engine. This engine powers the Delta III and Delta IV launcher upper stages, providing very high Isp performance.

Weighing less than 100kg (220lbs), its main dimensions are given in the figure 6, showing the terrific capabilities of Snecma Propulsion Solide’s technology.

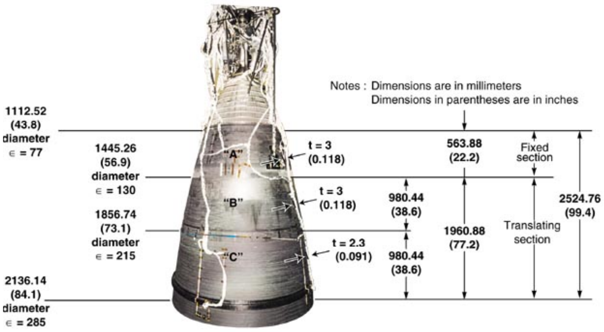


Figure 6: Key figures of the RL10 B-2 Novoltex® carbon-carbon extendible nozzle extension

Figure 7: RL10 B-2 at AEDC firing test (altitude simulation)

The first altitude simulation test was successfully performed at AEDC in 1997 (figure 7). Up today this Novoltex® C-C nozzle extension has contributed to the success of all Delta IV missions, including the Heavy version, by perfect operation in flight. Since 1995, 76 Novoltex® Carbon-Carbon RL10B-2 nozzle extensions were manufactured.

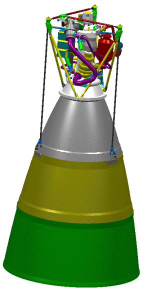
Early in this decade, an advanced 3D C-C material dubbed Naxeco® Carbon-Carbon was chosen to replace Novoltex® Carbon-Carbon nozzle components in two new major programs: P80, a 80 metric ton propellant SRM to boost Vega as the first stage of this future European small launcher; and Vinci®, an expander cycle LOx-LH_2 LRE to power a future upgrade of the Ariane 5 upper stage.

Its development was initiated in the early 90s on the basis of Novoltex® heritage and as the next generation of 3D needled preform, targeting the following improvements:

- Get higher raw material sustainability in using carbon fiber commercial grade instead of pre-oxidized (uncarbonized) PAN (Poly Acrylo Nitrile) fibers
- Reduce manufacturing cost and production cycle in simplifying and eliminating some process operations, mainly raw material complexity and the textile preform carbonization necessary to transform Novoltex® from Pre-Oxidized PAN into Carbon
- Reduce the technical risk from significant shrinkage of the Pre-Oxidized PAN preform in the carbonization process which requires prior calibration to master deformation control and maintain reproducibility
- Eliminate complex, and costly carbonization furnace investment, especially when huge dimensions are needed to manufacture large parts. As Naxeco® is already carbonized, no dedicated carbonization furnace is required.

Yet with these advantages, the main characteristics and achievements from the Novoltex® heritage are preserved with Naxeco®. Additional comparison of differences is provided in section 3.

Naxeco® Carbon-Carbon has been considered sufficiently mature to use it for the P80 Vega launch vehicle first stage nozzle throat (496mm [19.52”] internal diameter by 500mm [20”] height) and the Vinci® deployable nozzle extension whose main features are indicated in figure 8. Note that, the fixed part of the nozzle extension is attached to the regenerative combustion chamber at a low area ratio. Hence the first section of the nozzle extension has to survive very high temperatures, around 1500 C. For this specific domain and on the basis of the HM7 Novoltex C-SiC nozzle extension experience, Silicon Carbide densification was chosen while Carbon matrix densification of Naxeco® was selected for the two aft sections of the exit cone. So the fixed cone is Naxeco® C-SiC and the two extendible sections are Naxeco® C-C.



	A cone	B cone	C cone
Entrance diameter (mm)	653,2 (Σ 22,4)	/	/
Exit diameter (mm)	1329,74 (Σ 93)	1820,82 (Σ 174)	2150 (Σ 243)
Length (mm)	880,2	1036,66	1036,66
Membrane thickness (mm)	2,3	2,3	2,3

Figure 8: Key characteristics of the Vinci® Naxeco® carbon-carbon extendable nozzle extension

The P80 was successfully ground test fired in November 2006 with outstanding throat and overall performance, as predicted (figure 9).

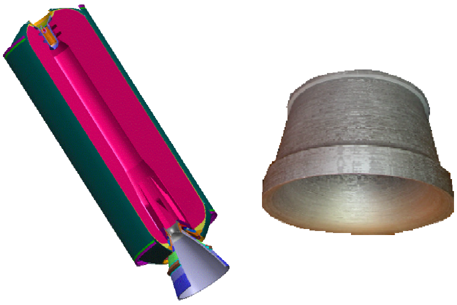


Figure 9: P80 Naxeco® carbon-carbon Nozzle throat

Programmatic reasons lead Europe to concentrate its efforts to Ariane 5 return to flight following the V517 failure at the end of 2002. As a result, Vinci® development was slow down and then transformed in a demonstration program as part of the Future Launcher Preparatory Program (FLPP), shifting its eventual incorporation in an Ariane 5 upgrade around 2015. The first complete Vinci® nozzle extension altitude simulation firing test with the fixed Naxeco® C-SiC cone and the two aft Naxeco® C-C cones is planned at the beginning of 2008 at Lampoldhaussen in Germany. For an earlier 2007 test, the engine will be equipped with the Naxeco Carbon-Silicon Carbide fixed cone alone.

Today, more than 500 metric ton of Carbon-Carbon are produced in SAFRAN group in three locations. Snecma Propulsion Solide in Bordeaux is the cradle of the 3D Carbon-Carbon development, in particular with Novoltex® and Naxeco® needled preforms. The second is Messier Bugatti in Lyon, France, and the third is Messier Bugatti in Walton, Kentucky-USA. These latter two production plants are dedicated to C-C brake disc mass production, based on the needled preform and CVI Carbon densification processes that were developed originally by Snecma Propulsion Solide.

Snecma Propulsion Solide remains the High Temperature Ceramic and Carbon Composites Center of Excellence of the whole SAFRAN group. Therefore, R,T&D efforts for material, process and product applications are done there in support and benefit of all of SAFRAN Group’s companies. Moreover, Snecma Propulsion Solide, drawing on its expertise on SRM, has a very thorough design capability with very sophisticated tools specific for Carbon-carbon and Ceramic Matrix Composites. In combination with material & process expertise and a unique campus of facilities capable of different densification processes and matrix natures, with capacities ranging from laboratory size to as large as 2.5 meters diameter and 3 meters high, it provides Snecma Propulsion Solide with the integrated mastery of the complete chain from early research to design to product manufacturing. Snecma Propulsion Solide is positioned to offer to an exceptional level of service of our worldwide customers.

2. 3D Novoltex® and Naxeco® textile reinforcement for composites.

Novoltex®

Developed beginning in the late 70s, Novoltex® process produces an ultrafine 3D preform using automated needling technology. Various preform shapes, including flat panels, hollow cylinders and cone frusta, are constructed using the proprietary Snecma Propulsion Solide Novoltex® fabrication method.
The process readily accommodates local thickness build-ups where necessary.
The Novoltex® process is much more reliable and reproducible than the 2D involute lay up that was formerly used for carbon-carbon exit cones because it is 3D in nature, which produces excellent mechanical properties in all directions.
Interlaminar shear, for example, is typically three to four times as great as that of 2D involute carbon-carbon exit cone materials.

In the Novoltex® process, pre-oxidized PAN carbon precursor fibre staples are positioned atop a pre-oxidized PAN carbon precursor fabric. The preform consists of a stack of layers of this dual-layer material for flat shapes or a tape-wound hollow cylinder or cone frustum for nozzle throat or exit cone parts.
As each layer is added (by tape winding for cones) a needling head with hundreds
of hook-fitted needles passes over the dual-layer material and punches the pre-oxidized PAN fibre staples through the fabric layers, transferring the staples perpendicularly and through the fabric layers, forming the third direction of reinforcement (figure 10). Hooks are designed so that the fibers stay where they have been carried when the needles leave the perform. Needling is carried out after each layer so that, at the end, each zone of the preform, through the thickness, has received the same amount of transferred fibers. As shown in Figure 11 which is a microphotograph exhibiting needled staple fibres perpendicular to the fabric layers, this provides Novoltex® its good through-the-thickness homogeneity.

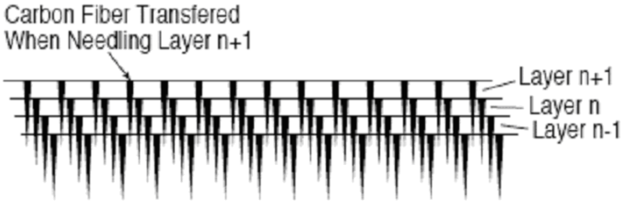


Figure 10: generation of 3D Novoltex® carbon weave with needling process

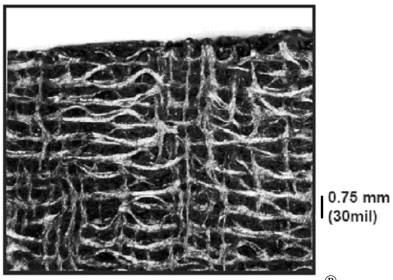


Figure 11: micro-section of Novoltex® carbon-carbon shows 3D characteristics

The cone frusta or cylinder perform shapes made of needled dual-layer fabric-staple Novoltex® broad goods are transferred from the winding mandrels to adequate support tooling for the next two process steps to achieve textile construction ready for densification: (1) carbonization to 1 652°F (900°C) to transform fibers in carbon, (2) further heat treatment to 2912°F (1600°C) to purify carbon by eliminating nitrogen and alkaline contents as well as to stabilize fibers.
Then, Novoltex® preform is removed from the graphite tooling for further densification process
Novoltex® was initially developed to accommodate the carbon chemical vapor infiltration (CVI) densification process, but is also compatible with other densification matrices (such as resin, pitch, silicon carbide, and alumina), thus leading to a wide family of Novoltex® based composites.

The fabric layer spacing in Novoltex® is on the order of 0.75 mm, preserving the 3D nature even in very thin membranes, such as the 2.3 and 3.0 mm membranes of the RL10 B-2 cones.

Naxeco®

In the 90s the development of Naxeco®, a Novoltex® derivative, was started. The aim was to use a raw material made of commercial grade carbon fibres instead of carbon fibre precursor pre-oxidized (uncarbonized) PAN (Poly Acrylo Nitrile) fibres, as it is the case for Novoltex®. This allows using fibres with higher characteristics, simplifying the overall manufacturing process and decreasing the cost by deleting the carbonization step, while keeping the 3D performance advantages of the final Carbon-Carbon material. Moreover, deletion of the carbonisation operation in the Naxeco® process also reduces industrial risk by eliminating significant shrinkage undergone during carbonization of Novoltex® performs.

In the Naxeco® process, tows of carbon fibres are stretch-broken, then aligned to form layers which are webbed, one above the other, along two different directions (usually ± 45°) to constitute rolls of basic non crimped fabric raw material dubbed Primeco®. The Naxeco® preform consists in a stack of Primeco® layers for flat plates or tape-wound of Primeco® for hollow cylinders or cone frustra for nozzle throat or exit cone constructions.

As for Naxeco®, as each layer is added (by tape winding for cones), a needling head with hundreds of specific hook-fitted needles passes over the dual-layer Primeco® and punches the non-crimped carbon fabric to carry carbon filaments through and perpendicular to the stack up of Primeco® tape layers, creating the third direction of reinforcement. As for Novoltex®, each volume of the preform has received the same amount of transferred carbon filaments providing the preform construction with good through-the-thickness homogeneity.

Nevertheless, with conical shapes as nozzle extensions, fiber orientations differ on Naxeco® from Novoltex®. Oriented along meridian and circumferential main directions of the cone with Novoltex®, fibers are now positioned at ± 45° from these main directions with Naxeco®(figure 12).

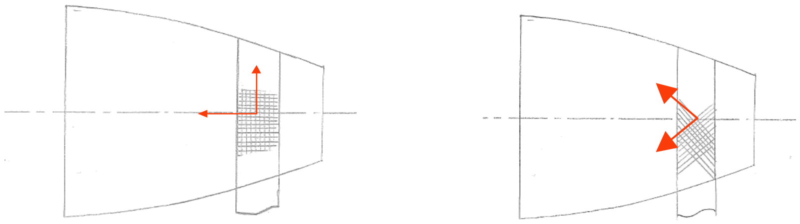


Figure 12: fiber orientation in Novoltex® & Naxeco®

Novoltex®:

Fibers are in meridian and the circumferential directions.

Naxeco®:

Fibers are positioned ± 45°/ meridian and circumferential directions.

The cone frusta or cylinder preform shapes made of needled dual-layer Primeco® are then removed from needling mandrel to be heat treated to 2912°F (1600°C) to purify carbon, eliminating nitrogen and alkaline content, as well as to stabilize Naxeco® preforms before densification. This is accomplished in the densification furnace; no separate carbonization furnace is needed.

The fabric layer spacing is aimed at 0.75 mm, same as for Novoltex®(figure 13). Nevertheless, some further Primeco® / Naxeco® process improvements are under investigation in order to achieve reduction of the layer spacing thickness, which will be of interest to decrease the minimum thickness of membrane and weight of nozzle extension.

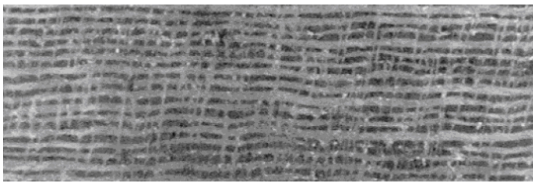


Figure 13: micro-section of Naxeco® carbon-carbon shows 3D characteristics

Figure 14: Advanced missile exit cone Naxeco® preform: note the small entrance diameter and the large diameter ratio from top to bottom

Naxeco® preform technology is progressively replacing Novoltex® in rocket engines applications. For example, it is already implemented in the P80 SRM nozzle (throat and exit cone), the Vinci® deployable nozzle extension, and an advanced missile exit cone (figure 14).

Snecma Propulsion Solide has several needling machines which are capable to produce up to 7000 x 2500 x 60 mm flat panels and 2600 mm diameter x 3000mm axisymmetric preforms such as cones and cylinders.

3. Novoltex® and Naxeco® Carbon-Carbon interest for large and light Nozzle Extensions.

The nozzle has to face very high temperature combustion gas and has to transfer
the thrust to the vehicle. Indeed the heat flux and the mechanical load are strongly dependant of the engine type: solid propellant, storable liquid propellant or cryogenic propellant, as well as expansion ratio and other interface requirements.

To demonstrate that Novoltex® and its successor Naxeco® C-C are definitely of interest for Liquid Rocket Engine large and light Nozzle extensions, a comparison with a well known refractory metallic alloy, Haynes 188, is hereafter presented, first their main intrinsic properties, and then how they comply with loads in operation. The table here after displays main characteristics comparison.

MAIN CHARACTERISTICS	REFRACTORY ALLOY HAYNES 188	NOVOLTEX & NAXECO C-C	COMMENTS
Density	9	1,7	C-C is 5 times lighter
Mechanical at 1000 °C (allowable)			
• Strength (Mpa)	60 to 80 (460 at RT)	40 (the minium in meridional direction)	C-C is 5 times less rigid with similar strength at high temp. Note : • C-C characteristics are rather unsensitive to temp • HAYNES has higher characteristics at RT.
• Modulus at origin (Gpa)	150 (230 at RT)	30	
• Strain Σ (%)	0,2 elastic (25 % at rupture → large creeping)	0,5 (non linear behavior)	
Thermal expansion coefficient (from RT to 1000 °C)	12 to 18×10^{-6}	$0{,}5$ to $1{,}8 \times 10^{-6}$	C-C features 10 times less thermal expansion.
Thermal (from RT to 1000°C)			
• Conductivity (W/m.K)	11 to 26	16 to 30	C-C is 4 times more diffusive
• Heat capacity (J/kg.K)	400 to 580	800 to 1800	
Temperature limit for use (°C)	1080	> 2000	Very high thermal margin with C-C

Lower density , higher diffusivity and low thermal expansion combined with higher temperature capability provide advantages to Novoltex® and Naxeco® C-C for Nozzle Extension use.

Considering the main constraints (example mass) and loads in operation that a nozzle extension has to withstand, nozzle extension performance is analyzed for both materials, Haynes 188 and Novoltex® and Naxeco® C-C. Main conclusions are gathered in the two following tables.

<table>
<tr><th>N.E CONSTRAINTS / LOADS</th><th>COMMENTS</th><th>PERFORMANCE</th></tr>
<tr><td>Mass</td><td>As light as possible.
Manufacturing constraints :
• SEPCARB ≥ 2.3 mm
• HAYNES ≥ 0,8 mm (welding demand).</td><td>Mass HAYNES ≈ 1.8 x Mass Novoltex & Naxeco C-C</td></tr>
<tr><td>Heat flux</td><td>Very high temperature.
HAYNES limited to max 1080°C.</td><td>Use of HAYNES is less robust than C-C face to overheating risk (rupture of film cooling, combustion heterogeneity, H2 consuming to improve film cooling effectiveness).</td></tr>
<tr><td>Thermal shocks and temperature gradients</td><td>Very severe for radiative N.E.
➢ Resistance proportional to $K = \frac{\sigma . \lambda}{Eo\, \alpha}$
<table>
<tr><th>K</th><th>RT</th><th>1000°C</th></tr>
<tr><td>Novotex & Naxeco C-C</td><td>43</td><td>16</td></tr>
<tr><td>HAYNES</td><td>3,9</td><td>0,7</td></tr>
</table>
➢ High allowable strain to avoid permanent deformation.
<table>
<tr><th></th><th>Σ %</th></tr>
<tr><td>Novotex & Naxeco C-C</td><td>< 0,4</td></tr>
<tr><td>HAYNES</td><td>< 0,2</td></tr>
</table></td><td>Novotex & Naxeco C-C is much more suitable for radiative N.E.</td></tr>
</table>

<table>
<tr><th>N.E CONSTRAINTS / LOADS</th><th colspan="3">COMMENTS</th><th>PERFORMANCE</th></tr>
<tr><td rowspan="5">**Dynamic loads**</td><td colspan="3">Very high design driver for a deployable N.E. (boost phase)
➢With the same design, dynamic fatigue is proportional to :
• E/ρ in the membrane zone
• E/ρ^2 in singular areas (local flexion loads)</td><td rowspan="4">• Because of thicker membrane thickness per manufacturing construction, Novotex & Naxeco C-C N.E. should behave better than HAYNES N.E. in dynamic environment.</td></tr>
<tr><td></td><td>E/ρ</td><td>E/ρ^2</td></tr>
<tr><td>Novotex & Naxeco C-C</td><td>18</td><td>10</td></tr>
<tr><td>HAYNES</td><td>26</td><td>3</td></tr>
<tr><td colspan="3">➢ Novotex & Naxeco C-C are insensitive to LCF and HCF unlike HAYNES</td><td>• Novotex & Naxeco C-C better "E/ρ^2" factor is beneficial for easy design and reliable N.E. connections and singular zones (flange ; stiffners ; tapered zone ;…)</td></tr>
<tr><td rowspan="4">**Transient mechanical loads**</td><td colspan="3">Very severe, in particular during on ground tests (altitude simulation blowback,…)
➢Risk of buckling proportional to inverse Et^3 ratio</td><td rowspan="4">Novotex & Naxeco C-C is less sensitive at high temperature
Because of thicker Novotex & Naxeco C-C membrane thickness per manufacturing construction , to make HAYNES at same "Et^3" ratio:
→ Increase thickness, BUT:
⇨ Mass ≥ 3,2 x Novotex & Naxeco C-C Mass
→ Add circonferential stiffners, BUT:
⇨ Permanent deformation in between stiffners.</td></tr>
<tr><td></td><td colspan="2">Et^3</td></tr>
<tr><td>Novotex & Naxeco C-C</td><td colspan="2">365</td></tr>
<tr><td>HAYNES</td><td colspan="2">77</td></tr>
<tr><td>**Damage tolerance**</td><td colspan="3">➢Hole effect ratio : Novotex & Naxeco C-C = 0,9 to 1
HAYNES = 0,3
➢ Novotex & Naxeco C-C keep integrity and survive to possible local over heating when an accidental perforation occurs in the membrane</td><td>Novotex & Naxeco C-C is better and safer.</td></tr>
</table>

Nozzle extension performance is globally better with Naxeco® C-C than with Haynes 188. Moreover, Naxeco® C-C damage tolerance superiority and high thermal margin capacity face to over heating in engine operations provide safety and increase operational reliability, in particular if film cooling failure or severe combustion heterogeneity are experienced.

4. Maturity of Composite Nozzle Extension materials.

The world's largest carbon-carbon nozzle extension is now flying routinely and successfully in the Delta IV launch vehicles(including Heavy version).

For the future, a trade study based on performance, weight, cost and schedule selected a Naxeco® Carbon-Carbon large extendible nozzle extension for the Ariane 5 upper stage engine Vinci® in 1999 and on choice of C-SiC for the part of the radiative-cooled nozzle extension fixed to the regenerative nozzle. The first test of Vinci® equipped with its full nozzle extension is scheduled in early 2008.

Conclusion

The maturity of Novoltex® C-C successor, Naxeco® C-C, is now proven for rocket motor and engine nozzle applications. Manufacturing is being streamlined to industrial levels.

Development of Naxeco® C-C nozzle throats and nozzle extensions are underway at Snecma Propulsion Solide.

Snecma Propulsion Solide Nozzle Extension expertise and its world class 3D Novoltex® and Naxeco® C-C are available to help customers to succeed in new and challenging projects such as the ARES upper stage engine J-2X.

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