# PTAH-SOCAR FUEL-COOLED COMPOSITE MATERIALS STRUCTURE - STATUS 2007

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## ABSTRACT

One of the key points for the development of dual-mode ramjets operating up to Mach 8 or more is the mastery of fuel-cooled composite materials structures, which are needed, at least, for the combustion chamber.
MBDA France and EADS ST have been working on the development of a particular technology for such structures taking advantage of the background of MBDA France in the field of dual-mode ramjet and fuel-cooled structures and of ASTRIUM-EADS ST in the field of high-temperature composite materials. They have developed an innovative technology for advanced monobloc cooled C/C/SiC structures. The paper gives an updated status of the development of PTAH-SOCAR technology, including test results, and presents some results obtained during system and demonstrator studies.

## NOMENCLATURE

| | |
|---|---|
| e | wall thickness (m) |
| hg | heat convection coefficient (W/m²/K) |
| K | permeability (m²) |
| Mf | Flight Mach number |
| P | Pressure |
| Pduct | Hot gas pressure |
| Pcooling | Pressure in cooling channel |
| S | frontal area (m²) |
| Taw | Adiabatic wall temperature (K) |
| Tw | Hot wall temperature (K) |
| ρ | density (kg/m$^3$) |
| μ | dynamic viscosity (Pa.s) |
| ΔP | Pressure difference |

## ACRONYMS

| | |
|---|---|
| CVI | Chemical Vapor Infiltration |
| DMR | Dual-Mode Ramjet |
| EADS-ST | ASTRIUM-EADS Space Transportation |
| FEM | Finite Element Method (structures) |
| ISP | Fuel specific impulse |
| LRE | Liquid Rocket Engine |
| LSI | Liquid Silicon Infiltration |
| 03S | One Side Straight Stitching |
| PAO | Protection Against Oxidation |
| PSD | PTAH-SOCAR Duct |
| PSR | PTAH-SOCAR Rocket duct (37 mm diameter axisymetric cooled duct) |
| PSS | PTAH-SOCAR sample (flat panel) |
| PST | PTAH-SOCAR Tube |
| PTAH | Paroi Tissée Application Hypersonique |
| RBCC | Rocket Based Combined Cycle |
| RCVI | Rapid CVI process |
| RLV | Reusable Launch Vehicle |
| SOCAR | Simple Operational Composite for Advanced Ramjet |
| SSTO | Single Stage to Orbit |
| TSTO | Two Stage to Orbit |
| TUM | Technical University of Munich |

## INTRODUCTION

Advanced cooled structures have been studied worldwilde for application to heat exchangers, high speed vehicles, scramjets and dual-mode ramjets (DMR) as well as future liquid rocket engines (LRE). They use high temperature materials, metallic and more and more composite (C/SiC, SiC/SiC, …). Different cooling techniques are used. To achieve performance and to limit the risk, the cooled structures are combining these different existing possibilities, leading often to complicate and costly structures.
The present paper gives an updated status of the development of PTAH-SOCAR technology, including test results, and presents some results obtained during system and demonstrator studies both for DMR and LRE (and other systems). The background on active protection systems for high speed airbreathing propulsion is previously described.

### High speed airbreathing propulsion

In a large part of the flight regime, the air-breathing mode appears to be a good solution for future Reusable Space Launchers (RLV). Dual-mode ramjets have been studied to propel such TSTO (Two Stage To Orbit) or Single Stage To Orbit (SSTO) vehicles. For example, in the scope of the French PREPHA program, the study of a

generic SSTO vehicle led to conclusion that the best type of airbreathing engine could be the dual-mode ramjet DMR (subsonic then supersonic combustion)[1],[2]. Airbreathing launchers could typically use hydrogen-fueled DMR. Less energetic fuels like hydrocarbons could also be used at a Mach number lower than 8, to take advantage of their higher density. In this case, the engine must be able to manage two different fuels.[3] Some projects abroad propose to integrate the rocket engines within the DMR, leading to Rocket Based Combined cycles engines (RBCC).
Hypersonic military applications are typically associated with liquid hydrocarbons scramjets and a maximum flight Mach number of 8.

The propulsive performance (thrust, consumption) of the DMR have to be optimised, computed and at-best demonstrated.
But another major concern is the capacity to build such an engine, and to estimate its robustness and its weight. Light high performance metallic or composite fueled-cooled structures are needed, at least, for the combustion chamber[4].
Vehicle performance analysis, even simplified, is required to do the trade-off of all these characteristics of the propulsion system.

## Active thermal protection of walls

For the application envisaged, the basic technique to ensure the thermal strength of the combustor is the use of the fuel to cool the engine before being injected.

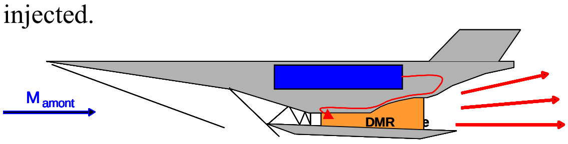


*Figure 1: regeneratively cooled DMR*

On this topic, work led by MBDA FRANCE has been associating research institutes and industrial partners, system and paper studies and extensive technology evaluating process[4]. Main conlusions are given hereby.
Several circuits of active cooling systems have been compared to ensure good behaviour of the engine walls, with respect of the combustion-required fuel mass flow. Many configurations of cooling are envisaged, such as series of channels of rectangular shape or pin fins channels.
The pin-fin circuit (Figure 2) was confirmed as more efficient[5] than the more classical machined-channels.

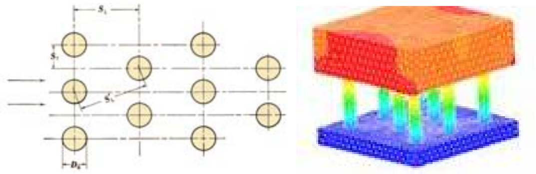

*Figure 2 : pin fin configuration of cooling channel*

One of the interest of the pin-fin circuit is the easy management along the walls of the DMR combustor, which is often diverging (Figure 1).
Convection cooling may be associated with transpiration. This technique is especially usefull to cope with local heat fluxes increase caused for example by strong pressure gradient due to interaction of an incoming shock with the boundary layer. It is also an interesting way to manage local heat fluxes close to injectors[6].
The interest of using composite structures (able to operate at temperature over 1800 K in oxidizing environment and with a typical density of 2) have been demonstrated thanks to several analytical and computational studies and to actual technology experimental testing (benefit in weight, benefit in thermal capability, benefit in injection strut drag, …)[4].
The mass comparison between a metallic and a carbon/carbon structure for the same dual-mode ramjet has been evaluated [7, 8] showing 30% benefit in weight.
In 1993 began this innovative cooperation on cooled high temperature composite structures, up to the test of the St-Elme[9] injection strut in 1997.
Over the past years, the German part of EADS-Space Transportation has, together with various partners, worked intensively on developing uncooled components for hypersonic véhicles (fuselage, air intake, nozzle) and liquid rocket propulsion systems[10].
Several manufacturing process can be used for the transformation of the preforms to composite complete structures (C/C or C/SiC, CVI, LPI, LSI routes, …). LPI and LSI routes are mostly development in the German part of EADS. Besides material and process development, this ceramic-LRE-oriented project[11] also encompasses the development of special metal/ceramic and ceramic/ceramic joining techniques as well as studying and verifying NDI (Non Destructive Investigation) processes for the purpose of testing components.

The PTAH-SOCAR technology takes benefit of this background and takes most of the advantages of the different techniques with minimizing the drawbacks.

## COMPOSITE PTAH-SOCAR TECHNOLOGY

This work is a cooperative effort between MBDA France (Le Plessis Robinson and Bourges), EADS-ASTRIUM- Space Transportation in Ottobrunn and Bordeaux, EADS-"innovative works" (formerly "CRC") in Ottobrunn, Toulouse and Suresnes, with some laboratories and subcontractors.

## PTAH-SOCAR genesis

This In-house Effort of MBDA FRANCE and EADS-ST leads to Low cost, highly reliable, effective Fuel-Cooled Structure Technology. The patented idea has been to develop and preliminary check a concept of C/SiC structure with the following advantages :

- no bonding system (nor brazing, nor gluing…)
- complete combustion chamber structure in one part ("monobloc")
- limitation of connecting problems
- no problem for realizing corners of a 2D combustor
- limitation of possible leakage problems
- no need of machining internal channels
- easier integration of specific systems (injectors, flame-holders..)

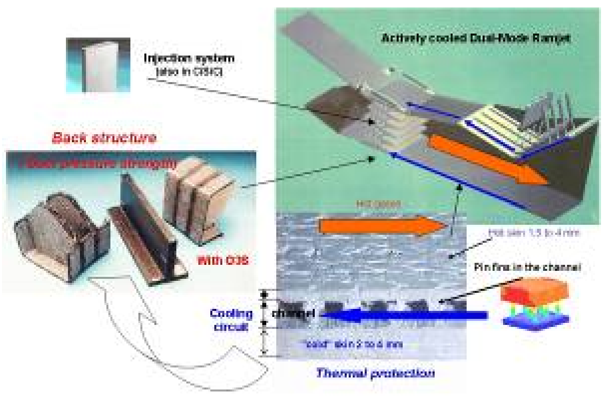


*Figure 3 : general idea of PTAH-SOCAR*

As shown on Figure 3 the main ideas for the manufacturing of a whole DMR engine with PTAH are the following :

- Monobloc actively cooled combustion chamber obtained at preform state before its densification process (whatever this one : C/C or C/SiC, CVI or LSI)
- Linking by stitching of complex woven preforms
- Hot and cold skins linked together by stitching with carbon yarn
- Stitching treads go through the cooling channel (Figure 6)
- Back Structure needed to hold the combustion chamber pressure (may be external or integrated at preform state, based on carbon honeycomb , corrugated skin or a system of O3S assembled stiffeners).

The PTAH-SOCAR specific weight for the heat protection system is lower than 10 kg/m2 (density of this CMC material is closed to 2000 kg/m3). With the back structure, the total specific weight is 30% lighter than metallic advanced cooled structures.

The necessary models of the cooled structure and the associated feasibility were checked on the basis on gazeous densification, leading to C/C or C/SiC cooled structures. The period 1999/2001 was used to check with limited amount of funding and aggressive time schedule the key-points of the PTAH-SOCAR technology, as summarized in Figure 4 .

| | |
|---|---|
| **Hot test of panels** | PSS1, PSS2A, PSS2B |
| **Cooling effectiveness** | PSS tests |
| **In-shape** | Manufacturing of U |
| **Mechanical strength** | Test and computations |
| **Permeability** | Integral measurement on PSS test |
| **Material characterization** | To be enhanced |
| **System and CFD** | Extensive for DMR First idea for LRE |
| **Innovative effort** | Patented |

*Figure 4: feasibility status (based on CVI C/SiC material)*

Details on these results and further analysis have been presented in the hypersonic conference held in Orleans, France, in October 2002[12].

The 2 main routes of C/SiC densification of such structures can be summarized in the following figure :

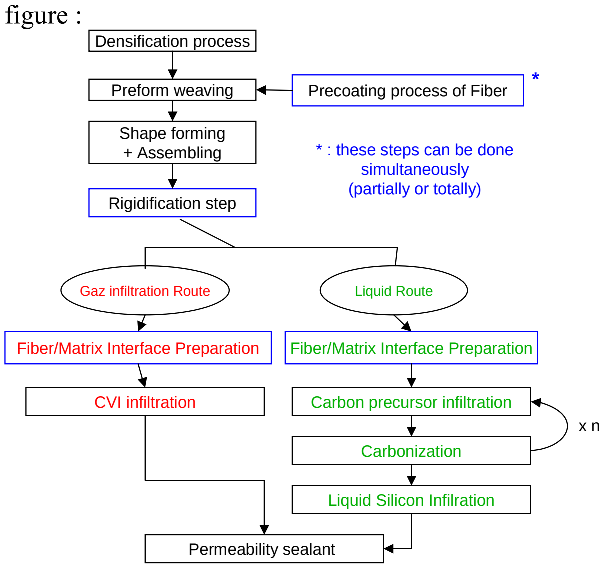

*Figure 5 : among the possible manufacturing routes to obtain C/SiC composite for PTAH-SOCAR*

The objective of the LSI Route is to create multidirectional (3D) textile structures combined with a cost-effective infiltration process the so-called SICTEX®-material. This process is based on Liquid Silicon Infiltration. After successful test of uncooled LSI LRE engines, the adaptation of the process to the PTAH-SOCAR technology was undertaken.
In 2002, the PTAH technology began to be investigated with EADS Germany partners with the cost-effective technology based on Liquid silicon infiltration. First technological results obtained essentially with the Liquid Route were presented[13] in 2003.
A baseline LSI route has been defined, preliminary characterized and refined with two simultanate targets : to simplify the process (low risk, low cost) and to check the complete manufacturing capability on a monobloc duct able to be hot tested.
The current manufacturing process leads to straight stitching yarns, as shown Figure 6.

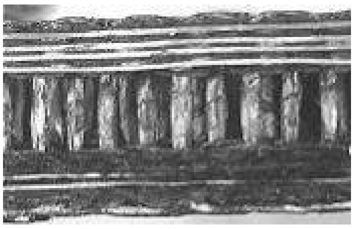

*Figure 6 : Straight stitched yarns from PTAH preform*

Remark that the corresponding pattern is very close to the high efficiency heat exchanger shown on Figure 2.
After some trials, the reference LSI process allows to correctly protect the yarns[20], as shown on right part of the Figure 7.

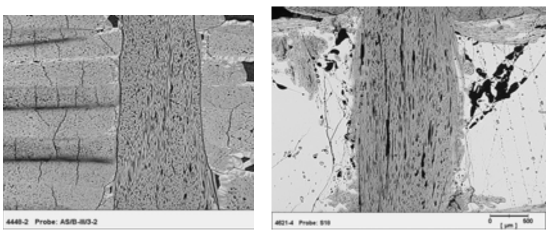

*Figure 7 : undamaged yarns :CVI route (left) and optimized LSI process (right)*

Burst test of several PSS panels performed have demonstrated for the current PTAH-SOCAR architecture a high pressure capability. Due to tooling limitations, it was not possible to burst the panels at more than 80 and 90 bar of internal pressure. Detailled computations performed afterwards, when new mechanical characterization was performed on the new reference manufacturing process confirmed this level of mechanical strength (Figure 16).

This optimized RCVI-LSI process is currently the reference densification method for PTAH-SOCAR structures, the readiness of this technology is given in details in the paper presented at the 2005 Hypersonic Technologies Conference[14].
The LSI route was combined with the PTAH idea and investigated at different levels, from plate sandwich samples up to complete subscale cooled ducts.

For the PTAH technology, several system “paper” studies have been performed, mainly on dual-mode ramjets (with hydrogen or hydrocarbon as fuel). Preliminary investigation has also been performed on Liquid-Rocket Engines. The corresponding models, for example implemented in the NANCY code[15], have been consolidated with data acquire during mechanical characterization on one hand and PSS cooled panel testing on the other hand.

## First experimental demonstration : PSS testing

This first experimental program aimed at developing and testing several small cooled panels, called PSS (PTAH-SOCAR Samples), in order to :

- tune and validate the manufacturing process,
- check the mechanical resistance of the technology,
- precisely evaluate the accessible performance in term of cooling capacity
- estimate the leakage with nitrogen or kerosene during hot test.

So, the PSS takes the simple shape of a plane rectangular current part of the cooled structure (130x80 mm²). PSS is placed in a water-cooled stainless steel frame, which supplies the PSS with nitrogen or kerosene, to be tested at the exit of a scramjet.
The thermal behaviour of a PTAH-SOCAR cooled panel has been checked during hot test, with decreasing mass flows of coolant (gaseous nitrogen, air, regular liquid kerosene). Maximum wall temperature was over 1800 K without damage and the cumulative duration of hot tests was 5 minutes for each PSS.
The extensive testing of such panels (Figure 8) allowed to check in actual environment the technology and the associated modelling, in a step by step approach.

| coolant | Heating (scramjet, ER=0, ER=1) | No external heating | Test hardware |
|---|---|---|---|
| Cold N2 | ■Thermal modeling<br>■Hot permeability<br>■Hot burst test | Cold permeability | PSS1, PSS2A, PSS2B, PSS3, PSS4 |
| Cold air | ■Thermal modeling<br>■Oxidation behaviour | Cold permeability | PSS3, PSS4<br>*PSD* |
| Cold kerosene | ■Thermal model. without decomposition<br>■Coking effect on permeability<br>■First part of engine circuit | Cold permeability | PSS1, PSS2A, PSS2B, PSS3, PSS4 |
| Preheated air | ■Thermal modeling<br>■Oxidation behaviour | ■Thermal modeling (inner part)<br>■Unsteady behaviour<br>■Oxidation behaviour | PSS3, PSS4 |
| Preheated kerosene | ■Thermal modeling with decomposition<br>■Coking effect on permeability<br>■Last part of engine circuit | ■Thermal modeling (inner part)<br>■Unsteady behaviour | PSS3, PSS4 |

*Figure 8 : PTAH-SOCAR cooled structures testing*

These results have been complemented with permeability data and mechanical characterization.

## Permeability results

Leakage mass flows were roughly and integrally measured with more and more efficient techniques with GN2 and with kerosene, in order to obtain data for cold and hot permeability analysis. The available data were analysed and compared with available information on porous structures.
The Darcy's law was confirmed to be mostly applicable in the conditions of PSS test :

$$\dot{m} = \frac{\Delta P}{\left( \mu / \rho \right)} \times \frac{S}{e} \times K$$

K = Permeability (m²)

While increasing the temperature of the wall, analysis of the leakage measures of PSS panels leads to the conclusion that the permeability increases with the temperature (when the coolant is nitrogen).
This result was confirmed after comparizon with two test campaigns of hot permeability estimation of other thermostructural composites in different conditions. It is nevertheless opposite to other available results, particularly with brazed CMC system[16] with unreactant gas.
If the coolant is regular kerosene, possible coking within the porous hot skin can reduce its permeability after a given time, which is difficult to be quantitatively predicted by computations but was experimentally shown.
These two effects may counterbalance.
If a particular level of transpiration is needed for a given application, the permeability can be adjusted by playing on the preform, the densification or the sealing processes. At the opposite, if leakproofness is required, for specific system requirement or simply to be able to perform a burst test of the cooling channels, an additional sealing is applied. Permeability can then vary from $10^{-11}$ to $10^{-18}$ m².

## Mechanical characterization

Mechanical tests have been realized on skins (derived from sandwich) at ambient temperature and in hot conditions. Temperature increases the mechanical properties of the obtained C/SiC skins[20]. Burst test of PSS2 panels were conducted in cold and hot conditions with the same results. Specific testing has been realized at EADS-CRC in Suresnes. Test investigates tensure, compression and shear of samples of PTAH skins as well as complete sandwiches (Figure 9).

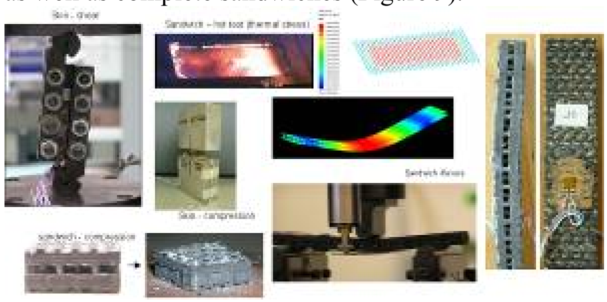

*Figure 9 : mechanical characterization*

Additional mechanical characterization was conducted in 2006 and 2007 on skins and sandwich to take into account the last refinements of the material process as well as to use higher dimension samples (AITM standards).

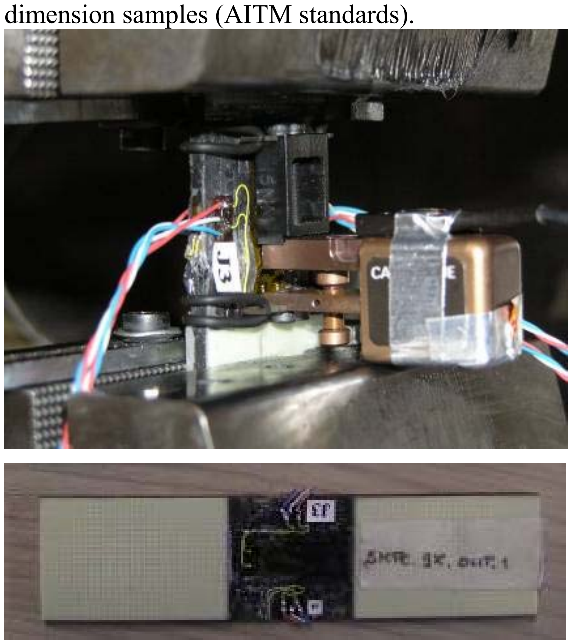

*Figure 10 : new compression test of PTAH skin*

Directly from these test, as well as in connection with different Finite Element Method computations, this work allows to refine the material characteristics (moduli, …) and first level engineering limits (simple failure criteria for skins and yarns).

# COMPLETE DUCTS DEMONSTRATION

## Demonstration of 2D duct manufacturing capability

Several samples, components or ducts were studied and manufactured, before the hot test of a cooled duct subscale demonstrator "PSD" done in

2005 in cold conditions and, in January 2006, in hot conditions.

*Figure 11 : example of PTAH-SOCAR step by step demo*

One particular effort was done to evaluate several ways of in-shape manufacturing of the PTAH-SOCAR structure, to save manufacturing time.

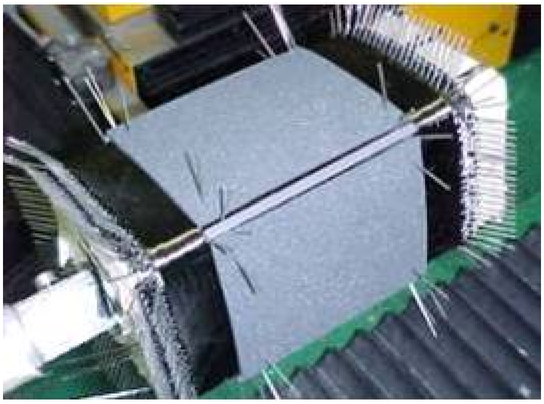

*Figure 12 : PTAH SOCAR Duct preform manufacturing*

The Figure 12 in the workshop shows the channel mandrels used to generate the channel between the internal hot skin and the "cold" external one (not yet woven in this picture).

To check the whole process, it was decided to concentrate on the manufacturing of some subscale PTAH-SOCAR ducts, called PSD. These monobloc cooled ducts can then be tested between metallic frame in the ONERA supersonic combustion test cell in Palaiseau, France.
The corresponding CAD assembly is shown Figure 13 and later on Figure 17.

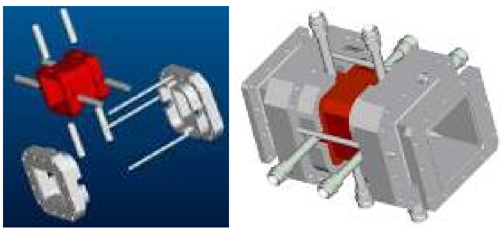

*Figure 13 : PSD assembling for testing*

The complete preform is obtained on a special tooling, then transfered to the densification ovens. Additional sealing and final proof test are then realized (Figure 14).
Between each critical step, Non Destructive Investigation is conducted, by using X-rays or neutron tomography.
Final proof test is possible thanks to the stainless steel frames and tubes compatible with the test facility.

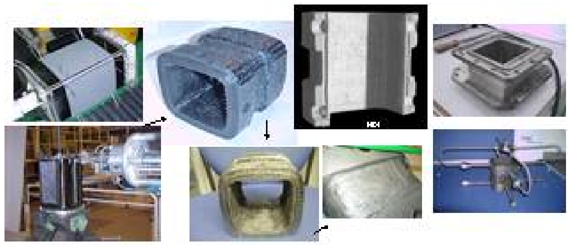

*Figure 14 : manufacturing steps of PSD assembly*

**<u>Successful mechanical test of PSD</u>**

By using the first set of PTAH-SOCAR material characterization, some preliminary computations were realized on actual structures. The currently preferred modelling associates shells for the skins and beams for each stitched yarn, with two different computational approaches. The SAMCEF code uses here the anisotropic characteristics of the material, while the CASTOR/FEM engineering code assumes isotropy. The analysis of the yarns behaviour as well as the skin stresses are similar between the two models.
The order of magnitude of the displacements as well as the maximum stresses (refered to the material ultimate one) are the same with the two approaches, as shown in details in [17]. Nevertheless, the isotropic engineering model overestimates the tensile stress in the corner yarns: the isotropic CASTOR/FEM model calculates its at 38 % of the yarn ultimate stress instead of 33% with the anisotropic SAMCEF model.
In 2005, it was possible to test –in cold conditions- the pressure effect on the external skin of PSD ducts. A laser extensometer of EADS-CRC is used to measure the max displacement of the central part of one external skin, that can be compared with the pre-computed one under the same pressure.

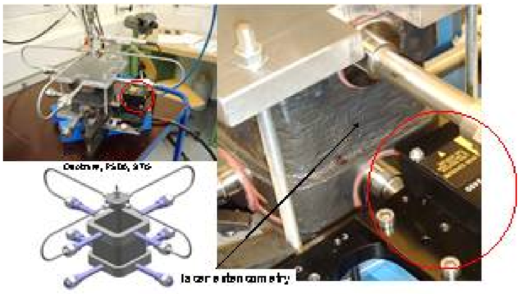

*Figure 15 : cold pressure test of PSD0 with laser extensometry*

Pressure is increased by water in both channel (Pcooling) and main flow (Pduct) areas.
The figure below compares the two computational approaches and the extensometer results.

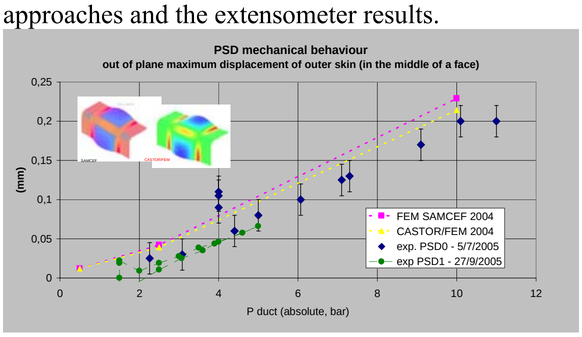


*Figure 16 : computed/measured internal pressure effect on PSD*

Even if the geometry of 2004 computations is slightly different from the tested ducts, a good engineering agreement was found.
Moreover, work is on progress to enhance the mechanical characterization if such a structure, to prepare refined computational models and failure criteria. But the tools are considered as ready for any engineering design of a PTAH-SOCAR engine.

## Successull hot testing of PSD in scramjet environment

After these mechanical non destructive mechanical characterization, the PSD1 duct has been sent at the end of 2005 to ONERA Palaiseau test center in order to be tested in hot conditions.
The characteristics of the test series held in ATD5 test cell on an existing supersonic combustion chamber were the following:

- Flight conditions : Mach 7.5
- Supersonic combustion air/H2
- Transient behaviour.
- Air as coolant (no other coolant was usable).

Incoming mass flow, coolant air pressures and temperatures were measured as well as Tback (external wall) by Thermocouples and IR camera.
Displacement laser sensor provided by EADS-CRC was used.

The PSD1 was tested in hot conditions during the whole planned test program, which included a step by step approach and severe 3D effects on cooling between the 4 faces (each PSD side communicates internally with its neighbours through the corner, and each has its own input and output). 12 hot runs were performed.
It was as far as known the first successfull scramjet hot test of a monobloc cooled C/SiC duct. Details can be found in [17].

The information given by the IR camera (visible on the bottom left part of Figure 17) are similar to the level given by corresponding Tback thermocouples.

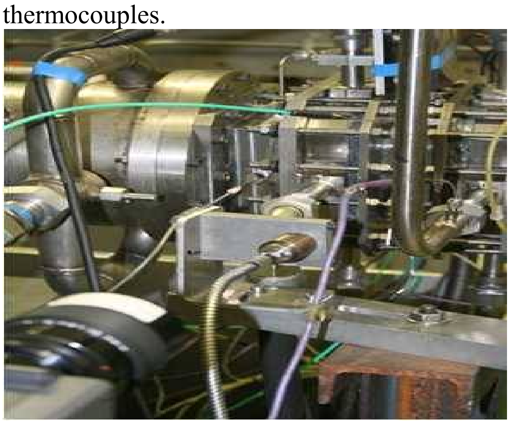

*Figure 17 : PSD1 cooled duct in ATD5 test bench*

After these successfull PSD test series, work is going on with development of PTAH-SOCAR technology.

## OTHER TESTS

After test and analysis of such subscale ducts, greater structures are planned to be manufactured and tested, for example within the hypersonic METHYLE test facility in Bourges[18]. To prepare these further DMR demonstration, as well as to investigate PTAH application to actual systems, models and technology results are available, for cooling (thermics and permeability) and for mechanics.

Many applications of PTAH-SOCAR cooled structures are under investigation (Dual-Mode Ramjet, Liquid Rocket Engines, fuel cells, heat exchangers, micro combustion , transpiration cooling, …). Figure 18 sumarizes this work in the present decade.
In connection with the applied structures, the data base is under enhancement thanks to basic experiments (mechanical or thermal characterization, environment compatibility, …).

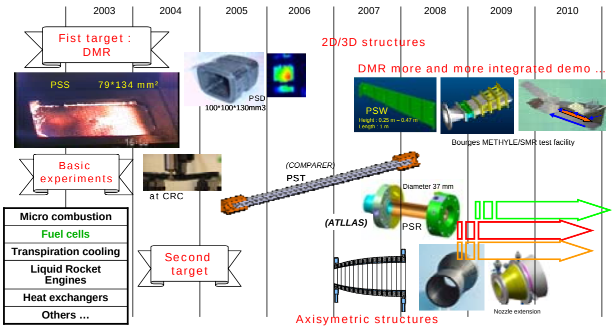


*Figure 18 : possible PTAH structures development*

Some cooled axisymetrical PTAH structures will be tested, particularly in oxygen/kerosene high pressure environment, within the ATLLAS project[19].

## LRE application

Preliminary investigations have been done of the possibilities and interest of using the PTAH technology for axisymetric Liquid Rocket Engines and presented in Joint propulsion conference[20] in 2004.

Manufacturing process adaptation, mechanical strength estimation have shown possible interest. It seems quite easy to manufacture the cooled part of the engine, the uncooled part of the nozzle in the same process with CMC material. Anti-leakage treatment can be limited to external skins and combustor part, leading to transpiration positive effect at the throat region.

After some preliminary studies, a project of subscale LRE nozzle extension has been drawn.

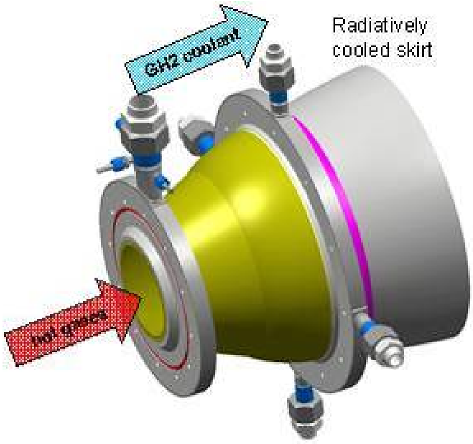


*Figure 19 : project of subscale PTAH LRE nozzle extension*

This common definition phase has included PTAH cooling circuit computations with existing models. Results with the NANCY code[15] are detailed in [17], with H2/O2 combustion at Mixture ratio =6 and combustion pressure of 100 bar and GH2 cooling.

This PTAH nozzle extension design is under refinement, and will take benefit of the new technological characterizations of PTAH structures, especially PSR hot testing.

## Test of simple PSR ducts in LRE environment

Manufaturing and test of such LRE nozzle extensions are planned before 2010.

In the mid-time, within the scope of the ATLLAS program[19], some small diameter PTAH structures will be tested in a kerosene-oxygen rocket combustion chamber under various conditions.

Previoulsy, some metallic cooled systems as well as radiatively-cooled CMC ducts had been tested in a smaller LRE water-cooled test chamber located at Munich university center (TUM) at Garching in Germany[21].

The figure below shows one CAD assembly of PTAH 37 mm diameter PSR cooled duct to be tested at Munich Technical University under LRE environment.

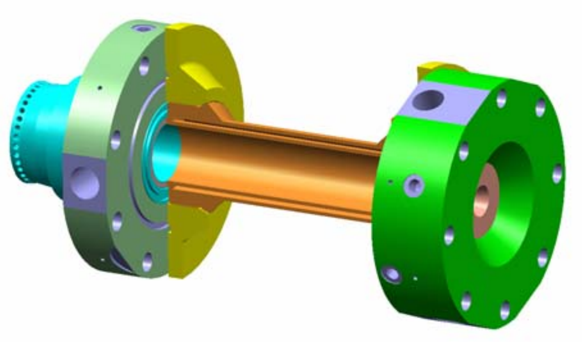

*Figure 20 : Assembly of 37 mm diameter PTAH duct for LRE testing*

The PSR cooled duct (in orange in Figure 20) is equipped with integrated small shoulders and assembled into a water-cooled modular LRE facility.

In the TUM facility, a wide range of Mixture Ratio as well as coolant mass flow can be investigated with a combustion chamber pressure up to 100 bar. PSR test series are planned up to 2008, in a step by step approach comparable to the PSS one (Figure 8). No preheating of the coolant is planned for the test at TUM.

Preliminary thermal and mechanical computations were performed with NANCY code and simple buckling analysis (no back structure is planned for these 37 mm diameter PSR test).

These test series will allow to investigate the PTAH materials compatibility in high pressure LRE environment, with hydrocarbon, water, CO2 and oxygen medium.

**PST tube**

The work led by MBDA-France on advanced cooled technologies includes many studies. By the coupling of NANCY and SENKIN, engineering computations allow to take into account the change of physical properties of the fuel (modelled as C12H26 for example) with its chemical decomposition[22]. Some projects investigate the capability of equiping such cooled structures with specific measurements on the decomposed coolant[23].

To evaluate such a possibility, and to perform basic experiments on PTAH-SOCAR pin-fin tubes, design and manufacturing of a PTAH-SOCAR tube (PST1) was made.

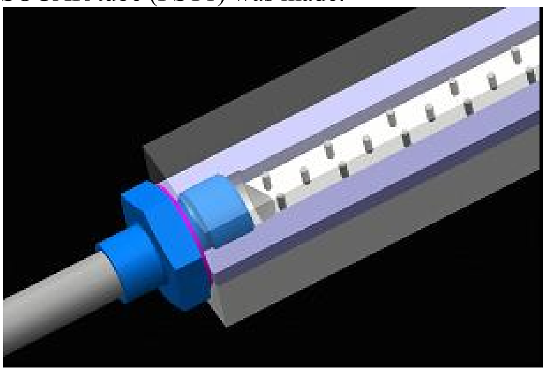

*Figure 21 : PTAH-SOCAR Tube CAD view*

This tube is to be tested in a high temperature oven with a small mass flow of hydrocarbon in an existing academic test bench at Bourges, which used up to now metallic tubes.

## CONCLUSION

Composite cooled materials would give high benefit to high speed propulsion.

PTAH technology is an innovative solution based on existing background of MBDA FRANCE and EADS-ST. The PTAH-SOCAR concept is very promising, whatever the densification process to be chosen.

The technology has been investigated and its feasibility had been demonstrated (hot test of several panels "PSS", in-shape pieces, …). Detailed analysis has been performed, with particular emphasis to material characterization, and hot permeability estimation. In addition to already used gaseous densifications, LSI was confirmed to be a promising way, suitable to PTAH-SOCAR technology and very cost-effective. LSI is now the reference process and deals with "short" densification time (days instead of weeks for CVI). This second PTAH-SOCAR technology phase was considered as achieved in 2006 after the sucessfull test series in supersonic combustion of a subscale actively-cooled complete duct (PSD1) and the associated analysis.

Work is going on, thanks to different projects, with additional characterization (including PSR small ducts high pressure GOX/kerosence testing), to prepare the manufacturing and test of PTAH larger structures of DMR and LRE in actual environment.

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