PERSEUS / PEGASE AN OUTSTANDING EXPERIMENT

TO MIX SPACE PASSION, EDUCATION AND TECHNOLOGY

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SUMMARY

PERSEUS is a CNES project dedicated to young people within a university or an associative frame. The objective of this project is to develop a set of ground and flight demonstrators, in connection with a future project of a nano-satellites launch system.

In this frame, since mid-2006, AJSEP has led the sub-project PEGASE dedicated to the student design, manufacture and test of hybrid propulsion structures (oxidizer tanks, combustion chambers and nozzles). Four universities and engineering schools are deeply involved (Arts et Métiers ParisTech, campus of Bordeaux-Talence, IUT Bordeaux 1, Université Bordeaux 1, CR-IMA Mérignac, Ecole des mines d'Albi –Carmaux) and a High school (Lycée de la Mer in Gujan Mestras).

For each student team, the main purpose of the project is to complete an entire development loop (design, manufacture and test) within nine months. This approach makes the study a multiplicity of different designs feasible, in order to explore either low cost, low mass or innovative solutions.

GLOSSARY

AJSEP: Association Jeunesse Science Espace Passion

CNES: Centre National d'Etudes Spatiales

PEGASE: Projet Etudiant Girondin - Activités Sciences Espace

PERSEUS: Programme Etudiant de Recherche Spatial Européen Universitaire et Scientifique

GENERAL PRESENTATION

The PERSEUS PROJECT

In late 2005, CNES started a project named PERSEUS, the objectives of which are:

- to promote innovations and developing promising technologies applicable to space transportation systems
- to achieve these activities by young peoples within a university or an associative frame , driven by an educational initiative increasing their motivation for space jobs
- to develop a set of ground or flight demonstrators, enabling the definition of a detailed file for a future project of a nano-satellites launch system.

AJSEP association – Le Haillan

Within this context, AJSEP has been leading the sub-project PEGASE since mid-2006, making students teams design, manufacture and test hybrid propulsion structures (oxidizer tanks, combustion chambers and nozzles).
AJSEP is a PLANETE SCIENCES subsidiary association, mainly composed of SNECMA PROPULSION SOLIDE employees (still active or retired). Thanks to its dual origin (youth association and industrial space experience), AJSEP has established students teams management rules dedicated to the PERSEUS/PEGASE project. For each students team, the main purpose of this project is to complete an entire development loop (design, manufacture and test) within nine months. This approach makes the study a multiplicity of different designs possible, in order to explore low cost, low mass or technological breakthrough solutions. With the experience acquired during the previous years, students' teams are able to study and develop more and more complex designs.
Since mid-2006, about forty students have been working each year on this exciting project.

Arts et Métiers ParisTech, campus of Bordeaux-Talence

Arts et Métiers ParisTech is a prestigious higher education engineering school, with 1,000 graduates per year, on 8 campuses in France. Its first mission is to train qualified engineers in the fields of mechanical engineering, power engineering and industrial engineering.
The campus of Bordeaux-Talence is particularly involved in aeronautics and space engineering with 2 dedicated syllabuses, one of them being focused on materials, structures, processes, design and propulsion.
Projects take an important part in educational activities, and the school is equipped with modern workshops, allowing designing, manufacturing and testing products: CAD, machining, forming, composite materials, etc. For the PEGASE project, an agreement with Lycée de la Mer was signed, in order to use and develop their filament winding machine.
During the projects, students are particularly well-supervised by professionals, both technicians and researchers, which improve their practical and scientific abilities.

IUT Bordeaux

The University Institute of Technology from Bordeaux is a department of Bordeaux 1 University. Its main mission is to train technicians in Science & Engineering field and give to students strong foundations to continue their training.
The University Institute of Technology can rely on high technology resources and numerous industrial relations in various fields as mechanical, materials, electrical, computer and civil engineering. Actually over 2000 students are following one of the 26 training available.
For three years, the Materials Science Department and the Mechanical Engineering department have gathered in order to take part in the sub-project PEGASE. Each year, about 15 students, supervised by teachers and researchers, enjoy developing an innovating propulsion structure.

IMA Mérignac

IMA (Engineering & Aeronautic Maintenance) is a resource centre of University of Bordeaux – Science & Technology. This place is mainly devoted to the teaching of aircraft maintenance, but is also accessible to other student from Bordeaux University so as industrials for practice of R&D projects. Two main training are host at IMA respectively at license and master level with two specialties in avionic equipments maintenance and aero-structures design and repair. About 100 students graduate each year in these specialties.

Project and training period in industries are important part of these formations. For their projects students have now access to plane hangar equipped with various maintenance equipments, manufacturing robot, NDE apparatus, simulation and CAD lab, and composite fabrication lab. Master level project mainly deals with structural repair design, optimization and characterization. About 10 students are involved every year at IMA in PEGASE activities.

Ecole des mines d'Albi –Carmaux

The Ecole des Mines d'Albi-Carmaux belongs to the GEM (Groupe des Ecoles des Mines) network that brings together 7 prestigious French engineering schools and train more than 6200 students and 1000 PhD's in the field of science and technology.

The Ecole des Mines d'Albi-Carmaux trains engineers to deal with all aspects of an industrial process combining a wide knowledge in science, technology and economics, as well as inter-personal skills such as management and communication. Amongst the 8 final year majors two are dealing with materials, mechanics and forming processes: material engineering and Materials for aeronautics and space industries. Students stay more than 12 months in industry or abroad for training.

During their project periods, students are hosted by the research center and they have access to their facilities. The PEGASE project is performed in the frame of the Innov'Action project period aiming to promote innovative research and development skills. For manufacturing purposes the 5 students of the team had access to the production and test facilities of the Research Center on Tools, Materials and Processes.

TECHNICAL EDUCATION

As most students involved in the PEGASE project doesn't have any initial knowledge about rocket propulsion, a series of lectures has been prepared and is given at the beginning of each yearly development loop.

These lectures deal with:

- rocket propulsion fundamentals: combustion, thermodynamics of fluid flow, chamber mass flow rate and nozzle isentropic flow, thrust equations and performance coefficients for both solid and hybrid propulsion,
- solid and hybrid rocket main structural components: metallic and composite (filament wound) tanks and combustion chambers, internal thermal insulations, nozzles,
- for the above rocket components, the lectures focus on design and dimensioning, materials selection, preliminary and detailed analysis, manufacturing and testing.

In addition, a half-day conference is also organized in cooperation with CNES and 3AF at the beginning of each yearly student technological challenge, dealing with:

- space transportation systems fundamentals: liquid, solid, hybrid and nuclear propulsion systems, satellite launchers design, state of the world family of launchers and comparison of their performances,
- the PERSEUS nano-satellite launcher project: roadmap, launch options (ground or air launch), propulsion options (advanced liquid and hybrid motors) and its several sub-projects,
- the PEGASE/PERSEUS sub-project: technological goals, schedule and main technical specifications for the next coming school year,
- a general presentation given by a CNES executive manager about the present, near future and long term programs for space transportation systems.

For the duration of their projects, students' teams are guided and assisted by one or two dedicated AJSEP trainers who answer to the students' questions and check that the students work complies with the technical and the schedule requirements of the PEGASE project.

The point of view… Ecole des mines d'Albi –Carmaux

Solid Rocket propulsion and launcher design are far from the core skills of the Ecole des Mines d'Albi-Carnaux engineers. Nevertheless those who were selected for this project have professional projects related with space industry. That's why they where enthusiastic during the lectures given by AJSEP specialists: starting from the thermodynamics and the combustion environment in the various propulsion systems, the nozzle design and candidate materials where introduced. Moreover they had the chance to visit the "Snecma Propulsion Solide show room" where all successive solid propulsion nozzles produced and tested over more than 40 years where visible.

But all along these lectures the particularities of the hybrid combustion environment was highlighted and open questions where addressed. So this first lectures were also the occasion to start close connections between the AJSEP specialists and the student team. Often technical questions are addressed by mail and detailed responses come always very quickly.

The PEGASE project gives the opportunity to start with theoretical initial skills and to conclude with a physical final part and this is not often the case during an educational cursus. In order be able to reach this goal in this short time, students have to use all other technical skill coming form their basic cursus like CAD, material science, mechanical and thermal finite element simulation, project management …

STRONG REQUIREMENTS IN DOCUMENTATION

The management, schedule and documentation requirements of the PEGASE project are closely derived from the CNES program management requirements, in a lighter version which is compatible with the students' capabilities in terms of technical and time resources.

At the beginning of each yearly project, students' team receive a complete set of requirements prepared by AJSEP, including a project management file and the technical specifications files for the motor components they are in charge of.

The project management file provides the detailed schedule of the yearly project and defines its main milestones. These milestones consist in several progress meetings and formal reviews, including:

- a presentation meeting where AJSEP trainers summarize and analyse with the students' team the schedule and the technical specifications of the project; a special attention is paid to the project reviews and the associated required documentation,
- a preliminary design review (PDR) where the students' team presents its organization and tasks sharing as well as its main technical choices for the motor component it has to develop,
- a critical design review (CDR), generally in two phases, where the students present the definition file, the justification file, the risks management file and the costs file of their project; this milestone is a mandatory step to allow the start of the manufacturing process,
- a test readiness review, in order to check that the motor components comply with the test specifications and safety requirements,
- a test results review, where the results of the tests are analysed and compared with the predictions, and where students have to summarize what they have learned throughout their project.

At each of the above reviews, students have to provide a complete set of documentation, either a first version or an updated one, including the design file, the justification file, the manufacturing file, the risks assessment and mitigation file and the costs file of their project.

The point of view…IMA Mérignac

These strong requirements in documentation are crucial to manage such an ambitious project which aims to achieve a full loop of design – fabrication – testing in only 9 months. For the student, updated documentation and regular meeting with partners make the objectives clear since the start of the project. Imposed milestones with indicators to measure the progress are a very efficient way to impose regular work despite heavy teaching schedules. More important, to an educational point of view, this organization offers the only opportunity to student during their scholarship to cope with real development and qualification process even if during small period and with reduced volume of documentation.

So as in industry, this documentation requirements force students to justify all key definition parameters, during the design phase, realization, and before testing. This ensures that risk is mastered and that qualification test would be ran by the end of the year. In the context of PEGASE organization with growing number of partner and tight schedule, such documentation is now necessary for every partner to refer to a common source.

At last, this documentation is important to record every year the growing experience in the design of these motor components. It forces student to record all possible data concerning their work most of whose are generally forgotten by the start of the next project. This growing database is very important for keeping the coordinates of subcontractors, so as price, time of manufacturing etc... Are also mentioned failed experiments so as quantitative data indicating the performance of manufactured components. Such an effort to transmit the information every year is important, the biggest difficulty being now to get lost in such a large amount of information.

COMPETITION BETWEEN THE STUDENT TEAMS

The technological competition is organised between the different students' teams. Each of them will receive a set of technical specifications in September, the same specifications for each type of rocket components (oxidiser tanks, combustion chambers and nozzles).

The objective is to design, analyse and manufacture one of the hybrid rocket components part within the scholar year and to demonstrate that it fulfils the above specifications.

	2006 -2007	2007 -2008	2008 -2009	total
Tank	3 designs	3 designs	2 designs	8
Combustion chamber		3 designs	2 designs	5
Nozzle			3 designs	3
				16

Table 1: AJSEP – PEGASE designs quantity

In order to avoid similar architectures for each type of components, each team will optimize one of the following design characteristics: mass, cost or technical breakthrough (or "crazy ideas").

The point of view…IUT Bordeaux 1

The fact that students with different background and different skills are working on the same components is really mind-opening. Major problems linked with the component design, process and test are faster mentioned, each team making one's contribution.

The difference in design goal is another of the key factors in the sub-project PEGASE success. This point incites students to find different design solutions from one team to another. In addition, it facilitates discussions between teams during the different reviews, because the fear to be "copied" by another team considerably decreases.

AN EXPERIMENTAL LOOP EACH YEAR

The interest for the students and for the PERSEUS project is to achieve the test before the end of the scholar year …and it is very tough to do. Managing by the schedule and the strict respect of dates for critical key points, more or less one per month, is essential. All the key point dates are fixed in June the year before.

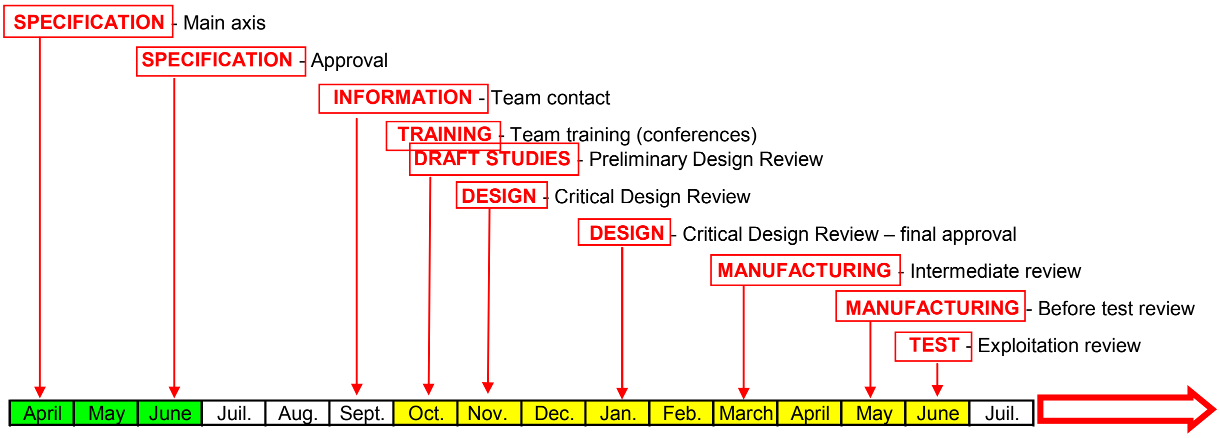

Figure 1 – AJSEP an experimental loop per year

The point of view…Arts et Métiers ParisTech, campus of Bordeaux-Talence
The main interest of the process is that it makes students aware of the different activities they will have to deal with during their carrier. It is very different from classical teaching, where all the subjects are taught quite independently. Here, technical and scientific aspects are important, but management too, particularly management of budget, time, and relationship while working under pressure. Furthermore, obligation of results imposes risk management, with alternative solutions when problems appear. Waivers may be accepted by AJSEP if the rocket component doesn't comply with the specifications but each time, justifications are required.
And the experimental reached results are particularly interesting: students have to compare them with estimations given by calculation and simulation, so that they can understand the limits of modelling (the importance of hypothesis, accuracy and field of use) and the difficulties of measuring.
That is why the project is so formative, both for students and for school which progress each year.

MEASURABLE RESULTS

At mid-June 2009, the structures of the year have been manufactured but not yet tested. The results on figure 2 are still preliminary. Nevertheless, after 3 years on the tank development, it is interesting to notice:

- a reduction of performance between year 1 and year 2 due to the increase of specifications
- a improvement of performance between year 2 and year 3…if the theorical rupture pressure is obtained.
- a high difference of cost and performance between the 2 teams

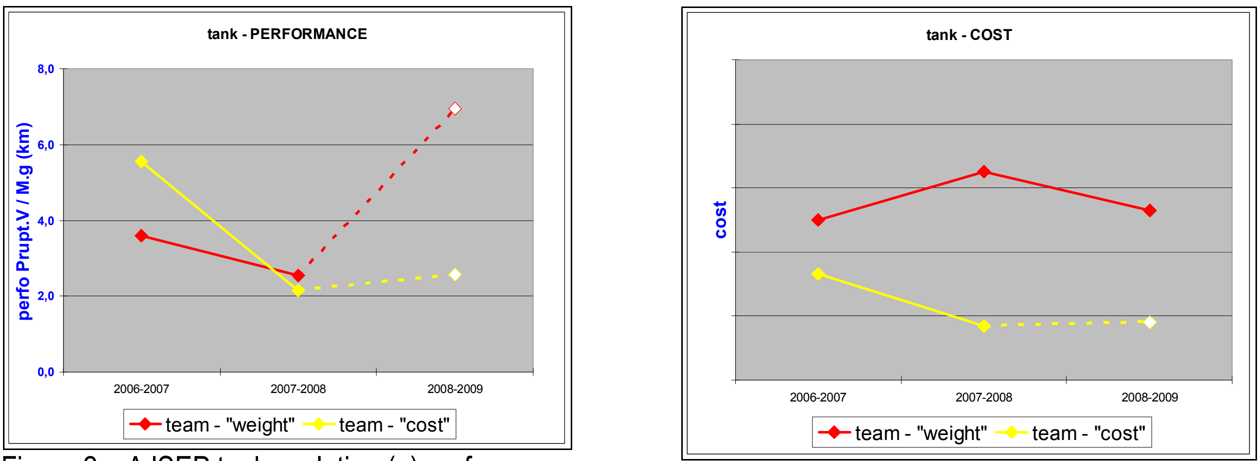

Figure 2 – AJSEP tank evolution (a) performance (b) cost

Arts et Métiers ParisTech results

From the beginning of the challenge, Arts et Métiers has to optimize the mass of the rocket components. Solutions with composite materials have been chosen, even if they are more expensive than metallic ones. Theoretical and practical abilities have been acquired, to conceive, calculate and manufacture filament wound structures, the evolutions of which are given in the following table.

	Year 1	Year 2	Year 3
Cryogenic tank	*1 tank, with aluminium liner and high strength composite*	*2 tanks, liners in Teflon® and polyurethane, high strength composite+ interstage skirts*	*2 tanks, liners in Teflon® , high strength composite+ interstage skirts and metallic frames*
Combustion chamber		*1chamber with thermal protection (silicone + carbon fibres), high strength composite+ interstage skirt*	*2 chambers with thermal protection (silicone + carbon fibres), high strength composite+ interstage skirt + paraffin*

Table 2: Rocket components made by Arts et Métiers

Manufacturing of the different components of cryogenic tanks and combustion chambers is partly made by subcontractors, but the students are completely in charge of the management and of the final assembly.

The main technical difficulty for cryogenic tanks is to manufacture the lightest liner, compatible with the use of liquid oxygen and with the filament winding process. We first chose to manufacture an aluminium liner but we realized that prohibitive costs were necessary to obtain small thicknesses (<1mm). That is why we then developed *Teflon®* -based liners (compatible with liquid oxygen), but the *Teflon®* sheets wrapping requires many technical adjustments to ensure a perfect tightness of the tank. Another solution was investigated with the University, consisting in manufacturing a polymer liner, but it is still not mature. Each year, important progresses concerning the manufacturing process can be noticed. Finite element calculations procedures have been established (particularly for the cylinders), in order to optimize the solutions. Simulation tools for filament winding now allow composite fibres placement in an optimal way.
Concerning the combustion chamber, we chose to use a silicone-based thermal protection, reinforced with carbon fibres. During years 2 and 3, we optimized the process of dimensioning the internal thermal protection. First we determined how long the different materials were exposed to high temperatures, thanks to transient calculations. Then we more precisely modelled ablation phenomena to reduce the thermal protection thickness and mass in the combustion chamber. An accurate characterization of the thermo physical properties of the insulation material is now necessary to further improve the dimensioning of the thermal protection.

A hydraulic test bench was conceived and manufactured during year 1, to test and qualify the different tanks and combustion chambers by pressurizing them up to 200 bar. For compression tests, we use the dedicated bench developed by IUT Bordeaux 1, and for thermal tests, the dedicated bench developed by University Bordeaux 1- CR IMA is used.

Figure 3: ENSAM 2009 (a)Filament winding of a combustion chamber, (b)Cryogenic tank and combustion chamber

IUT Bordeaux 1 results

IUT Bordeaux 1 students working on cryogenic tank and combustion chamber have to minimize the cost of the components. For the nozzle, the goal is to find a “crazy idea”. All the components made by IUT are listed in the table below.

	Year 1	Year 2	Year 3
Cryogenic tank	*1 tank with 2 aluminium parts made by spinning and welded together*	*2 tanks with 3 aluminium parts joined by welding*	*2 tanks with 3 aluminium parts joined by welding*
Combustion chamber		*1 combustion chamber (3 aluminium parts joined by welding) and a thermal protection (silicone + carbon fibres)*	*2 combustion chambers (3 aluminium parts joined by welding), a thermal protection (silicone + carbon fibres), and a fuel block*
Nozzle			*2 nozzles with tungsten throat and exotic wood exit cone*

Table 3: Rocket components made by IUT Bordeaux 1

Concerning the cryogenic tank and the combustion chamber, the use of a metallic solution enables low costs. The aluminium alloy selected for the cryogenic tank is fully compatible with Liquid Oxygen and get as well better mechanical properties at cryogenic temperature than room temperature. The cylinder part is obtained from a roll bended plate with a longitudinal weld. The tank extremities (with skirts) are directly machined and then welded to the cylinder. A special attention is required to the welding quality and inspection (Full X-ray inspection). As well, welded coupon are made and tested to refine the prediction of tank burst pressure.
Concerning the thermal protection, several materials have been tested year 2 (first year of combustion chamber design) such as mixed silicone and carbon powder, carbon fibres reinforced silicone, carbon fibres reinforced clay, … Carbon fibres reinforced silicone material appears to be the best candidate in term of thermal conductivity, ablation resistance and cost. Thanks to specific lectures proposed by the AJSEP, students were able to develop an analytical simulation tool in order to size the thermal protection according to exposure time, gaz temperature and type of fuel. The thermal protection manufacturing was completely realized at IUT Bordeaux 1 by students.

The nozzle is designed with an objective of « crazy idea ». Nevertheless, one major difficult is to find materials for the nozzle throat. The temperature conditions (up to 3500°K) and the oxidizing atmosphere leads us to use tungsten for the throat. The main innovation lies in material used for exit cone and thermal protection. First, natural petrified wood was used, but thermal tests made at IMA Mérignac have shown the brittle behaviour of this material. Then an exotic wood naturally rich in silica was used. All parts, with the exception of the tungsten nozzle throat made by a subcontractor, were machined at IUT Bordeaux 1 and then bonded with a structural adhesive. The figure 4 shows these different parts and the final nozzle.

Figure 4: IUT 2009
(a) Nozzle: separate parts and final assembly (upper left), (b) Combustion chamber during compression test

IMA Mérignac results

The IMA has been involved in PEGASE activities through four different projects:

- the design of cryogenic tank and combustion chamber with the requirement to propose innovative solutions,
- the design and fabrication of nozzle with reduced costs,
- the design and fabrication of thermoplastic liner as subcontractor of ENSAM cryogenic tank team.

Beside, IMA was in charge of the characterization of flame resistance and heat protection properties of the various thermal insulation systems developed by members of PEGASE for protection of nozzle and combustion chambers.

All these different studies were very challenging for students of IMA due to a reduced 5 to 6 month period in PEGASE activities before 5 month period as trainee in industry. The PERSEUS project gives our students many additional skills in space propulsion system, material properties, design, but also management documentations and relation with contractor and subcontractor. Projects objectives and main results are summarized in table 4.

Year 1	Year 2	Year 3
Flamme test : *Oxyacethylenic flame with K thermocouple for temperature measurement*	*Combustion chamber :* PEDH tank – combustible material also used as structural envelop	*Lost Cost nozzle :* Wood + graphite + tungsten composite nozzle. Tungsten parts obtained by plasma forming for nozzle throat
Cryogenic tank : Polyamide-imide tank “Rotomoulé”FAILED	*Cryogenic tank :* Polyamide – imide tank Machining of PAI blocks. Assembly with screws fillets + adhesive bonding	*Cryogenic tank liner :* Polyamide imide aluminium liner. All parts obtained by plastic deformation of plate. Adhesive bonding assembly

Table 4: Test facility and Rocket components made by IMA Mérignac

The students of IMA were in charge of project with innovation as main requirements. While IUT chose metal design as low cost solution and ENSAM composite as the lightest design, we consider polymer to be an innovative solution for structural part in space application. Polyamide-imide was promoted for his elevated mechanical properties at high and low temperature so as for oxygen compatibility. Up to now this material has been in aerospace application mainly for small parts obtain by machining. In the context of PEGASE, we explore innovative way to manufacture large size structure with this polymer material that are rotomolding, machining and assembly, high temperature forming. Up to now these developments are still not mature even if high temperature forming seems to be a promising solution for fabrication of large parts with small thickness of Polyamide-imide. To an educational point of view these projects give the students the opportunity to get more familiar with polymers properties and manufacturing which are not promoted in aerospace formations.

Also to promote the use of polymer for aerospace structural application, we proposed a PEDH monoblock combustion chamber. The design has to prove that the remaining thickness after complete reaction with the oxidant is sufficient to cope with the internal pressure. This development has now been stopped since paraffin is now preferred as solid propellant.

To face with other problematic we switch to the design of low cost component competing with other group on nozzle development. As low cost materials we chose wood as main constituent of the nozzle and to face the high temperature at the nozzle throat we chose tungsten deposited by plasma forming to reduce the material quantity. Others high temperature parts are made by graphite. Test will be running in summer 2009 to verify the performance of this solution.

As last contribution in PEGASE activity, IMA was in charge of flame test to qualify the thermal insulation systems used in nozzle and combustion chamber design by student group of IMA, IUT, ENSAM and mines d’Albi. Different kinds of systems were tested mostly made of silicon with or without carbon (fibers, powder ...), so as concrete or argil. All samples are exposed to oxyacetylene flame (3100°C) during 100s, with the temperature measured on the rear size to verify that temperature doesn’t exceed 100°C in this period.

Ecole des mines d'Albi –Carmaux results

This year (2008-2009) was the first time that a team from the Ecole des Mines d'Albi-Carmaux (EMAC) had the chance to take part to this project. The "Nozzle Red team" had to design and manufacture a "Low Mass Nozzle". This requirement - combined with the oxidative exhaust gaz environment - was the driver for inorganic material choices. On going research activities in the EMAC research Center of Tools Materials and Processes were important input for the final choices.
In the final configuration the nozzle is composed of four main parts: an aluminium machined part to ensure the interface with combustion chamber, a silicon refractory concrete nozzle throat, a insulating *Zircar®* based part machined from a flat plate with an laminate object manufacturing (LOM) technology, and a basalt fiber reinforced geopolymer matrix composite material as exhaust nozzle part (see figure 5). All parts are assembled with ceramic based glues.
Final mass is only 25% of the maximal allowed mass!
In order to reach this goal, transient thermal finite element simulation where performed and flame tests where conducted at IMA facilities. Type K thermocouples were inserted during manufacturing and where located at three different interfaces in order to be able the compare test prediction (see fig 5), with the future tests results

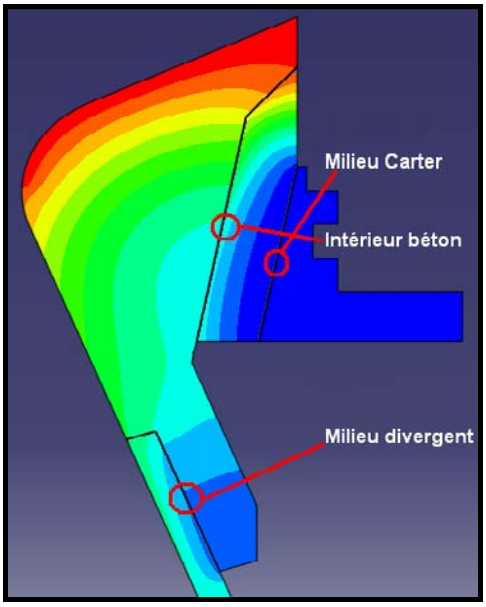

Figure 5 : the Ecole des Mines (a) Low Mass Nozzle (b) Nozzle Thermal simulation

CONCLUSION : KEY SUCCESS FACTORS

After 3 years, the principles taken into account have proven their efficiency:

- the students receive – through a dedicated technical education - the basis to achieve an ambitious project.
- the requirements give them a work relationships experience
- the competition between teams promotes the designs diversity and push the teams to do their best.
- The complete experimental loop done each year by the students is a solid project management experience.

The PEGASE sub-project results are measurable, either on designs variety, the performance point of view, or on the costs aspects.

….it is time now to be faced to motor firing test to do another technical step.