Technology maturation for the next generation re-ignitable cryogenic upper stage

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Abstract
Following the ESA decision in November 2012, both the Ariane 5 Midlife Evolution (A5ME) development as upgrade of the existing Ariane 5 launcher, as well as the preparation of NGL / Ariane 6 as its successor will be pursued further. Both launchers rely on enhanced performance Upper Stages including the cryogenic re-ignitable VINCI engine. Thanks to this re-ignition capability, this new Upper Stage shall be "versatile" in the sense that it shall fulfill customer needs on a broader spectrum of orbits, not limited to those typically used for commercial telecommunications satellites (i.e. mainly Geosynchronous Transfer Orbits, GTO). In order to meet the challenges of versatility, new technologies are currently being investigated. These technologies are mainly related –but not limited– to propellant management during the extended coasting phases with the respective heat transfer into the tanks and the required multiple engine re-ignitions.
Within the frame of the ESA Future Launchers Preparatory Programme (Period 2 Slice 1), the Cryogenic Upper Stage Technology project (CUST) aimed to mature critical technologies to such a Technology Readiness Level (TRL) that they can be integrated into the baseline A5ME Upper Stage development schedule. In addition to A5ME application, these technologies can also be used on the future next generation European launcher.
For CUST1.2, Astrium responsibilities comprise roles as both overall Upper Stage responsible and Prime Contractor, as well as being responsible for maturation activities for selected technologies.
After a short overview on the Astrium tasks as system responsible, this paper gives some details on the elaboration of requirements including the link to the application programmes (in particular A5ME). In the following sections, it describes the technologies selected for maturation, namely Sandwich Common Bulkhead, Versatile Thermal Insulation, Propellant Management Devices, a Gas Port Phase Separator and Propellant Pre-conditioning, followed by an evaluation on the technologies' impacts on a future Upper Stage and the maturation status achieved in CUST1.2, including an outlook on the next steps for follow-up activities.

1. Introduction

As part of the Future Launcher Preparatory Program (FLPP) from ESA, the Cryogenic Upper Stage Technology (CUST) program was dedicated to advancing enabling technologies for re-ignitable versatile cryogenic upper stages, jointly required by the near term and future launcher scenarios currently under consideration. More specifically, the activities were split into 1) confirming the technology needs and then 2) the maturation and advancement of technologies in particular for the short and mid-term scenario. The overall objective of CUST is the maturation of selected technologies for cryogenic upper stage up to a Technology Readiness Level (TRL) of 6.
In the frame of the CUST 1.2 contract between ESA and ASTRIUM a set of technologies was selected and matured according to Technology Development and Verification Plans (TDVP's). To execute those plans, functional specifications for each technology were established and updated later on (e.g. to streamline with A5ME latest status or to detail requirements further as necessary). The technology providers were managed by ASTRIUM prime while executing the activities (also including major re-views like SRR, PDR, CDR and a number of TRRs and PTRs) described in the TDVPs. For those reviews, ASTRIUM also reviewed and approved all delivered documentation. The activity was concluded with final presentations, including a Technology Readiness Level assessment as part of a Stage Impact Assessment from upper stage point of view which was prepared by ASTRIUM prime.
Two topics are additional to the nominal maturation activities, but are not specifically detailed in the frame of this paper: The TEXUS 48 sounding rocket flight to support the verification of critical functions of the ASTRIUM PMD

technology with two experiments and, as part of the so-called "Objective 2", a second loop of CUST 1.1 for a Jettisonable Fluid Ground Connector (JFGC) involving RUAG Switzerland. More details can be found in [1] and [2].

2. CUST 1.2 Overview and programmatic background

CUST 1.1 was started in February 2008 and completed in February 2009, with investigated technologies based on results of a previous ESA study named CTech and a technology selection workshop that resulted in a list of technologies proposed for maturation.

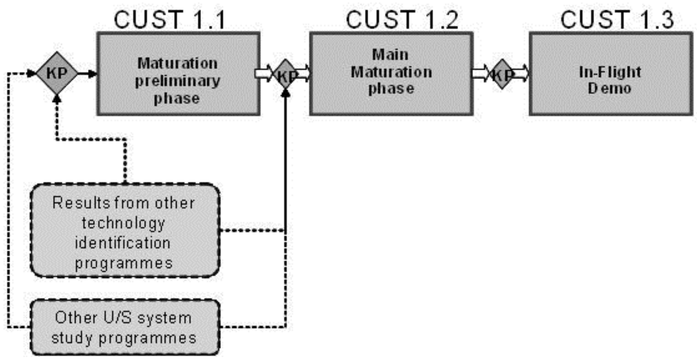

Figure 1: Overview of the CUST Program

CUST 1.2 was the logical follow on of CUST 1.1 (see Figure 1) and started in December 2009 with an ATP, fully contracted in mid-2010 and finished with the final presentation in December 2012. After selection by ESA, the following technologies were retained from CUST 1.1 and chosen for maturation within CUST 1.2:

- **T1**: External Versatile Thermal Insulation (VTI)
- **T2**: Inner wetted thermal insulation with sandwich common bulkhead (IWTI / CB)
- **T4**: Propellant management device (PMD, 2 concepts)
- **T5**: Propellant pre-conditioning prior re-ignition (PPC)
- **T6**: Gas port phase separator (GPPS)

As Prime contractor for the Ariane European launcher family in production and development, Astrium has the possibility to combine the system and technology level view and to ensure consistency in between the two areas. Therefore, the industrial organization is comprised of ESA as the customer with ASTRIUM GmbH as Prime for the CUST 1.2 activities, and the subcontractors (technology providers) managed by ASTRIUM GmbH. Various level 2 subcontracts throughout the European space community were involved in the CUST project contributing with their expertise to the success of the project (e.g. for preparation, execution of tests and hardware manufacturing) and supporting the maturation activities of ALAT, TAS-I, MT-A and ASTRIUM.

Figure 2: Level 1 subcontractors to the main contract of ASTRIUM GmbH

3. ASTRIUM Prime Activities

3.1 Project Management

As far as both management of the overall CUST project itself and the management of technology maturation activities is concerned, ASTRIUM acts as Prime Contractor and hence was in charge of:

- The establishment of the capabilities necessary to conduct the activities and adequately complete the project in terms of technical, schedule and cost targets with appropriate organisation and processes.
- The performance of the overall technical activities in accordance with the proposal and the contract, including the organization and overview of the Progress Meetings and reviews. The organization of the reviews was focused on the industrial organization only.

In particular as far as the management of its subcontractors was concerned, ASTRIUM acted as unique point of contact, leading technical, planning and financial negotiations under the lead of the project manager.

3.2 Engineering Activities

Functional specifications / A5ME coordination

System Engineering (SE) activities were of particular importance during CUST1.2 due to the programmatic set-up of the FLPP and A5ME activities as the closest application programme. Organised as parallel and - at least to some extent - independent programmes, coordination and regular coherence checks were essential in order to keep the CUST and A5ME programme aligned as far as necessary / possible.

In order to guide technology maturation from system point of view, functional specifications for each technology were established, with the main focus on A5ME as the closest application programme. Tailored to the individual technologies and their critical aspects, they included (list non-exhaustive):

- Update of missions requirements (new reference missions)
- Detailed mechanical loads & thermal environments (by flight phases where necessary)
- Ullage pressures and temperatures by flight phase
- Update of propellant budgets
- Definition of detailed filling scenarios
- Implementation of Load spectra & DTA requirements (depending on the technology)
- Detailed specification of geometrical constraints (e.g. U/S interfaces or forbidden / allowed areas)
- Maneuver sequences
- SCATE architectures
- Cleanliness requirements etc.

The main focus of the CUST/A5ME interaction was put on the establishment of the CUST1.2 requirements before and around the technology SRR's late 2009 / early 2010 in order to achieve a well-defined starting point for the technology maturation activities w.r.t. requirements status. Afterwards, during continuous meetings, the evolution of A5ME was monitored on a weekly basis. Amongst the important topics tracked were:

- A5ME Performance Improvement Taskforce (PITF)
- Evolution of reference missions / ballistic phase strategies
- Evolution of SCATE configuration
- Evolution of tank configuration / CB selection
- Evolution of loads and environments
- Evolution of thermal insulation concept

For the large A5ME reviews specifically (namely Launch System Concept Review LSCR and Launch System PDR), relevant A5ME stage documentation (e.g. U/S functional and technical specifications), as well as other technical notes related to thermal, mechanical or functional aspects) were reviewed in order to evaluate possible baseline changes and their potential impact on CUST.

On the one hand, there was an interest to closely couple the A5ME development and the technology maturation programmes (especially CUST) for those technologies that have been selected as part of the A5ME baseline. Harmonising the technology maturation thus assists in reducing the risk for the next A5ME development steps. On the other hand, it is also obvious that major maturation delays due to repeated requirement update cycles might lead to delays in TRL achievement in time for the critical A5ME milestones. As a result, it was decided to harmonise mostly thermal environments and insulation concepts with the status as of late 2010 for the AirLiquide PMD / PPC technologies. This resulted in several Requests for Deviations that were made applicable to the AirLiquide PMD and PPC technology maturation. For the remaining technologies, these requirements were NOT made applicable, since the impact was considered to be limited to justify major programmatic disruption of the individual activities.

Stage impact assessment

The Stage Impact Assessment aims to provide the follow-up or application programme with detailed information on what has been achieved and what still needs to be done in terms of maturation / development activities for each technology. Additional objectives of this activity are, from an Upper Stage point of view, to assess the impact of the technologies and their main critical performance parameters on the A5ME Upper Stage as compared to the baseline at that time, as well as the identification of impacts if the individual technologies do not meet the requirements as specified in the FSP's. The Stage Impact Assessment was elaborated in two major steps:

- Step 1 for technologies' System Requirements Reviews (SRR's); main aim was a first assessment as to what the technologies' critical parameters were and what impact those parameters might have on U/S main parameters, such as performance, operations, programmatics etc.
- Step 2 as consolidation of Step 1 at the end of the technology maturation activities, reflecting the final technology status; update with the latest figures from large scale testing and analyses

Detailed activities were ([3], excerpt):

- Comparison between A5ME baseline and new technology w.r.t. to main engineering budgets (e.g. mass, propellant budget, thermal budget, power budget, cost, reliability etc., tailored for the individual technology w.r.t. its criticality)
- Performance of sensitivity studies for critical areas up to SRR, analyses / evaluation with final maturation results near the end of the technology maturation
- TRL assessment:
    - TRL evaluation used a finer granularity, providing the assessment for four large areas:
        - Most important functions (as a basis for the maturation activities)
        - Analyses (as a basis for justification of feasibility)
        - Materials (as a basis for analytical justifications)
        - Processes (as a basis for the H/W to be manufactured)
    - For the "Functions" sections, the ESA TRL scale could be used more or less directly for the evaluation; as a general "rule of thumb", TRL 6 (" [...] Representative model or prototype system […] tested in a relevant environment […] ") was awarded in case "two out of three" categories were fulfilled for testing, the categories being "Large scale", "relevant acceleration conditions" and "cryogenic fluids". In case of deviations, the TRL was reduced accordingly.
    - For the other sections, since the nature of the individual technologies themselves differs greatly, said TRL scale was tailored, enlarging and detailing it, and also taking into account Ariane 5 heritage if necessary

4. Technology maturation overview

The following chapters present, separately for every technology, a summary of the activities performed in frame of the CUST 1.2 project. First the technical concept of the technology is presented very briefly with a sketch of the technology itself. The second part of the activity summaries the TRL assessment from stage point of view. The final chapter provides the main conclusions regarding each individual technology and the activities performed. For details of the technology, tests and maturation activities performed please refer to [1] and [2].

4.1 Versatile Thermal Insulation (VTI) - TAS-I

A next generation cryogenic upper stage has to comply with a multitude of requirements and contribute to the launcher mission flexibility, versatility and performance. The potential versatile missions with long coasting phases increase the need of an insulation system optimized not only for the on-ground and ascent phase but also for the coasting phase. This results in the need to have a thermal protection of the propellant tank that is effective on ground (mainly free convection), during ascent (mainly aero-thermal heating) and during the coasting phase (mainly radiation in vacuum and external heat fluxes).

Taking all this into account the VTI is designed to provide optimized insulation capability for the different phases during a versatile mission: MLI during the coasting phase and insulating foam for the on-ground and ascent phase. To optimize the performance the mass of the protective sandwich cover panels is jettisoned during the ascent phase.

TAS-I VTI - Technical concept and activity overview

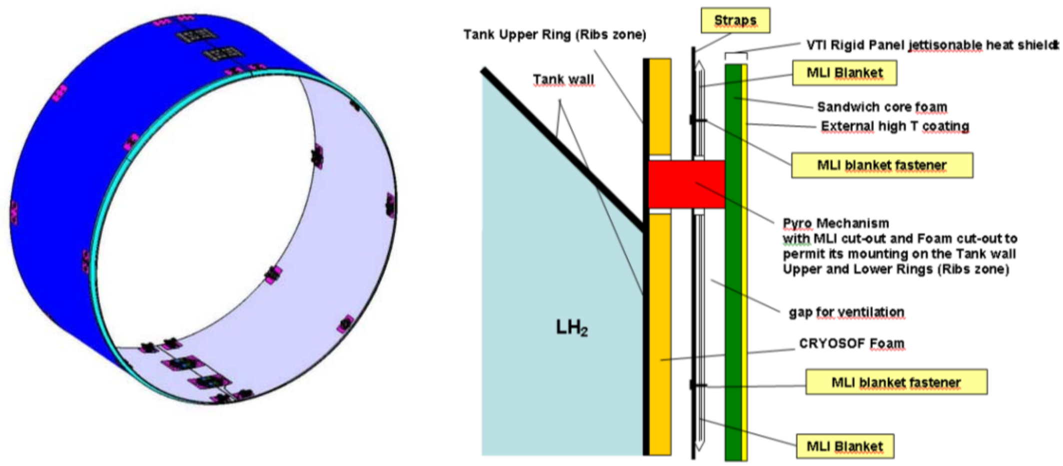

Figure 3: VTI 2-panel configuration and schematic insulation concept [2]

A set of jettisonable sandwich panels (skins: CFRP and epoxy resin system; core: foam), forming a cylindrical envelope around the LH2 tank, is mounted via separation mechanisms located at the upper and lower skirts on the exterior of the upper stage. The panels themselves are interconnected and mounted to the stage via several pyro nuts. They are provided with an external layer of closed cell thermal insulation, intended to shield from aero-thermal heating during ascent. An additional element of this concept is an MLI mounted between the baseline stage insulation and the internal skin of the panels. The cavity between stage side and panel needs to be purged with a dry inert gas and vented during ascent. Despite the small gap, the MLI shall remain intact after jettisoning of the panels. The technology aims to:

- Minimize the performance penalty on the GTO configuration by abandoning of devices and equipments not relevant for GTO mission, the number of supports not needed for GTO mission (but for versatile) should be a minimum.
- Maximize commonality of the versatile stage configuration by implementation of additional hardware (versatile kits) either replacing or complementing the GTO hardware.

The identified target technologies have to be proven in accordance with the TRLs/IRLs to which the development is aimed prior to their potential application to flight hardware. In the frame of the technology maturation, material samples, scaled demonstrators (SD's) and Scaled model (SM) have been tested using the following overall logic:

- Phase 1: Technologies Assessment and Preliminary Design (ending with PDR)
- Phase 2: Technologies Detailed Design (ending with CDR)
- Phase 3: Manufacturing and Testing (ending with FP)

The test items complexity is basically summarized by the following for categories:

- Basic Materials Sample testing
- Breadboard testing (e.g. technological joints, etc.)
- Scaled Demonstrators testing "SD" (separation test, thermal aspects, MLI depressurisation)
- Scaled Model testing "SM" (vibration)

VTI - TRL Assessment from System Point of View

In summary, Table 1 shows the TRL status for the above mentioned areas:

Table 1: Astrium TRL assessment for VTI

Area	TRL Status (min/max)	Remarks
Functional feasibility	3-5	Mostly 5 in priority one functions with exceptions for separation (test was cancelled, TRL 3) and flutter evaluation (TRL 4)
Analyses	3-5	Analysis TRL: Separation: 3-4, mechanical: 5, thermal: 4-5, Aero-elastic (flutter): 4
Material Characterisation	5	-
Processes	4-5	TRL 4-5 for SM due to difficulties in panel manufacturing, TRL 5 for basic processes

Some tests which have been excluded from the maturation for programmatic reasons (e.g. project re-orientation) are needed in order to take the last step the verification towards TRL 6, as well as more detailed investigations concerning flutter. However, it has to be mentioned that with the analyses and tests performed a high overall maturity of the VTI was reached and the development shows a good status at the end of this part of the development process.

Next Steps for VTI

The major suggestions for improvements of the technology maturation are (excerpt):

- The VTI should be implemented/optimized for one defined launcher geometry including the interfaces at the top and bottom of the VTI (aerodynamic ramps). This activity should include a trade-off regarding the total number of panels taking into account all relevant aspects (thermal performance, flutter, separation, reliability, etc.)
- Thermal performance of mechanisms connection should be improved.
- Reliability analysis should be repeated and improved after trade-off.
- A set of coupled load analysis should be done with the relevant launcher model to update the loads (this should include at least: random, QSL, sine, acoustic, aero-dynamic and aero-thermal)
- The main suggestions for future activities are (see chapter 3.7.3 of [RD 35] for additional suggestions and de-tails):
- Increase maturity of panel manufacturing by building full size segments or full size model
- Increase maturity of the separation by performing a scaled or full size separation test (in air if air is considered for analysis activities)
- Increase maturity of aero-elastic (flutter) analysis
- Increase maturity of thermal performance function by mechanism bread board thermal tests and representative scaled model thermal tests

4.2 Sandwich Common Bulkhead (SCB) - MT-Aerospace

A Common Bulkhead as a Sandwich structure has the potential to reduce significantly the heat transfer between the LOX and LH2 tank compartments, thus minimizing LH2 boil-off mass and significantly reducing the risk for LOX sub-cooling or icing. As a consequence, it also removes U/S restrictions in terms of ballistic phase strategy. The activity of MT-A for the Sandwich Common Bulkhead (SCB) comprised the definition and analysis of suitable concepts, material characterizations on sample level, thermal breadboard testing and the demonstration of the key manufacturing steps by dedicated application breadboards. Starting point of the investigations was a MT-A proposed concept approach consisting of a specific core material, situated in-between two thin aluminium face sheets, and an innovative thermal decoupling element at the equatorial region.

MTA SCB - Technical concept and activity overview

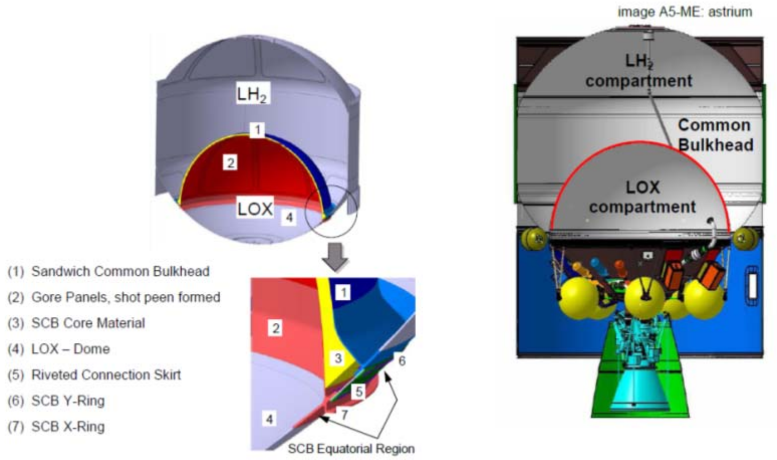

Figure 4: Upper Stage concept with Common Bulkhead separating LH2 & LOX

The activity comprised the definition and analysis of suitable concepts, material characterizations on sample level and the demonstration of the key manufacturing steps by dedicated application breadboards. The main achievements can be summarized as follows:

- A comprehensive data base of the main core materials (foam and honeycomb) for RT and cryogenic temperatures. Moreover, the corresponding test methods have been developed.
- A broad range of promising SCB concepts was established and analysed. Even though some critical points are still open, the feasibility for the major areas of the finally selected concept has been demonstrated.
- The basic manufacturing steps of a SCB have been developed and verified on a scaled bread-board level.
- A number of potential NDI methods were identified able to detect typical failures (sample level).

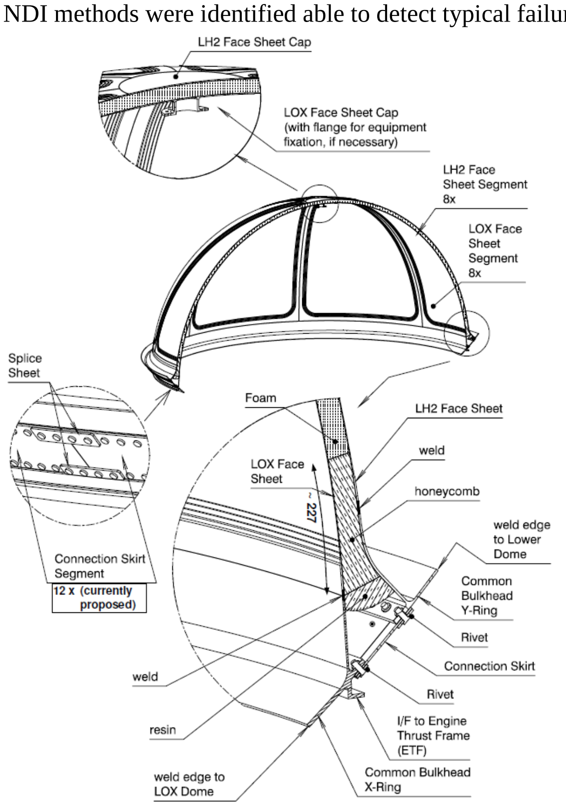

Figure 5: Overview of the SCB design proposed by MT-A

SCB - TRL Assessment from system point of view

In summary, Table 2 shows the TRL status for the above mentioned areas:

Table 2: Astrium TRL assessment for SCB

Area	TRL Status (min/max)	Remarks
Functional feasibility	4	-
Analyses	3	structural feasibility not shown, especially in equator region
Material Characterisation	1-6	TRL 1: Epoxy Resin TRL 6: Facesheets
Processes	2 - 4	TRL 2: NDI TRL 4: Thermoforming

Generally speaking, the achieved maturity during CUST1.2 level is lower than originally expected (Target: TRL 4). What is also obvious is that there is a large scattering in the values. This is due to the fact that a multitude of processes and different materials needed to be used for the latest baseline SCB concept, due to some technical challenges detected during the course of the maturation activities. Since the respective activities to increase maturity levels for every single item were not planned at the beginning of the project, only a limited number of them could be accommodated within the given time frame and limited project budget.
However, although the goal of overall TRL 4 was not fully reached for this complex technology, a great step forward was taken towards maturation of a functional SCB, especially for some of the critical manufacturing processes. A broad range of promising SCB concepts have been investigated and analysed. The concept feasibility was demonstrated for the undisturbed dome regions of the concept, but further investigations are still necessary to understand the structural behaviour of the critical equator region and topics are identified for further developments in future activities as described above. A comprehensive data base of the main core materials (foam and honeycomb) was also achieved for room temperature and cryogenic temperatures. However, in order to further reduce the risk for a follow-up development programme, some important further steps need to be taken, the most important of which are thermo-mechanical testing and increase of process robustness.

Next Steps for SCB

For a next step towards TRL 4, the following activities are identified to be necessary and recommended (excerpt):

- Further and intensive basic investigations regarding the development of reliable foam material law and failure criterion, mandatory to obtain correct stress results for strength verification (including poisson ratio and foam compressibility)
- Continuation of sample testing to enlarge statistical database for strength allowables
- Sample tests regarding the I/Fs of the material combinations foam/HC/epoxy/Face sheets
- Compatibility tests of foam-to-foam gluing adhesives.

In order to reach TRL6, one can envisage manufacturing and thermo-mechanical testing of down scaled- or full-size demonstrators as the next steps. Additional manufacturing demonstrators (scaled or full-scale) are considered necessary to further mature the technology with respect to:

- Foam application on full size
- Gore panel forming with full size / scaled geometry
- Welding / sealing / gluing technologies

4.3 Propellant Management Device (PMD) - Astrium

The upper stage propellant tank of A5ME is configured as a two compartment liquid oxygen (LOX) and liquid hydrogen (LH2) tank. The restart capability of cryogenic upper stages is a key function for the next generation of upper stages. This includes the Ariane 5 ME as well as a potential Ariane 6 upper stage. The capability to carry out missions such as GTO/GTO+ or LEO with a low weight penalty is one of the interesting scenarios for the future. The ASTRIUM PMD technology maturation is focused on propellant management in both tanks, thus achieving the main functions of providing sufficient propellant in the right pressure and temperature state to the engine, as well as making sure that the liquid is bubble free. The main assets of the technology are to have propellant available without additional settling and a payload gain for missions with multiple re-ignitions and to prevent LOX outlet warming. In addition, dedicated elements could be used for specific needs (e.g. outlet design without start basket function).

AST PMD - Technical concept and activity overview

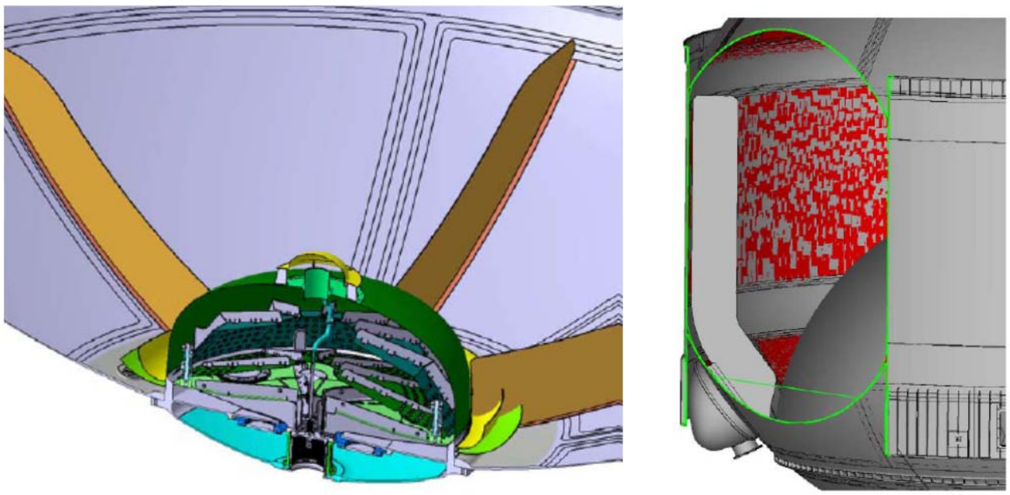

Figure 6: AST PMD concept implemented in LOX (left) and LH2 tank (right)

Generally there are two different ways to reach an engine restart, either by providing a pre-acceleration by a secondary propulsion system or by propellant management devices which store a sufficient amount of liquid at the tank outlet. This liquid may then be used whenever needed. The PMD in this context becomes more and more beneficial with respect to the mass penalty, the larger the number of restarts anticipated. The provided concepts for cryogenic Propellant Management devices are therefore of interest for all future re-ignitable upper stages. It was therefore the goal to develop two PMD concepts, one for LOX and one for LH2, using A5ME as a reference configuration. A large number of tests were carried out during the project in order to verify the PMD concepts (amongst them a 1:1 scale functional test in LN2 conditions of both LOX and LH2 PMD). All tests were accomplished successfully. The tests also include two modules on the TEXUS 48 sounding rocket verifying the functionality of the devices. The combination of the different aspects with differently scaled models and differing environments provides thorough information on the PMD performance and also proves the functioning of the proposed concepts. All mission phases can be handled, and the devices are compliant with the given requirements.

AST PMD - TRL Assessment from system point of view

In summary, Table 3 shows the TRL status for the above mentioned areas:

Table 3: Astrium TRL assessment for AST PMD

Area	**TRL Status (min/max)**	**Remarks**
Functional feasibility	4-6	TRL 4 for LH2 PMD mechanical aspects, TRL 6 for LOX PMD functional topics
Analyses	6	-
Material Characterisation	9	Standard materials
Processes	5	Screen manufacturing as driver

The results of the activity show that a substantial achievement was made for the technology within the project's duration and the activities were completed satisfactorily so that in the end the PMD reaches its targeted overall TRL of 5/6.

Next Steps for AST PMD

The PMD technology maturation status is already resulting in a good TRL, however there are a few activities which can still be recommended for a more detailed verification of some aspects of the technology. Those recommendations are listed below:

- Ground testing with real fluids
- Full scale Al2219 manufacturing and vibration test
- Suborbital flight under LH2 conditions

Although all those steps are considered beneficial for the PMD development, a main focus lies on the real scale tests with the real test fluids as well as a suborbital flight with LH2. Those steps will mature the technology to a TR level of 6.

4.4 Propellant Management Device (PMD) - AirLiquide Advanced Technologies (ALAT)

The upper stage propellant tank of A5ME is configured as a two compartment liquid oxygen (LOX) and liquid hydrogen (LH2) tank. The ALAT technology maturation is focused on the management of the propellant, combining the PMD technology and the propellant pre-conditioning in both tanks in order to achieve the main functions of providing sufficient propellant in the right pressure and temperature state to the engine, and also making sure that the liquid is bubble free. The main asset of the technology is its mass and the low degree of complexity.

ALAT PMD - Technical concept and activity overview

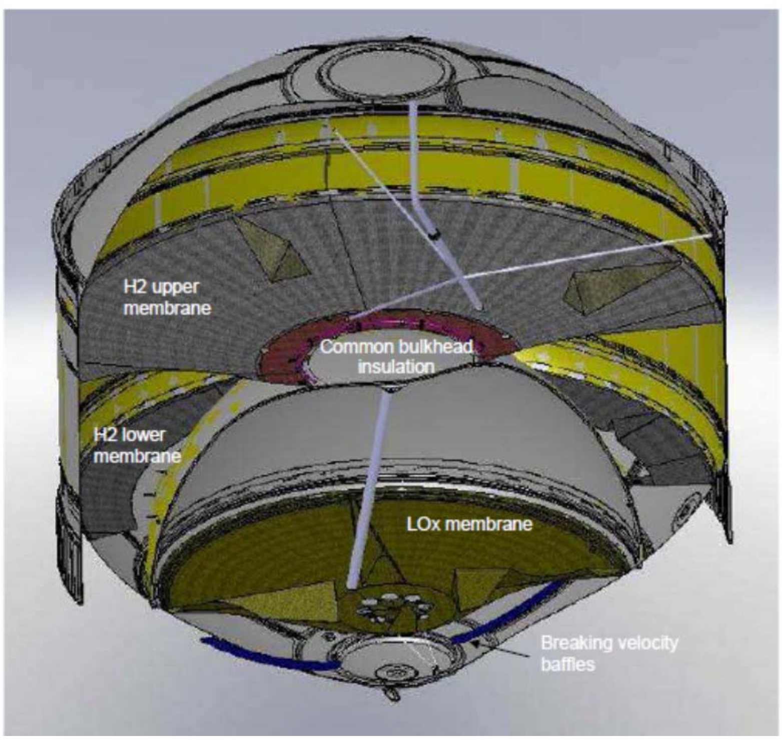

Figure 7: ALAT PMD concept - implementation in LOX and LH2 tank

Engine re-ignition following low gravity ballistic phase is a main feature of planned future Ariane 5 upper stage. Before engine re-ignition, the propellant has to be available in sufficient quantity, and in acceptable thermodynamic state (pressure, temperature) to feed the operating engine until all propellant is re-settled at the outlet by the thrust produced, thus enabling boost completion. ALAT proposes to achieve it by the use of geometric device, not relying on capillary forces:

- two soft membranes in RLH2
- one soft membrane and breaking velocity baffles in RLOX

On LH2 side, this PMD can provide liquid for engine ignition without settling need in isothermal conditions. However, settling or roll is necessary to evacuate bubbles created by LH2 vaporization, due to pressure cycles and/or heat fluxes. In the absence of roll, the use of propulsive vent is recommended in that purpose (coupling with AL PPC technology). LH2 PMD also limits boil-off losses during ballistic phases and maneuvers, by preventing the liquid to wet the upper part of tank. On LOX side, GH2 propulsive vent (coupling with AL PPC technology), or auxiliary thrust (with a mass penalty), is used for final settling of LOX. The LOX PMD reduces settling needs by keeping the propellant in the lower part of the tank before settling (membrane) and improving the damping of fluid motion during settling (breaking velocity baffles).

The solution has been functionally designed with an extensive use of CFD tools. The ability of the code to simulate the behavior of cryogenic propellant in tanks has been verified since several years by Air Liquide in the frame of ECA projects (for propulsive phases) and Research and Technologies national projects (for low gravity phases). Yet, two breadboard tests performed in the frame of CUST 1.2 project enabled to confirm the ability of the CFD code to model correctly specific configurations encountered in PMD/PPC technologies:

- “sloshing and wave tests”, for strong fluid motion (waves, motions damping)
- “neutral buoyancy tests” for static positioning in tank under reduced gravity

In addition, reduced scale specimens of the H2 and O2 membranes were manufactured and implemented on a scaled down demonstrator for ground functional tests. The ability of the membranes to withstand the ground operations such as filling, pressurization, depressurization and draining could thus be evaluated.

ALAT PMD - TRL Assessment from system point of view

In summary, Table 4 shows the TRL status for the above mentioned areas:

Table 4: Astrium TRL assessment for ALAT PMD

<table>
<tr><th>Area</th><th>TRL Status (min/max)</th><th>Remarks</th></tr>
<tr><td>Functional feasibility</td><td>5/6</td><td>TRL 6: Phases with acceleration
TRL 5: Phases under micro-g</td></tr>
<tr><td>Analyses</td><td>6</td><td>-</td></tr>
<tr><td>Material Characterisation</td><td>Not assessable</td><td rowspan="2">not assessed; material / process characterization done in another project</td></tr>
<tr><td>Processes</td><td>Not assessable</td></tr>
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The results of the activity show that a substantial achievement was made for the technology within the project's duration and the activities were completed satisfactorily so that in the end the TRL as indicated by ALAT (TRL5) is considered realistic by ASTRIUM for reasons listed above, with some elements even at or close to TRL 6. PMD reaches an overall TRL of 5.

Next Steps for ALAT PMD

The PMD technology maturation status is already resulting in a good TRL, however there are a few activities which can still be recommended for a more detailed verification of some aspects of the technology. Those recommendations are listed below:

- PMD mock-up
- Suborbital flight for transient phases
- Interface lines/membranes

Even though all of those steps are beneficial for the PMD development, a main focus is the suborbital flight as it offers a lot of verification possibilities which are significant for a step towards a technology TRL of 6.

4.5 Propellant Pre-conditioning (PPC) - ALAT

The upper stage propellant tank of A5ME is configured as a two compartment liquid oxygen (LOX) and liquid hydrogen (LH2) tank. The ALAT technology maturation is focused on the management of the propellant, combining the PMD technology and the propellant pre-conditioning in both tanks in order to achieve the main functions of providing sufficient propellant in the right pressure and temperature state to the engine, and also making sure that the liquid is bubble free.

ALAT PPC - Technical concept and activity overview)

Engine re-ignition following low gravity ballistic phase is a main feature of planned future Ariane 5 upper stage. During the several hours of ballistic phase, thermal energy is entering LH2. On LOX side, bulk liquid should rather cool because of heat leaks toward LH2, but local heat fluxes can introduce bubbles, particularly in the feed line. Before engine ignition, the propellants have to be available in acceptable thermodynamic state (pressure, temperature, quality) to feed the engine. A propellant pre-conditioning operation is thus required to:

- cool LH2
- remove bubbles that can have formed locally in both LH2 and LOX tanks and/or feed lines.

Comparative studies have been performed to select the proper means to perform LH2 cooling and LH2/LOX de-bubbling resulting in the following recommendation:

- LH2 cooling by de-pressurization
- Bubble evacuation from propellant by settling

Within CUST 1.2 activities, the AIR LIQUIDE solution was matured on the basis of a specification based on the A5ME project:

- tank geometry and insulation system
- missions (MEO, GTO+/GTO+ and LEO)
- thermal environment
- dynamic environment and maneuvers
- thermodynamic state of LH2 before engine re-ignition

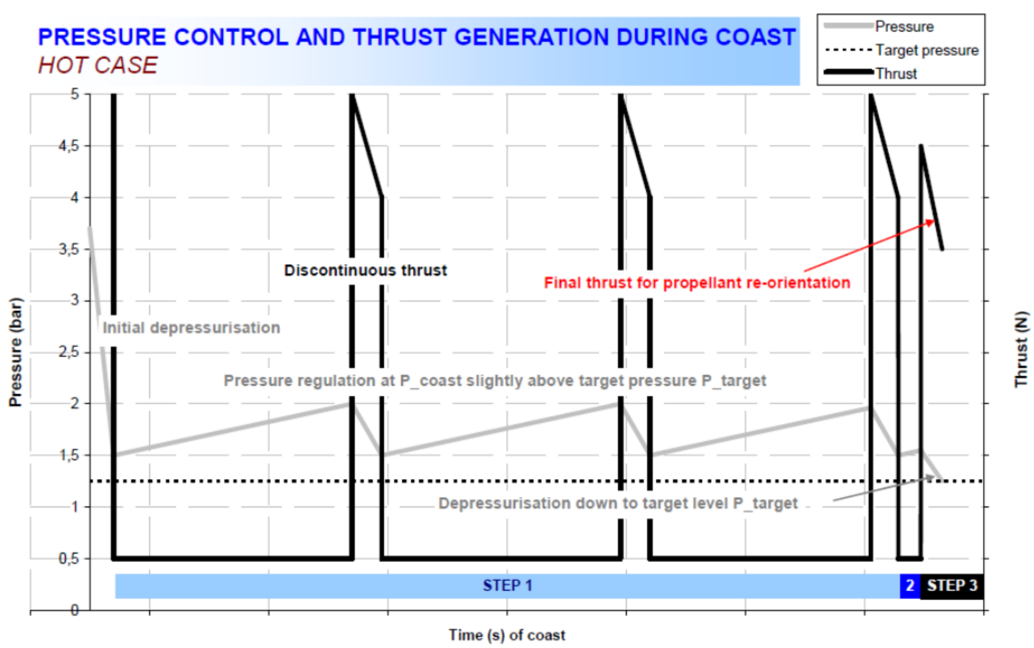

Figure 8: ALAT PPC - pressure control concept

LH2 thermal conditioning

LH2 thermal preconditioning is performed by pressure control. The targeted liquid temperature is reached by achieving the corresponding saturation pressure (or less) before re-ignition sequence. Pressure control is performed by tank vent control.

To improve overall mass budget of both PMD and PPC technologies, the propulsive vent is used for liquid settling, which can benefit:

- propellant positioning prior restart
- boil off losses

The pressure control logic was studied and defined with a specifically developed mathematical model. Parameters were adjusted to fit with all the studied mission constraints. Complementary mathematical models were also used to get relevant information necessary for the Pressure control model (Heat flux, wetted surface de-pending on LH2 mass and dynamic environment, nozzle operation) as well as to evaluate GHe penalties for re-pressurization. Scaled down demonstrator tests enabled to adjust the pressure control model in ground conditions, and showed that it can be considered as a satisfying tool for preliminary tuning of PPC hardware (orifice diameter) and pressure control logic.

De-bubbling

Two solutions have been studied for de-bubbling:

1. Use of the acceleration provided by chill-down in order to “de-bubble”. It was studied by CFD to evaluate the potential of the “free” chill down acceleration (imposed anyway for other needs) for de-bubbling issues. With further studies of bubble diameter and validation of the model used to define it, it could be sufficient for de-bubbling needs.
2. Settling with auxiliary thrusters before re-pressurization, in order to cover the need of small bubbles evacuation. It is performed by two hot-gas attitude control thrusters (for equilibrated thrust), with an associated hydrazine mass penalty. The sequence has been designed through an analytical tool. Ground tests enabled to validate the correlation chosen to evaluate the bubble rise velocity, in conditions not so far from flight application. Besides, these tests suggest that bubble diameters in flight might be larger than anticipated, thus further reducing the settling needs.

ALAT PPC - TRL Assessment from system point of view

In summary, Table 3 shows the TRL status for the above mentioned areas:

Table 5: Astrium TRL assessment for ALAT PPC

<table>
<tr><th>Area</th><th>TRL Status (min/max)</th><th>Remarks</th></tr>
<tr><td>Functional feasibility</td><td>5/6</td><td>TRL 5: For debubbling</td></tr>
<tr><td>Analyses</td><td>6</td><td>-</td></tr>
<tr><td>Material Characterisation</td><td>Not applicable</td><td rowspan="2">Since PPC is mainly an operation, no material / process maturation was conducted</td></tr>
<tr><td>Processes</td><td>Not applicable</td></tr>
</table>

The results of the activity show that a substantial achievement was made for the technology within the project's duration and the activities were completed satisfactorily so that in the end the TRL as indicated by ALAT (TRL5) is considered realistic by ASTRIUM for reasons listed above, with some elements even at or close to TRL 6. PMD reaches an overall TRL of 5.

Next Steps for ALAT PPC

The PMD technology maturation status is already resulting in a good TRL, however there are a few activities which can still be recommended for a more detailed verification of some aspects of the technology. Those recommendations are listed below:

- Suborbital flight under LH2 conditions (e.g. for verification of bubble behavior)
- Adding additional H/W (e.g. valves) and implementation of the PPC into a working environment

4.6 Gas Port Phase Separator (GPPS) - Astrium

The upper stage propellant tank of A5ME is configured as a two compartment liquid oxygen (LOX) and liquid hydrogen (LH2) tank. The AST GPPS technology maturation is focused on the management of the propellant (i.e. avoiding wetting of the gas port) in both tanks and thus to achieve the main function of providing liquid free tap-off of ullage during all flight phases. The main asset of the technology is to provide liquid-free gas during active SCATE phases and the prevention of icing and freezing in the lines and valves.

AST GPPS - Technical concept and activity overview

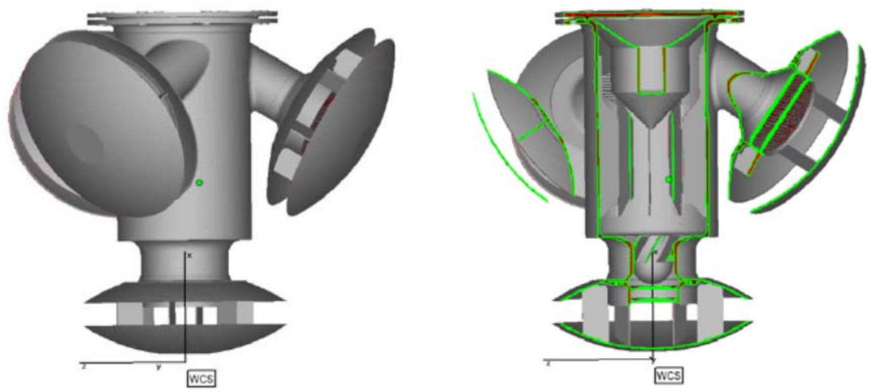

Figure 9: GPPS concept design

It contains four trumpet-shaped inlet ports covered by shield plates and a cylindrical central section, the so called reservoir. The design for the LOX and LH2 tank is identical which is also beneficial for streamlining the development and a future production process. The GPPS main function is to separate any liquid that enters the device from the gas phase and thus to ensure that a defined volume of gas is available for expulsion. Capillarity is the driving physical principal behind the design of the GPPS and is used both in the double screen element and in the vanes inside the reservoir. The device is a passive device, without valves or other moving parts. The device is able to fulfill the specified requirements and ensures liquid-free gas venting via the gas port. The same device may be used for both LH2 and LOX. In this context the device is usable not only for the reference configuration A5ME, but also e.g. for an Ariane 6 upper stage without changing the configuration.
A large number of verification tests were carried out under 1g as well as 0g conditions, both with non-cryogenic test liquids (e.g. HFE-7500), LN2 as well as LH2. In summary the tests show that the concept will work as anticipated. The GPPS is considered a feasible technology which may increase the robustness of future stages with respect to liquid-free gas venting.

AST GPPS - TRL Assessment from system point of view

In summary, Table 3 shows the TRL status for the above mentioned areas:

Table 6: Astrium TRL assessment for AST GPPS

Area	TRL Status (min/max)	Remarks
Functional feasibility	5	-
Analyses	6	-
Material Characterisation	9	Standard materials
Processes	5	Screen manufacturing as driver

Some tests which have been excluded from the maturation before the beginning of CUST1.2 are needed in order to take the last step the verification towards TRL 6.

Next Steps for AST GPPS

The GPPS technology maturation status is already resulting in a TRL which is matching the target. However there are a few activities which can still be recommended for a more detailed verification of some aspects of the technology. Those recommendations are listed below:

- Suborbital flight
- Full scale manufacturing and vibration test
- Sloshing test

5. Conclusion

Regarding the overall TRL, the original target of TRL 5/6 was achieved for all functional technologies. However, as a result of the inherent differences between the technologies, the overall TRL achieved for the "functional" technologies ("equipments") is higher when compared to the manufacturing-driven technologies ("structures") since the maturation effort could be focused on fewer critical items.

Nevertheless, for all technologies, significant progress has been made towards the TRL targets; especially for the most critical items (functions, processes, etc.). These targets have generally been reached using detailed analyses as well as large-scale testing, various breadboard and drop tower testing under micro-g condition. For those tests, scaled and full scaled models have been built supported by many hardware suppliers and manufactures spread throughout Europe.

As a consequence, the remaining development risk for any follow-up programme has been reduced significantly thanks to these maturation activities. From U/S point of view, these encouraging results ultimately justify the technology choices made during the early phases of the FLPP CUST programme.

6. Acknowledgements

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