Development of an Attitude Control and Propellant Settling System for the aA5ME Upper Stage

D. Kajon[(1)], F. Masson[(2)], T. Wagner[(1)], D. Welberg[(1)], T. Büchner da Costa[(1)] , J. Mansouri[(3)]

[(1)] Airbus Defence & Space - Space Systems: Airbus-Allee 1, 28199, Bremen, Germany
[(2)] CNES: Direction des lanceurs, 52 rue Jacques Hillairet ,75612 Paris Cedex, France
[(3)] ESA: Directorate of Launchers, 52 rue Jacques Hillairet, 75012 Paris Cedex, France

email: daniele.kajon@astrium.eads.net

Abstract

For the adapted Ariane 5ME Upper Stage, an Attitude Control and Propellant Settling System is being developed. Ariane 5ME, the next version of the Ariane launcher, will require for its new cryogenic upper stage attitude control capabilities for roll control, propellant settling, payload release, coasting phases and for stage de-orbiting. More functions and performance are requested to the attitude control system in comparison to the current upper stage ESC-A, due to long coasting phases, de-orbitation requirements and re-ignition capability of the new Vinci engine enabling versatile missions. During the re-ignition preparation phase, dedicated propellant settling thrust needs to be provided to allow for a restart of the Vinci engine after the ballistic phase. Various propulsion systems were considered as potential candidates due to the wide range of requirements, while extensive work of requirements engineering was performed to reduce this range. For the down-selection of technologies, several aspects have been considered; among them performances, capacity of fulfilling the mission specific needs, robustness, availability and technology maturity, recurring and non-recurring costs, compliance with REACH regulations and selection of ITAR free hardware. Due to the variety of functions and resulting thrust levels, multiple subsystems are used to fulfil the required tasks: a Cold Gas Reaction System (CGRS) using boil-off gas from the main hydrogen propellant tank and a Hot Gas Reaction System (HGRS) consisting in a “fully independent” system. Other subsystems also contribute to propellant settling function: the Purge Flow System (PFS), which is already on-board to ensure the correct purge of the Vinci engine chill-down propellants, and the Vinci engine to be used as a cold gas thruster with helium already on-board for tank pressurization purposes. CGRS technology is derived from the ESC-A SCAR subsystem. HGRS down-selection led to consider only liquid mono-propellant propulsion systems. Liquid bi-propellant, solid and hybrid propulsion systems were before also considered as candidates at an earlier development step due to the requirements linked to stage separation and de-orbitation. A HGRS allows more flexibility and higher thrust level than CGRS, permitting their use also for propellant settling and for the de-orbitation function; however it is heavier, more expensive and complex. Trade-offs were performed during the development taking into account the several aA5ME missions (GTO, GTO/GTO+, LEO), leading to the selection of the actual baseline of the Attitude Control and Propellant Settling System for the aA5ME Upper Stage looking for the best compromise between performances, costs, reliability, versatility, development risks and operational constraints.

Nomenclature

A5ECA	Ariane 5 Evolution Cryotechnique A
A5ES	Ariane 5 Evolution Storable
A5G	Ariane 5 Generic
aA5ME	adapted Ariane 5 Mid-life Evolution
ADN	Ammonium Dinitramide
CGRS	Cold Gas Reaction System
CT	Cold (Gas) Thruster
EBS	Equipment Bay Structure
ELS	Elongated Lower Skirt (of LH2 tank)
EPC	Etage Principal Cryotechnique (Principal Cryotechnic Stage)
ESA	European Space Agency
ESC-A	Etage Supérieur Cryotechnique - A (Upper Cryotechnic Stage - A)
GTO	Geostationary Transfer Orbit
HGRS	Hot Gas Reaction System
HT	Hot (Gas) Thruster
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
LSPDR	Launch System Preliminary Design Review
MIB	Minimum Impulse Bit
PFS	Purge Flow System
SCAR	System de Contrôle d’Attitude et Roulis (Attitude and Roll Control System)
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
TBC	To be confirmed
TRL	Technology Readiness Level

Introduction

The aA5ME Program [1] [2] proposes an evolution of the A5ECA launcher to satisfy future market demands for increased payload masses and extended mission flexibility. It will use a new Upper Stage featuring the Vinci engine, more powerful and with re-ignition capability.

To satisfy the demands, additional functions and performance are requested to the attitude control system in comparison to the current upper stage ESC-A. During re-ignition preparation phase, dedicated propellant settling thrust needs to be provided for a restart of the engine after the ballistic phase.

This article introduces the considerations and trade-offs performed during the development of the program until now, which lead to the actual baseline of the Attitude Control and Propellant Settling System for the aA5ME Upper Stage. Candidate concepts are identified and traded; multiple sub-system down-selection and description of the selected systems are given.

The updated aA5ME architecture, which represents the best compromise selected between performances, costs, reliability, versatility, development risks and operational constraints, is described. At the end, the future outlook and conclusions are shown.

Main missions

3 main missions have been retained for aA5ME, which shall be qualified at the end of the development.

- *GTO mission with perigee decrease (GTO PD)*: mission with only one Vinci boost. First part is similar to the actual A5ECA GTO mission. After payload release, the perigee is decreased, in order to limit the remaining time of the aA5ME Upper Stage spent in space.

- *GTO mission with direct de-orbitation (GTO DDO)*: mission with two Vinci boosts. First part is similar to the actual A5ECA GTO mission. Then, after the payload release, a boost is provided in order to de-orbit the stage. This de-orbitation boost is currently foreseen to be performed with the Vinci engine, which is therefore re-ignited; however also the option with a hot gas system de-orbitation boost is considered, as it would remove the needs for the Vinci re-ignition preparation and re-boost.

- *GTO/GTO+ mission*: mission with two Vinci boosts. After first Vinci boost, the first payload is released on a GTO trajectory. A long ballistic phase of 2,5 hours follows. Vinci is then re-ignited, in order to increase the perigee, which makes it easier for the satellite to reach the geostationary orbit, and also using a decreased apogee to avoid the pollution of the geostationary orbit by the stage. Then, the second payload is released.

Secondary missions are missions that should be qualified, but accepting a certain delay (from 6 months to 2 years) in development with respect to the main missions. Among secondary missions, the most studied was the LEO mission, which was once a main mission and it is the most dimensioning e.g. for propellant under-loading and payload mass.

- *LEO mission*: mission with three Vinci boosts. First Vinci boost is to reach an intermediate orbit, with apogee of 300 km. Second boost is to circularise the orbit. The payload is then released. A last boost of the Vinci performs the de-orbitation of the stage.

The aA5ME Attitude Control and Propellant Settling System has been designed taking into account the needs of GTO PD, GTO DDO, GTO/GTO+, LEO.

Needs for an Attitude Control and Propellant Settling system

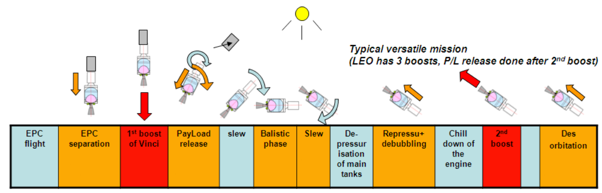

Figure 1: Sequences of a typical versatile mission

The attitude control needs are similar to the one of the ESC-A stage, which were fulfilled with a cold gas reaction system, using LH2 boil-off resources. The distancing needs for upper stage separation are also similar to ESC-A needs, which were fulfilled with solid separation rockets.

These needs are:
- During Upper Stage separation, longitudinal acceleration shall be provided for distancing the stages from each other and to have good thermal exchanges for an effective engine chill down.
- During Vinci boosts, the spin motion induced by the engine nozzle shall be compensated (roll control).
- For payload release, a series of manoeuvers need to be performed to have the specific spin state on 3-axes orientation required by the payload, and ensuring it reaches a safe distance from the stage.
- For ballistic phase, the stage is first re-oriented in a direction favourable for the sun orientation. Then, the stage is set in a spin motion in order to limit the thermal fluxes entering the propellant and to avoid hot spots. At the end of the ballistic phase, the stage is spun down and re-oriented in the direction of the re-boost.
- For engine re-ignition preparation and payload release, the perturbing torques, mainly due to propellant motion in the tanks, have to be compensated, so that the stage remains in a stable orientation.

Especially for payload release, the thrust should be a compromise between the propellant needed to perform the manoeuvers (a low thrust induce lower propellant consumption) and the duration of the manoeuvers (high thrust induce a lower manoeuvres duration). High thrust is also helpful for the distancing of the upper stage from the payload, but could induce more propellant disturbance. Attitude control may require very small Minimum Impulse Bits (MIB), below 10 Ns, to perform precise manoeuvres e.g. for payload release.

Compared to ESC-A, new needs appear for aA5ME, which are the needs for propellant settlement and for stage de-orbitation.

- For all versatile missions, there is a need to settle the propellant at Vinci engine re-ignition preparation. Re-ignition preparation is a set of manoeuvers aiming at conditioning of the propellants, chilling down the engine and restoring the tank pressures compatible with turbopumps good functioning. Settling the propellant during these phases prevents liquid ingestion in the pressurization system, limits the thermal exchanges with ullage volume, increases the gaseous bubble transport in the liquid to the surface and insures that

there is always enough propellant at the tank outlet, i.e. inlet of the engine feeding lines. In addition, a longitudinal acceleration is necessary to have good thermal exchanges during the engine chill down.
- For LEO mission, the propellant must be settled during separation of the Upper Stage from the first stage EPC. Propellant settling prevents sloshing and induced pressure drop in the ullage volume in the tank. Due to propellant under-loading, the ullage volume is very large for LEO mission and the pressurisation system would not be able to compensate the pressure drop. With propellant settling, the pressure drop is strongly reduced.
- De-orbitation boosts for missions with direct de-orbiting. The requested ΔV could be either provided by the Vinci engine re-boost or, as an option, with a hot gas reaction system with relative high longitudinal thrusts.
- The stage shall be controlled during all flight phases, including passivation, with additional constraints compared to ESC-A.

The settling thrust should be adequate to compensate external perturbations, but not too high to avoid shutting on/off for propellant saving, leading to re-amplification of the sloshing. Settling thrust does not require a low MIB. Thrust to be provided for the de-orbitation boost is considerably higher than attitude control thrusts.

The several needs of the aA5ME versatile missions lead to a set of requirements comprising:

- Distancing requirements
- Attitude control requirements
- Propellant settling requirements
- De-orbitation requirements

Candidate concepts, preliminary trade-offs and first architecture

At the beginning of the design process for the attitude control and settling system, the initial requirements spread from low thrust and small MIB requirements for payload release, combined with very heavy payloads and challenging release strategies, up to requirements with steady state high thrust in the range of kN for distancing after stage separation and high ΔV to be provided for de-orbitation, in addition to a high variety of different functions to be performed.
This leads to a large candidate selection process and various propulsion systems were considered for the several functions:

- Cold Gas, with high pressure storage, solid gas generator or liquid storage, i.e. LH2 boil-off use
- Liquid Mono-Propellant, e.g. N2H4, ADN, H2O2, …
- Liquid Bi-Propellant, e.g. MON/MMH, H2/O2, …
- Solid, e.g. ESC-A Separation Rockets, …
- Hybrid

A look on the basic system assets/drawbacks was required in order to select the most suitable concept for the attitude control and propellant settling system. Several aspects have been considered, among them performances, capacity of fulfilling the mission specific needs, i.e. thrust level over time, robustness and simplicity of the concept, availability, technology maturation and TRL, recurring and non-recurring costs, compliance with REACH regulations limiting the use of hazardous and/or toxic chemicals, selection of ITAR free hardware and focus on the European market, in compliance with ESA practices. These aspects are summarized in Table 1.

	Assets	Drawbacks
Cold Gas (high pressure storage)	▪ Simple Technology ▪ Low cost ▪ Available during all mission phases ▪ Comply with REACH	▪ Low Isp
Cold Gas (solid gas generator)	▪ Simple Technology ▪ Comply with REACH	▪ Low Isp ▪ Ignition and burning time constraints
Cold Gas (liquid storage LH2 boil-off)	▪ Simple Technology ▪ Low cost ▪ A5ECA experience (high TRL) ▪ Boil-off for free ▪ Comply with REACH	▪ Low Isp ▪ Limitation on use (e.g. re-ignition)
Liquid Mono-Propellant (Hydrazine)	▪ High Isp ▪ A5G/A5ES experience (high TRL) ▪ Available during all mission phases	▪ REACH Regulation ▪ Complex Technology
Liquid Mono-Propellant (ADN)	▪ High Isp ▪ Comply with REACH ▪ Available during all mission phases	▪ Lower TRL ▪ Propellant Cost ▪ Complex Technology
Liquid Mono-Propellant (H2O2)	▪ Medium Isp ▪ Comply with REACH ▪ Available during all mission phases	▪ Lower TRL ▪ Storage of H2O2 ▪ Complex Technology
Liquid Bi-Propellant (MON-MMH)	▪ Highest Isp ▪ Available during all mission phases ▪ ATV exp. (high TRL)	▪ Technology with highest complexity
Solid Propellant	▪ High Isp ▪ ESC-A exp. (high TRL) ▪ Simple System ▪ Comply with REACH	▪ Limited use due to ignition and burning time constraints
Hybrid Propellant	▪ High Isp ▪ Available during all mission phases ▪ Comply with REACH	▪ Lowest TRL ▪ Complex Technology

Table 1: Assets/Drawbacks of the potential candidates

Extensive work of requirements engineering was performed, during which almost all propulsion systems were traded as potential candidates. For the down-selection of technologies, a main driver was the evolution of the requirements: the missions have not been changed, but an extensive work was performed to re-engineer the requirements and to reduce from high ranges of thrust and

MIB requirements down to lower ranges to come to a manageable set of requirements for attitude control and propellant settling, optimizing the use of cold gas resources and looking for the best possible combination for the different missions.

Based on analyses and trade studies, the candidates were narrowed down at programme decision gates and this led to the choice of the architecture for Launcher System Preliminary Design Review (LSPDR), consisting of the combination of cold gas and hot gas mono-propellant systems, whose development hence was initiated. The usage of the cold gas system was considered up to the extent of the estimated available resource in terms of time and mass.

The functions allocated to the different systems for each mission are depicted in Table 2. The first architecture retained for LSPDR is shown in Figure 2.

	GTO PD	GTO DDO	GTO/GTO+	LEO
Separation Phase	HGS	HGS	HGS	HGS
Roll Control Boost Phase	CGS	CGS	CGS	CGS (TBC)
1st P/L Release Phase	CGS (complete)	CGS (partially)	CGS (partially)	CGS (partially)
1st P/L Release Phase	CGS (complete)	HGS (remaining)	HGS (remaining)	HGS (remaining)
2nd P/L Release Phase	-	-	CGS (complete)	-
Re-Ignition Preparation	-	HGS	HGS	HGS
Perigee Decrease	HGS (TBC)	-	-	-
Direct-Deorbitation	-	Vinci	-	Vinci
Apogee Increase	-	-	HGS	-
Attitude Control up to Apogee	HGS (TBC)	-	-	-
Attitude Control up to De-Orbiation	-	HGS	-	-
Coasting Phase in settled Mode	-	-	CGS	CGS
Attitude Control in Coasting Phase	-	-	HGS	HGS
Passivation Phase	CGS	CGS	CGS	CGS (TBC)

Table 2: Allocation of functions for each mission

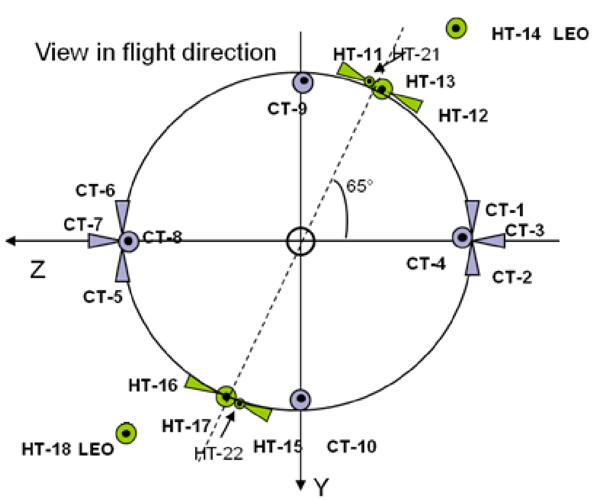

Figure 2: First A5ME architecture

Cold Gas Reaction System

The CGRS is designed in similarity with the ESC-A Attitude and Roll Control System (SCAR); it is a cold gas reaction system fed with gaseous hydrogen tapped from the hydrogen tank through the pressurization circuit. The aA5ME CGRS flow schematic is shown in Figure 3.

During the Vinci engine boost phase, the CGRS performs the roll control of the stage and is fed with gaseous hydrogen tapped from the engine regenerative circuit; the two other axes are controlled by the engine gimballing. During the ballistic phase, it performs 3-axis control (roll, pitch and yaw) and can provide longitudinal thrust if necessary. CGRS valves can be also used to depressurize the LH2 tank if necessary.

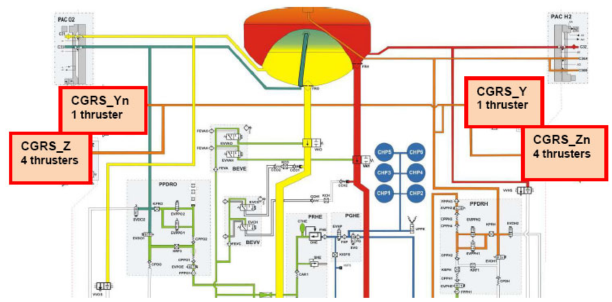

Figure 3: CGRS flow schematic

The thrusters are mounted on the Elongated Lower Skirt (ELS) of the LH2 tank, similar to the outer SCARs from ESC-A. The CGRS clusters consist of a baseplate with valves-nozzles assembly connected to the upper stage pressurization circuit.

For system analysis at upper stage level, a model was developed on EcosimPro v4.4.0 software platform [3]. It is used as a numerical functional performance tool of the CGRS to predict and validate the thrust level and specific impulse, the pressure evolution and evaporated masses in the LH2 tank. The EcosimPro aA5ME CGRS Model schematic is shown in Figure 4.

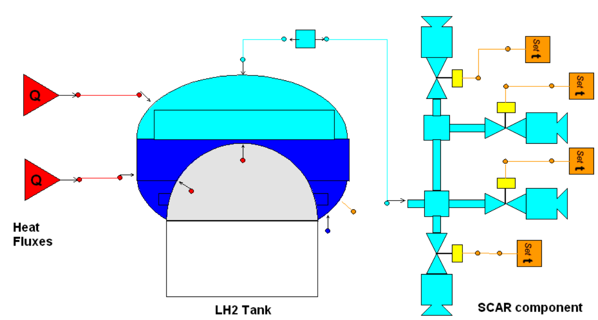

Figure 4: EcosimPro aA5ME CGRS Model

An initial thrust around 55 N for the CGRS, about the level of ESC-A SCAR, was found to be a good compromise on aA5ME as well.

Hot Gas Reaction System

The HGRS is a “fully independent” subsystem of the aA5ME upper stage, allowing generation of thrust during all mission phases. This is of interest for upper stage separation, de-orbitation of the stage or during re-ignition preparation phases, when propellant settling is required and the main tank pressure is raised back to nominal level after de-pressurisation for temperature conditioning.

The thrust levels possible with the HGRS are typically one order of magnitude higher than the ones feasible with the CGRS. Therefore manoeuvre durations can be greatly reduced and thus allowing a higher flexibility w.r.t. mission operations.

The HGRS in its layout proposed post-LSPDR featured 4 longitudinal mono-propellant thrusters and 4 propellant bladder tanks for GTO-DDO. The system was based on mono-propellant technology and hydrazine was chosen as the reference propellant, since ADN and H2O2 green propellant technologies were not sufficiently mature yet. Experience with hydrazine was available from the existing A5G and A5ES launchers attitude control systems. However, in order to comply with REACH regulations, maturation studies were initiated in parallel to the hydrazine development programme in order to allow for a change of technology.

In order to comply with safety reasons on ground, a dedicated pyro valve assembly was integrated in the system to prevent any undesired hydrazine leak or hot gas reaction on ground. This pyro valve assembly is only activated during EPC flight, shortly after lift-off.

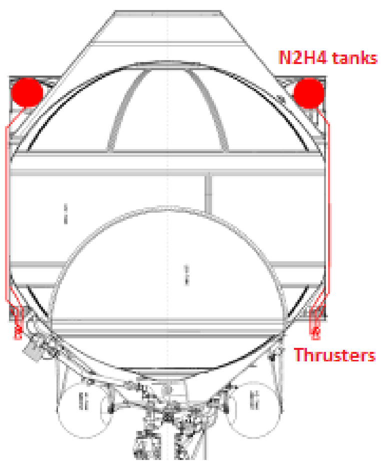

Figure 5: HGRS accommodation on aA5ME

With respect to the accommodation of the HGRS on the stage, different positions of the tanks and thrusters have been traded with focus on system weight and achievable lever arms leading to an accommodation of the tanks on the upper part of the stage on the Equipment Bay Structure (EBS), the feed lines going through the cable duct and the thrusters internally on the lower part of the ELS, rotated by 90° each. Figure 5 depicts the accommodation of the HGRS on the aA5ME upper stage.

The selected HGRS system re-used hardware components developed for the Ariane 5 G and Ariane 5 ES launchers, mainly the hydrazine bladder tanks, the pyro valve assembly and the 400 N thrusters, giving a high credibility of component maturity and availability.

The HGRS could be installed as a kit for versatile missions, thus allowing a cost and mass optimised approach for nominal GTO missions without re-ignition. Figure 6 presents the post-LSPDR design of the HGRS with a 6 tanks configuration.

Hydrazine is no more the reference now, H2O2 being selected as the baseline. More details on the H2O2 HGRS are given in the "*Future Outlook*" paragraph.

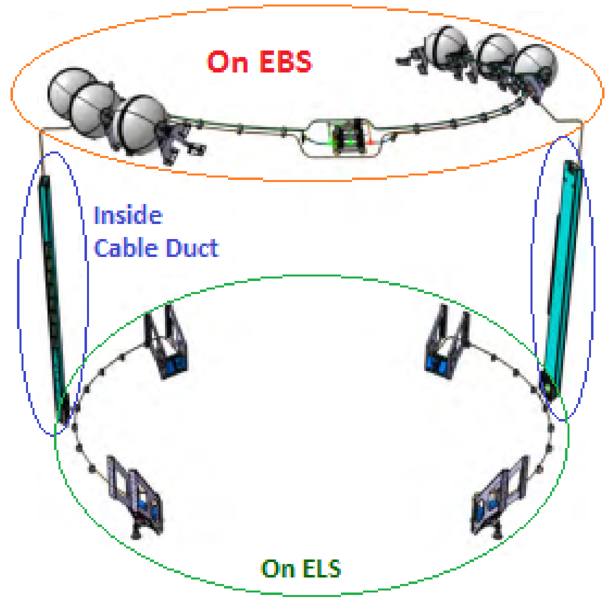

Figure 6: HGRS post-LSPDR Design

Purge Flow System

Before Vinci ignition during EPC ascent phase and Upper Stage separation the engine chill-down has to be performed as well as prior to re-ignition. The oxygen and hydrogen Purge and Balancing nozzles located on the ELS are used to purge the chill-down flows via the stage purge circuit.

As a secondary function, they also provide longitudinal thrust which can be used to support the stage separation; these thrusters are additionally connected to the out-gassing circuit of the main propellant tanks to provide longitudinal thrust in case of need, e.g. during re-ignition preparation or for payload distancing, as already performed in A5ECA.

The thrust profile during the chill-down depends on the chill-down sequence and on the purged mass flows. Approximately 25 N up to 70 N are expected in total. The thrust level during out-gassing depends on the tank thermodynamic conditions with a maximum thrust level also around 70 N. The thrust between the Purge and Balancing nozzles will be equilibrated by using dedicated calibration orifices in the two branches of the purge circuit to provide the stage with a pure longitudinal thrust without excessive disturbing torques.

Helium Flushing

As another possibility to create longitudinal thrust, the aA5ME propulsive system allows to use the Vinci engine as a cold gas thruster when not used for the main boosts. Helium gas is already on-board for tank pressurization and

valve command purposes, and therefore it could be used to create thrust by expelling it through the Vinci engine.
Two possibilities are available by the stage and engine flow architecture: the helium can be expulsed by LOX dome flushing i.e. the oxidizer engine injection dome is flushed with helium, or with a feed lines flushing where about 30 g/s of helium are flushed into the main feed lines and expanded through the engine nozzle. Both possibilities make use of calibrated orifices to limit the mass flow. These circuits main function is to flush the engine on ground and before long coasting phase to remove trapped liquid propellant; their use for thrust creation is an interesting additional function.

The thrust level that is created with helium flushing depends on the gas temperature and on the engine thermal state. In total it could vary between 60 N to 75 N.

The use of helium flushing for thrust generation shall however be limited, as the resources on-board are limited and the impact on the helium budget is significant. The advantage to use helium flushing shall always be traded with the need to bring additional helium vessels and therefore additional mass.

Main trade-off

The Attitude Control and Propellant Settling System architecture as presented in Figure 2 remained to be optimized because several open points were identified, namely the confirmation of the optimized initial thrust level for the HGRS and a re-assessment of the re-ignition preparation sequence. Both points were not mature in terms of concepts and therefore requirements at the time of LSPDR.

The architecture change that was proposed after LSPDR was driven by two main aspects: the first one was a change of assumptions related to the use of cold gas and helium resources during the re-ignition preparation. Up to LSPDR, it was not foreseen to use these resources preventing therefore settling and attitude control with helium, which was needed for re-pressurization of the LH2 tank for re-ignition. This assumption was relaxed after LSPDR following the optimization of helium resources, and analyses on the helium budget and on the Vinci use as cold gas thruster. The consequence was that the CGRS and helium flushing could be used during re-ignition preparation allowing an optimization of the use of HGRS and CGRS during this flight phase. Along with a refinement of the durations for re-ignition preparation, the impact on helium consumption was studied and considered acceptable. The second aspect driving the review of the architecture was the need to reduce costs and complexity of the architecture, e.g. the reduction of the number and type of thrusters. In terms of feasibility assessment and performance, the controllability of all maneuvers during all flight phases was also studied.

Three additional architectures were traded on top of the LSPDR architecture:

- a "*simplified HGRS + CGRS*" solution featuring the same CGRS as during LSPDR but only 4 longitudinal hot gas thrusters, all with the same thrust level.
- an "*all cold gas*" solution, without HGRS on board.
- an "*all hot gas*" solution, without CGRS on board and limited use of helium and LH2 boil-off resources.

The "*simplified HGRS+CGRS*" solution was then selected as the baseline, featuring 10 cold gas thrusters and only 4 longitudinal hot gas thrusters.

The Table 3 summarizes qualitatively the trade-off between the selected options:

	LSPDR	Simplified HGRS + CGRS	No HGRS	No CGRS
Performances	REF	++	-	--
Costs	REF	+	++	+
Reliability and risk mitigation	REF	-	--	-
Compatibility with functions	REF	=REF	-	-
Versatility for different missions	REF	+	-	-
Development risks	REF	=REF	+	+
Operational Constraints	REF	=REF	+	+

Table 3: Main trade-off table

To summarize the criteria, which were studied and used for the trade-off:

Performances
As mentioned above, efforts were made to find the best share of manoeuvres between HGRS and CGRS resulting in an optimised overall mission performance. Major inputs were the definition of optimum HGRS thrust level (found to be around 200 N as initial thrust), the optimised use of cold gas and helium resources for parts of the mission, the consideration of the different dry masses of the two systems, the use of engine chill-down purge flows to generate thrust with the PFS, the optimised use of propellant residuals and LH2 boil-off to feed the CGRS and finally the helium flushing through Vinci. It was also identified that the use of the HGRS for de-orbitation provides a very interesting gain in performance, which needs to be traded mainly with other criteria such as risks, costs, complexity and operational constraints.

Costs
In terms of both non-recurring and recurring cost, the impact of having an HGRS on board is significant. The

reduction of complexity in terms of numbers of valves, thrusters, tanks and thrust levels improves the overall cost figure. Therefore the “*cold gas only*” solution remains by far the most competitive in terms of cost.

Reliability and risk mitigations

The reliability of the different systems (CGRS, PFS, HGRS, helium flushing) was assessed and their proposed optimised use was subject to a risk analysis. This analysis showed that a full suppression of the HGRS could be feasible, mainly by using PFS and LOX dome and feed lines helium flushing instead of HGRS for settling purposes, CGRS for all roll control and the VINCI engine itself for de-orbitation boost. More details on the potential HGRS suppression are also given in the “*Future Outlook*” paragraph.

Compatibility with functions

In the frame of the feasibility analysis for optimised architecture, an important aspect was the assessment of compatibility with functions (e.g. attitude control, propellant settling, de-orbitation, etc.) of the different systems (CGRS, PFS, HGRS, helium flushing). The result was a re-allocation of the functions to be performed throughout the mission for each system.

Versatility for different missions

At LSPDR, the architecture was still depending on the mission. A major goal of the re-engineering of the requirements and the distribution of functions and architecture optimisation was to find an architecture that is optimised for the main missions and allows keeping the required versatility of the overall launcher.

Development risks

The risks in developing a new HGRS are higher than for the CGRS especially because the experience with such cold gas systems is available from the existing ESC-A SCAR featuring a similar thrust level. Another important aspect was the availability of technologies on the European perimeter: the candidate selection was done between the existing hydrazine technology, with an adaptation to reach the optimised thrust level, or new developments of HGRS systems using green propellants. Due to the REACH regulations, the use of hydrazine is no longer the preferred option and the “green” alternative using H2O2 propellant was selected. Since this technology is under maturation in Europe higher development risks and efforts must be taken into account. More details on the H2O2 HGRS are given in the “*Future Outlook*” paragraph.

Operational constraints

Operational constraints were investigated, e.g. in terms of thermal control and different handling constraints of the propellants on ground. The considered flight constraints include the accommodation of the HGRS within the upper stage depending on the proposed technology, the not yet tested use of the PFS during chill-down (thrust level and efficiency remain to be confirmed) as well as the optimal use of cold gas resources.

Updated aA5ME architecture

Following the results of the main trade-off shown in the previous chapter, the aA5ME Upper Stage Attitude Control and Propellant Settling System architecture is updated, as depicted in Figure 7.

This architecture features the use of a CGRS composed by 10 cold gas thrusters (CT-1 to CT-10), unchanged from the first preliminary trade-off architecture and located on the ELS of the LH2 tank. The architecture of the oxygen (O2BN+O2PN) and hydrogen (H2BN+H2PN) PFS purge and balancing nozzles is also unchanged, also on the ELS. On the contrary, the HGRS has been considerably simplified, featuring now only 4 longitudinal hot gas thrusters (HT-1 to HT-4) also located on the ELS.

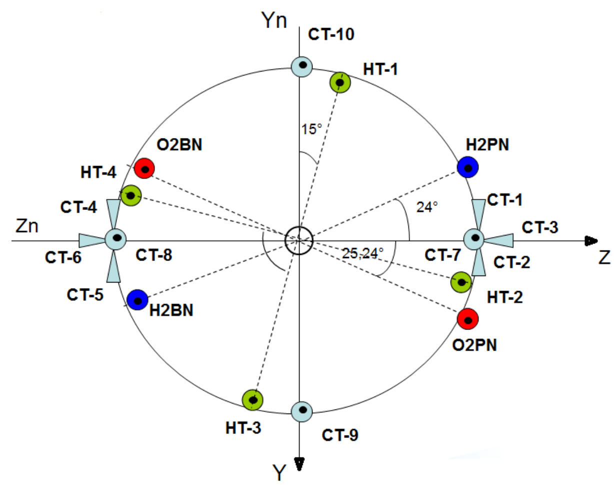

Figure 7: Updated aA5ME architecture

The different functions are allocated to each single system by dedicated phase-by-phase analyses.

It is foreseen to use the PFS during the chill-down of Vinci engine including the GTO missions upper stage separation; the CGRS will be used for roll control during boost and for the attitude control during payload release, as performed by the SCAR in the A5ECA mission; the CGRS will be used also to perform the attitude control during long coasting phase and re-ignition preparation phase, thus making use of the LH2 resources evaporated because of the incoming heat fluxes, and to support the orbit liberation and stage passivation manoeuvres, both by de-pressurising the LH2 tank and by performing attitude control. Although not shown in the architecture, the Vinci engine can be used as a cold thruster by helium LOX dome or feed lines flushing to create settling thrust prior to engine re-ignition.

It is foreseen to use the HGRS only to provide longitudinal thrust. This thrust would be used to provide efficient risk mitigation for the first aA5ME flights during several phases, in particular prior to re-ignition of the Vinci engine for propellant settling. Longitudinal thrust could also be used for manoeuvres during payload release and to provide the stage with the necessary ΔV for orbit liberation.

The thrust levels of the CGRS and the HGRS have been defined with analyses performed at system level. The thrust level of the CGRS will be around the same range of ESC-A SCAR i.e. around 55 N. The thrust level of the HGRS will be around 200 N at beginning of mission and it will operate in blow-down mode. The thrust level of the purge flow system depends on the tank conditions and on the Vinci engine thermal state and chill-down sequence.

Future Outlook

Recently, several analyses are performed at upper stage and launcher system level to show the technical feasibility of suppression of the HGRS, at least for the reference missions. The impact of the HGRS suppression on mission characteristics such as payload release duration and the ballistic phase strategy is assessed. Alternative solutions are proposed for manoeuvres which were previously covered by HGRS and the main issue remains the replacement of the HGRS thrust used for propellant settling. For GTO missions the baseline alternative solution is thrust generation by helium flushing. For GTO/GTO+ missions different scenarios are proposed and the feasibility of the mission is confirmed. Extra helium resources are required when suppressing the HGRS, meaning extra weight for additional helium vessels; however the HGRS suppression remains interesting for costs reasons. For LEO mission a dedicated thrust device is needed anyway to provide sufficient thrust during separation.

A detailed risk analysis for HGRS suppression was also performed for all flight phases. Identified risks are: not sufficient thrust provided by the PFS, liquid ingestion in the pressurisation system, excessive sloshing in tanks, LH2 boil-off different than expected, not enough helium resources for settling, unexpected propellant behaviour due to lack of experience during the coasting and re-ignition preparation phases. For each risk the criticality has been determined and risk mitigation solutions proposed. Although no blocking points for the architecture "*all cold gas*" were found, HGRS is very useful for risk mitigation, with the target to suppress it if the risks can be reduced after the first flights. For LEO mission, an HGRS would be however needed. Due to recent launcher system analyses and commonality aspects for aA5ME and Ariane 6 programmes, it is underlined that a very promising use for HGRS is to perform the de-orbitation boost in the place of Vinci re-boost, as some performance gain is expected.

The HGRS development programme for the hydrazine propellant in the frame of aA5ME has been stopped while the H2O2 HGRS development has started. H2O2 HGRS is a monopropellant system developed at Nammo (Norway), based on green propellant technologies. Thrust is produced by means of catalytic decomposition of Hydrogen Peroxide (H2O2).

Main assets of H2O2 HGRS are:

- Hydrogen peroxide is non-toxic. Handling would be simpler than hydrazine and requires only limited safety equipment.
- Lower need of system heating.
- Lower hot gas temperature generated during catalytic decomposition, meaning less thermal loads for the design of thruster and thruster bracket on the stage.

Main drawbacks of H2O2 HGRS are:

- Lower Isp compared to Hydrazine, which would limit the performance gain expected.
- Lower TRL, so increased effort of development necessary to respect the tight schedule for aA5ME.

The position of the H2O2 HGRS on the aA5ME upper stage is object of consolidation, and several studies are ongoing to find out the best architecture and accommodation, also in view of the wished commonalities between aA5ME and Ariane 6.

Ariane 6

Ariane 6 development is initiated in 2013. Current status is that it will be developed in parallel to aA5ME, with decisions expected at next Ministerial Council for the end of 2014. Ariane 6 is a one-payload new launcher, aiming at answering the new commercial challenges that Ariane will face in the future, especially with regard to costs and flexibility.

The Ariane 6 upper stage will remain cryogenic, re-using the Vinci engine, but featuring new separated tanks. Current baseline for the attitude control system features a CGRS, with a HGRS used only as a kit for GTO DDO mission. The use of a HGRS is justified by the de-orbitation function, as it offers significant performance gains with regards to the de-orbitation performed by Vinci. When HGRS is on board to perform de-orbitation, it can also be used for attitude control during the long ballistic phase.

The proposed global architecture of Ariane 6 Attitude Control and Propellant Settling System is similar to the one of aA5ME (cfr. Figure 7). The type and thrust level of HGRS for Ariane 6 remains to be consolidated; the CGRS, PFS and the helium flushing through Vinci will be the same as in aA5ME, only with minor adaptations due to the different stage configuration.

Conclusions

For the adapted Ariane 5ME Upper Stage, an Attitude Control and Propellant Settling System is being developed. The aA5ME Program proposes an evolution of A5ECA launcher using the Vinci engine with re-ignition capability. Additional functions will be performed by the attitude control system and more performance is requested in comparison with ESC-A upper stage due to long coasting phases, de-orbitation constraints and Vinci re-ignition. During re-ignition preparation phase, dedicated propellant settling thrusts are provided for a restart of the engine after the ballistic phase.

Trade-offs were performed during the development of the program, which led to the actual baseline architecture representing the best compromise selected between performances, costs, reliability, versatility, development risks and operational constraints. Candidate concepts were identified and advantages and drawbacks traded; multiple sub-system down-selection and description of the selected systems, now in development, were also presented.

The baseline aA5ME architecture features the use of a Cold Gas Reaction System, composed by 10 thrusters, and oxygen and hydrogen Purge Flow Systems located on the ELS of the LH2 tank, in similarity with ESC-A. The Vinci engine can be used as a cold thruster with helium LOX dome or feed lines flushing, to create settling thrust prior to engine re-ignition. Additionally, it is foreseen to use a Hot Gas Reaction System with H2O2 propellant, which can be used to provide settling thrusts, for efficient risks mitigation for first aA5ME flights, and optionally to provide the stage with the necessary ΔV for orbit liberation. It has been considerably simplified from the LSPDR, featuring now only 4 longitudinal thrusters that are located on the ELS. The different functions are allocated to the separate systems through dedicated phase-by-phase analyses.

Acknowledgements

The work described in the present paper was performed by the European Space Agency (ESA) and its institutional and industrial partners, with Airbus Defence & Space acting as prime contractor for the aA5ME Program.

The activities reported in the paper are only a part of the efforts undertaken within the program. The authors greatly thank and acknowledge the European Space Agency (ESA) for the continuous support to the program.

References

[1] C. Poincheval, A. Juhls, R. Albat, J. Vila
A5ME: The multi-mission heavy lift version needed for the end of the decade, IAC-11-D2.1.5, 2011

[2] A. Juhls, J. Krüger, P.Alliot, J-F. Delange, E. Edeline, M. Thalamy, P.D. Resta, JM. Bahu
Development of the aA5ME upper stage, AIAA 2013-4057

[3] EcosimPro Modelling & Simulation Tool v4.4.0
EAI, Spain, 2008, http://www.ecosimpro.com