MITIGATION MESURES ON THE ARIANE 5 LAUNCHERS

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ABSTRACT

Since the beginning of the Ariane 5 development, space debris mitigation concerns have been taken into account.

At system level, the trajectory of the main stage EPC has been constrained in order to avoid a long life time in orbit followed by an uncontrolled reentry. Operational constraints have also been applied to the upper composite in order to avoid payload pollution and collision risks.
At stage level, numerous modifications have been implemented, mainly for the various passivation systems : addition of pyrotechnical valves and specific nozzles led to a higher stage complexity.

Following the first nine flights of Ariane 5, we now have plenty of data showing how efficient our measures have been.

1. INTRODUCTION

At the end of a launcher mission, the spent upper stage is orbited close to the payload.

Ideally, one should deorbit it in order to avoid any debris generation. Unfortunately, an active deorbitation associated with controlled reentry is practically to complex to perform : the impact on payload is high, the operations associated to deorbitation are complex, safety on ground associated to direct reentry is still a concern and modifications of the upper stages are often very expensive ; for this reason, no space faring nation ever considered systematic deorbitation of spent upper stages yet.

On the Ariane launchers, it was decided to implement an intermediate step and to avoid any mission related debris other than the passivated upper stage.

The high level requirement is defined in the CNES “Space Debris Mitigation Standard”, MPM-50-00-12, Issue 1-Rev 0, dated Apr.19, 1999.

- one single inert structure for a single launch, whatever the orbit

- two inert structures maximum for multi-payload launch, whatever the orbit.

This double requirement can be split into lower level specifications :

- payload separation shall not generate any debris : the pyrotechnical cuts shall be clean, pyrotechnic bolts shall be trapped, clamp bands shall be equipped with catchers,

- all propulsive systems (main propulsion and attitude control system) shall be passivated : chemical energy shall be removed (propellant flushing) and pressure shall be lowered (pressurant),

- obviously, passivation shall not lead to any debris generation,

- no risk of overpressure shall occur in electrical cells and batteries,

- use of solid propulsion in orbit shall be avoided (aluminum droplets and slag),

- satellite placement shall not lead to any risk of collision.

These high level measures have been applied to both Ariane 4 and Ariane 5.

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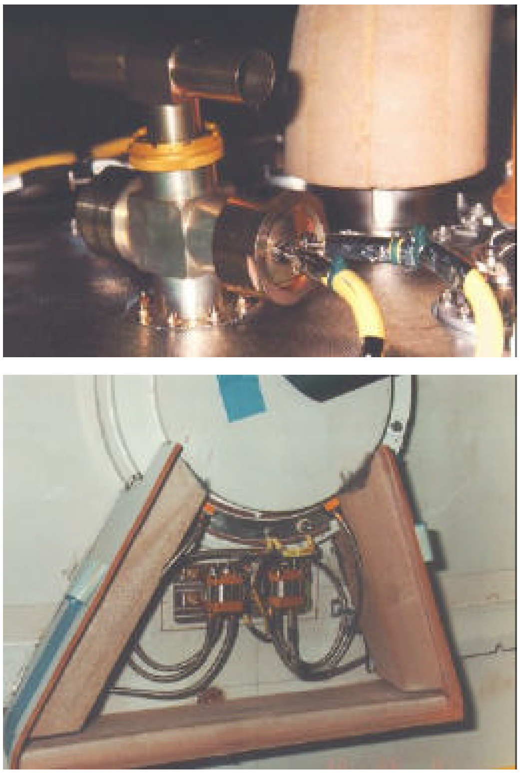
2. ARIANE 5

Ariane 5 is architectured around a Lower Composite consisting of two solid propellant boosters EAP and a central cryotechnic stage EPC, and an Upper Composite including Vehicle Equipment Bay VEB (which houses the Hydrazine Attitude Control System SCA), the upper stage EPS and upper composite structures Speltra (multiple launch structure), payload adaptors and fairing. A general view of the launcher is given.

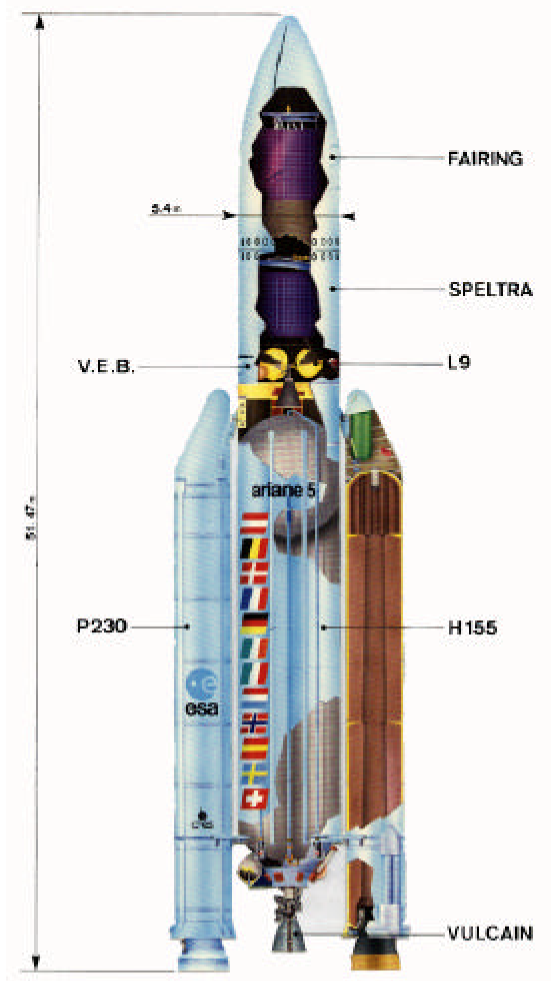
2.1. Impact of debris mitigation rules on EPC trajectory

The optimal GTO ascent trajectory, due to the selected staging of the launcher based on a large cryotechnic stage, would lead to orbit the EPC at its cut-off : optimal perigee would be close to 150 km.

The preliminary studies led in CNES considered an active deorbitation of the EPC, but this solution was rapidly found complex : deorbitation was to occur at the second apogee due to splash down constraints, and an attitude control system was necessary in order to properly orientate the deboost thrust (therefore requiring an on board computer, extended life duration, aso…).



EPC passivation system



This choice was abandoned and the selection of an even higher perigee was then studied : the idea was to leave the stage on a stable orbit (perigee higher than 200 km) and to passivate it.

This solution was also rejected for debris mitigation concerns : even though the reentries would have been early, the debris generation in Low Earth Orbits (crossing space stations zones) was considered as unacceptable.

The reference solution was then to lower the perigee in order to achieve a direct controlled reentry (perigee lower than 70km). The impact of this choice was important : payload loss was about 500kg (GTO orbit) and the upper stage EPS had to be increased (from 7 tons to 10 tons).

Passivation of the EPC led to major modifications of the stage :

- a pyrotechnical valve was added on the Liquid Oxygen tank (fig. top), T-shaped in order to guarantee the lack of perturbing torque, with redunded orders for reliability concerns,

- a huge valve (ϕ 260 mm, fig. bottom) was added in the upper part of the Liquid Hydrogen tank wall, including a throat shape : passivation induces a tumbling motion of the EPC, with high rotation speed (in the order of 90 °/s), helping us to predict accurately the behavior of the stage during reentry, and the associated splash-down zone in the Pacific Ocean.

These modifications had a very strong impact on the development of EPC : they were technically complex, closely associated to critical pressure evolutions in the tanks (shaker effect), and led to a long and costly development with extensive testing.

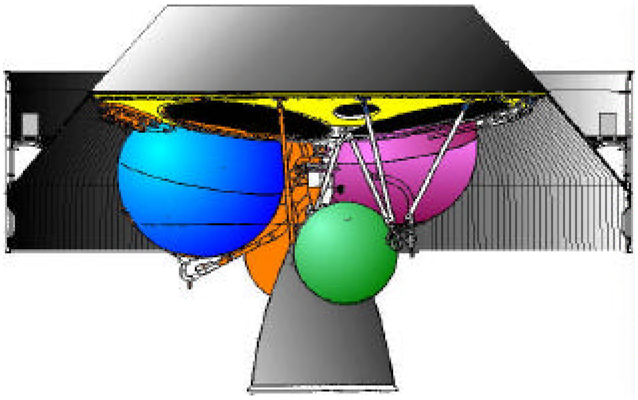
2.2. EPS passivation

2.2.1. EPS description

The EPS is a bi-propellant pressure fed stage developed by Astrium GmbH ; at lift off, it contains 9.6 tons of propellant (2 x 3200 kg N2O4 and 2x 1600 kg MMH), 30 kg Helium pressurant at 400 bars ; the Aestus engine produces 30 kN vacuum thrust.

A general view of the EPS propulsion is given in the following picture

At the end of the mission, the EPS typically houses the propellant reserve (2 x 75 kg N2O4 and 2 x 50 kg MMH in average) pressured at 20 bars ; there is also less than 50 bars Helium in the two high pressure vessels.



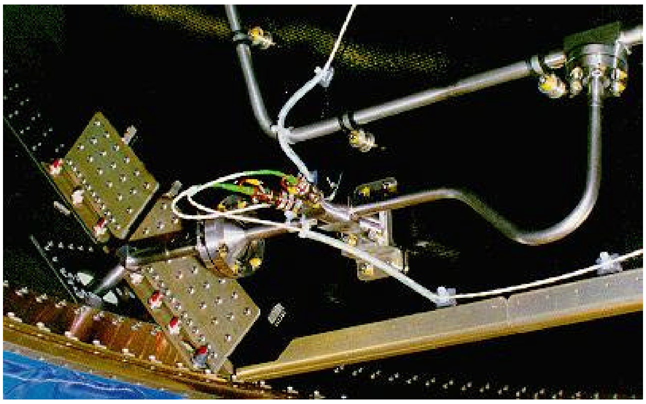
Thermal analyses of the final condition of the stage show that this situation could be stable : a small blow-down is performed before engine cut-off and provided that the stage would be properly oriented with respect to the sun, the pressure evolution would be such that no risk of explosion is feared.

Nevertheless, and mainly in order to cope with explosion risk potentially triggered by Hypervelocity impacts, it was decided since the early steps of the stage definition to passivate the EPS.

2.2.2. EPS passivation system

The EPS passivation system includes :

➥ specific hardware added on the Low Pressure inlets of the propellant tanks : additional line, T shaped doublet of nozzles (designed to be reaction less), pyrotechnical valve electrically activated at the end of the mission (redunded for reliability) and a burst disk introducing a second mechanical barrier for ground safety (see figures).



Pyro valve of EPS stage

➥ operational constraints : after the last payload separation, the stage is properly oriented, depending on mission analysis, then spun in order to locate the propellants ; the pyrotechnic valves are then actuated and the SCA passivation is performed.

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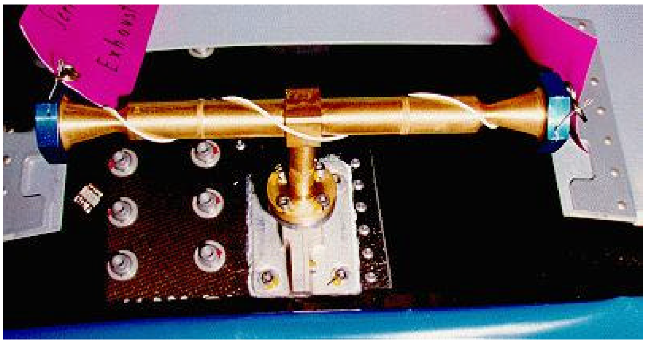
The High Pressure vessels are naturally depleted after some 10 hours through a permanent leak ; the « leak before burst » and high burst pressure (800 bars) design anyhow means that no risk of explosion can be feared.



Passivation nozzles

At the end of the process, no propellant remains in the tanks : evaporation (or sublimation) of the propellants is a long process which can take several years, but since the tanks are open to vacuum, the draining is effective.

The passivation of the EPS imposed numerous studies, long, complex and expensive :

⇘ the parasite torque applied to the upper composite during passivation is rather important : although the passivation nozzles are locally reaction less, the integral of the parietal pressures on the conical structure of the stage leads to a ΔV in the order of 1 m/s associated with a tilting torque : complex modelizations were required to estimate this effect and to include it in the Mission Analysis simulations.

The attitude sensors on the VEB allowed us to assess this effect in flight.

⇘ two pyro valves have to be opened simultaneously : a variant with sequential opening was studied but was rejected as to complex (due to duration of the passivation and to asymmetrical torque). We had then to demonstrate that no hypergolic reaction between the two propellants would occur. Theoretical demonstration was first performed, then a small test was done by Astrium GmbH in Bremen demonstrating the lack of reaction.

⇘ The risk of ice generation was also studied. Since the gas-liquid mixture is expelled in vacuum, a steep temperature decrease is encountered at the throat : we had to verify that there was no risk of clogging.

We also wanted to check that during the passivation, no ice particles were ejected into space.

Theoretical studies were performed at ESTEC (di-phasic simulations including condensation) followed by tests at ONERA Fauga (Mie and Reynolds diffusion with Laser tomography).

The conclusions were very encouraging : there is no risk to clog the passivation pipes and the maximal size of potentially ejected ice particles is in the range of 100Å.

⇘ the EPS passivation is associated with ejection in the vacuum of propellant vapors which could contaminate the payloads. A pollution model was derived, modeling the theoretically maximal deposit versus spherical coordinates and time, and included in the Mission Analysis simulation software. With this very conservative approach, the final selection of the maneuvers leads to negligible levels of pollution (typically 100 times lower than the requirements).

⇘ last, obviously, there shall not be any collision during payload separation ! This statement is nevertheless complex to demonstrate : we consider a collision probability lower than 10-4 and validate it through Monte Carlo simulations including all dispersions (residual masses, SCA, thrust, …) and uncertainties (Mass, centering and inertia ranges, stage performance, …) ; the effect of EPS passivation is of course included.

2.2.3. *EPS flight experience*

All these systems and studies were used during flights.

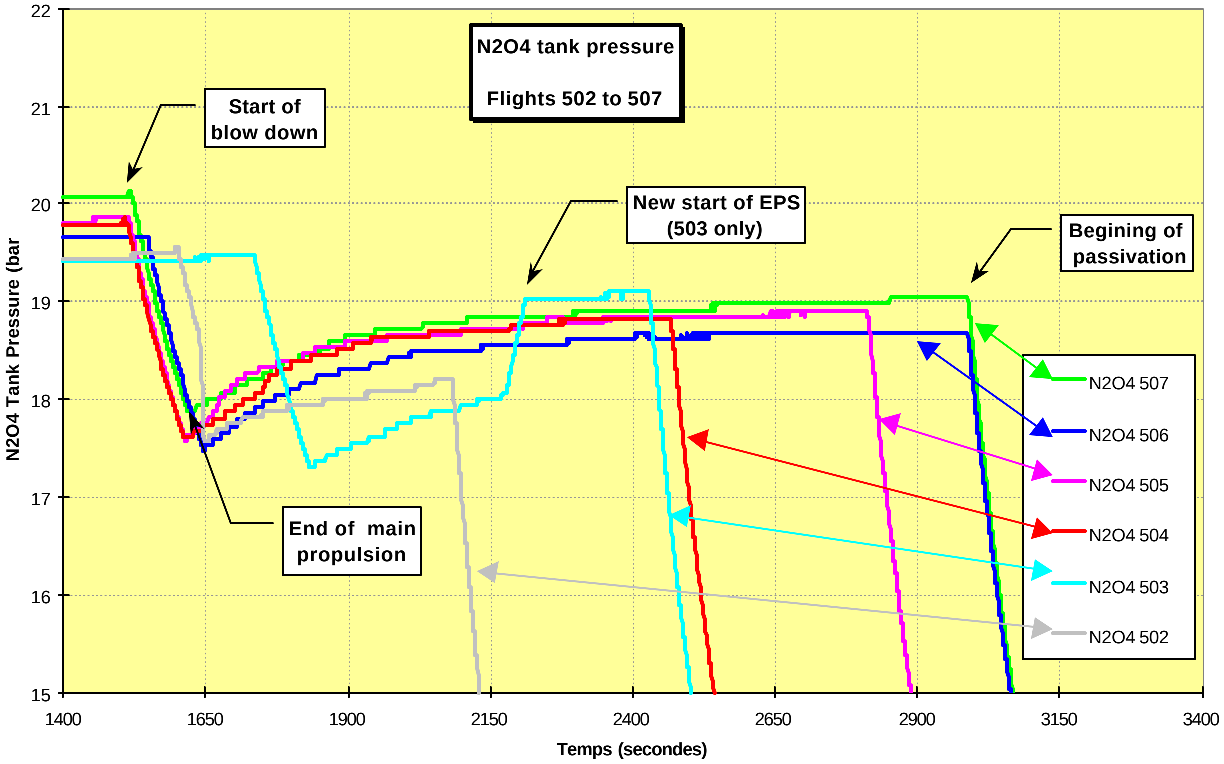
The following table presents the propellant mass remaining in EPS stage for the flight 502 to 507.

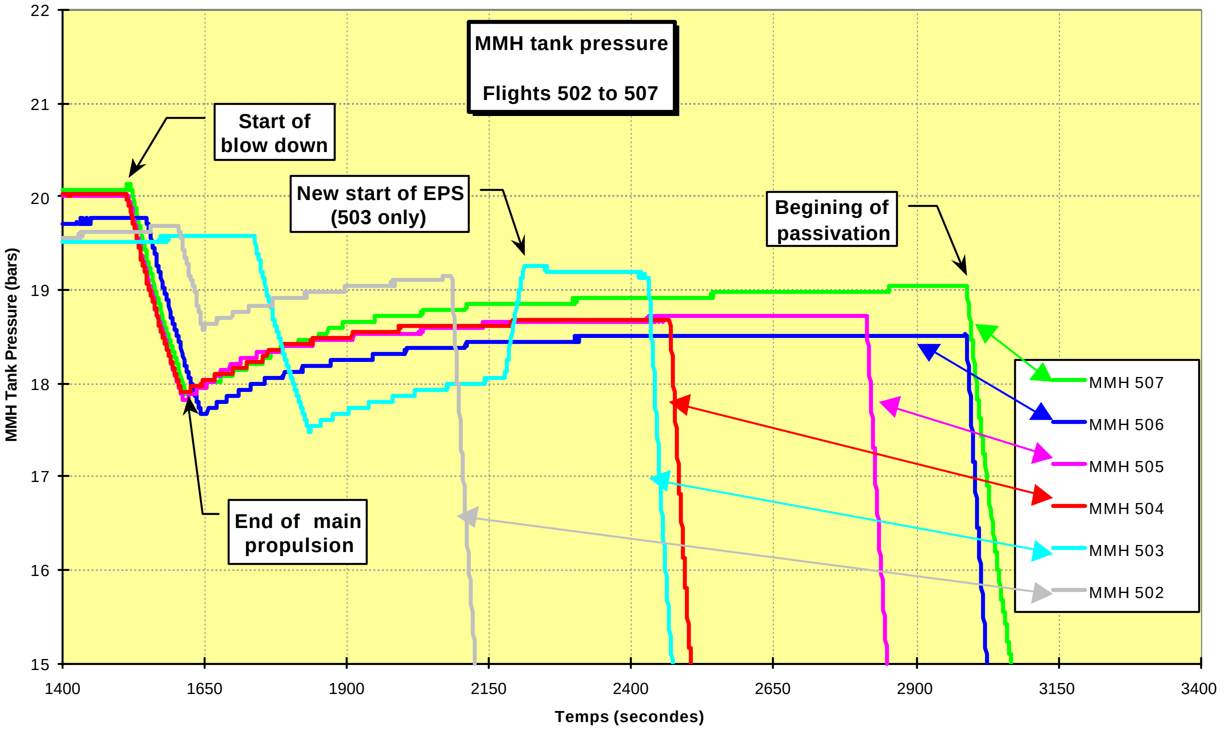
There are also the predicted mass obtained during flight analysis studies :

	502	**503**	**504**	**505**	**506**	**507**
Predicted mass (kg)	157	267	394	382	306	197
Flight mass (kg)	0	237	423	369	288	188
D (kg)	157	-30	29	-13	-18	-9

⇨The abnormal value of 502 was due to the EPC torque, compensated with the SCA.

⇨During the other nominal flights, we have between 150 kg to 450 kg to passivate.



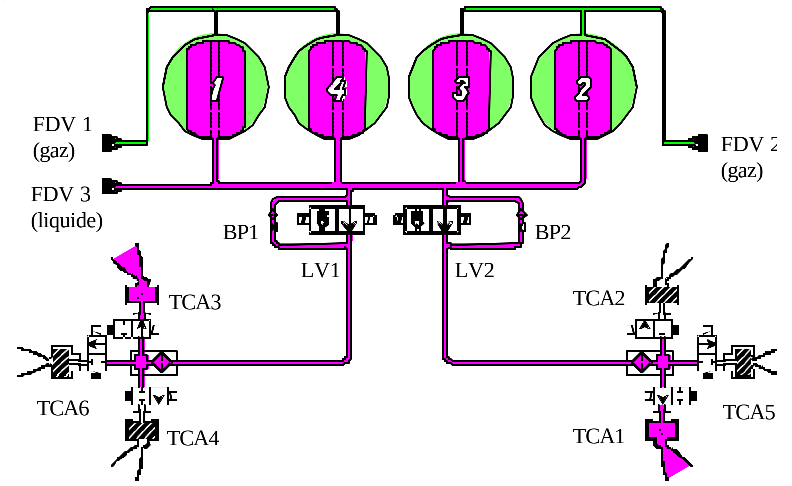


The two previous charts display the impact of the passivation on the pressure of N2O4 and MMH.

For each flight between 502 to 507, we can see the good efficiency of the passivation. The pressure in tanks decreases between the nominal flight pressure to the normal pressure for the end of the mission.

2.3. SCA passivation

The hydrazine Attitude Control System SCA consists in two Titanium spherical tanks with polymer bladder 3 x 38 kg Hydrazine; the pressurant is Nitrogen (Beginning Of Life : 26 bars); two pods of three 400N thrusters enable a near 6 DOF control.



Fonctional view of Ariane 5 SCA system

At the end of the mission, the SCA can have residual pressures up to 20 bars and up to 50 kg propellant (values are strongly mission dependant) :

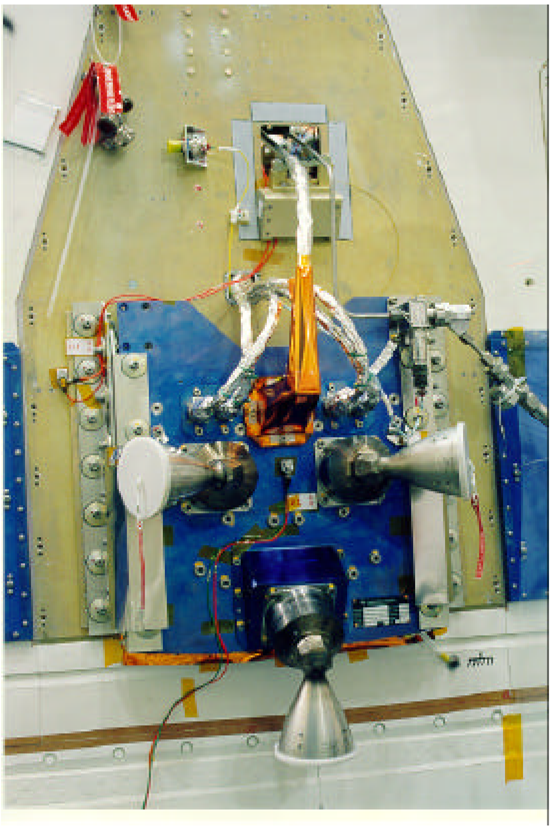
As for the EPS, we showed that without any action, there is no risk of explosion : even in the worst thermal conditions, temperature remains far below Hydrazine decomposition, and the burst pressure of the tanks is above 70 bars.

Nevertheless, to cope with the risk of Hypervelocity impacts, we chose to passivate the SCA as much as practical.

Unfortunately, the full depletion of Hydrazine is not easily achievable due to design constraints : there is a strong risk of flash explosion when the liquid is totally expelled and when the vapors encounter hot spots (this mishap has been observed on various occasions on satellites).

It was therefore decided to limit the passivation to a pressure lower than the “hypervelocity threshold pressure” (defined as the pressure above which a puncture leads to an explosion, and below which a puncture only leads to a leak).

The first step of the determination of this pressure was the selection of dimensioning case : we specified a probability of non-explosion of 10^{-4} from which we deduced a set of debris masses and speeds.



Ariane 5 SCA block

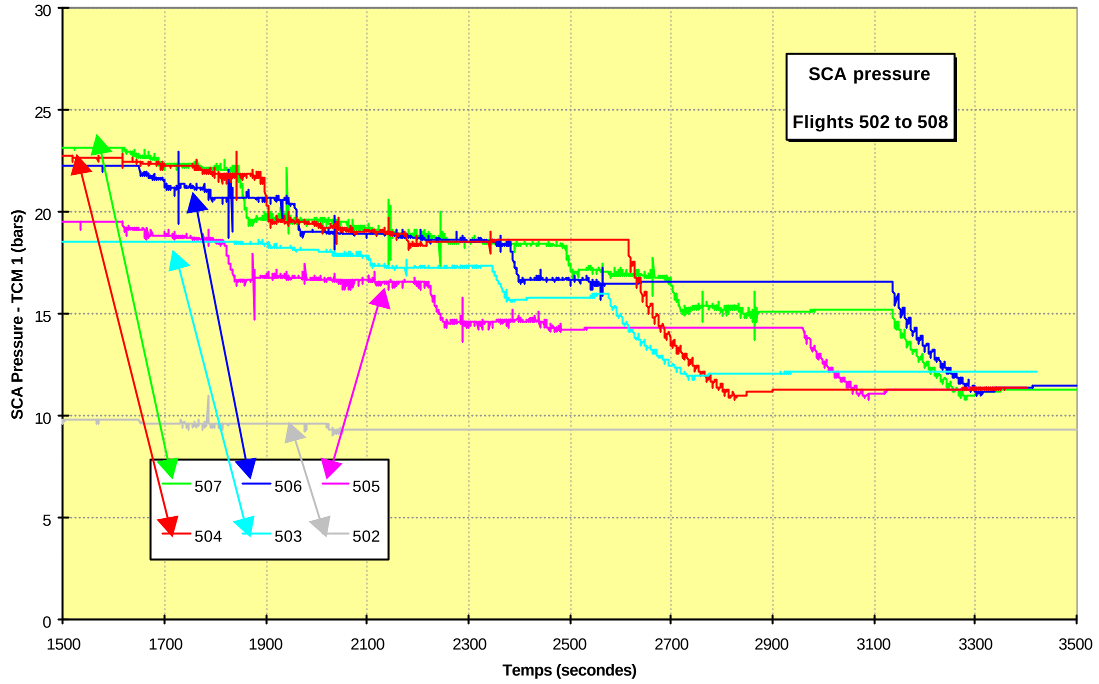
A theoretical determination of the threshold pressure was then performed by ESI (Rungis-France).

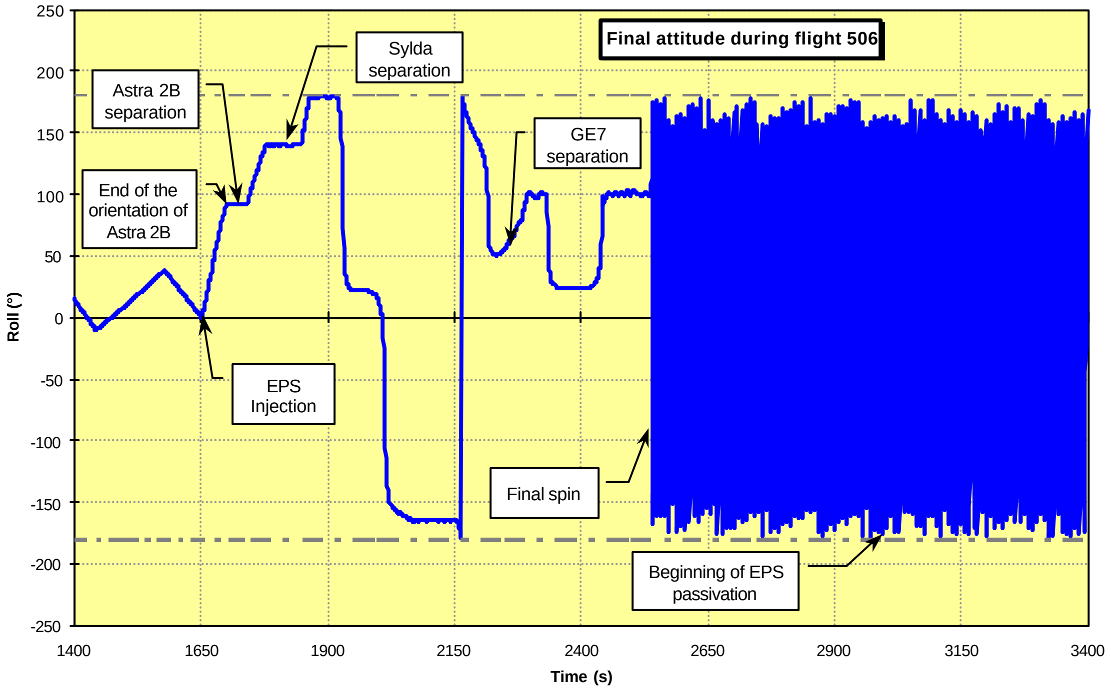
It was demonstrated that the tank should withstand the impact of an Aluminum debris, 1 mm in diameter, at 15 km/s when pressurized with 18 bars.

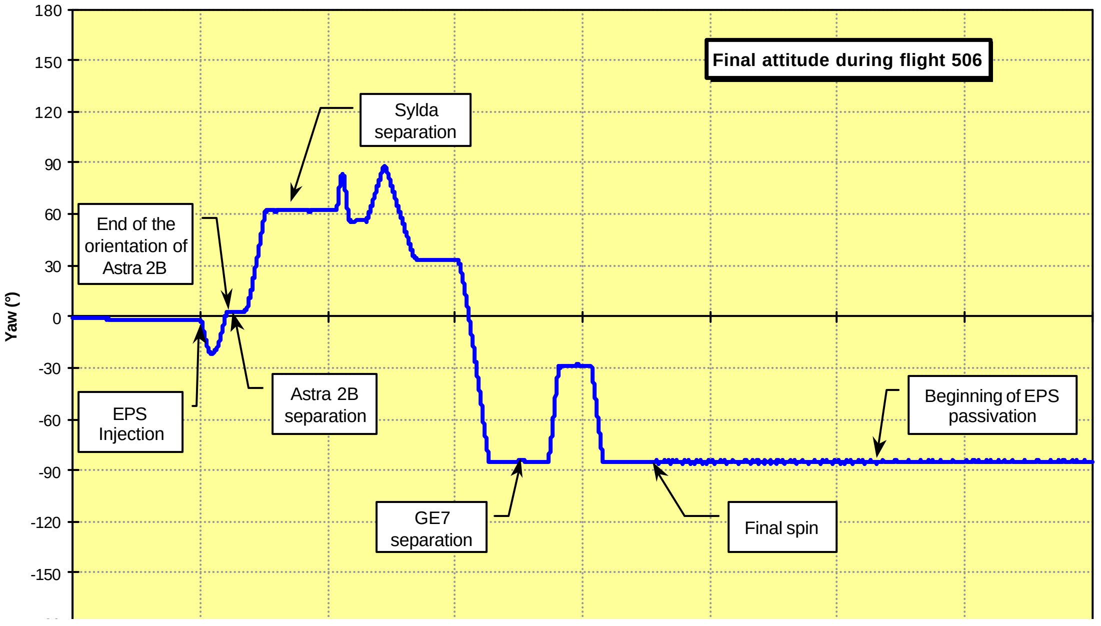
A specific test was defined with ESTEC and performed at EMI (Freiburg-Germany) : a 1 mm debris launched at 9 km/s impacted the tank filled with 18 bars : the result was precisely equal to the test simulation, i.e. a 3.2 mm hole.

This test gave us a good confidence in our approach : we decided to depressurize the SCA at the end of mission up to a pressure below 15 bars (including 20% margin).

The flight results confirm our good confidence and the nominal working of the SCA passivation.


SCA pressure
Flights 502 to 508
SCA Pressure - TCM 1 (bars)
30
25
20
15
10
5
0
1500
1700
1900
2100
2300
2500
2700
2900
3100
3300
3500
Temps (secondes)
507
506
505
504
503
502


Final attitude during flight 506
Roll (°)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1400
1650
1900
2150
2400
2650
2900
3150
3400
Time (s)
Astra 2B separation
Sylda separation
End of the orientation of Astra 2B
GE7 separation
EPS Injection
Final spin
Beginning of EPS passivation


Final attitude during flight 506
Yaw (°)
180
150
120
90
60
30
0
-30
-60
-90
-120
-150
Sylda separation
End of the orientation of Astra 2B
EPS Injection
Astra 2B separation
Beginning of EPS passivation
GE7 separation
Final spin

2.4. Attitude during passivation of EPS and SCA

During the passivation of EPS and SCA, we can observe the attitude of the upper stage. The roll and yaw time evolution of a typical flight are displayed in the previous charts.

We can see the good stabilization of the upper stage to resist at the parasite torque. There are not perturbations remaining on the upper stage. This repeated observation demonstrates that the feared perturbation is well controlled thanks to reaction-less nozzles.

One should also note that pollution of the payloads due to propellants during passivation was modeled, validated through specific tests led by Astrium-GmbH with QCM sensors, and taken into account as specific constraints during the end of the mission.

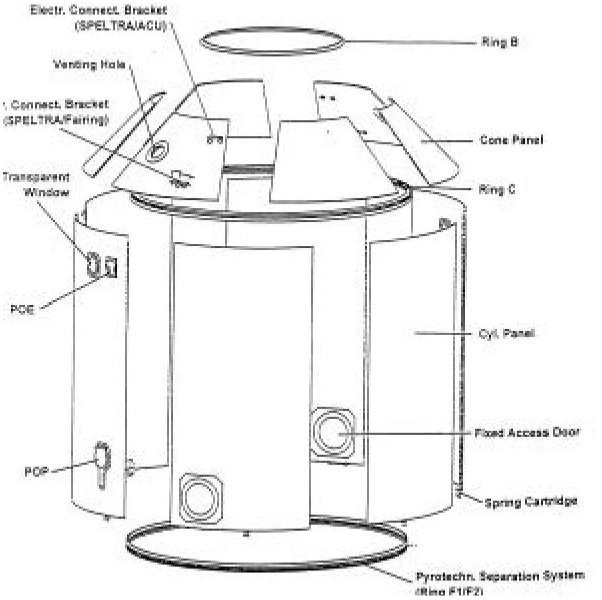
2.5. Speltra separation

As for the other upper composite structures, the Speltra separation system has been designed so that no associated debris is generated.

The design is based on the use of a pyrotechnical chord, leading to the expansion of a leak tight tube shearing the structural walls : no debris is generated in the process.

We checked the cleanliness of the separation during the development tests. The qualification was obtained with optical means.

The separation of Speltra (and similar way of all the orbited structures) is fully compliant with our debris mitigation rules.



2.6. Electrical batteries and cells

The use of Ag-Zn electrical cells nominally produces gaseous Hydrogen. In order to avoid any critical overpressure, the cells are equipped with release valves calibrated at 1.2 bars ; the total final volume of Hydrogen trapped in the cell is less than half a liter. Natural leaks lead to a total passivation of the cell within a few months.

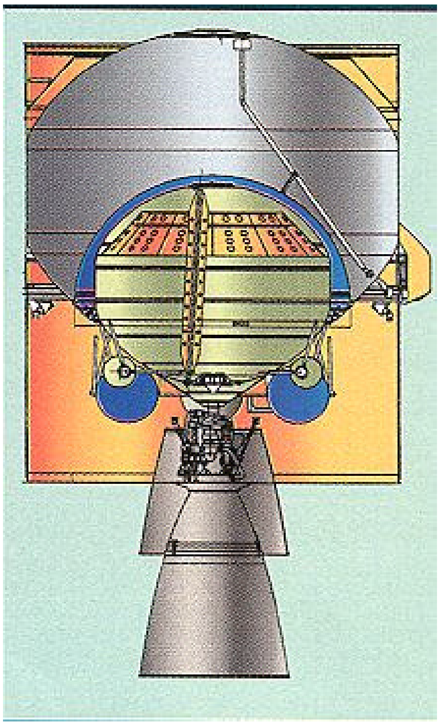
Nominally, the Ni-Cd batteries are cut before reaching total discharge; therefore, there is no production of gaseous Hydrogen and at the end of the mission, the battery only contains 100 cm^3 air at 1bar maximum. The natural discharge of the battery leads to a total passivation in less than 50 days.

There design choices and the operations of the electrical items of Ariane 5 are fully compliant with our debris mitigation rules.

3. NEW DEVELOPMENTS

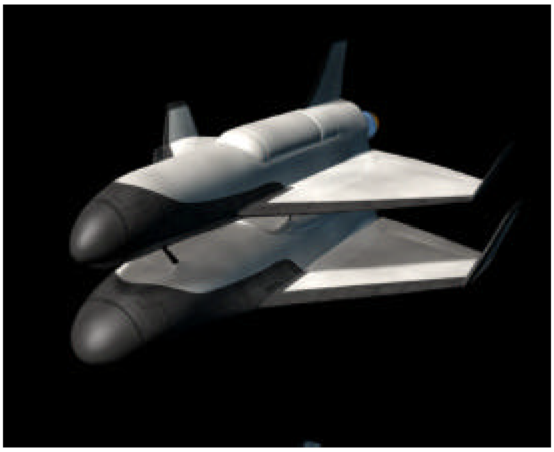
Studies are still undergoing in order to improve the debris mitigation measures of launchers derived from Ariane 5, including upgraded versions of the launcher :

➭ Minimization of the final GTO perigee is under study. With the new upper stages (ESC-A and ESC-B), the GTO perigee will be near 200 km (significantly less than actual EPS perigee).



ESCB stage

➩ Perigee lowering maneuvers are also under consideration : residual propellants could be used to give a ΔV in the proper direction at the proper time. The practical implementation of this maneuver is however complex : controllability of the upper stage is very difficult once all payload are released and mission duration would be drastically increased.



Artistic view of a typical RLV

➩ The debris mitigation rules described here are included (and applied) in the requirements of new stage (ESC-B), future Expendable Launcher (ELV) or of the upper stage located in the payload bay of a future Reusable Launcher (RLV).

➩ In case of direct GEO insertion with an Ariane upper stage, the reorbiting rules applicable to satellites would be considered (perigee increase by a minimum of 300 km followed by passivation of the stage.).

4. CONCLUSION

The current set of requirement applied to the Ariane launchers is very efficient :

➩ No operational debris is generated during the satellite placement in mission.

➩ The passivation of EPS and SCA seems very efficient : no breakup has been observed on any passivated stage (Ariane 4 and 5). The passivation aspects have been clearly well done during each flight Ariane 5 (502 to 508).

Nevertheless, progress and improvement can still be made :

➩ lowering of GTO perigee after the end of mission (with ESC-A and ESC-B stages).

➩ full passivation of SCA is under study.

We are convinced that the current situation is the most efficient set of rules within realistic constraints : situation is the result of our best efforts to mitigate the orbital debris. The CNES rules are clearly defined in our standard, are well known from all our manufacturers and are taken into account at the very beginning of the development of new stages. We believe that similar rules applied to all current and future launchers would greatly contribute to debris mitigation.

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ACRONYMS – ABBREVIATIONS

DOF	Degree Of Freedom
EPC	Main Cryotechnic Stage
EPS	Upper Storable Stage
ESC	Upper Cryotechnic Stage
GTO	Geostationary Earth Orbit
SCA	Attitude Control System
Speltra	Dual Payload Structure
VEB	Vehicle Equipment Bay