ARIANE DEBRIS MITIGATION MEASURES

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ABSTRACT

Since 1990, actions have been taken to prevent in orbit generation of space debris linked to the operations of the European Ariane launcher.
Following the in orbit breakup of V16, nine months after its launch, modifications have been implemented to the Ariane 4 upper stage in order to avoid the fragmentation of its tanks.

The hardware modification implemented to the Ariane 4 upper stage, briefly recalled, appears very efficient : no tank rupture ever occured since its implementation, and the telemetry shows a correct evolution of the tank pressures.

Considering the positive experience on Ariane 4, similar constraints were included in the requirements for Ariane 5.

The upper stage EPS is passivated after completion of the mission, and the Hydrazine Attitude Control System is safed.
Nominal operations of the launcher do not produce any debris : natural outgassing of batteries, leaktight separation systems, clampbands with catchers, and so on.

Details of the solutions and of their performance are described.

A summary of the main requirements relative to space debris mitigation is given ; these design rules will be imposed on the future European launcher programs.

1. GENERAL RULES FOR LAUNCHER DEBRIS MITIGATION

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 a controlled reentry is practically to complex to perform : the impact on payload is high, the operations associated to the deorbitation are complex 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 consider an intermediate step and to avoid any mission related debris other than the passivated upper stage.
The high level requirement is thus "to leave only one single inert structure per satellite, whatever the orbit".

This requirement can be split into lower level specifications :
- payload separation shall not generate any debris: the pyro 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 (aluminuim 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 4

2.1. Introduction

Ariane 4 is a three stage vehicle with optional solid and/or liquid versions ; the six versions are displayed on figure 1.

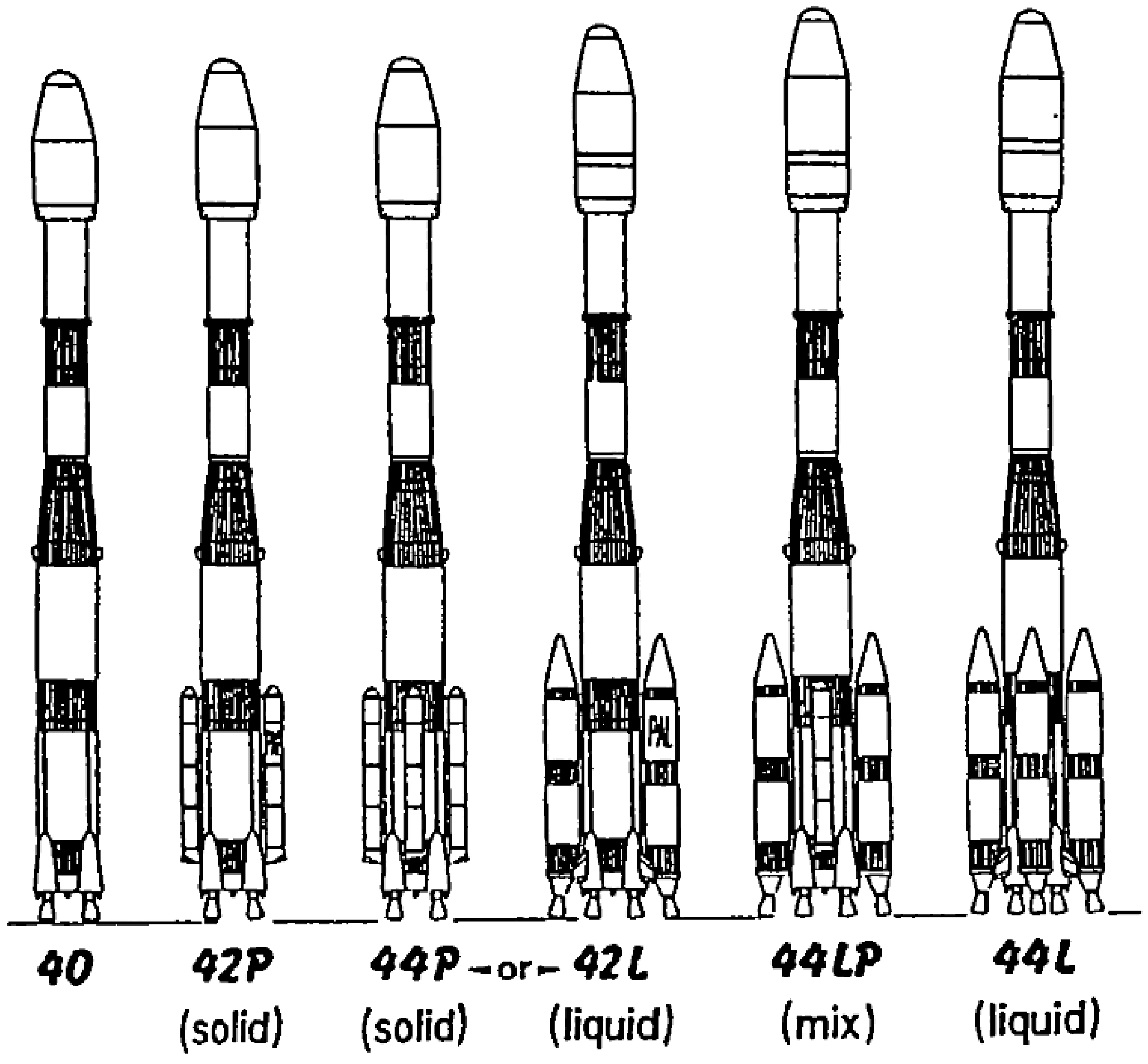


Figure 1 : Ariane 4

During a typical mission, schematized on figure 2, the boosters naturally fall down on ground close to the launch pad, and the first stage, the fairing and the second stage naturally fall down in the ocean. The Upper Composite, shown figure 3, including the thrid stage, the Spelda (multiple payload structure) and the payload adaptors is injected into the same orbit as the payloads.

2.2. Post flight condition

At the end of the mission, after payload separation, the Upper Stage H10 is still a highly hazardous element containing an important remaining energy.

Typical initial conditions are (mean values) :

	Hydrogen	Oxygen
Liquid mass	70 kg	110 kg
Gas pressure	2.7 bar	2 bar
Gas temperature	150 K	170 K

A fast pressure build up is often encountered, resulting from vaporization of cryogenic liquids.

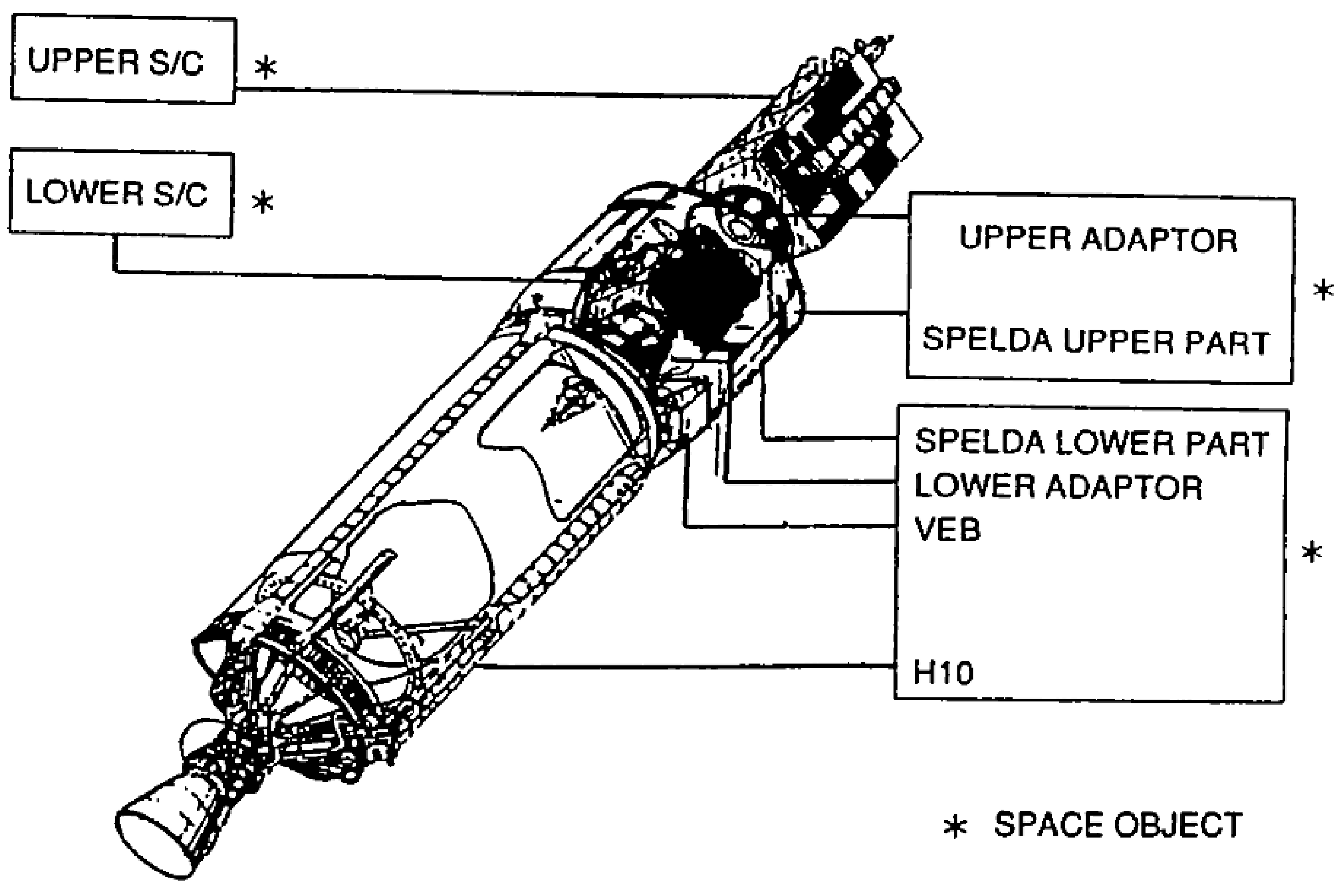


Figure 3 : Ariane 4 upper composite

The design of the H10 stage, shown in figure 4, includes a common bulkhead separating the Oxygen and Hydrogen tanks ; this specific design is associated with desing constraints that shall be met althrough the mission :

- gas pressure shall always be higher on Hydrogen side than on Oxygen side
- pressure difference shall be included between 0.5 bar and 2 bar

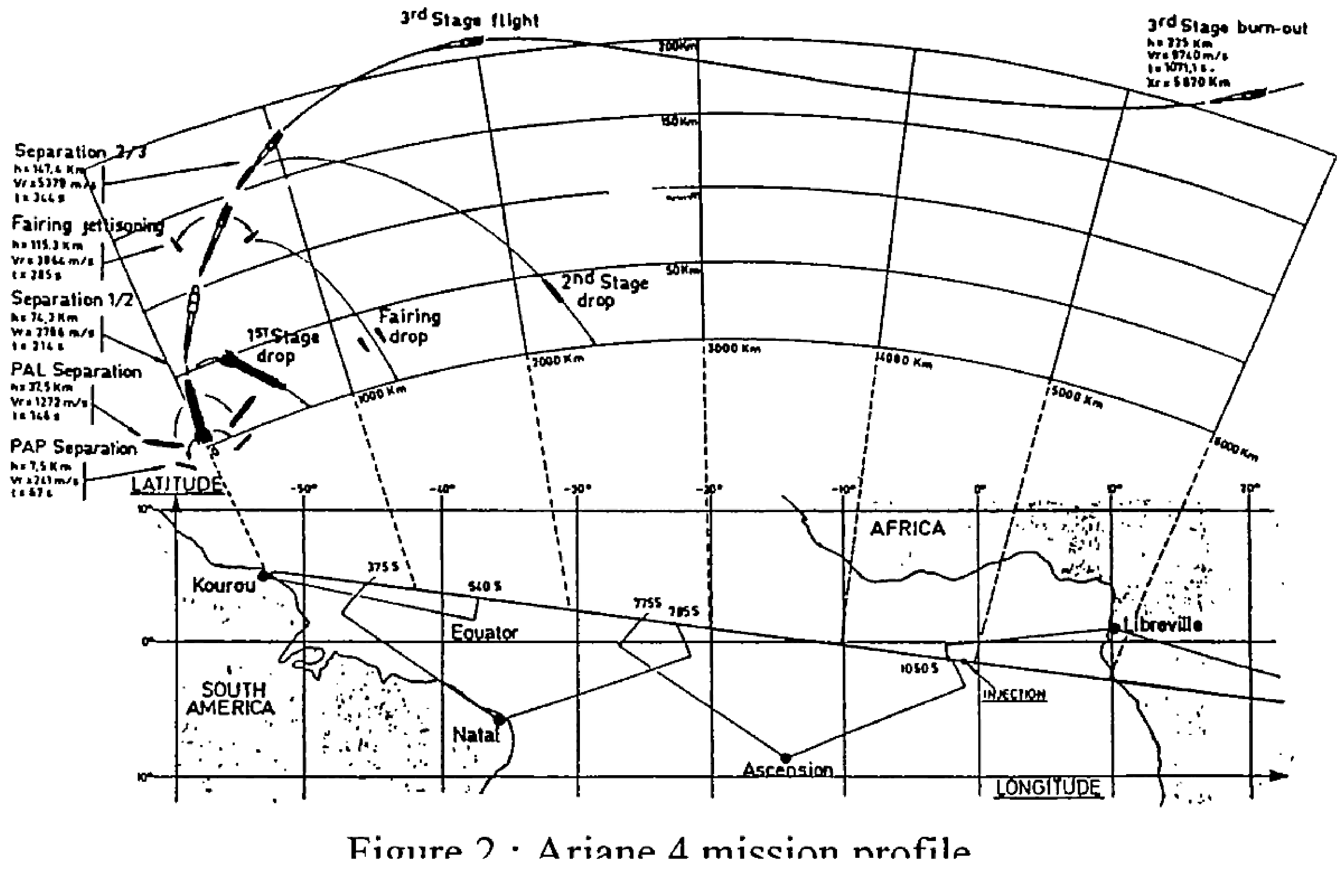


Figure 2 : Ariane 4 mission profile

Consequently, protective measures have been considered including :

- pressure relief valves with threshold pressures of 3.3 bar on Hydrogen side and 2.35 bar on Oxygen side
- adequate use of the available gases during the SCAR phase (satellite placement depicted in Figure 5) : the gazeous Hydrogen is expelled through SCAR nozzles for spin, despin and attitude control and the gazeous Oxygen is expelled through venting nozzles for axial thrust

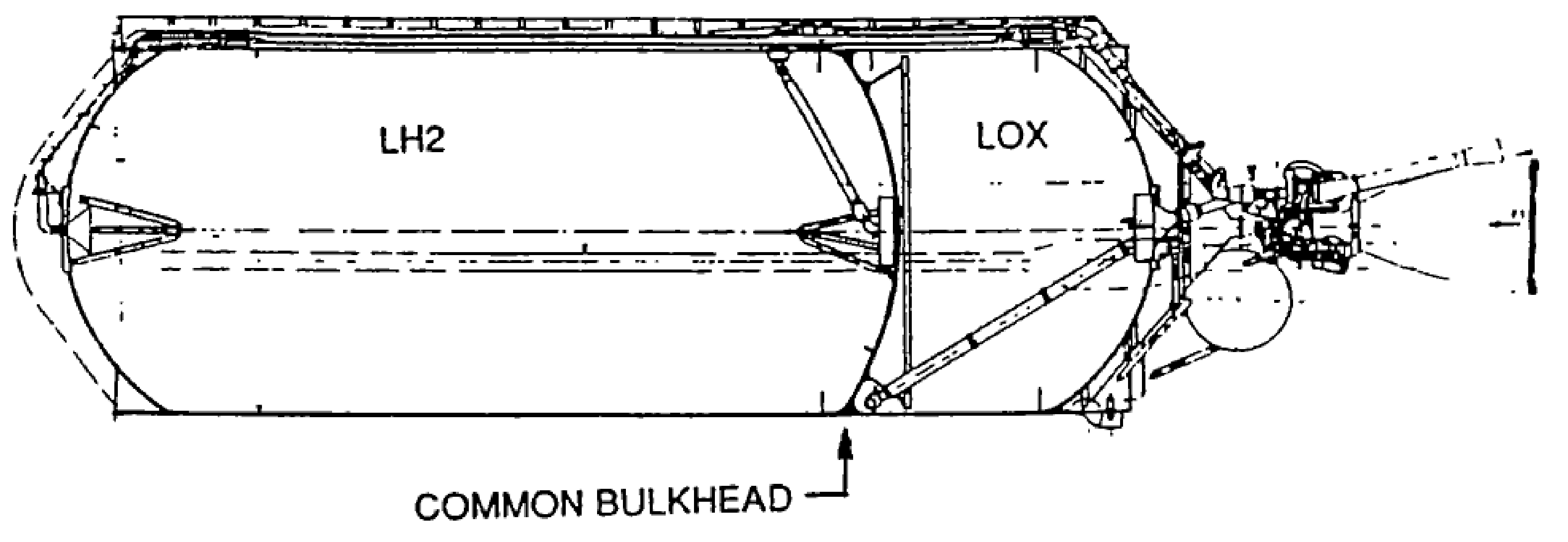
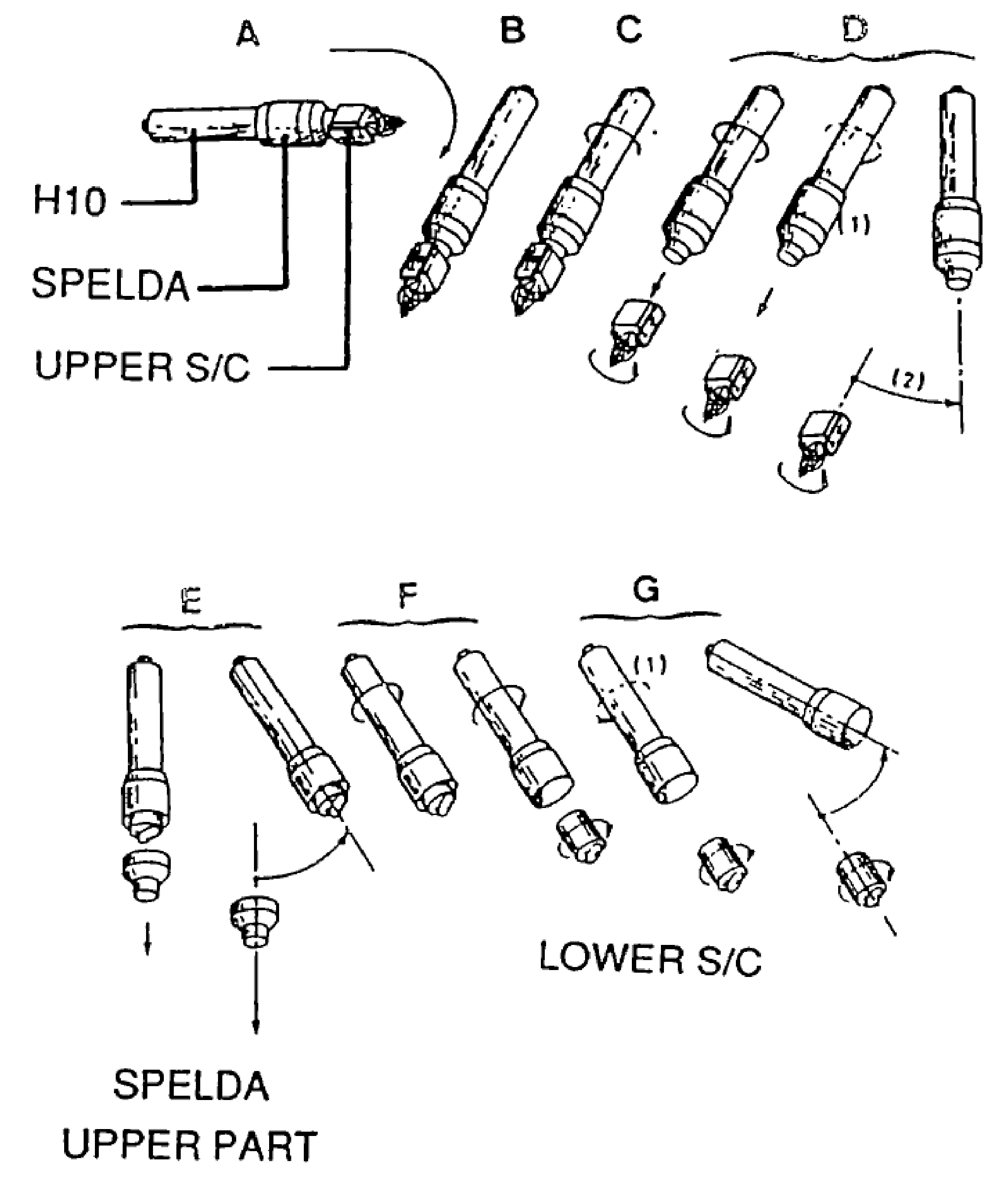


Figure 4 : H10 tank configuration



A and B : Orientation of composite (3rd stage + payload) by 3rd stage roll and attitude control system (SCAR)
C : Spin up by action of SCAR (2)
D : Separation of upper spacecraft. Then spin down (1) and reorientation by action of SCAR

E : Upper SPELDA jettisoning. Reorientation as requested by inner spacecraft.
F : Spin up and separation of inner spacecraft.
G : 3rd stage avoidance maneuver (spin down, reorientation of 3rd stage, spin up at 5 rpm and Lox valves opening).

Figure 5 : SCAR phase

2.3. H10 passivation

The explosion of the third stage of the mission V16 in November 1986 (Spot mission in Sun Synchronous Orbit launched in February 1986) generated a large amount of orbital debris, with an important dissemination resulting from precession of individual orbits (see figure 6, computer simulation of the evolution of fragment orbits from the V16 upper stage explosion).
Since the orbits of those debris are very stable, the natural decay being extremely low (several hundreds of years), decision was taken to determine the origin of this explosion and to define preventive measures.

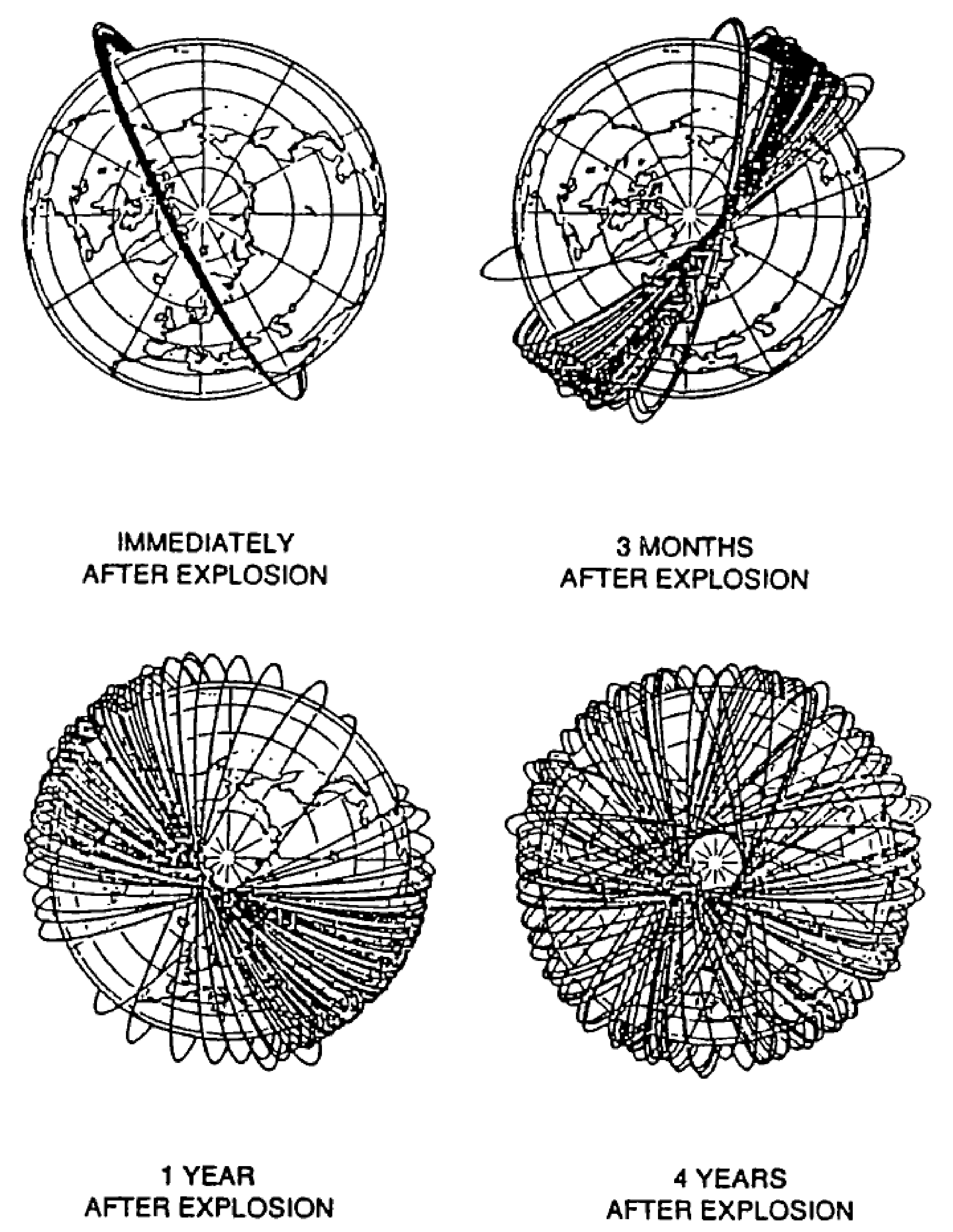


Figure 6 : Simulation of the evolution of the debris generated by V16 upper stage explosion

A CNES / Arianespace working group was created working in close relation with NASA and NORAD from November 86 to July 87. The detailed inquiry showed that there was no anomaly on flight data, thus on hardware. Determination of the scenario showed that battery explosion could be rejected, accidental tank pyro destruction also, tank wall rupture from random thermal cycling was possible but that the common bulkhead rupture from overpressure of one or the other side was the most probable cause for explosion. The working group recommanded to render the tank inert by full venting just after the mission.

The H10 passivation was defined through an ESA development programme ; the milestones were :

- Preliminary Design Review in November 1988
- Critical Design Review in July 1989
- Qualification Review in December 1989

The selected solution consisted in pressure relief valves definitively maintained open by means of add-on pyro devices (see diagram figure 7) :
- the LOX valve is blocked in open position by a pyro rod adapted from a bolt cutter
- the LH2 valve has a permanent leak from a pilot part through pyro valve (tubing cutter)

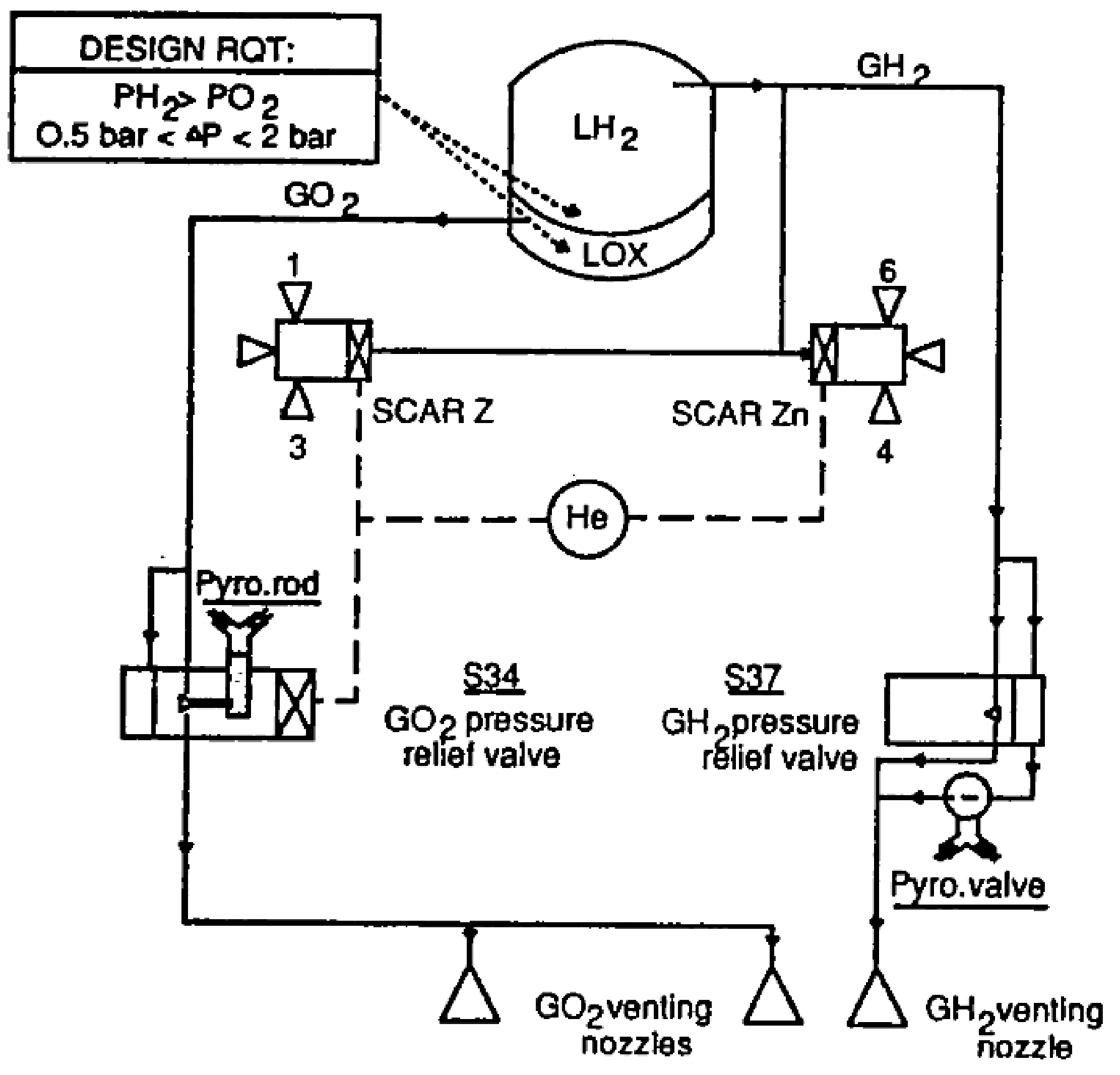
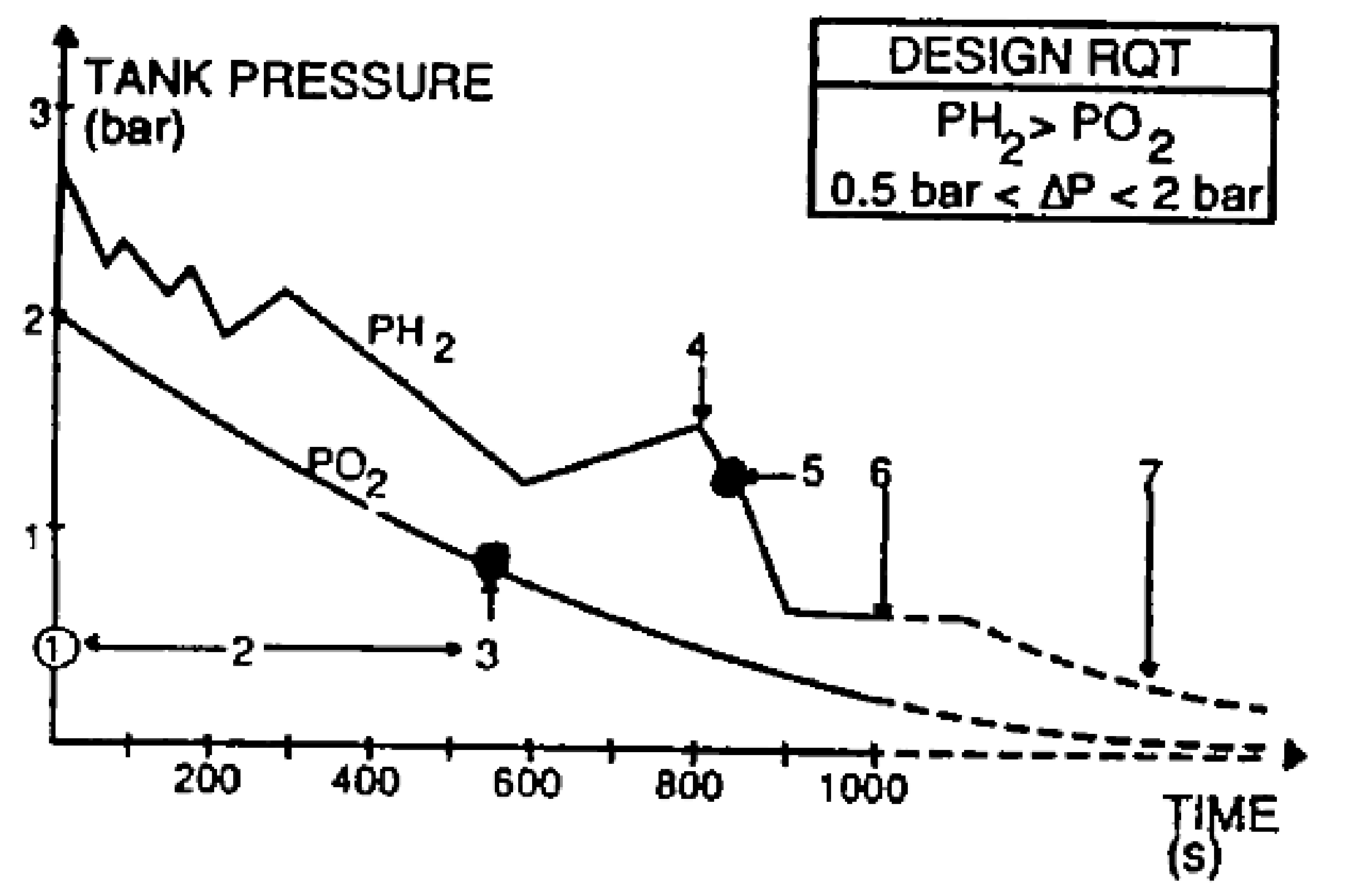


Figure 7 : pressurant gas venting system



EVENTS

① End of H10/Payload separation

② H10/Payload avoidance phase (LOX valve commanded open)
Associated H10 attitude control (SCAR's)

③ LOX valve pyro rod firing (valve blocked open) ←

④ Opening of SCAR 1+3+4+6

⑤ Closure of SCAR 1+3+4+6
LH2 pyro valve firing . (opened position) ←

⑥ New max H2 tank regulated pressure (approx. 0.6 bar)

⑦ Permanent GH2 leak through opened pyro valve (LH2 valve closed)

Figure 8 : H10 passivation sequence

The operating sequence is timely adapted in the SCAR sequence in order to respect the required pressure decay profile (see figure 8).

The passivation system was first implemented on V35 flight in January 1990, then was implemented on all the SSO flights, and finally on all flights from V60 onwards (since October 1993).

The H10 passivation system proved to be very efficient ; as an example, the pressure evolution in both Hydrogen tank (upper curves) and Oxygen tank (lower curves) of seven recent flights is displayed in figure 9 : the pressure decay is evident.

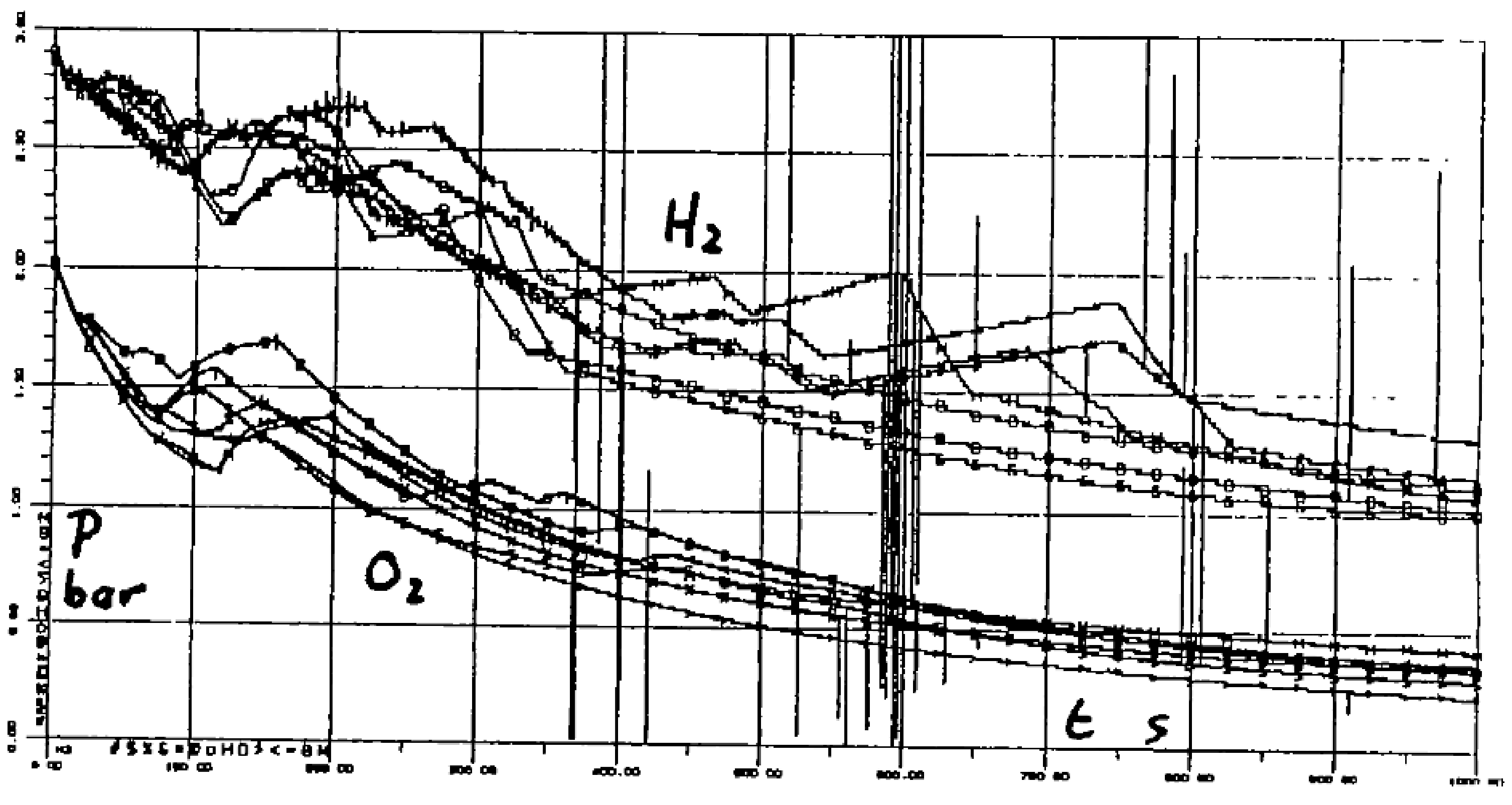


Figure 9 : H10 pressure decay (7 flights)

3. ARIANE 5

3.1. Introduction

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 the 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 figure 10.

3.2. 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 : otimal 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 to 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 (therfore requiring an on board computer, extended life duration, aso...).

This choice was abandonned 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 of the stage (perigee lower than 70 km). The impact of this choice was important : payload loss was in the order of 500 kg (GTO orbit) and the upper stage EPS had to be increased (from 7 tons to 10 tons).

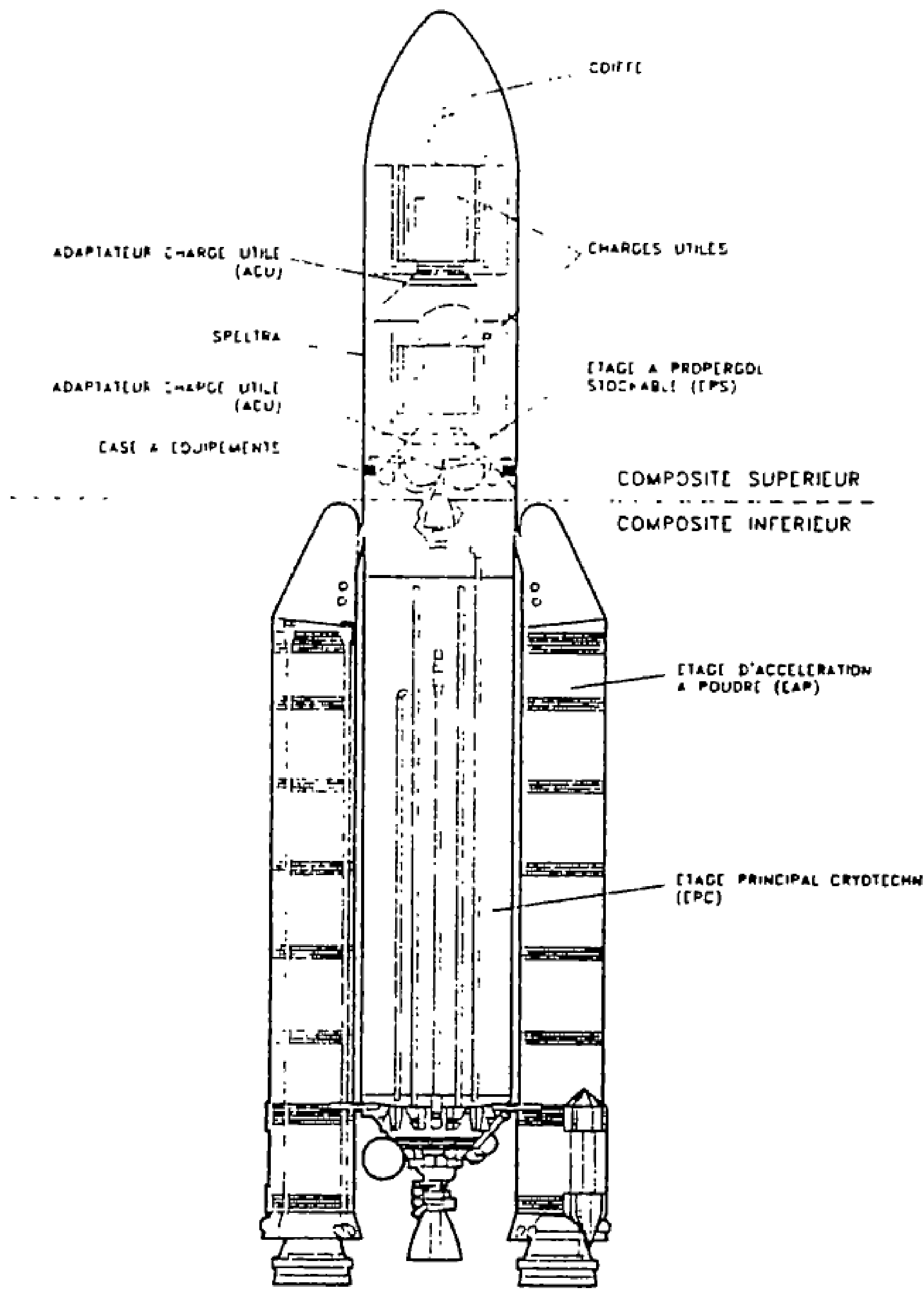


Figure 10 : Ariane 5

3.3 EPS passivation

EPS description
The EPS is a bi-propellant pressure fed-stage developed by DASA ; at lift off, it contains 9.6 tons propellant (2 x 3200 kg N_2O_4 and 2 x 1600 kg MMH), 30 kg Helium pressurant at 400 bars ; the Aestus engine produces 30 kN vacuum thrust.

A scheme of the EPS propulsion is given on figure 11.

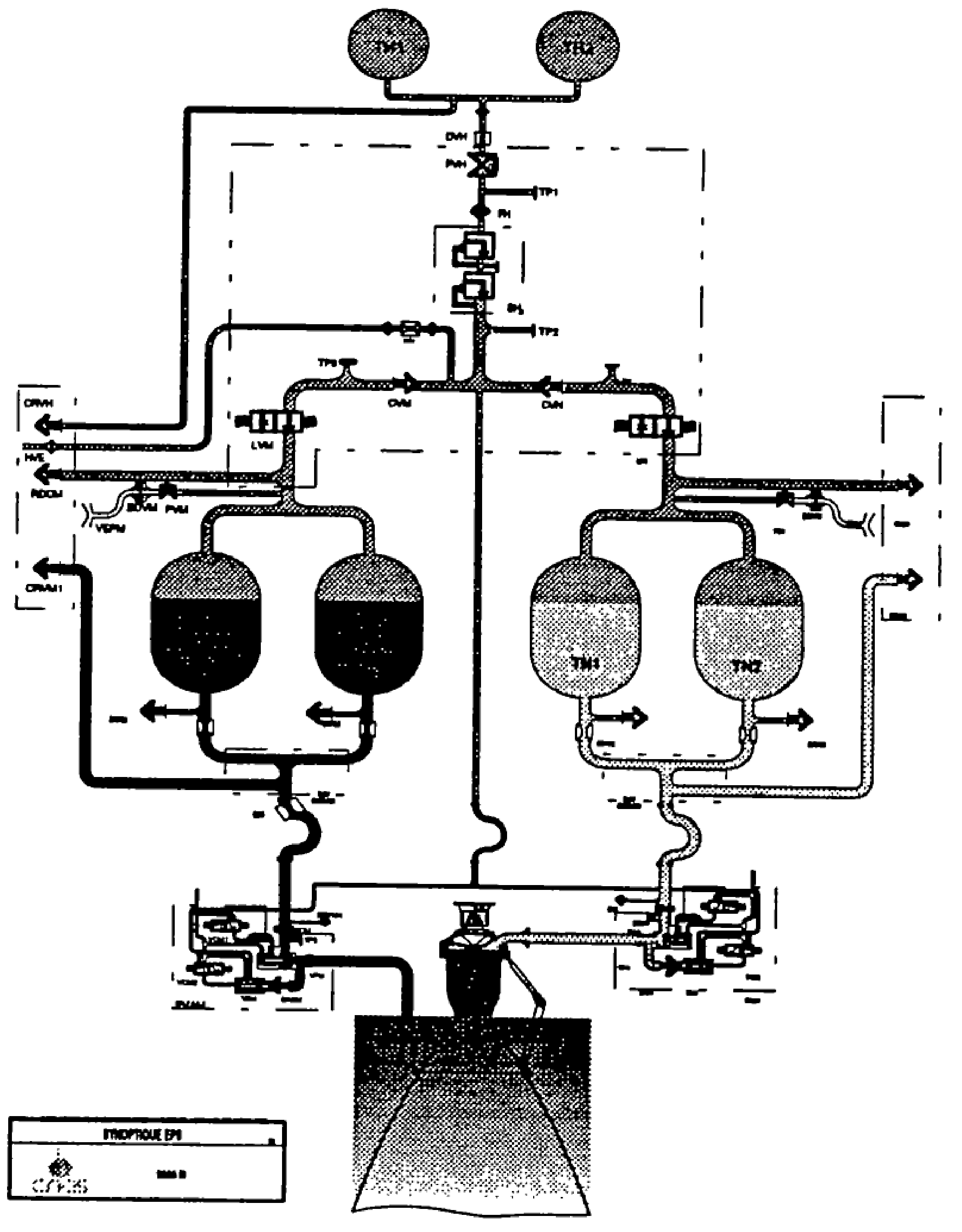


Figure 11 : EPS propulsion

At the end of the mission, the EPS typically houses the propellant reserve (2 x 75 kg N_2O_4 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 Hypervelocity impacts, it was decided since the early steps of the stage definition to passivated the EPS.

EPS passivation
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), pyro valve electrically activated at the end of the mission and a burst disk introducing a second mechanical barrier for ground safety (see figure 12)
- 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 pyro valves are the actuated and the SCA passivation is performed.

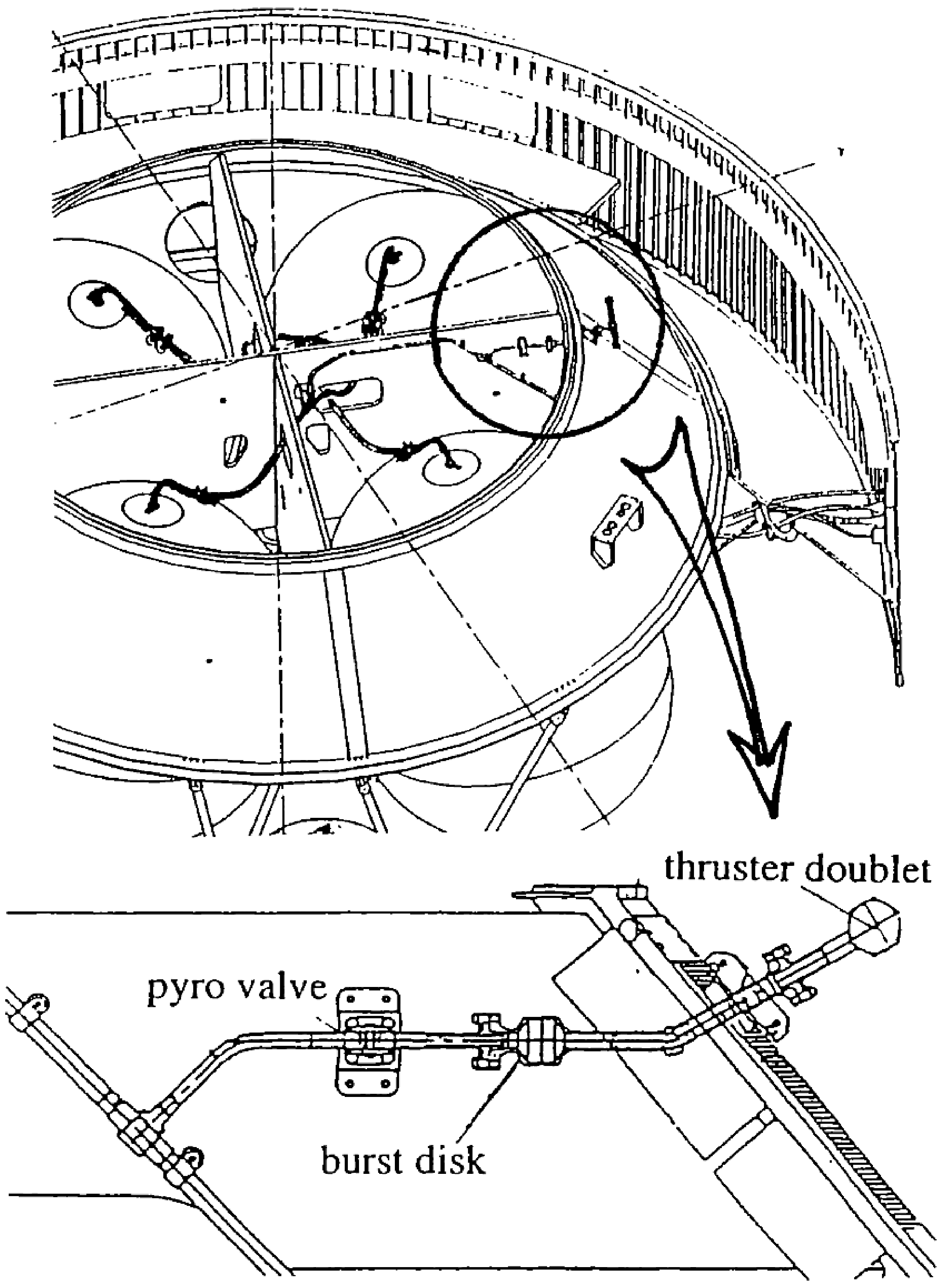


Figure 12 : Additional hardware

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.

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.

A typical evolution of the pressures during the passivation is shown on figure 13.

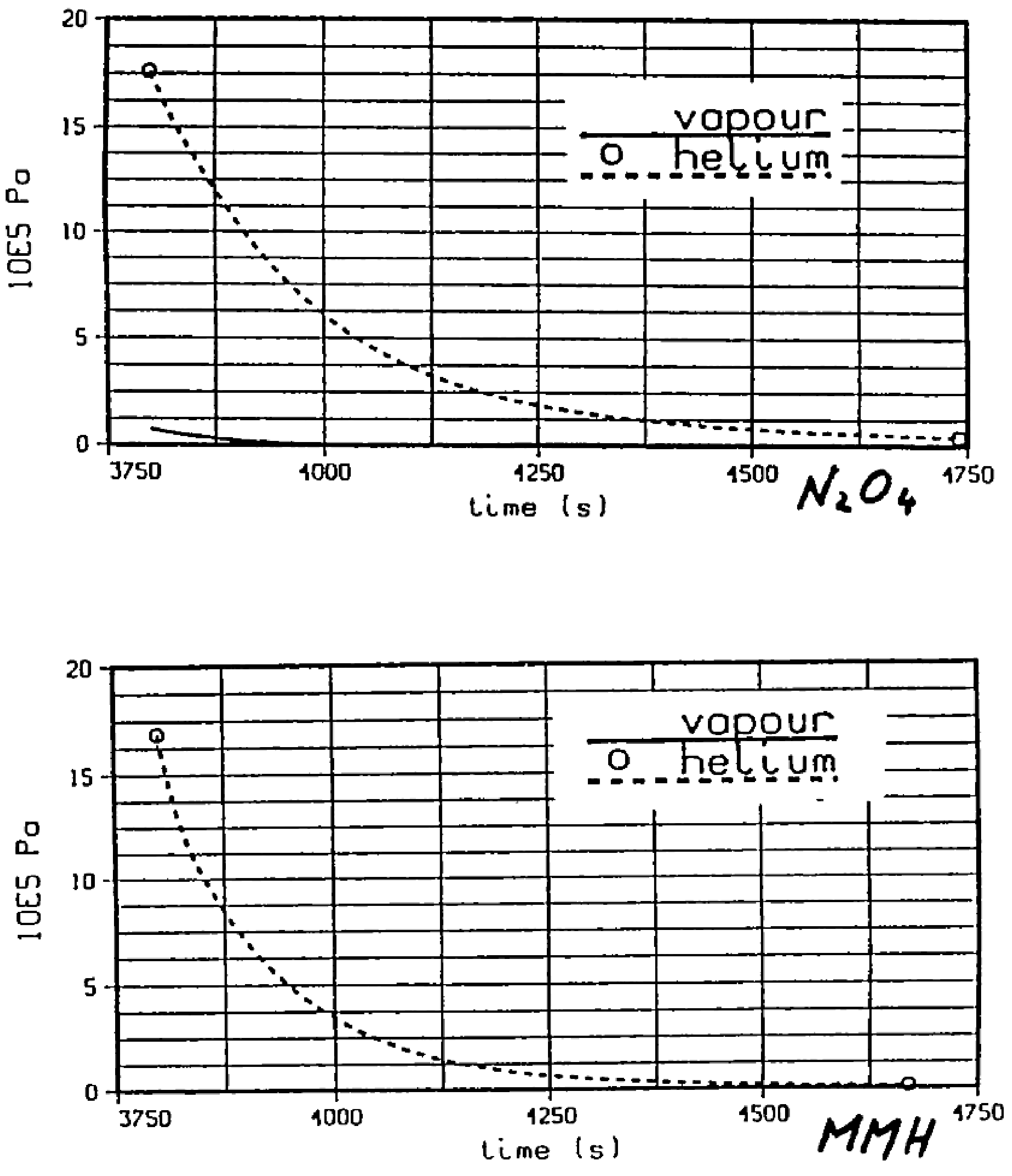


Figure 13 : Pressure evolution during passivation

Related studies

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 modelisations were required to estimate this effect and to include it in the Mission Analysis simulations.

  The attitude sensors on the VEB will allow us to assess this effect in flight

- the 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 torques).

  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 DASA 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 clogg the passivation pipes (flight data will confirm it) and the maximal size of potentially ejected ice particles is in the range of 100 Å.

- the EPS passivation is associated with ejection in the vacuum of propellant vapours which could contaminate the payloads

A pollution model was derived, modelling 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 manoeuvres leads to negligible levels of pollution (typically 100 times lower than the requirements).
Specific transducers are implemented on the launcher for the first flights in order to validate this model.

- 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 unknowns (Mass, centering and inertia ranges, stage performance, ...) ; the effect of EPS passivation is of course included. Comparaison between previsions and flight data will help us to validate this demonstration.

3.4. SCA passivation

The Hydrazine Attitude Control System SCA consists in two Titanium spherical tanks with polymer bladder housing 2 x 38 kg Hydrazine ; the pressurant is Nitrogen (Beginning Of Life : 26 bars) ; two pods of three 400 N thrusters enable a near 6 DOF control.

The scheme of the SCA is given in figure 14.

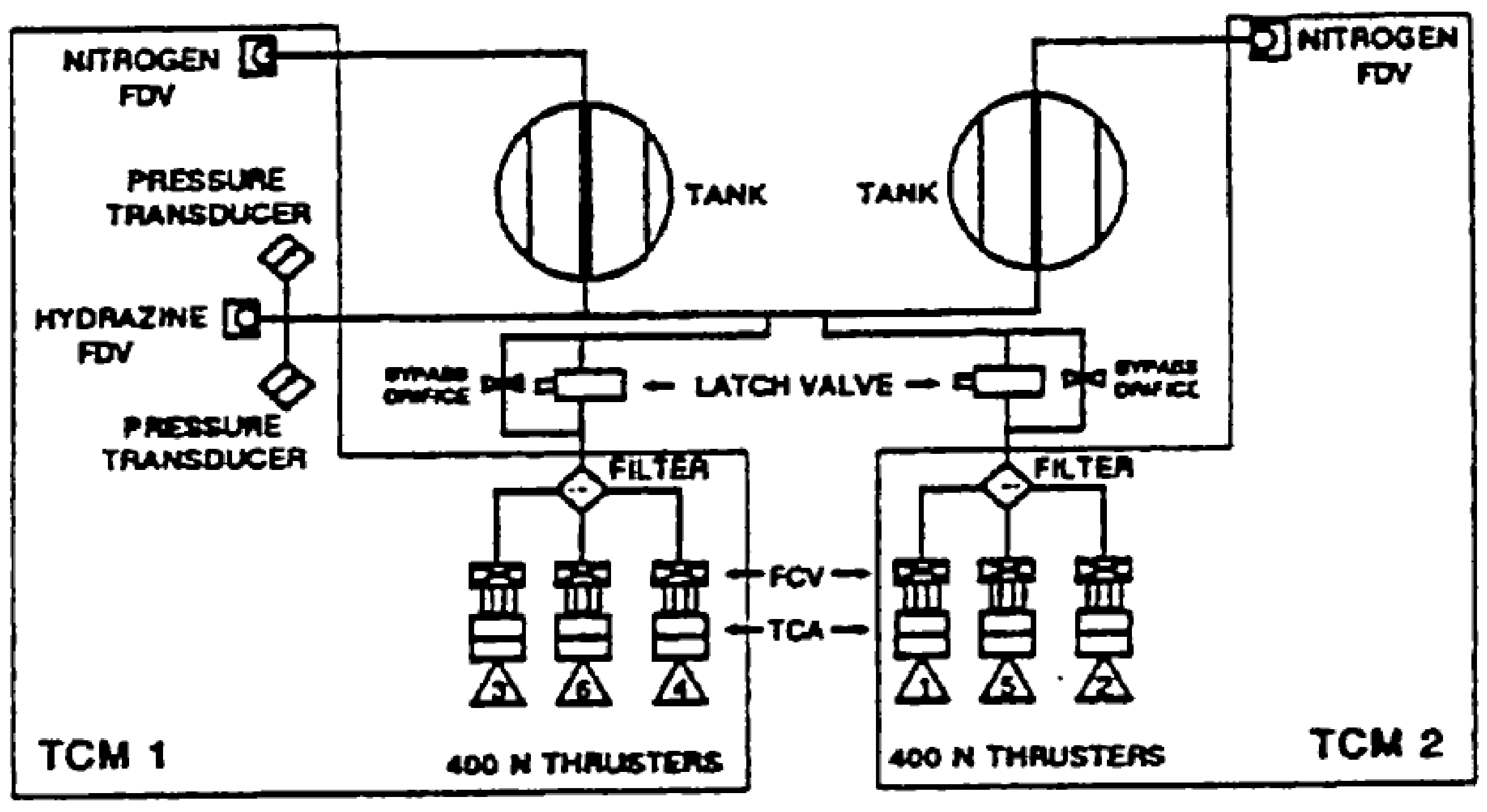


Figure 14 : Attitude Control System SCA

At the end of the mission, the SCA can have residual pressures up to 20 bars and up to 50 kg propellant (values 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, temperatures remain 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.

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 vapours encounter hot spots.
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 whic a puncutre only leads to a leak).

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

A theoretical determination of the threshold pressure was then performed by ESI, using the EFHYD2D code : it was demonstrated that the tank should withstand the impact of an Aluminium 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 in Freiburg : a 1 mm debris launched at 9 km/s impacted the tank filled with 18 bars : the results 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)

3.5. 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 and only a minor pollution can be observed (dust).

We checked the cleanliness of the separation during one of the development test.

The obscuration ratio was measured using pollution trapping panels (covering more than 180°) : figure 15 details the test set-up.

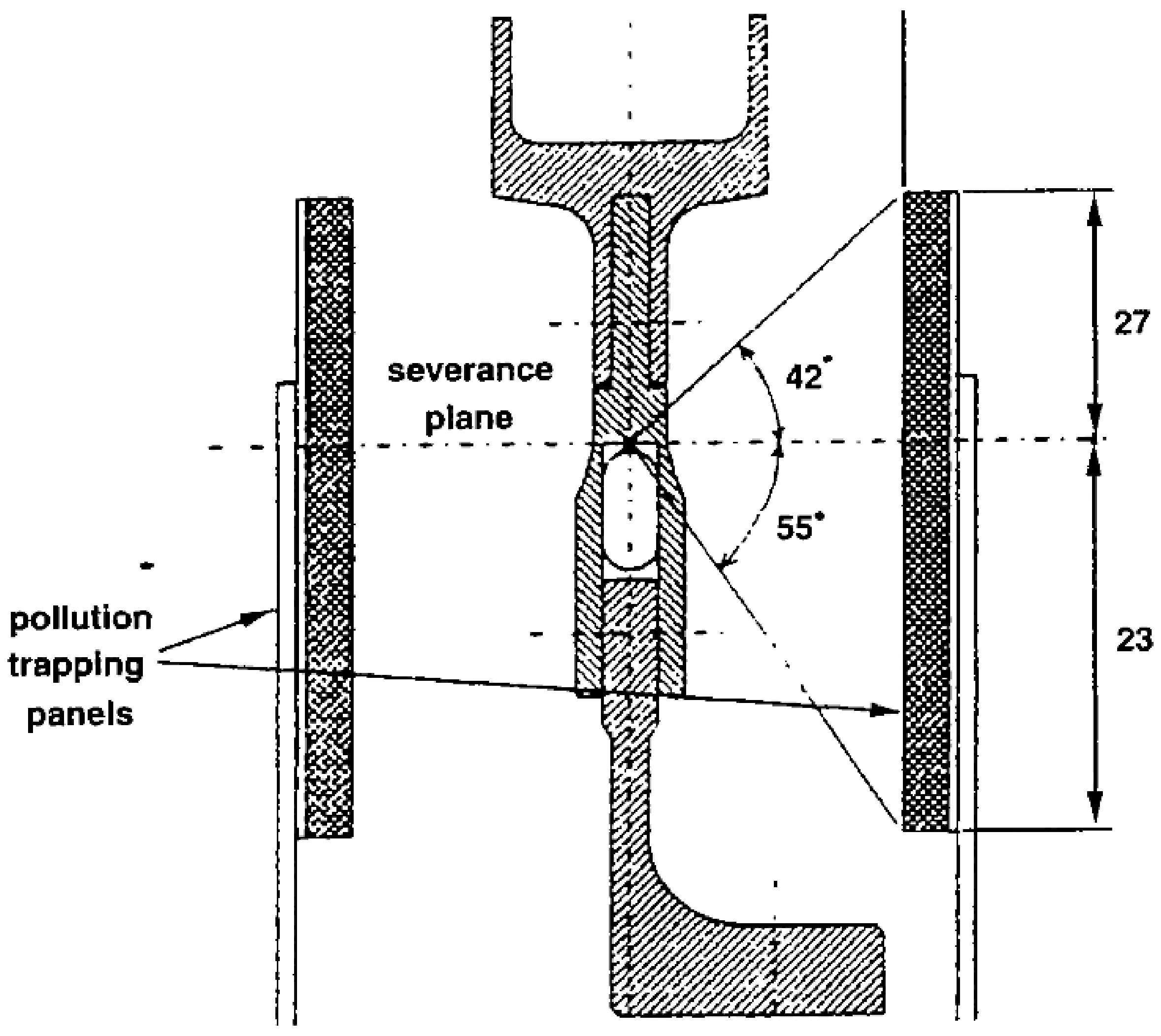


Figure 15 : Obscuration ratio measured during Speltra separation test

The results were extremely good : the observed obscuration ratio were 19.10^{-6} on the internal side and 88.10^{-6} on the external one, for a typical requirement of 5.10^{-3} (Hughes).
The separation of Speltra (and in a similar way of all the orbited structures) is fully compliant with our debris mitigation rules.

3.6. Electrical batteries and cells

The use of Ag-Zn electrical cells nominally produces gazeous 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 litre. Natural leaks lead to a total passivation of the cell withn a few months.

Nominally, the Ni-Cd balleries are cut before reaching total discharge ; therefore, there is no production of gazeous Hydrogen and at the end of the mission, the battey only contains 100 cm3 air at 1 bar maximum. The natural discharge of the battery leads to a total passivation in less than 50 days.

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

4. FUTURE PROJECTS

4.1. Launchers derived from Ariane 5

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 : different ascent trajectories are considered, and a low GTO perigee is one of the elements of the trade off leading to the selection of upper stages upgrades
- perigee lowering manoeuvres 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 manoeuvre is however complex : controllability of the upper stage is low without payload and mission duration would be drastically increased.
- the debris mitigation rules described here would of course be included in the requirements of any new stage
- 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).

5. CONCLUSION

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

- no Ariane 4 upper stage has ever been encountered since the passivation is implemented
- no operational debris is generated during the satellite placement mission

Ariane 5 is the first launcher ever designed with debris mitigation measures included in the requirements from the begining of the development.

Nevertheless, progress can still be made and improvement can still be made : lowering of the GTO perigee after the end of the mission and full passivation of the SCA are 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. We believe that similar rules applied to all current and future launchers would greatly contribute to debris mitigation.