Maneuvers to Reduce Ariane 5 Upper Stage Lifetime Duration in Orbit

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ABSTRACT

The Cryogenic Upper Stage on Ariane 5 (ESCA) uses the HM7B engine which is a heritage of the Ariane 1 Upper Stage engine. This induces that ESC stage is not re-ignitable in orbit, as such a feature can be avoided for GTO (Geostationary Transfer Orbit) launches from French Guiana. As a result, it is not possible to perform a controlled reentry of the Upper Composite once the launcher's main mission is completed. As Ariane 5 was designed well before 2008, it has to justify of its best effort in the aim at respecting the so called "25-years rule" relative to the maximum life duration on orbit (Article 55 of the Technical Rules of the French Space Operations Act).

The upcoming Ariane 6 launcher is fully compliant since Upper Stage will be re-ignitable and deorbited with a controlled atmospheric reentry.

In order to do our best effort and minimize the A5 Upper Composite life duration on orbit, ARIANEGROUP, ARIANESPACE, ESA (European Space Agency) and CNES (French Space Agency), have joined efforts to implement, recurrently, maneuvers to reduce lifetime by using remaining onboard energy to decrease altitude of the Upper Composite GTO orbit after payloads' injection. The technical approach is to use residuals propellants, after commercial phase, to create, by cold liquid / gas ejection, a delta velocity in an optimized direction, without introducing any hardware change to the current launcher system definition. LH2/GH2 (liquid and gaseous hydrogen) are ejected through the HM7B nozzle, without re-ignition, which allows to reach a certain level of thrust enabling to reduce both perigee and apogee altitudes and therefore the Upper Composite's life duration.

After some experimental flights, maneuvers for Upper Stage perigee/apogee decrease are now implemented as the reference for the ESC end of flight before final passivation.

This article will expose maneuvers applied at the end of Upper Stage flight and gains expected in term of life duration minimization. Durations will be compared with Upper Composite previous situation without maneuver.

1 INTRODUCTION

Ariane 5 launcher basic configuration was developed late 80's and 90's with a first successful flight in 1998. The ECA configuration (Ariane Cryogenic Stage), currently the only one on the market, uses an Upper Stage engine, the HM7B, which was initially on Ariane 1 (1979) and was continually improved until Ariane 4 last flights.

At that time, the Upper Stage engine re-ignition capacity was not a need for any satellite mission and for any Ariane launched from French Guiana. This was a specificity compared to main competitors using launch bases with higher latitudes. As a matter of consequence, a controlled reentry at the end of the mission was not possible.

Nowadays, the international key issue of space debris mitigation is well spread over the space community, and the French Space Operation Act [6] (FSOA) established technical rules is one of the major asset to mitigate risks of Space Debris proliferation. In France, and more generally in Europe, these rules are applicable for developments occurred after 2008, in particular for Ariane 6 and Vega developments.

However, for objects developed and produced before 2008, as our Ariane 5 launcher, the article 55 “Interim provisions” is applicable:

“The authorization application files for launch operations using a launch system which was operated for the first time from French territory before 4th June 2008 can refer to the technical files already examined by the Centre National d’Etudes Spatiales, in particular within the framework of existing international agreements, especially those concluded with or through the European Space Agency. In this case, the requirements of paragraph 6 of article 21 of this order do not apply. If it can be duly proven that the requirements of paragraph 5 of article 21 of this order cannot be implemented, the launch operator will do everything it can to approach the thresholds mentioned.”

As already established by some studies [3], [4] and [7], the Geostationary Transfer Orbits (GTO) have quite complicated dynamic properties which can greatly influence the orbital lifetime and its scattering of objects in such orbits. Due to their orbital parameters, Ariane 5 GTO missions cope with these phenomena and, as a consequence, the calculated lifetime at 90% of probability is, in average, 70 years. So above the 25-years rule of the article 21.

As required in article 55 of FSOA technical rules, since several years, Ariane 5 teams AGS (ArianeGroup), ESA (Europe Space Agency), AES (Arianespace) and CNES (French Space Agency), have worked together to reduce to the best of their ability Ariane 5 Upper Stage orbital life in order to come closer to the 25 years.

In the first chapter of this article, we will explain the Ariane 5 Upper Stage orbital life situation up until a few months ago. Clearly, the 25-years rule could not be fulfilled, so we worked jointly to find solutions in order to reduce this lifetime. This is treated in the second chapter. In the third part, we will detail the maneuver that have been implemented in standard practices for some months to reduce the life duration by decreasing perigee/apogee altitudes at the end of the flight just before passivation. Finally, in the last part, we will provide a feedback about several flights on which these manoeuvers were implemented.

2 STATUS OF ARIANE 5 END OF LIFE UNTIL 2018

2.1 Classical GTO mission

Up until 2018, the usual sequence for an Ariane 5 GTO mission was the following:

- H0: Lift off and the ascent phase: Solid Rocket Motor (EAP) boosters and Main Cryogenic Stage (EPC) thrusts
- H0 + ~2 min: EAP boosters’ separation
- H0 + ~10 min: EPC Vulcain 2 engine extinction and separation from ESCA (Ariane 5 Cryogenic Upper Stage)
- H0 + ~20 min: ESCA HM7B engine extinction
- H0 + ~20 min to H0 + ~40 min: Separation of upper payload, Sylda (dual launch adaptor) and lower payload
- Passivation

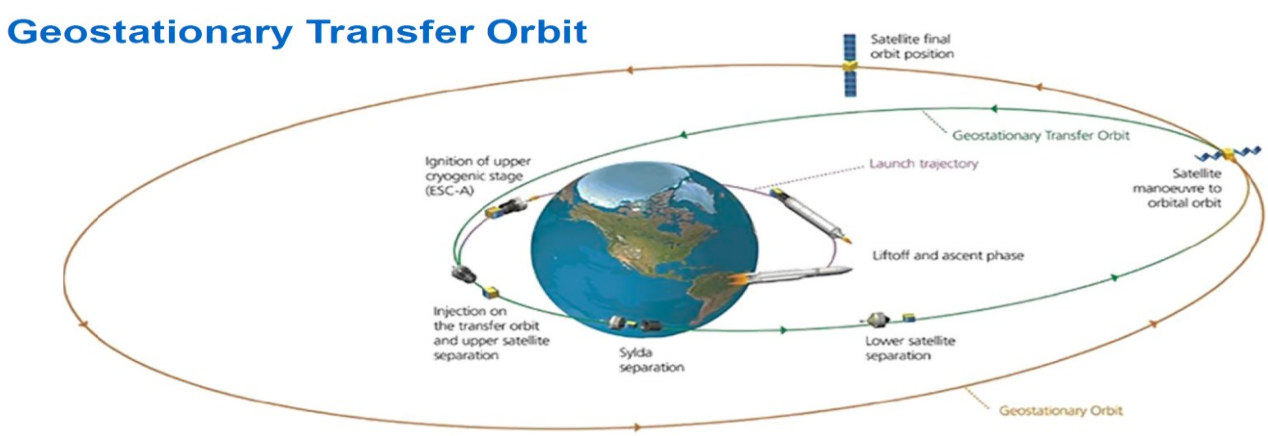

Fig. 1. GTO Ariane5 usual sequence

Payloads separations occur after the first passage of the perigee of the GTO orbit with a true anomaly for the upper payload around 40° and for the lower payload around 60°. Between each separation and after the last one, distancing manoeuvres are done to prevent any collision between Upper Stage, Sylda and payloads. After that, ESCA stage is perpendicularly oriented to the orbit plan and put in final spin to prepare its disposal phase. This is needed to guarantee the conservation of orbital parameters during passivation. With this constraint, minimum impact on trajectory is expected during the outgassing process of passivation.

Since Ariane first flights, passivation phase is applied leading to empty propellant tanks and de-activate any other energy sources. Thus, explosion risks due to on-board energies are reduce closed to zero and debris generation are mitigated.

The FSOA technical rules require that this final disposal phase is in real time visibility, recorded and transferred to ground station network for telemetry data exploitation. As a consequence, the duration limitation of this phase is to be taken into account in the building of the sequences.

The functional principle of the propellant passivation is illustrated by the simplified scheme Fig. 2. At the end of the main Payloads mission phase, liquid residuals are in low quantity. Helium and gaseous Oxygen mixing pass through a relief valve and is evacuated by oxygen purge nozzles (green circuit in Fig. 2). Valve is opened by an actuator and locked by a pyro-actuator. For gaseous hydrogen (GH2), there are two phases: pre-passivation and passivation (Orange circuit in Fig. 2). During the pre-passivation phase, GH2 is evacuated mainly by nozzles of the attitude control system. For the passivation phase, remaining GH2 is evacuated through a valve, pyrotechnically maintained open, and sent away by the passivation Nozzle.

As valves stay opened, the rest of the propellant (liquid and gas) is evacuated progressively and therefore no overpressure could occur in tanks until empty.

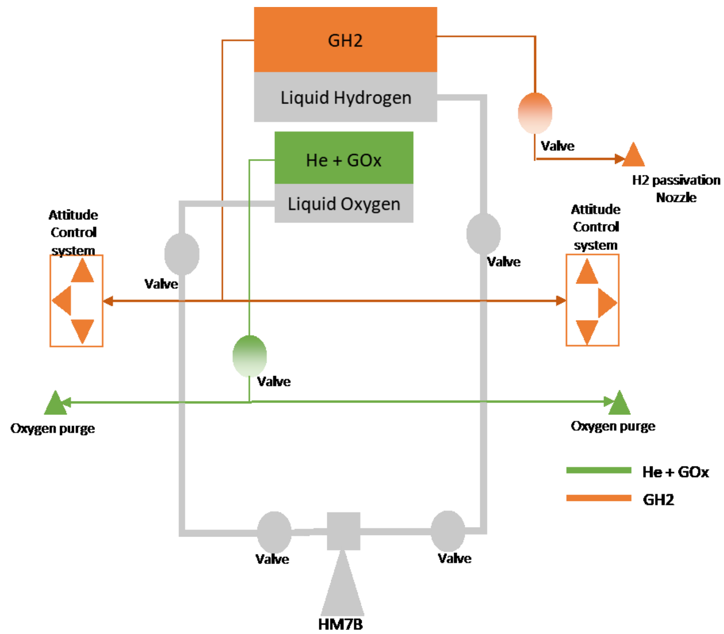

Fig. 2. Ariane 5 passivation functional scheme

2.2 The STELA tool presentation

As part of the French Space Operation Act (FSOA), CNES developed the STELA software to evaluate object lifetime in orbit and its conformity regarding the fourth FSOA criterion:

- C1: Orbital life duration below 25 years
- C2: No LEO (Low Earth Orbit) crossing within 100 years
- C3: No GEO (Geostationary Earth Orbit) crossing after 1 until 100 years
- C4: No GEO crossing within 100 years

References [1] and [2] present the methodology applied and the software.

The STELA tool computes long – term orbital propagations for objects in LEO, GEO and GTO. It is based on a semi – analytical method which, using Runge – Kutta method, numerically integrates differential equations describing average orbital parameters evolutions and considering dynamical effects significant for each orbit type (moon-solar perturbations, solar radiation pressure, atmospheric friction….

Long term orbit propagations are really sensitive to initial conditions: initial orbital parameters, launch date and hour which render moon and solar positions with respect to the object orbit and thus particular influences. Moreover, some key hypotheses like reflecting area, drag area, drag coefficient and reflectivity coefficient have a significant impact on computation results. One of the biggest hypotheses is the solar activity which it takes randomly based on past experience. FSOA "good practices" guidelines recommend the use of normalized methods and values. In order to be exhaustive in constraints that could impact orbital lifetime, STELA offers the possibility to choose orbital perturbations to take into account moon-solar perturbation, Earth potential order…

Geostationary Transfer Orbits, due to their high eccentricities and phenomena related to the moon and earth potential perturbations, have specific dynamical properties that can complicate propagations' behaviour and forecasts ([3] and [4]). Sensitive changes on parameters or coupling between natural perturbations can generate resonances impacting in significant way the lifetime. So, to estimate their lifetime, a statistical approach based on Monte-Carlo computations is implemented in STELA and life duration estimation in a more appropriate way, is given with a probability of 90% associated to a confident interval at 95%.

2.3 ESCA Orbital lifetime

In order to clarify the GTO dynamic problematic with respect to the estimation of life duration, the figure below illustrates an example of GTO resonance [3]. With the same initial conditions, a slight change in the surface/mass ratio can have an important impact on the semi-major axis evolution and on the re-entry duration.

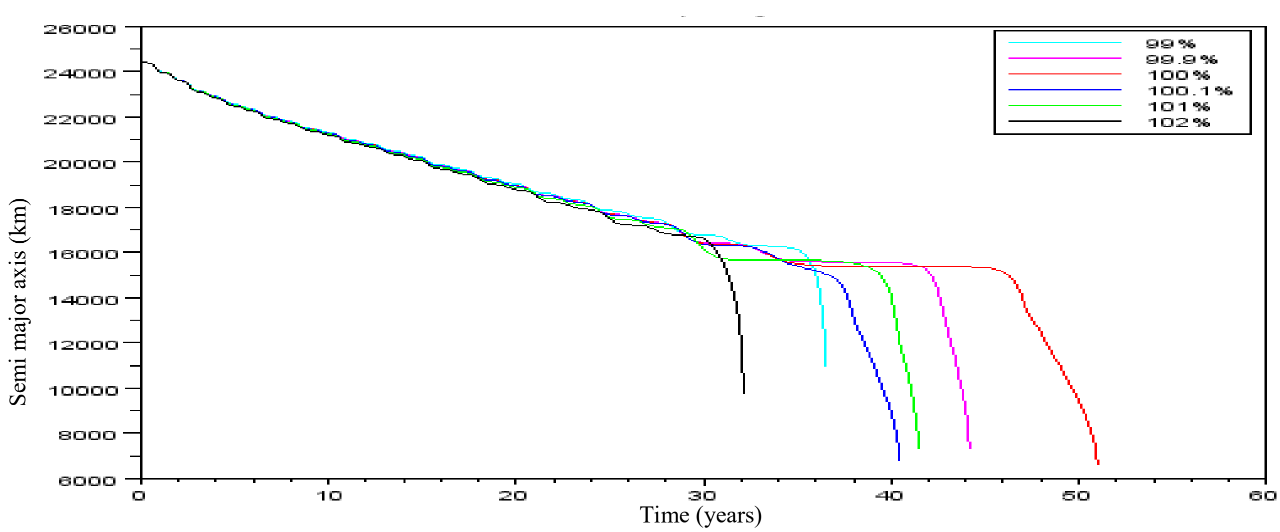

Fig. 3. Evolution of semi-major axis for different Surface/mass ratio and life duration impacts

In their article [7], D-A Handschuh & al did a complete evaluation of Ariane launcher debris in GTO. Ariane Objects' TLE (Two Line Element) made available by USSPACECOM site space-track.org was implemented in STELA and propagated over 200 years on a thousand Monte Carlo calculations. For Ariane 5 ECA rocket bodies (ESCA), status done in 2013 give an estimated average lifetime of 85 years at 90% confidence.

A new computation has been performed with A5 ECA flights between 2005 and 2018: 61 Upper Stages have been catalogued on Space Track site. The average total lifetime at 90% was estimated to be at least 70 years taking into account the fact that STELA stopped its extrapolations to 100 years.

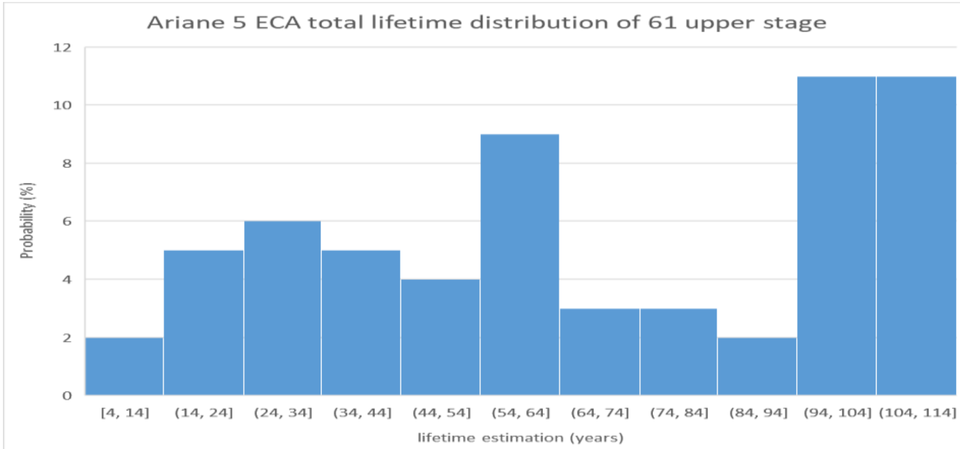

Fig. 4. Total lifetime distribution of Ariane 5 ECA rocket bodies

3 THEORITICAL STUDIES TO REDUCE ESCA ORBITAL LIFETIME

Already in their article of 1997 [5], Bonnal, Sanchez and Naumann opened discussions on the reduction of perigee altitude as a debris mitigation measure for the forthcoming Ariane 5 launcher to reduce its lifetime in orbit. This concern was also emphasized in the other article, written in collective CNES/ESA/AES approach in 2009 [8].

Since 1997, some theoretical analyses have been done to study the effective utility in reducing the perigee altitude, as well as which kind of maneuvers could be interesting to implement on Ariane 5 and their feasibility at the end of flight.

The figure below illustrates the fact that reducing perigee has a real interest to reduce ESCA orbital lifetime. The study evaluates the resulting lifetime for GTO launch occurred all over the year for a lift-off time between 21:30 and 00:30. As can be seen, with a perigee of 250km, the possibility to respect the 25-years rule is almost zero. The more the perigee decreases, the more the possibility to respect the 25-years rule is high.

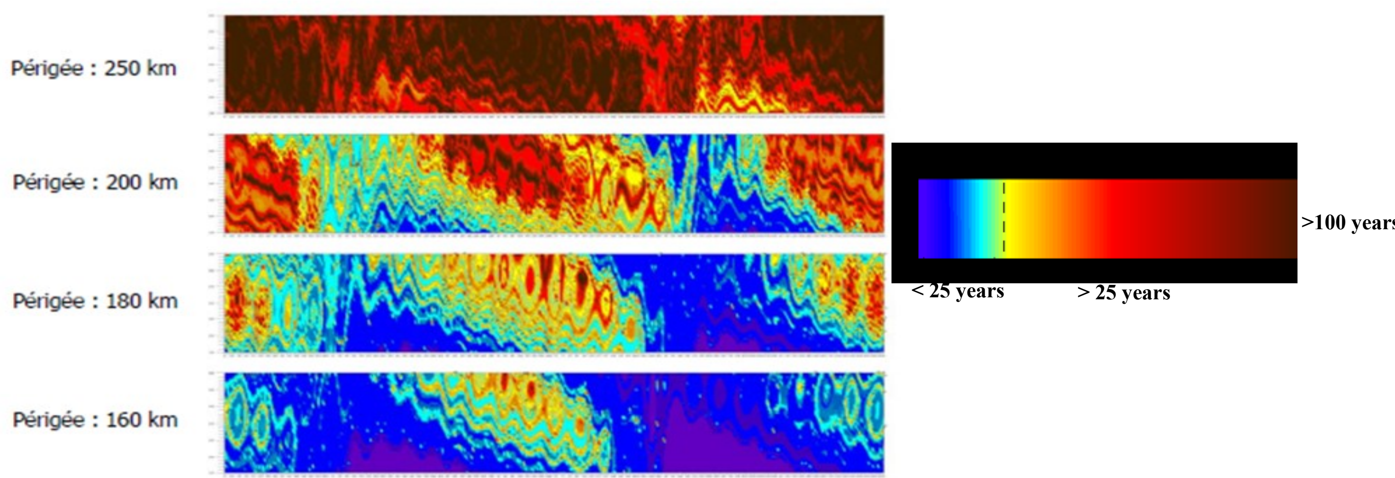

Fig. 5. Orbital Lifetime evolution function of perigee altitude

The question is how can we reduce the ESCA perigee with the HM7B engine which is not re-ignitable? In 2006, first studies evaluated the available thrust by outgassing H2 residuals through HM7B nozzle without firing it, in cold gas ejection. Estimations gave approximatively 80N at the beginning of outgassing for a LH2 (liquid hydrogen) tank pressure of 1.8 bars. Then, thrust is decreasing progressively with the pressure (Fig. 6)

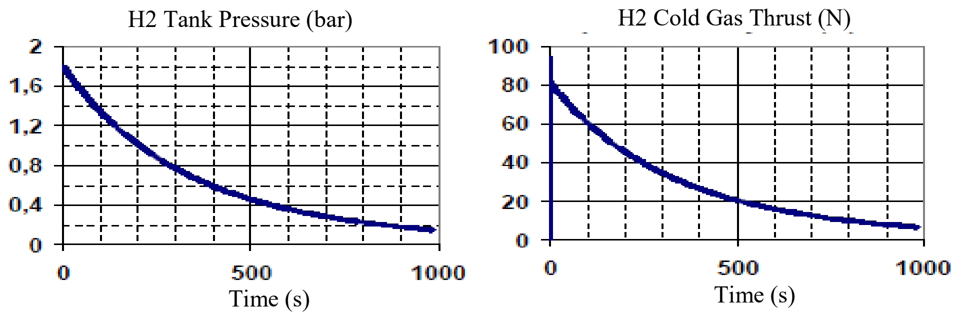

Fig. 6. LH2 cold gas thrust evolution with the pressure

Therefore, using the cold gas impulse generated by the HM7B nozzle could allow the reduction of orbital parameters and thus the most efficient lifetime reduction if the manoeuvre is done in the optimal way at the optimal moment. The conclusions of these investigations were illustrated in the figure below (Fig. 7.). As explained earlier, to better reduce the lifetime in orbit the perigee altitude has to be decreased and to do that optimally, the boost has to be done by a quick impulsion on apogee in the opposite direction to the orbital speed direction. This kind of maneuvers would not affect other orbital parameters.

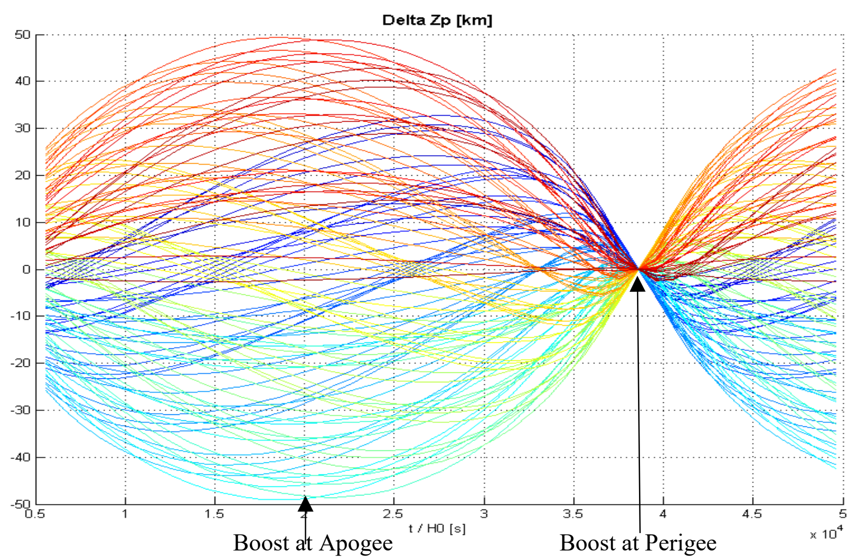

Fig. 7. Perigee altitude modification according to the moment and direction of boost occurrence

Moreover, as the thrust decreases progressively with the pressure, and taking benefit of propellant regeneration, having a multi-boost strategy could better enhance perigee altitude reduction (Fig. 8) [9].

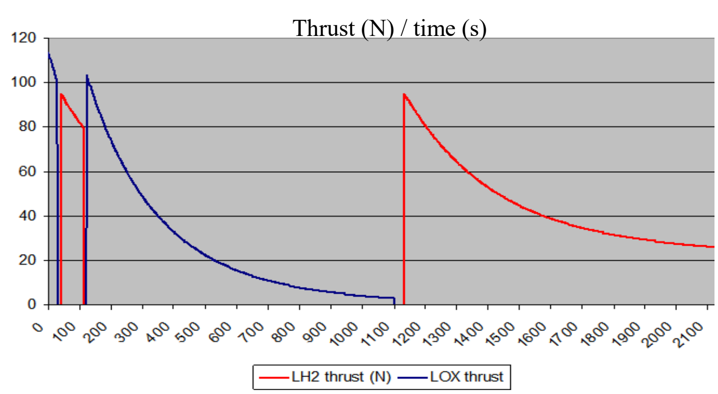

Fig. 8. Example of a multi-boost strategy

However, to define the mission characteristics, some operational constraints and other Launch System requirements, which might limit the overall possibilities in particular for multi-boost strategy, have to be taken into account such as ground stations network, batteries limitations, Upper Stage qualified domain…

4 FLIGHTS MANEUVERS TO REDUCE ESCA ORBITAL LIFETIME

4.1 Principle of the flight maneuver

Since 2015, experimental maneuvers have been flight tested at the end of main Payloads mission just before passivation operations.

The first experiments were conducted on three current GTO flights after payloads separations. Among others, we tested LH2 chill down and manoeuvers by using first LH2 and GH2 cold gas ejection by the main HM7B chamber and nozzle, followed by oxygen gaseous (GOx) ejection by oxygen purges nozzles. Then, a combination of LH2/GH2 cold gas boost by HM7B nozzle with a GOx boost by oxygen purges nozzles. The main lessons learned and confirmations are the following: a GOx+Helium boost is less efficient than a LH2 (even GH2) boost by a factor 2. A combination of both impulses has a favourable impact. The pressure levels in both tanks and the quantity of residuals drive the efficiency of the thrust and its associated duration.

In 2018, two flights were tuned specifically to perform, after Payloads released, a ripe manoeuvre to reduce apogee altitude and learn more about the impulse efficiency of this more mature sequence. Based on those in-flight experiments, an identification of the LH2 tank pressure model during HM7B LH2/GH2 chill-down has been performed, allowing reliable predictions in terms of perigee/apogee decrease.

With this feedback from flight experience, the feasibility of such a manoeuvre was acquired and its design fixed. Results have allowed authorizing, since early 2019, the recurrent implementation within the flight mission of this consolidated sequence to reduce perigee/apogee altitude in order to reduce the ESCA orbital life duration. We called it the End Of Life Manoeuvre (EOLM). After Payloads release, general principles of EOLM phase definition lie on:

- a distancing and re-orientation manoeuver named Collision and Contamination Avoidance Manoeuvre (CCAM), ensuring short-term distancing with payloads, during which longitudinal depointing and delta velocity (ΔV) of the Upper Composite are estimated in order to detect potential Attitude Control System or oxygen purges nozzles failures
- a distancing continuation with He pressure threshold to be checked in order to pronounce GO/NOGO in EOLM sequence.

Namely, as Upper Composite passivation achievement is mandatory to be realised, a GO/NOGO test was implemented in the flight software to control, at the end of the Payloads mission phase, key parameters allowing or not the realization of the EOLM new sequence prior going to the passivation phase. This GO/NOGO test verifies:

- Nominal HM7B engine shut down: no depletion stop
- Nominal HM7B nozzle position
- Nominal functioning of the attitude system control
- No failure in the Inertial Reference System
- Nominal functioning of oxygen purges to control the delta velocity provided by distancing after the last payload release
- Nominal Helium command pressure to guarantee helium needs until end of passivation

The positive diagnosis of these tests done onboard allows EOLM pursue. The principle is then to eject simultaneously oxygen and hydrogen residuals by cold gas boosts in the optimal direction to reduce the final apogee/perigee of the Upper Composite. Considering the mission constraints: payloads separations near the perigee, residual electrical power budget of batteries and visibility for passivation phase by a ground station network, waiting the apogee to be the most efficient to reduce perigee and perform EOLM is not possible. Moreover, using the benefit of propellant regeneration and performing multi-boost is also not possible
Consequently, EOLM manoeuvers are performed as soon as possible after payloads injection to maximise the possible chill-down duration. During that phase, gaseous and liquid hydrogen are ejected by HM7B nozzle without re-ignition and gaseous mix oxygen/helium is ejected by oxygen purges as shown Fig. 9.

At the end of chill-down, a classical passivation sequence occurs. The order of magnitude of the maximum EOLM sequence duration is about 1000s, considering constraints mentioned before.
In case of NOGO, a standard passivation as formerly is implemented in the flight software.

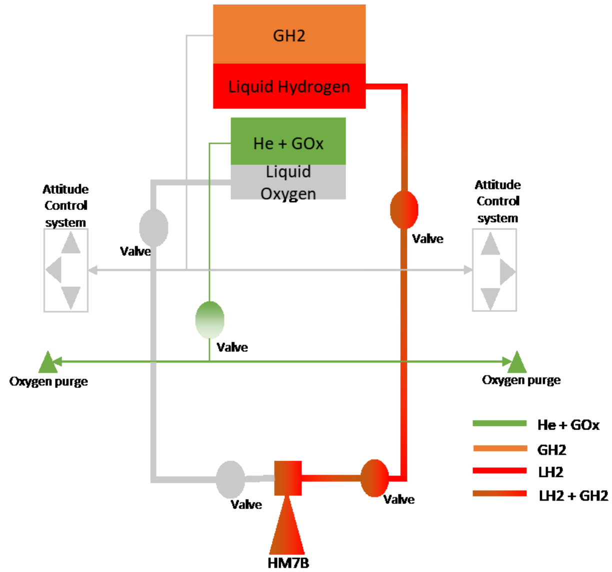

Fig. 9. Principle of the EOLM to reduce Apogee/perigee altitudes

Moreover, to optimize the execution of this sequence, some other parameters have to be taken into account:

- Impulse delivered from hydrogen passing through HM7B nozzle is twice more efficient than impulse delivered from oxygen passing through purge nozzles.
- Thrust delivered from liquid hydrogen residuals is more efficient than from gaseous hydrogen.
- As soon as H2 diphasic flow passes through the nozzle, efficiency of impulse strongly decreases.
- Pressures of residuals also impacts the thrust: the more the pressure is the more powerful the thrust is.

So, as we experiment during the first five sequence occurrences, quantity and pressure of residuals are stronger leading parameters.

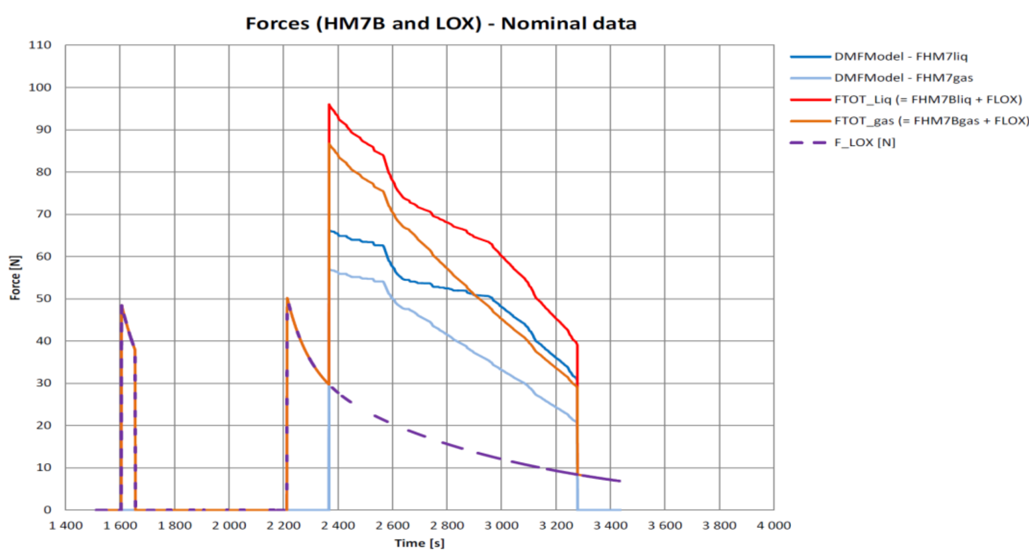

Fig. 10. For L5104, predicted nominal ranges of thrusts evolutions

This is the level of "Best Effort" that can be achieved with Ariane 5 Upper Composite without any modification of the existing design and the in-flights results of EOLM sequence implementation, paragraph bellow, show the real positive effect of this strategy.

At the end of EOLM sequence, the passivation is done as required and described in paragraph 2.1 and Fig. 2.

4.2 Results of EOLM implemented in flights

In 2018, some flights have experimented the EOLM strategy and, since the beginning of 2019, this sequence has been implemented as a standard practice as long as it is compatible with the main Payloads GTO mission and the usual Ariane 5 configuration (no addition of helium sphere, no additional battery, no software modification because already implemented for experiments needs, no additional ground station activated to track Upper Composite).

The flight VA246 L5104, launched in December 2018, was one of the first EOLM application targeting a GTO with an apogee close to 35800 km and a perigee close to 263km. The estimated lifetime in case of NOGO (no EOLM) was near 54 years at 90% of probability. As the test passed in the GO branch, EOLM was performed and the estimated lifetime, based on TLE data giving an apogee near 35500 km and a perigee near 200 km, is close to 25 years at 90% of probability with a level of confidence of 95%. This maneuver allowed to get closer to the goal of the 25 years.

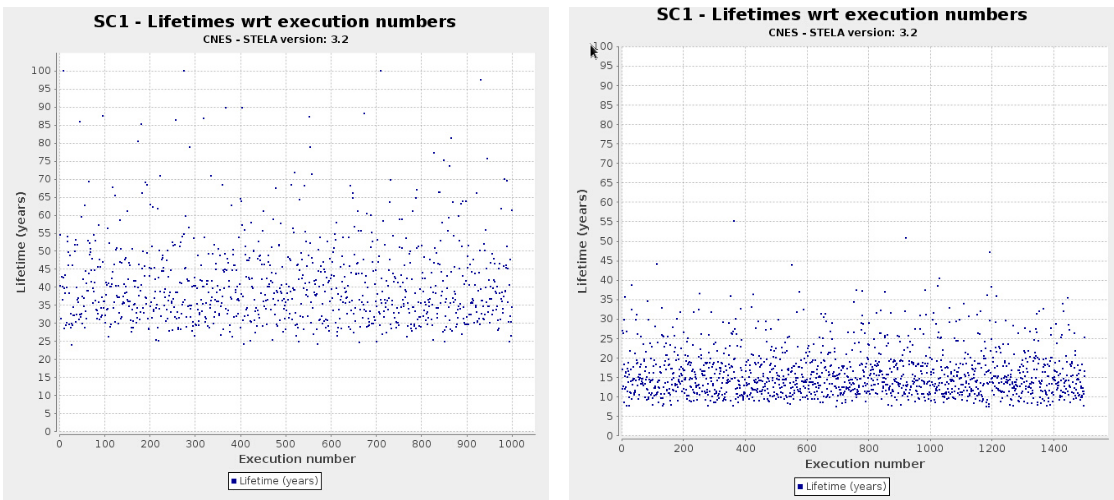

Fig. 11. Monte Carlo calculations without EOLM (left) / with EOLM (right)

In June 2019, VA248 L5107 performed an EOLM which allow to reduce the lifetime duration of around 30 years. Indeed, the prevision without EOLM gave 62 years at 90% of probability while STELA computation, done after flight with TLE data's, estimate the life duration at 31 years at 90% of probability.

The last flight with EOLM done in August 2019 (VA249 L5109) is in line with previous experience. The reduction is estimated near 20 years. Without the EOLM, the lifetime was estimated at 32,65 years at 90% of probability. After flight, the estimation, based on TLE, gave 14,2 years which allow to respect the 25-years rule.

These results definitively prove the great interest of this sequence's implementation. The orbital lifetime of the Ariane 5 Upper Stage is decreased drastically. Due to particular dynamic behaviours at each launch, it is not possible to generalize these results and quantify a level of lifetime reduction for future Ariane 5 ECA GTO missions.

5 CONCLUSION

For several years, Arianespace, ArianeGroup, ESA and CNES have worked together to reduce Ariane 5 ECA Upper Composite lifetime in orbit and made their best efforts to get closer to the so-called 25-years rule. First, theoretical studies gave key parameters to realize the optimal maneuver. As the HM7B engine is not re-ignitable, the most effective way is to produce a cold gas impulse boost at apogee to drastically reduce perigee altitude. Gox/He and

LH2/GH2 boosts have to be realised simultaneously by oxygen purge on one hand and the main HM7b engine for hydrogen in the opposite direction to the orbital speed direction on the other hand. To optimise it, it is also useful to take benefit of tank pressure regeneration and performing multi-boost. Due to Launch System constraints, it is not possible to implement this optimal strategy, anyhow the estimations are good enough to significantly reduce the lifetime durations. It must be underlined that neither hardware nor software modification was necessary to implement in order to use residual energy on board to improve Ariane 5 compliancy with the so-called “25-years” rule.

Now, the sequence named End Of Life Manoeuvre is defined and applied as a standard practice on Ariane 5 GTO missions. The implemented flight sequence begins at the end of the main Payloads mission after payloads separations. It means that boosts are done after the perigee. Hydrogen and oxygen residuals are ejected simultaneously by cold gas to produce thrusts in the appropriate direction to the orbital direction. Cold hydrogen goes through the HM7B nozzle without any re-ignition and cold oxygen go through purges nozzles. As a consequence on orbital parameters, apogee and, to a lesser extent perigee, decrease inducing a reduction of the orbital life duration.

EOLM was implemented on all flights, each time it was possible considering payloads constraints, and results prove the real benefit of this maneuver: Ariane 5 Upper Stage lifetime in GTO has been reduced between 20 and 35 years on these first flights.

Even if we have to keep in mind that results cannot be generalised due to mission specificities, launch date, STELA hypothesis…, Ariane5 team did their best to improve the situation with respect to launcher lifetime in orbit without any evolution of the Upper Composite, using cleverly the energy still available on board rather than losing it for free in passivation.

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