THE AEROBRAKING SAIL FOR LAUNCHER UPPER STAGE DEORBITING: CONCEPT FEASIBILITY & TECHNOLOGICAL SOLUTIONS

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ABSTRACT

From 2004, Astrium Space Transportation is working with CNES on a solution for space debris mitigation in the frame of the Microscope Satellite program. This solution consists in using aerodynamic draft for satellite deorbiting. Such a concept – called "aerobraking sail" - is feasible only by using ultra-light deployable structures called "Gossamer structures", which advantages are the low occupied volume in folded configuration, the low mass and the low manufacturing cost for a large deployed surface. Theses structures and the associated technologies are currently under development at Astrium Space Transportation.

Using this background on the aerobraking sail concept and the associated Gossamer structures technologies, Astrium Space Transportation decided to propose a solution for launcher upper stages deorbiting.

A concept feasibility analysis was performed in order to define aerobraking sail architecture and size that could fulfil the need. In parallel, technological solutions using Gossamer inflatable and rigidizable technology were reviewed and compared.

1. PRESENTATION OF AEROBRAKING SAIL CONCEPT AND ASSOCIATED ASTRIUM EXPERIENCE

The aerobraking sail concept consists in increasing surface over mass ratio of orbital objects. The aerodynamic drag being increased, the deorbiting duration of the object is reduced. This deorbiting solution is completely passive, no control of the object being necessary. Due to the atmosphere density reduction with altitude, this concept can work only for objects passing through LEO region at altitudes under 700 to 800 km.

To increase significantly the surface over mass ratio of the object to be deorbited, it is necessary to deploy an additional surface as light as possible. Gossamer "Ultra-light structures" technology was retained for this concept because of its interest in terms of mass & stored volume.

The development of such a system is in progress for the CNES Microscope satellite. After the various selection performed, the concept retained for the passive aerobraking system of Microscope – IDEAS – is two dihedral surfaces called "wings". The surfaces are realised by stretched membranes, deployed with an inflatable and rigidizable boom.

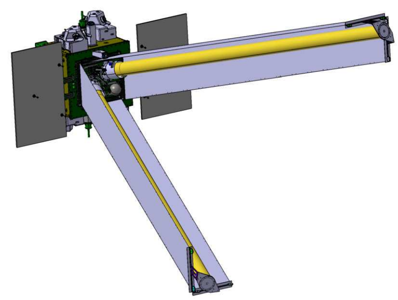

Figure 1 : IDEAS system deployed on Microscope satellite

The technology retained for IDEAS has a TRL of 4. The project is currently in phase B for a flight end of 2013 and a deorbiting 2 years later.

Figure 2 : aerobraking system wing - 3 metres breadboard

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2. ASTRIUM EXPERIENCE ON GOSSAMER STRUCTURES

The Gossamer structures developed at Astrium Space Transportation are deployable and rigidizable in space.

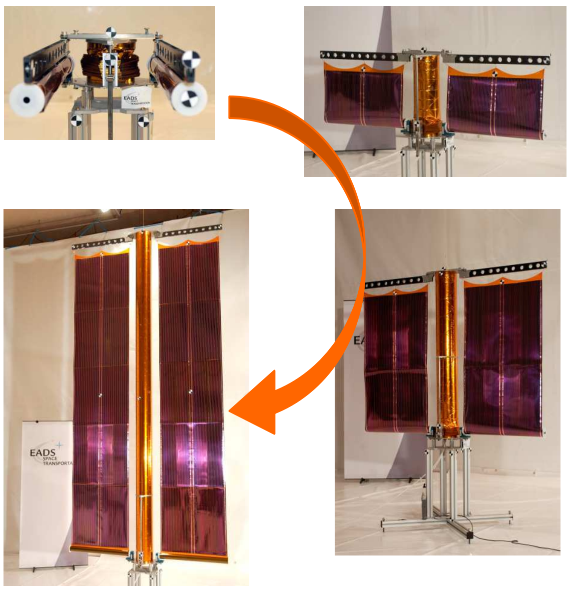

Figure.3 : Gossamer structure deployment concept

The major advantages of these structures are:

- The occupied volume during storage
- The mass
- The cost

To develop these structures, the following domains shall be mastered: folding, deployment control and rigidization.

- Folding efficiency is necessary to maximise the ratio between the deployed volume and the volume in folded configuration.
- Deployment control is necessary to ensure quality and repetitiveness of deployment.
- Rigidization is necessary to ensure correct mechanical behaviour of the structure deployed.

Several folding techniques are possible, depending on the material stiffness and thickness and on the volume available in stowed configuration.

Several rigidization techniques are possible:

- physical rigidization (solvent evaporation, Sub-Tg),
- chemical rigidization (thermal curing, photocuring),
- mechanical rigidization (metallic laminate yielding).

The Gossamer structures developed at Astrium Space Transportation are mainly composed of flexible membranes, ensuring the function itself of the system (for our case the surface that will generate the drag), and a flexible tube, ensuring the deployment and the rigidization. Deployment of the membrane is performed by inflating the tube. The tube is maintained inflated at the end of the deployment until rigidization is done.

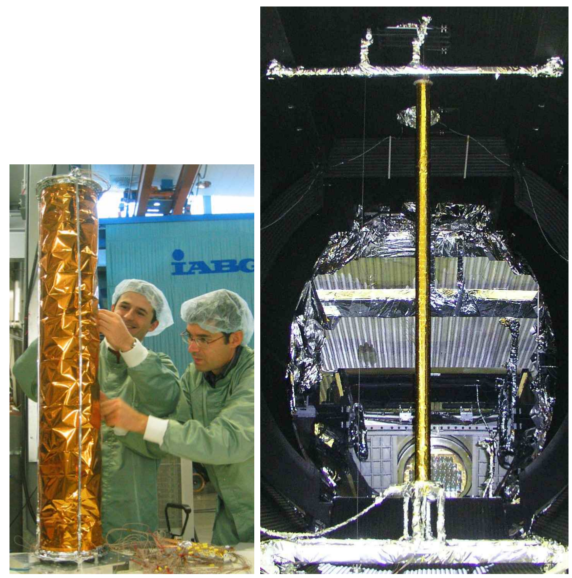

Figure 4 :1 metre and 4,5 metres tubes during test campaigns

3. UPPER STAGE DEORBITING ISSUE

After having injected its payload, the upper stage of a launcher becomes non operational and, as a consequence, a debris. IADC mitigation guidelines [1] recommend to deorbit every objects passing through the LEO region in a duration of less than 25 years.

Most of the upper stage, especially those on GTO orbits, is concerned by this rule.

Considering this need and its experience on the aerobraking sail concept and the associated technological solutions, Astrium Space Transportation decided to propose a solution for launcher upper stages deorbiting.

A concept feasibility analysis was performed in order to define aerobraking sail architecture and size that could fulfil the need. These feasibility studies were performed using characteristics representative of an Ariane 5 class upper stage. Deorbiting simulations were performed to define the aerobraking system necessary characteristics and the optimum for launcher performance.

4. PROPOSED ARCHITECTURE FOR THE AEROBRAKING SYSTEM

Preliminary architectures were studied to give inputs for the deorbiting simulations and to assess main characteristics of the aerobraking system. The following points were looked at:

- Mass budget with respect to deployed surface
- Maximum reachable surface

The study was performed using knowledge coming for other Gossamer projects such as IDEAS.

Two architecture concepts were proposed:

- An aerobraking system composed by several wings of IDEAS type (with size depending on surface to reach)

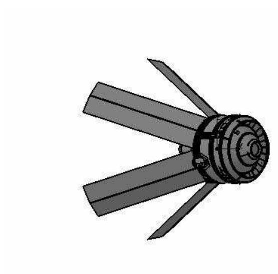

Figure 5 : wings architecture

- An aerobraking system with faceted conical shape, more efficient in terms of mass but more complex in terms of deployment

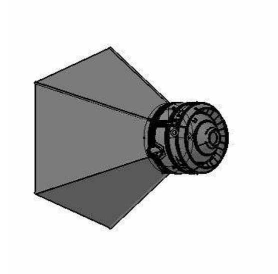

Figure 6 : conical architecture

For each concept, architecture was defined taking into account layout constraints.

The number of wings for the wings architecture, the number of faces for the conical architecture and the inclination with the stage longitudinal axis were chosen to reduce as much as possible the dispersion between minimum and maximum effective surface.

The tubes length considered to establish mass versus surface data were between 5 and 17 metres, the maximum length being considered as reachable considering the current maturity level of the technologies. The tube radius was defined to ensure sufficient mechanical behaviour.

The mass versus surface resulting for these analyses is given hereafter. Effective surface is the medium value of projected surface of the complete system (upper stage + aerobraking system) in all directions of projection. Physical surface is the real deployed surface of the aerobraking system alone.

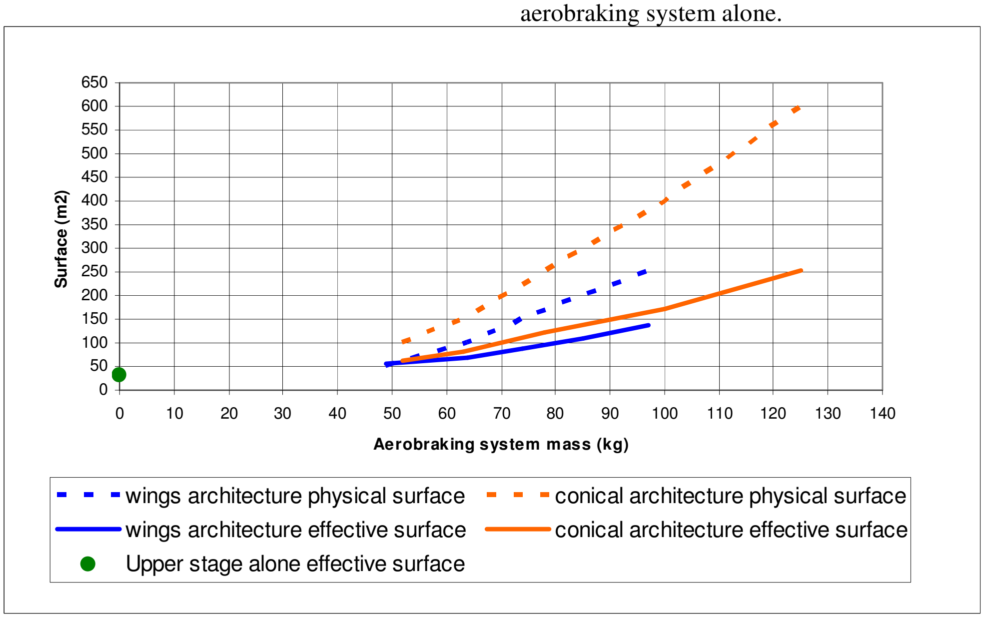

Figure 7 : effective and physical surfaces function of aerobraking system mass for both architectures

5. DEORBITING SIMULATIONS

In order to size the aerobraking system, a parametric relationship must be established between the fall-out duration and the effective surface.

The fall-out simulations have been run with the following hypotheses :

- The vehicle (empty stage+aerobraking system) is modelled as a weighting point, with a ballistic coefficient $S.C_X/m$
- The forces acting on the vehicle are the weight and the drag
- The other forces (moon and sun attraction, radiation pressure, …) are considered as negligible.

The drag must indeed be the dominating orbit perturbation if a 25 years fall-out is targeted. Nevertheless the other forces may have a significant influence on the fall-out duration depending on the initial geometry of the orbit. They should therefore be taken into account when designing more accurately the aerobraking system.

The Earth gravitational potential is modelled to the 2^{nd} zonal harmonic (J2). Higher degrees terms have no secular influence on the semi-major axis and on the eccentricity and where considered as not influent on the fall-out duration. The J2 term was taken into account since it modifies the altitude of the oscillating injection perigee and therefore the efficiency of the aerobraking.

The drag assessment depends on the atmosphere model. The atmosphere features vary with a number of parameters, among which the solar flux is the most influent. The solar flux level is measured at 10.7 cm wavelength and it evolves with 11 years period. The flux bounds are highly variable from one cycle to the other, and are not predictable. For fall-out durations of about 25 years (about 2 cycles), it has been assumed that the solar activity was keeping a constant mean level throughout the simulation.

The simulations have been run with the Jacchia 70 model, which takes into account the solar flux level, and with the simpler US76 model, considered as a mean model. For the Jacchia 70 model, two mean level values have been considered (F10.7 = 150 and 200) in order to assess the sensitivity of the fall-out duration to this parameter.

The fall-out durations are assessed for two initial orbits corresponding to the Ariane 5 main missions :

- A GTO at 7 deg inclined
- A SSO at 800 km

For each orbit, different simulations are run varying the initial perigee altitude and the system ballistic coefficient.

The figures 8 and 9 plot the fall-out durations versus these 2 parameters :

- The initial perigee altitude ranges between 200 km and 300 km for the GTO, between 500 km and 750 km for the SSO
- The ballistic coefficient ranges between 0.020 m²/kg and 0.055 m²/kg. These bounds are representative of the upper stage equipped with a “wings” or a “conical” aerobraking system.

These plots are the drivers for designing the aerobraking system (surface and mass). A trade-off can then be made between the launcher performance (depending on the injection perigee) and the mass penalty (due to the aerobraking system).

For a targeted fall-out duration of 25 years, the following recommendations may be issued :

- For a GTO injection, the initial perigee altitude must not exceed 275 km to have a reasonable aerobraking surface. For perigee around 250 km, a great sensitivity of the fall-out duration to the solar flux, and also to other forces (Moon and Sun attraction) is observed. In order to ensure the efficiency of the aerobraking whatever the perturbations, a sufficiently low perigee altitude (225 km -250km) must be preferred.
- For a SSO injection, the sensitivity of the fall-out duration to the solar flux is even greater. In order to ensure the fall-out with a reasonable aerobraking surface, it is necessary to first decrease the perigee altitude to about 600 km, before the aerobraking system becomes efficient. This preliminary manoeuvre requires another system and the benefit of the aerobraking system becomes less obvious.

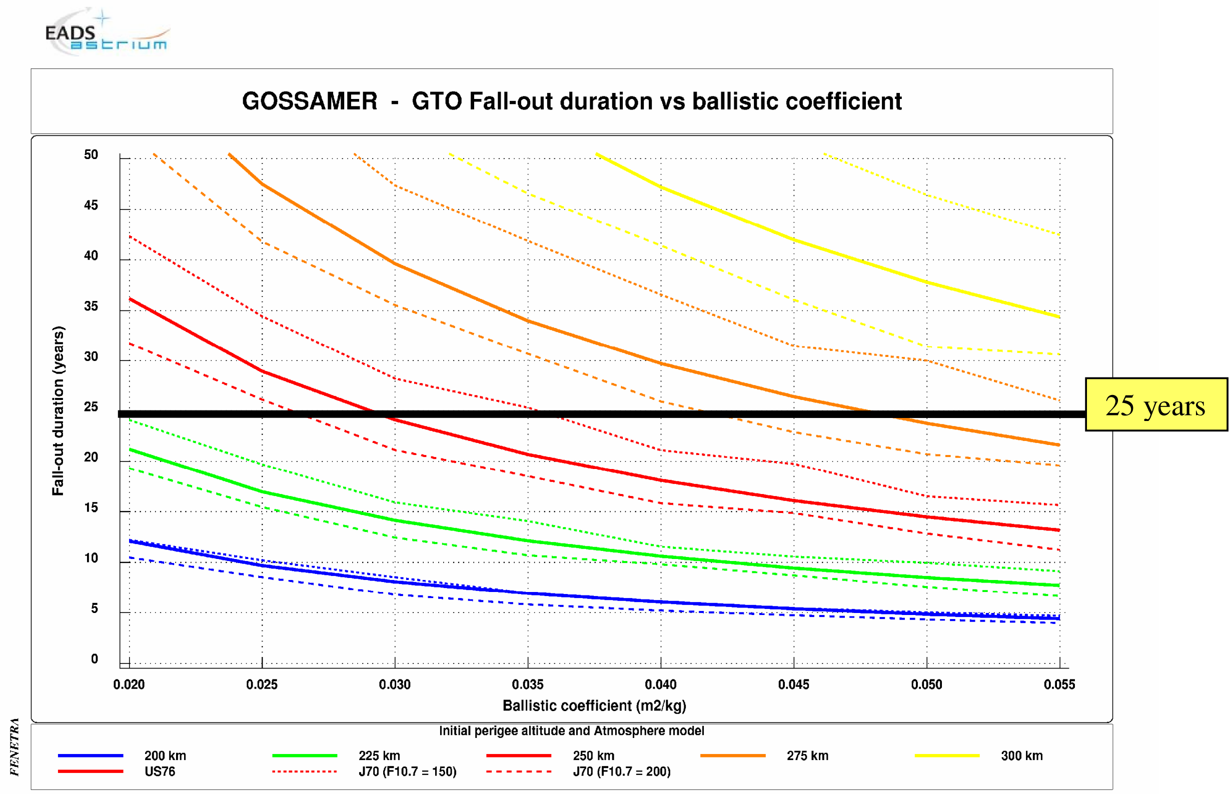

Figure 8 : GTO fall out duration

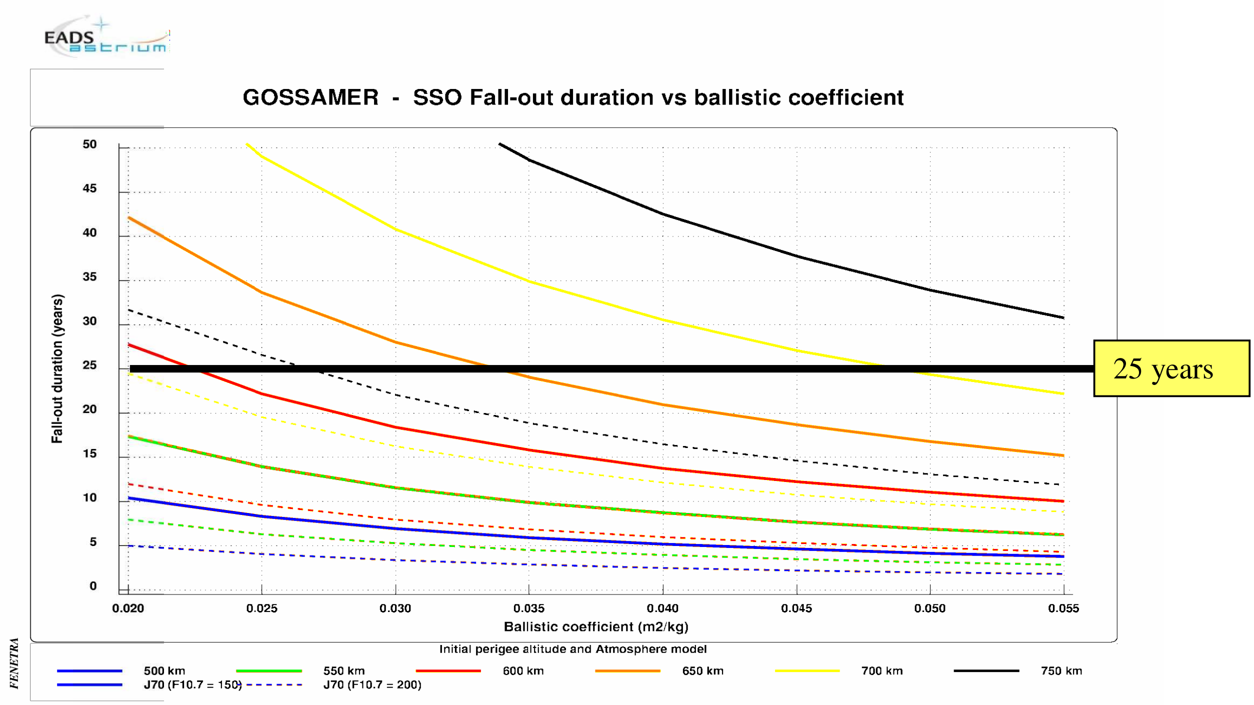

Figure 9 : SSO fall out duration

6. MAIN CHARACTERISTICS AND ADVANTAGES OF AN AEROBRAKING SYSTEM

Using the results of deorbiting simulations, main characteristics of an aerobraking system for an Ariane 5 class upper stage in GTO mission can be assessed.

This system shall have :

- A physical deployed surface of about 350 m^2
- An efficient deployed surface of about 150 m^2 (including upper stage surface)
- Deployable mast of about 12 metres long

The system mass is about 90 kg.

The system has many advantages with respect to other deorbiting solutions.

- It is a passive mean for deorbiting, not needing any control system at the beginning or during the fall out (the system could even work in some degraded cases).

- It can be designed as an autonomous system (only 1 order from the launcher with self-timer is a possibility).

- It is a solution with very limited pre-launch operations & monitoring

- It is a solution with very low safety issues : no use of "dangerous" products (only Nitrogen for inflation)

7. CANDIDATE GOSSAMER TECHNOLOGIES

Among technologies of inflatable and rigidizable tubes in development at Astrium Space Transportation or in cooperation, three are retained as candidate because of acceptable maturity level:

- Aluminium/kapton laminate tube rigidized by yielding ensured by tube pressurization (TRL 4)
- Composite tube polymerized in-orbit after light initiation (TRL 4/5)
- Composite tube rigidized by solvent evaporation (TRL 4/5)

The aluminium/kapton laminate technology is the one used for IDEAS project. It is foreseen to achieve TRL 5 end of 2009.

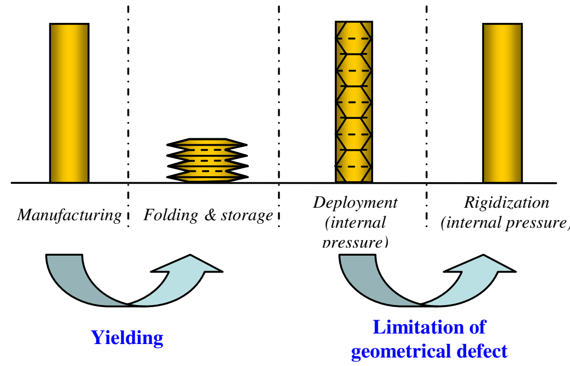

Figure 10 : laminate technology principle

The in-orbit polymerization of composite technology is under development under an ESA contract. It is foreseen to reach TRL 5 end of 2009.

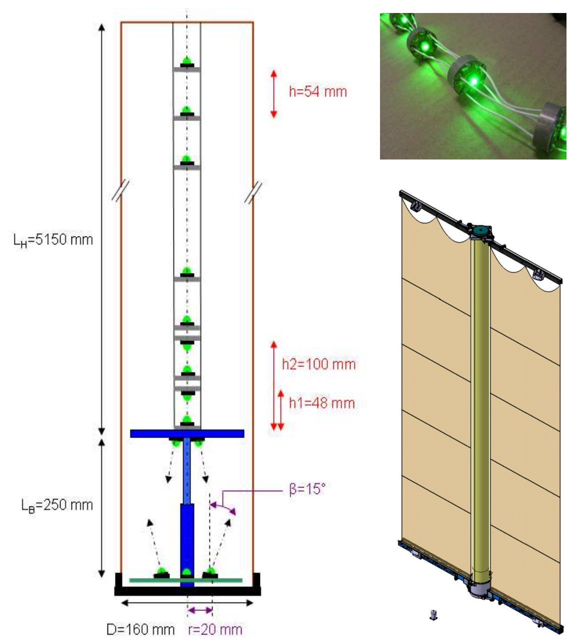

Figure 11 : In-orbit polymerisation technology overview

The solvent evaporation technology is under development by Lavochkin Association (Russia), in collaboration with Astrium Space Transportation. It is foreseen to reach TRL 6 mid 2009 with an in-flight experiment on a Soyuz launch.

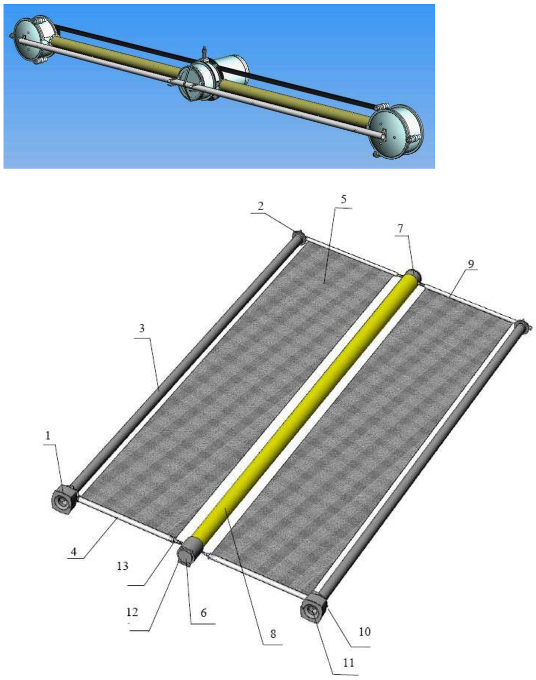

Figure 12 : Lavochkin association solvent evaporation technology overview

All these technologies are possible candidate for an upper stage aerobraking system. The choice can be done only when having a set of requirements taking into account upper stage constraints.

8. CONCLUSIONS

Among possible solution to deorbit, the aerobraking sail has many advantages.

This solution shall be considered for the future as an alternative to classical propulsion systems, and taken into account in launcher pre-development.

Nevertheless, some feasibility consolidation activities and system pre-sizing shall be performed to be ready to propose this solution to a "customer".

9. REFERENCES

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