RESULTS OF THE DEPLOYABLE MEMBRANE & ADEO PASSIVE DE-ORBIT SUBSYSTEM ACTIVITIES LEADING TO A DRAGSAIL DEMONSTRATOR

Thomas Sinn[(1)], *L. Tiedemann*[(1)], *A. Riemer*[(2)], *R. Hahn*[(2)], *T. Spöwitz*[(3)], *P. Seefeldt*[(3)], *M. Sznajder*[(3)]
S. Reershemius[(3)], *S. Meyer*[(4)], *M. Zander*[(4)], *K. D. Bunte*[(5)], *T. Cardone*[(6)], *D. Teti*[(6)], *R. Knockaert*[(6)]

(1) *HPS GmbH, Hofmannstr. 25-27, 81379, Munich, Germany, EMail: sinn@hps-gmbh.com*
(2) *HTS GmbH, Am Glaswerk 6, 01640, Coswig, Germany, EMail: arne.riemer@htsdd.de*
(3) *DLR German Aerospace Center - Institute of Space Systems, Robert-Hooke-Str. 7, 28359, Bremen, Germany, EMail: tom.sproewitz@dlr.de*
(4) *DLR German Aerospace Center - Institute of Composite Structures and Adaptive Systems, Lilienthalplatz 7, 38108, Braunschweig, Germany, EMail: sebastian.meyer@dlr.de*
(5) *ETAMAX SPACE GmbH, Frankfurter Str. 3d, 38122, Braunschweig, Germany, EMail: k.bunte@etamax.de*
(6) *European Space Agency – ESTEC, Keplerlaan, 1, 2201 AZ, Noordwijk, The Netherlands, EMail: tiziana.cardone@esa.int*

ABSTRACT

The development of a passive de-orbiting subsystem was pursued in the ESA GSTP projects “Deployable Membrane” (DM) and “Architectural Design and Testing of a De-orbiting Subsystem” (ADEO) raising the TRL of the subsystem to TRL 5/6. The ADEO subsystem is a scalable drag augmentation device that uses the residual Earth atmosphere present in low Earth orbit. For initiation of the de-orbit maneuver a large surface is deployed which multiplies the drag effective surface of the satellite. Thereby the drag force is increased as well causing accelerated decay in orbit altitude. Advantageous about a drag augmentation device is that it does not require any active steering and can be designed for passive attitude stabilization thereby making it applicable for non-operational, tumbling spacecraft as well.

1 INTRODUCTION

The space debris environment especially in the low earth orbit is an increasing risk for all spaceflight missions. Without effective mitigation measures the debris density will increase to a level where spaceflight becomes more and more endangered. Especially collision fragments will become a dominant part in the debris population larger than 1 cm. Therefore, to ensure safety for future space flight, end-of-life de-orbiting of satellites and upper stages is necessary [1].

For the de-orbiting of satellites in the low earth orbit using an on-board de-orbiting device, several concepts are applicable. They are based either on a propulsion system or on interaction with natural phenomena in the low earth orbit. If a satellite utilizes a propulsion system it can be an advantage that only additional propellant needs to be added to perform a de-orbit maneuver. Using a propulsion system at the end of life requires the functionality of the propulsion system after ~10-15 years in orbit as well as the need for a GNC (Guidance, Navigation & Control) system to ensure the force vector acts in the desired direction. For satellites that do not have an adequate propulsion system and to ensure that a reliable de-orbit can be performed an independent de-orbit module should be considered, either as main de-orbit solution or as a backup system to ensure a redundancy for the de-orbitation. The ADEO subsystem presented here relies on the utilization of the natural drag decay in low earth orbit by increasing the drag area of the satellite at EOL.

Drag augmentation devices (sometimes referred to as Dragsail) are using the residual earth atmosphere present in the low earth orbit [1], [2]. For initiation of the de-orbit maneuver a large surface is deployed which multiplies the drag effective surface of the satellite. Thereby the drag force is increased as well causing accelerated decay in orbit altitude. Advantageous about a drag augmentation device is that it does not require any active steering and can be designed for passive attitude stabilization. Thereby it is also applicable for non-operational, tumbling spacecraft. In order to accelerate the natural orbit decay the drag area needs to be increased without significantly increasing the mass of the satellite. It is therefore necessary to deploy a very light-weight dragsail at EOL (End of Life) of the satellite. This kind of structures is known as gossamer structures.

Within the ESA projects Deployable Membrane and ADEO, the Gossamer-1 technology [3]-[7] developed at the German Aerospace Center (DLR) is adapted and further developed for the dragsail application. In contrast to the previous development the ADEO system design aims for passive attitude stabilization with a pyramidal shaped dragsail and a deployment actuation implemented in a de-orbit module that would be mounted onto the main satellite bus.

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

2 THE ADEO SUBSYSTEM

2.1 Objective & Requirements

The main objective of the activity was to:

- design, manufacture and test a sub-system constituted by a boom and a membrane
- be used in LEO to augment the drag of small satellites (fit within VEGA envelope [9])
- de-orbiting period shall not exceed 25 years
- Provide high packaging density for high area/mass ratio.

This led to the following top level requirements:

- Ultra-light weight (lower mass than propellant)
- Scalable (capability to simply enlarge the drag area)
- Generic (adaptable for multiple type of LEO missions)
- Passively Stabilized (no GNC needed)
- Modular (also only single dragsail segments can be deployed).

2.2 Reference Mission

As a reference mission a satellite was selected that firstly would fit on the VEGA launcher [9] leading to a satellite mass of roughly 1000kg and secondly be used in LEO as it is the most critical orbit region. The de-orbiting time for different dragsail areas and orbit altitudes is shown in Figure 1.

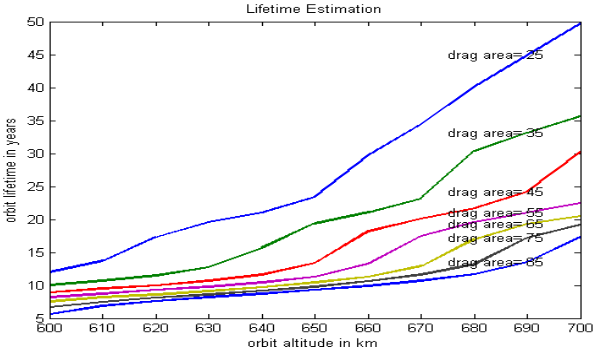

Figure 1. Orbital lifetime analysis for one ton satellite depending on orbit and dragsail area.

The selection was made to use a generic 1000 kg satellite in a 650 km orbit. To be compliant with the Space debris legislation to de-orbit within 25 years [10], a dragsail area of 25 m^2 was calculated.

2.3 ADEO Design

ADEO is a self standing subsystem with its own deployment mechanism and generic interfaces to the satellite, therefore it can be attached either on flat surfaces or with an adapter at almost every location on the satellite.

The ADEO subsystem consists of four deployable CFRP booms that span four membrane segments with a total area of 25 m^2 in a truncated pyramid shape configuration. Figure 2 shows the deployed ADEO subsystem with a dragsail area of 25m^2 deployed from a reference satellite with 1000kg mass.

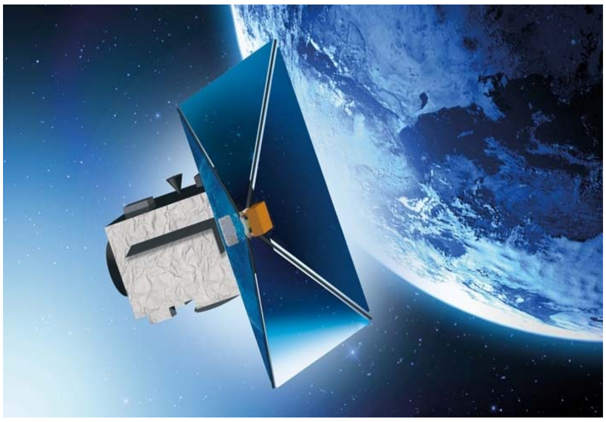

Figure 2. Artist impression of deployed ADEO attached to a one ton satellite

Figure 3 (left) shows the ADEO subsystem during launch and before deployment in stored configuration while the deployed subsystem is shown in Figure 3 (right).

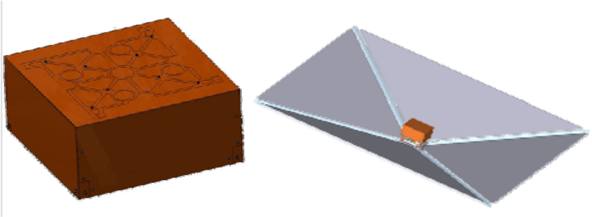

Figure 3. ADEO launch configuration (left), ADEO deployed configuration (right)

The dragsail area is separated in four equal triangular membranes. These membranes are folded and coiled around four membrane spools which are located on each side of the ADEO subsystem. While the membranes are made of an aluminum coated polyimide foil, its coating thickness was chosen such that it provides sufficient protection from the space environment. To prove the survivability of the membrane material in the space environment over 25 years de-orbiting time, multiple environmental tests were performed at material and sample level in the DM activity, including mechanical strength and stiffness tests, thermal cycling, atomic oxygen exposure tests, UV exposure tests, and high velocity impact tests, as well as crack propagation tests at room and reduced temperature (more details in 4.2.3).

The booms and the membranes are protected by one main cover during launch and the in-orbit storage period. Once the time for deployment initiation has come, the cover will be lifted by guided springs through Hold Down and Release Mechanism (HDRM) actuation in the centre of ADEO. Within the cover also the launch locks for the boom and membrane spools are removed. Figure 4 shows the lifted cover configuration ready to start deploying the booms and therefore the membranes. The membrane will be deployed by using CFRP booms forming a double omega profile and therefore a stable configuration once deployed. The current booms of ADEO are theoretically unlimited in length, but currently restricted by the mold tools to about 4.5 m, while scaled up booms are already producible up to 14 m in length. When expanding the tools, for all diameter sizes, much larger boom lengths can be realized in the future The four CFRP booms are located in the corners of the membranes and therefore also in the corners of the ADEO subsystem. A motor is used to pull out the booms through guiderails to initiate the membrane deployment.

Figure 4. ADEO lifted cover configuration (ADEO demonstrator)

The ADEO demonstrator built and tested as part of the ADEO activity has the size of 234 x 462 x 462 mm3 and a mass of just 19 kg. As the scalability of the subsystem was one of the main requirements in this activity, the dragsail subsystem was designed to be adaptable for smaller as well as larger satellites. Further details on the ADEO analysis can be found in [11].

Therefore, the ADEO subsystem covers dragsail areas from 2 m^2 to more than 200 m^2 for satellites from 100 to over 1500 kg leading to a mass of ADEO from 10 kg to 45 kg covered by three different classes with the following dragsail areas:

• ADEOsmall	2 m^2 to 10 m^2
• ADEOmedium	5 m^2 to 70 m^2
• ADEOlarge	50 m^2 to > 200 m^2

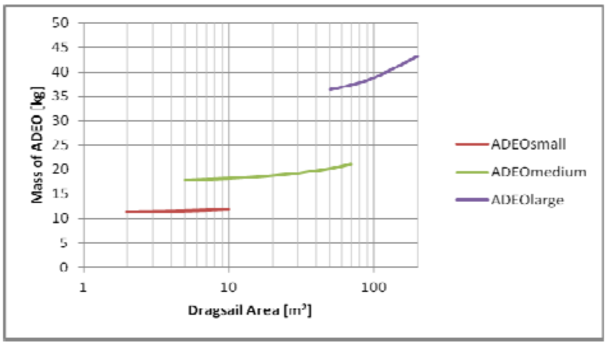

Figure 5. Scalability of ADEO subsystem

3 BREADBOARD CAMPAIGN

To verify the functionality of the design, breadboards of the most critical components were manufactured and thoroughly tested. These breadboards included the boom spool, the membrane spool as well as the membrane itself.

3.1 Boom Spool Breadboards

The boom spool breadboard tests had the purpose to validate the functionality of the boom deployment device, to obtain the necessary pull out forces for the motor selection as well as to validate the load carrying capacity of the boom in combination with the boom spool breadboard at selected points of deployment and operation. While Figure 6 (left) shows the boom spool breadboard with the stowed boom on the shaker during vibration testing at the facilities of DLR Bremen, the following mechanical testing the boom spool breadboard with the boom at different deployed lengths at the *DLR Space Structures Lab@ Uni* of DLR Braunschweig is shown in Figure 6 (right).

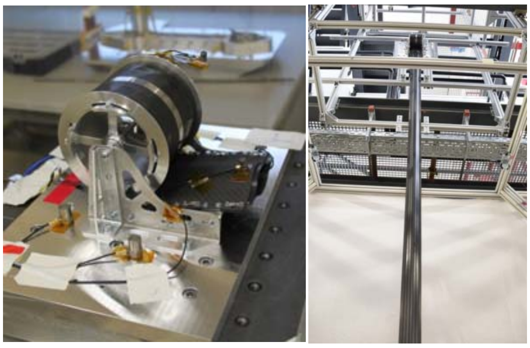

Figure 6. Vibration test z-axis (left), mounted ADEO bread board with a free boom length of 2.5 m (right)

3.2 Membrane Spool Breadboard

The membrane spool breadboard tests had the purpose to validate the functionality of the membrane unspooling device as well as to obtain the necessary pull out forces for the motor selection.

Vibration tests have been carried out in sine and random. In Figure 7, the membrane spool assembly is shown in the set-up for the vibration test in the z axis.

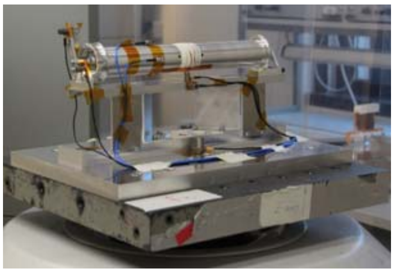

Figure 7: Membrane spool vibration test z-axis

For a functionality test, the rotating force / pull out force of the membrane spool was measured before and after the vibration test, no change was recorded.

3.3 Membrane Breadboards

A zig-zag folded membrane segment coiled onto a spool has been tested in scope of the DM project. The objective was to assess the deployment behavior and forces acting as a result of the spool break and adhesion forces of the membrane layers.

The test has been carried out at the DLR Institute of Space Systems by means of the modified Gossamer-1 deployment test rig. Two linear units equipped with three axis force measurement sensors were used to simulate the boom-deployment and force monitoring. Figure 8 shows the measurement of the linear units deploying the membrane breadboard during the Deployable Membrane deployment. The peaks are approximately appearing at the same time showing a symmetrical deployment.

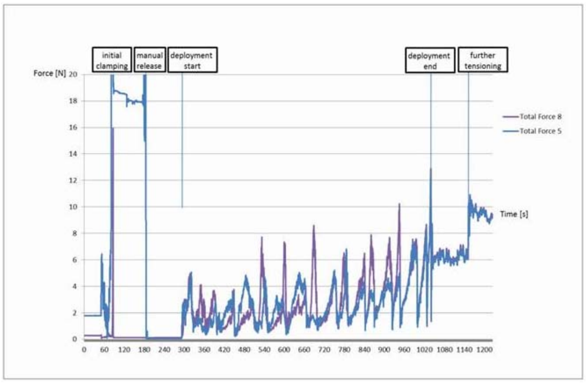

Figure 8: Comparison of the local force at both membrane interfaces

Two different membrane patterns have been tested successfully after vibration and decompression test. An inspection of the membrane was carried out afterwards with particular emphasis on the coating condition.

4 ADEO TEST CAMPAIGN

The results of the breadboard test campaign were assessed and improvements were implemented in the design when necessary to manufacture an ADEO demonstrator to be thoroughly tested.

The ADEO subsystem together with material samples were verified with a test as you fly approach covering all the mission phases:

Launch:	First a **vibration test** (representative sine and random loads on all three axes) was carried out simulating the launch loads followed by a **rapid decompression** test mimicking the pressure decrease during launch (Vega launcher depressurization profile).
In-Orbit Storage:	The temperature change of an orbiting space craft was mimicked via **thermal cycling** test.
Deployment:	The deployment was initiated with **mechanism activation in hot and cold TVAC conditions** leading to a **full deployment** (partial in **TVAC** and rest in ambient)
De-Orbit:	The **survivability** of the materials during the **25 year de-orbiting** time was verified by extensive **Atomic Oxygen (tested @ ESA/ESTEC labs), UV and thermal cycling** tests. Furthermore, the effect of **space debris impacts** was verified by analysis and impact tests.

4.1 Demonstrator Test Campaign

For the ADEO demonstrator test campaign, a full demonstrator was build with two booms instead of four and one membrane segment instead of four. The other membrane and boom spools will be replaced by mass dummies without membranes and booms. The remainder of the structure and mechanism are identical to the flight model.

4.1.1 Functionality Test 1

To prove the functionality of the ADEO subsystem before the beginning of the test campaign, a functionality test including HDRM firing and full deployment of the system was carried out.

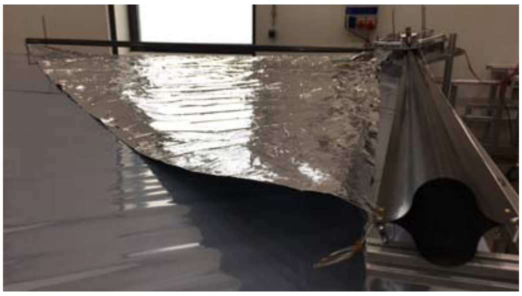

Figure 9. ADEO fully deployed: functionality test 1

The deployment showed that the deployment mechanism consisting of motor and boom worked well. In the following, the boom, membrane and HDRM were restored and reset to ready the ADEO subsystem for the next tests.

4.1.2 Vibration Test

The ADEO subsystem was tested for the following sinus and random loads on all three axes.

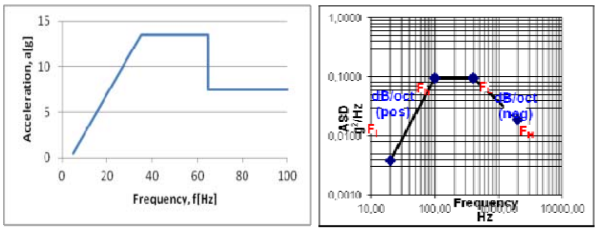

Figure 10. Vibration test load

The vibration test was concluded successful. No difference between pre and post vibration test states of the most critical parts, mainly the membrane, the HDRM as well as the launch locks was observed.

4.1.3 Rapid Decompression

Following the vibration test, the rapid decompression compression test was carried out.

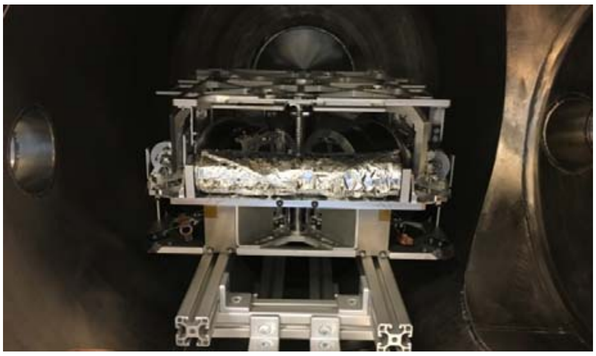

Figure 11. ADEO in rapid decompression chamber

The venting profile is given in Figure 12. The Vega reference is taken from venting diagram provided in the Vega user manual [9]. Note that the pressure decrease during the first approximately 20 s is higher compared to the reference and thus the test is more conservative. After approximately 100 s the two curves align again.

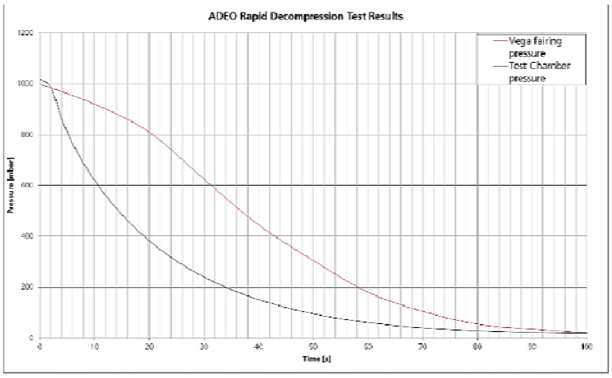

Figure 12. Venting profile during the fast decompression test. The black graph shows the achieved pressure decrease during the test and the red graph shows the fairing pressure during Vega launch [9]

No changes on the membrane package and on the membrane material could be observed and therefore the test was concluded successful.

4.1.4 Functionality Test 2

After the firing of the HDRM, the ADEO subsystem was placed on the ambient deployment rig and a full deployment as part of the functionality test 2 was carried out.

Figure 13. Fully deployed ADEO demonstrator after 2nd functionality test

The deployment showed that the deployment mechanism consisting of motor and boom worked well also after vibration and rapid decompression test. In the following, the boom, membrane and HDRM were restored and reset to ready the ADEO subsystem for the next tests.

4.1.5 Environmental Test

In stored configuration, the ADEO demonstrator was subjected to thermal cycling over eight cycles from -30°C to +40°C in the climate chamber.

From the climate chamber, the ADEO demonstrator was brought to the WSA TVAC chamber for the firing of the HDRM in hot and cold conditions in vacuum.

During the TVAC deployment tests, the booms with membrane were deployed for 0,6 m during the cold and hot deployment.

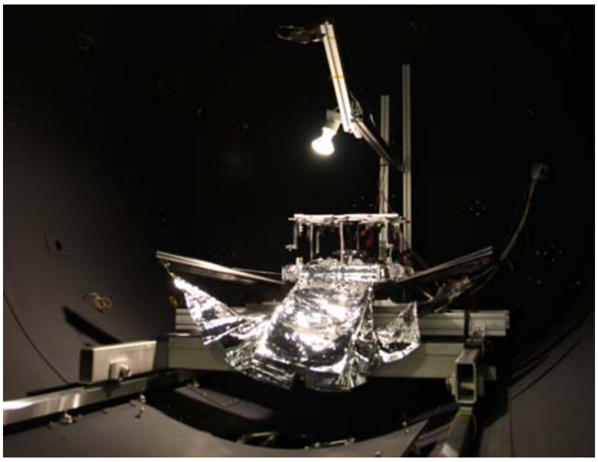

Figure 14. Partially deployed ADEO in TVAC chamber

From the partially deployed state, the ADEO demonstrator was fully deployed in ambient conditions without any issues.

Figure 15. Full deployed ADEO at the end of demonstrator test campaign

With the full deployment, the demonstrator test campaign was concluded fully successful covering the phases launch, in-orbit storage as well as deployment.

4.2 Sample Campaign

To verify the survivability of the materials during the long in orbit storage period (~15 years) as well as the de-orbit phase (~25 years), a dedicated sample campaign has been carried out on the booms as well as the membrane.

4.2.1 Boom Creep Samples

The boom creep test had the purpose to investigate the creep behavior of the booms when stored for longer time at reduced and elevated temperatures. The dependency of the plastic deformation of the CFRP material on stowage time, temperature and up-reeling radii were investigated. Within ADEO only a reduced creep test campaign, as defined by the granted funding, was performed and herein described as preliminary creep test study to emphasize the importance of extended tests in future projects.

In this preliminary study flat CFRP specimens were reeled on cylinders of different diameters and stored under different temperatures. The deformation of the specimens resulting from the mechanical and thermal loading was measured at certain time steps.

The viscoelastic long-term stowage behavior of the CFRP material can be described by the creep-compliance according to [8] and the stress relaxation. In [8] the results from the preliminary creep test study are further evaluated in order to determine a first estimation of the long-term stowage behavior of the CFRP material. By means of this investigation a degradation of about 40% of the stress relaxation modulus after 20 years of stowage under room temperature could be estimated. For more precise estimations of the degradation of the stress relaxation modulus as well as for estimations for other stowage temperatures further tests are necessary. Furthermore subsequent finite element analysis should be done for estimating the change of the deployed booms shape with the reduced relaxation modulus after 20 years of stowage. Consequently further analysis of the reduction in load capability of the boom should be conducted.

4.2.2 Boom Impact Samples

To investigate the influence of space debris impacts on the boom, boom impact tests on four boom samples have been carried out. While samples #1. #2 and #4 were hit in the centre, #3 was hit off centre, near the boom flange, but still kept in the test campaign. The impact object is a nylon cylinder with diameter of 4 mm and a length of 2 mm. It is shot with a velocity of ~4 km/sec, thus hitting the samples with an impact energy of about 800 J. Figure 16 shows exemplary boom sample #1 after the impact. On the left image of Figure 16 the test set up in front view is showing the boom sample in a fixture and a film screen to protect the sample from the gas gusts from accelerating the projectile, which travels thru the screen without any significant deceleration. The right image of Figure 16 is showing the test setup from the back view. It is clearly visible that the impact damage on the back shell of the boom, where the projectile exits, is larger than the impact damage on the front shell, where the projectile hits first. While penetrating the front and leaving a sharp damage about the size of the diameter of the impact object itself, the projectile carries along fragments of the front shell that disperse over the travel distance and hit the back shell causing more severe impact damages. Following the impact tests, the degree of damage on the samples was determined under a digital microscope with a magnification of 20x by measuring, as shown in Figure 17, the diameter of clearance (diameter 1), the diameter of damage (diameter 2) and the area of removed materials (marked red, area 1) on both sides. The visible difference when comparing the damages on the shell´s front and back side of a boom, and the values for all four tested samples as listed in Table 1, demonstrate the mechanics of an impact in such a thin layer CFRP shell boom. Additionally to direct damages by an impact, cracks and rips were observed solely on the front shells. This is assumed to have its origin in the buckling of the shell (giving in) when being hit by the impact object.

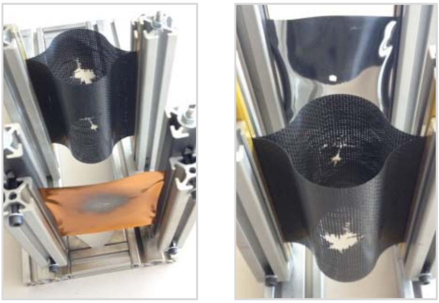

Figure 16: Boom sample #1 after impact (left: front view; right: back view)

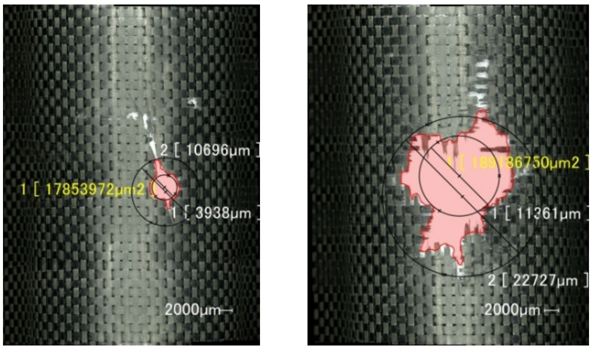

Figure 17: Impact damages of boom sample #1 on front side (left) and backside (right)

Table 1: Measured degrees of damage

Sample No./ Side	Diameter of Clearance [mm]	Diameter of Damage [mm]	Area of removed material [mm^2]
#1 Front	3.94	10.70	17.85
#1 Back	11.36	22.73	189.19
#2 Front	3.76	5.99	13.42
#2 Back	5.79	14.94	72.73
#3 Front	4.14	6.24	18.08
#3 Back	5.52	9.60	39.61
#4 Front	4.19	7.33	19.85
#4 Back	7.84	19.61	131.74

4.2.3 Membrane Samples

A wide test campaign with membrane test samples has been carried out in scope of the DM project where over 70 samples have been tested to their environmental resistivity and mechanical behavior. The samples are made of coated polyimide foils provided by different suppliers. Additional polyimide samples have been coated individually in order to assess their environmental and mechanical behavior.

Identical to the space debris assessment of the booms, also membrane samples were subjected to space debris impacts with the same test method described in 4.2.2. The impact hole and cracks were inspected by microscope.

Following the impact test, an ambient thermal cycling test at the University of Technology Dresden has been performed. The specimens with different coating thicknesses were cycled 20 times between temperatures of -80°C and 220°C about a total of 31 hours.

Some samples have been tested additionally to its behavior in Atomic Oxygen (AtOx) and Ultraviolet (UV) environment. The AtOx test has been carried out at ESTECs AtOx test facility where 20 year exposure time has been simulated. Afterwards the samples have been exposed to UV radiation at DLR Bremen Complex Irradiation Facility where one year deployed in orbit has been simulated. Thermo-optical properties measurement in combination with weight measurement and mechanical tests were carried out to access the degree of degradation.

The test campaign was extended to assess the crack propagation behavior. Cracks growing as a result of space debris and micro meteorite impact shall not result in a significant loss of drag area.

It can be concluded that the membrane is capable to withstand the 25 years deployed in orbit with minor changes of the mechanical and thermo-optical properties.

5 CONCLUSION

The ADEO subsystem has been designed to be **Modular** (easy AIT), **Generic** (can be easily adapted to any platform, attachable with a few bolts), **fully Passively Stabilised** (no GNC needed) and **Scalable** (for satellites between 100 and over 1500 kg).

For a typical spacecraft of 1 ton to be flown by VEGA and placed at an altitude of 700 km at EOL, an ADEO subsystem demonstrator (ADEOmedium class, 25m^2 full membrane area) has been designed, built and tested, raising the TRL of the subsystem to **TRL 5/6** (all environmental loads have been tested, including AtOx tests for the membranes). The ADEO demonstrator volume is 234x462x462 mm^3 with a mass of just 19 kg (which will be further reduced in the future thanks to Additive Layer Manufacturing for brackets and CFRP press forming technologies for the cover now in aluminum). In comparison, the required hydrazine needed for a similar Hohmann transfer was calculated with 121kg and shown a **saving of 84% in mass by putting on board the ADEO system**.

In conclusion, the developed ADEO subsystem offers:

- All technologies, parts and materials from **European Companies**
- Means to **de-orbit passively** within **25 years, no GNC required**
- **Modular** and **scalable subsystem** for satellites from **100 kg – >1500 kg** (dragsail area from **2 m^2 to >200 m^2**)
- **Adjustable pyramidal** angle from 0° (flat dragsail) to 60°
- **Lower mass** compared **to propellant and engine mass** required to de-orbit
- Materials that can **withstand >25 years de-orbiting time** (space debris impact, UV, ATOX and thermal cycling test campaign)
- **Verified by test for launch loads** (vibration and rapid decompression) and **orbital loads** (thermal cycling and deployment in hot and cold TVAC conditions) leading to **TRL 5/6**
- A **building block technology** applicable for other space applications making use of **large functional areas.**

It is foreseen that the ADEO subsystem will reach **TRL 7 by 2019** and through an In-Orbit Demonstration mission **TRL 8** in **2019/2020**. A first **commercial flight** of the space proven ADEO could be carried out already in **2020/2021**.

REFERENCES

1. Vincent L. Pisacane, Fundamentals of Space Systems, Johns Hopkins University / Applied Physics Laboratory Series, 2005, second edition
2. NN, IAA Position Paper Space Debris Mitigation, ESA SP-1301, ESA, ISBN 92-9092-445-4, 2004
3. Leipold, M., Garner, C. E., Freeland, R., et al. ODISSEE, A proposal for demonstration of a solar sail in earth orbit, Acta Astronautica 45/4, 557-566, 1999.
4. Agnolon D., Study overview of a solar sail demonstrator: GEOSAIL, DLR/ESA, 2008.
5. Leipold, M, Eiden, M., Garner, C. E., et al., Solar sail technology development and demonstration, Acta Astronautica 52/2, 317-326, 2003.
6. Leipold M., Widani C., Groepper P., et al. The European Solar Sail Deployment Demonstrator Mission, Proceedings of the International Astronautical Congress, 2006.
7. Seefeldt, P., Spiez, P., Spröwitz, T. et al., Gossamer-1: Mission Concept and Technology for a Controlled Deployment of Gossamer Spacecraft, Advances in Space Research, 2016 (submitted and under review)
8. Meyer, S., Zander, M.E., and Hühne C., Preliminary Creep Test for estimating the long term stowage behaviour of DLR’s CFRP booms, In ECSSMET 2016 - European Conference on Spacecraft Structures, Materials & Environmental Testing, Toulouse, France, 27-30 September 2016 , CNES/ESA/DLR.
9. Arianespace, VEGA User’s Manual, Issue 4 Revision 0, April 2014
10. Space Debris Mitigation Policy for Agency Projects (ESA/ADMIN/IPOL(2014)2)
11. T. Sinn, P. Seefeldt, A. Riemer, S. Meyer, T. Spröwitz, R. Hahn et al., Design, Analysis and Testing of the ADEO passive De-Orbit Subsystem Demonstrator, ECSSMET 2016 - European Conference on Spacecraft Structures, Materials & Environmental Testing, Toulouse, France, 2016.