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ESR - Executive Summary Report
Aerobraking MLI

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1. Introduction

1.1 Scope

The executive summary report aims to summarise the test campaign and results of the aerobraking MLI project, conducted as a pre-study for ESAs upcoming Venus mission EnVision in an understandable and concise manner.

1.2 Acronyms

AAC	Aerospace & Advanced Composites GmbH
acc.	according
AD	Applicable Documents
ATOX	Atmospheric Oxygen
BB	breadboard
BGA	Beyond Gravity Austria GmbH
CVCM	Collected Volatile Condensable Material
DML	Declared Materials List
DMPL	Declared Mechanical Parts List
DPL	Declared Processes List
DMS	Document Management System
DTG	Derivative Thermogravimetry
e.g.	for example
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
etc.	and so on
FTV	Fast Thermal Vacuum (Test chamber at ESTEC)
i.e.	this is
IRS	Institut für Raumfahrtsysteme Stuttgart
ITO	Indium Tin Oxide
mil	0.001 inches
MLI	Multi-Layer Insulation
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
PA	Product Assurance
PEEK	Polyether Ether Ketone
PSA	Pressure Sensitive Adhesive
QA	Quality Assurance
RD	Reference Document
RISE	Research Institutes of Sweden
RML	Recoverable Mass Loss
S/C	Spacecraft
S/O	Stand-Off
SiO_x	Silicon Oxide
TBC	To Be Confirmed
TBD	To Be Defined
TGA	Thermo-Gravimetric Analysis
TML	Total Mass Loss
UV	Ultraviolet Radiation
VDA	Vacuum Deposited Aluminium

2. Documents

The following documents form part of this document to the extent specified here-in.

In the event of a conflict between this document and the Applicable Documents (AD), the AD shall have the precedence. Any such conflict should however be brought to the attention of Beyond Gravity Austria GmbH (BGA) for resolution.

This document has been established based on the issues of ADs and RDs as given below. Issue changes of ADs and RDs will lead to an update of this document only in case of impacts on its content.

2.1 Applicable Documents

AD1	ESA-TECQEE-SOW-020352, Iss. 2.1	Statement of Work - Characteriz. of MLI materials and definit. of MLI blanket for aerobraking env.
AD2	P-12101-MIN-0001-RSA	Kick-off Meeting Aerobraking
AD3	Email M. Holynska dtd. 10/11/21	Comments TN1.1 Aerobraking MLI
AD4	Email A. Jasjukevics, dtd. 03/11/21	EnVision: AG TRS review iss 2
AD5	Email M. Holynska dtd. 12/12/21	ESA inputs on Aerobraking project

2.2 Reference Documents

RD1	ENV-EE-09-RQ-001, Iss. 1D1	Requirements for Envision Improved MLI
RD2	P-12101-SPC-0001-RSA, Iss. 3	TN1.1 - Consolidation of Requirements and approval conditions for the MLI
RD3	P-12101-TNO-0001-RSA, Iss. 1	TN2.1: Selection of candidate materials and preliminary design
RD4	P-12101-PLN-0001-RSA, Iss. 2	TN2.2: Test plan
RD5	P-12101-TRP-0001-RSA, Iss. 2	TN3.1 - Combined Sample Level Test Report
RD6	P-12101-TNO-0002-RSA, Iss. 1	TN4.1&TN4.2 Final MLI Breadboard Design and Results of manufacture and testing of MLI Breadboard
RD7	P-12101-REP-0001-RSA, Iss. 1	FR - Final Report Aerobraking MLI

3. EnVision Aerobraking MLI

The 5th medium class mission in ESA's Cosmic Vision Plan will be sending a spacecraft to Venus, one of Earth's neighboring planets. The mission will give insights into Venus' geological history and its atmosphere.

Due to the high transfer speed required to go from Earth to Venus, the satellite will need to slow down in order to reach its final position in an orbit around Venus. For this, the upper Venus atmosphere will be used to help the spacecraft brake. Like when an object enters Earth's atmosphere, this will result in a lot of heat. Additionally, the upper atmosphere has high densities of atomic oxygen (ATOX), which is very aggressive and decomposes many materials. Because of this, the spacecraft needs a resistive and insulating outer layer in order to survive this so-called aerobraking manoeuvre without damage.

The outer layer of satellites is typically Multi-Layer Insulation (MLI). This type of insulation provides excellent protection from heat in the vacuum of space. MLI consists of many thin layers of foil, separated by spacer material and works by reflecting the thermal radiation back into space. Usually, the foils are made of polymers, which would be susceptible to damage from atomic oxygen. In order to prevent such damage, one can use an outermost layer made of a different material.

The goal of the pre-study summarized in this document was to select an MLI lay-up that would be suitable for the mission parameters. The large focus of the study lay on the high temperature capabilities of the used materials. For the outer layer, the ATOX resistance was an additional deciding factor. Over the course of the study, materials were selected based on heritage and the known requirements and additional testing was done, in order to qualify the materials for use in the mission environment.

The detailed description and results of the study can be found RD7 and the references therein.

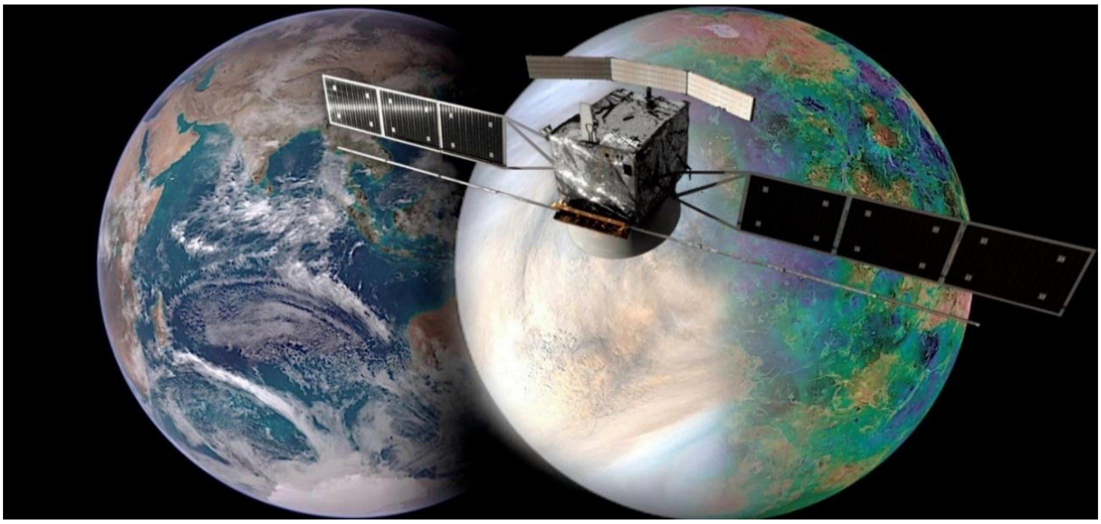

Figure 3-1: Artist interpretation of the EnVision Mission[1]

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[1] © NASA / JAXA / ISAS / DARTS / Damia Bouic / VR2Planets

4. Material Pre-Selection

For the mission, many requirements have to be satisfied but not all off them are relevant for each part of the spacecraft. In RD2, the requirements that will determine the material selection and required testing were consolidated from the many references listed there. The main conditions the materials have to be capable of are a steady state temperature of +350°C and during the aerobraking manoeuvre a combined heat flux of 7kW/m² and a freestream ATOX fluence of 5×10^{21} atoms/cm². Furthermore, the MLI performance better than

- GL = 0.009 W/(m² K),
- GR = 0.005,

Need to be satisfied during the entire mission duration. Here GL is the linear heat transfer coefficient, describing the heat conduction through the insulation and GR is the radiative heat transfer coefficient, which describes how well heat radiation is able to pass through the insulation.

The required temperature of +350°C immediately leads to several restrictions on the potential MLI materials. For the inner layers, Kapton is a common material that is capable to withstand the temperature. It is a Polyimide that is frequently used and has good availability. Other common materials are not qualified to the required temperatures. For the spacer net, separating the inner foil layers, only a Glass Fibre spacer is capable of the required temperatures. This material comes with some drawbacks as it is relatively heavy and particle shedding.

For the outer layer the ATOX resistance needs to be considered as an additional constraint. In RD3 a detailed trade-off was performed, pitching several known materials against each other. From these, the following were selected for further testing, as they showed the most promise:

- ITO/SiO_x / Kapton / VDA,
- Glass Fabric 41-L,
- White coated Titanium foil,
- Black coated Titanium foil.

ITO/SiO_x coated Kapton

The Polyimide Kapton is itself not resistive to ATOX at elevated levels, but the Indium Tin Oxide / Silicon Oxide coating offers protection. This material is sometimes used in environments with medium ATOX concentrations.

Glass Fabric 41-L

Glass Fabric 41-L is a glass-based material used for high temperature insulation. While no heritage is available for this fabric in environments with atomic oxygen, the base material suggests that it should be able to withstand such conditions and thus it was decided to carry out the required tests.

White Coated titanium

The white coating is ceramics based and can be applied to Titanium in order to create an outer layer material that is very resistive to all kinds of environments and capable of very high temperatures. The white color of the coating promises favourable thermo-optical properties.

Black Coated Titanium

This special black coating is another option that can be applied to Titanium. It is of a different nature than its white competitor, but the main difference is the change in thermo-optical properties due to the different color.

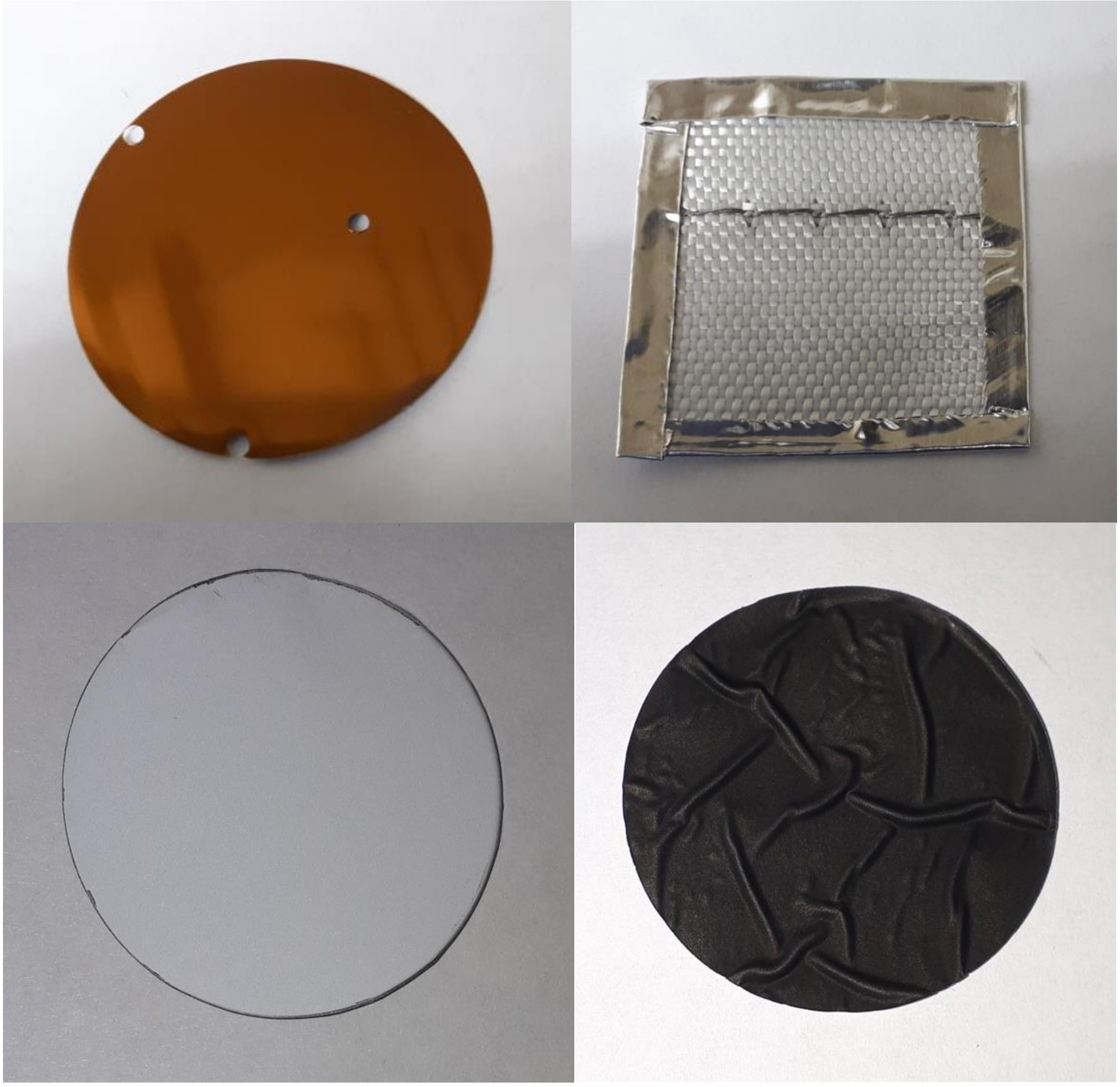

Figure 4-1: The materials for the sample level test campaign. From top left to bottom right: ITO/SiO$_x$ Kapton, Glass Fabric 41-L, white & black coated Titanium

The materials described above and depicted in Figure 4-1 were tested during the sample level test campaign. For the Glass Fabric 41-L, a heat-cleaned sample was sometimes included in the tests. This was because the material has a seizing, which is necessary for the weaving process, that decomposes hat high temperatures and can cause cleanliness issues and changes in the material properties.

5. Sample Level Testing

The tests performed on the selected outer layer materials were:

- Thermo-Gravimetric Analysis (TGA),
- Outgassing Test,
- High Temperature Thermal Exposure,
- Atmospheric Exposure.

5.1 Thermo-Gravimetric Analysis (TGA)

This Test evaluates the thermal stability of a material by increasing the Temperature in a controlled manner and continuously measuring the weight of the sample. Typically, at certain temperatures, de material will start to decompose and lose weight. Another possibility is that chemical reactions, starting only at elevated temperatures, lead to a mass increase.

The TGA showed promising results for all materials for the target temperature of 350°C. Only the Kapton foil shows a clear upper limit where the material decomposes, starting at around 450°C. The other materials remain stable up to high temperatures. The Glass Fabric initially loses some mass, which can be attributed to the decomposition of the seizing on the material, which is required for the weaving process. The white coated Titanium foil was very stable up to around 650°C, where it slowly started to increase in mass. This may have been due to titanium oxidization. The black coated titanium foil showed slow mass gain already at low temperatures and then an increase in this behaviour around the same temperature where the mass gain of the white coated foil started. The low-temperature gain was likely due to a reaction of the black coating with the atmosphere which then got overlaid by the titanium oxidization at higher temperatures. All materials are suitable for the target temperature of 350°C.

5.2 Outgassing & High-Temperature Exposure

Organic materials typically release gases contained inside the material when put into a vacuum. This effect is enhanced when the outgassing happens at high temperatures. Strong outgassing behavior can lead to contamination of instruments which can impair mission success. Thus, only certain outgassing thresholds are allowable. Metals do not outgas and thus were not part of the test. Thus, the coated Kapton foil was tested and two Glass Fabric samples, one which was heat cleaned.

The outgassing test was performed at higher temperatures (300°C) than typical, in order to reflect the mission conditions. The Kapton foil and the heat-cleaned Glass Fabric showed acceptable outgassing behavior, with very few released contaminants, while the untreated Glass Fabric cannot be used as is.

The High-Temperature exposure test functioned very similar to the Outgassing test, but at 350°C for different durations of 1d, 4d and 10d. Like in the Thermo-Gravimetric Analysis, the high-temperature stability of the materials was investigated. All materials showed good behavior in this test, meaning that they are suitable to be used for the required times at the temperature of 350°C.

5.3 Atmospheric Exposure

The heart of the sample level test campaign was a combined heat load and atmospheric oxygen test, performed by using a plasma wind tunnel. This test exposed the samples to comparable ATOX loads and simultaneously to heat flux. Samples of all materials were tested and the resulting erosion on the material was evaluated. The samples and test setup can be seen in Figure 5-1. The test in progress can be seen in Figure 5-2.

Figure 5-1: Samples for the test and sample holder in the plasma wind tunnel chamber

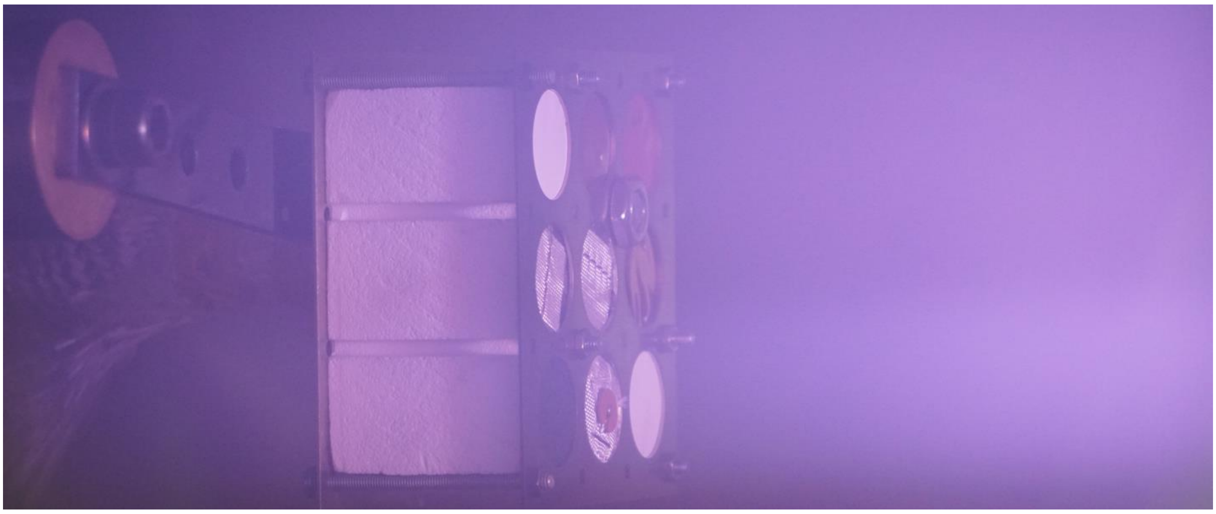

Figure 5-2: Samples during the plasma wind tunnel test

In total, the samples were subjected to plasma plume of pure oxygen for 60 minutes during which the samples reached up to around 400°C. A post-test visual inspection showed that all candidate materials, except for the coated Kapton foil, are suitable for use as an outer layer during the aerobraking phase of the EnVision mission. The Glass Fabric showed a similar discoloration to what is observed after the heat cleaning procedure. The Kapton foil, on the other hand, showed significant damage, as can be seen in Figure 5-3.

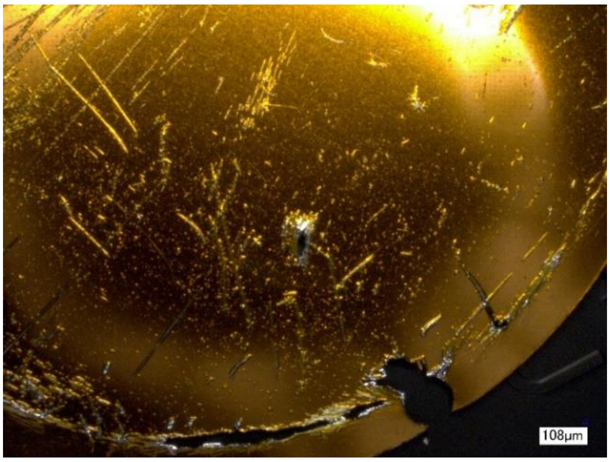

Figure 5-3: ITO/SiO$_x$ Kapton foil after the Plasma Wind Tunnel Test

6. Thermal Cycling Breadboard

Based on the results of the sample level test campaign, the Glass Fabric 41-L was selected as the outer layer material for the final breadboard. The material showed excellent ATOX behavior and is more readily available than the Titanium foils with better manufacturing capabilities.

For the insulation package, 22 inner layers made of vacuum deposited aluminium (VDA) coated 0.3mil (=0.0076mm) Kapton foil, separated by Glass Fibre Spacer was chosen. The lay-up symbol is depicted in Figure 6-1.

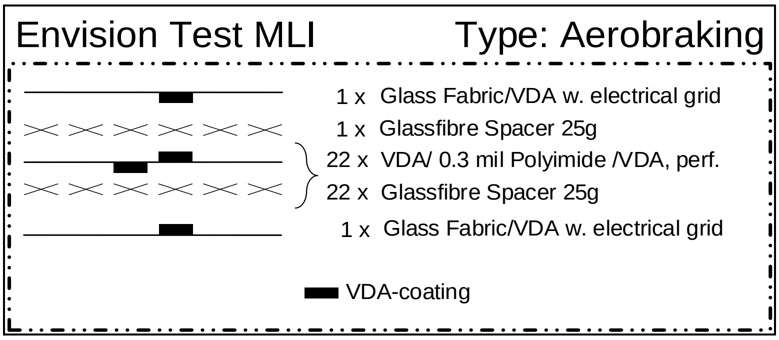

Figure 6-1: 3d Calorimeter Cube Lay-Up

The final test was composed of 3 calorimeter tests, in order to determine the heat transfer coefficient of the insulation and more than 2000 cycles between -150°C and +350°C. This test is representative of the aerobraking manoeuvre, which will have a similar number of cycles at these temperatures. The goal is that the performance of the insulation should not change over the course of the test. The 3 calorimeter tests were done before the cycling campaign, in the middle and at the end.

For the purpose of the test, a 3-dimensional sample MLI was manufactured, equipped with thermocouples, in order to measure the temperatures during the test, and a heater on the inside, in order to establish a temperature difference between inside and outside. The assembly is shown in Figure 6-2. The cycling then was done in vacuum chambers at ESTEC facilities, depicted in Figure 6-3.

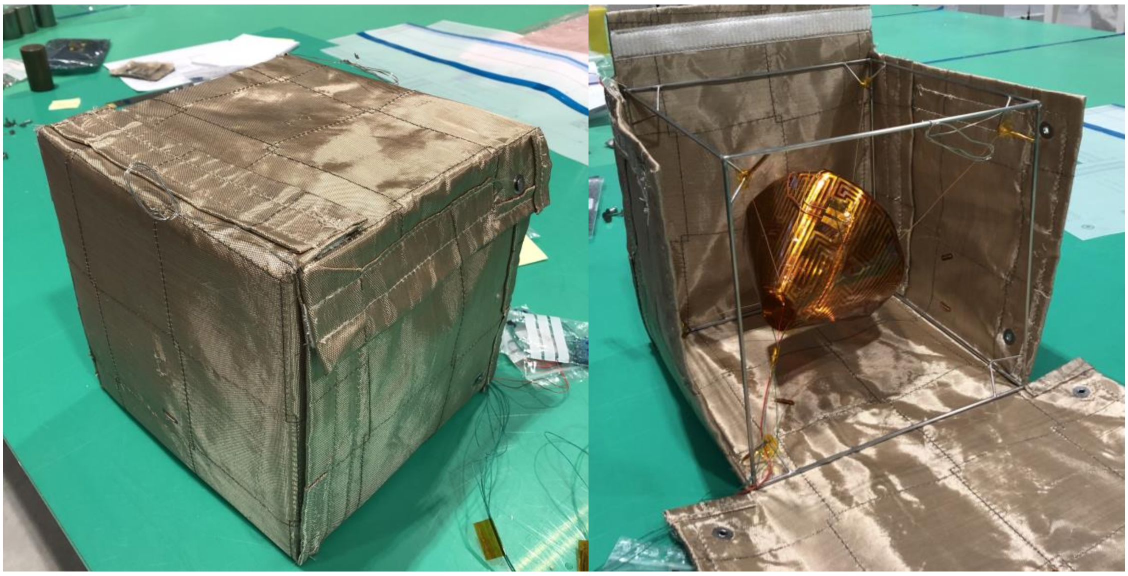

Figure 6-2: Calorimeter Cube assembled with heater (right)

Figure 6-3: Aerobraking MLI Cube in the FTV chamber for thermal cycling

In total, 2246 cycles between a cold temperature of -150°C and a hot temperature of +350°C were done, with dwell times between 100 seconds and 300 seconds. The calorimeter tests found no significant change in the insulation capabilities of the sample MLI, as is depicted in Figure 6-4, which is a great confirmation of the stability of the used materials and has to be considered a great success.

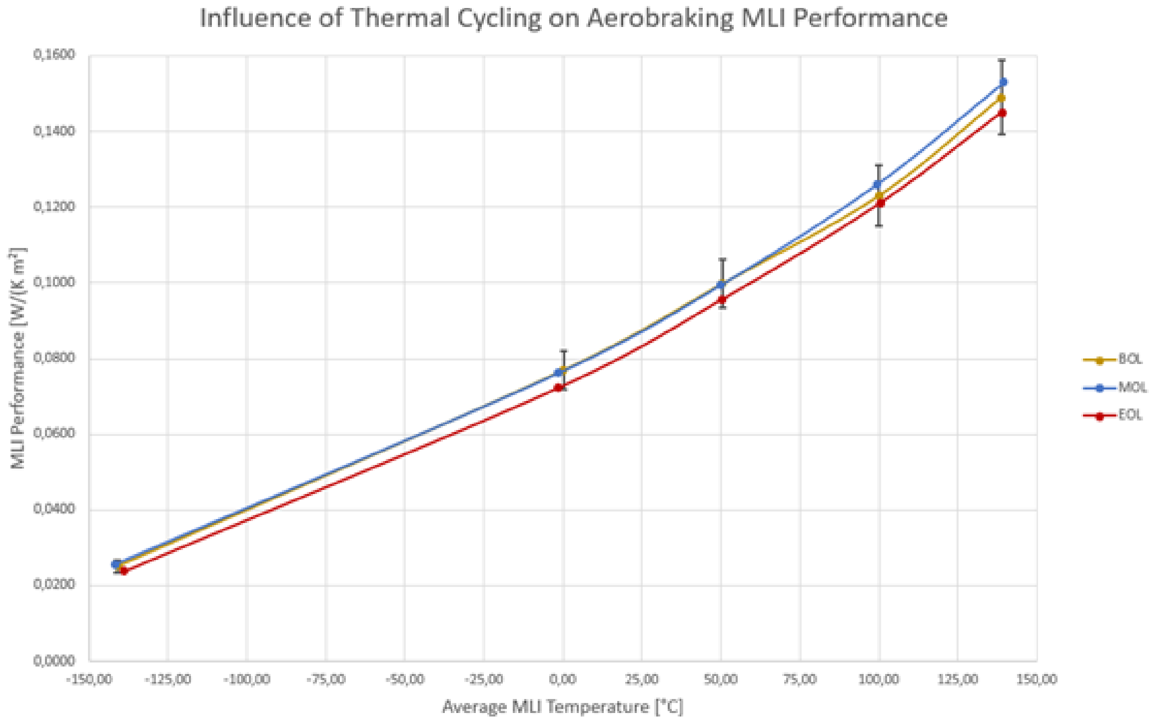

Figure 6-4: Aerobraking MLI performance graph over the cycling campaign

The post-test inspection of the MLI did not show visual changes in the MLI. Only a slight discoloration of the Hook-Loop Fasteners used to close the overlaps was visible upon closer inspection. This can be easily avoided by a corresponding design, letting the Hook-Loop Fasteners end further away from the edges. Other than that, the MLI and all manufacturing methods, like sewing, proved viable even after the extensive testing done.

7. Conclusion and Outlook

Over the course of this study, a MLI lay-up, suitable for the use as aerobraking MLI for EnVision was found. The most demanding task was finding an outer layer material that is capable to withstand the combined exposure to heat flux and atomic oxygen. With the Glass Fabric 41-L, a material was found and tested under very representative conditions, that is suitable for the task and has good manufacturing capabilities. Especially the plasma wind tunnel test, where the material was subjected to a combined heat and atomic oxygen flux, was very convincing evidence. The outgassing characteristics and change in thermo-optical properties can easily be managed by a simple heat-cleaning procedure, after which the material is very stable.

The thermal cycling campaign further showed that the lay-up and manufacturing techniques are more than adequate for the task, as no change in performance or condition was visible after more than 2000 cycles between -150°C and +350°C.

With this convincing evidence, the search for an MLI lay-up for the EnVision aerobraking manoeuvre has produced a promising candidate that is considered to be used for the mission.