Project :

COMPACT OPENING LOUVER WITH VARIABLE THERMO-OPTICAL PROPERTIES

COOLER

Title :

Executive Summary

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TABLE OF CONTENTS

TABLE OF CONTENTS

(Continued)

TABLE OF FIGURES

TABLE OF TABLES

SCOPE

This document resumes the COOLER project, from the Breadboard test results with two baseline concepts to the Engineering Model Test Campaign.

ABBREVIATIONS

ACRONYM	MEANING
AD	Applicable Document
RD	Reference Document
BBM	BreadBoard Model
BBM+	Refurbished BreadBoard Model
EM	Engineering Model
GSE	Ground Support Equipment
HW	Hardware
LLD	Launch Locking Device
N/A	Not Applicable
SoW	Statement of Work
TBC	To Be Confirmed
SMA	Shape Memory Alloy

APPLICABLE & REFERENCE DOCUMENTS

Applicable Documents		
Doc. Id.	**Document Nr.**	**Document Title**
[AD 1]	211-ES.2098	Proposal COOLER
[AD 2]	ESA-TRP-TECMTT-AUD-SOW-009337	Statement of Work
[AD 3]	COOLER-CSE-TN-08	EM Test Plan (Iss2)

Reference Documents		
Doc. Id.	**Document Nr**	**Document title**
[RD 1]	COOLER-CSE-TN-03	Trade-off selection
[RD 2]	COOLER-CSE-TN-04	Preliminary designs and test plan
[RD 3]	COOLER-CSE-TN-05	Breadboards Tests and Design Selection Report
[RD 4]	COOLER-CSE-TN-06	Detailed Design Report
[RD 5]	COOLER-CSE-TN-11	EM Test Report
[RD 6]	COOLER-CSE-TN-12	Test Evaluation and further work

1 INTRODUCTION

Louvers are thermal control elements placed over external radiators to tune heat rejection from typically a factor 1 when fully closed to 5 when fully open. The COOLER (Compact and in-plane opening louver with variable thermo-optical properties) mechanism developed is a device (of 1 dm^2 total area) used to adjust the power dissipation of a radiator to a varying heat source designed to reject heat in the range 0.1 W to 10 W. When the heat source is on, it heats up the mechanism, triggering its opening thus increasing the radiator dissipating capability. When the heat source is off (or when it is cool enough), the device cools down triggering its closure and thus insulating the radiator.

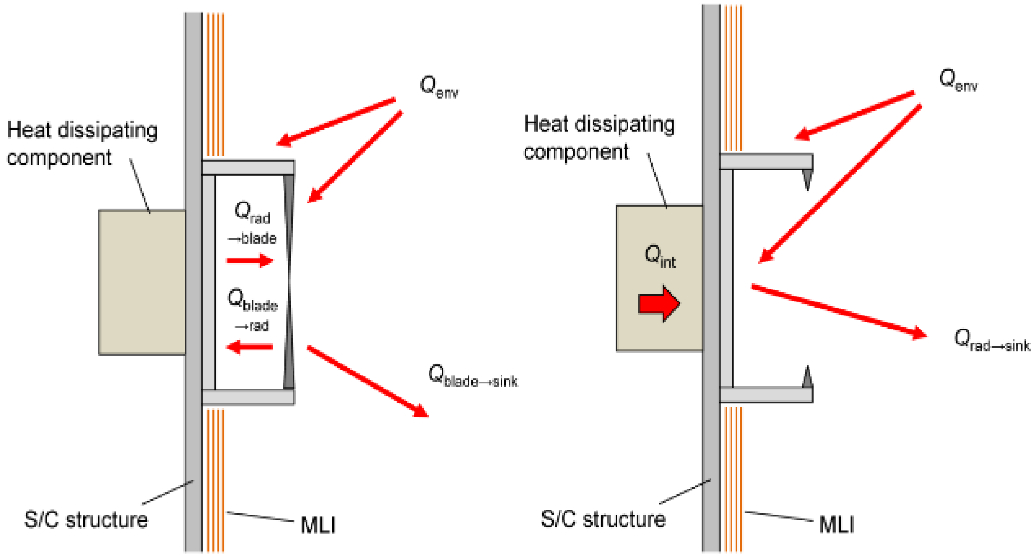


Figure 1-1: Simplified schematic of the principal radiative heat exchanges, closed (left), open (right)

Main radiator specifications

The critical requirements for the radiator are:

- Targeted for CubeSats and compact instruments
- Compact radiator design 100 mm x 100 mm x 30 mm
- Heat rejection capability >85% when fully open
- Heat rejection range 0.1W to 10W / device of 1dm2
- Single actuator with activation range -50°C to +90°C
- Friction free

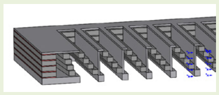
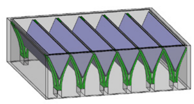
A trade-off study was performed evaluating eight different concepts before two candidates were selected for prototype testing. Following the prototype tests in vacuum conditions, an Engineering Model was designed, manufactured and tested in a representative environment (Vacuum performance test, thermal balance tests for model correlation, environmental TVAC tests and vibration).

1 LOUVERS CONCEPTS

1.1 Louvers concepts trade-off selection

The various concepts are ranked according to the various criteria. Whenever the ranking is associated with a comment, the comment is provided under the table. [RD 1]

Table 1-1: Concept trade-off

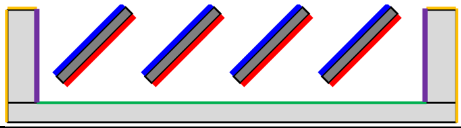
Criterion	Rating	Concept 1 	Concept 2 	Concept 4 	Concept 8 
In-plane	3	3	3	3	1
Heat rejection	3	1 (1.34W)	3 (3.29W)	1 (1.68W)	2 (2.34W)
Compactness	2	1	3	3	2
Mass	1	2	2	2	2
Scalability	1	2	2	2	2
Reliability	3	1	2	1	3
Complexity	2	2	1	2	3
Friction free	2	2	2	2	3
Versatility	2	1	1	1	1
Fail open	3	1	1	1	1
Resilience	2	2	1	3	3
	Total	**38**	**47**	**44**	**49**

1.2 Selected actuator technology

The selected actuator technology is **Shape Memory Alloy** (SMA) actuators. They have been selected for their easy implementation in a very lightweight and simple louver design. In the next steps of the activity CSEM will rely on NIMESIS expertise for the design and sizing of SMAs.

1.3 Selected coating technologies

The technologies selected to coat the various surfaces of the louvers are illustrated in Figure *1-1*.



	Surface	Prime choice
	Space facing surface of louver blades	SolarBlack, optionally with top coat
	Radiator facing surface of the louver blades	Alum alloy with low surface roughness
	Main radiator surface	Enbio SolarWhite
	Outer surfaces of the structure	MLI or Enbio SolarWhite
	Internal surfaces of the structure	Alum alloy with low surface roughness

Figure 1-1: Selected coating technologies

2 BREADBOARD DESCRIPTION AND TESTS

From the four concepts developed further with the preliminary design, two concepts were selected for breadboarding. This section describes the two BBM concepts manufactured (Concept 2 & Concept 4) and the conclusions of the BBM test campaign. The BBM test campaign objective was the selection of the concept to be manufactured and tested for the Engineering Model based on the experience and results of the BBM [RD 3].

2.1 Concept C2: Diaphragm Iris description

The Hexagonal diaphragm iris concept works as an iris but where each of the 6 fans are independent. The closing is performed by expansion of each fan around its pivot point. This pivot point is generated by RCC (Remote Centre Compliance) flexible hinges arrangement

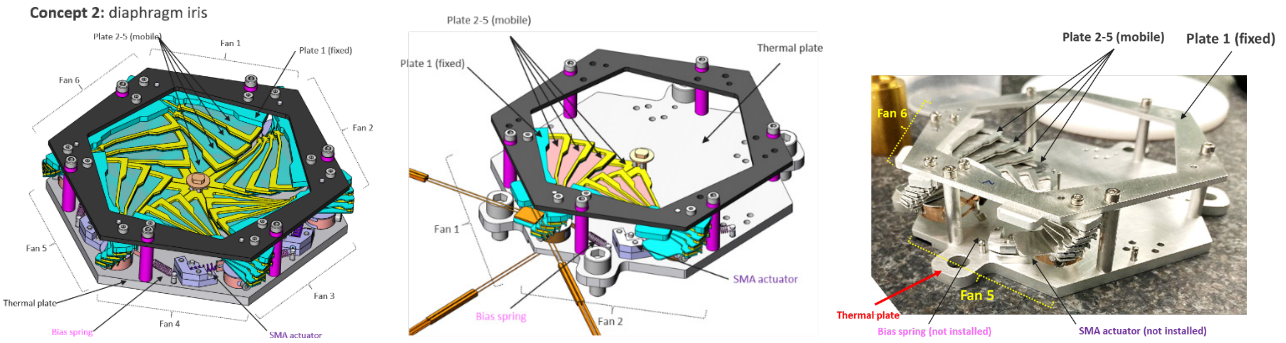
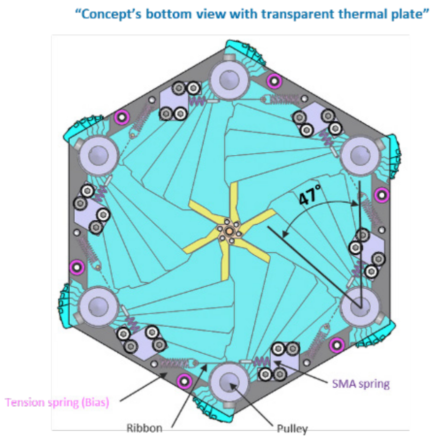


Figure 2-1: CAD model of BBM Concept 2 fully equipped (left) and as manufactured (right)



Actuator	6 independent SMA springs
Bias spring	6 independent tension springs
Angular stroke	47°
Linear stroke	~5mm (for a pulley radius of 6mm)
Maximum actuation force	1N for 1 fan segment without margins
Initial position of the concept	Normally closed

- Guiding architecture: Series
- 1 actuator per fan segment
- 4 blades for 47° coverage corresponding to angular stroke of 11,75° for each blade.
- Opening area **4'205 mm²**

Actuation principle: Pulley and ribbon

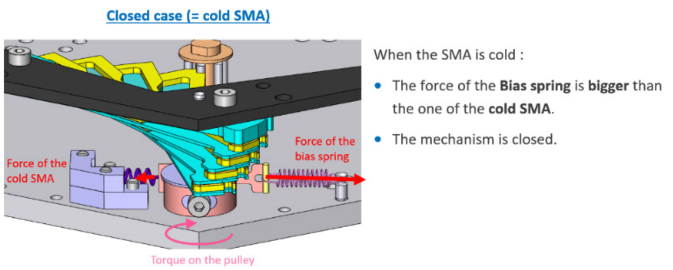


Figure 2-2: Passive actuation with SMA

2.2 Concept C4: Flexible grid description

The Flexible grid concept is based on a stack of grids that are moved linearly one after the other in order to occult the surface. The guiding of the grids is performed through flexible hinges in a parallelogram arrangement.

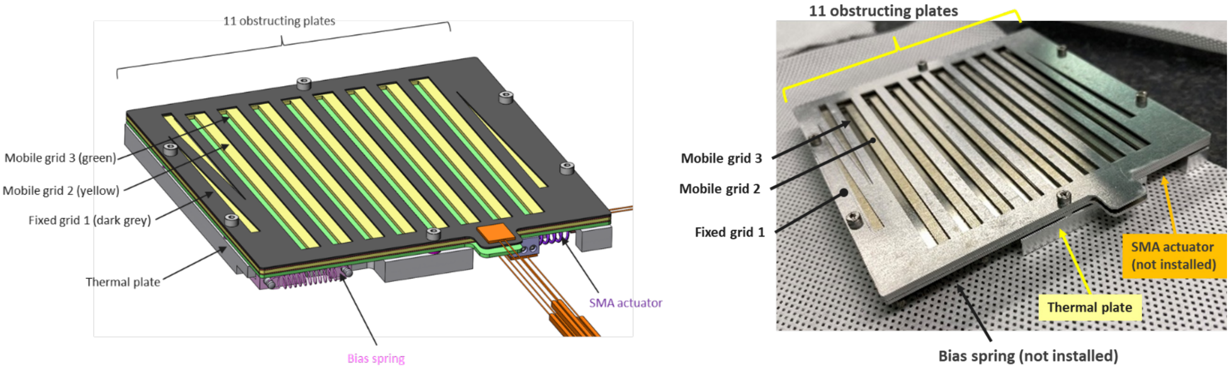
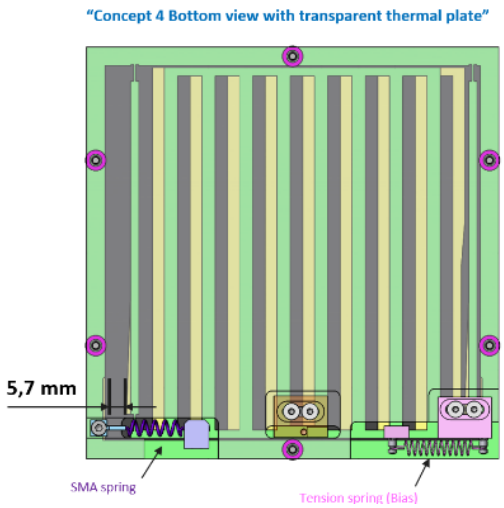


Figure 2-3: BBM Concept 4 Flex Grid as manufactured



Actuator	1 SMA spring
Bias spring	1 tension spring
Linear stroke	5,7 mm (for the mobile green grid) and 2,85 mm (for the mobile yellow grid)
Maximum actuation force	1.6N without margins
Initial position of the concept	Normally closed

- Guiding architecture: Parallel
- 1 actuator for all the stages
- **Opening area: ~4'200 mm^2**

The actuation principle uses a normal bias spring to maintain the grids in the closed position against an end-stop. When the heat from the baseplate reaches a predefined value, the SMA (Shape Memory Alloy) actuator heats up and is activated. When the SMA is hot, the force of the bias spring is smaller than the one of the hot SMA, thus the mechanism opens. When the SMA is cold, the force of the bias spring is larger than the SMA thus maintaining the mechanism closed.

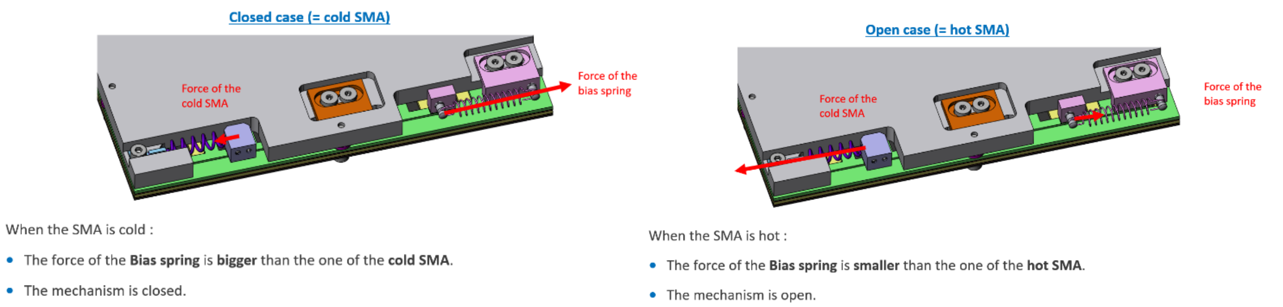
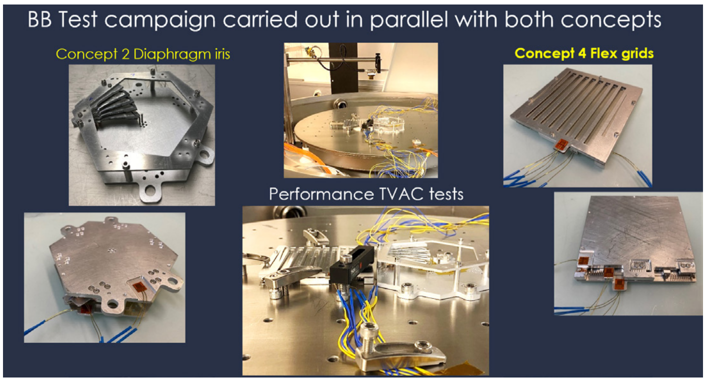


Figure 2-4: Passive actuation with SMA

2.3 Breadboard tests

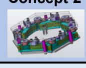
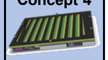
The BBM test campaign consisted of the following tests and performed on both models as per the critical requirements in the specifications:

- TVC baseplate stability
- Mechanism sensor measuring stability for actuator temperature points
- Measure the opening/closing time
- Measure stability of opening/closing temperature set points
- Full closed to full open temperature range



BBM Performance evaluation and selected EM concept

For the EM selection of the louver concept, a global trade-off table has been compiled using the requirement from TN-02 (Requirements document and BBM performance tests atm/vac blue cells):

Criterion	Description	Related requirement	Rating	Concept 2 	Concept 4 
Vacuum	The COOLER concept properties shall be able operate in vacuum and 10mbar of CO2.	FPR1	2	3	3
Heat rejection	The COOLER concept shall have a heat rejection capability greater than 85% when fully open compared to a perfect black surface with same footprint.	FPR2	3	3	1
Heat rejection	The COOLER concept shall be designed to reject heat in the range 0.1 W to 10 W.	FPR3	3	3	1
Heat rejection	The COOLER concept shall be driven by a single actuator.	FPR4	3	1	3
Complexity	Mechanism is not complex and thus have a less risks in the development	FRP4	2	1	3
Opening/closing	The actuator shall guarantee the **opening/closing** of the COOLER concept properties within a minute from the moment the opening/closing temperature is reached.	FPR5	3	1	3
Set point stability	Stability of the opening and closing set points shall be ± 1°C.	FPR6	3	2	3
Temp sensors	Temperature sensors shall be used to command the active actuator or as monitoring sensors for passive actuator.	FPR8	1	3	3
Friction free	The mechanism is friction free	FRP9	2	1	2
Heat rejection	The clearance between two movable and overlapping blades shall be such to avoid blockage of the system and limit entrance of parasitic heat.	FPR10	3	1	3
Heat rejection	Parasitic heat entering the system in closed configuration shall be less than 15 W/m2.	FPR11	3	2	2
Control system	The control system shall be analyzed for most important parameters (stability, bandwidth, dynamic and static accuracy, resolution, and generation of and susceptibility to disturbances at the interfaces of the mechanism).	FPR12	0	1	1
Fault propagation	Propagation of any type of fault shall be prevented.	FPR13	0	1	1
Compactness	The COOLER concept shall have a flat interface on the hot side for mounting onto the dissipating unit mounting plate and on the cold side for the in-plane opening to the sink.	IR2	2	3	3
Compactness	The COOLER concept shall have a mounting surface area of about 100 mm x 100 mm equal to 1U cubesat face area	IR3	2	2	3
Temp range	The COOLER concept properties shall have a full closed to full open temperature range of 15°C to 20°C and be selected/adjusted within the range -50°C to 90°C.	IR4	3	2	2
In-plane	Mechanism have an "in plane" architecture	IR1	3	3	3
Resilience	Resilience to mechanical loads The COOLER concept shall sustain a mechanical environment in each of the 3 orthogonal axes : Sinus and Random	ER2	2	1	3
Mass	Lightweight system: The COOLER concept shall have a mass/ unit area < 8 kg/m2.	PRR1	1	2	2
Scalability	The COOLER concept design shall be applicable to surface areas ranging from 0.1 x 0.1 m2 to 0.3 x 0.3 m2. The system can easily be adapted to an area 9x bigger	DR1	1	2	3
Temp set points Versatiliy	The COOLER concept design shall allow the temperature set-points to be changed. Mechanism is easy to adapt to the mission: the actuation temperature can be changed easily	DR2	2	1	1
Fail open	The mechanism is capable of remaining in open configuration in case of failure to avoid overheating of underneath unit	DR6	3	1	1
Reliability	Mechanism has low source of error, embedded redundancy	xx	3	2	1
Cooler	**Concept 4 with 113 points selected for detailed design for EM.**	**Total**		**94**	**113**

3 EM SELECTED CONCEPT C4 THERMAL ANALYSIS

3.1 The FEM Model Description

The Finite Element model of the louver Breadboard that is created for the Thermal Analysis is described in the current chapter along with the obtained results. Two different configurations are considered; the louver in closed and in open configuration. A Heat Transfer Steady State Analysis is performed in both configurations. The Heat Transfer mechanism is only via conduction and via radiation. The FEM analysis which provides detailed results is complemented by a network analysis for comparison and a small parametric study.

3.2 Louver Effective Emissivity – FEM Results

The effective emissivity of the louver is calculated by the following formula:

$$\varepsilon_{eff} = \frac{Q}{\sigma * A * VF * (T_{bp}^4 - T_{ambient}^4)}$$

Where, Q is the applied heat at the bottom of the thermal plate, T_{bp} is the temperature of the base plate, σ is the Stefan-Boltzmann constant, and VF is the view factor (In this case VF =1) of the surface A =0.01m^2. Although the radiating surface of the thermal plate is less than 0.01 m^2 the effective emissivity is calculated with respect to radiating area of 100x100 mm^2 which is a radiating area of a Cube Sat 1U.

As it can be noticed for the open configuration where the applied heat is high enough, the effective emissivity is relative constant since over 90% of the total heat is radiated by the thermal plate. On the contrary, on the closed configuration where the applied heat is very low (0.1 W), the conduction becomes more significant especially in a low ambient temperature. The heat is transferred via conduction to the grids and to the top cover and is emitted to space from their top surfaces. The high emissivity of those surfaces due to coating, increases the overall effective emissivity for this particular case to 0.59.

Load Case	Configuration	Applied Heat (W)	Ambient Temperature (^{0}C)	Thermal Plate Temperature (^{0}C)	Effective Emissivity
LC 1.1	Open	10	20	207.5	**0.384**
LC 1.2	Open	10	-273.15	188.9	**0.387**
LC 2.1	Closed	0.1	20	26.4	**0.265**
LC 2.2	Closed	0.1	-273.15	-141.7	**0.591**

Table 3-1: Louver Effective Emissivity – FEM Results

In any case, the effective emissivity of the louver calculated from the thermal FEM analysis is quite low for the open configuration with respect to the requirement FPR2 of [AD 2].

4 BBM+ TEST CAMPAIGN

4.1 BBM+ Flexible grid description

The BBM+ was used as part of the “EM” test campaign. Parts of this mechanism were recuperated from the Breadboard (BB) used during the initial phase of the project. The evaluation of the tests is limited to the BBM+ as an assembly and not concentrated on the component level tests performed during the BB and EM phase.

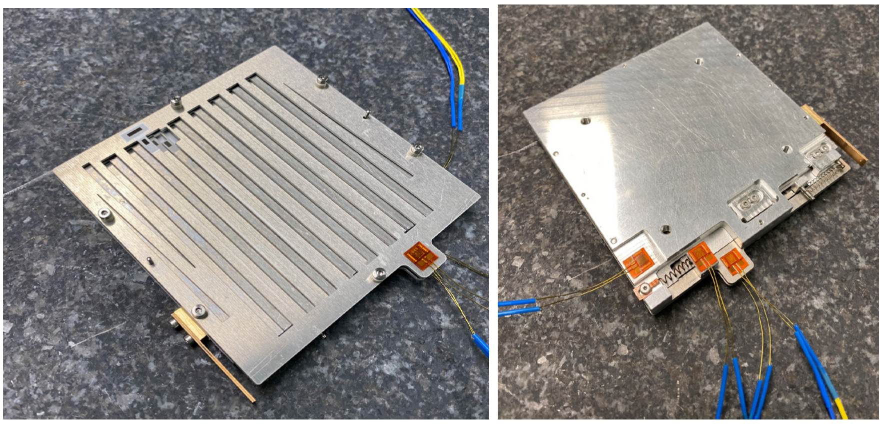


Figure 4-1: BBM+ Concept 4 Flex Grid

4.2 Functional tests in ambient conditions (ER4)

Functional tests were performed in ambient conditions prior the vacuum tests at CSEM. These simplified tests are to be repeated during certain points of the EM Test campaign to verify that the mechanism is operating as expected. Instead of a hot plate as a source of heat (used during BBM tests), a hot air gun is used to locally heat the SMA and produce the required movement of the mechanism. Hot air gun Setting: 140°= 120°C ±10° (temp. on SMA). Various orientation with respect to gravity were tested. Functional tests with hot air gun showed **stroke = 5.7mm being reached**.

The following tests verify the following mechanical requirements:

- FPR9 friction free
- FPR10 clearance between two movable and overlapping blades
- ER4 work in every position with respect to gravity

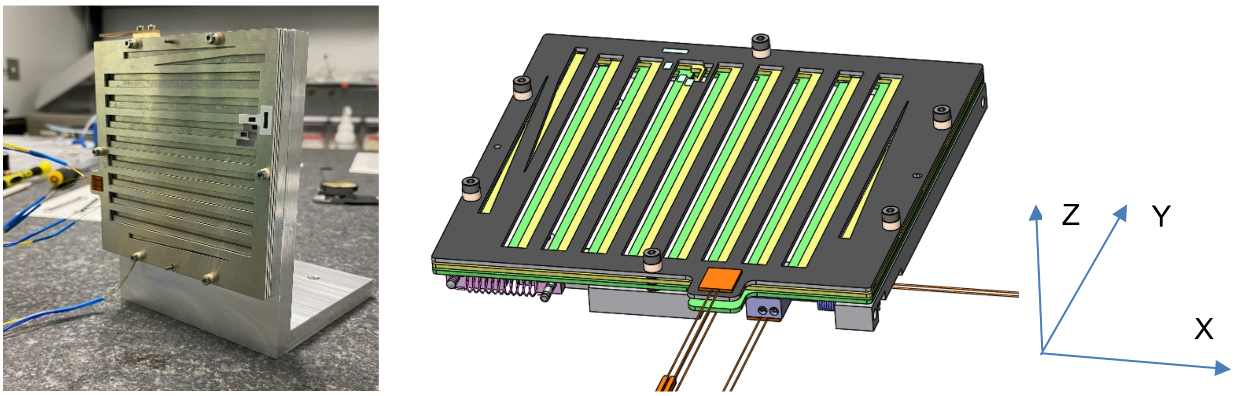


Figure 4-2: BBM+ assembled on GSE plate (Configuration gravity along +X direction, left)

4.3 Performance tests under vacuum conditions

The **final test configuration (vertical)** of the mechanism with a thermal blanket (simplified MLI) showed similar results to the BBM initial tests performed in the horizontal configuration.

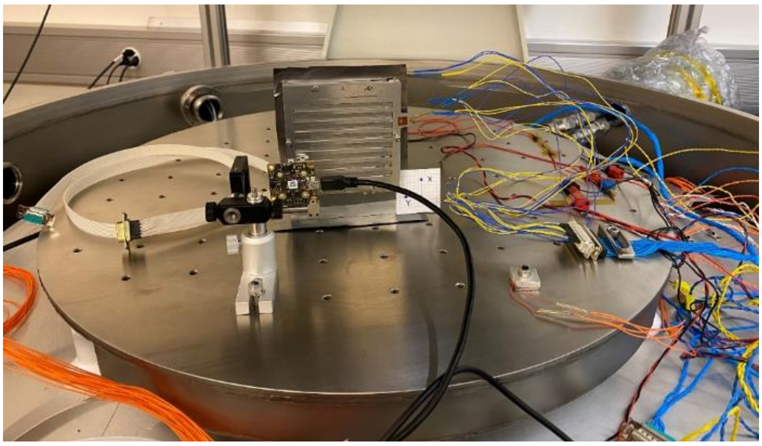


Figure 4-3: BBM+ model integrated on TVC baseplate with camera and support

Measure the opening/closing time (FPR5: T<1min)

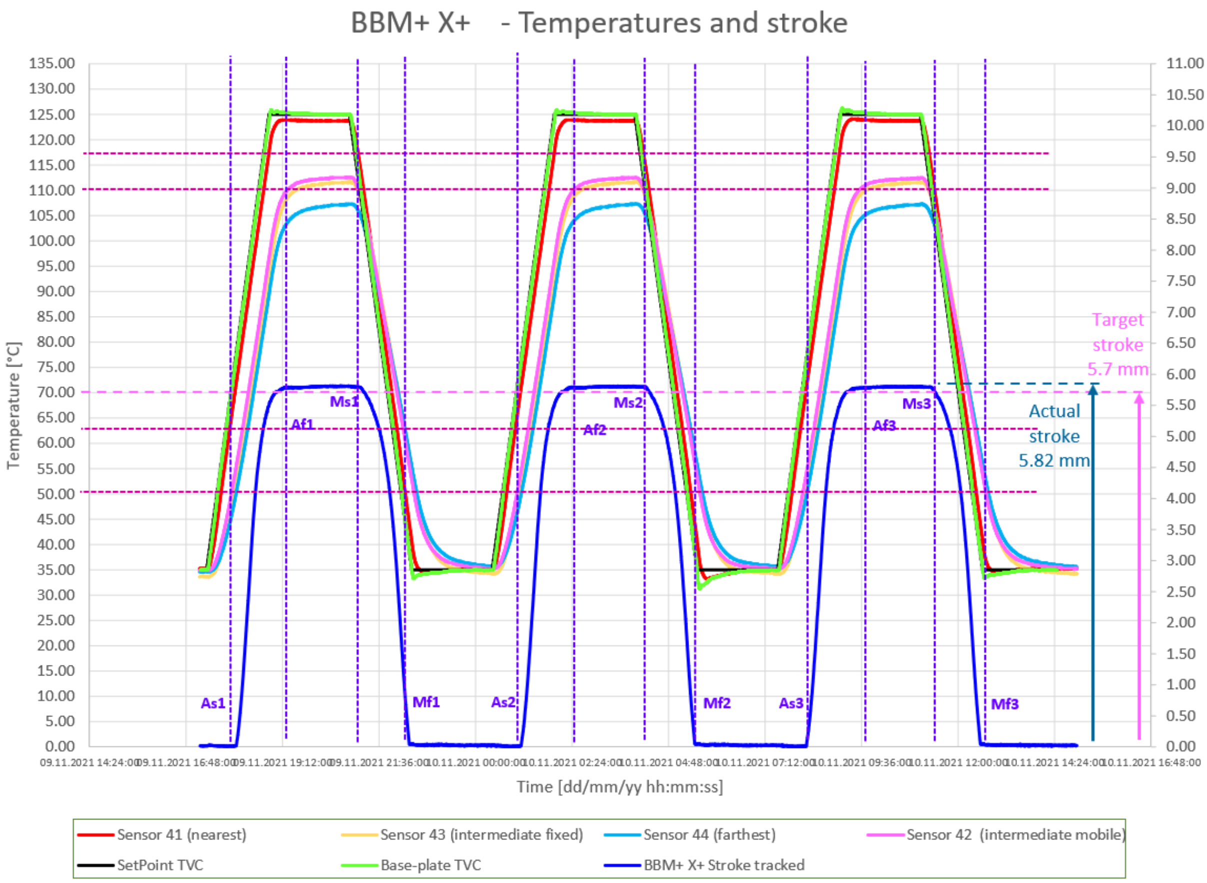


Figure 4-4: Temperature stability at plateaus and overall stroke

General conclusion of the performance tests under vacuum: The mechanism performed as expected.

4.4 Thermal Balance tests

The thermal balance tests of the COOLER device were separately tested in the locked closed and locked open configurations. For each test, the complete Unit Under Test (UUT) was composed of the COOLER device connected to a thermal baseplate. In addition, a bare aluminium baseplate and a baseplate coated with a black thermo-optical coating were tested in order to allow for correlation of data with a thermal model.

BBM+ (EM) under test

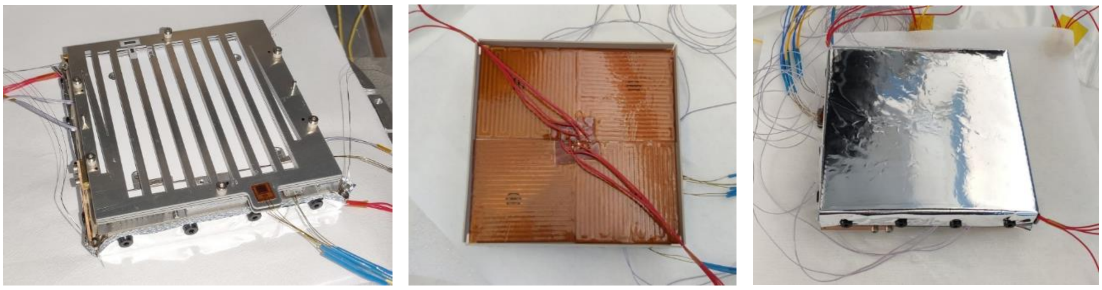


Figure 4-5: BBM+ open configuration (left), Kapton foil heaters (centre), with MLI (right)

Single-step test Closed configuration

For the single-step test, an overview of the temperatures recorded for the thermal baseplate temperature to reach **90°C**.

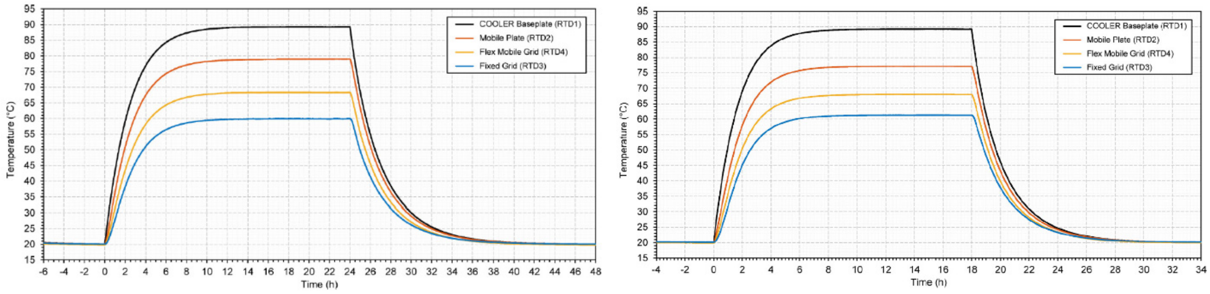


Figure 4-6: Temp. profiles for single step closed (left) & open (right) configuration

Thermal balance test summary results

A summary of the heater power levels required to reach **90°C** during the **single-step tests** is given in the table below.

Test Article	Power (W)	Baseplate Temperature (°C)
COOLER closed configuration	2.344	89.98
COOLER open configuration	3.400	90.01
Bare aluminium baseplate	1.455	89.57
Black coated baseplate	5.035	90.06

4.5 Environmental vibration tests

The mechanism was prepared for the vibration tests with the installation of the dummy launch locking device and all bolts locked with EC2216.

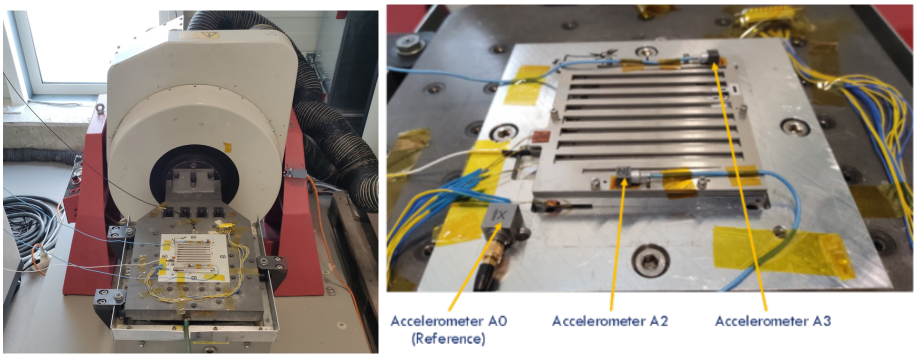


Figure 4-7: EM on slip table (Y-axis configuration)

After the vibration test campaign, FOTEC performed a visual inspection and a reduced functional test:

- No damage observed to the DUT except for two spacer elements that were found detached during visual inspection
- Functional test with hot air gun was successful except for unsteady movement of the louver
- Mechanism **closing** seems to work correctly
- Mechanism **opening** does not seem to work correctly (jerky movement) due to friction between flexible grids caused by loss of spacers during vibration tests.

General conclusion of vibration tests: According to the pass/ fail criteria, the EM passed the vibration tests successfully.

4.6 Environmental Thermal Cycling tests

A thermal vacuum cycling test with the EM was performed successfully with a temperature range of +100°C to -60°C for 8 cycles. The vacuum level was always below 1*10^5 mbar.

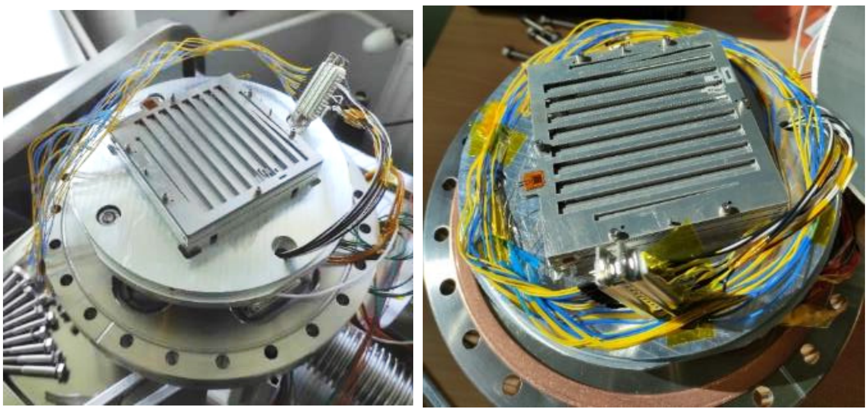


Figure 4-8: EM setup on thermal chamber baseplate

After the TVAC test campaign of 8 cycles, the DUT was visually checked. No damage of the DUT was observed.

General conclusion of TVAC tests: According to the pass/ fail criteria, the EM passed the TVAC tests successfully.

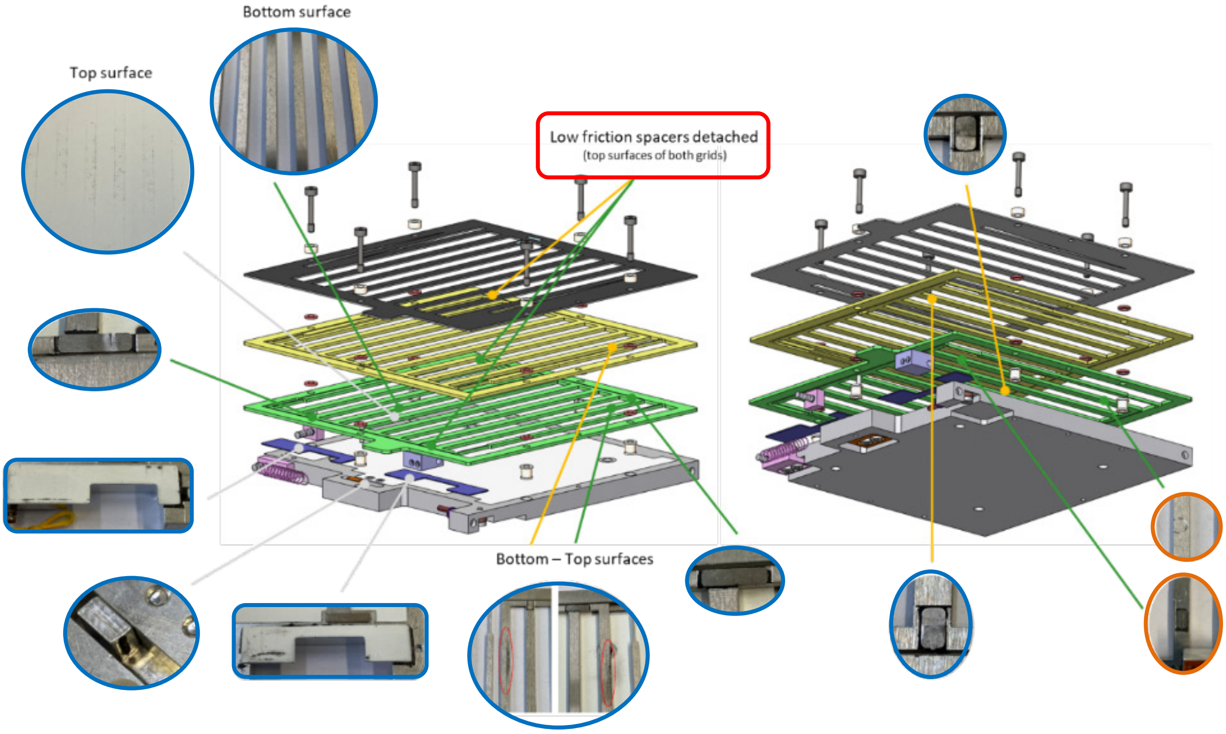
4.7 Reduced functional tests & inspection after environmental tests (ER4)

A close inspection of the hardware was performed on the EM following the completion of the environmental tests prior to disassembly for inspection, a functional test was performed using a hot air gun in laboratory conditions which confirmed the mechanism’s jerky movement during operation as per the tests performed by FOTEC after the vibration tests.

A general inspection was performed followed by a detailed inspection as part of the disassembly procedure. The main observations are listed below and are considered to be the most pertinent.

- All flexures remained intact, and no damage observed visually or during operation
- 1 low friction spacer fallen off from top surface of top flex grid during vibration tests
- 1 low friction spacers fallen off from top surface of bottom flex grid during vibration tests
- Wear marks between top and bottom grids during X-direction vibration tests. LLD blocks flex lower grid against end-stop but upper grid had additional movement due to pin/groove interface which allowed an additional 1-2mm displacement creating scratches
- Cylindrical marks on bottom surface of bottom flex grid: FOTEC used screws that were slightly too long (~1mm). By screwing them, the screws pushed on the blades of the flex grid.

In the image below is a list of the observations made during inspection and their source.



Impact marks related to vibration testing contact and abrasion. Does not affect movement.

Areas related to friction sources and jerky movement during operation (horizontal config.)

Handling error during assembly

General conclusion of functional tests after environmental tests

The cause of the jerky movement when opening the mechanism has been attributed to the two mobile flex grids are in contact with one another in one or more places. The exact cause of the creation of this friction is a combination of the various sources identified above but primarily due to the low friction spacers that were detached during the vibration tests.

4.8 Thermal performance current situation w.r.t. requirements

The original requirement FPR3 of COOLER-CSE-TN-03 demands heat rejection capability in closed 0.1 W and open 10 W configuration (no specific operating temperature range) which were impossible to respect. Considering updated and realistic operating conditions for a payload in the satellite between -20 C and +40 C, **the requirement has been corrected where the ideal louver should emit 0.15 W (closed) and 4.44 W (open)**, with a ratio open/closed of 30. The difference in heat rejection between open and closed is 4.3 W.

For the actual COOLER louver device with the assumed operational temperatures and based on the **numerical effective emissivities** which include the opening fraction, we get **0.30 W (closed) and 1.80 W (open)**, a ration open/closed of 5.9 which is not that bad, and a difference between open and closed of 1.5 W. With the **measured emissivities** this is **0.28 (closed) and 1.7 W (open)** with the same ratio, but a slightly reduced difference to 1.4 W. This is neither brilliant nor dramatically bad, and the louver might be used in applications with limited heat rejection. Looking only at the effective emissivities is a bit deceptive. It is the rejected heat which counts.

5 GENERAL CONCLUSION

The test campaign was performed successfully according to the test plan (TN-08, Iss2). The Engineering Model mechanism (BBM+) incorporated modifications following the recommendations stemming from the results of the BreadBoard test campaign. There was a good agreement found between the ENBIO thermal balance measurements and HERON's thermal model predictions.

The functional tests both at atmospheric and vacuum conditions performed as expected with temperature reactivity and stroke displacement of the flexible grids in various orientations with respect to gravity. The majority of the specifications are compliant with respect to the test plan. The test campaign from a mechanism point of view was successful.

The mechanism underwent Thermal Balance Tests at ENBIO for correlation of thermal data with Heron's thermal simulation model. This was followed by the environmental tests both for vibration and thermal cycling performed by FOTEC which were both successful. Following the random vibration tests, minor issues were observed such as abrasion between grids and where three grid spacers fell off. The result was some erratic behavior of the grids while opening but the mechanism reached its final position under thermal loading (functional tests). The thermal cycle tests were also performed successfully without any particular comments from FOTEC.

The thermal efficiency of the louver mechanism as a radiator was not optimum and this was already addressed during the Critical Design Review. Due to the configuration of the design, based on mechanical simplicity and reliability, the difference in effective emissivity of the louver mechanism between the open and closed configurations is not as high as expected.

Configuration	Applied Heat (W)	Ambient Temp. (°C)	Thermal Plate Temp. (°C)	Effective emissivity
Open	10	20	207.5	0.384
Closed	0.1	20	26.4	0.265

The choice of the design for the project was based on several criteria. The thermal target was mostly based on view factor, and less on obstruction. The heat rejection of concept 4 was already estimated to be low according to the trade-off. The outcome is therefore not a complete surprise. Mechanical considerations further reduced the performance of the current design by reducing the number of blades. The criterion of compactness has weighted heavily in the selection of the concepts.

The current louver design is not suited for major improvements. The performance is not close to the ESA requirements in corrected form (updated operating temperature range -20°C to +40°C) but may find specific applications. The positive outcome of this project is the acquired knowledge and experience in mechanical concepts. The SMA actuators operated as expected and proved to be suitable for the application. The mechanical FEM predictions were correct, together with an accurate judgement of the thermal performance with numerical models.