DOI: 10.13009/EUCASS2023-386
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Development and Qualification of the Avionic Support Structure of the Ariane 6 Upper Liquid Propulsion Module

Mark Güthler†, Andreas Schmieder*, Christian Dröge*, François Gori*, Guillaume Gouverne*, Alexander Milke**
** ArianeGroup GmbH*
Airbus-Allee 1, 28199 Bremen, Germany
mark.guethler@ariane.group† - andreas.schmieder@ariane.group - Christian.droege@ariane.group - francois.gori@ariane.group - guillaume.gouverne@ariane.group - alexander.milke@ariane.group
† Corresponding Author

Abstract
ArianeGroup (AG) is the Ariane 6 Launcher prime contractor and integrator, with ArianeGroup Bremen being responsible for development and integration of the A6 Upper Stage, the so-called Upper Liquid Propulsion Module (ULPM). Within this ULPM development perimeter, AG BRE is also responsible for the support structures that house the Launcher on-board electronics, the so-called equipped Avionic Support Structures (UL-eAvSS). This paper gives a comprehensive overview on the development of these UL-eAvSSs with a focus on qualification activities, in particular justifications achieved by tests, from component (e.g. dampers, thermal control hardware) to sub-system level (e.g. UL-eAvSS dynamic testing, UL-eAvSS thermal vacuum test), as well as system tests like the combined U-ITS / UL-eAvSS Modal Test.

1. Introduction

Targeted for an inaugural launch in 2023, Ariane 6 will be the launcher work horse for future European access to space. ArianeGroup (AG) is the Launcher prime contractor and integrator, with ArianeGroup Bremen being responsible for development and integration of the A6 Upper Stage, the so-called Upper Liquid Propulsion Module (ULPM). Within this ULPM development perimeter, AG BRE is also contributing a significant number of so-called "own parts", i.e. elements / components developed and qualified in-house. Amongst those are the integrated cable-duct or "Raceway", the non-cryogenic lines, as well as the support structures that house the Launcher on-board electronics, the so-called equipped Avionic Support Structures (UL-eAvSSs). Placed in between the ULPM Liquid Hydrogen (LH2) and Liquid Oxygen (LOX) tanks, attached to the ULPM Inter-Tank Structure (U-ITS) in a technically challenging location due to its very cold environment, the UL-eAvSS' main function is - throughout the entire launcher mission - to provide a comfortable environment to the avionics equipment (including the Inertial Measurement Unit (IMU) as a main contributor to Guidance, Navigation and Control (GNC) functions), keeping the equipments within their required temperature range, as well as within their limits regarding mechanical loads (static and dynamic accelerations, acoustic loads, shock). This paper gives a comprehensive overview on the development of the UL-eAvSS with a focus on qualification activities, in particular justifications achieved by tests, from component (e.g. dampers, thermal control hardware) to sub-system level (e.g. UL-eAvSS dynamic testing, UL-eAvSS thermal vacuum test), as well as system tests like the Launcher Combined Test (CT) campaign in French Guyana and the combined U-ITS / UL-eAvSS Modal Test.

2. A short history of UL-eAvSS accommodation and position on the A6 Launcher

During the conceptual studies for the next generation European launchers in the early 2010s in the frame of ESA-funded programs (e.g. Future Launcher Preparatory Programme System Studies, FLPP SYS), as well as the first AG high-level launcher trade-off studies, all Upper Stage configurations with separated LH2 and LOX tanks contained a larger or smaller "empty" cavity in between the propellant tanks. Despite the fact that this cavity was going to have a rather cold environment, it was considered to be attractive for the placement of a dedicated avionics container. This would save a significant amount of structural mass compared to the existing Ariane 5 configuration, where the avionics are placed in the Vehicle Equipment Bay (VEB), a comparatively heavy structure on top of the Upper Stage, in the main general loads path (see Figure 1 for comparison of A5 and A6 avionic positions). At the time, it was also assumed

DOI: 10.13009/EUCASS2023-386

that advances in avionics would lead to a comparatively convenient and simple, rack-like support assembly, where individual cards with low dissipation would be integrated in individual drawers, that could then easily exchanged and maintained, as well as properly insulated from the expected cold environment.

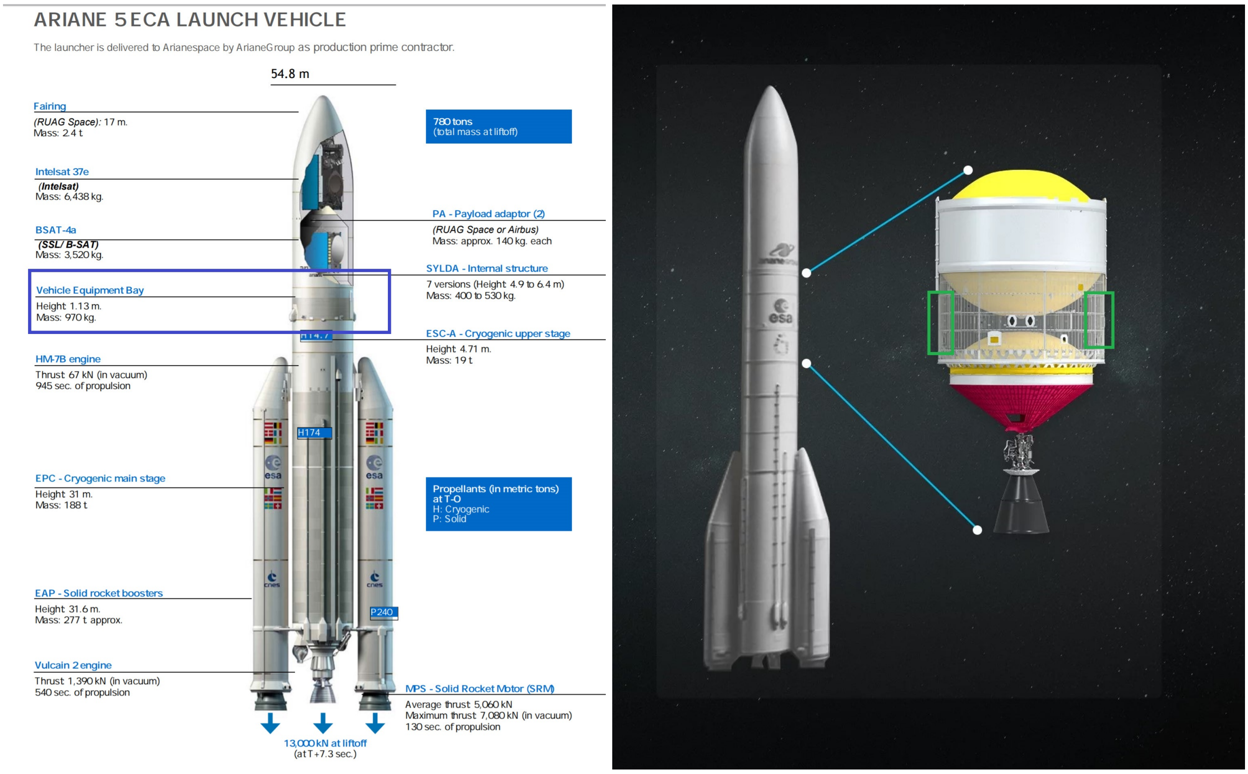

Figure 1: A5 ECA (left, [1]) vs. A6 avionics placement (right, [2])

For the final A6 Upper Liquid Propulsion Module (ULPM) configuration as it exists today, the two positions (spaced at 180° on the Launcher circumference for redundancy reasons) within the inter-tank cavity were retained. However, as the A6 flight avionics development ultimately turned down a more classical road of individual shielded boxes, and dissipation levels started to rise with more functions added to the more conventional (now heavier and bigger) electronic boxes, especially the thermal aspects became more challenging.

3. UL-eAvSS main functions and challenges

The main function of the UL-eAvSS is to provide a suitable mechanical and **especially thermal environment** to the installed avionics equipment, so they are able to execute their intended functions and tasks. In more detail, the UL-eAvSSs shall:

- Protect and mechanically/thermally confine the avionic boxes from the intertank environment
- Extract the heat from the equipment in order to provide the items with an environment compatible with their qualification temperatures
- Properly control mechanical loads so that boxes are safe
- Guarantee dynamic de-coupling with respect to the primary structure of the ULPM (especially related to shock loads)
- Provide access for ground operations, even on launch pad
- Provide an environment conditioning
- Provide proper electrical bonding to all boxes

In addition, there is also a link towards Launcher GNC functions, since the Inertial Measurement Unit (IMU) is also located inside the UL-eAvSS, and functional requirements have been defined accordingly.

In its maximum configuration, the UL-eAvSS must accommodate a large part of the launcher electronics, as well as the corresponding harness (see Table 1 for an overview).

DOI: 10.13009/EUCASS2023-386

Table 1: A6 avionics equipment accommodated in the UL-eAvSS

Acronym	Equipment
APU BAT	Auxiliary Power Unit (APU) Batteries
CMFU	Centralized Multi-Function Units
CMTP	APU Controller
CNF	Tank Level Sensor Conditioners
FBAT	Functional Batteries
IMU	Inertial Measurement Units
MCAU	Multi-Channel Acquisition Units
OSBF	Optical Safety Barrier
PBAT	Pyro Batteries
PFU	Pyro Firing Units
TMTX	Telemetry Transmitters

The overall design of the UL-eAvSS is driven by several needs and challenges:

- To have **late access** to be able to **exchange equipments** very late in the mission, if necessary on the launch pad; therefore, each UL-eAvSS is accessible via three dedicated access doors in the U-ITS
- **De-couple equipments from dynamic (mainly shock) loads**: Early calculations showed that a multitude of UL-eAvSS equipments were only marginally above their allowable shock loads without additional dampers. It was therefore decided to introduce a global shock damper system for the UL-eAvSS suspension; in addition for the IMU, additional elastomeric dampers were introduced to avoid excessive noise on the GNC loop.
- **Thermal environment for equipments**: This is considered to be the biggest challenge, as the avionics equipments need to be
    - kept warm on ground as soon as the tank filling starts; most equipments are passive or in stand-by at the time
    - kept cool when they become active shortly before lift-off and in-flight to avoid overheating

  On ground, a Helium conditioning system has been implemented using dedicated thermal bags when necessary, where Helium is used for both thermal conditioning of the equipments within the UL-eAvSS as well assisting in the flushing of the overall inter-tank cavity.

  During flight, several equipments are highly dissipative:
    - The on-board computers
    - The telemetry transmitters (especially for the first flights where more data is transmitted for long periods of time), and in particular
    - The controller for the auxiliary power unit (APU), that is (amongst other functions) used to produce settling thrust for the tank propellants for extended mission phases.

  For these equipments, dedicated thermal control solutions have been developed and are described in the following paragraphs.

4. UL-eAvSS development / qualification perimeter and main components

4.1 Basic structural design

The main body of the UL-eAvSS comprises an Aluminium housing (~1800mm x 1000mm x 500mm), suspended in the A6 ULPM Inter-tank structure (U-ITS) by means of struts / damper elements with rod ends in an (almost) statically determined way. The inner shelves are dismountable to facilitate installation of harnesses. Access for late maintenance / replacement of avionics is given by the means of 3 quick-removal access doors for each UL-eAvSS (see Figure 2).

DOI: 10.13009/EUCASS2023-386

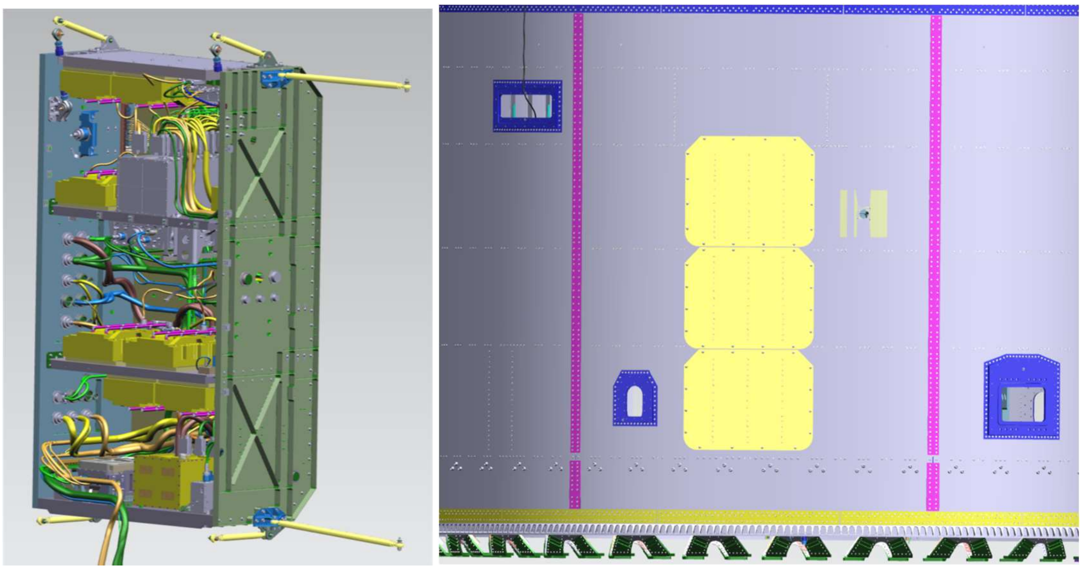

Figure 2: UL-eAvSS1 layout (left) and Inter-tank structure (U-ITS) access doors (right)

4.2 Dampers

UL-eAvSS global shock dampers

Basically derived from a commercial friction spring damper concept, the Ringfeder dampers were developed specifically to AG launcher needs and specifications, in particular regarding reliability and damage tolerance. They are supposed to carry a load of up to 20kN per side, attenuate the shock loads transmitted to the avionics by stage and fairing separation events, as well as limiting the damper/strut forces transmitted to the U-ITS structure thanks to the applied spring pre-tension.

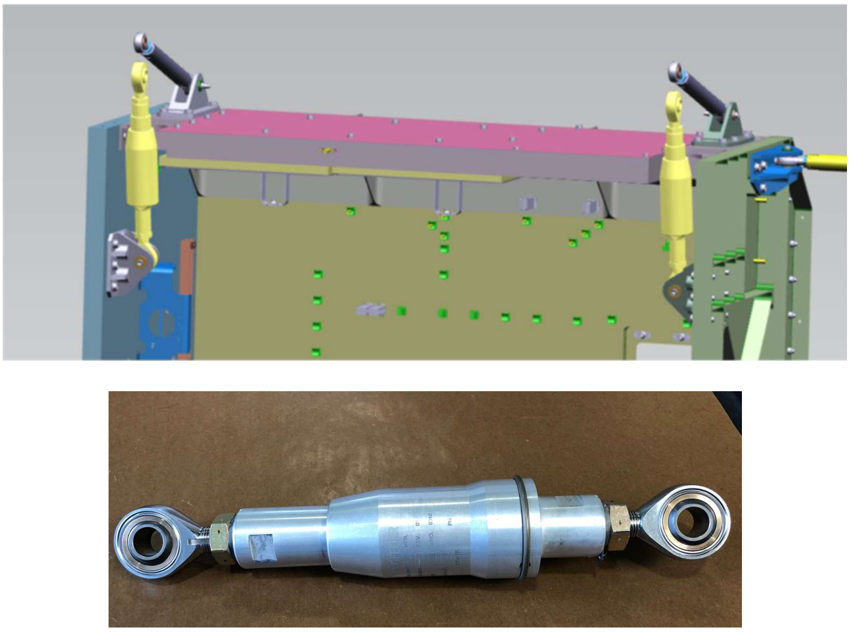

Figure 3: UL-eAvSS Ringfeder dampers (top: Position in the UL-eAvSS; bottom: Qualification unit)

Elastomeric IMU SMAC dampers

Also starting from a commercially available design, the overall design and in particular the elastomeric composition was tuned to frequencies to best de-couple the IMU from the launcher dynamic environment.

DOI: 10.13009/EUCASS2023-386

4.3 Specific Thermal Hardware

Besides the conditioning system mentioned above – mainly used for temperature control on ground, there are several specific thermal components within the UL-eAvSS that protect highly dissipative equipments from overheating in flight (Figure 4):

- **Thermal straps:** Off-the shelf, space qualified HiPeR flex links (thermal straps, details see [4]) to enhance heat transfer from the APU motor pump controller (CMTP) to colder areas (e.g. U-ITS ring frame)
- **Phase Change Material (PCM) Container**: Paraffene-filled containers have been used in the past on A5 for specific missions and configurations to act as heat buffer, mainly for control attitude thrusters in pulse mode, in particular for high heat thermal load peaks. In contrast, for A6 application on highly dissipative equipments, the melting enthalpy of the used wax creates a very efficient thermal capacitive storage. In addition, thanks to Additive Layer manufacturing (ALM) technology (aka 3D-print), the Aluminium containers can now be produced as single pieces, creating the necessary enclosure with fragile internal lattice structure for efficient heat distribution in a single print job, greatly improving mechanical strength and avoiding leakage problems caused by the traditional welding seams.
- **Aluminium Doubler w/ heat pipes**: Introduced to increase robustness against increases in CMTP dissipation, an Aluminium doubler plate with integrated, Ammonia filled heat pipes (space-qualified and off-the shelf) improves the distribution of heat from underneath the equipment towards the thermal straps and the additional PCM containers.

Whereas some of these elements are already generally known and used in space applications (e.g. heat pipes, PCM containers, straps), the application in a Launcher environment is not always straight forward (e.g. de-priming of heat pipes under adverse acceleration), so that some extensive testing was necessary to justify the usage on A6.

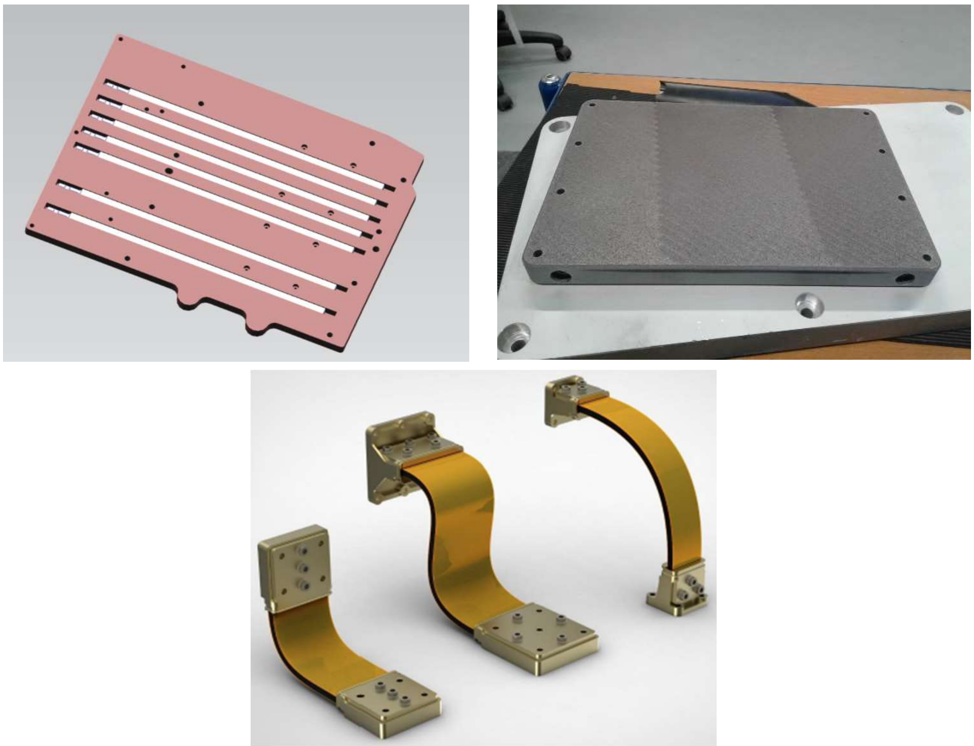

Figure 4: Specific UL-eAvSS thermal control elements
(from left to right; top row: Aluminium doubler with heat pipes / 3D-printed PCM container;
bottom row: HiPeR Flex links

DOI: 10.13009/EUCASS2023-386

5. Qualification and test logic

To cover the entire scope of UL-eAvSS functions and to optimize / simplify as much as possible the tests needed, the numerous verification activities were conducted on the lowest complexity level possible. However, in order to take into account some more complex thermal phenomena and structural-mechanical interactions, subsystem and system tests cannot be fully avoided. Table 2 gives an excerpt of those verification activities linked to testing.

Table 1: A6 avionics equipment accommodated in the UL-eAvSS

Verification activity // level	**Compo-nent**	**"Sub-assembly"**	**UL-eAvSS**	**ULPM / Launcher**
Ringfeder Damper tests	X	-	-	-
SMAC IMU Damper qualification tests	X	-	-	-
Rod end test	X	-	-	-
PCM container tests	X	-	-	-
Aluminium doubler w/ embedded heat pipes	-	X	-	-
CMTP / UL-eAvSS thermal vacuum test	-	X	-	-
UL-eAvSS dynamic model (DM) vibration test	-	-	X	-
UL-eAvSS modal test w/ U-ITS	-	-	-	X
UL-eAvSS combined launcher thermal test in Kourou	-	-	-	X

Some of the more prominent tests are described in more detail in the chapters below.

6. Component testing

6.1 3D-printed PCM Containers

Here, in addition to the thermal function, material and process parameters of the 3D-printed material needed to be elaborated, as well as printing process stability:

- Material qualification (tensile, fatigue, hardness, conductivity, density, composition etc.)
- Thermal performance test

As the calculated structural margins are significant, no dedicated dynamic test was considered necessary.

Regarding mechanical and global material properties of the 3D-prints, test results were globally as expected. Especially the tensile strength was found to be well in-line with the needed values:

	Q1+Q2	Q1+Q2
	Rp02	**Rm**
mean	**209,7**	**355,5**
stdev	**9,2**	**10,3**
n	20	20
A-value		
k	3,274	3,274
Allowable		
X	179,7	321,7

Figure 5: Resulting A-values for two print jobs

DOI: 10.13009/EUCASS2023-386

For the thermal testing on container level, the main results can be summarised as follows:

- **Temperature Homogeneity**: The temperature gradients within the PCM container are globally rather small, both in thickness and in-plane direction. This shows that the heat transfer via the internal lattice structure and the side wall of the container is working well. In case of asymmetric heating, temperature gradients increase in particular in plane. A larger thickness has some advantages in this case, since it reduces the gradients. Nonetheless, the effect was not considered significant enough to justify an increase of the container face sheet thickness, especially considering mass penalty.
- **Heat storage capacity and phase-change plateaus**: In general, the tests confirmed the overall thermal capability of the PCM container, and the assumptions made in the thermal analysis concerning this capacity. This is also confirmed for the asymmetric heating case.
- Generally, the overall **concept feasibility** as well as the detailed thermal capabilities and performance of the PCM container **have been successfully demonstrated**. These generic results confirm the assumptions made for the thermal analyses.

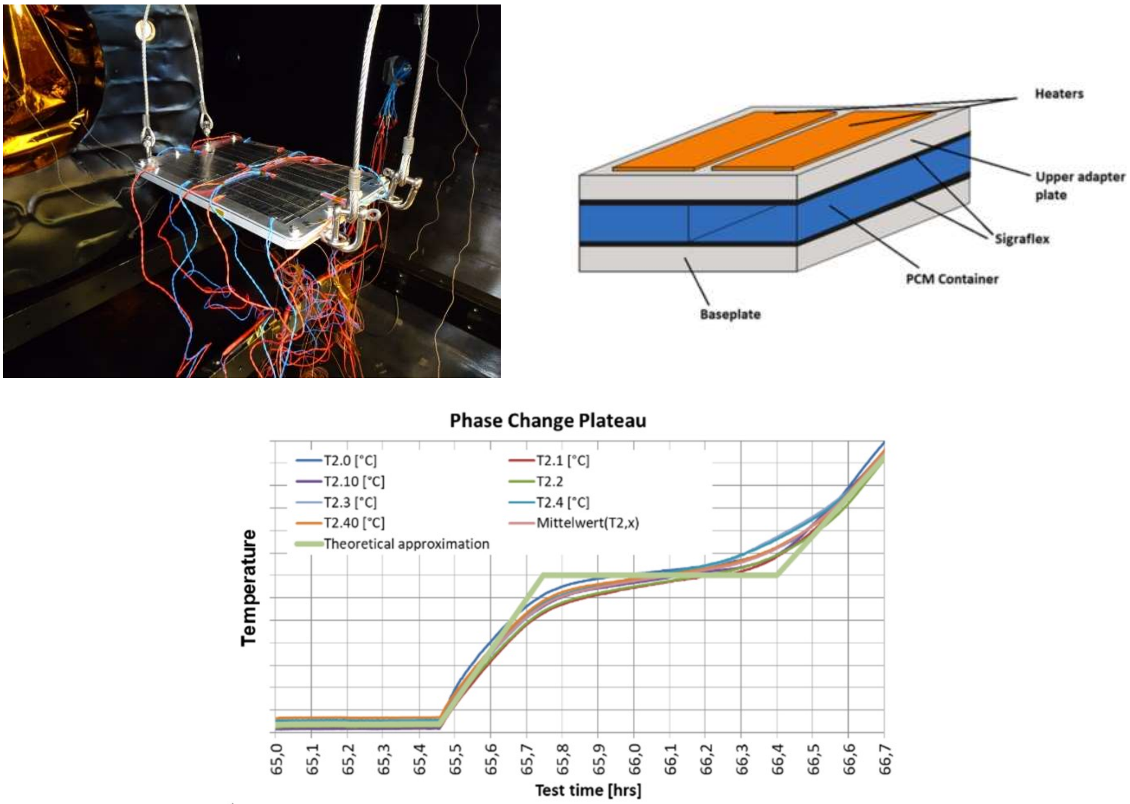

Figure 6: Thermal testing test-set up (H/W / schematic) and temperature results for phase change

6.2 Aluminium doubler w/ embedded heat pipes

As explained above, due to adverse accelerations during Launcher Boost phases, there is the risk of the so-called heat pipe (HP) “de-priming”, i.e. the break-down of the capillary pumping mechanism. As a consequence, the main test objectives were

- Thermal Performance / conductance
- HP Priming stability during Orbital coast phases requirement
- HP Re-priming velocity after boosts

DOI: 10.13009/EUCASS2023-386

The main results can be summarized as follows:

- Global concept is working as expected w.r.t. heat transfer;
- Glue thickness between Aluminium and HPs is one driver for the overall temperature gradient - although sufficient for the current needs, the glue layer will be reduced for future doubler manufacturing to further enhance global heat transfer
- Re-priming is quick and very efficient; no issues are expected for A6 applications

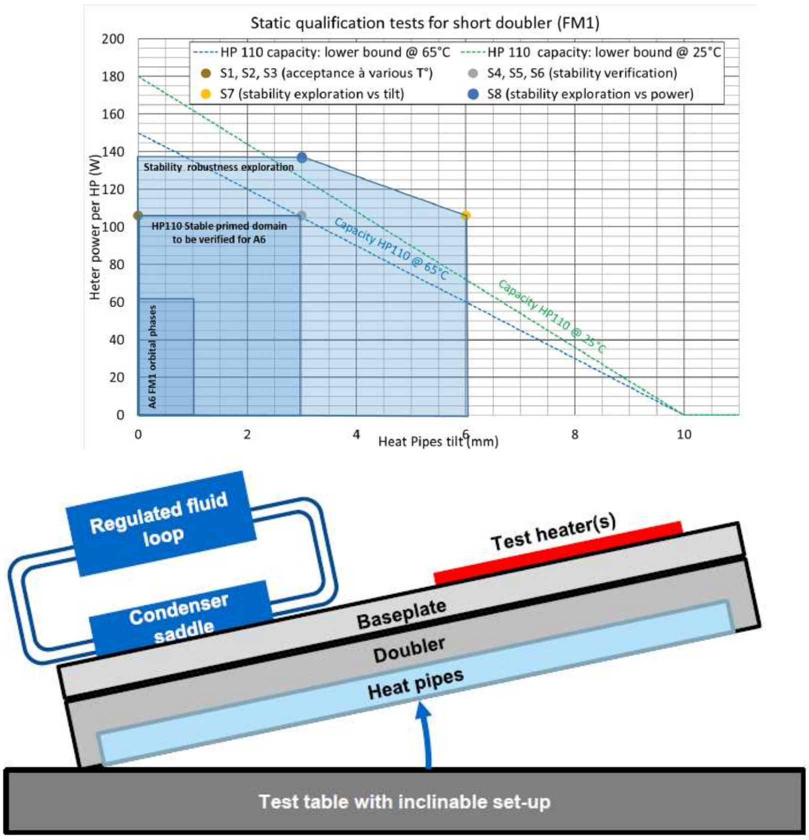

Figure 7: HP doubler test set-up and static functional doubler domain

6.3 Friction spring dampers

As the main function of the dampers is a structural one, the tests focussed mainly on the structural integrity aspects, albeit at different temperatures:

- Strength (tension & compression tests at RT, hot and cold temperatures)
- Fatigue / life cycle testing and cracks after life-cycle testing

Throughout the campaign, all dampers exceeded their requirements, and can be considered fully qualified for their application on A6.

DOI: 10.13009/EUCASS2023-386

Figure 8: Ringfeder Damper (top left: Compression test at -90°C;
bottom left: Temperature evolution during cyclical loading; right: Qual unit before life-cycle tests

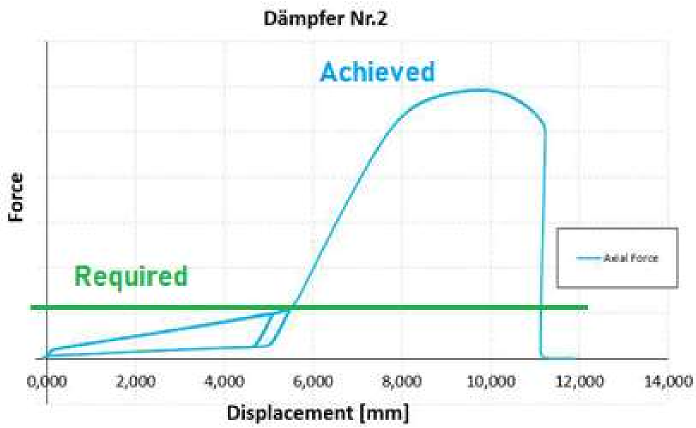

Figure 9: Ringfeder Damper yield and ultimate test after life-cycle testing

6.4 Elastomeric IMU dampers

In contrast to the global shock dampers as described above, the elastomeric IMU dampers also need to fulfil a more complex function, that is to dynamically de-couple the IMU from the launcher, thus reducing unwanted and detrimental noise (e.g. by angular movements) on the IMU signals and thus the GNC accuracy. As a consequence, the test programme was more comprehensive, encompassing:

- Pre-definition of new elastomer composition (pre-testing)
- Ultimate load test at RT, low and high temperatures
- Stiffness test at operational temperature range and RT
- Eigenfrequency of damped system, at operating temperature range and RT, and corresponding g loads
- Mechanical suspension transfer function

Although the damper frequencies ultimately were slightly below than what was originally expected, the impact on noise level is considered to be limited. The remaining mechanical performance is fully in-line with the respective requirements.

DOI: 10.13009/EUCASS2023-386

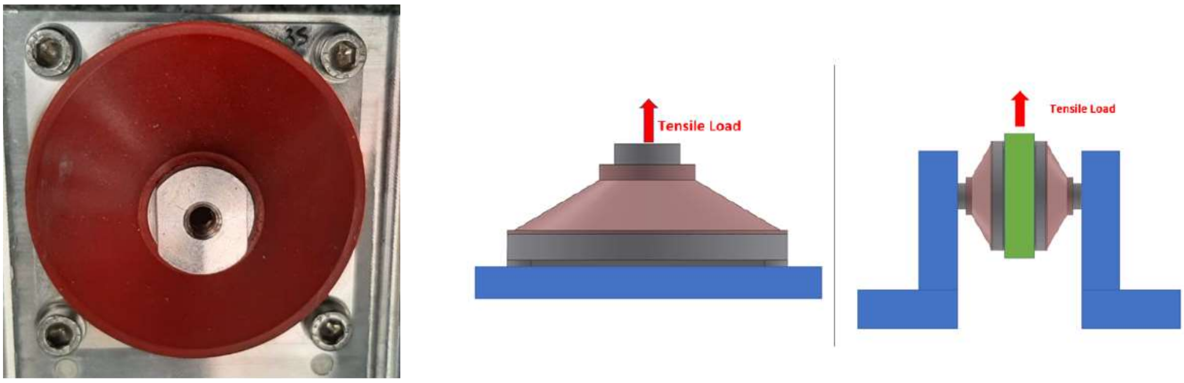

Figure 10: SMAC Elastomeric damper ultimate load testing (radial / axial)

7. Subsystem and system level testing

7.1 UL-eAvSS and CMTP combined TVAC testing

Due to its high dissipation levels over a prolonged period of time, a complex thermal control concept needed to be set-up around the CMTP, using thermal straps, an Aluminium doubler with heat pipes and PCM containers. Whereas the individual components had been verified by tests, the overall justification had been entirely relying on thermal analyses. As these analyses showed very little or no margin, it was decided to conduct some integrated thermal vacuum testing using a representative flight set-up (shown below) and mission representative dissipation levels, simulating transient temperature behaviour during the mission as well as steady state balance steps to be used for model correlation. The main objectives of this test are

- To refine the thermal mathematical model (by correlation with test data)
- To refine the mathematical dissipation models
- To confirm the temperature mission predictions
- To regain some margins if possible

Although the correlation activities and test exploitation are not finally completed, first results indicate that for a representative mission profile the measured temperatures are lower than analytically predicted, indicating some additional robustness of the applied solution.

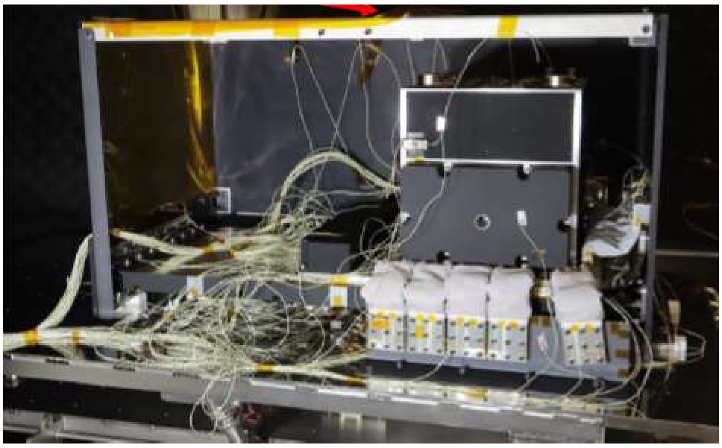

Figure 11: CMTP / UL-eAvSS combined thermal vacuum test

DOI: 10.13009/EUCASS2023-386

7.2 UL-eAvSS dynamic model (DM) testing

The dynamic test was conducted comparatively early in the programme (in summer 2020) with the following main objectives:

- to determine the global dynamic behaviour (i.e. response frequencies, damping etc.) of the hard-mounted UL-eAvSS structure
- in longitudinal axis: to determine the impact of the two operation modes of the Ringfeder friction dampers (inactive/active) on the global dynamic behaviour
- to determine the transfer functions at the individual equipment interfaces
- An additional passenger objective was to measure stress levels in the highest loaded areas of the UL-eAvSS, as well as strut forces via strain gages, in order to support mechanical justification

The test results have been used to correlate the dynamic models and enhance predictions using the Launcher Stage Coupled Dynamic Analysis.

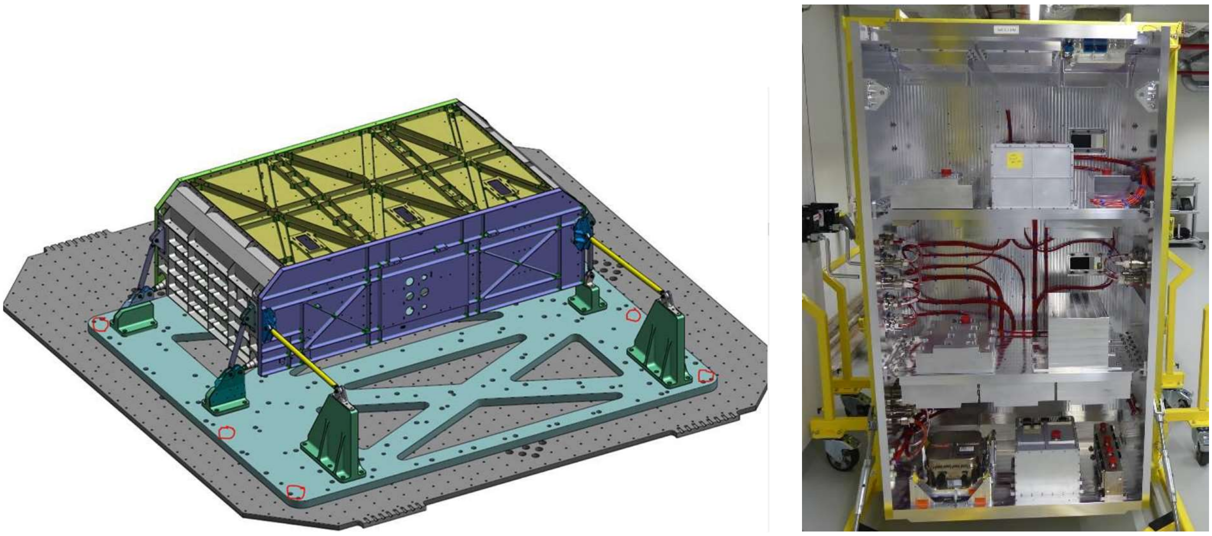

Figure 12: UL-eAvSS dynamic test (test-set up and UL-eAvSS test model)

7.3 UL-eAvSS / U-ITS combined modal test

As a replacement of the ULPM overall vibration test cancelled due to budgetary constraints, using a flight representative combined U-ITS / UL-eAvSS structure, this test aims to determine the main suspension modes of the UL-eAvSS when integrated to the ULPM inter-tank structure (U-ITS) for validation of the analytical model used for the structure-dynamic verification. The modal survey test determines the modal parameters (frequencies, mode shapes, damping and generalized masses) of the main target modes predicted by the dynamic analysis model for subsequent model correlation.

The main results can be summarised as follows:

- As can be explained by the specific UL-eAvSS suspension (with rotatable rod end bearings for angular compensation), a certain ”rattling” effect is present; its influence makes the interpretation of the results somewhat more complex
- In order to better represent the axial suspension mode (that was showing some discrepancy to the predicted values), the stiffness of the UL-eAvSS horizontal panels within the FE model was increased substantially, leading to a significantly improved correlation; this might indicate that the impact of the stiffness of the mounted equipment (e.g. via base plates) might play a bigger role than originally anticipated
- Potentially detrimental UL-eAvSS global rotation modes are highly damped and therefore uncritical

DOI: 10.13009/EUCASS2023-386

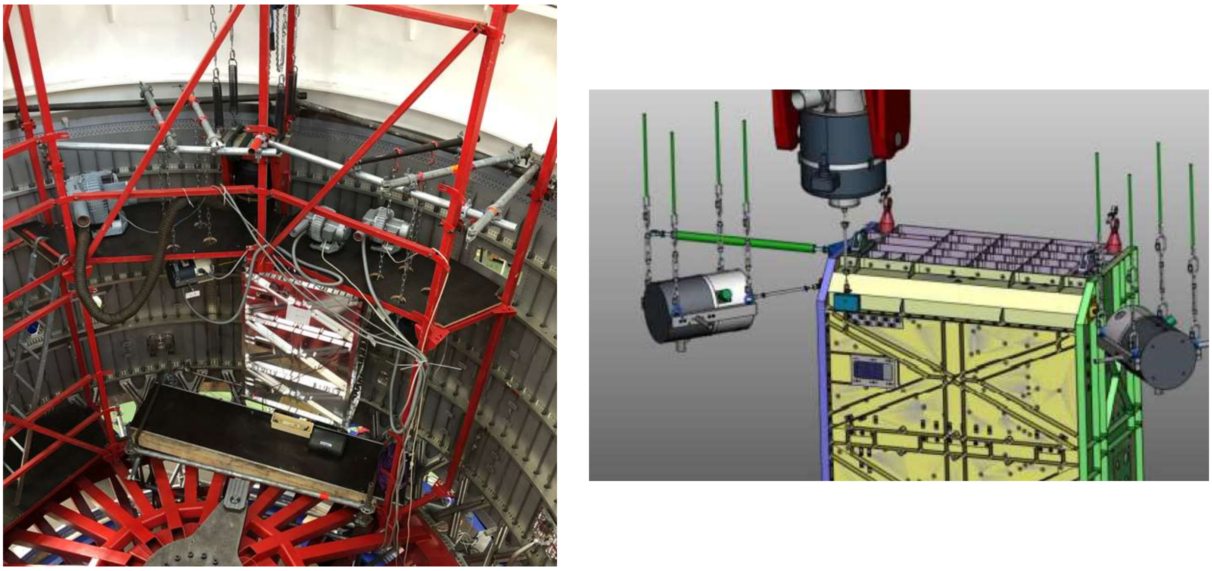

Figure 13: U-ITS / UL-eAvSS modal test: Test H/W (left) and excitation positions (right)

7.4 A6 Launcher / Launch Base combined tests (CT) in Kourou

As shown in Figure 14, the A6 Launcher / Launch Base combined test in Kourou has multiple objectives, the most important of which are the common qualification of all nominal and off-nominal procedures (filling, draining, synchronized sequence, Vulcain engine ignition and others) during launch operations. For the UL-eAvSS, it will for the first time provide realistic thermal environments for the justification of the implemented thermal control measures and will validate the temperature results from analytical predictions. As of today, unfortunately, no results can be shown yet.

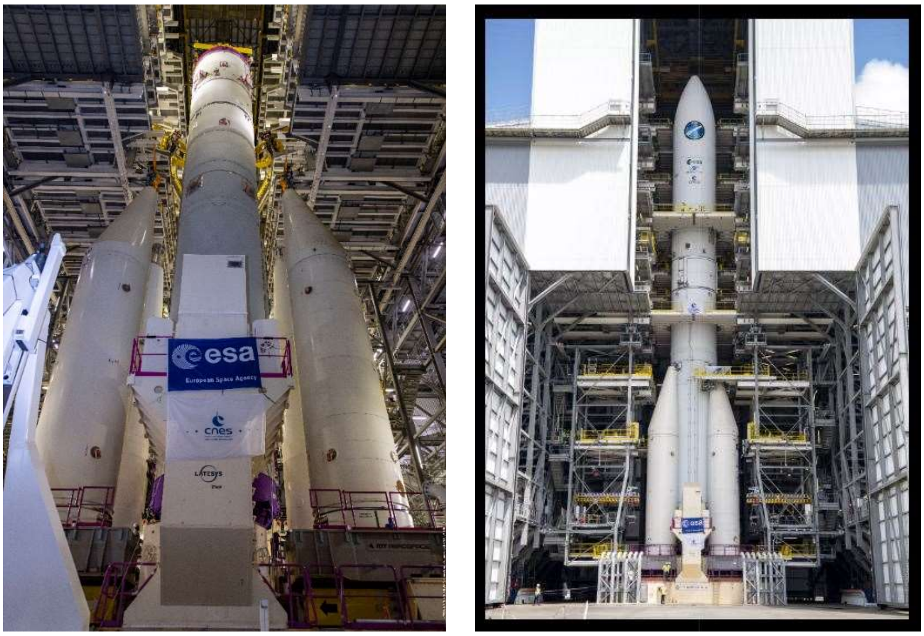

Figure 14: Combined test launcher / launch base configuration in Kourou [3]

DOI: 10.13009/EUCASS2023-386

8. Conclusion and outlook

This paper summarises the extensive test campaigns on material, component, subsystem and system level conducted in the frame of the development of the Ariane 6 ULPM equipped Avionics Support Structures (UL-eAvSS). Despite the functional challenges, the necessity to either develop completely new thermal control solutions or to adapt existing ones to a Launcher environment and the complex structural mechanical and dynamic justification, the qualification of the UL-eAvSS is very well advanced. The Launcher Combined Test (CT) campaign in French Guyana will give additional elements to finalise the justification for first flight(s), FM1 thermal exploitation will clear the way to full qualification for other versatile missions.

Acknowledgements

The authors would like to express their thanks and gratitude to everyone involved in the aforementioned activities, both to the teams within ArianeGroup as well as on subcontractor level, in particular the support of the people at Geradts, Ringfeder, Carl Hirschmann, SMAC, EHP, Airbus DS NL and Oerlikon, as well as all the test facilities (IABG, IMA, Atlas, Testia, OVSQ) and many others.

References

[1] https://forum.raumfahrer.net/index.php?action=media;sa=media;in=51192
retrieved on May 12th, 2023

[2] https://press.ariane.group/arianegroup-developpe-phoebus-pour-lesa-un-demonstrateur-du-futur-etage-superieur-dariane-6-en-materiaux-composites-6089/?lang=deu
retrieved on May 12th, 2023

[3] https://www.ariane.group/de/neuigkeiten/erstes-zusammentreffen-des-ariane-6-zentralkoerpers-mit-der-startrampe/
retrieved on May 17th, 2023

[4] ICES-2017-107 - Development of Pyrolytic Graphite Applications in Spacecraft Thermal Control Systems, 47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina

All other figures taken from ArianeGroup internal sources / documents.