Development of a Practical Approach for Thermal Vacuum Cycling Tests for CubeSat Applications

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***Abstract*—For a CubeSat-based mission to succeed, several development stages are required: concept definition, technology development, verification and validation, and, finally, integration and launch. Among these stages, one of the most critical is testing the CubeSat's systems and subsystems, as it ensures they can withstand the harsh conditions encountered during and after launch. Thermal-related tests are particularly significant, as they ensure the CubeSat remains operational throughout multiple orbits under constant vacuum exposure and thermal variations. To simulate these conditions, the thermal vacuum cycling test (TVCT) must be performed. Although this test is considered one of the most critical in the qualification process, it is often procedurally complex, costly, and not easily accessible to university-based groups, especially for preliminary evaluation. Furthermore, defining and conducting the TVCT are not straightforward tasks. Standards such as those established by the European Cooperation for Space Standardization (ECSS) specify parameters and requirements for TVCT, often tailored to high-performance facilities. As a result, applying these procedures to small-scale or low-cost setups becomes challenging, particularly when the objective is preliminary or subsystem-level evaluation. To address these constraints, the Laboratory of Applications and Research in Space (LARS), in partnership with SpaceLab from Federal University of Santa Catarina (UFSC), developed an adapted set of procedures for performing TVCTs using a low-cost thermal vacuum chamber (TVAC), focusing on accessibility while maintaining methodological rigor. To verify the methodology, an open-source electrical power system (EPS) model and conformal coating materials were tested in accordance with the proposed procedures, enabling a preliminary evaluation of component behavior under thermal-vacuum conditions. The tests were conducted at pressures ranging from 1×10^{-2} mbar to 1×10^{-5} mbar. Cooling was provided by liquid nitrogen, while thermal control was achieved through electrical resistances controlled by a proportional–integral–derivative (PID) control system, resulting in ambient temperature variations of approximately -20°C to 55°C. The EPS components were evaluated before and after the tests and showed consistent performance, indicating no degradation from vacuum exposure or temperature cycling. The test campaign also allowed assessment of the operation of the EPS's integrated heaters, which performed as expected, and of a commercial conformal coating, which showed poor performance under thermal-vacuum conditions. These results demonstrate that the proposed set of procedures helped conduct preliminary evaluations and can be replicated by other groups using similar facilities. Moreover, the LARS's TVCT provides a viable and accessible alternative for initial testing before more rigorous qualification campaigns.**

***Index Terms*—Thermal Vacuum Cycling Test, Thermal Vacuum Chamber, CubeSat, Electrical Power System.**

I. Introduction

For a CubeSat-based mission to succeed, several development stages are required, including concept of operations (CONOPS) definition, requirements and risk identification, technology development, manufacturing, verification, and validation. Typically, these steps follow a V-model-like iterative cycle until the system is ready for launch [1]. Within this process, testing of CubeSat systems and subsystems ensures they can withstand the harsh environmental conditions encountered during launch and in orbit. Among the thermal tests required for the mission approval, the thermal vacuum cycling test (TVCT) is considered one of the most critical and representative [2]. Conducted in a thermal vacuum chamber (TVAC), this test assesses whether a CubeSat and/or its individual components remain operational over multiple simulated orbital cycles under continuous vacuum exposure and alternating hot and cold conditions.

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Despite being essential in the qualification process, the TVCT is often procedurally complex, expensive, time-consuming, and thus largely inaccessible to university-based teams, especially for preliminary or subsystem-level evaluations. In Brazil, for instance, the *Laboratório de Integração e Testes* (LIT), with more than 38 years of experience, is the most specialized facility for dynamic, thermal, and environmental testing for satellites, CubeSats, and space components [3]–[5]. However, its high operational costs and long scheduling lead times make it impractical for early-stage, rapid, or iterative verification campaigns. Moreover, defining and executing a TVCT is not a trivial task. Although established standards, such as European Cooperation for Space Standardization (ECSS), prescribe detailed test parameters, limits, tolerances, and protocols [6], they are primarily designed for high-end, high-fidelity facilities. Consequently, applying these procedures directly to small-scale or low-cost setups can be challenging, especially when the goal is rapid, subsystem-focused validation rather than full mission qualification.

To overcome these economic and management barriers, low-cost, small-scale, in-house-built TVACs have emerged as versatile solutions to broaden access to thermal vacuum testing for CubeSats. In this context, several university research groups have developed custom TVACs tailored to specific requirements, CubeSat dimensions, and experimental objectives. [7] and [8] designed, thermally modeled, and constructed a TVAC capable of accommodating a 6U CubeSat, enabling vacuum bakeouts and the testing of UV spaceflight hardware through a coupled vacuum UV monochromator. Similarly, [9] developed an in-house-built transparent TVAC and combined experimental testing with thermal modeling to investigate the thermal behavior of a hyperspectral camera for a 6U CubeSat, highlighting the role of such facilities in assessing the impact of payload design choices.

Beyond general thermal vacuum testing, several studies have employed in-house-built TVACs specifically to perform TVCTs, aiming to evaluate the durability and operational performance of CubeSat subsystems under extreme vacuum and repeated thermal loads. [10] details the development of a dedicated temperature control and monitoring system for CubeSat TVCT, validated through environmental qualification of the TRIO-CINEMA flight models. [11] conducted TVCTs on a xenon feed unit used on an electric propulsion system. [12] and [13] performed qualification and acceptance TVCTs with eight and four cycles, respectively, to validate the 3U communication CubeSat TURKSAT-3USAT, comparing experimental results with thermal simulations. In a similar context, [14] conducted four cycles of TVCTs to validate the 2U educational, scientific, and technology demonstration CubeSat EIRSAT-1, performing functional tests on subsystems under hot and cold extreme conditions to detect and investigate anomalous behavior.

These studies demonstrate the feasibility of conducting TVCTs in low-cost TVACs; however, variations in chamber design and the lack of clearly defined, accessible testing procedures for the experiments indicate that further investigation is needed to establish scalable, accessible, and reproducible approaches for TVCT implementation in university laboratories. Following this trend, the Laboratory of Applications and Research in Space (LARS) has developed its own low-cost TVAC [15] and, in collaboration with SpaceLab at the Federal University of Santa Catarina (UFSC), now proposes a structured set of TVCT procedures suitable for resource-constrained academic environments. These procedures prioritize accessibility while preserving methodological rigor, enabling early-stage environmental validation of CubeSat subsystems.

The remainder of this paper is organized as follows: Section II describes the materials and infrastructure used, detailing the TVAC architecture, vacuum and thermal subsystems, and instrumentation. Section III outlines the proposed TVCT procedure step by step. In contrast, Section IV presents its experimental validation with two distinct case studies, including the tested subsystem (an open-source electrical power system (EPS)) and the test profiles. Section V presents the case studies' results and lessons learned, along with the limitations of the current setup and potential improvements. Finally, Section VI concludes the paper with a summary of contributions and directions for future work.

II. Thermal Vacuum Chamber

The TVAC at LARS features a specialized architecture designed for testing components and CubeSats up to 6U [15] (Fig. 1) . Custom built by Fhaizer Autoclaves, the cylindrical chamber has nominal external dimensions of 78 cm in length and 45 cm in diameter, resulting in a total volume of 0.174 m^3. Access and monitoring are facilitated by a sealed door and an observation window located at opposite ends of the chamber. The internal test section, measuring 65 cm in length and 37 cm in diameter, is enclosed by a shroud, a cylindrical metallic sheet painted with matte black paint, that acts as a high emissivity neighborhood. Around the shroud, a metallic serpentine tubing is installed for the cooling system. A study conducted at LARS [15] found that isothermality was absent across the test volume, posing a challenge for TVAC operation. However, in the present study, chamber non-isothermality does not significantly affect the results, given the temperature uniformity at the chamber center and the small size of the tested components relative to the test section.

The thermal control of the TVAC is achieved through a coordinated heating and cooling system that simulates the temperature variations of the space environment. The cooling system operates by transporting nitrogen throughout the serpentine, allowing the shroud to be cooled evenly via forced convection. Then, the nitrogen is discharged through an outlet hose to the external environment, as shown in Fig. 1. The system uses approximately 150 liters of liquid nitrogen, manually controlled, to lower the shroud to -80°C. The heating system relies on two internal electrical resistances powered by a TDK-Lambda GEN-300-5 programmable power supply and controlled by a Propotional Integrative Derivative (PID) control system with 0.5, 0.02, and 0.2 as parameters, obtained



Fig. 1: TVAC with the cooling nitrogen cylinder connected at LARS.

through trial and error. The ambient mean temperature is used as the PID controller setpoint to reach and maintain the chosen cold and hot plateau temperatures, ensuring results adhere strictly to the experimental profile.

The vacuum system employs a dual-stage approach to achieve the required conditions for the TVCT. The process begins with a primary vacuum stage controlled by the Edwards nXDS10iC dry scroll mechanical vacuum pump. Once the required crossover pressure is reached, the Edwards T-Station 75 turbomolecular pumping station is engaged to achieve high-vacuum levels. This combined system can maintain an internal pressure of up to 1×10^{-5} mbar. The Edwards APG100-XM pressure sensor continuously monitors the vacuum level, integrated with a digital gauge controller, ensuring precise measurements and stability throughout the test.

The data acquisition and control system is centralized to provide real-time monitoring of all critical parameters via LabVIEW 2020. Temperature is measured using type T thermocouples placed throughout the experiment and the chamber, which are interfaced with a National Instruments NI-9214 temperature acquisition module. To monitor the TVAC temperature, three thermocouples were freely positioned in the environment surrounding the tested components, and one at the ceiling of the shroud. All data communication (*e.g.*, temperature and voltage) between the internal and external sides of the chamber is accomplished via in-house-built hermetically sealed feedthroughs.

III. Thermal Vacuum Cycling Test

The TVCT is an environmental procedure designed to verify the functionality and structural integrity of satellites and their components under the stress of high vacuum and cyclic extreme temperature to simulate space conditions [1]. The test requires the components to be subjected to a continuous vacuum while undergoing a specific number of thermal cycles between defined hot and cold temperature plateaus, target temperatures at which the testing element is maintained. Precise parameters regulate each cycle, including established heating and cooling transition rates and stabilization criteria, often defined as the rate of change in temperature within test tolerance, to ensure the unit has reached thermal equilibrium [6]. The objective is to demonstrate that the equipment can survive and operate while exposed to the thermal gradients and vacuum-induced outgassing characteristic of the orbital environment [2].

Unified technical language is provided by standards in TVCT, ensuring the spacecraft hardware is verified with a common baseline of rigor, regardless of where it was built. These documents establish rigorous benchmarks to verify spacecraft reliability through standardized thermal margins and vacuum protocols, serving as a mission's insurance policy to ensure that every component has withstood conditions more extreme than those it will actually face in orbit. The primary standards for TVCT are ECSS-E-ST-10-03C, MIL-STD-1540 (SMC-S-016), and GSFC-STD-7000. For CubeSat testing, NASA LSP-REQ-317.01 Rev. B is the most widely used standard [6].

The TVCT procedure begins with the vacuum stage described in [15]. First, the components to be studied are positioned inside the chamber, the instrumentation is connected to the feedthroughs, and the door is sealed. The vacuum process is then initiated with the mechanical vacuum pump until approximately 9×10^{-2} mbar, at which point the turbo molecular vacuum pump is activated. Both pumps operate simultaneously until the vacuum stabilizes around 1×10^{-2} mbar, at which point the mechanical pump is turned off. Its valve is closed, leaving the turbo molecular pump operating alone throughout the experiment.

The thermal cycling stage of the TVCT procedure was derived from the works of [6], [10]–[14] and was conducted in accordance with the standards ECSS-E-ST-10-03C and GSFC-STD-7000B. After the vacuum procedure is completed, the thermal cycling stage is preferably initialized by the cold cycle, since it consumes less nitrogen to achieve the cold setpoint, considering the initial temperature of the components and internal ambient is at room temperature (*i.e.*, 23-25°C) and not at the hot setpoint, usually above 50°C. Therefore, the thermal cycling procedure can be conducted as follows:

1) Cold part:
    a) For the cold slope, the nitrogen valve is completely open to allow a fast decrease of overall temperature, and the cold setpoint is set.
    b) When the ambient mean temperature reaches 2°C above the cold setpoint, the nitrogen valve is 50% closed.
    c) When the ambient mean temperature reaches the setpoint, the PID controller automatically starts to operate to maintain that temperature. The first two oscillations are disregarded when they exceed the stabilization criteria. And after that, the plateau time is counted.
    d) When the plateau time is finished, the nitrogen valve is completely closed, and the cold part ends.

2) Hot part:
   a) For the hot slope, the setpoint is changed for the hot plateau temperature, and the PID controller immediately starts to operate to reach that temperature.
   b) When the ambient mean temperature reaches the setpoint, once again, the first two oscillations are disregarded, and after that, the plateau time is counted.
   c) When the plateau time is finished, the nitrogen valve is completely open, the hot part ends, and the cycle is reinitialized.

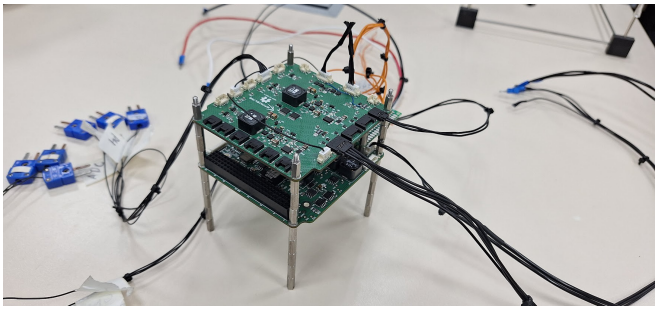
The TVCT continues until the required number of cycles is reached or until the nitrogen is finished.

IV. Case Studies

In this section, two independent test campaigns conducted using the low-cost TVAC are presented to demonstrate the viability of the TVCT procedures developed for the low-cost chamber at LARS. The tolerances allowed, the number of cycles, and the pressure level of each test were based on the standards ECSS-E-ST-10-03C and GSFC-STD-7000B, and are shown in Table. I. More details are explored in the following subsections. Each campaign addressed distinct objectives: the first aimed to evaluate the functionality of two open-source EPSs, Electrical Power System 2.0 (EPS2) [16] and Reliability Enhanced Electrical Power System (RE^{2}PS) [17]; the second aimed to evaluate the performance of a resin used in the EPS2's heaters as well as the integrity of a commercial conformal coating under consideration for use in multiple SpaceLab's missions.

A. First Test Campaign: Open-Source EPSs

The first test campaign evaluated two open-source EPSs developed by the SpaceLab group: the EPS2 and the RE^{2}PS. Both are 2U-compatible subsystems featuring maximum power point tracking (MPPT), battery management, and multiple regulated power buses. The objective was to assess and compare their functional resilience under representative low-Earth orbit thermal cycles in vacuum, as part of a subsystem-level screening prior to mission integration. Both units were mounted in the chamber using standoffs, as shown in Fig. 2a, and tested simultaneously, as depicted in Fig. 2b. The behavior of the battery and photovoltaic panel was emulated using external power supplies connected via the chamber's power feedthroughs. Telemetry and log data were acquired via the thermocouple feedthroughs, as dedicated signal feedthroughs were not yet available. Moreover, thermocouples were added



(a)



(b)

Fig. 2: Setup used during first test campaign: (a) Both EPS models stacked; (b) Subsystems inside the chamber.

to RE^{2}PS, as it has no built-in temperature sensors, whereas EPS2 was monitored using its internal sensors via its microcontroller unit (MCU) and a dedicated battery monitoring integrated circuit (IC). The intended thermal-vacuum profile comprised three full cycles between $-20\,^{\circ}\mathrm{C}$ and $55\,^{\circ}\mathrm{C}$ (with tolerances of $\pm 4\,^{\circ}\mathrm{C}$), with $30\,\mathrm{min}$ dwells at each temperature plateau and a stabilization criteria of $1\,^{\circ}\mathrm{C}/10\,\mathrm{min}$. The test was to be conducted under stable vacuum conditions below 1×10^{-5}mbar (with a tolerance of $\pm 80\,\%$) throughout its duration.

B. Second Test Campaign: Heater Operation and Coating Integrity

The second test campaign evaluated two distinct aspects: *i)* the thermal coupling efficiency of a custom thermal interface material (a mechanical resin mixed with graphite) used between battery cells and heaters in the EPS2, and *ii)* the integrity of a commercial conformal coating under thermal-vacuum stress. Two EPS2 units were tested simultaneously: one with batteries thermally bonded to the heater using the graphite-resin compound, and one without any thermal interface material (right and left units in Fig. 3, respec-

TABLE I: TVCT parameters of standards versus study cases.

	ECSS-E-ST-10-03C	GSFC-STD-7000B	First Test Campaign	Second Test Campaign
Temperature Tolerance	$\pm 4\,^{\circ}\mathrm{C}$	$\pm 2\,^{\circ}\mathrm{C}$	$\pm 4\,^{\circ}\mathrm{C}$	$\pm 4\,^{\circ}\mathrm{C}$
Pressure Tolerance	$\pm 80\,\%$	$\pm 80\,\%$	$\pm 80\,\%$	$\pm 80\,\%$
Chamber pressure	$\leq 1 \times 10^{-5}\,\mathrm{mbar}$	$\leq 1.33 \times 10^{-5}\,\mathrm{mbar}$	$1 \times 10^{-5}\,\mathrm{mbar}$	$1 \times 10^{-5}\,\mathrm{mbar}$
Number of cycles	4	4	3	6

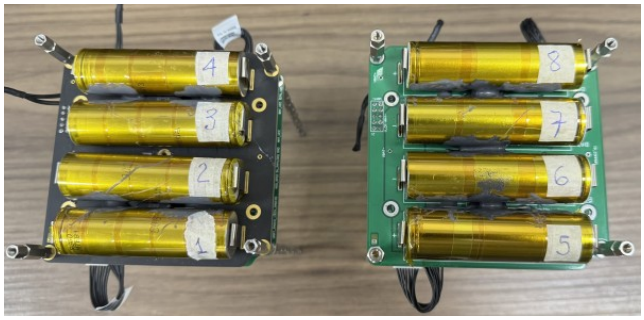


Fig. 3: Battery boards used during TVCT testing.

tively). Another noteworthy observation is the placement of the heaters: in one EPS model, they were located between batteries 1–2 and 3–4, while in the other, they were positioned between batteries 5–6 and 7–8, as shown in Fig. 3. In this campaign, only the heaters located between batteries 3–4 and 7–8 were intentionally activated to enable a comparative assessment of the thermal interface under active and passive heating conditions. Additionally, several unpowered printed circuit boards with varying application methods and conformal coating thicknesses were placed in the chamber to assess coating adhesion and cracking susceptibility (see Fig. 4). No external power emulation was required, as all units remained unpowered during the test.

Temperature measurements were obtained using both the onboard RTDs integrated into the EPS2 units and external thermocouples attached directly to the surface of each battery. This dual-sensor approach enabled a direct comparison of the thermal response with and without the graphite-resin interface, allowing for an assessment of its actual contribution to thermal coupling during cycling. The intended thermal-vacuum profile comprised six full cycles between $-20\,^{\circ}\mathrm{C}$ and $50\,^{\circ}\mathrm{C}$ (with tolerances of $\pm 4\,^{\circ}\mathrm{C}$), with $10\,\mathrm{min}$ dwells at each temperature plateau and a stabilization criteria of $1\,^{\circ}\mathrm{C}/10\,\mathrm{min}$. The test was to be conducted under stable vacuum conditions below 1×10^{-5}mbar (with a tolerance of $\pm 80\,\%$) throughout its duration. The increased number of cycles and reduced dwell time were chosen to emphasize mechanical stress from thermal expansion and contraction, rather than long-term thermal exposure.

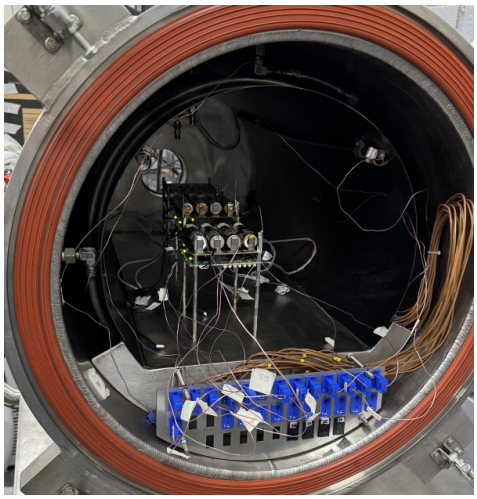
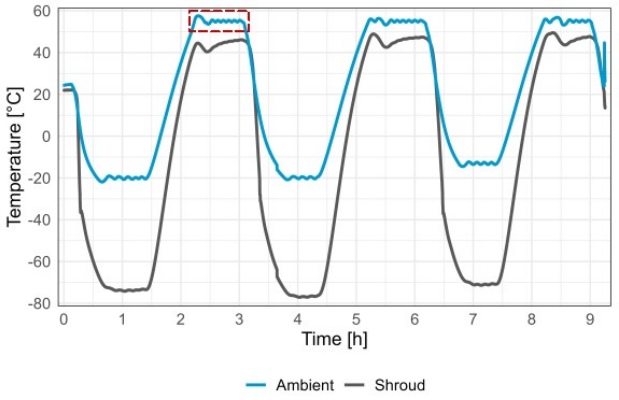


Fig. 4: Test setup mounted inside the TVAC.

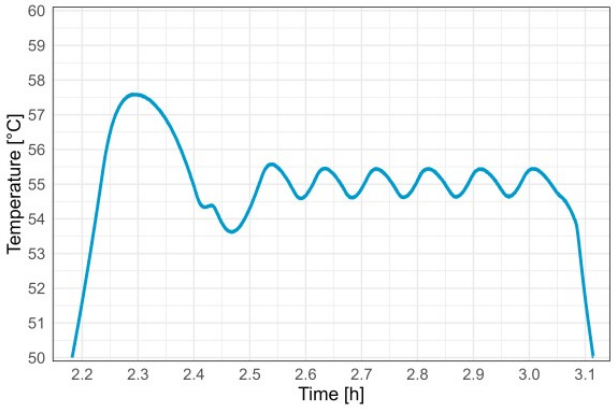
V. Results and Discussions

A. First Test Campaign: Open-Source EPSs

The proposed TVCT procedure was successfully executed during the first test campaign, in which all three planned cycles were fully completed, as shown in Fig. 5a. The hot plateaus stabilized at a mean ambient temperature of $55\,^{\circ}\mathrm{C}$, while the cold plateaus reached $-20\,^{\circ}\mathrm{C}$ in the first two cycles and $-13\,^{\circ}\mathrm{C}$ in the last, given that the nitrogen tank was already at $30\,\%$ of its total capacity by the final cycle. This unexpected lack of nitrogen at the final plateau can be justified by the manual opening of the tank, which allows more discharge of nitrogen than necessary. As illustrated in Fig. 5b, a zoomed view of the first hot plateau, only the first temperature oscillation needed to be excluded. This change in the procedure was extended to all other plateaus, and subsequent stability allowed clear determination of both



(a)



(b)

Fig. 5: First test campaign temperature profile: (a) Shroud and ambient, full test; (b) Zoom in (red region) on the first hot plateau of the ambient.

stabilization and dwell periods. Hot plateaus maintained a mean variation of $1.1\,^{\circ}\mathrm{C}$ along $30.8\,\mathrm{min}$, and cold plateaus showed $1.2\,^{\circ}\mathrm{C}$ along $27.8\,\mathrm{min}$ each, satisfying the specified stabilization criteria ($1\,^{\circ}\mathrm{C}/10\,\mathrm{min}$) and dwell period ($30\,\mathrm{min}$) requirements.

The requested stable vacuum condition was partially satisfied, with different vacuum levels for the hot and for the cold stages: approximately 5×10^{-2}mbar and 3×10^{-5}mbar, respectively. This discrepancy, which directly affects the tolerance established, stems from increased outgassing at elevated temperatures, hindering stable high-vacuum maintenance, a well-documented phenomenon in thermal-vacuum testing [1]. Furthermore, signal instability was observed in the thermocouple feedthroughs: partial communication loss occurred with the EPS2 during the test (Fig. 6), and the temperature reading from the thermocouple attached to the RE^{2}PS was lost entirely. Nevertheless, functional tests conducted before and after the thermal-vacuum cycle confirmed full operability of both units. Additionally, continuous telemetry from the RE^{2}PS was maintained throughout the test, and no anomalies (such as abrupt current drops or unexpected shifts in power consumption) were observed in the external power supplies feeding the EPSs. This indicates that neither unit experienced functional failure during the test, supporting the conclusion that both EPSs operated reliably under thermal-vacuum stress.

Overall, the test validated the PID-based thermal control strategy and confirmed that the chamber can reproduce representative orbital thermal profiles for subsystem-level screening. Although the final cold plateau fell short of the target due to nitrogen limitations, this highlights a practical constraint rather than a methodological flaw. Upgrading to an automated nitrogen valve could mitigate waste and extend cold-phase duration. Similarly, while vacuum levels deviated from the standards, they remained stable within each phase. They were sufficient to stress-test EPSs components under relevant conditions, rendering costly pump upgrades unnecessary for preliminary campaigns. Future iterations will benefit from dedicated signal feedthroughs and improved thermocouple interfaces to enhance data reliability during thermal-vacuum cycling.

B. Second Test Campaign: Heater Operation and Coating Integrity

The TVCT conducted during the second test campaign (Fig. 7) presented deviations from the requested thermal profile and highlighted infrastructural limitations. The main discrepancies were related to the number of completed cycles and to the ambient mean temperature and stabilization criteria during the cold stage. The number of requested cycles posed a challenge from the outset, as previous TVCTs performed at LARS using a single liquid nitrogen tank were limited to three cycles. Completing additional cycles would require a second nitrogen tank to support the latter portion of the test. The cold stage struggled to reach the required setpoints due to a reduced liquid nitrogen load, approximately $20\,\mathrm{L}$ less than in the first campaign, and an operational issue during the first cold slope. In this campaign, a nitrogen outlet hose with a larger diameter led to excessive nitrogen flow, further depleting the available supply. After this issue was identified, the hose was replaced with the same model used in the first test campaign. To mitigate nitrogen consumption, the cold setpoints were adjusted to $-9.5\,^{\circ}\mathrm{C}$ for the first plateau and $-11\,^{\circ}\mathrm{C}$ for the subsequent two. During the plateaus, the nitrogen valve remained fully closed, and the PID controller remained inactive. Despite these adjustments, the setpoints were sufficiently low to stress the components thermally, and the ambient temperature naturally decelerated and stabilized, with a mean variation of $1.3\,^{\circ}\mathrm{C}$ over $16.7\,\mathrm{min}$.

Although deviations were observed during the cold stage, the ambient mean temperature during the hot plateaus reached the required $50\,^{\circ}\mathrm{C}$, with a mean variation below $1\,^{\circ}\mathrm{C}$ over approximately $13.0\,\mathrm{min}$, fulfilling both the stabilization criteria and the dwell period. The vacuum performance was identical to that observed in the first test campaign, indicating that it is inherent to the TVAC system and the vacuum pumps employed rather than to the specific test procedure. During the

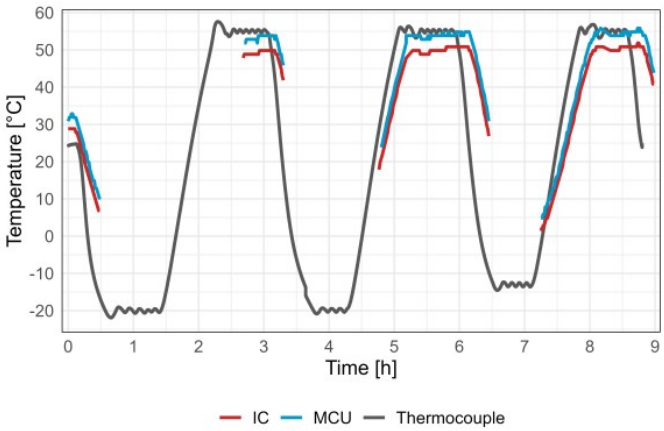


Fig. 6: Communication loss with EPS2.

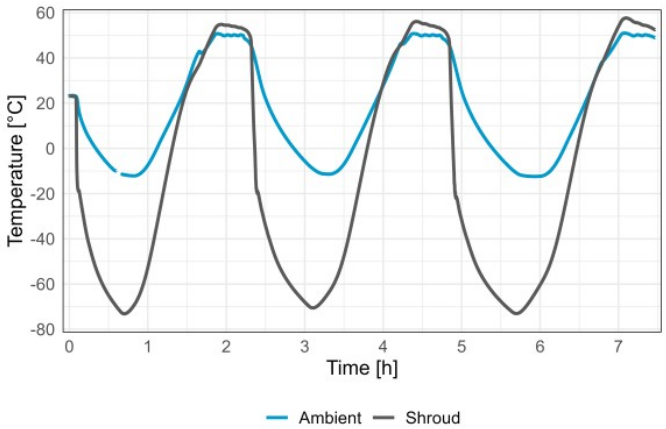
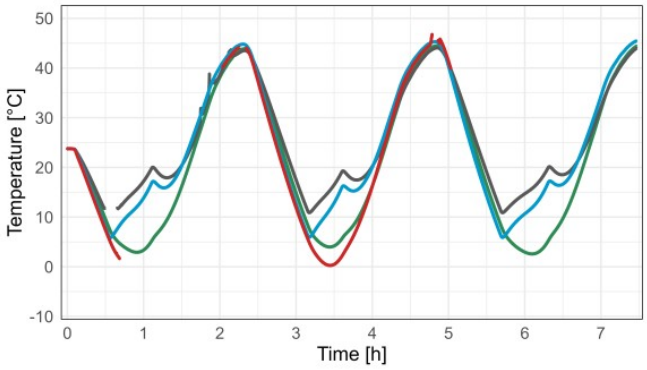


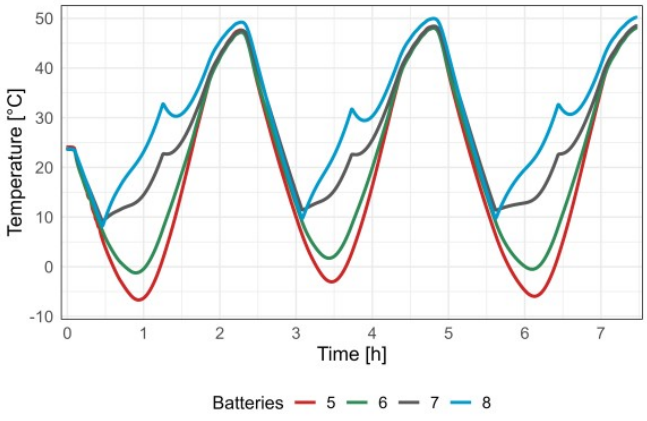
Fig. 7: Temperature profile of shroud and ambient of second test campaign.

second test campaign, no communication losses were observed in either EPS2 unit. This allowed comparison of onboard telemetry with temperature measurements from the chamber thermocouples, enabling analysis of the thermal behavior of battery assemblies with and without the graphite–epoxy thermal interface.

As shown in Fig. 8a and Fig. 8b, only the heaters located between batteries 3–4 and 7–8 were activated during the test, while the remaining heaters remained off. This selective activation strategy enabled evaluation of thermal interface performance under both active heating and purely passive thermal coupling conditions. The heat generated by the activated heaters also contributed to the difficulty in maintaining well-defined cold plateaus during the TVCT, as the thermal input partially counteracted the chamber's cooling capability. When the heaters were activated, batteries thermally coupled via the graphite–epoxy compound exhibited significantly higher temperatures than those without the thermal interface. In this condition, batteries 7–8 reached temperatures of approximately $34\,^{\circ}\mathrm{C}$ and $24\,^{\circ}\mathrm{C}$, whereas batteries without the compound reached only about $20\,^{\circ}\mathrm{C}$ and $13\,^{\circ}\mathrm{C}$. This result confirms the effectiveness of the graphite–epoxy compound in enhancing heat transfer from the heaters to the batteries. However, under cold conditions without heater activation, the same batteries exhibited lower minimum temperatures, indicating greater heat transfer to adjacent components. While the compound improves thermal coupling during heating, this behavior highlights a trade-off that should be considered in future designs.



(a)



(b)

Fig. 8: Temperature profile of batteries: (a) 1-4; (b) 5-8.

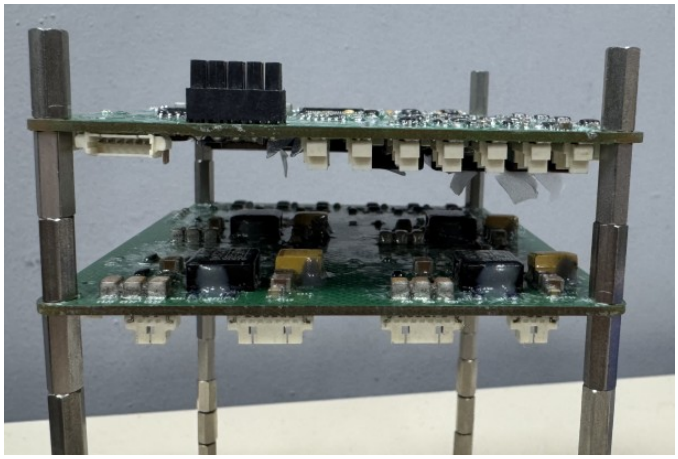


Fig. 9: Cracking and delamination of the conformal coating after thermal-vacuum cycling.

Additionally, the commercial conformal coating evaluated in this campaign performed insufficiently under thermal-vacuum cycling. As shown in Fig. 9, extensive cracking and partial delamination were observed throughout the test, indicating inadequate adhesion to the substrate. The detachment of the coating also generated loose particles on the boards, introducing contamination risks. These results demonstrate that this formulation is unsuitable for space applications and should be replaced by a more robust alternative. Overall, the second test campaign further demonstrates the viability of the TVAC chamber for subsystem-level evaluations, while revealing additional operational constraints and material-related issues that were not evident in the first campaign. These observations provide valuable insight into the setup's capabilities and current limitations, supporting its use for preliminary testing and guiding future improvements.

VI. Conclusions

This work presented a low-cost, step-by-step TVCT approach for subsystem-level evaluation of CubeSat EPSs, integrating experimental procedures, instrumentation choices, and practical constraints encountered during early development. The proposed procedure proved to be effective in exposing the studied components to the extreme conditions tested in a traditional TVCT, and in maintaining stable temperatures in all plateaus, fulfilling the required criteria. Two test campaigns were conducted using the same TVAC infrastructure, enabling both validation of the setup and comparative analysis of different design and material choices.

The challenges faced during testing were related to infrastructural and instrumentation limitations, rather than procedure

flaws. Regarding vacuum performance, the tests showed that the chamber was unable to maintain pressure levels within the tolerances typically required by applicable standards. Significant pressure variations were observed during the test campaigns, particularly during transitions between thermal phases, but with stabilization at the hot and cold plateaus. Regarding the cooling system, the tests were compromised when the last cold plateau of the first campaign and all plateaus of the second campaign could not reach the setpoint. This occurred due to the lack of nitrogen, which was triggered by the manual opening of the tank valve in both tests, and a reduced load and unnecessary waste in the second campaign. While these conditions were insufficient for strict qualification purposes, they remained stable enough to expose relevant thermal and material-related behaviors at the subsystem level.

Instrumentation-related limitations were consistently observed throughout the tests. The reuse of thermocouple feedthroughs for temperature sensing introduced contact and interface issues, affecting measurement stability. Additionally, the absence of dedicated feedthroughs for communication and sensing signals increased setup complexity and limited flexibility during testing. These aspects indicate that improvements in connector interfaces and the addition of dedicated feedthroughs for data acquisition would significantly enhance measurement reliability and repeatability. Despite these limitations, the test campaigns successfully enabled the identification of thermal behaviors, material incompatibilities, and design trade-offs relevant to early-stage development. The results support the use of the proposed TVAC setup as a practical screening tool prior to formal qualification testing, while also providing clear guidance for incremental improvements to the chamber and its instrumentation.

Future work will include the implementation of the suggested improvements to enhance the overall TVAC performance, which include, but are not limited to: acquisition of an automatic valve in the nitrogen tank to avoid unnecessary waste; purchase of a second nitrogen tank to double the number of cycles; verification that every nitrogen load is approximately 150 liters; acquisition of a cryogenic vacuum pump able to maintain the pressure level more stable throughout the test; and purchase of vacuum specialized power and temperature feedthroughs to avoid loss of signal during tests and to increase the communication channels. Furthermore, future work includes conducting TVCT with other CubeSat components and subsystems to further validate the feasibility and reproducibility of the procedure with any studied part.

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