University of Toronto Aerospace Team Space Systems Division

SS-FINCH-0020

FINCH Thermal Vacuum Testing Plan

Revision 1.1

2022-07-05

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[What we need]

[Who Supplies them]

[Where to place with respect to the satellite and TVAC chamber]1

Reviewers: *xx*

Revision History

Revision #	Changes	Date
1	First Revision of TVAC Testing Plan	2022-05-25
1.1	Added electrical and data setup Updated TVAC cycles based on ICD. Revised functional tests	2022-07-05

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1. General

1.1. Purpose

The purpose of this document is to outline the Thermal Vacuum (TVAC) Chamber Testing procedure for the FINCH remote sensing satellite mission. The plan details the high level and functional tests to be conducted within each stage of the procedure and outlines the equipment and logistics required for TVAC testing. The test is to be conducted for acceptance purposes to demonstrate satisfaction of spacecraft design and hardware with the objectives stated below.

1.2. Objectives

The test objectives are as follows:

1. The payload shall perform satisfactorily within the vacuum and thermal mission limits.
2. The thermal design and the thermal control system shall maintain the affected hardware within the established thermal limits during planned mission phases, including survival/safe-hold
3. The hardware shall withstand the temperature conditions of transportation, storage, launch, flight, and manned spaces.
4. The quality of workmanship and materials of the hardware shall be sufficient to pass thermal cycle test screening in vacuum

The information in this document complies with the testing requirements for single-unit proto-qualification testing provided by our launch provider. When encountering a TVAC test parameter that was not specified by the launch provider, the default parameter suggested by the NASA LSP-REQ-317.01 Revision B standard was used. This standard presents cubesat specific best practices derived from various other standards, most notably GSFC-STD-7000 B and MIL-STD 1540 B.

1.3. Relevant Design Overview

The TVAC Campaign concerns the operational functionality of all subsystem components. It will also monitor the satellite on a system level for any structural deformations due to heating and cooling. The thermal design of FINCH is split into three sectors: Panel Design, Payload Design, and Battery Pack Design. Note that specific materials mentioned below are not finalized.

Panel Design concerns the outward facing panels of the satellite. Perforated DE076 Multi-layer Insulation (MLI) will be used on the panels with incident solar radiation: +X, +Y, -Y, +Z, and -Z. An outer layer of DE330 MLI will then be applied on top of the DE076. The -X face does not receive direct solar radiation, therefore it does not require MLI. It will be thermally controlled using Aluminum/Kapton 100HN/3M 966 Tape. The Silver Kapton Tape provides similar performance and occupies less volume at a reduced cost.

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Payload Design concerns the thermal control of the FINCH-Eye. Assuming that no MLI will be required, the Payload should be sufficiently controlled using low emissivity tape. A critical Payload component is the FINCH-Eye imaging sensor. This has an embedded thermoelectric cooler to ensure it stays within its specified temperature range.

Battery Pack Design concerns the insulation of the batteries for the FINCH satellite. Thermo optical tape will be used to passively control the temperature of the battery pack rather than MLI insulation between bracket and batteries. Active heaters will be implemented to ensure it stays within its operating ranges.

1.4. Abbreviations

The following are common abbreviations used in this document:

TVAC: Thermal Vacuum
TBT: Thermal Balance Test
TCT: Thermal Cycling Test
OPTICS: Payload Optics Campaign
OPP Hot: Operational Hot Cycle
OPP Cold: Operational Cold Cycle
FT: Functional Test

2. Mission Requirements

The satellite must be able to withstand the hot and cold temperatures of its orbit, as well as withstanding multiple transitions between the two extremes. All structural components should show minimal evidence of deformation. All functional components should be within their non-operational ranges when not in use and within their operational ranges when in use.

2.1 Detailed Thermal and Structural Requirements

The specific non-operational and operational limits of each functional component are outlined in the thermal budget. These components must stay within their respective temperature ranges for the satellite to reliably function as intended. FINCH will require a margin of 5°C from the max and min to be maintained throughout the mission.

3. Preparation and Logistics

This information provided in this section assumes that we are using the MDA TVAC Chamber and we are interfacing with Side 1. This is subject to change.

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3.1. Data Measurement Logistics

3.2. Electrical Component and Data Recording Set-up

The MDA TVAC Chamber Side 1 interface is depicted in figure 2 (exterior) and figure 3 (interior). It consists of 4 9-pin D-sub interfaces and 1 50-pin D-sub interface.

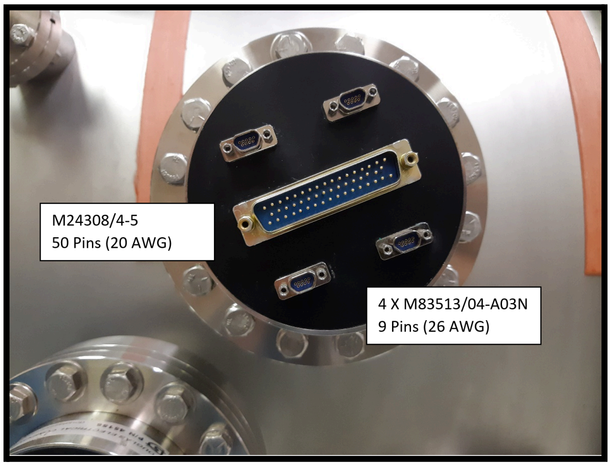

Figure 1: MDA Outer TVAC Interface

Figure 2: MDA Inner TVAC Interface

The connection on FINCH is XXX which must be converted into the D-sub. All signal paths and power paths from FINCH will be transformed into a XXX-pin D-sub using a wire harness. Figure X should be consulted when setting up the circuitry for the TVAC Chamber. This depiction is only meant to illustrate the connections between components, not represent the physical location each component should be relative to another.

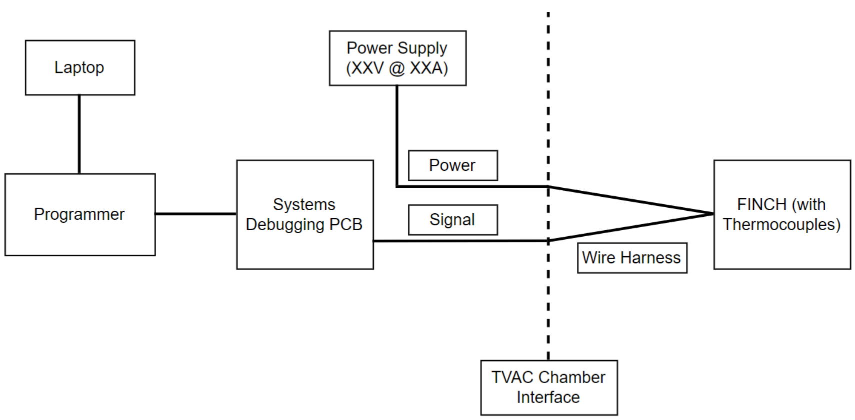

Figure 3: TVAC Electrical Setup

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The setup procedure is detailed below. Note that this procedure and the diagram above assumes that we are externally powering the satellite by feeding power through the TVAC chamber interface.

Connect the MDA provided thermocouples to the predetermined locations on FINCH.

1. Connect the wire harness to the [FINCH's CONNECTOR TYPE] on FINCH.
2. Connect the power path to the inner XXX-pin D-sub TVAC Chamber interface.
3. Connect the signal path to the inner XXX-pin D-sub TVAC Chamber interface.
4. Connect the outer XXX-pin D-sub TVAC Chamber interface to the power supply set to XXXV with a XXXA current limit using a XXX connector.
5. Connect the outer XXX-pin D-sub TVAC Chamber interface to the Systems Debugger PCB using a XXX connector.
6. Connect the programmer to the System debugging PCB using a XXX connector.
7. Connect the programmer to a laptop using a micro-USB to USB connector.

3.3. Spacecraft Preparation

3.3.1. Cleaning Standard

[Direct to proper cleaning document once created]

3.3.2. Bakeout

[Direct to proper bakeout document once created]

3.3.3 Thermocouple Placement

[Write and attach a diagram of where thermocouples are to be placed]

3.3.4 Physical TVAC Chamber Setup

[Write and attach a diagram of how FINCH will be mounted inside the TVAC Chamber. Options to consider: (1) suspending FINCH with wires from the chamber ceiling or (2) using a mechanical mount on the ground with little contact area]

4. Test Descriptions

The following section outlines the TVAC test parameters used for testing. It also details the tests which will take place during the TVAC campaign.

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4.1 Overview of Test Parameters

The following table outlines the test parameters used in the campaign, along with their tolerances.

Parameter	Value (with Tolerance)
Operational Hot Temperature	66˚C (+ 2˚C)
Operational Cold Temperature	-29˚C (- 2˚C)
Non-Operational Hot Temperature	75˚C (+ 2˚C)
Non-Operational Cold Temperature	-40˚C (- 2˚C)
Plateau Dwell Time	1 hour
Ramp Rate	2.5˚C/min (± 0.1˚C)

Table 1: TVAC Test Parameters

The ramp rate was chosen based on FINCH's orbital period (2.5˚C/min is representative of the time FINCH spends in the Earth's eclipse and in the Sun's rays). All other parameters were chosen based on launch provider requirements and the standards mentioned in section 1.

4.2 Thermal Balance

The thermal balance test is a non-operational test and will be the first test to take place within the TVAC chamber. It will use the temperature ranges detailed above, but will include a prolonged plateau of 3 hrs for both the hot and cold soak, resulting in a total dwell time of 6 hrs. The thermal balance test has 3 main goals:

1. Expose the spacecraft to prolonged hot temperatures before TVAC testing begins. This acts as a secondary form of bakeout.
2. Verify the adequacy of the thermal control system during prolonged exposure to the maximum and minimum temperature
3. Validate and correlate the mathematical thermal model to actual spacecraft response so we can better model the behavior of the spacecraft

4.3 Thermal Cycling

Thermal Cycling will occur right after thermal balance testing. Cycling between temperature extremes has the purpose of checking performance through functional testing during both stabilized conditions and transitions. Transitions cause temperature gradient shifts inducing stresses which can help uncover workmanship errors. The cycles will follow the general maximum, minimum, and dwell time parameters detailed above.

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4.3.1. Non-operational Cycles

FINCH will undergo 1 non-operational cycle at the beginning of the thermal cycling test. This serves as a means to ensure any abnormal temperature fluctuations will not cause FINCH's hardware to fail. The maximum temperature of the hot cycle will be +75˚C and the minimum temperature of the cold cycle will be -40˚C, these temperature margins satisfy the acceptance testing standards and are unrelated to orbital parameters.

4.3.2. Operational Cycles

Following the non-operational cycle, FINCH will undergo 6 operational cycles. These cycles ensure that FINCH is able to operate adequately in its orbit environment. 4 operational cycles will contain various functional tests, outlined in Section 4.4. These cycles will follow the general maximum, minimum, and dwell time parameters detailed above. The remaining 2 operational cycles will be dedicated to payload verification (see Section 5), which will not follow the general parameters detailed above.

4.4. Functional Tests

Functional tests will be run throughout the operational cycles. Each functional test is categorized into one or more groups. A group being tested means that each of the functional tests inside it are conducted, in the order they are presented in the table (i.e. For the Start Group, EPS-OBC Start Demonstrations would happen before Telemetry Data Packaging, since it is higher in the table). The tests and groups are outlined in the table below.

Test Name	Group	Description	Phase
EPS-OBC Start Demonstrations	Start	Start-up capability will be demonstrated to verify that the satellite will turn on after exposure to the extreme temperatures that may occur in orbit.	OPP Hot OPP Cold
Telemetry Data Packaging	Start	Verify that data can be exchanged between the OBC MCU and the RF MCU	OPP Hot OPP Cold
Subsystem Power On	Start	A check is performed (via physical wires) to confirm all essential loads (EPS, ADCS, PAY, OBC, etc.) are turned on upon power ON of the spacecraft [2]	OPP Hot OPP Cold
Thermal Data Stream	Data	Obtain data from thermal sensors	OPP Hot OPP Cold
ADCS Data Stream	Data	Obtain data from the ADCS sun sensors, IMU, and other measurement devices	OPP Hot OPP Cold
Payload Data	Data	Obtain data from the payload sensors (e.g.	OPP Hot

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Stream		Imaging Sensor)	OPP Cold
Imaging Test	Imaging	Take an image with the FINCH Eye to confirm its functionality at various temperatures	OPP Hot OPP Cold Transitions
Payload TEC	Imaging Hot	Verify the ability of the TEC to bring the FINCH Eye to its imaging temperature ranges	OPP Hot Transitions
ADCS Guidance Algorithm Test	Hot	Run ADCS guidance algorithms using fictitious data and assess temperature increase	OPP Hot
Antenna and Imaging Sensor mixed test	Hot	Verify that thermal control can be maintained when the antenna and imaging sensor are both actively operating (most heat on FINCH generated from these)	OPP Hot
Immediate Compression	Fast Compress	Immediately fully compress the image taken in the imaging functional test to confirm compression functionality	OPP Hot OPP Cold Transitions
Unit Compression	Unit Compress	Fully compress image after a certain amount of time has passed since imaging	Transition
Split Compression	Split Compress	Verify the ability of the compression algorithm to pick up and complete an unfinished compression	OPP Hot OPP Cold Transitions
Image Data Packaging	Fast/Unit /Split Compress	Check if compressed data is successfully loaded on the FPGA (Data Path is as follows: Pay MCU → RF MCU → RF MEM → RF MCU → FPGA)	OPP Hot OPP Cold Transitions
TVAC Temperature Sensors	—	Read all temperature sensors to ensure hardware is within allowable/operational limits	Constant
Safe Mode	—	Manually force the satellite into safe-mode and verify its ability to recover from the safe state	1 cycle

Table 2: Functional Tests to be Conducted

5. Payload Verification Plan

The payload verification plan will take place during 2 operational cycles as shown in Figure 1. The OPTICS phase of the plan will range from a set temperature of -30˚C to +65˚C. Following subsystem TVAC recommendations from the NASA-GFSC-7000 standard, the temperatures will be subject to a 10˚C margin, making the actual range -40˚C to +75˚C. Dark noise testing will be

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completed between 5˚C and 30˚C within each cycle, at 5˚C increments. The testing procedure is described previously in detail in SS-FINCH-0010 Payload Verification Plan, and it is the recommended reference for further information.

6. Detailed Testing Procedure

6.1. Prior to Entering TVAC Chamber

Assuming that the satellite is already fully assembled and bakeout has taken place, these are the actions that must occur before the TVAC chamber is closed and depressurized.

1. The satellite must be weighed prior to attaching any external data collecting equipment
2. Thermocouples must be attached at the positions described in section 3.3.3
3. All electrical and data collecting equipment is setup as described in section 3.1
4. The satellite is powered on and all functional tests are run to ensure everything is nominal
5. The satellite is place on the baseplate which will act as the control temperature
6. The satellite is placed inside the TVAC chamber as described in section 3.3.4

6.2. Pre-Test Procedure

Once the satellite is sealed inside the TVAC Chamber, the following steps shall occur:

1. The TVAC chamber will be depressurized to a pressure no greater than 10^{-5} torr
2. Once fully depressurized, another full set of functional tests shall be run to ensure depressurization did not damage any components and that data is being received
3. The satellite shall be powered off to start the TVAC order of operations

6.3. Order of Operations in TVAC Chamber

Table 1 outlines the exact order of operations required from the TVAC operator to perform the test, along with expected durations. This test has been designed under the assumption that we are using the MDA Brampton TVAC chamber. The dwell plateaus begin once the control temperature is within 2°C of the set temperature. For example, steps 4 and 5 would look as follows:

1. Set chamber temperature to 75°C
2. Wait until control temperature is within 2°C of 75°C
3. Wait 0.5 hour
4. At the completion of 1 hour, set the chamber temperature to -40°C
5. Wait until control temperature is within 2°C of -40°C
6. Wait 0.5 hour

Step #	Description	Set Point	Plateau Duration

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001	Ambient Initial	21˚C	0.5 hr
002	TBT Hot Soak	66°C	3 hr
003	TBT Cold Soak	-29°C	3 hr
004	Non-OPP Hot	75°C	0.5 hr
005	Non-OPP Cold	-40°C	0.5 hr
006 - 013	4 OPP Hot and Cold Cycles	66°C and -29°C	14 hrs
014 - 15	OPTICS	Various	3.8 hr (entire time)
016	Ambient Final	21˚C	0.5 hr

Table 3: TVAC Order of Operations (durations do not include transition time)

The total minimum time the TVAC campaign will take, including transition times, is estimated to be 1642.2 minutes (27.37 hrs or 1.14 days). The actual duration will be greater than this due to waiting for the control temperature to reach within 2°C of the max and min temperatures (may take a few extra hours) and waiting for the vacuum to pump down (may take several hours to days).

The test plan profile of the different phases and functional tests is presented below. Note that two identical TCT-OPTICS sections follow the TBT and Non-Operational cycles. A larger, detailed image of one of the TCT-OPTICS sections is shown as well.

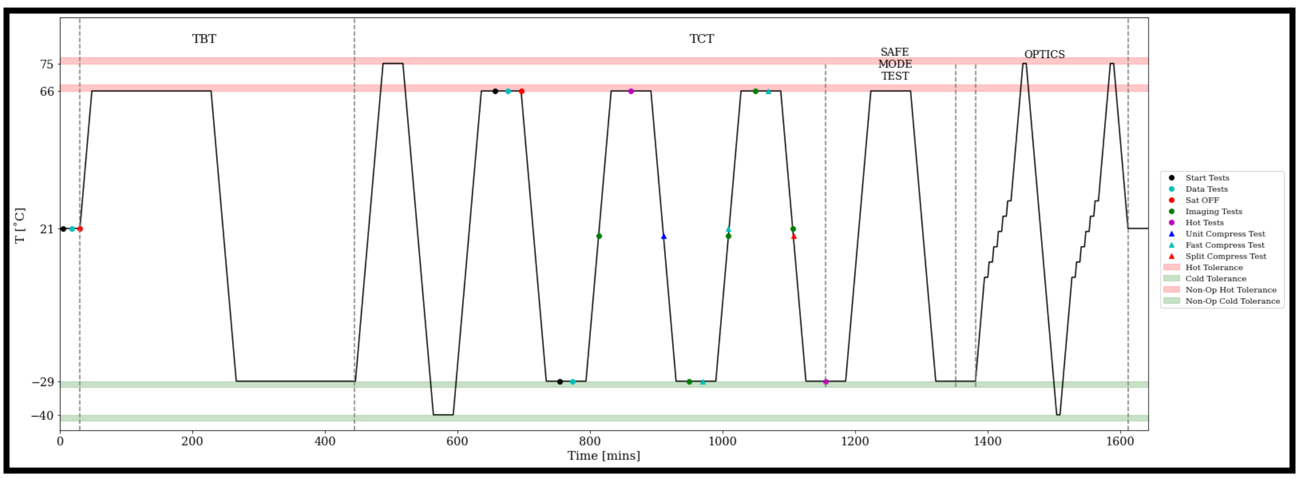

Figure 4: Test profile with the different phases and functional tests identified

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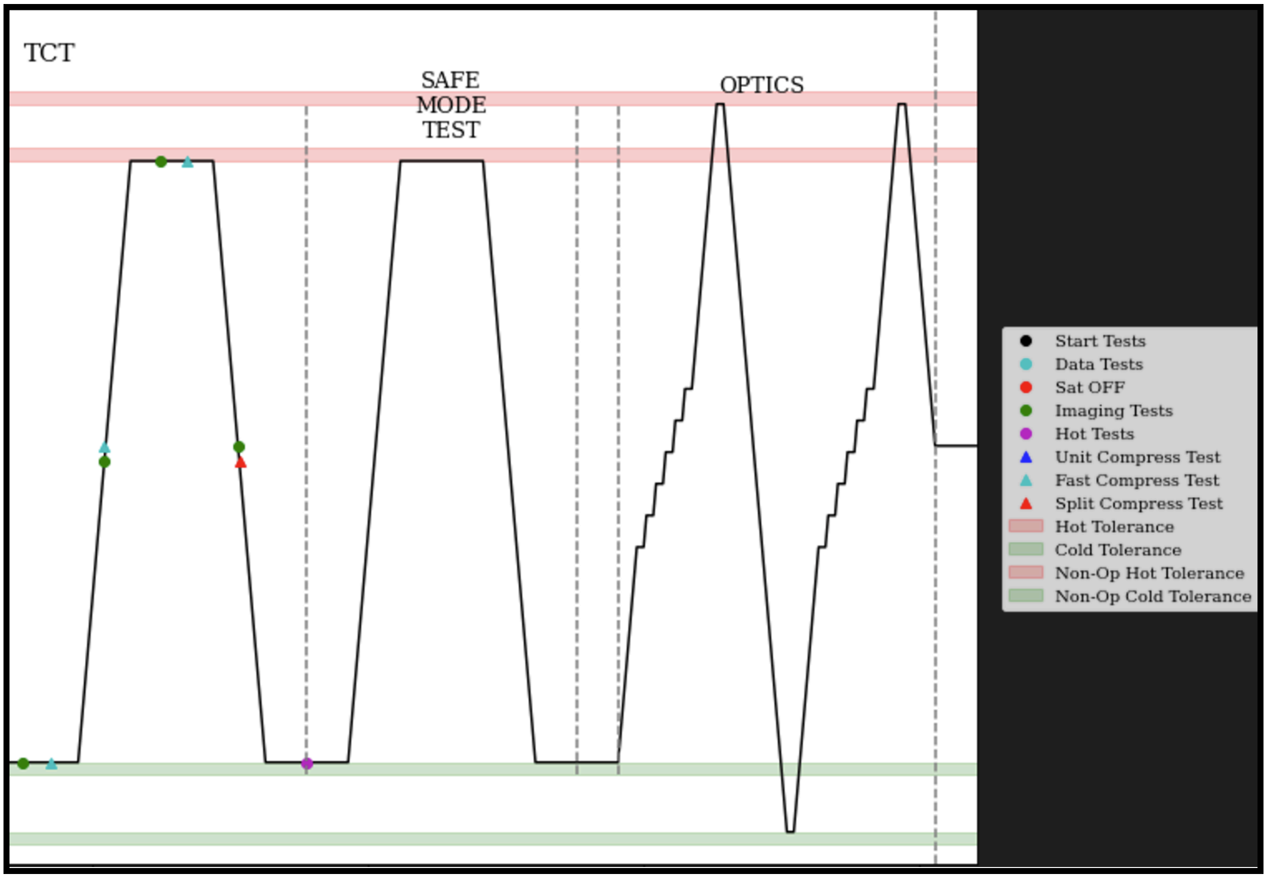

Figure 5: Detailed TCT-OPTICS Section

Below is a description of the symbols used in the legend:

Black Circle - Start Tests; All FTs in the ‘Start’ group are executed
Cyan Circle - Data Tests; All FTs in the ‘Data’ group are executed
Red Circle - Sat OFF; The satellite is turned in preparation for a future test
Green Circle - Imaging Tests; All FTs in the ‘Imaging’ are executed
Purple Circle - Hot Tests; All FTs in the ‘Hot’ group are executed
Blue Triangle - Unit Compress Test; All FTs in the ‘Unit Compress’ group are executed
Cyan Triangle - Fast Compress Test; All FTs in the ‘Fast Compress’ group are executed
Red Triangle - Split Compress Test; All FTs in the ‘Split Compress’ group are executed
Red Region - Hot Tolerance; Represents the +2˚C hot tolerance
Green Region - Cold Tolerance; Represents the -2˚C cold tolerance

Once the cycling tests have concluded and the satellite has reached an ambient temperature of 21°C ± 2°C, the chamber can be repressurized to the outside pressure.

6.4. Post TVAC Chamber Operation

Once the chamber is pressurized and the chamber seal is unlocked, the following shall occur.

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1. The satellite shall be removed from the TVAC Chamber
2. All external data recording devices attached to the satellite shall be removed
3. All structural components should be thoroughly checked and any detectable damage should be noted
4. The satellite shall be weighed

The TVAC campaign is now over.

6.5. Failure Conditions and Contingency Plan

The TVAC test will be considered a failure if the satellite is unable to meet all objectives delineated in Section 1.2 of this document. In particular, the test will be a failure if any of the following occur:

- There is significant structural damage due to thermal stresses (cracks, breaks, etc.)
- There is an evident failure on the system or subsystem level
- The satellite was unable to successfully complete all functional tests
- The thermal control was unable to maintain the correct temperatures at any given time

Section 6.5.2 details the procedure to be followed in any of these instances.

If none of the above failure modes occur, then the spacecraft has successfully completed the TVAC campaign.

6.5.1 Other TVAC Blockers

The TVAC test may need to be paused or postponed due to reasons aside from satellite failure. These can be categorized into the following:

1. Cleanliness: The satellite must undergo bakeout before TVAC. If the satellite has not been baked out or it contains substances that could potentially contaminate the TVAC chamber during the test, then TVAC must be postponed until the satellite has been thoroughly cleaned.
2. Connection issues: This includes, but is not limited to, loose bolts, soldering defects, and faulty wiring.
3. Ground support equipment failure: This refers to any failure related to harnessing, debugging, and data collection equipment.

6.5.2 Failure Response

In the event of failure or a blocker to TVAC:

1. Stop the test. The satellite shall be examined to determine the nature of the failure or blocker and which component was the cause of this. This includes determining at which point of the TVAC test did the failure occur and distinguishing if it is a mechanical or programming concern.

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2. Address the source of the failure.
    a. If there is a physical failure on the satellite (i.e., one of the failure modes outlined in Section 6.5 occur or there are cleanliness or connection issues), take it out from the chamber and repair or replace the necessary component.
    b. If there is a programming failure on the satellite, stop any running programs and analyze/debug them.
    c. If there is a ground support failure, fix or replace the connections.
3. Restart TVAC. Depending on the severity of the failure and the response required, TVAC may be restarted on the same day or a few days after. Especially if components are replaced, it is important to conduct the test again from the beginning to determine if the satellite meets all the objectives of TVAC.

7. References

[1] Perl, E. (2006). Test Requirements for Launch, Upper-Stage, and Space Vehicles. Test Requirements for Launch, Upper-Stage, and Space Vehicles

[2] Dunwoody, R. (2022). Thermal Vacuum Test Campaign of the EIRSAT-1 Engineering Qualification Model. Aerospace | Free Full-Text | Thermal Vacuum Test Campaign of the EIRSAT-1 Engineering Qualification Model | HTML (mdpi.com)

[3] Kubicka, M. (2022). Thermal Vacuum Tests for the ESA's OPS-SAT Mission. Thermal vacuum tests for the ESA's OPS-SAT mission | SpringerLink

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