Method for CubeSat Thermal-Vacuum Cycling Test Specification

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The CubeSat is a type of a small satellite developed for specific missions: space science, communications, technology validation, earth observation, military applications, and others. To survive the harsh launch and space environments, the CubeSats shall pass through a series of tests such as vibration, thermal-vacuum cycling test, bakeout and visual inspection. Usually for CubeSat missions, reliability is regarded as low priority and most of tests are specified just for launch vehicle requirements attendance. The authors' bibliographic review showed a lack of information about how to specify CubeSats tests. This paper focuses on thermal-vacuum cycling test. This test is necessary to evaluate the satellite survivability under the thermal environment and verify the absence of workmanship errors and materials defects. Specifically, the objective of this paper is to bring to the CubeSat community a method to establish comprehensive and coherent thermal-vacuum specifications. The use of this method aims to increase CubeSat systems reliability and therefore mission success

Nomenclature

EVS	=	environmental specifications
CDS	=	cubesat design specification
P-POD	=	poly picosatellite orbital deployer
TBT	=	thermal balance test
TCT	=	thermal cycle test
TVCT	=	thermal vacuum cycling test
TRP	=	temperature reference point

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I. Introduction

NOWADAYS for most CubeSat projects reliability is regarded as low priority, and testing is done mainly for launch requirements attendance. For that reason, and usually to save costs and time, many projects do not perform an appropriate test program, which would identify potential in-orbit failures.

One of the important environmental tests that CubeSat test programs should consider is the thermal-vacuum cycling test (TVCT.). This test simulates the expected pressure and temperature variations experienced by the CubeSat during its mission.

To run a TVCT, test operators need a complete set of test specifications. To develop such specifications, CubeSat projects usually choose the same specifications of previous CubeSats with similar orbital parameters. Other CubeSat projects use, without the proper tailoring or analysis, very generic specifications that could lead to a simulation not representative of the real expected environment.

This work aims to propose a method to develop a complete set of TVCT specifications, while showing the sources of information and their relationship required to produce such specifications.

The method uses information from sources, such as standards and CubeSat design documents, as inputs to perform activities that lead to a complete set of typical TVCT specifications items.

The method herein proposed does not comprehend the use of sun-simulators nor other class of satellites than CubeSats. Additionally, the scope of this work is only related to TVCT, therefore it does not consider how to produce thermal balance test (TBT) specifications or bake-out procedure specifications, which are as well of great importance for nanosatellite programs. (This method should not be use for TBT specification, because the TBT is a test executed for verification to performance of thermal control inherent of each CubeSat.) The next sections of this work are structured as follows: Section 2 describes typical satellite testing characteristics, such as testing sequence, test models, and model philosophy. Section 3 describes the TVCT, highlighting its objectives and the rules and standards that regulate the TVCT for general spacecraft and CubeSats. Then, this section provides more details on CubeSats TVTC about the equipment that is used, how is the test execution procedure, and the typical items that a TVCT specifications consists of. Section 4 describes how is a CubeSat thermal vacuum cycling test. Section 5

describes the proposed method to develop a complete set of TVCT specifications for CubeSats. Section 6 states some conclusions of this work. In the Finally section, shows the references that were used to produce this work.

II. Satellite Testing

A. Typical Sequence in a Test Program

A Typical tests sequence is established by considering first the tests that are most likely to cause the small satellite to be disassembled if a malfunction occurs. Environmental tests are performed last and follow the sequence of the environments that the small satellite would experience during its flight to orbit. This sequence is referred as "Test as you fly" and consists on performing environmental tests in the following order: vibration, acoustic and thermal vacuum tests. This sequence also helps to identify vibration and/or acoustic problems that are only revealed after further thermal stresses. [1-2]

Aforementioned factors are the reason of performing thermal vacuum tests at the end of test campaign, only followed by a final functional test for ensuring that the small satellite is still working properly. Figure 1 illustrates a typical satellite test sequence.

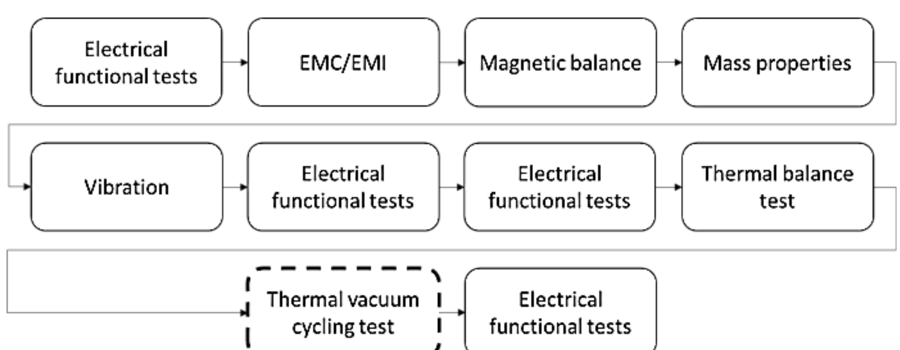

Figure 1. Typical Test Sequence. Adapted [3]

B. Test Models and Model Philosophy

Test is one of the requirement verification methods. Thus, being part of the verification, it can also be realized in different development stages along the project life cycle: qualification, acceptance, pre-launch, and in-orbit; in different levels: equipment, subsystem, element, segment or overall system; and in different models: engineering, structural, thermal, qualification, flight, protoflight and others. [4]

Test Models

The most used test models in spacecraft projects are described below. [3]

- Structural Model (SM): Used for mechanical design validation;
- Thermal Model (TM): Used for thermal design validation;
- Radio-electric Model (RM): Used for radio-frequency design validation;
- Engineering Model (EM): Used for electrical design validation;
- Qualification Model (QM): Used for qualification level testing;
- Flight Model (FM): Model that will be launched. It is tested at acceptance levels.
- Protofligh Model (PFM): Flight model on which a partial or complete protoflight qualification test campaign is performed before flight.

The use of a model with more than one purpose is a recurring approach between nanosatellite projects in order to reduce cost and schedule. It is common, for example, the union of engineering and qualification models (EQM).

Model Philosophy

Model philosophy is selected by defining the optimum number and type of physical models. This definition takes into consideration the confidence in the product verification, schedule, costs and risks.[1]

The Design verification is carried out on flight representative models (e.g. prototype models). The workmanship verification (acceptance main objective) is carried out on the final products (e.g. flight models, and spares).[1]

According to the European standard ECSS, there are three basic options of model philosophy in space programs[4-5]:

- *Prototype Approach:* Qualification testing conducted on Qualification Model (QM) with qualification levels and duration. Acceptance testing conducted on Flight Model (FM) with acceptance levels and duration.
- *Protoflight Approach:* Qualification testing conducted on the same model to be flown (PFT), generally with qualification levels and reduced duration (acceptance).
- *Hybrid Approach:* This approach refers to a mix of the previous two model philosophies.

III. Thermal Tests

A. Thermal Tests

Several types of thermal tests are required for development, performance validation and to ensure the survivability of the satellite in operation. This tests can be performed in components, subsystems and systems levels. The thermal testing usually includes a Thermal Cycle Test (TCT), Thermal Vacuum Cycling Test (TVCT), Thermal Balance Test (TBT), and Bake-out test.

Thermal Cycle Test (TCT): Is generally executed in ambient pressure through the use of environmental chambers. This test is usually executed to subsystem or system level. The test article will be exposed to a series of cycles of hot and cold temperatures. The thermal cycling generate an environmental stress in the test article that allows to identify material and workmanship defects.

Thermal Vacuum Cycling Test (TVCT): This test subjects the test article to a series of cycles of hot and cold temperatures in a high vacuum environment. Space simulation chambers and thermal vacuum chambers are used to perform this type of test. This test is executed to subsystem or system level. During the development of TVCT, are performed functional tests for the performance verification of the subsystem or system.

Thermal Balance Test (TBT): Space simulation chambers and thermal vacuum chambers are used to perform this type of test. The purpose of the test is: Demonstrate the performance of the thermal control system to maintain the temperatures within the operational limits.

Verify the performance of the satellite thermal design when it is exposed the space thermal environment conditions. This test is also used to measure the thermal deformations in the system.

The TBT and TVCT are used to demonstrate the capability of the subsystem or system to tolerate the consequences of the continuous thermal cycling during operation in the space environment. The selection of number of thermal cycles in TBT and TVCT depend of the type of test level.

Bake-out Test: The test article is exposed a high temperature in a high vacuum environment during a determined time for to estimulate their outgassing. This test is executed to subsystem or system levels. Thermal vacuum chambers are used to perform this type of test. In the case of the cubesats, Bake -out test is executed for fulfill a requierement established to launch. The Bake-out test requirements are usually come from the launch provider.

B. Test Levels

The thermal tests are performed at various temperature levels in a each test levels. The test levels are : Development Tests, Qualification Tests, Acceptance Tests, and Protoflight Qualification Tests.

Development Tests: Also known as engineering tests, are performed to obtain information about the design of the system and reducing the risk in moment of their fabrication. The requirements of this test not specified in military or commercial standards.

Qualification Tests: In this test, the system or subsystems are tested at higher temperature levels than experienced in a mission. This test usually reveals design flaws in the system. The qualification test serve to verification of the hardware design and the manufacturing process. The subsystem or system using in this test is not considered for the flight.

Acceptance Tests: The temperatures levels of the acceptance test are established through the thermal model of the system. The thermal conditions in this type of test is less severe than qualification test. The acceptance test serve to performance verification of the system and workmanship. This test is perform after the qualification tests. The thermal conditions in this type of test is less severe than qualification test . It is performed under environment conditions no more severe than those experienced by the subsystem or system in it mission.

Protoflight Qualification Tests: The temperature levels experienced by the satellite in durance the development of this test are generally in between the temperature levels of qualification and acceptance test.

C. General Rules and Standards

Next we describe the general rules and standards available to determine the temperature and pressure levels of thermal tests, considering the type test level.

GSFC-STD-7000. [6]

The GSFC-STD-7000 provides requirements for performing environmental verification. It intends to demonstrate by test or analysis the satisfactory performance of hardware in the expected mission environment, and that minimum workmanship standards have been met. This standard applies to spacecraft, subsystems, and components to be launched on expendable launch vehicles (ELVs). This standard states that thermal-vacuum test is required for any spacecraft in order to demonstrate satisfactory operation in modes representative of mission functions at the nominal operating temperatures, at temperatures in excess of the extremes predicted for the mission, and during temperature transitions.

The GSFC-STD-7000 describes that thermal-vacuum test is required to demonstrate that the spacecraft performs satisfactorily within the vacuum and thermal mission limits. The test item shall be (as possible) in flight configuration and it shall prevent unrealistic environmental conditions (based on hardware characteristics or orbital predictions) that could induce test failure modes. Test heaters on the spacecraft or the removal of thermal insulation may be required to achieve proper and safe temperatures.

The GSFC-STD-7000 describes the required temperature margins (above the maximum and below the minimum expected temperatures), number of temperature cycles, dwell time that allows engineers to execute performance tests on each soak for all modes of operations, and the pressure that shall be used for the qualification testing of a spacecraft. (See Table 1.)

This standard also states that abbreviated functional tests shall be performed at each hot and cold soaks and during transitions, while full functional tests (or performance tests) shall be performed at least one during a hot soak and once during a cold soak, exercising complete primary and redundant operations (unless impractical). At least 100 trouble-free hours of functional operations at hot and cold soaks must be demonstrated.

The unique requirement for acceptance thermal-vacuum tests within this standard is that the temperature margin shall be of 5°C.

This standard also refers to possible interfaces with the test item. The test item could be on a conductive interface or suspended with low conductance cables. If the conductive interface is used, then, its temperature shall be equaled to the temperature of the test item by using heaters in order to minimize the heat flow through this path (since it will not exist in the space). This standard states that the test article shall be thermally coated as in flight conditions.

MIL-STD-1540D. [7]

The MIL-STD-1540D, which is the last version of the MIL-STD-1540, intends to help the development of detailed verification requirements for assuring that an article can function correctly and withstand stresses that it may encounter during its lifecycle. This standard suggests establishing test requirements considering several factors, such as: criticality to mission, sensitivity to environment, severity of environment, knowledge or uncertainty of environment, environmental time profile, similarity to previously qualified articles, ability to analyze vs. design margins, maturity of technology, product complexity, training and experience of manufacturing, assembly, integration, and test personnel, and the use of automated vs. operator performed operations.

In addition to aforementioned factors, this standard does not describe any value for any test. However, it suggests referring to the MIL-HDBK-340A for obtaining testing requirements.

MIL-HDBK-340A. [8]

This handbook is related to the MIL-STD-1540 standard, so it provides guidance for developing test programs. The MIL-HDBK-340A describes the required number of temperature cycles, the dwell time, and the pressure that shall be used for qualification and acceptance testing of a spacecraft. This handbook does not state values for temperature margins. (See Table 1.)

This handbook states that during the hot and cold soaks, the unit temperatures are not allowed to go outside their qualification or acceptance range at any time during the qualification or acceptance tests. It also states that during each soak, the operating time should be divided approximately equally between redundant units.

ECSS-E-ST-10-03C. [1]

This standard describes the requirements for performing verification by testing of space segment elements (spacecraft). This standard states that thermal vacuum test shall be performed for any equipment or spacecraft that is expected to operate under a vacuum environment.

For thermal vacuum tests, the ECSS-E-ST-10-03C describes the required temperature margins (above the maximum and below the minimum expected temperatures), number of temperature cycles, and the minimum pressure that shall be used for the qualification, the acceptance and protoflight (or protoqualification) testing of a spacecraft. (See Table 1.)

It states that it is not mandatory to include large appendages (e.g. solar arrays) in a space segment element. This standards states that a reduced functional test shall be performed prior the closing of the thermal vacuum chamber. The most severe operative configuration should be tested with regard to power time domain, the power consumption, and the thermal dissipation point of view. Also the equipment power ON/OFF status throughout the test (including transitions) shall be defined. Functional tests shall be performed at least in a hot and cold soak, as well as in redundancy chains.The standard states that the rate of temperature change during cooling and heating shall not exceed the rate projected for the mission.

TR-2004(8583)-1 Rev.A. [9]

This standard describes testing requirements for launch vehicles, spacecraft, subsystems and units. The TR-2004(8583)-1 Rev.A describes the required temperature margins (above the maximum and below the minimum expected temperatures), number of temperature cycles, dwell time, and the pressure that shall be used for the qualification, acceptance and protoflight (or protoqualification) testing of a spacecraft. (See Table 1.)

This standard describes that a thermal cycle begins with the spacecraft at ambient temperature. Then, the temperature is raised to the high temperature level and stabilized. Subsequently, the temperature is reduced and stabilized. It also states that performance tests shall be conducted during the first and last thermal cycles at both the hot and cold temperature limits. The performance tests during the last cycle shall be free of failures. The operating time shall be divided approximately between primary and redundant units. During the other cycles, functional tests and monitoring of critical parameters shall be performed. The standard also states that if simulation of the ascent environment is desirable at the beginning of the test, the first cycle may begin with a transition to a cold thermal environment

D. Cubesat Rules and Standards

CubeSat Design Specification (CDS) Rev.13. [10]

The CDS Rev.13 states that CubeSat testing shall be performed according to launch vehicle requirements. In the absence of information of the launch vehicle, the standards GSFC-STD-7000 or the MIL-STD-1540 can be used for deriving testing requirements. Additional testing requirements can be established to ensure the safety of the CubeSat, the P-POD (Poly Picosatellite Orbital Deployer is Cal Poly's standardized CubeSat deployment system.), and the primary mission. Figure 2. shows the CubeSat General Testing Flow Diagram suggested by CDS.

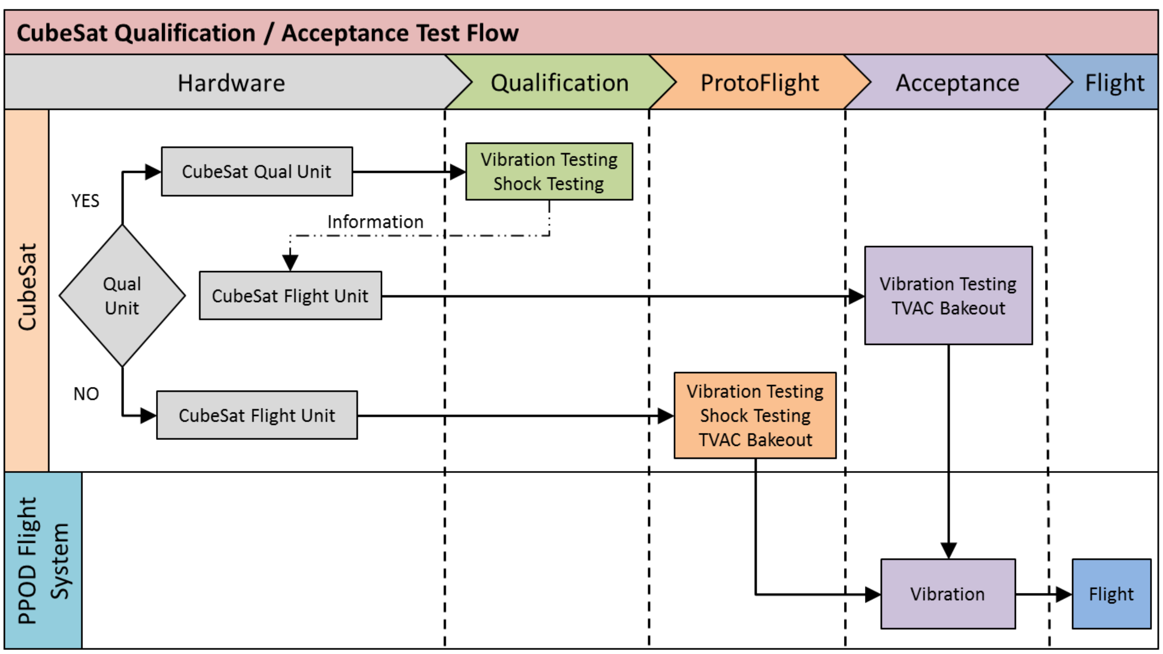

Figure 2. CubeSat General Testing Flow Diagram. Credits: CubeSat Design Specification (CDS) Rev.13. [10]

The CDS Rev.13 does not describe TVCT. It also does not states the TVCT as mandatory for CubeSats.

NASA LSP-REQ-317.01 Rev.B. [11]

This standard describes the requirements placed on CubeSats for integration on NASA Launch Services Program (LSP) Expendable Launch Vehicles (ELV). The NASA LSP-REQ-317.01 Rev.B describes the required temperature margins (above the maximum and below the minimum expected temperatures), number of temperature cycles, dwell time, and the pressure that shall be used for the qualification, acceptance and protoflight (or protoqualification) testing of NASA's CubeSats. (See Table 1.) This standard states that the transition shall be less than 5°C/minute at any test level (qualification, acceptance, or protoqualification). It also adds that a minimum range of temperatures from -14 -3/+0°C to +71 -0/+3°C shall be used for qualification, from -9 -3/+0°C to +66 -0/+3°C for acceptance, and from -14 -3/+0°C to +71 -0/+3°C for protoqualification (or protoflight).

The following table shows a summary of all conditions suggested by the standards and guidelines reviewed in the sections C and D this present chapter.

Table 1. Comparision between rules and standards

		Rules & Standards				
		GSFC-STD-7000.[6]	**MIL-HDBK-340A.**[8]	**ECSS-E-ST-10-03C.**[1]	**TR-2004 (8583)-1 Rev.A.**[9]	**NASA LSP-REQ-317.01 Rev.B.**[11]
Qualification	**Chamber pressure**	$1.33\text{x}10^{-3}$Pa (10^{-5} torr)	$13.3\text{x}10^{-3}$Pa (10^{-4} torr)	10^{-3} Pa ($7\text{x}10^{-6}$ torr)	$13.3\text{x}10^{-3}$Pa (10^{-4} torr)	$13.3\text{x}10^{-3}$Pa (10^{-4} torr)
	Temperature margins*	10°C	No info.	See [f]	10°C	10°C
	Number of cycles	4	13[a] or 3[b]	4	8	8
	Dwell time	24h	8h[c] or 4h[d]	No info.	8h[c] or 4h[d]	1h
Acceptance	**Chamber pressure**	No info.	$13.3\text{x}10^{-3}$Pa (10^{-4} torr)	10^{-3} Pa ($7\text{x}10^{-6}$ torr)	$13.3\text{x}10^{-3}$Pa (10^{-4} torr)	$13.3\text{x}10^{-3}$Pa (10^{-4} torr)
	Temperature margins*	5°C	No info.	See [g]	0°C	5°C
	Number of cycles	No info.	13[a] or 3[b]	3[e]	4	2
	Dwell time	No info.	8h[c] or 4h[d]	No info.	8h[c] or 4h[d]	1h
Protoqualification	**Chamber pressure**	No info.	No info.	10^{-3} Pa ($7\text{x}10^{-6}$ torr)	$13.3\text{x}10^{-3}$Pa (10^{-4} torr)	$13.3\text{x}10^{-3}$Pa (10^{-4} torr)
	Temperature margins*	No info.	No info.	See [f]	5°C	10°C
	Number of cycles	No info.	No info.	3[e]	4	4
	Dwell time	No info.	No info.	No info.	8h[c] or 4h[d]	1h
Tolerances	**Pressure**	±80%	±80%	±80%	+0/-80%	No info.
	Temperature	±2°C	±3°C (-54°C to +100°C)	Tmin +0/-4°C Tmax -0/+4°C (T>-193.15°C)	±3°C (-54°C to +100°C)	No info.

* This temperature margins are with respect to the worst expected temperatures
[a] If no thermal cycling test was performed before
[b] If thermal cycling test was performed before
[c] First and last thermal cycles
[d] Intermediate cycles
[e] Plus 1 more back up cycle that can be decided to be performed during tests
[f] Qualification and protoqualification temperature limits are reached when any equipment reaches its qualification temperature limits. Its qualification limits represents the maximum and minimum acceptance temperatures and a 5°C margin.
[g] Acceptance temperature limits are reached when any equipment reaches its qualification temperature limits. Its qualification limits represents the maximum and minimum design temperatures and a 5°C margin.

The review shows that the described standards and guidelines are somewhat different in some of the requirements for thermal vacuum tests. The generality of these standards and guidelines make them applicable to many different missions, no matter its sizing, schedule or available budget. The application of this robust and general standards when applied to CubeSats missions could lead to overspending time and money, which is mainly what is desired to be avoid when planning a CubeSat mission.

IV. CubeSat Thermal Vacuum Cycling Test

A. Test Equipment

The test equipment are Space Simulation Chambers. This systems used to recreate as close as possible the environment conditions that satellite experienced into space as well as serve to space components qualification and material research used in satellite. There are two types of space environment simulators, there one two types of space environemtn simulators, one of them witing solar simulator system and another one without this system. Systems without solar simulator are known as Thermal Vacuum Chambers. This systems simulate with closeness the vacuum and cold space environment.[12] Figure 3. shows a thermal vacuum chamber.

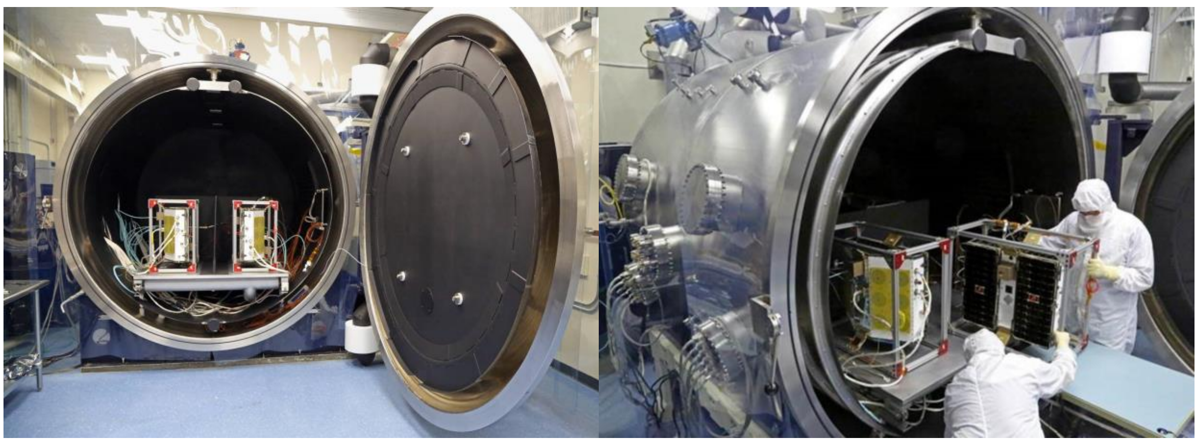

Figure 3. Thermal Vacuum Chamber. Credits: Southwest Research Institute - San Antonio, Texas.

The thermal vacuum chambers have several vacuum pumps and cryogenic shrouds.The function of the pumps is to produce a desirable vacuum level in a reasonable time, conserving such level during development all test. The cryogenic shrouds are mechanisms that provide a similar environment to the cold heat sink of space. By controlling the temperature of the shrouds, it is possible to produce high and low temperatures in function of time following a specific test profile for the satellite.[12]

B. Test Execution

The development of a CubeSat TVCT is usually divided in three phases. [13-14]

Set-up and instrumentation**:** In this phase the CubeSat shall pass to a complete functional test in order to crosscheck with the functional test after the TVCT . The thermo-couples are installed in the CubeSat in the specific point where the temperature will be recorded and monitored. The CubeSat may be suspended inside de chamber using nylon wires or it can be placed in a mechanical support equipment. This equipment shall have the minimal physical contact with the CubeSat, and the material shall be wisely chosen.

Test readiness review board (TRRB)*:* This meeting is conducted to asses if the test objectives, specimen, specifications, equipment, set-up, safety and hazard conditions and workmanship are well defined and ready to proceed to test.

Test**:** The Thermal Vacuum Chamber generate a specific level of vacuum and will then start the temperature cycling according to specification of test. The soak time is driven by a specific thermo-couple (or set of thermo couples), which shall be wisely chosen. Depending on the case, if a certain control thermo-couple is chosen, in order to achieve and maintain its desired temperature the other subsystems of the CubeSat may achieve higher temperatures than expected, damaging the system.

***Specimen Removal and Results Analysis*:** After the test is finished, the chamber is pressurized to ambient pressure using gaseous nitrogen. Then the chamber port is opened and the CubeSat is removed from chamber. After that test results are analyzed a test report is written.

C. Test Typical Specification Items

Prior to run a TVCT, test engineers need the specifications of the test, detailing each and every condition on how the specimen shall be tested to verify its requirements. According to the European standard ECSS[1], the test specification describes several characteristics such as: test requirements, test approach, ground support equipment and tools, test sequence, test conditions (levels and duration), pass/fail criteria and schedule. There are several differences between big satellites and small satellites. These differences are not just size, but also complexity, reliability and costs. Therefore, the TVCT test specification of small satellites such as CubeSats may be very much tailored. However there are some basic items that form the basis of all TVCT.

This sub-section covers a brief description of each parameter of a generic CubeSat TVCT specification, such as the soak temperatures and pressure level. In another perspective, using the method described in section 5 to a real CubeSat project should result in the specific values of each item described herein. In the end of this sub-section some specification examples of CubeSats are given. Figure 4. shows a typical thermal cycling test profile and Figure 5. shows a typical pressure level profile for a test.

Following, the typical CubeSat TVCT specification parameters are defined and examples of typical CubeSat parameters are given:

***Temperature Soaks*:** It comprises the maximum and minimum temperatures that shall be experienced by CubeSat. They are usually in Celsius. Ex: -15°C and +50°C.

***Temperature Transition (Ramp) Rate*:** Refers to the temperature transition rate which the CubeSat shall be heated or cooled. Ex: ≤ 5°C /min.

***Temperature Stabilization*:** Also known as stabilization criteria. Defines the criterion to consider that the Cubesat temperature has reached a stable (or nearly stable) temperature within test tolerance. Ex: Temperature change is less than 1°C/10 min. [15]

Soak Time: It is also called as "dwell at plateaus" by some organizations. Is the total time at plateau temperatures (hot or cold temperature soaks). The time starts to count after the temperature soaks are reached by control thermo-couples. Ex: 2 hours.

Test Interfaces (Mechanical and Electrical): Mechanical interfaces comprehend all equipment that will interface the Thermal vacuum chamber and the CubeSat, or in other words, how the CubeSat will be installed inside the chamber. A wise choice of such interface is important for conductive thermal isolation, because such a small CubeSat with a small heat budget, the heat leakage through the mechanical supports is an important contribution for the thermal balance.[4] Electrical interface is all cabling used for functional testing during TVCT. These cables are connected in the CubeSat, and pass to outside the chamber via chamber's feedthroughs to be connected to the electrical ground support equipments.

***Pressure Level*:** Is the pressure level in which the test shall run. The vacuum measuring unit is usually expressed in mbar, Torr or Pa. Ex: 10-4Torr.

***Pressure Drop Rate*:** Is the maximum pressure drop rate that shall be imposed to the CubeSat in order to avoid undesired effects such as corona discharge. It may be expressed in the same units that pressure level. Ex: 3,92kPa/sec.

Number of Cycles: Is the number of "loops" between hot and cold temperature the CubeSat shall be tested. Ex: 4 cycles.

***Test Profile*:** The test profile is defined by temperature and pressure graphs.

***Tolerances*:** Is the range of variation permitted in the specified parameters values such as temperature and pressure. Ex: ±2°C for temperature and +0/-80% for vacuum level (pressure).

***TVCT Functional Tests*:** Are the functional tests performed with the CubeSat to verify if it properly withstands the thermal-vacuum environment. These tests in CubeSats usually verify if power is being supplied and signal transmission are being transmitted, both with the correct values.

***Pass/Fail/Abort criteria*:** Pass and fail criteria address the conditions to approve or reprove the tested CubeSat, and also detail the means by which such conditions shall be verified. Abort criteria defines the conditions followed by test operator to stop testing given abnormal situations.

Instrumentation Information**:** It can be divided in thermo-couples position and control thermo-couple. In order to control the temperature during TVCT of specific areas the thermo-couples shall be strategically positioned. Also known as Temperature reference point (TRP), the control thermocouple is defined settled as reference for temperature soaks.

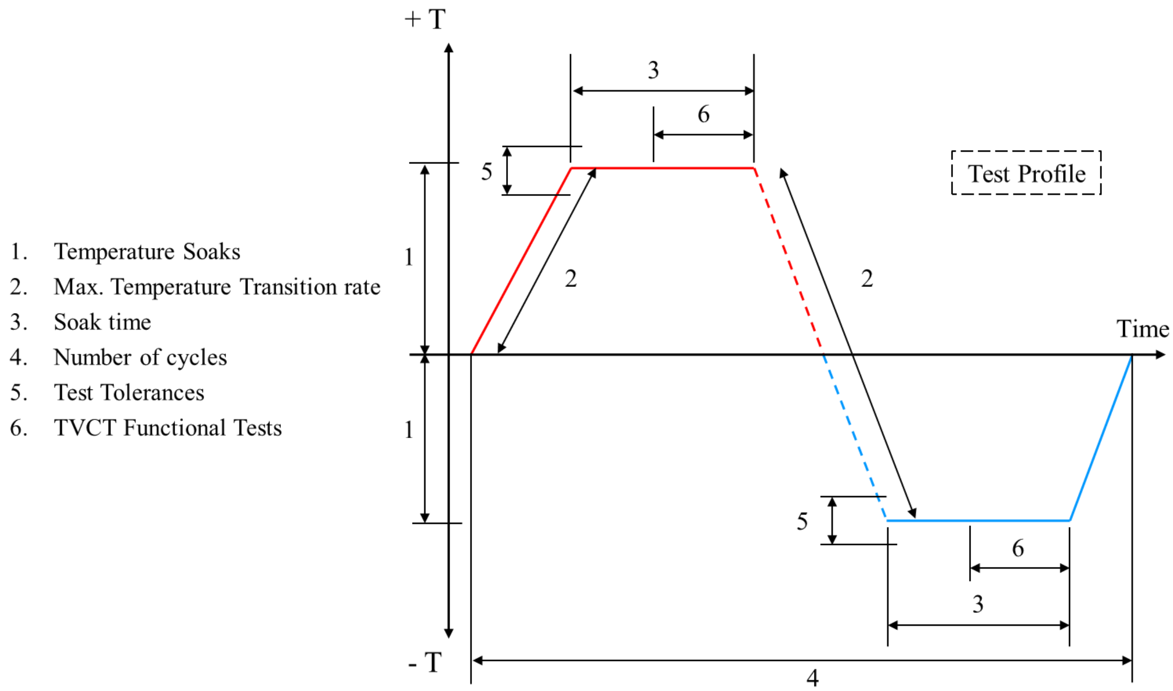

Figure 4. Typical thermal cycling profile.

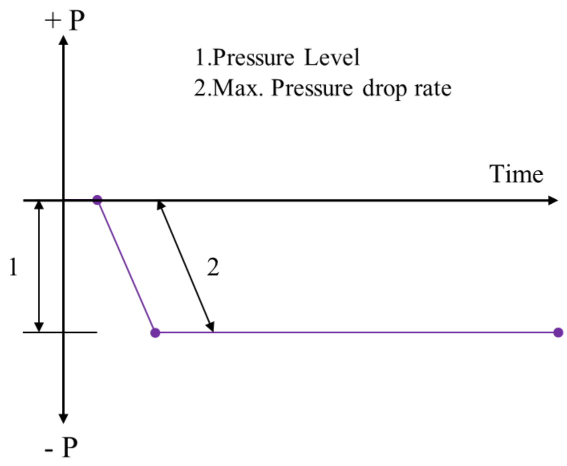

Figure 5. Typical pressure level profile.

Right below a table depicts the different basic TVCT specification items chosen for each CubeSat project. [14-16-17-18]

Table 2. CubeSat projects and their respective TVCT specification items.

CubeSat	Model	T °C max	T °C min	Vacuum Level	Number of Cycles
QB50	Proto flight	+50	-20	10^{-5}mBar	4
Step Cube Lab	Flight	+35	-35	< 10^{-5} Torr	2
AAU CubeSat	Flight	+85	-10	<0,01Torr	1
Swiss Cube	Flight	+50	-45	<10^{-5} Pa	4
NanoSact-BR1	Fligh	+50	-10	< 5x10^{-5} mBar	2
SERPENS	Flight	+42	-15	< 5x10^{-5} mBar	3

V. Method for Thermal Vacuum Cycling Test Specifications

The following method is composed by processes that must be performed in order to deliver TVCT specifications. The parallel flowchart processes herein follow no specific sequence. This flowchart also displays the sources of information and the inputs that each of those processes shall consider. At the end, a complete set of specifications will form the TVCT specification document. The flowchart assumes available resources (e.g. people, cost and time) and knowledge to perform each process, and that the sources of information are already defined when planning the TVCT.

A. Sources of Information

Orbital Parameters: These parameters define the trajectory in which the CubeSat will orbit the Earth. These values usually come from the orbit design activity and will depend mainly on the mission and launch constraints. Examples of such parameters are semi major axis, eccentricity, inclination and argument of perigee.

Launch vehicle requirements: CubeSats are generally launched as piggy-backs. Therefore, CubeSats must comply with a set of launch requirements to prevent the other satellites and the launch vehicle from damage. These requirements usually come from launch provider, and they are mostly related to the dynamic environment (shock and vibration) and materials outgassing properties.

CubeSat design*:* This input is related to the outcomes of the CubeSat design process, such as mechanical and electrical layout and interfaces, requirements, components operating temperatures, dissipated power and functional tests characteristics.

Thermal-vacuum chamber and sensors specification*:* This input refers to thermal-vacuum chamber and sensors capacities, interfaces and accuracies.

Standards: This input refers to the selected standard that is being adopted by the project. This standard will deliver reference values to run a TVCT.

Other Requirements: This input refers to all other requirements that may apply to the CubeSat TVCT specification. These requirements may be related to concerns such as handling, contamination, or programmatic constraints.

B. Process

Environmental analysis: This process consists on the identification and analysis of the different environments that the CubeSat will experience. The outcome of this process is usually known as environmental specification (EVS), and it describes dynamic, thermal, radiation and other conditions for each environment.

Thermal Analysis*:* This process is one of the most important for a TVCT. It consists on analyzing thermal environment to determine the maximum predicted environment (e.g. temperature range and temperature transition rate) and critical regions that shall be monitored during tests.

Temperature soaks definition: These temperatures are defined according to model suggested margins, which come from the chosen standard, and the predicted environment.

Temperature transition rate definition*:* This rate will depend on equipment capacity and the maximum rate that is expected during mission.

Mechanical and electrical interfaces definition: The interfaces definition will depend on the CubeSat interfaces (mechanical and electrical) and thermal-vacuum chamber characteristics.

Pressure level definition: This process consists on a trade-off among the predicted level, the value suggested by the chosen standard and Thermal vacuum chamber capacity.

Pressure drop rate definition: This definition is made considering the predicted value from the environmental analysis and thermal-vacuum chamber capacity.

TVCT functional test planning: This process identifies from the CubeSat functional test plan what shall be tested during thermal-vacuum cycling test.

Soak time definition: This process will be a trade-off between the required time to perform the thermal-vacuum cycling functional tests and the soak times suggested by the chosen standard.

Test tolerances definition: This process defines test tolerances according to suggested values from the chosen standard and the test sensors accuracy.

Pass, fail and abort criteria definition: These criteria shall be wisely chosen by developers based on the CubeSat requirements.

Instrumentation setup definition: The instrumentation setup is defined according to critical temperature areas, access or physical constraints to place test sensors and the mechanical interfaces defined to the test.

Test profile definition: The both temperature and pressure profiles shall be defined with the following inputs: temperature soaks, transition rate, pressure level, number of cycles, pressure drop rate and soak times.

C. Output

TVCT specifications**:** All the inputs composing TVCT specifications shall be revised and validated, and then, they may be delivered as a formal document. This document will be sufficient for test operators to execute the complete test.

Finally in the figure 6. show the Method For CubeSat Thermal Vacuum Cycling Test.

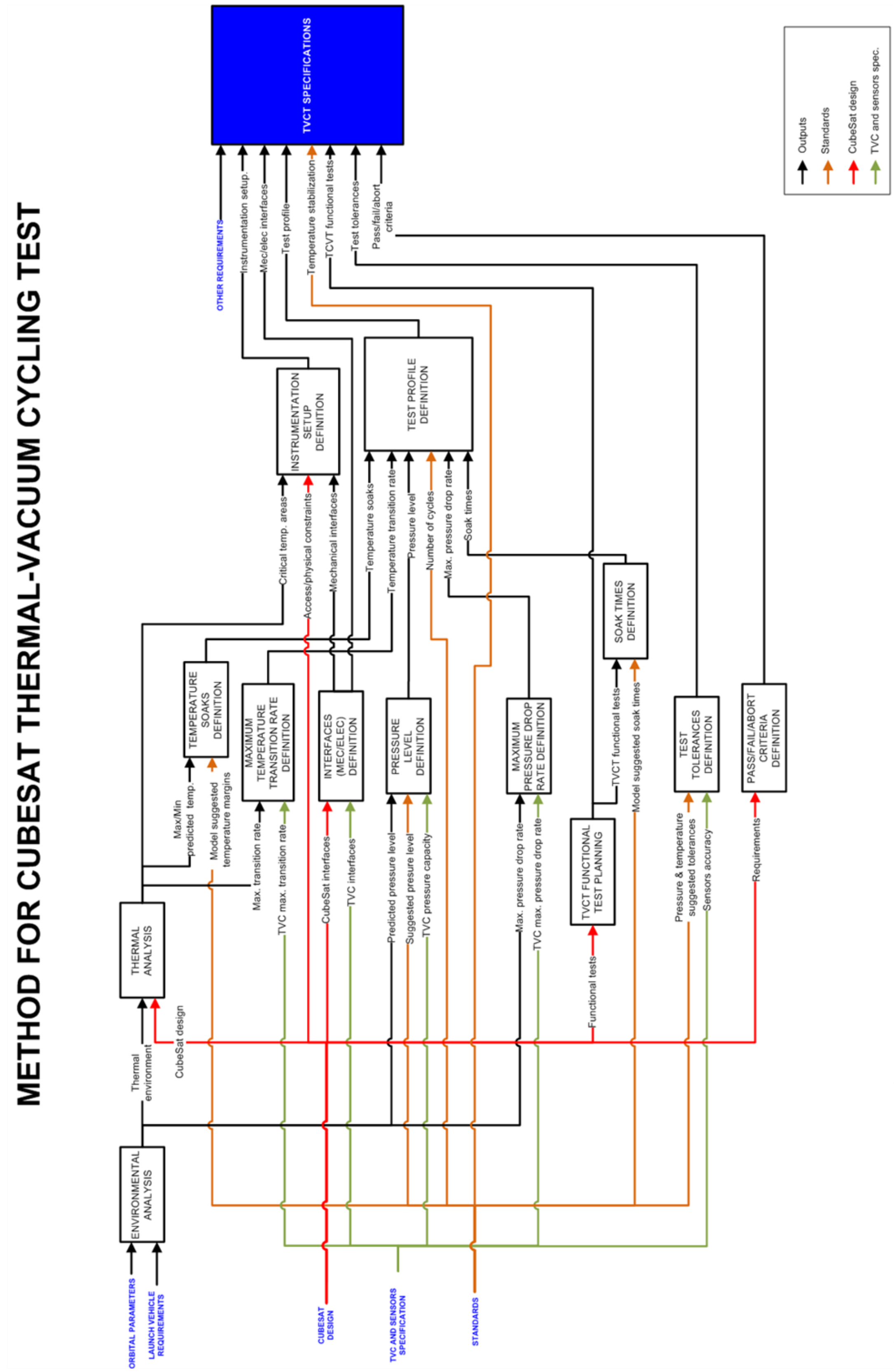

Figure 6. Method for Cubesat Thermal – Vacuum Cycling Test

VI. Conclusion

This paper described a method to develop a complete set of TVCT specifications, which allows CubeSat developers to verify the system capability to undertake the space environment in order to potentially increase system reliability rates and mission success. The method herein proposed could be used as a framework by CubeSats development teams that do not have the proper expertise to specify a complete set of TVCT specifications.

The method allows its user to not forget about any of the items that the specifications should have and to trace where each specification comes from. The produced TVCT specifications represent a complete set of requirements that can be followed by any internal or outsourced test operators.

This method should not be use for TBT specification, because the TBT is a test executed for verification to performance of thermal control inherent of each CubeSat

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