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Development Of A Small Thermal-Vacuum Chamber Using Systems Engineering Philosophy

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Picosatellites and nanosatellites environmental testing are usually outsourced, and they can be very expensive for some academic institutions. Thermal-vacuum tests usually comprehend an important amount of such costs. An in-house development of a thermal-vacuum chamber has great potential to lower these costs, and also diversify the educational project research scope. The objective of this paper is to describe the Systems engineering methodology used to develop a thermal-vacuum chamber to be used for environmental testing picosatellites and nanosatellites. This paper describes a morphology, structure materials, necessary supplies for operation, internal and external interfaces, data acquisition systems, pumping systems (low, medium, high and ultra-high vacuum), ways and means of heat transfer, temperature ranges, operating pressure and general operation of the designed thermal-vacuum chamber. The work also considered the general small satellite thermal-vacuum testing requirements to develop the chamber specification. The study showed that the design of a small thermal-vacuum chamber is feasible and very promising. Using an in-house chamber tends to reduce overall testing costs, and opens more research and development opportunities for students involved in space area.

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Introduction

There is an increasing trend in the research sector of space science and education in developing small satellites. Its development evidences an excellent cost-effective for scientific experiments, also being a low risk platform for space missions. [1] The Table 1 below shows the classification of satellites by mass.

Class	Mass (kg)	
Conventional Large Satellite	>1000	
Conventional Satellite	500 – 1000	
Minisatellite	100 – 500	Small Satellite
Microsatellite	10 – 100	
Nanosatellite	1 – 10	
Picosatellite	< 1	

Table 1. Classification of Spacecrafts by Mass [1]

Small satellite classes are developed for specific missions (Space science, Communications, Technology Verification, Earth observation, Military applications and others). To start the operation phase they also need to meet all conventional space product life cycle development phases: viability, conception, detailed, detailed design, manufacturing and integration and testing. In the integration and test phase, the satellite is assembled, integrated and tested. Figure 1 shows an example of AIT (Assembly, Integration and Test) process for Picosatellite and Nanosatellite.

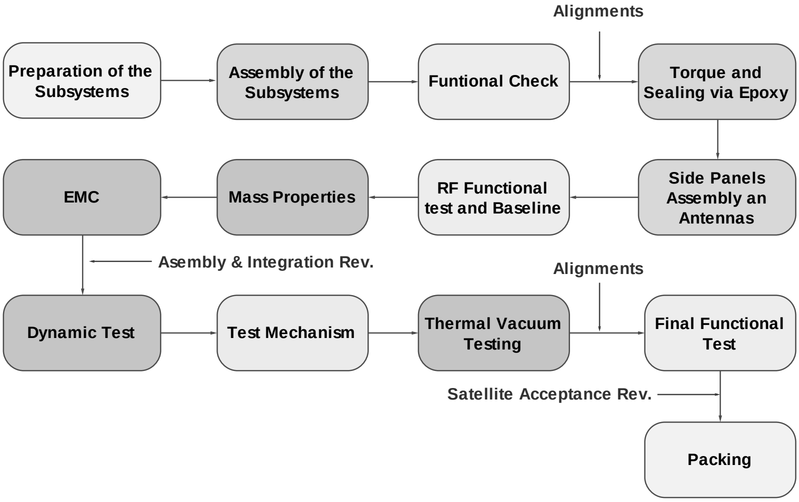

Fig. 1. AIT Process of Small Satellite. [2]

During small satellites environmental testing, which is part of AIT process, space environment simulation systems play a key role to qualification of each satellite systemic models (Engineering Model, Qualification Model and Flight Model).

Space Environment

The space environment main characteristics experienced by satellites orbiting the Earth are: high vacuum, an infinite very cold sink, sun's radiation, total darkness, also Earth propagated radiation. The space environmental phenomena are showed in Figure 2.

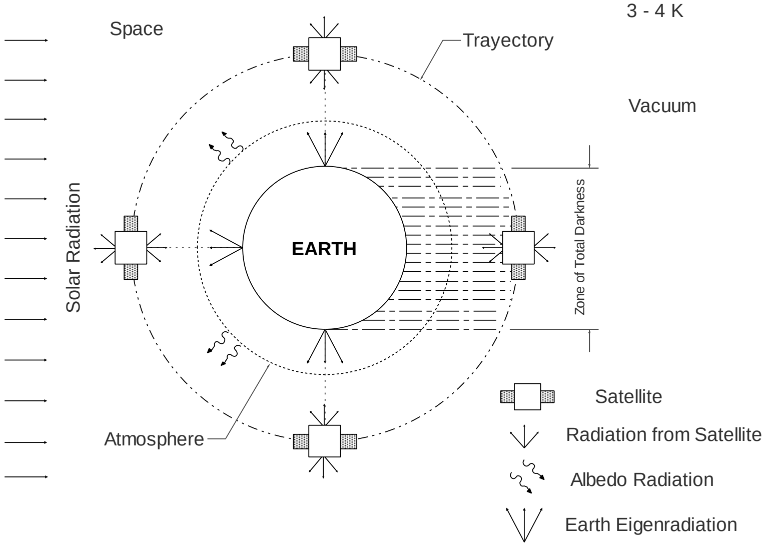

Fig. 2. Space environment characteristics. Adapted [3] [4]

A satellite in space experiences an intense radiation when exposed to the sun. When the satellite is in penumbra (without sunlight) it experiences an environment inherent dissipated cold effect. These conditions experienced by satellites in space allow to calculate their temperature during operation, which is determined by a balance between satellite internal heat, radiant energy absorbed by satellite and radiant energy emitted to space by satellite surfaces. [5] The space environment phenomena are described below.

Pressure

The pressure experienced by satellites varies from 1 x 10^{-3} mbar near Earth atmosphere to 1 x 10^{-12} mbar in deep space. In a pressure of more than 1 x 10-6 mbar, the molecular mean free path is very wide, which reduces heat transfer to solar radiation.

The Solar radiation

The solar radiation is a high intensity energetic phenomenon, which represents an approximate 1400 W/m^2 heat flux in the satellite surface. The absorption of such energy would generate a very high temperature inside the satellites, however, just a fraction of heat is absorbed due to space environment characteristics and satellite surfaces physical properties. [6] [7]

Cold Temperature (Space Heat Sink)

Deep space is similar to an infinite dissipation black body, where a passive body experiences a balance temperature between -270.15°C (3K) and -260.15°C (4K). [6] This concept implies that the heat emitted by a satellite will not return to it. [5]

Albedo and Eigenradiation of the Earth

Albedo is the fraction of incident solar radiation reflected by the Earth or the moon, which reaches satellite depending on its position and distance. The Eigenradiation is the Earth's thermal radiation, which allows the balance between absorbed solar radiation and the Earth's generated heat. [4] Albedo is approximately 0.48 kW / m^2, and the Earth's radiation is approximately 0.23 kW/m^2. The values that can take both forms of radiation depend on the relative position of the satellite to the Earth and Sun. [6]

Space Simulation Chambers

Also known as thermal-vacuum chambers, these systems are used to recreate as closely as possible the environmental conditions that satellites experience in space. These systems analyze satellites behavior, evaluating its thermal balance and functionalities to ensure mission success and survivability. Figure 3 demonstrates two classes of thermal-vacuum chambers installed in the Integration and Testing Laboratory (LIT) of the National Institute for Space Research (INPE).

Fig. 3. Thermal-Vacuum Chambers. Courtesy of LIT – INPE

1. Space environment simulation

It is stated that thermal-vacuum chambers simulate space environment conditions with close proximity, because to generate a temperature of -269.15°C (4K), without any reflectivity as in space, would be economically unviable. Therefore, after analyzing chambers data since its invention and also Stefan Boltzmann law analysis, it was historically opted to generate temperatures from -195.85°C to -173.15°C (77.3K - 100 K), which only represent a small error percentage to assess satellite in low temperatures, without significantly affecting thermal balance study. [3] [5] [6] Due to this reason it was established the trend of using heat transfer surfaces which generate the minimal temperature of -173.15°C (100K).

For thermal balance study and analysis is essential to ensure the thermal loads that the satellite will receive from several sources of radiation in space. This radiation sources are transformed in high temperatures experienced by satellite according to its position in space and materials characteristics. The thermal loads can be simulated through solar simulators or using heat transfer surfaces. Solar simulators can generate thermal loads similar to the Sun using high intensity infrared lamps, but with an excessive cost due to high power consumption, preventing their use in some simulation systems. Therefore it is used to replace them by heat transfer surfaces that can generate temperatures greater than 126.85ºC (400K).[3] Albedo and Eigenradiation are not simulated in thermal-vacuum chambers since their values are diffuse and depend on the satellite position relative to the Earth and Sun, among other characteristics.[6]

Given these restrictions and limitations, thermal-chambers only simulate space vacuum and temperature cycling, which is experienced by satellite due to its intermittent exposure to solar radiation. It should be noted that the satellite is mathematically modeled using softwares, which use the exact values of all phenomena experienced in space.

Problem

Most of thermal-vacuum chambers in several space research centers were originally designed to test large satellites. Figure 4 shows the contrast between large and small satellites

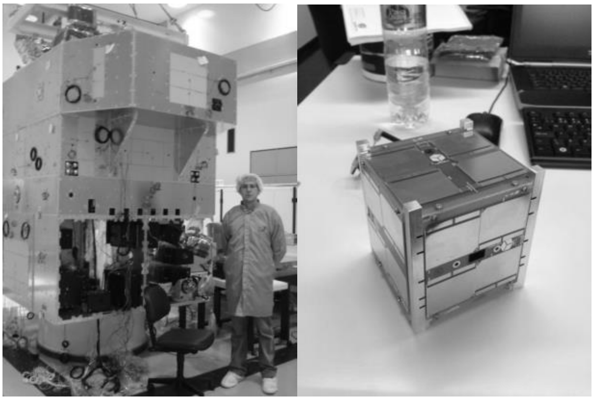

Fig. 4. Satellite CBERS 3 (left) and CubeSat AESP14 (right). [2]

When testing small satellite in thermal-vacuum conditions, the available chambers in the market are usually oversized for small satellites, which usually rises testing costs complicating the mission development.

Because of that, the Systems Concurrent Engineering Laboratory (LSIS) of the National Institute for Space Research (INPE) has the initiative to develop space environment simulation systems in a small scale, which better fits small satellites needs to meet thermal-vacuum testing requirements. This development uses a systems engineering philosophy, which is described in this paper.

Systems Engineering

Systems engineering is conceived as a multidisciplinary group of organized knowledge focused for high complexity systems development. [9]

Systems engineering philosophy states that the development of any kind of system starts from a need for a specific product or service. The need may be expressed by individuals or organizations, which in systems engineering language are called stakeholders. The needs scope comes from a very systematic communication between systems engineers and stakeholders. [10]

When stakeholders’ needs are well defined, they are organized and classified to be further transformed in requirements, which eventually will be implemented in a product that satisfies users expectations.

The product requirements are usually stated in a textual form, describing system functions and capabilities. The requirements shall be unambiguous, measurable and verifiable.

After requirements definition, a detailed analysis is made to classify and allocate them to functions or services that the system must do. This process builds a primary functional view of the system, where each function will be further allocated to a group of possible solutions. [10]

1. Using Systems engineering philosophy

For development of the small thermal-vacuum chamber from the systems engineering philosophy, it will be identified the possible stakeholders, their needs and the requirements which the system shall meet.

Stakeholders

The stakeholders of the Thermal-vacuum chamber are: space research institutions, AIT Laboratories, education institutions, space product development companies and military organizations.

Needs

The stakeholders need a thermal-vacuum space simulation system adapted for small satellite dimensions.

The stakeholders need a system that can meet usual small satellites thermal and vacuum requirements conditions.

Requirements

Dimensions

- The space system simulation system shall be able to encapsulate picosatellites, nanosatellites or CubeSats.

Environmental

- The system shall generate a high vacuum environment (10^{-7} mbar to 10^{-3} mbar).
- The system shall generate temperatures from -173.15ºC to 126.85ºC.

Control

- The system shall have an operation control system.
- The system shall provide ways for communication between specimen and chamber’s exterior during the simulation.
- The system shall inform the real-time pressure and temperature inside chamber.
- The system shall permit internal chamber visualization during a simulation.

Through the requirements analysis it was possible to allocate requirements into physical systems that integrates the simulation system. The Figure 5 identifies the systems that integrate the thermal vacuum chamber.

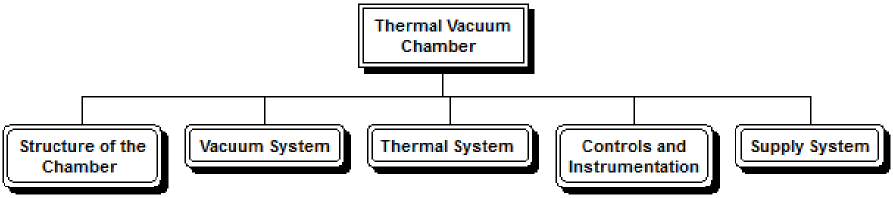

Fig. 5. Systems that integrate the thermal vacuum chamber

To identify ways in which the systems meet the requirements from systems engineering analysis, each system is following described. The description also addresses development and operation requirements, providing historical data as a source of argument for selection. Likewise, each system component and their functions are also described. After these systems descriptions, the characteristics of the proposed thermal-vacuum chamber will be further exposed.

Results

Based on the described criteria for the selection of the chamber physical structure, and the requirements that materials must meet to recreate the space environment phenomena, the characteristics of the thermal vacuum chamber is determined to run tests on small satellites.

1. Structure of the Chamber

- The criterion to simulate pressure and maximum dimensions that the specimen can have, were the fundamental requirements to determine the volume of the chamber.

- The vacuum level to be simulated in the chamber should range from 10^{-3} mbar (medium vacuum) to 10^{-8} mbar (ultra-high vacuum).

- The Picosatellite and Nanosatellite maximum dimensions were studied from a baseline developed by the systems engineering team.

- In the case of Cubesats, also classified as small satellites, was possible to know their different configurations and determine their dimensions from the Cubesat Design Specification Rev. 13 document of the California Polytechnic State University [11]. Figure 6 illustrates the types of Cubesats for which the vacuum chamber is designed.

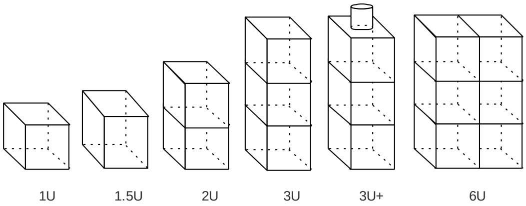

Fig. 6. Cubesat Specifications. [11]

Given these criteria, the volume and type of structure of the space simulation chamber that will test the small satellites is determined. In Figure 7 isometric views of the designed Chamber X are shown. Specific chamber structure sections and its singularities were designed fulfilling a series of requirements established in “*An international Code 2013 ASME Boiler & Pressure Vessel Code- VIII Rules for Construction of Pressure Vessels”* [12].

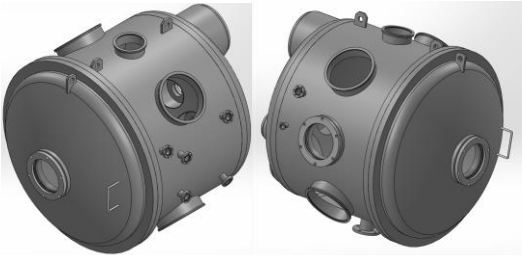

Fig.7. Small Thermal Vacuum Chamber / Chamber X

Right below a list of features of Chamber X are described.

Shape: Cylindrical with dome ends.
Internal Volume: 750 L
Maximum Weight of the Specimen: 50 Kg
Material of Structure: 304 Stainless Steel.
Internal Surface Finish: Polished#4 for General Purpose
Welding: Tig Weld Throughout
Sight Glass / View Port: Borosilicate Glass (Pyrex®)
Material of Flanges: 304 Stainless Steel.
Types of Flanges: ISO-K/Clamp Flanges, CF Flanges, NW Flange and ANSI-ASA flange.

The Viewports allow the small satellite visualization when they are tested. The chamber has multiple connections in which it is possible to install sensors, residual gas analyzer or other mechanisms that contribute to its operation. The flanges installed in the chamber body, to which are attached feedthrough ports, are the means by which it is possible to communicate the test object with the outside, without altering the conditions of simulation.

2. Vacuum System

In order to obtain a high vacuum level inside the chamber, as part of compliance with the environmental requirements that the space simulation system must generate, the following section describes how the vacuum system is distributed, connected and interconnected to meet such requirement. Figure 8 shows the identification of components that integrate the vacuum system and its connection with the developed chamber by a piping and instrumentation diagram (P&ID).

To generate vacuum in the chamber, the system has two interconnected pumping units. One dry vacuum pump is used to reduce the pressure inside the chamber from 1013 mbar to 10^{-2} mbar, and a turbomolecular pump to relieve pressure from 10^{-2}mbar to about 10^{-8}mbar. Dry pump functions as a primary pumping unit in the system, and operates as backing pump for turbomolecular pump. The maximum level of vacuum that can be generated inside the chamber depends on the efficiency of pumping units, the level of conductance in lines and appropriate control of cleaning, which avoids the presence of undesirable gases.

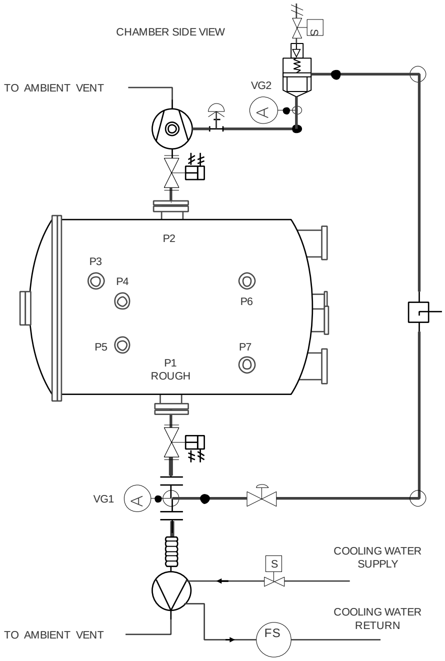

Fig. 8. Vacuum System – Chamber X

The system has two electro-valves connected to the chamber between each pumping unit, which function to allow the evacuation of gases and ensure the preservation of a specific vacuum level (once it is obtained).

The system uses three (3) Thermal Conductivity pressure gauges to establish 3 different points. The first sensor (VG1) provides the pressure between the pump and dry vacuum chamber. The second sensor (VG2) measures the pressure at the top end of the connecting line between the dry pump and Turbomolecular pump. The third sensor (VG3) performs pressure readings ranging from rough to medium vacuum generated inside the chamber. It is connected to the chamber using a CF flange.

The system has two (2) sensors for pressure readings ranging from medium to ultra-high vacuum, penning type sensor (VG4) and a sensor for electrical ionization (VG5) are installed to the chamber.

To determine the gaseous composition inside the chamber and their pressure during operation, it is used a residual gas analyzer or mass spectrometer (MS).

Venting

The chamber X uses filtered gaseous nitrogen to return the chamber to room pressure. The Figure 9 shows on the P&ID the installation of components that integrates the venting.

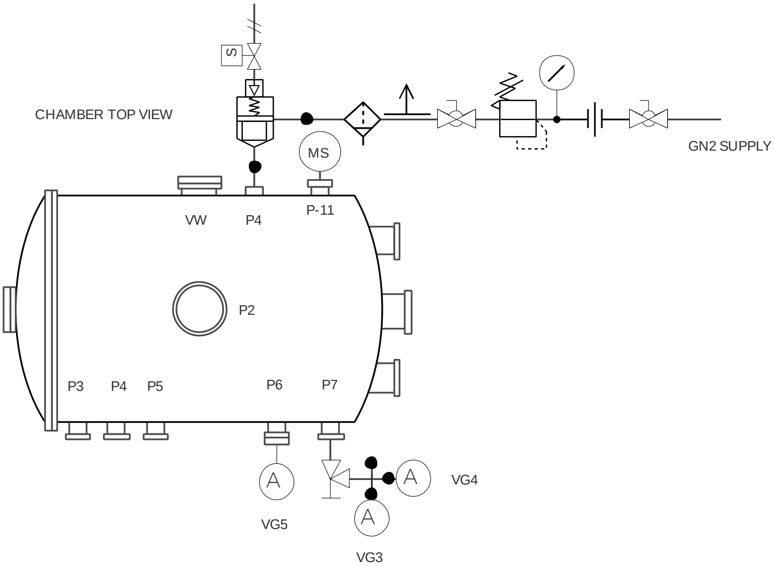

Fig.9. Vacuum Chamber Venting – Chamber X

A filter installed on the GN2 inlet line prevents access of impurities or microparticles, which can significantly damage or contaminate the specimen and the chamber. The gaseous nitrogen access control to the vacuum chamber for pressurization is carried out by a pneumatic poppet valve angle, operated by a solenoid valve that allows the passage of compressed air for activation.

3. Thermal System

This thermal system uses gaseous nitrogen for operation. It has the ability to generate a temperature range from -180°C to 150°C inside the chamber. Cryoshrouds has D-type tubes and bat wing (Figure 10), which integrate the heat transfer surfaces in the four (4) areas of thermal control, which circulates GN2 from gaseous nitrogen thermal conditioning unit (GNTCU). 1110 Aluminum was selected for surface panels shrouds, and 6061 Aluminum as a material for their flow paths. The shrouds exposed area to the test specimen receives a surface finish with cat –a –lac black painting.

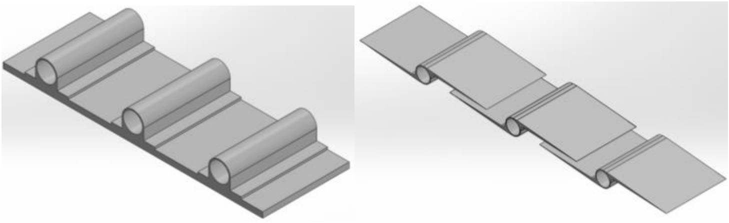

Fig.10. Thermal Shrouds - D-tube on Sheet & Bat wing

The chamber has connections on the after part to feed the shrouds and the thermal platen support with GN2. The lateral chamber flanges allow to feed with GN2 the front area of thermal control of the chamber. The thermal system of the chamber X is shown in the diagram of Figure 11.

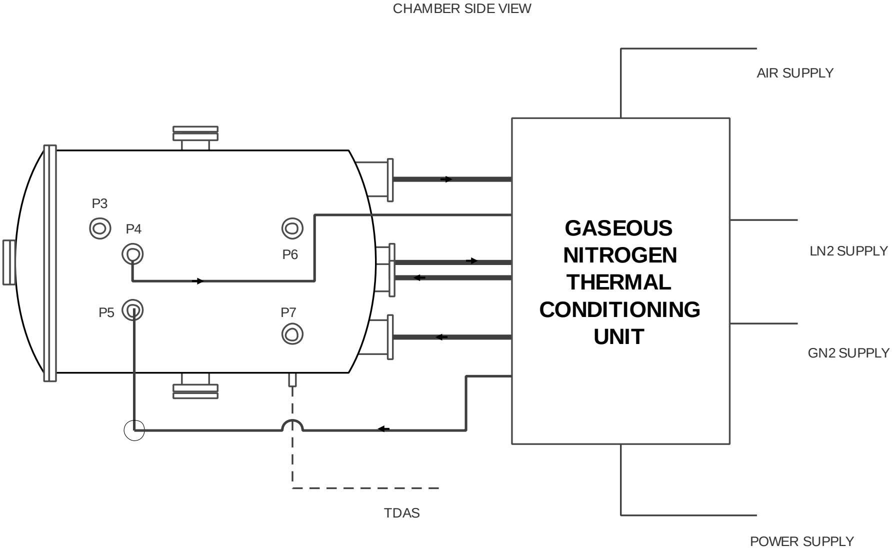

Fig. 11. Thermal System – Chamber X

The GNTCU uses liquid nitrogen injected at various pressures, electricity, water for cooling internal components, in addition to compressed air for the operation of their proportional flow control valves and ventilation valves. The pipes connecting the GNTCU to the chamber have a vacuum jacketed insulation. The chamber has a point at the bottom through which the thermal shrouds sensors communicate the control system information concerning the temperature on surfaces. This line of sensors exiting the chamber is interconnected to Thermal Data Acquisition System (TDAS) in the control unit.

4. *Compressed Air Supply*

The thermal and vacuum system it is provided compressed air at different pressures for operation of its electro-pneumatic valves. Figure 12 illustrates in P&ID the distribution of devices that integrates the circuit of compressed air supply

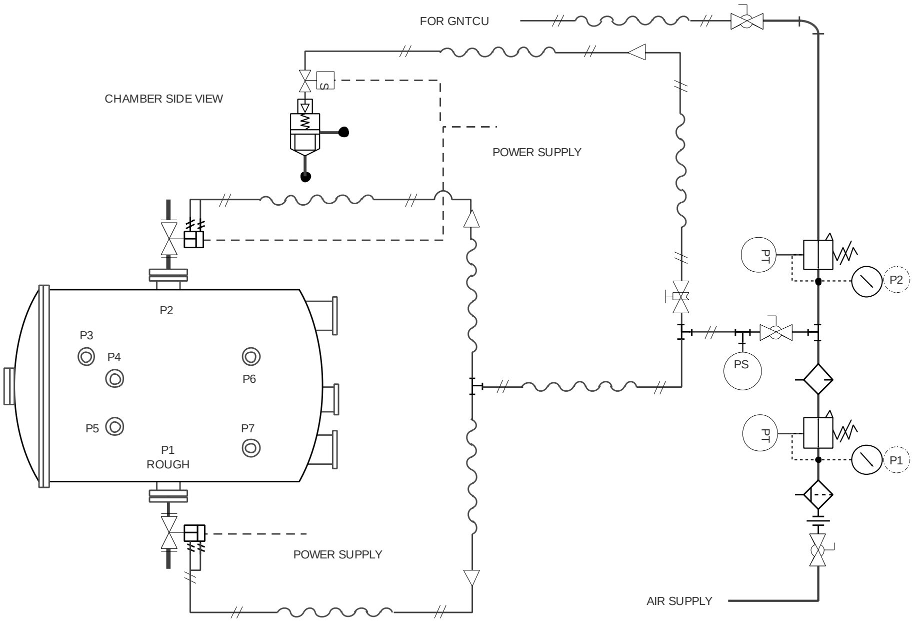

Fig. 12. Compressed Air Supply – Chamber X

This compressed air supply circuit is composed of several manually controlled valves, pressure switch, pressure transmitters, filter, lubricator and pressure regulators to supply two pneumatic lines at different pressures. The control system of the chamber shall consist of PLC units.

Conclusions

There is a strong trend in developing small satellite for different space missions. For its correct development, the satellite needs to run environmental tests, including a thermal-vacuum test, which is executed through a thermal-vacuum chamber. Therefore, these satellites are usually tested in test equipment for convetional (big) satellites, rising total test costs. This justifies the developent of a small thermal-vacuum chamber, called Chamber-X, main scope of this work. This paper presented the Chamber-X development, which is a thermal-vacuum chamber adapted to small satellites. The test equipment has an internal volume of 750 liters, allowing to test picosatellites, nanosatellites and CubeSats, from mass less than 1 Kg to maximum 50 Kg. The development of this Chamber was based on a systems engineering philosophy to capture users needs, and trasform them in requirements and specifications, until allocate functions to physical parts. Through the development of this work, it was possible to establish a basic methodology for developing a space simulation system to run environmental tests on small satellites. By transforming the space environment phenomena experienced by a conventional mission of a small satellite in requirements, which were allocated to functions, it was possible to determine the systems that compose the designed space simulation chamber. The study showed that the design of a small thermal-vacuum chamber is feasible and very promising. Using an in-house chamber tends to reduce overall testing costs, and opens more research and development opportunities for students involved in space area.

References

[1] Martin N. Sweeting and Craig L. Underwood: *Spacecraft Systems Engineering – Cap 18. Small Satellite and Applications. Fourth Edition.* Published 2011 by John Wiley & Sons, Ltd.

[2] BÜRGER, E. E. *Proposta de método para AIT de pico e nanossatélites. 2014. 306 p.* (sid.inpe.br/mtc-m21b/2014/02.13.16.21-TDI). Dissertação (Mestrado em Engenharia e Gerenciamento de Sistemas Espaciais) - Instituto Nacional de Pesquisas Espaciais (INPE), São José dos Campos, 2014. Disponível em: <http://urlib.net/8JMKD3MGP5W34M/3FNSPK2>. Acesso em: 28 nov. 2014.

[3] S Mercer, *Cryogenics: A Technological Tool for Space Scientist*, 1968. Cryosystems Ltd.

[4] Wilfried Ley, Klaus Wittmann, Willi Hallmann: *Handbook of Space Technology*. Published 2009 by John Wiley & Sons, Ltd.

[5] B .H. Goethert: *Space Simulation Chambers*, 1964, North Atlantic Treaty Organization.

[6] R A Haeferr: *Vacuum and Cryotechniques in space research*, 1972, 2nd Annual Ultra High Vacuum Conference – University of Swansea, Vacuum/Volume 22/Number 8,

[7] David G. Gilmore: *Spacecraft Thermal Control Handbook – Volume I: Fundamental Technologies Second Edition*, 2002.

[8] Ken Harrison: *Engineering a Better Vacuum Chamber*, 2015, www.gnbvalves.com.

[9] Geilson Loureiro, *A System Engineering and Computer Engineering Framework for the Integrated Development of Complex Products .Ph.D. Thesis Loughborough University*, 1999.

[10] Cecilia Haskins, CSEP, *Systems Engineering Handbook –A Guide for System life Cylce Processes and Activities 3ed*, 2011. INCOSE.

[11] Cal Poly SLO: *CubeSat Design Specification Rev.13 The CubeSat Program, California Polytechnic State University*, 2015. http://www.cubesat.org/images/developers/cds_rev13_final2.pdf

[12] American Society Mechanical Engineers - ASME: *Pressure Vessel Code-An international Code, VIII Rules for Construction of Pressure Vessels Division 1*, 2013 Ed. ASME