Development of a Thermal-Vacuum Chamber for testing in Small Satellites

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There is a strong trend in developing small satellites for different space missions (space science, communications, technology verification, earth observation, military applications, and others). For its correct development, the small satellite needs to run environmental tests, including a Thermal-Vacuum Test, which is executed in a Thermal-Vacuum. The Thermal-Vacuum Chambers are used to simulate as closely as possible the space environment conditions experienced by satellites in operation. These systems analyze satellite thermal behavior and functionalities to ensure mission success and survivability. Most of Thermal-Vacuum Chambers in several space research centers were originally designed to test large satellites. When testing small satellites in thermal-vacuum conditions, the available chambers in the market are usually oversized for small satellites, which usually increases testing costs complicating the mission development. Because of that, our multidisciplinary professionals team 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. The objective of this paper is to describe the methodology used to develop a Thermal-Vacuum Chamber to be used for environmental testing in Microsatellites, Nanosatellites and Picosatellites. For the development of this chamber, was used a Systems Engineer philosophy. For the development process was followed the next steps sequence: first (1st), it was captured the needs of stakeholders. Second (2nd), the needs of stakeholders were transformed into requirements and assorted according to their character (functional, performance and constraint requirements). Third (3rd), the established requirements was discussed and validated with stakeholders. Fourth (4th), the accomplishment of the requirements was assigned to parts, units and components that integrate the systems that compound the thermal vacuum chamber. This work also considered the general small satellite thermal-vacuum testing requirements to develop the chamber specification. 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 chamber. This paper describes the basic systems and devices that compose the designed Thermal Vacuum Chamber.

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Nomenclature

AIT	=	assembly integration and testing
EMC	=	electromagnetic compatibility
GN_2	=	gaseous nitrogen
LC	=	level controller
LN_2	=	liquid nitrogen
MS	=	mass spectrometer
PLC	=	programmable logic controller
P&ID	=	piping and instrumentation diagram
QF	=	quick flange
TCU	=	thermal conditioning unit
TDA	=	thermal data acquisition
VG	=	vacuum gauge

I. Introduction

There is some increasing trend in the research sector of space science and education to develop 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.

Table 1. Classification of Satellite by Mass. [1]

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

Small satellites 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 design, manufacturing and integration and testing. In the integration and test phases, the satellite is assembled, integrated and tested. Figure 1 shows the usual activities that comprise assembly, integration and test of satellite. For execution satellite tests program is required the uses of different types of facilities: Vibration test facility, Acosutic test facility, Mass properties test facility, Thermal Vacuum Chamber, EMC test facility, Magnetics test facility and others.

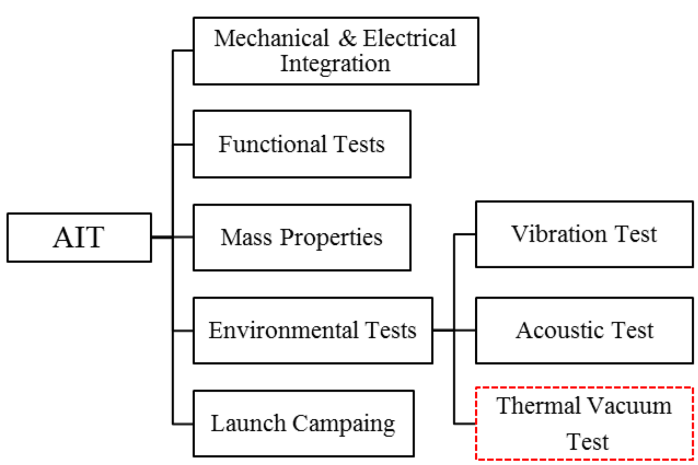

Figure 1. Activities in the AIT process.

During small satellites environmental testing, which is a 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).

II. Space Environment

The main space environment phenomena experienced by satellites orbiting the Earth are: high vacuum, cold space environment and different sources of radiation. The space environment phenomena are described below in the Table 2.

Table 2. Space environment characteristics

Space Environmental Phenomena	Description
Pressure	The pressure varies from 1 x 10^{-3} mbar near Earth atmosphere to 1 x10^{-12} mbar in deep space.
The Solar Radiation	High intensity energetic phenomenon, which represents an approximate 1400 W/m^2 heat flux in the satellite surface.
Cold Space Environment	Temperature < 4K Absorptivity =1.0
Albedo	Approximately 0.48 kW / m^2. *
Eigenradiation of the Earth	Approximately 0.23 kW/m^2.*

* This value depends on the relative position of the spacecraft to the Earth and Sun

A satellite in space experiences an intense radiation when it is exposed to the sun. When the satellite is into the umbra (without sunlight) it experiences an environment of extreme coldness. These conditions allow to calculate the satellite 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. [2-3]

III. Space Simulation Chambers

The Space Simulation Chambers are systems used to recreate as close as possible the environment conditions that satellite experiences into space, as well as serves to space components qualification and material research used in satellite. The systems allow the satellite thermal behavior to be analysed. [4] There are two types of space environment simulators, the ones with solar simulator and the ones without. Systems without solar simulator are known as *Thermal Vacuum Chambers.* [5] These systems also recreate the space environment conditions, including solar radiation, by using different devices in the test setup. Figure 2 shows two classes of space simulation chambers.

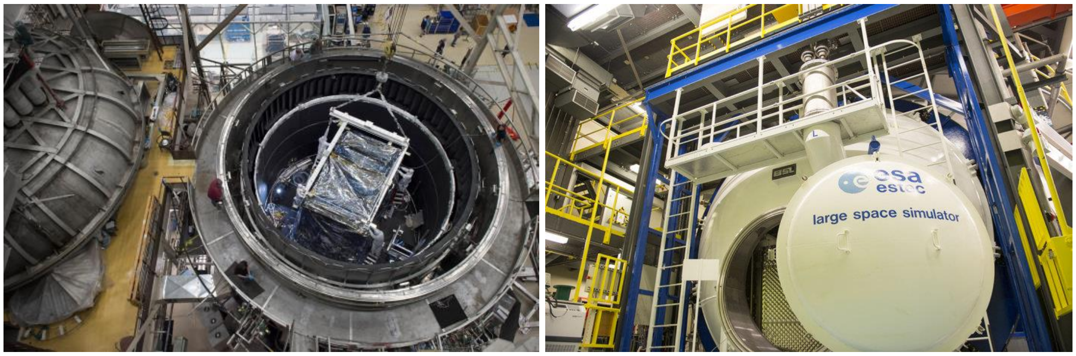

Figure 2. (Left) Space Environment Simulator (SES) NASA Goddard Space Flight Center and (Right) Large Space Simulator (LSS) ESTEC Test Centre, ESA.

IV. Space Environment Simulation

Space simulation chambers simulate the space thermal environment 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.[2-5-6] 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. The solar simulator is a compounded system with an artificial light source adjusted through optical mechanisms and filters that provide intensity and spectral composition similar to sunlight for the satellite test. 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).[5] Albedo and Eigenradiation are not simulated in thermal vacuum chambers since their values are diffuse and depend on the satellite position relative from the Earth and Sun, among other characteristics.[6]

Given these restrictions and limitations, the Thermal Vacuum Chambers simulate with closeness the vacuum and cold space environment. Beyond this, through the use of other devices to the system (electrical heaters, infrared heaters or Cal-Rods) is possible to simulate the thermal loads that will be experienced by satellite when exposed to solar radiation during its operation. It should be noted that the satellite is mathematically modeled using software, which use the exact values of all phenomena experienced in space.

V. Problem

Most of thermal vacuum chambers in several space research centers were originally designed to test large satellites. Figure 3 shows the contrast between large and small satellites.

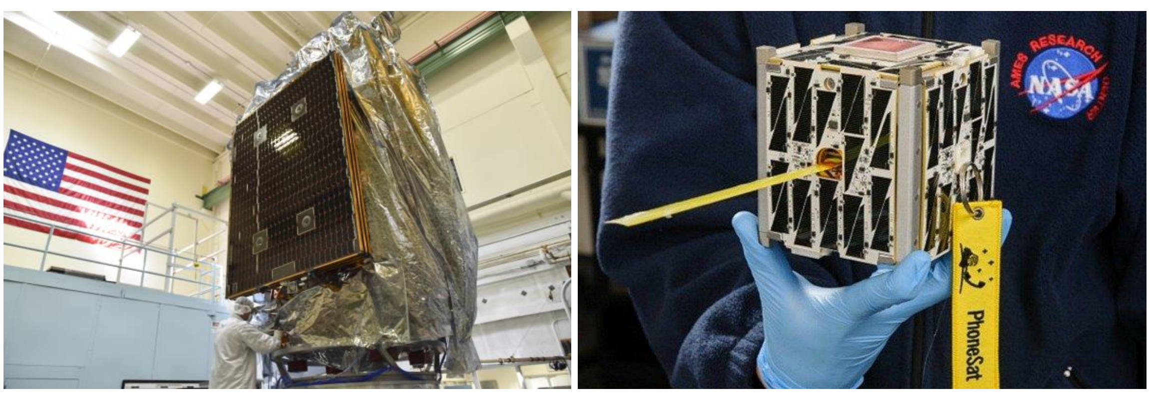

Figure 3. (Left) The JPSS-1 Satellite - NOAA & NASA and (Right) CubeSat - PhoneSat 2.5 NASA/ARC

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, our multidisciplinary professionals team 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.

VI. Using Systems Engineering Philosophy

Systems engineering is conceived as a multidisciplinary group of organized knowledge focused on high complexity systems development. 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. 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. For development of the 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.

A. Stakeholders

The stakeholders of the Thermal-vacuum chamber are: Space Research Institutions, Assembly Integration and Test Centers, Research & Development Laboratories for Space Products, Education Institutions, Space Product Development Companies and Military Organizations.

B. Needs

The following is a list of needs established through the interviews development to stakeholders:

- The stakeholders need a system that generate the space thermal environment.
- The stakeholders need a space thermal environment simulation system adapted for small satellite.
- The stakeholders need a space simulation system that allows execution of all Thermal Test (Thermal Vacuum Test, Thermal Cycling Test and Thermal Balance Test.) required for development and verification of small satellites.

C. Requirements

Due to the text limitation for the publication of the article, it is not possible to list all requirements that the space simulation system must have. The following list have the main requirements which were established through systems engineering analysis to the design of the system:

- The space simulation system shall be able to encapsulate Picosatellites, CubeSats, Nanosatellites and Microsatellites.
- The system shall generate a high vacuum environment (1×10^{-3} mbar to 1×10^{-7} mbar or less).
- The system shall produce high vacuum in less than one (1) hour.
- The system shall generate a hydrocarbon-free vacuum.
- The system shall generate temperatures ≤ -173.15ºC and ≥ 126.85ºC.
- The system shall have an operation control system.
- The system shall provide ways for communication between small satellite and vacuum chamber exterior during the environment simulation.
- The system shall inform the real-time pressure and temperature inside vacuum chamber.
- The system shall provide a means for acquiring data from the pressure and temperature experienced by the test object.
- The system shall permit internal chamber visualization during an environment simulation.
- The system materials shall preserve its mechanical properties under radiation, and extreme temperature changes (≤ -173.15°C and ≥ 126.85ºC.) and high vacuum and ultra vacuum (1×10^{-7} mbar to 1×10^{-12} mbar.).
- The system materials vapor pressure shall be minimal when it is exposed to high temperatures (≥ 126.85ºC.) during operation.
- The system structural materials shall be impermeable to gases, with a surface to prevent impurities and substances retention.
- The system shall be designed to maintain a high structural rigidity.

- The system materials shall not react in vacuum.
- The system materials shall not react with other adjacent materials.
- The adjacent materials thermal expansion shall match the system without generating undesirable distortions and mechanical interactions.
- The system materials shall not excessively emanate gases under high-energy particles interaction.
- The system materials shall have a low outgassing potential (less than 10^{-6} mbar ls-1 cm^{-2}.) under vacuum.
- The system materials shall have proper degassing properties for manipulation.
- The system materials shall be suited to minimize or cancel the presence of sources of steam and undesirable gases.
- The system shall be designed to be installed in cleanrooms and clean zones.

Through the requirements analysis it was possible to allocate requirements into physical systems that integrates the simulation system. The designed system is called Thermal Vacuum Chamber X. The Figure 4 identifies the systems that integrate chamber.

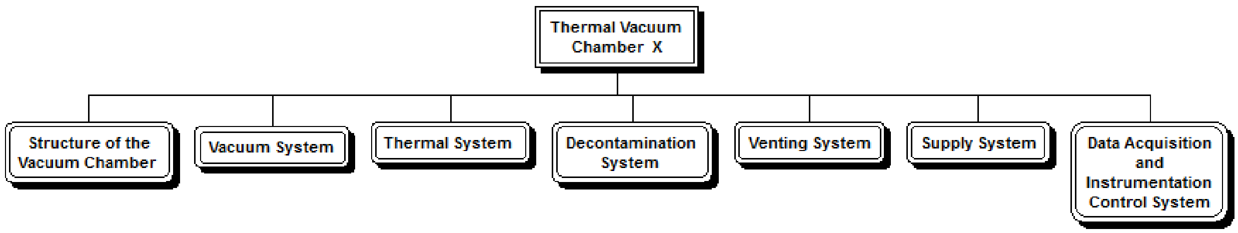

Figure 4. Systems that integrate the Thermal Vacuum Chamber X.

To identify ways in which the systems meet the requirements from systems engineering analysis, each system is described in the following. 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.

VII. Thermal Vacuum Chamber X

In the following is performed a description of each system that integrates the Thermal Vacuum Chamber X, also some basic criteria and requirements to its function and interaction with the test specimen.

A. Structure of the Vacuum Chamber

The chamber structure also known as vacuum chamber, allows the conservation of vacuum and thermal radiation phenomena, which are very important characteristics to simulate the space environment; it also houses the test specimen.[7]

There are several structural shapes for thermal vacuum chambers, but not all of them have a good structural rigidity which prevents their collapse by pressure changes (internal/external difference) and other stresses. Figure 5 shows the different chamber shapes and their rigidity level.

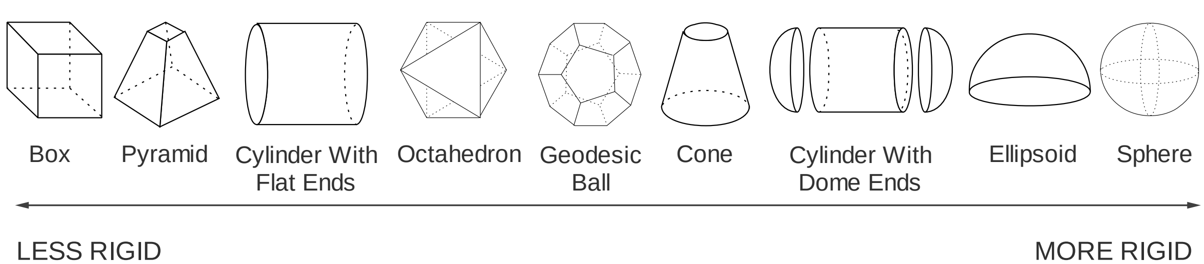

Figure 5. Types of vacuum chamber shapes and rigidity level of the shapes. Adapted [8]

A very common way to increase the structural rigidity of these shapes is through the use of stiffening rings. Considering the stiffness characteristics of different shapes, as well as the manufacturability and the historic market trend, a cylindrical structure with dome ends is the shape selected for the morphology of the Thermal Vacuum Chamber X.

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*".[9] In Figure 6 isometric views of the designed Thermal Vacuum Chamber X are shown.

The chamber is fabricated of type 304 Stainless steel with the inner surface polished to a No 4 mill finish to minimize outgassing and radiation, all flanges, connections and fittings are constructed of 304 stainless steel. These materials were selected for the vacuum chamber structure and fittings to minimize or cancel the presence of sources of steam and undesirable gases. The internal surface of the vacuum chamber is polished, reduced their effective surface area and adsorption capacity.

The chamber structure and his support base are designed to maintain a high structural rigidity in order to prevent vibrations caused by different sources such as pumps operation, flow of fluids and other mechanical or electro-mechanicals devices connected in their structure.

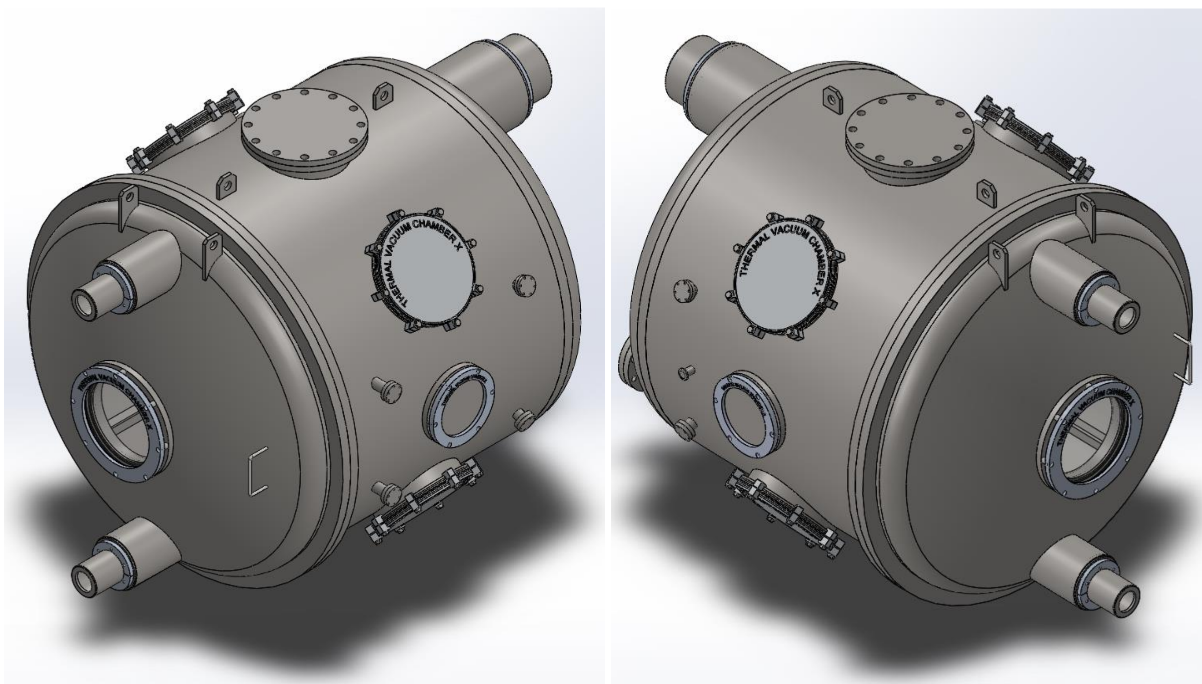

Figure 6. Thermal Vacuum Chamber X

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

Shape: Cylindrical with dome ends.
Internal Volume: 1950 Liters
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, QF Flange and ANSI-ASA flange.

The Viewport allows the small satellites visualization when they are tested. The chamber has multiple connections in which it is possible to install sensors, residual gas analyzers 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.

B. Vacuum System

The vacuum system function is to produce a desirable vacuum level in a reasonable time, also to maintain such level during all test.[7] 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 7 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).

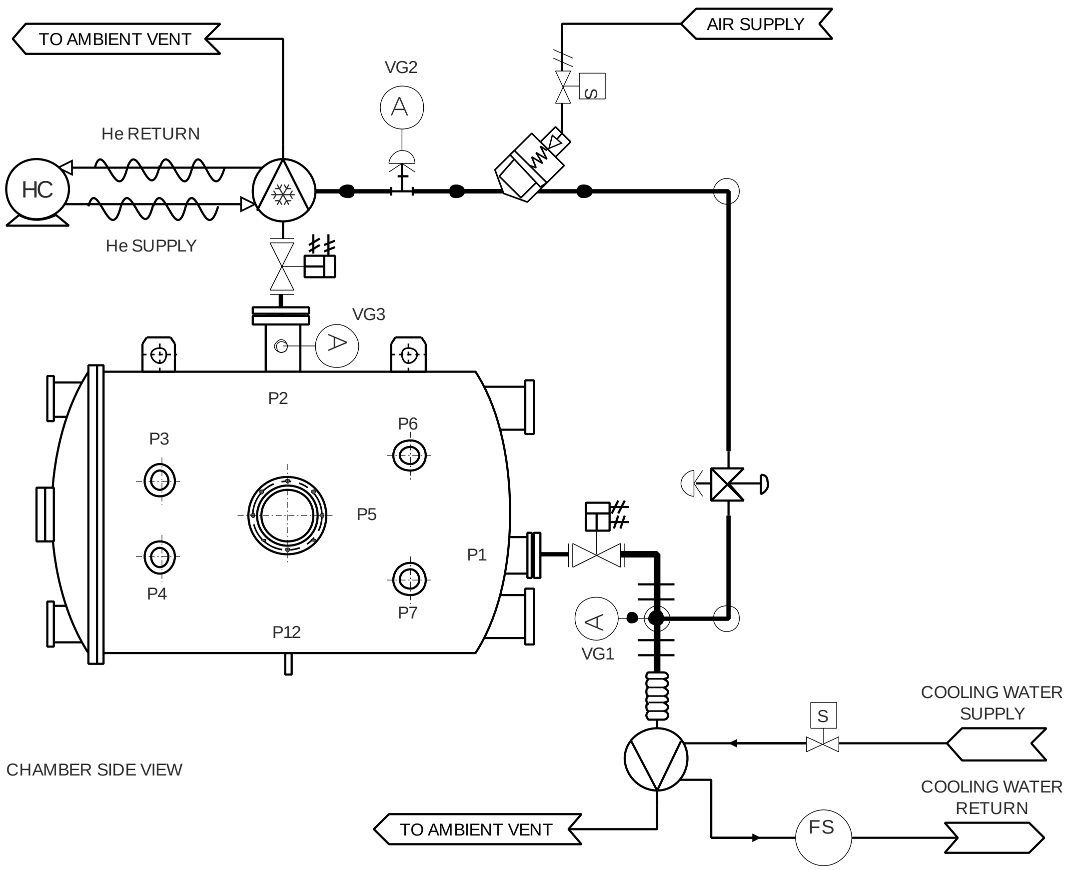

Figure 7. Vacuum System - Thermal Vacuum Chamber X

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 1 x 10^{-3} mbar, and a cryogenic pump to relieve pressure from 1 x 10^{-3} mbar to about 1 x 10-8mbar. Dry pump functions as a primary pumping unit in the system, and operates as backing pump for cryogenic pump. The backing pumping necessary for the initial operation of the cryogenic pump is achieved by a connection line from the dry mechanical vacuum pump. This pumping process is necessary because of the mechanical performance limits of existing pumping units. 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. The cryogenic pump is mounted directly on the high vacuum valve, which is in turn mounted directly to the upper of the chamber, maximizing conductance in the system. The components selection that integrates the vacuum system of the chamber ensure high vacuum acquisition in a very short period of time (less than 15 minutes) on a clean environment checked, protecting the integrity of test object system.

The dry mechanical vacuum pump is dynamically balanced and vibration isolated from other equipment using a flex coupling and special supports. The system has two electro-pneumatic gate valves connected to the chamber between each pumping unit, which functions to allow the evacuation of gases and ensure the preservation of a specific vacuum level (once it is obtained). The system uses three Thermal Conductivity pressure gauges to establish the pressure level in three different points. The first sensor (VG1) provides the pressure between the dry pump and the vacuum chamber. The second sensor (VG2) measures the pressure at the top end of the connecting line between the dry mechanical vacuum pump and cryogenic pump. The third sensor (VG3) performs pressure readings ranging from rough to medium vacuum generated inside the chamber. It is connected between the vacuum chamber and cryogenic pump using a QF flange style connection. 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 vacuum 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).

C. Thermal System

The thermal system function is to reproduce as close as possible the heat sink of space (cold environment). The thermal system represents the mechanism by which it is possible to simulate in a cycling manner the solar radiation effects and total darkness experienced by satellites in their missions.[7] The thermal system of the thermal vacuum chamber X is shown in the diagram of Figure 8.

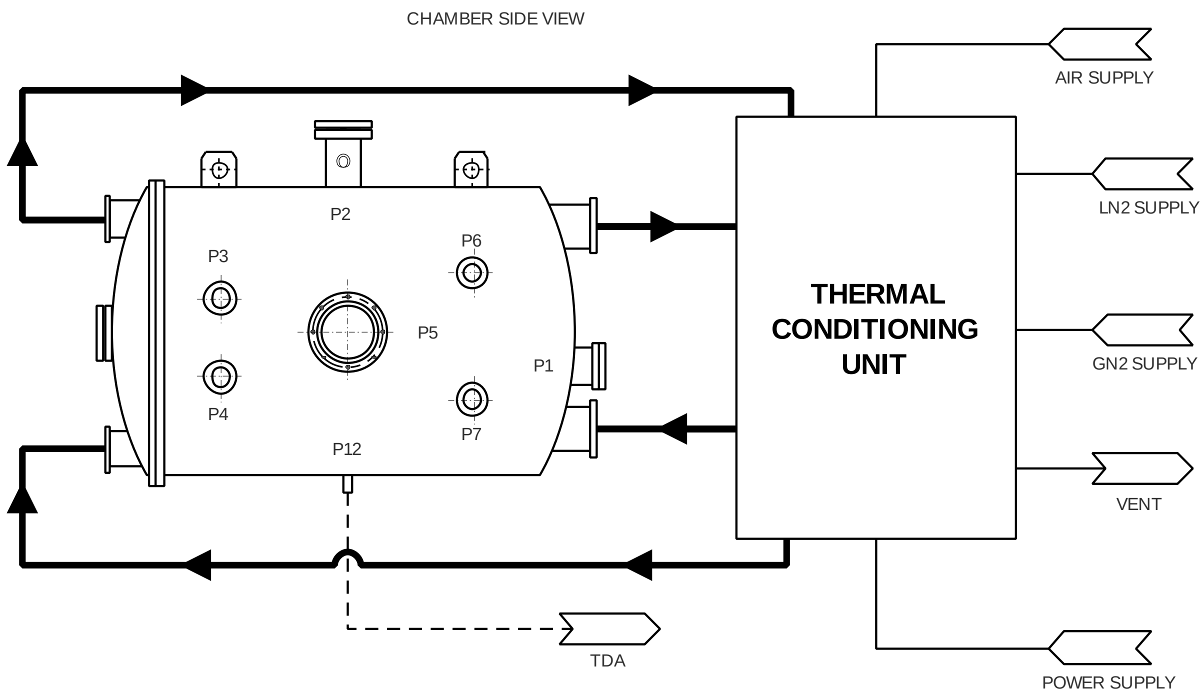

Figure 8. Thermal System – Thermal Vacuum Chamber X

The thermal system is comprised of a three zones thermal shroud to maintain the required thermal environment in the vacuum chamber, by means of a Thermal Conditioning Unit.

This Thermal System uses liquid nitrogen (LN_2) and gaseous nitrogen (GN_2) for operation. It has the ability to generate a temperature range from -180°C to 150°C inside the chamber by means of recirculating gaseous nitrogen controlled by a TCU. This system provides a possibility to work with liquid nitrogen to generate -196C inside the chamber through flooded thermal shrouds. This system provides a level controller (LC) of liquid nitrogen measures the required amount of liquid to fill the shroud. After completely fill the internal volume of the shroud with liquid nitrogen, sensors installed in the flow lines monitor their state to keep its temperature stable. When one wants to end the cold cycle, the shroud is drained by actuating a valve installed in the supply lines.

Cryoshrouds has D-type tubes and Bat-Wing (Figure 9), which integrates the heat transfer surfaces in the three areas of thermal control, which circulates gaseous nitrogen and liquid nitrogen from a TCU. One type of 1000 series aluminum alloy was selected for specific surfaces in the set, and two types of 6000 series aluminum alloy were the materials selected for shrouds and their main flow circuit. These materials have a low outgassing potential.

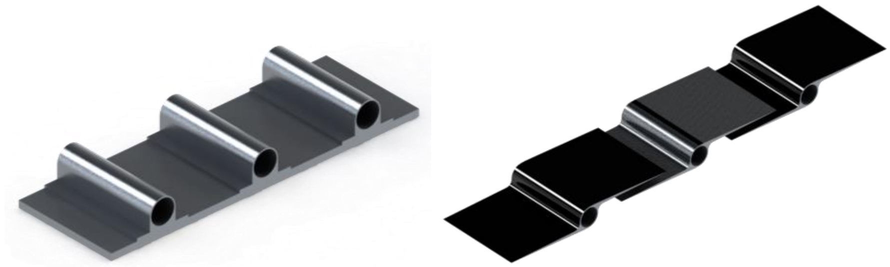

Figure 9. Thermal Shrouds – D-Tube on Sheet & Bat Wing

The thermal system is composed of three zones thermal shroud to maintain the required thermal environment in the vacuum chamber. The figure 10 shows the thermal shrouds of the Thermal Vacuum Chamber X. The shrouds exposed area to the test specimen receives a surface finish with special black painting to obtain high absorptivity and high emissivity to obtain adequate heat transfer by radiation. [10] This special paint exhibits good property of emissivity and low outgassing rate. The external surface of shrouds is special polished to minimize radiation exchange with the vacuum chamber walls. The shrouds surfaces and central piping's are sized and connected in a manner that provides nearly uniform flow and heat transfer throughout the entire system. Parallel flow paths are provided to and from each of the three shroud sections to facilitate the cryogenic substances supply, recirculating and exhaust.

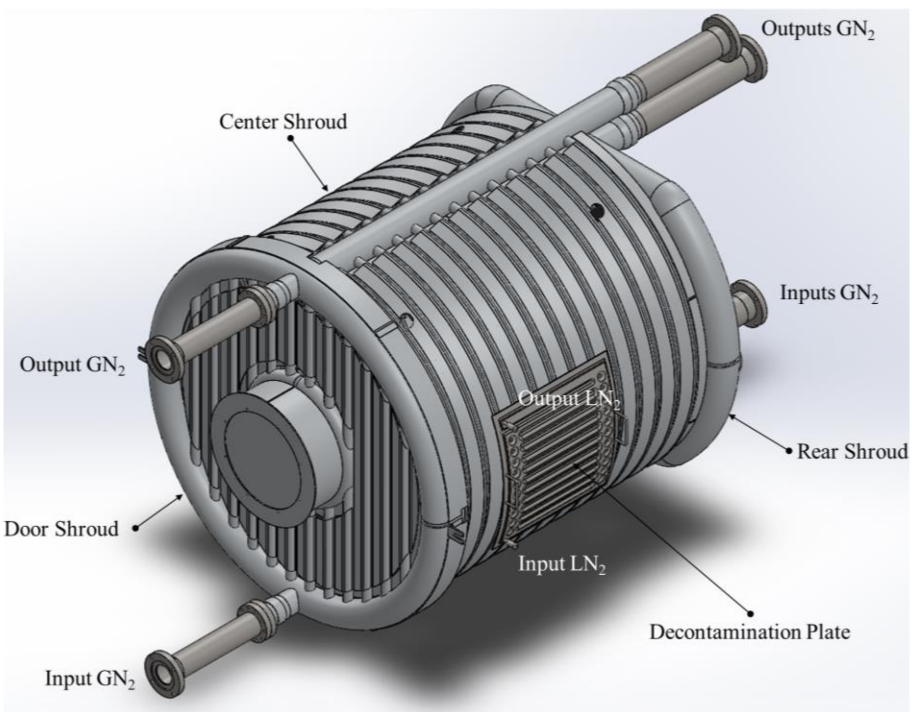

Figure 10. Thermal System - Thermal Shrouds – Door, Center and Rear Shroud.

The pipes that connect the TCU to the chamber have a vacuum jacketed insulation. In order to prevent loss of the substance cryogenic properties, it is used this type of insulation pipes. The chamber has a point at the bottom through which the thermal sensors installed in the shrouds surfaces communicate the temperature data on the surfaces to the control system. This line of sensors exiting the chamber is interconnected to Thermal Data Acquisition (TDA) in the control system.

D. Decontamination System

The decontamination system function is to achieve a significant reduction of the contamination due to outgassing generated by compounds and materials inside the vacuum chamber during an environmental test. This system generate a significant temperature reduction in a specific part of the inside the vacuum chamber, reducing the vapor pressure and capturing the molecules in suspension, allowing a clean control of the process, obtaining different vacuum levels inside the chamber more faster. This process considerably reduces the work of the pumping units. The Figure 11 shows on the P&ID the installation, distribution and localization of components that integrate the decontamination system.

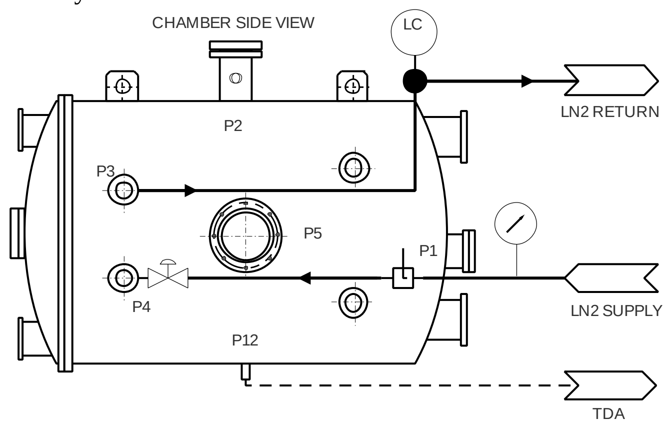

Figure 11. Decontamination System - Thermal Vacuum Chamber X

This system comprises a liquid nitrogen supply line, control valves, pressure gauge, a cryopanel electro-polished, temperature and level sensors which are installed on the extension of the piping circuit. The cryopanel located inside the vacuum chamber is flooded with liquid nitrogen and captures gaseous molecules that collide on their surface and turns them into crystalized solid particles (Inverse sublimation or deposition.). Liquid Nitrogen is fed into the bottom of cryopanel section through control valve, and the resulting liquid nitrogen is vented from the panel by means of connection pipe at the top of the same.

E. Venting System

The venting system permits the pressure inside the vacuum chamber to return to atmospheric pressure. This system permits to open the chamber ensuring safety for system operators through the increase of chamber's internal pressure normalizing the environmental conditions. This system uses filtered gaseous nitrogen to return the chamber to room pressure. The Figure 12 shows on the P&ID the installation, distribution and position of components that integrates the venting.

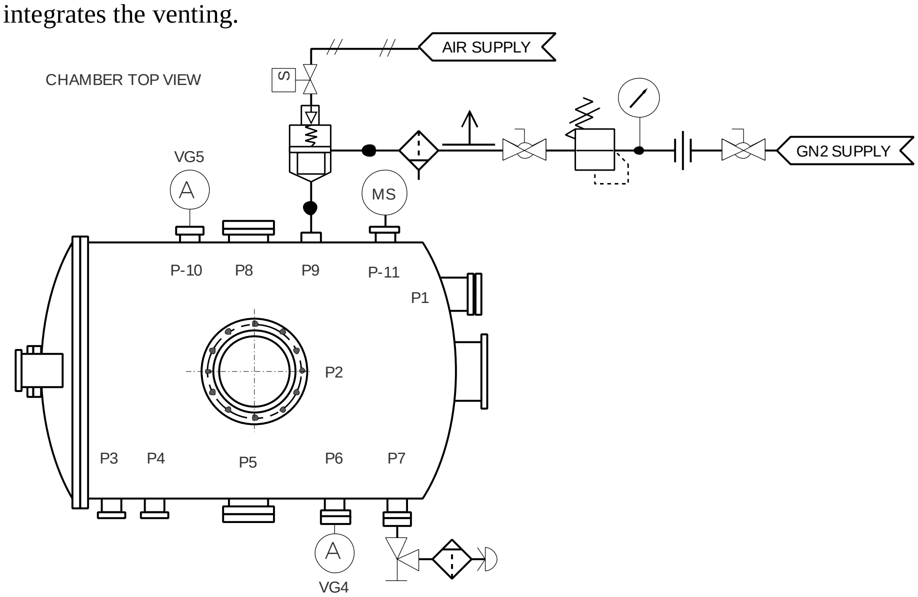

Figure 12. Venting System – Thermal Vacuum Chamber X

A filter installed on the gaseous nitrogen 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. This system provides a manual angle valve connected to the chamber as a means for auxiliary pressurizing with filtered air. This section of the system should be used under special conditions or emergency case.

F. Supply System

The supply system provides and manages the necessary resources (water, electricity, compressed air, specific substances, etc.) to operate the devices.[7] The supply system consists of pneumatic and hydraulic lines, where are installed flow control valves, relief valves, filters, lubricators, pressure regulators and different gauges.

The thermal and vacuum system is provided compressed air at different pressures for operation of its electro-pneumatic valves. Figure 13 illustrates in P&ID the distribution of devices that integrates the circuit of compressed air supply.

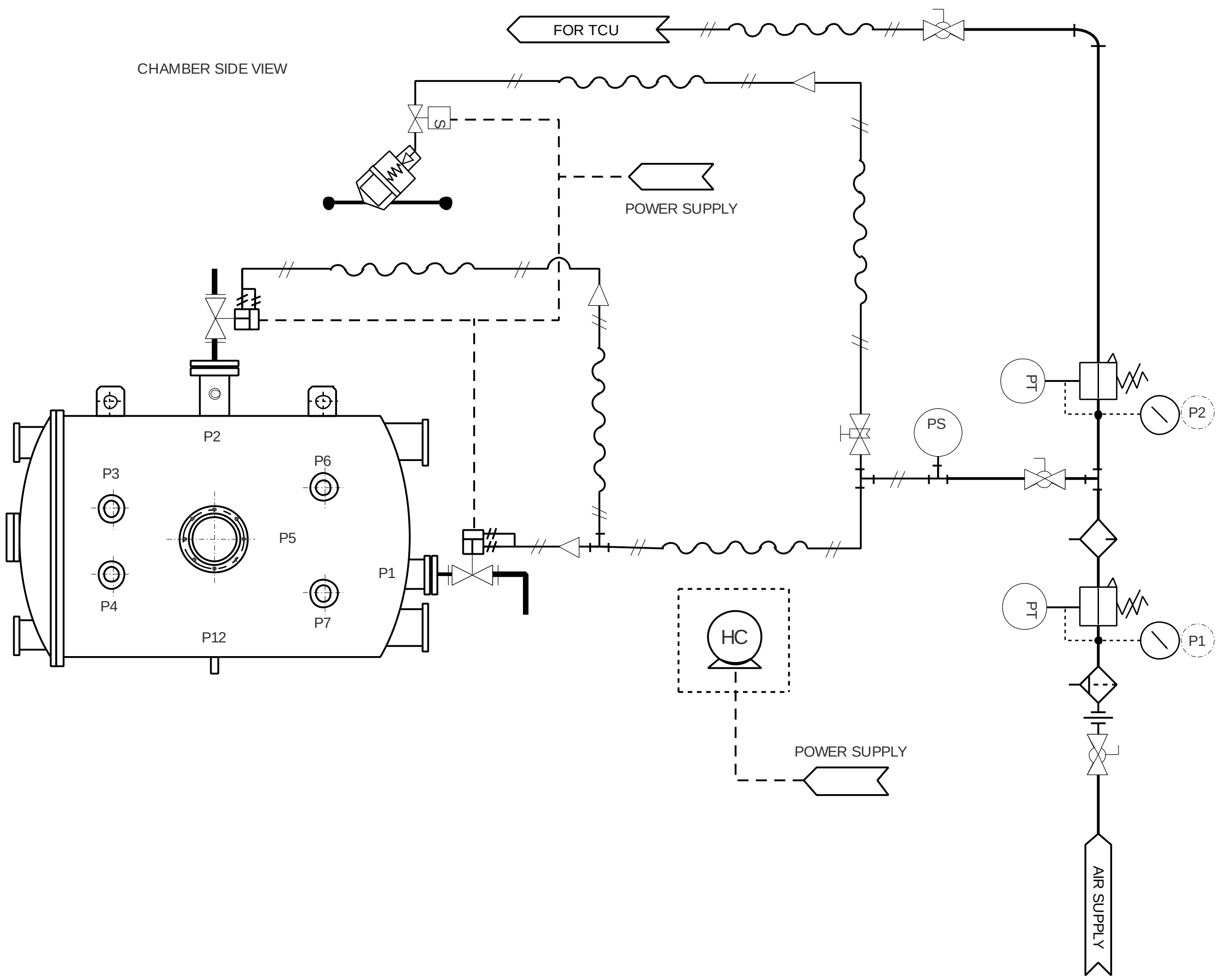

Figure 13. Compressed Air distribution – Thermal Vacuum Chamber X

In order to establish comparison criteria between the space simulation chambers offered in the market and the vacuum thermal chamber X, describes in detail the resources used by each systems that integrates it, since this information is relevant when purchasing an environment space simulation system on the market. Following the table 3 describes of type of supply used by each system for operate.

Table 3. Type of supply used by each system

	SYSTEMS OF THE THERMAL VACUUM CHAMBER				
UTILITIES	Vacuum System	Thermal System	Decontamination System	Venting System	Control and Instrumentation System
Water	**X**	**X**			
Compressed Air	**X**	**X**			
Liquid Nitrogen		**X**	**X**		
Gaseous Nitrogen	**X**	**X**		**X**	
Gaseous Helium	**X**				
Electricity	**X**	**X**	**X**	**X**	**X**

The vacuum system designed uses water for cooling of the dry mechanical pump. This system uses compressed air at a specific pressure to operate the electro-pneumatic gate valves. This allows to sealing the vacuum chamber and connection lines between the pumping units. The compressed air is filtered and lubricated for the distribution.

The Vacuum System also uses electricity to power pumping units, helium compressor and the control valves.

The Thermal System uses liquid and gaseous 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 Venting System uses dry gaseous nitrogen to return the vacuum chamber to ambient pressure.

The Decontamination system uses liquid nitrogen for flooding of the cryopanel, and electricity for the operation of control valves and sensors.

The Vacuum Chamber Structure as means of conservation of thermal vacuum environment does not use any consumables.

The Data Acquisition and Instrumentation Control System only uses electricity to operate, which is distributed among its measuring, monitoring and control devices.

G. Data Acquisition and Instrumentation Control System

The Data Acquisition and Instrumentation Control System provide the mechanisms and interfaces to control and monitor the different mechanical, electronic and electromechanical devices that compose the Thermal Vacuum Chamber X. This system represents the interface through which the operator can exercise control and acquire information about the status of the systems and devices that form the thermal vacuum chamber. This system allows the operator to control the components involved in each stage of vacuum generation, and allows control, monitoring and intervention in the processes of temperature conservation and cycling. The control system of the chamber shall consist of PLC units, sensors and lines communication. This control system has interlocks, which protect the integrity of the systems, controlling unwanted decisions that can be made by operators. The PLCs control units of rough and high vacuum pumping, as well as vacuum gate valves, safety valves, thermal devices and other components that are part of the thermal vacuum chamber systems. Such controllers are connected to a central processor where their operating status is displayed on a Supervisory Control and Data Acquisition Program.

VIII. Conclusion

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 are determined to run tests on small satellites. In Figure 14 isometric views of the designed Thermal Vacuum Chamber X are shown.

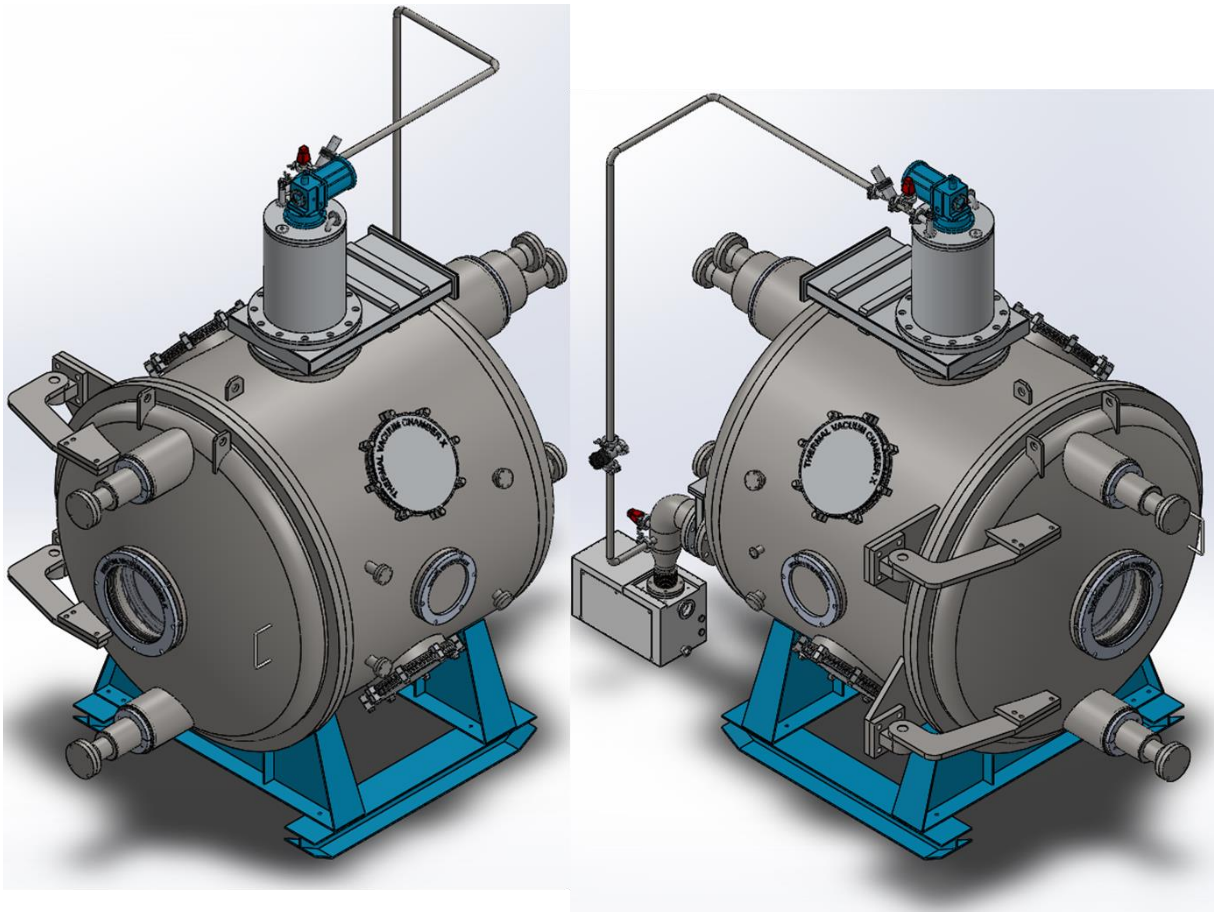

Figure 14. Thermal Vacuum Chamber X

The basic criterion determined for the vacuum chamber material selection is the compliance with the established requirements, as well as the tendency to use for the type of simulation processes intended to take place. There are not any specific rules or standards which describe the necessary criteria to build space simulation chambers. The pressure vessel international design standards were used as reference. Using international standards for the design of the chamber was necessary to make some appropriate adjustment to design the thermal vacuum environment simulation.

Not all pumping systems are suitable or entirely suitable for use in thermal vacuum chambers for space simulation, given that some of these by the nature of their operation use lubricant oils or greases for cooling components or for vacuum generation. This condition represents a risk due to probability of migration of polluting vapors into the vacuum chamber. For this reason, the pumping system selected for our Thermal vacuum chamber is integrated by a dry mechanical vacuum pump and one cryogenic pump. The high vacuum pumping unit and decontamination cryopanel will maximize system capture coefficients, thus effecting faster removal of the contaminants present in the test volume. In the Thermal Vacuum Chamber X it is not necessary to integrate the cold traps or traps into the vacuum system because the selected pumping units are oil-free and hermetically sealed. Considering the internal volume of the vacuum chamber X, as well as the capacity and suction speed of the dry mechanical pump selected for the vacuum system, is not necessary the uses of the support pump or second phase to reach medium vacuum at the interior of the chamber.

The structure of the vacuum chamber X has several flanges available for an additional high vacuum pump installation (for example a turbo molecular pump), which serves as a redundant pumping unit for the vacuum system.

The chamber support frame structure has been designed to maintain a high structural rigidity in order to prevent vibrations caused by different sources such as pumps operation, flow of fluids and other mechanical devices connected to the chamber. The thermal vacuum chamber meets the requirements to be installed in cleanrooms and clean zones.

There is a strong trend in developing small satellites 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 conventional (large) satellites, rising total test costs. This justifies the development of a thermal vacuum chamber, called Thermal Vacuum Chamber X, main scope of this work. This paper presented the Thermal Vacuum Chamber X development, which is a space simulation chamber adapted to small satellites. The test equipment has an internal volume of 1950 liters, allowing to test Picosatellites, Nanosatellites, CubeSats and Microsatellites, from mass less than 1 Kg to maximum 50 Kg.

The thermal vacuum chamber X was designed to serve as a test medium for small satellites. However it can also serve as a test medium for various types of small spacecraft (Flyby spacecraft ,Orbiter spacecraft, Atmospheric spacecraft, Lander spacecraft, Rover spacecraft, Penetrator spacecraft, Observatory spacecraft and Communications spacecraft) or spacecraft subsystems, which can be inserted into the interior of the vacuum chamber taking care of the dimensional constraints imposed by the size of the thermal system and the capacity of the permissible weight has the test article support and the platen support of the thermal vacuum chamber X.

The development of this space simulation chamber was based on a systems engineering philosophy to capture users' needs, and transform 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. S., and Craig, L.U., *Spacecraft System Engineering,* 4th ed., John Wiley & Sons, Ltd, United Kingdom, Chap. 18.

[2]Goethert, B. H., *Space Simulation Chambers and Techniques*, Technical Editing and Reproduction ltd, London, 1964, Chaps. 2,3,4,5.

[3]David, G. G., *Spacecraft Thermal Control Handbook – Volume I: Fundamental Technologies,*2nd ed., The Aerospace Press, El Segundo California, 2002, Chaps. 2, 19.

[4]Nuss, H. H., "Space Simulation Facilities and Recent Experience in Satellite Thermal Testing," *Vacuum*, Vol.37, No. 3/4, 1987, pp.297-302.

[5]Mercer, S., "Cryogenics: a Technological tool For Space Scientists," *Cryogenics*, Vol.8, Issue 2, 1968, pp. 68-78.

[6]Haefer, R. A., "Vacuum and Cryotechniques in Space Research," *Vacuum,* Vol.22, Issue 8, 1972, pp. 304-314.

[7]Chisabas, R. S., "Space Simulation Chambers State-Of-The-Art," 67th International Astronautical Congress (IAC), Guadalajara, Mexico, 2016.

[8]Harrison, K., "Engineering a Better Vacuum Chamber," GNB Corporation, URL: http://www.gnbvalves.com/pdf/EngineeringaBetterVacuumChambe.pdf [cited 17 January 2017].

[9]American Society Mechanical Engineers – ASME, "Pressure Vessel Code – An International Code, VIII Rules for Construction of Pressure Vessels Divisions 1," 2013.

[10]Gary, S. A., "Manufacturing of Cryoshroud Surfaces for Space Simulation Chambers," DynaVac, Hingham, MA, URL: http://www.dynavac.com/wp-content/uploads/2015/12/Space-simulation-Conference-2008-2.pdf [cited 17 January 2017]