Chapter 2

Space Thermal and Vacuum Environment Simulation

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Additional information is available at the end of the chapter

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Abstract

The space simulation chambers are systems used to recreate as closely as possible the thermal environmental conditions that spacecraft experience in space, as well as also serve to space components qualification and material research used in spacecraft. These systems analyze spacecraft behavior, evaluating its thermal balance, and functionalities to ensure mission success and survivability. The objective of this chapter is to give a broad overview on space simulation chambers, describe which are the environmental parameters of space that can be simulated in this type of ground test facilities, types of the space environment simulators, class of phenomena generated inside, and the technological evolution of these systems from its conception. This chapter describes the basic systems and devices that compose the space simulation chambers.

Keywords: space environment simulation, space simulation chamber, thermal vacuum chamber

1. Introduction

The spacecrafts are developed for various applications such as space science, navigation, communications, technology testing and verification, earth observation, weather observation, military applications, human space flight, planetary exploration, and others [1]. According to the type of mission destined to fulfill by the spacecraft, it is possible to classify them into several types such as Flyby spacecraft, Orbiter spacecraft, Atmospheric spacecraft, Lander spacecraft, Rover spacecraft, Penetrator spacecraft, Observatory spacecraft, and Communications spacecraft [2].

To start the operation phase, the spacecraft need to meet all conventional space project life cycle development phases such as Concept Studies, Concept and Technology Development, Preliminary Design & Technology Completion, Final Design & Fabrication, System Assembly Integration and Test (AIT), Launch Campaign, Operations & Sustainment and Closeout [3]. In the integration and test phases, the spacecraft is assembled, integrated, and tested. **Figure 1** shows the usual activities that comprise assembly, integration, and test of spacecraft.

For execution, spacecraft tests program is required for the uses in different types of facilities such as Vibration test facility, Acoustics test facility, Mass properties test facility, space simulation chamber, EMC test facility, Magnetics test facility, and others [4]. These facilities are designed to research, develop, test, and verify the performance of the spacecrafts. In these facilities, it is possible to simulate the environmental conditions experienced by the spacecrafts during the launch phase and their exposure to the space environment.

1.1. Thermal tests

Several types of thermal tests are required for development, performance validation, and to ensure the survivability of the spacecraft in operation. These tests can be performed in components, subsystems, and systems levels. The thermal testing usually includes a Thermal Cycle Test (TCT), Thermal Vacuum Test (TVT), Thermal Balance Test (TBT), and Vacuum Bake-out test [5].

Thermal Cycle Test (TCT): This 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 generates an environmental stress in the test article that allows to identify material and workmanship defects.

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

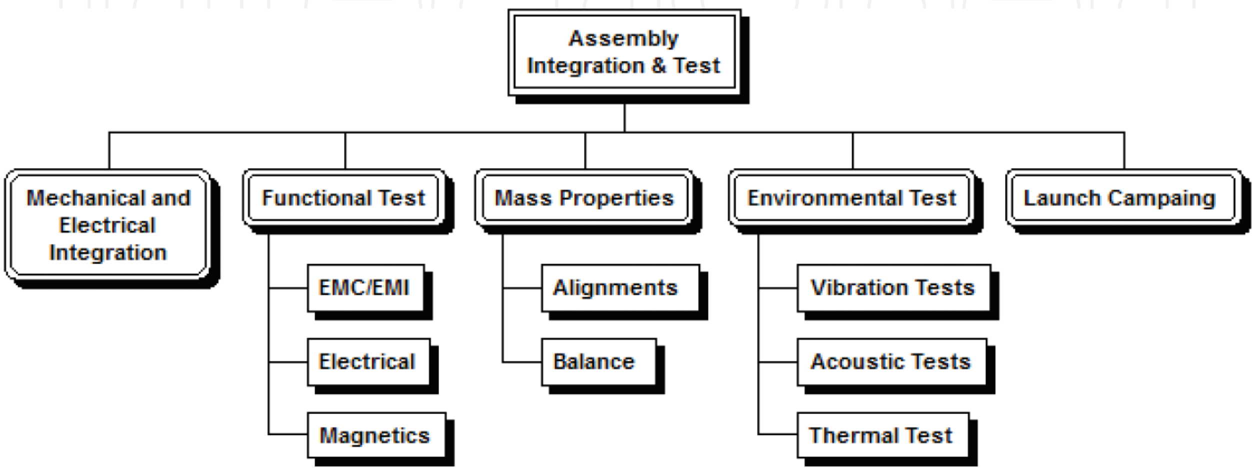

Figure 1. Activities in the assembly integration and test process.

Figure 2. (Left) Chamber A – NASA Johnson Space Center's and (Right) large space simulator (LSS) ESTEC test Centre, ESA.

Thermal Balance Test (TBT): Space simulation chambers are used to perform this type of test. The purpose of this test is: Demonstrate the performance of the thermal control system to maintain the temperatures within the operational limits. This test is necessary to verify the performance of the spacecraft 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 TVT 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 thermal environment. The selection of number of thermal cycles in TBT and TVT depends on the type of test level.

Vacuum Bake-out Test: The spacecraft is exposed to high temperature in a high vacuum environment during a determined time to stimulate their outgassing. This test is executed to subsystem or system levels. Space simulation chambers are used to perform this type of test.

The thermal tests are performed at various temperature levels established in each test levels. The test levels are: Development Tests, Qualification Tests, Acceptance Tests, and Protoflight Qualification Tests. Considering the type test level, general rules and standard are available to determine the temperature and pressure levels of thermal tests in subsystems and spacecrafts. Some rules and standards are: GSFC-STD-7000, MIL-STD-1540D, MIL-HDBK-340A, ECSS-E-ST-10-03C, TR-2004(8583)-1, NASA LSP-REQ-317.01, among others.

During spacecraft environmental testing, which is part of the Assembly, Integration and Test process (AIT), Space Simulation Chambers play a key role to spacecraft systemic models qualification (e.g. Structural Model, Thermal Model, Engineering Model, Qualification Model, Flight Model, and Protoflight Model). **Figure 2** demonstrates two types of space simulation chambers.

2. Space simulation chambers

The space simulation chambers are systems used to recreate as close as possible the environment conditions that spacecrafts experiences into space, as well as serves to space components qualification and material research used in spacecrafts. These systems allow the spacecrafts thermal behavior to be analyzed [6]. 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 [7]. These systems also recreate the space environment conditions, including solar radiation, by using different devices in the test setup. Space simulation chambers are designed to serve as a test medium for various types of spacecrafts and their subsystems.

3. Space environment

The ambient which experience the spacecraft consist in the combination of the space environment in function of the orbit where the mission will be developed (Low Earth Orbit, Medium Earth Orbit, Polar Orbit, Geosynchronous Orbit, and Interplanetary Orbit) and the environment generated by same spacecraft in operation [8]. The space environment main characteristics experienced by spacecraft orbiting the Earth are: high vacuum, cold space environment, and different sources of radiation. The space environmental phenomena are showed in **Figure 3**.

A spacecraft in space experiences an intense radiation when it is exposed to the sun. When the spacecraft is into the umbra (without sunlight), it experiences an environment of extreme coldness. These conditions allow to calculate the spacecraft temperature during operation, which is determined by a balance between spacecraft internal heat, radiant energy absorbed by spacecraft, and radiant energy emitted to space by spacecraft surfaces [5, 9].

3.1. Pressure

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

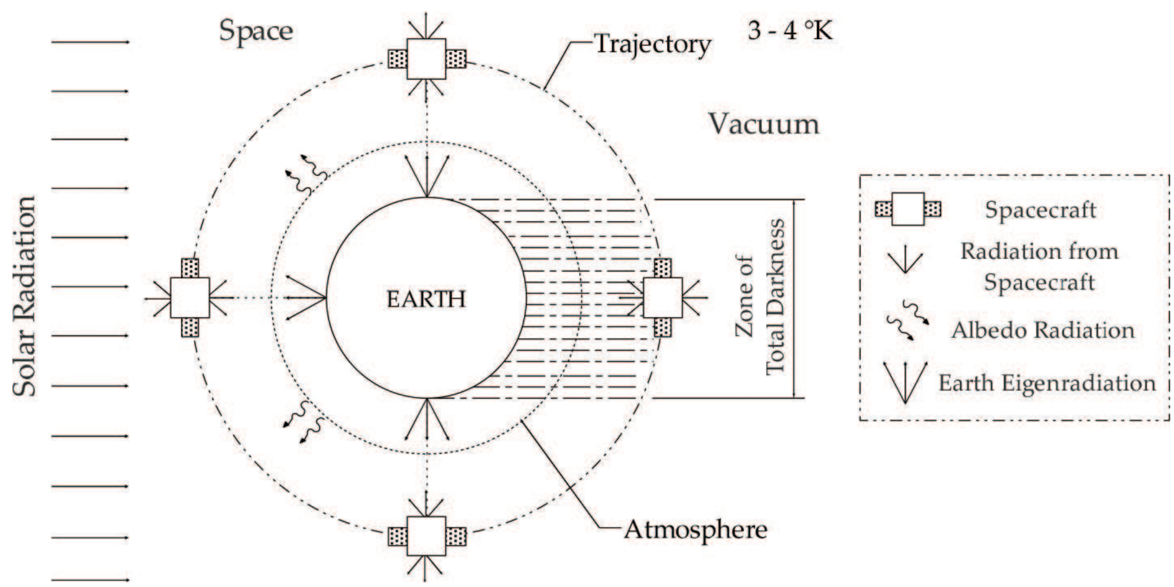

Figure 3. Space environment characteristics [3, 4].

3.2. The solar radiation

The solar radiation is a high intensity energetic phenomenon, which represents an approximate 1400 W/m^2 heat flux in the spacecraft. The heat flux change depending on the distance from the spacecraft to the sun. The absorption of such energy would generate a very high temperature inside the spacecraft, however, just a fraction of heat is absorbed due to space environment characteristics and spacecraft surfaces physical properties [5, 10].

3.3. 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 (3 K) and −260.15°C (4 K) [10]. This concept implies that the heat emitted by a spacecraft will not return to it [9].

3.4. Albedo and eigenradiation of the earth

Albedo is the fraction of incident solar radiation reflected by the Earth or the moon, which reaches spacecraft 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 [1]. 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 spacecraft to the Earth and Sun [10].

4. Space environment simulation

Space simulation chambers simulate the space thermal environment with close proximity, because to generate a temperature of −269.15°C (4 K), 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 to −173.15°C (77.3–100 K), which only represent a small error percentage to assess spacecraft in low temperatures, without significantly affecting thermal balance study [7–9, 10]. Due to this reason, it was established the trend of using heat transfer surfaces which generate the minimal temperature of −173.15°C (100 K).

For thermal balance study and analysis, it is essential to ensure the thermal loads that the spacecraft will receive from several sources of radiation in space. This radiation sources are transformed in high temperatures experienced by spacecraft 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 spacecraft 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 126.85°C (400 K) [7]. Albedo and eigenradiation are not simulated in thermal vacuum chambers since their values are diffuse and depend on the spacecraft position relative from the Earth and Sun, among other characteristics [10].

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), it is possible to simulate the thermal loads that will be experienced by spacecraft when exposed to solar radiation during its operation. It should be noted that the spacecraft is mathematically modeled using software, which use the exact values of all phenomena experienced in space.

In the space thermal environment simulation, it is not necessary to duplicate an ultrahigh vacuum level as that owns by outer space, but it is necessary to duplicate the effects that this environment generates in the materials, components, subsystems, and spacecraft systems. Due to the above mentioned, for the space environment simulation test, it is necessary to achieve a level pressure less than 1×10^{-6} mbar, because to this level is possible to properly evaluate the specimen and eliminate some undesirable effects such as the gas thermal conduction and arc and glow discharges [11].

5. Systems of the space simulation chambers

Through the study and analysis of environment conditions that shall be created by the space simulation chambers, it is possible to establish their basic composition. The conditions to be simulated are transformed into functions assigned to systems or a set of systems that will permit their generation. The basic systems that compose the space simulation chambers are shown in **Figure 4**.

The structure of the chamber, also known as vacuum chamber or vacuum vessel, allows the conservation of vacuum and thermal radiation phenomena, which is very important characteristics to simulate the space thermal environment; this also houses the test specimen.

The vacuum system function is to produce a desirable vacuum level in a reasonable time and maintain such vacuum level during all test time.

The thermal system function is to reproduce as close as possible the heat sink of space (cold environment). The decontamination system function is to achieve a significant reduction of

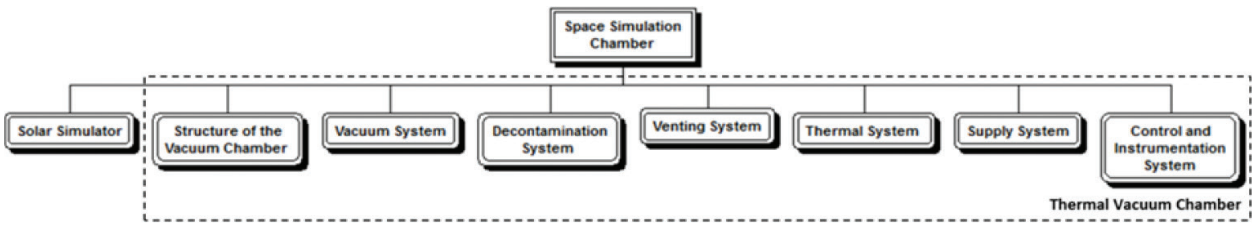

Figure 4. Subsystems that integrate the space simulation chambers.

the contamination due to outgassing generated by compounds and materials inside the vacuum chamber during an environmental test. The venting system permits the pressure inside the vacuum chamber to return to atmospheric pressure.

The supply system provides and manages the necessary resources (water, electricity, compressed air, specific substances, etc.) to operate the devices integrated in the systems of the space simulation chambers. The control and instrumentation system provide the mechanisms and interfaces to control and monitor the different mechanical, electronic, and electromechanical devices that compose the systems of the space simulation chambers.

The following sections will performed a description of each system that integrates the space simulation chambers, also some basic criteria and requirements to its function and interaction with the spacecraft or test specimen.

6. Structure of the vacuum chamber

The chamber structure allows the conservation of vacuum and thermal radiation phenomena, which are very important characteristics to simulate the space environment. There are several structural shapes for thermal vacuum chambers, but not all of them have a good structural rigidity which prevent their collapse by pressure changes (internal/external difference) and other stresses. **Figure 5** shows the different chamber shapes and their rigidity level.

A very common way to increase the structural rigidity of these shapes is through the use of stiffening rings. Stiffening rings, which are welded into the body extension, can reinforce structures that lack stiffness or have a considerable size. A cylindrical structure with dome ends is a typical design for a space simulation chamber. One criterion for defining the size of a chamber is the minimum operation pressure (vacuum level it would support). Another criterion is the thermal system size inside chamber and the maximum dimension of test specimen [11]. Taking into account the vacuum and thermal cycling generation processes, the materials for space simulation chambers manufacturing should meet certain requirements.

The material selection requirements for space simulation chamber manufacturing are stated below: the system materials shall preserve its mechanical properties under radiation, extreme

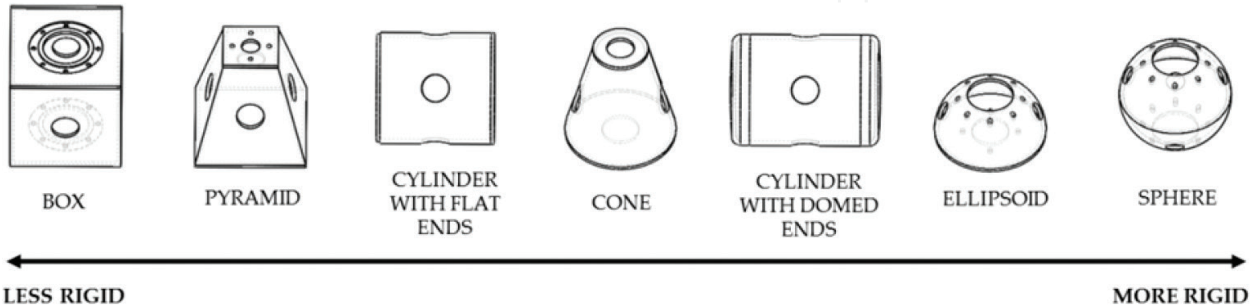

Figure 5. Chamber shapes and rigidity of the shapes [12].

temperature changes (≤ −173.15°C and ≥126.85°C), and high vacuum and ultra vacuum (1×10^{-7} to 1×10^{-12} mbar). The system materials vapor pressure shall be minimal when it is exposed to high temperatures (≥126.85°C) during operation. The system structural materials shall be impermeable to gases, with a surface to prevent impurities and substances retention. The structure of the vacuum chamber shall be designed to maintain a high structural rigidity. The system materials shall not react in vacuum and with other adjacent materials. The adjacent materials thermal expansion shall match the system without generating undesirable distortions and mechanical interactions. The materials of the system 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 (see **Figure 6**). The system shall be designed to be installed in cleanrooms and clean zones.

The basic criteria for the materials selection for space simulation chambers fabrication is the compliance of the previous defined requirements. The majority of space simulation chambers are fabricated from 300 series stainless steel [11]. For the chamber structure, type 304 stainless steel is used most frequently in vacuum systems [11, 12]. The 304 stainless steel is an appropriate material for vacuum chambers (also known as 18/8 stainless steel by its composition of 18% chrome and 8% nickel) given its properties such as low thermal conductivity, ductility, corrosion resistance, stiffness, weldability, and no magnetic reaction. Its surface shall be polished by several techniques (electro-polished, grained, bead blasted, machined/ground all over, and others) to homogenize, reducing the effective surface area, and adsorption capacity [14].

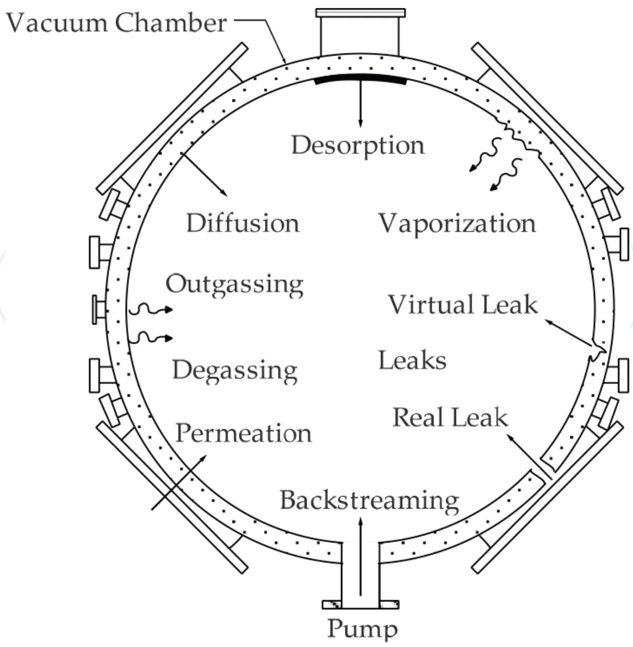

Figure 6. Potential source of gases and vapors in a vacuum chamber [13].

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6.1. Penetrations

The chambers structure surfaces have mechanical interfaces called Flanges that allow the connection between several devices or units such as pumps, valves, sensors, filters, residual gas analyzers, electrical feedthroughs, mechanical feedthroughs, and others. These flanges can be rotatable or non-rotatable type. Flanges are designed from international organizations codes (ISO, ANSI, and DIN) that determine their dimensions, performance, materials, application, and usages [14]. **Figure 7** shows some types of flanges usually used in space simulation chambers. To realize specific measurements or to monitor specific equipment processes and observe internal vacuum chamber phenomena, the chamber structures provide viewports flanges or observation windows. The viewports are specifically designed for vacuum, and to resist mechanical and thermal stresses generated by simulation system operation. The viewports discs are usually manufactured with a special glass, quartz, sapphire, or borosilicate. Depending on the viewport material and vacuum level generated inside the chamber, special materials are adopted for sealing. The viewport shall not contact any other surface than the sealing materials and the simulated environment.

6.2. Note

The sealing materials and techniques, types of welding for the structure union, and the general feedthroughs characteristics that can be used in space simulation chambers are not described in this chapter, given the textual extension that would be generated. However, author believe these are important topics and relevant for space environment simulators design. These topics will be addressed to future publications.

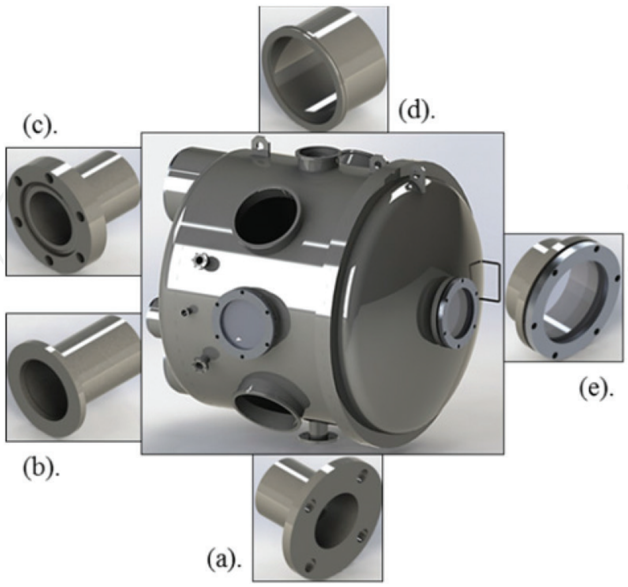

Figure 7. Common flange systems. (a) ASA flange, (b) KF flange, (c) CF flange, (d) ISO flange, (e) Viewport.

6.3. Rules and codes

There are no standards or specific rules that describe criteria to build space simulation chambers, however, pressure vessels international design standards are generally used for reference making the appropriate adjustments considering a vacuum chamber operation. The following standards define pressure vessels material selection, design, manufacturing, inspection, test, and certification:

- American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code, Section VIII: Rules for Construction of Pressure Vessels, Divisions I & II;
- PD 5500 Specification for Unfired Fusion welded pressure vessels, Sections 2 & 3 published by British Standard Institute (BSI);
- Code De Construction des Apparelis a Pression (CODAP) French code for construction of unfired pressure vessels issued by SNCT (Syndicat National de la Chaudronnerie, de la Tolerie et de la tuyauterie industrielle);
- The European Standard EN 13445 Unfired pressure vessels issued by CEN (European Committee for Standardization);
- The European Standard EN 13458-2 Cryogenic Vessels – Statics Vacuum, Insulated Vessels – Part 2: Design, Fabrication, Inspection, and Testing issued by CEN (European Committee for Standardization).

7. Vacuum system

The function of this system is to reduce the pressure inside the chamber by means of a controlled evacuation of particles in gaseous and suspension state, which generally comprises the air found inside the chamber. The typical constituents of dry air are: nitrogen (N_2), oxygen (O_2), argon (Ar), carbon dioxide (CO_2), neon (Ne), helium (He), methane (CH_4), krypton (Kr), and hydrogen (H_2) among others. The pumping systems has capacity of evacuate to ambient these types of gases to generate vacuum inside the chamber.

7.1. Pumping systems

The gases removal to achieve a specific level of vacuum within the chamber is executed step-by-step using different pumping systems, which can operate individually or in specific cases in an interconnected way. The interconnected pumping systems (roughing pump and/or backing pump with high vacuum pump) are used to achieve different levels of vacuum. Usually two types of units are used: one to decrease pressure inside the chamber from 1 to 10^{-3} mbar (rough vacuum/medium vacuum), and another to decrease the pressure from 10^{-3} 3 to 10^{-8} mbar or less (high vacuum). This pumping process is necessary due to mechanical performance limits existing in the pumping units. **Figure 8** shows the range of vacuum and vacuum pumps.

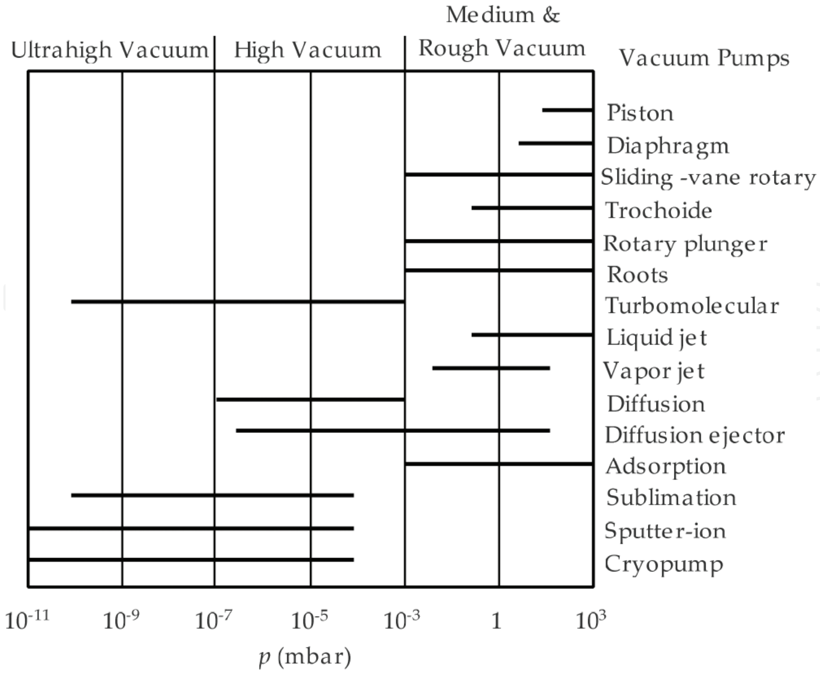

Figure 8. Ranges of vacuum and common working ranges of vacuum pumps [15].

The maximum level of vacuum that can be generated inside the space simulation chamber depends of the efficiency of the pumping units, the level of conductance in lines and appropriate control of cleaning, which avoids the presence of undesirable gases. It is worth to mention that not all pumping systems are suitable or entirely adequate to use in thermal vacuum systems for space simulation, given that some of these by the nature of their operation use lubricant components for cooling or for vacuum generation. This condition represents a risk due to probability of migration of polluting vapors into the chamber. When this happens, using filter elements as traps or a cold trap, it can reduce the effective capacity of the pumping unit [11]. Since the early 1980s, pumping systems have evolved mechanical and electronically, improving their performance, facilitating their operation, increasing their safety levels, reliability, cleaning, removing or replacing (in some cases) the use of consumables for operation and cooling of moving parts. The most used pumping systems for gases removal in space simulation chambers are: positive displacement pumps, cryogenic pumps, adsorption pumps, diffusion pumps, ion pumps and turbo-molecular pumps [11].

7.2. Traps and cold traps

The vacuum pumps that use oil for refrigeration or operation increase the oil vapor pressure control importance since the oil is exposed to the gases that are pumped from the vacuum chamber. If the oil vapor pressure is too high, it vaporizes when exposed to vacuum and may migrate to chamber, contaminating its interior [16]. The vacuum system is composed by foreline traps, refrigerated baffles and cold traps. Such devices are installed between the pumps and the vacuum chamber. They are used to remove contaminant particles and prevent backstreaming of oil vapors generated by pumps operation [16]. Foreline traps are devices composed by several types of filtering elements such as fibrous stainless steel sieve, fiberglass, or synthetic zeolite. These elements capture solid and gaseous substances that are potential system contaminants.

The refrigerated baffles and cold traps devices have cryogenic substances flowing to generate very low temperatures in their structure. These mechanisms restrain gaseous molecules that impact on their surface and transform them into crystalized solid particles (inverse sublimation or deposition) [16]. A significant temperature reduction at any part of the vacuum system reduces the vapor pressure, allowing a clean control of the process and faster achieving different vacuum levels inside the chamber. This principle is applied through the use of cold plates, decontamination plates, cryogenic pumps as well as the previously mentioned devices.

7.3. Pressure measurement

To measure the pressure inside the chamber, a variety of sensors for each vacuum level are used. Usually the sensors are divided into total pressure and partial pressure gauges. The total pressure gauges are classified from the operation of its internal mechanisms, which determine the pressure in a specific space, using hydrostatic pressure phenomena, thermal conductivity, or electrical ionization [14]. The partial pressure gauges determine the pressure of a gas mixture identifying their composition in a vacuum environment. In **Figure 9**, gauges for different ranges of vacuum are identified. Thermal conductivity and capacitive gauges (types of total pressure gauges) are generally used to determine the pressure in regions of low and medium vacuum. Usually it is used as hot and cold cathode ionization gauges and penning gauge to determining the pressure in regions of high and ultrahigh vacuum [14]. The adequate calibration of the vacuum gauges is fundamental to determine correctly the pressure level inside the vacuum chamber.

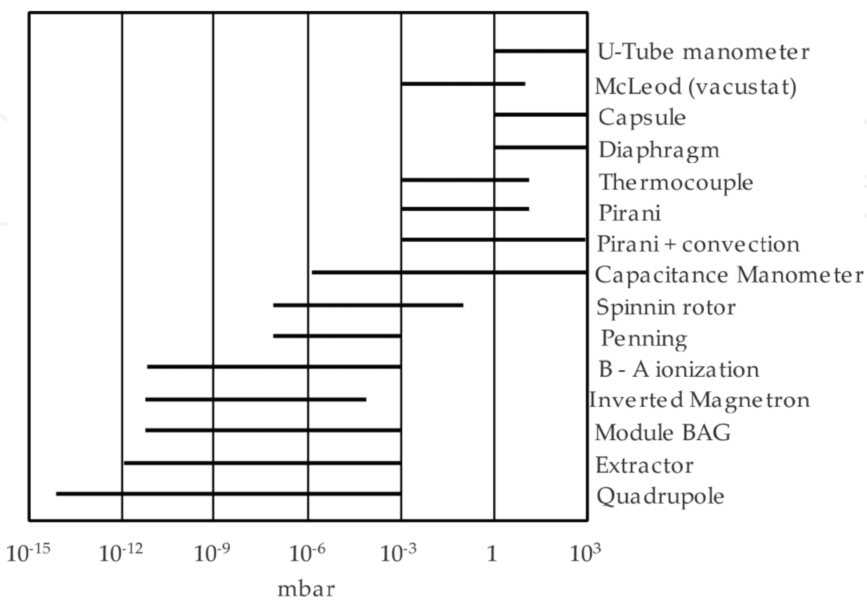

Figure 9. Pressure ranges for different gauges [14].

8. Decontamination system

This system generate a significant temperature reduction in a specific part 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. Usually, a cryopanel or a cold plate installed inside the vacuum chamber is flooded with a cryogenic substance and captures gaseous molecules that collide on their surface and turns them into crystalized solid particles (Deposition). Other types of device to collect condensable vapors are cold Fingers.

8.1. Contamination

Some techniques for the quantitative and qualitative analysis of the contaminants outgassed during space environment simulation test are: residual gas analysis, infrared spectroscopy, gas chromatography, mass spectrometry, quartz-crystal microbalance gravimetric, ultraviolet reflectance, and others [17]. The methods for detection sources of the contamination and measuring contamination during the development of the space environment simulation test are the direct and indirect methods [18]. A direct method for detection of the contamination is using the witness plates or reflective windows that are placed inside the space simulation chamber or in spacecraft. After the thermal vacuum test execution, the plates are analyzed through spectrometers to detect particulate pollutants. Residual gas analyzers and mass spectrometers are used to determine the gaseous composition inside the space simulation chamber and their pressure during operation. An indirect method for detection of the contamination is by means of the cleaning the witness plates after the thermal vacuum test execution. The film resulting from the cleaning process of the plates is analyzed through spectrometers [18]. The correct temperature and humidity level shall maintain the ideal environment for the space simulation chamber functioning.

9. Venting system

When testing procedures are finished and is necessary that the ambient pressure inside the chamber is returned, the vacuum system have a circuit of connected components, which allow access of filtered dry gas to increase the number of particles, reducing the mean free path. This procedure is used to open the chamber ensuring safety for system operators through the increase of chamber's internal pressure normalizing the environmental conditions. An inert gas is used, such as dry nitrogen gas (GN2), to vent the vacuum chamber to avoid pollution of objects that are housed therein. If ventilation is performed with other substances such as air or other compound gases, such substances can react with the surrounding temperature, causing water vapor molecules, and undesirable phenomenon of condensation which can be allocated in various areas within the chamber, contaminating exposed areas and the test specimen [5]. Usually, special filters are installed on the gas inlet line preventing access of impurities or microparticles.

10. Thermal system

The thermal system represents the mechanism whereby is possible simulate in a cycling manner the solar radiation effects and total darkness experienced by spacecrafts [7]. The cold heat sink of space can also be simulated. All phenomena described above are simulated with an approximation. To produce such conditions, the system uses a set of surfaces installed inside the chamber called "Thermal shrouds", and a number of external pipes connected in a hydraulic control circuit. The thermal shrouds, also known as cryoshrouds, are surfaces that are installed between the test object and the inner walls of the chamber in all directions. Thermal shrouds are mechanisms that provide a similar environment to the cold heat sink of space. This is obtained (between other factors) with the surface shroud high absorption coefficient for radiation in the parts that interact with test specimen. The shrouds have flowing circuits that are usually flooded by cryogenic substances, which can vary in temperature before reaching its interior, through an external thermal control process. The thermal platens are thermally controlled surfaces which have a similar operation to the shrouds, and generally the specimens are installed. The difference between shroud and platens are the thermal transfer characteristics. In **Figure 10**, the distribution of heat transfer surfaces in a space simulation chamber are identified.

Thermal shrouds and platens are generally manufactured in aluminum alloys 6000, 5000, and 1100 series. This series of aluminum alloys have low outgassing rates. The aluminum alloys are most frequently used in the manufacture of cryoshrouds surfaces, since it has a high thermal conductivity and high strength. However, nowadays is possible find on the market thermal shrouds made of 300 series stainless steel, which provides good characteristics for use in space environment simulation. Thermal shrouds need manufacturing treatments and special surface finish [19, 20].

10.1. Types of thermal shrouds and substances

There are various types of cryoshrouds profiles. **Figure 11** shows some of them.

Each of these profiles types can be adopted as thermal shrouds for space simulation systems. These profiles offers specific features of heat transfer, which depend mainly on: the type of material selected for the manufacture of its ducts and panels; the effective area occupying

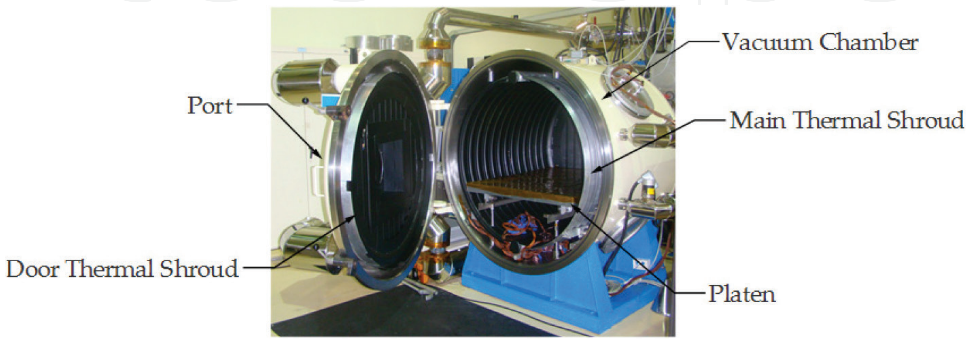

Figure 10. Thermal-vacuum chamber parts.

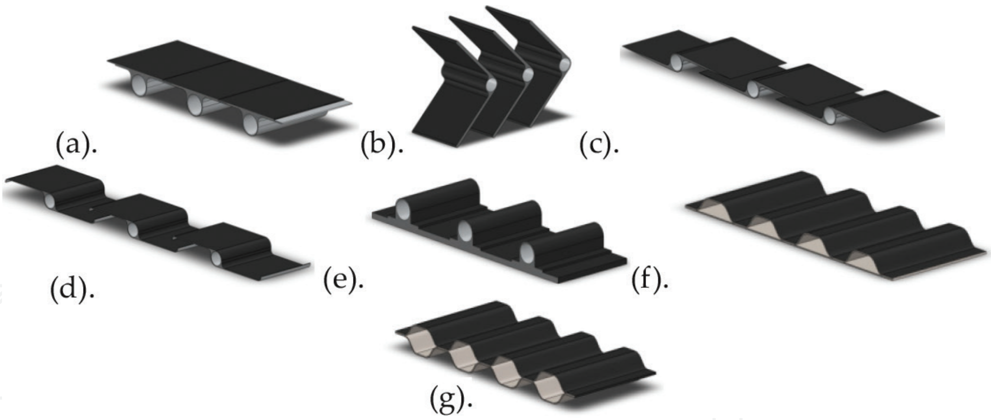

Figure 11. Different types of thermal shrouds. (a) Flat wing, (b) Chevron, (c) Bat wing, (d) Relieved bat wing, (e) D-tube on sheet, (f) Single embossed, (g) Double embossed.

each of their layers; the volume of the internal circuit; the type of fluid or substance to travel within; and surface finish.

Within the systems, external hydraulic circuit as well as the flow circuit of the internal thermal shrouds, flows a series of substances which by their properties can generate approximately −173.15°C (100 K), which is the minimum operating temperature required to develop a space thermal environment simulation [9]. Some substances as carbon dioxide (CO_2), oxygen (O_2), argon (A), carbon monoxide (CO), nitrogen (N_2), neon (Ne), hydrogen (H_2), and helium (He) have qualities thermal appropriates for using in the generation of the cold environment as the outer space. Some of these substances are difficult to handle, such as hydrogen and oxygen, which are highly flammable. Helium is an expensive gas, and the acquisition of high volumes in many cases is restricted. Nitrogen is a good choice for use in space simulators in liquid and gaseous state [9, 19]. In the liquid state (LN2), it has a temperature of −195.8°C, and in its gaseous state (GN2) under thermal/pressure control can reach temperatures from −180 to 150°C. In addition, nitrogen is relatively cheap and is commonly used in cryogenic processes. It should be noted that the nitrogen temperature ranges and the thermal load transmitted by the thermal shroud to the test object basically depend on the thermal control efficiency of the cryogenic substance and thermal shroud performance in terms of heat transfer and optical proprieties [19].

10.2. Generation of temperatures and considerations for environment simulation

By controlling the temperature that the fluid travels inside the thermal shrouds, it is possible to produce high and low temperatures in function of time following a thermal test profile [20]. These profiles are designed according to the nature of the spacecrafts mission and the type of thermal test: Thermal Balance Test, Thermal Vacuum Test, Vacuum Bake-out Test, and Functional Performance Test [5, 6]. During cycles, the distribution of heat transfer surfaces (thermal shrouds and platens) generates a series of desirable and undesirable thermal phenomena inside the vacuum chamber. The surfaces transfer heat to the specimen inside the chamber. The thermal shrouds do this transfer through radiation, and platens through conduction. In **Figure 12**, the basic components forms of heat transfer and other phenomena generated are identified.

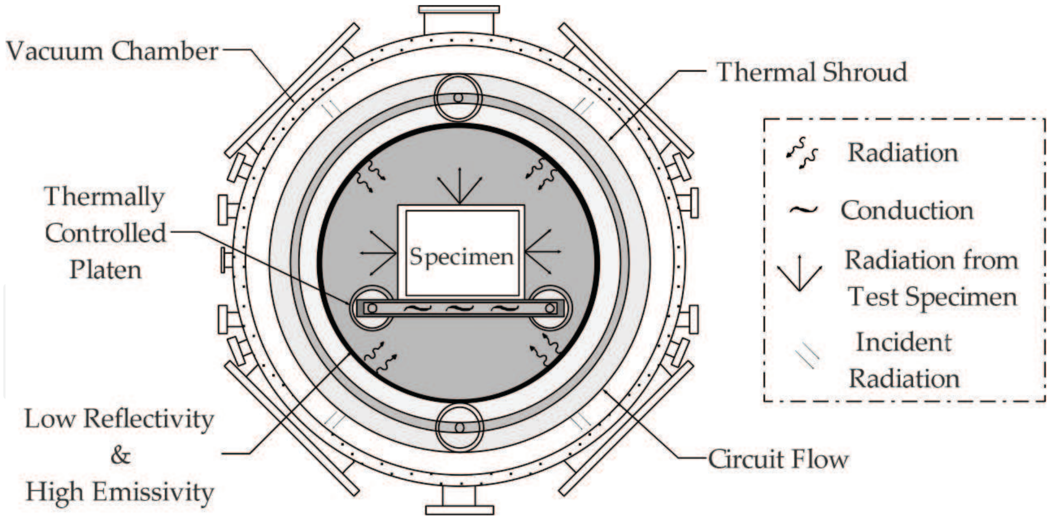

Figure 12. Basic components and heat transfer in the phenomena generated in the chamber.

It is important to note that to simulate the absence of thermal reflectivity, such as experienced by spacecraft in the space, and without influencing the test profile, the internal vacuum chamber areas, and the thermal shrouds receive a special surface finish. In addition, on account of the operation of thermal shrouds, a number of undesirable phenomena that alter the expected simulation environment are generated, and therefore is necessary to take into account a number of considerations to override such unwanted effects.

To simulate the space thermal conditions, the heat transfer surfaces must have a high radiation absorption coefficient, besides a characteristic of low reflectivity while remaining highly emissive. To accomplish this, the thermal shrouds area exposed to the spacecraft is coated with special black paint, which has low reflectivity in the visible spectrum, with a high capacity of radiation absorption [9, 19]. The coatings developed for this purpose have the capacity to withstand the vacuum and cyclic temperature changes, preserving its physical properties without distortion or outgassing in the test environment. To minimize the incident radiation that impacts the chamber by shroud functioning, both the chamber inner area and the exposed shroud surface shall have a special finish. Similarly, the internal chamber area shall be polished as part of the manufacturing process, giving a high gloss aspect to its surface, and the thermal shroud usually has a natural shine because of its manufacturing material. The amount of radiation between these surfaces is canceled by the surfaces finishes (emissivity between two walls).

10.3. Control temperature systems

To produce temperature changes within the space simulation chamber, there are a variety of forms the thermal control of the cryogenics substances that circulate through the internal thermal shrouds ducts. Some thermal control systems for space simulation chambers are: Gas-Bypass Flow System, Liquid Nitrogen Injection Systems, Gaseous Nitrogen injection Systems, Liquid and Gaseous Nitrogen Systems Combined, Thermal Conditioning Units (TCU), Helium refrigeration systems among others. Some of these systems mentioned above are classified as mechanical refrigeration systems, which use a closed-loop structure for recycling the cryogenic substances used as heat transfer vehicle in the thermal shrouds [20]. External piping system which circulates cryogenic substances, generally occupy considerable areas due to its size, and have a special thermal insulation to prevent energy loss during storage and fluid flowing into the system. In order to prevent loss of the substances cryogenic properties, a mechanical or vacuum jacketed insulation pipes is commonly used.

11. Solar simulator

In the space, environment simulation systems with solar simulators, the vacuum chamber design, vacuum system, and thermal system are designed from the solar simulation system technical and morphological characteristics [9]. Solar simulators are systems that reproduce the solar radiation phenomena experienced by spacecraft in space environment. The flux of incident solar energy on the spacecraft can be defined by intensity, spectral distribution, uniformity, and collimation. Collimation is an important effect for the spacecraft thermal balance, since it determines the spacecraft surfaces incident amount of energy, which needs to align with sunlight. Collimation also influences the behavior of spacecraft parts reflection [9]. The collimation of the solar radiation is determined by the sun incidents vector angle, which is 32 minutes of arc from earth distance. The solar simulator is composed by a set of lamps and a projector with a lens system (integrator) that points the generated light through a window to the chamber interior (See **Figure 13**). After that, the collimator mirror reflects the light to the test area in order to simulate the sun's natural collimation and light intensity [1]. The light source used by solar simulators is a set of lamps usually of Carbon-Arc, Xenon or Mercury-Xenon Compact-Arc types [9]. These simulators generate at least 1.35 KW m^{-2}. The unintended radiation, product from light sources, is reduced through refrigeration mechanisms that are usually cryogenic substances or water. The collimator mirror is composed by a number of segments of mirrors that reflect the integrator light. To maintain their proper functioning, the mirror segments inside vacuum chamber are cooled and heated with an isolated nitrogen circuit from the space simulation chamber thermal system [1]. Solar simulators can be classified in "modular type" or "simple reflector type" [9]. Both types of simulators have a set of mirrors that may be disposed as off-axis or on-axis position (see **Figure 13**).

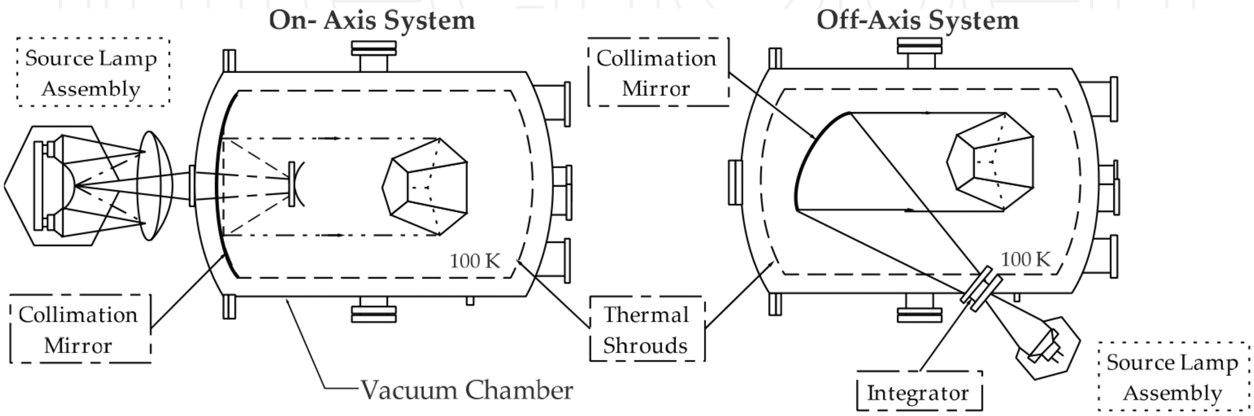

Figure 13. Two types of solar simulator configuration.

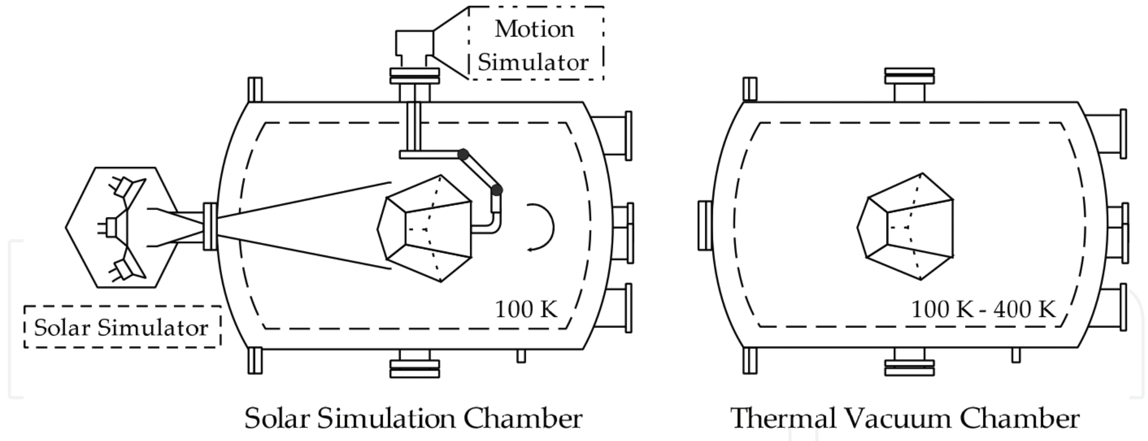

Figure 14. Space simulation chambers types.

The difference between them is that the test specimen emitted radiation does not return directly to the simulation system in an off-axis type configuration, decreasing the source of error by reflection in a test execution with solar simulator [9].

11.1. Motion simulator

A motion simulator allows to guide the spacecraft with respect to artificial solar beam [1]. The space simulation chamber with solar simulator may have a motion simulator system attached with external mechanisms or installed within the vacuum chamber (see **Figure 14**). Such system provides rotation (vertical or/and horizontal) to the tested spacecraft in order to distribute the solar radiation loads such as in the real operational environment. The motion simulator provides spacecraft orientation according to light direction or gravity vector [1]. In order to avoid undesirable thermal effects during tests, the motion simulator structure has the same temperature and optical characteristics than chamber thermal shrouds (see Section 10). The actuators and interior simulator mechanical components are maintained at atmospheric pressure through a special venting system [1].

The space simulation chambers with solar simulators have their vacuum chamber dimensions determined by solar simulator optical geometry, motion simulator size, and the volume used by cold environment simulation mechanisms [6].

12. Supply system

This system manages the necessary supplies for the operation of each of the devices in the space simulation chamber. The supply systems usually control water, compressed air, cryogenic substances, and electricity. The supply system consists of pneumatic and hydraulic lines, where are installed flow control valves, relief valves, filters, lubricators, pressure regulators, and different gauges.

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13. Controls and instrumentation system

The controls and instrumentation system represents the interface through which the operator can exercise control and acquire information about the status of systems and devices that form the space simulation chamber. This system allows the operator to control the components involved in each stage of vacuum generation, and allows to control, monitoring, and intervention in the processes of temperature conservation and cycling [20].

The primitive control systems are coupled consoles in multi-bays or racks, which have mimic panels that depict the distribution of the components that are part of the vacuum and thermal systems. The mimic panels have lights that inform the status of devices, as well as pushbuttons and selector switches through which the operator can control. In addition, these control racks have several sections that houses command transmission mechanisms, indicators of operational data, and analogic displays that report on the status of the systems in operation. These control systems have interlocks, which protect the integrity of the systems, controlling unwanted decisions that can be made by operators. Racks have multiple connection lines inside them, analog gauges, microprocessors, controllers with operational architecture Proportional – Integral – derivative (PID), and I/O modules. The I/O modules allow discrete data processing signals generated by the buttons/switches on mimic panels, and transform these signals into decisions to electropneumatic and electromechanical devices that are hosted on the extension of thermal and vacuum systems. Generally, the control racks have a section of light and sound type alarms, which communicate extreme temperature, pressure, blackouts, and low flow conditions of supplies for normal operation of components [20].

Modern control systems for space simulation chambers are computing platforms powered by the use of programmable logic controller (PLC), which enables automation for some stages of operation and safe manual control of vacuum processes acquisition and thermocycling inside the chamber. The PLCs control units of main and auxiliary pumping, as well as vacuum valves, safety valves, thermal devices, and other components are part of chamber systems. Such controllers are connected to a central processor where their operating status is displayed on a Supervisory Control and Data Acquisition Program (SCADA) [20]. These systems consist of robust information platforms, and modern graphical unit interface/human-machine interface that allows active interaction between the operator and the system. The chamber operator communicates control decisions using computers, in which the systems distribution is shown.

14. Conclusions

The space simulation chambers serve as a test medium for various types of spacecraft and their subsystems. There are two types of space environment simulators, the ones with solar simulator and the ones without. Systems with solar simulator are known as solar simulation chambers. Systems without solar simulator are known as thermal vacuum chambers. The space simulation chambers with solar simulators have their vacuum chamber dimensions determined by solar simulator optical geometry, motion simulator size, and the volume used by cold environment simulation mechanisms. The basic systems that compose the space simulation chambers are: Structure of the Chamber, Vacuum System, Decontamination System, Venting System, Thermal System, Solar Simulator, Supply System, and Controls and Instrumentation System. The space simulation chambers have several vacuum pumps and thermal 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 thermal shrouds are mechanisms that provide a similar environment to the cold heat sink of space. By controlling the temperature of the thermal shrouds, it is possible to produce high and low temperatures in function of time following a specific test profile for the spacecraft. In the space thermal environment simulation, it is not necessary duplicate exactly environment of the outer space, however, it is necessary to duplicate the effects that this environment generates in the materials, components, subsystems, and spacecraft systems. Using liquid nitrogen at 77°K as the cryogenic fluid for the thermal system operation, the space thermal radiation environment can be duplicated with an error of <1%. For the space environment simulation test is necessary achieved a level pressure less than 1×10^{-6} mbar, because to this level is possible properly evaluate the specimen and eliminate some undesirable effects. A contamination controlled environment is required in order to prevent damages to specimens and contamination to the vacuum chamber interior caused by airborne particles. The composition of the ambient inside the space simulation chamber can be identified and analyzed through equipments such as: gas chromatograph, mass spectrometers, quartz crystal microbalance (QCM), thermoelectric quartz crystal microbalance (TQCM), and witness plates.

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