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Space Simulation Chambers State-Of-The-Art

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Abstract

The space Simulation, are systems used to recreate as closely as possible the 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 paper 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 chambers, class of phenomena generated inside, and the technological evolution of these systems from conception (at the beginning of the 60s) to present moment (2016). This work also identifies the conventional operational requirements of various state-of-the-art commercial chambers, their morphology, type of manufacturing, structure materials, supplies necessary for its 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 control operation and monitoring requirements. The study allowed the definition and classification of operation, states, modes, passive and active operations and control and monitoring philosophy of the analyzed chambers.

Keywords: Space environment Simulation, Space Simulation Chamber, Thermal-Vacuum Chamber.

1. Space Simulation Chambers

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 (ex: engineering model, qualification model and flight model) [1].

The Space Simulation Chambers are used to simulate as closely as possible the space environment conditions experienced by spacecraft's. These systems analyze spacecraft thermal behavior and functionalities to ensure mission success and survivability [2]. Figure 1 demonstrates two classes of Space simulation chambers.

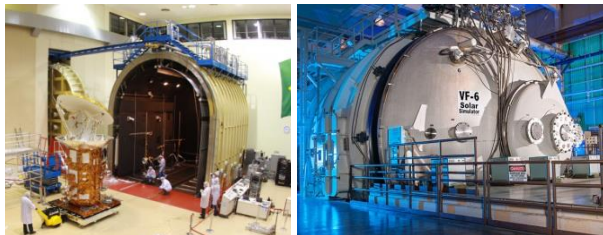


Fig. 1. (Left) 6 X 8 Thermal-Vacuum Chamber LIT – INPE and (Right) VF-6 Solar Simulator Chamber NASA – Glenn Research Center

2. Space Simulation Chambers Types

There are two types of space environment simulators, the ones with solar simulator and the ones without [3] (see Fig. 2). The systems with solar simulator allow to realize tests to determine thermal balance and to know the thermal distribution characteristics experienced by space vehicle during solar exposure. Systems without solar simulator are known as *Thermal Vacuum Chambers* [3]. These systems also recreate the space environment conditions, including solar radiation, through the use of different devices in the test setup.

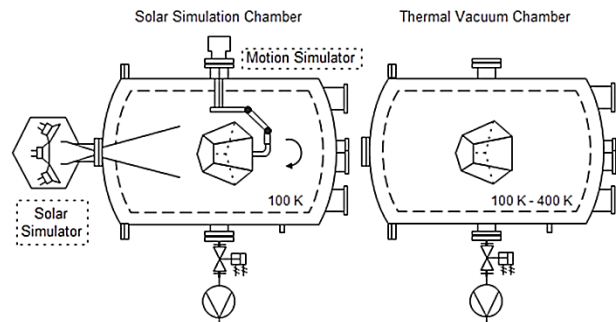


Fig. 2. Space Simulation Chambers Types

3. Space Environment

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.

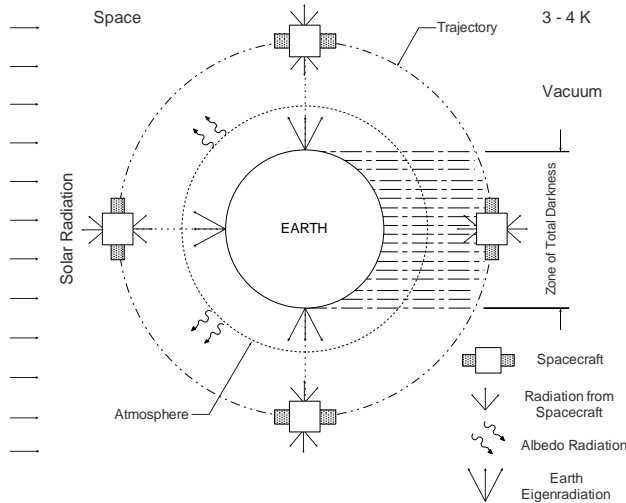


Fig. 3. Space environment characteristics. Adapted [3,4]

A spacecraft in space experiences an intense radiation when exposed to the sun. When the spacecraft is in 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 [5,7]. The space environment phenomena are described below.

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.

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 surface. The absorption of such energy would generate a very high temperature inside the spacecraft's, however, just a fraction of heat is absorbed due to space environment characteristics and spacecraft surfaces physical properties [6, 7].

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 (3K) and -260.15°C (4K) [6]. This concept implies that the heat emitted by a spacecraft will not return to it [5].

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 [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 spacecraft to the Earth and Sun [6].

4. Space Environment Simulation

It is stated that space simulation 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 spacecraft 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 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. 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 (400K) [3]. Albedo and Eigenradiation are not simulated in thermal-vacuum chambers since their values are diffuse and depend on the spacecraft position relative to 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 space vehicle when exposed to solar radiation during its operation. It should be noted that the spacecraft is mathematically modeled using softwares, which use the exact values of all phenomena experienced in space.

5. Space Simulation Chamber Systems

Through the study and analysis of phenomena created by space simulation chambers is possible to establish their basics systemic composition. These phenomena are transformed into function 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 the Figure 4.

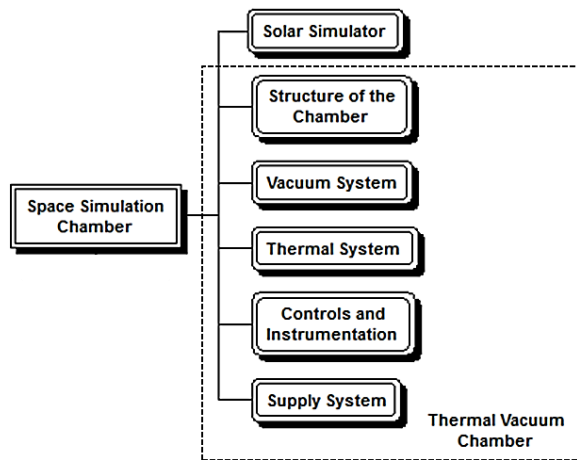


Fig. 4. Systems that integrate the Space Simulation Chambers.

The chamber structure is responsible of conserving the space environment phenomena; it also houses the test specimen.

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

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

The solar simulator is a device which artificial light source is adjusted through optical mechanisms (mirrors) and filters to provide specimen intensity and spectral composition similar to sunlight.

The control and instrumentation system provide the mechanisms and interfaces to control and monitor the different mechanical, electronic and electromechanical devices that compose the space simulation chambers.

The supply system provides and manages the necessary resources (water, power, compressed air, specific substances, etc.) to operate the devices.

In the space environment simulation systems with solar simulators, the vacuum chamber design, pumping system and thermal system are designed from the solar simulation system technical and morphological characteristics [5].

Following it is performed a description of each system that integrates the space simulator chambers, also some basic criteria and requirements to its function and interaction with the test specimen.

6. Structure of the Chamber

Also known as vacuum chamber, the chamber structure allows the conservation of vacuum and thermal radiation phenomena, which are very important characteristics to simulate the space environment.

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 specimen [8].

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.

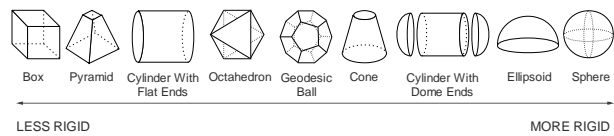


Fig. 5. Chamber Shapes and Rigidity of the Shapes. Adapted [9].

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. Considering the stiffness characteristics of different shapes, as well as the manufacturability and the historic market trend, a cylindrical structure with dome ends is a typical choice for a space simulation chamber.

6.1 Materials

Taking into account the vacuum generation processes and thermal cycling in its interior, the materials for chamber manufacturing shall meet certain requirements. The materials shall be suited to minimize or cancel the presence of sources of steam and undesirable gases (see Fig. 6). The material selection requirements for thermal-vacuum chamber manufacturing are stated below.

6.1.2 Requirements [10].

The materials shall preserve its mechanical properties under radiation, and extreme temperature changes ($\leq -173.15^{\circ}\text{C}$ and $\geq 126.85^{\circ}\text{C}$) and high/ultra vacuum (10^{-7} mbar to 10^{-12} mbar).

The materials vapor pressure shall be minimal when it is exposed to high temperatures during operation. It is important to note that: 1. The vapor pressure is different for all substances in different temperatures. 2. All metals evaporate depending on the temperature and vacuum level. 3. The materials evaporation rate is increased during high vacuum. [11]

The chamber structural materials shall be impermeable to gases, with a surface to prevent impurities and substances retention.

The chamber materials shall not react in vacuum and shall not react with other adjacent materials.

The adjacent materials thermal expansion shall match the system without generating undesirable distortions and mechanical interactions.

The materials shall not excessively emanate gases in an excessively under high-energy particles interaction.

The materials shall have a low outgassing potential (less than 10^{-6} mbar ls-1 cm²) under vacuum.

The materials shall have proper degassing properties for manipulation.

Degassing: The deliberate removal of gas from a material, usually by application of heat under high vacuum

Leak: In a vacuum technology, a hole, or porosity, in the wall of an enclosure capable of passing gas from one side of the wall to the other under action of a pressure or concentration differential existing across the wall.

Leak rate: in leak detection practice, leak rate is defined as the rate of flow (in pressure – volume units per unit time) through a leak with gas at a specified high pressure (usually atmospheric pressure) on the inlet side and gas at a pressure on the exit side which is low enough to have negligible effect on the rate of flow.

Outgassing: The spontaneous evolution of gas from a material in a vacuum.

Permeation: As applied to gas flow through solids, permeation is the passage of gas into, through, and out of a solid barrier having no holes large enough to permit more than a small fraction of the gas to pass through any one hole. The process always involves diffusion through the solid and may involve various surface phenomena, such as sorption, dissociation, migration, and desorption of the gas molecules.

Virtual Leak: 1-The evolution of vapor from a cold trap on which the vapor had previously condensed at higher pressures or lower trap temperatures. 2- The semblance of a leak in a vacuum system caused by slow release of sorbed or occluded gas. The term is sometimes used to include volatilization or disintegration of a material unstable under vacuum.

The definition of the following phenomena is according to John F. O' Hanlon – User Guide to Vacuum Technology [12].

Desorption: Is the heat-stimulated release of gases or vapors previously adsorbed on the interior walls of the system.

Diffusion: is the transport of one material through another. Gas diffusion to the interior wall of a vacuum system followed by desorption into the chambers contributes to the system outgassing.

Vaporization: A vapor is a gas above its condensation temperature and vaporization is the thermally simulated entry of molecules into the vapor phase.

Given the definition of every kind of undesirable phenomena inside the chamber, which may disturb the desired specimen environment or prevent its execution, this work has evaluated several types of materials and manufacturing processes, which reduces or cancel these occurrences.

The basic criteria used for the chamber's material selection is the compliance with the previous defined requirements, as well as the tendency to use for the type of simulation processes intended to take place. Figure 7 identifies outgassing rates for some types of materials usually used for vacuum systems manufacturing.

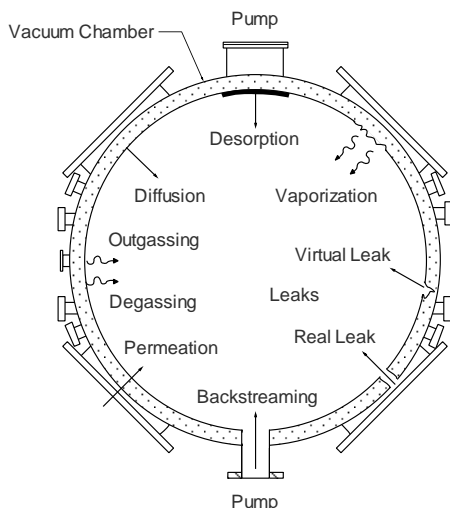


Fig. 6. Potential source of gases and vapors in a vacuum chamber. Adapted [12].

For better understanding the Figure 5 phenomena, each of them will be defined below, according to the American Vacuum Society [13].

Adsorption: The condensing of gas on the surface of a solid.

Back streaming: The direct flight of vapor molecules by scattering from the hot vapor jet or evaporation from hot nozzle parts in the direction of the mouth or intake part of a vapor pump.

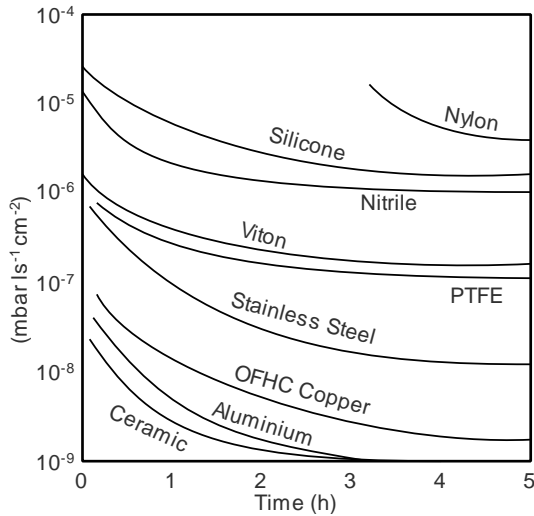


Fig. 7. Outgassing rates for various materials. Adapted [10].

For the chamber structure, type 304 Stainless Steel is used most frequently in vacuum systems [8,9,14]. The majority of space-simulation vacuum chambers are fabricated from 300 – series stainless steel [8]. The 304 stainless steel is a proven 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 [15].

6.2 Penetrations

The chambers structure surfaces have mechanical interfaces called Flanges that allow the connection between several devices such as systems, pumps, valves, sensors and filters. 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, application and usages [10]. Figure 8 shows some types of flanges usually used in space simulation chambers.

To realize specific measurements or to monitor with specific equipment the 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 disks are usually manufactured with a special glass, quartz, sapphire or borosilicate.

Depending on the viewport material and vacuum type level of the chamber, special materials are adopted for sealing. The viewport shall not contact any other surface than the sealing materials and the simulated environment.

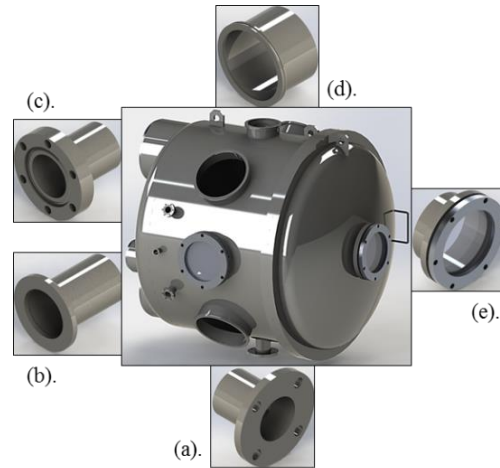


Fig. 8. Common Flange Systems. (a). ASA Flange (b). KF Flange (c). CF Flange (d). ISO Flange (e). Viewport

6.2.1 Note

The sealing types of welding and the general feedthroughs characteristics that can be used in chambers are not described in this paper, given the textual extension that would be generated. However, authors believe these are important topics and relevant for space systems simulators design. These topics will be addressed to future publications.

6.3 Rules and Codes

There are no standards or specific rules that describe criteria to build space simulation vacuum 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 [16]:

- 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 Appareils 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 comprise the air found inside the chamber. In Table 1 below identifies the types of molecules that usually compose the air with their approximate concentration.

Main Constituents	
Type	Molar Fraction
N ₂	0.7809
O ₂	0.2095
Ar	0.0093
CO ₂	0.00033

Table 1. Constituents of dry air. Adapted [17].

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 inter-connected 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 to 10⁻⁷ mbar (High Vacuum). This pumping process is necessary because of the mechanical performance limits of existing pumping units. Figure 9 shows the range of vacuum and vacuum pumps.

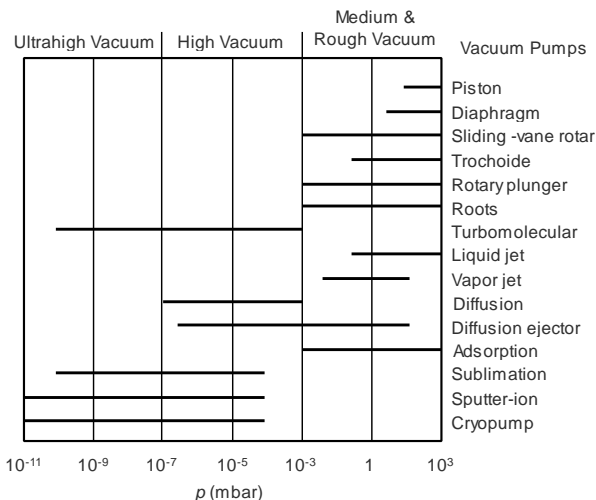


Fig. 9. Ranges of vacuum and common working ranges of vacuum pumps. Adapted [18].

It is worth to mention that not all pumping systems are suitable or entirely suitable for use in thermal-vacuum systems for space simulation, given that some of these by the nature of their operation use lubricant components for cooling components or for vacuum generation. This condition represents a risk due to probability of migration of polluting vapors into the chamber. This happens even using filter elements as traps or cold traps, which sometimes reduces the effective capacity of the pumping unit [8].

Since the early 80s, 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. In Figure 10 some types of vacuum pumps are shown [8].



Fig. 10. Vacuum Pumps for space simulation. (a). Cryopump-Cryo Torr 8 Helix (b). Diffusion Pump VHS-10-Varian (c). Turbopump TW501- Leybold (d). pHX Mechanical booster pump Edwards [19, 20, 21, 22].

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 gases that are pumped to chamber interior. If the oil vapor pressure is too high, it vaporizes when exposed to vacuum and may migrate to chamber, contaminating its interior [11].

The vacuum system is composed by Foreline traps, Refrigerated Baffles and Cold Traps (see Fig. 11). Such devices are allocated between the pumps and the vacuum chamber. They are used to remove contaminant particles and prevent Backstreaming of oil vapors generated by pumps operation [11].

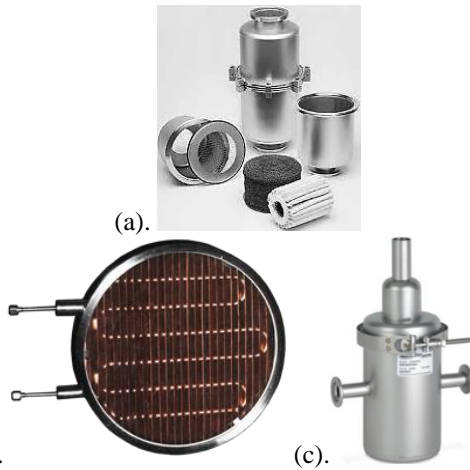


Fig. 11. (a). Foreline traps (b).Refrigerated Baffle (c). LN2 Cold Trap

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 turns them into crystalized solid particles (Inverse sublimation or deposition) [11].

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 [23].

7.3 Chamber Vent

When testing procedures are finished, and the ambient pressure inside the chamber is to be returned, the vacuum system have a circuit of connected components, which allow access to filtered GN2 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 GN2, to vent the vacuum chamber to avoid pollution and objects that are housed therein. If ventilation 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, harming the chamber and also the specimen [7,24].

7.4 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 [10]. The partial pressure gauges determine the pressure of a gas mixture identifying their composition in a vacuum environment. In Figure 12 gauges for different ranges of vacuum are identified.

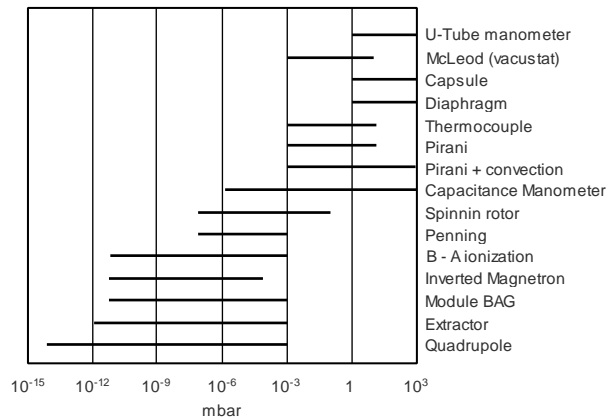


Fig. 12. Pressure ranges for different gauges. Adapted [10].

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 hot and cold cathode ionization gauges and Penning gauge for determining the pressure in regions of high and ultra-high vacuum [10].

8. Thermal System

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 space vehicles [3]. 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 “shrouds”, and a number of external pipes connected in a hydraulic control circuit.

8.1 Shrouds and Platens

The shrouds, also known as cryoshrouds, are surfaces that are installed between the test object and the inner walls of the chamber in all directions. 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 liquid or gaseous substances, which can vary in temperature before reaching its interior, through the external thermal control, which is commonly implemented mechanisms for heat exchangers. The platens are thermally controlled surfaces which have a similar operation to the shrouds, and are generally where the specimens are installed. The difference between shroud and platens are the thermal transfer characteristics. In Figure 13 the distribution of heat transfer surfaces in a vacuum chamber are identified.

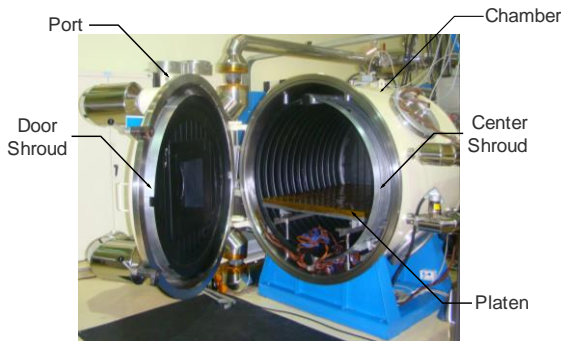


Fig. 13. Thermal-Vacuum Chamber parts. Courtesy of LIT - INPE

Shrouds and platens are generally manufactured in aluminum alloys 6000, 5000 and 1100 series. This series of aluminum alloys have low outgassing rates (see Fig. 6). The 6061 aluminum alloy is most frequently used in the manufacture of cryoshrouds surfaces, since it has a high thermal conductivity and high strength. However, nowadays it is possible to find on the market shrouds made of 300 series stainless steel, which provides good characteristics for use in such systems when receive manufacturing treatments and special surface finish [25,26,27].

8.2 Geometry

There are various types of cryoshrouds geometric profiles available in the market. Figure 14 shows some of them.

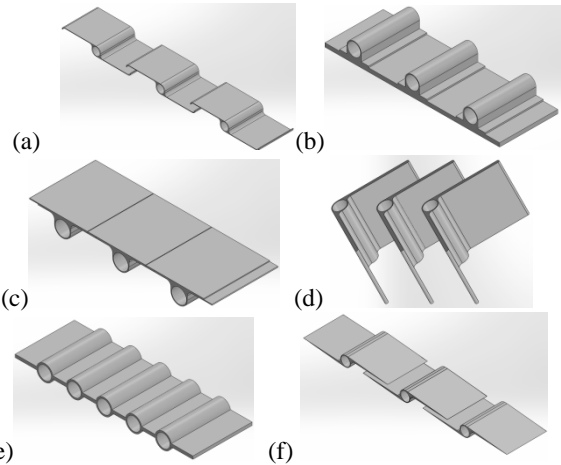


Fig.14. Different types of Thermal Shrouds. Adapted [25]. (a). Relieved Bat Wing (b). D-tube on sheet (c). Flat Wing (d). Chevron (e). Other configuration of D-tubes (f). Bat Wing.

Each of these profiles types that can be adopted by shrouds, offers specific features of heat transfer, depending mainly on: the type of material selected for the manufacture of its ducts and panels; the effective area occupying each of their layers; the volume of the internal circuit; the type of fluid or substance to travel within; and surface finish. Because of the scope and nature of this article, further information with respect to the design and calculations of these surfaces will be addressed to further works.

8.3 Substances

Within the system’s external hydraulic circuit as well as to the flow circuit of the internal shrouds, it is possible to flow a series of substances which by their properties can reach approximately -173.15°C (100K), which it is the minimum operating temperature required for simulation [1]. In Table 2 some substances are listed with their respective boiling point.

Symbol	Substance / Compound	Boiling Point °C
CO ₂	Carbon Dioxide	- 78.5
O ₂	Oxygen	-183
A	Argon	-185.8
CO	Carbon Monoxide	-191.5
N ₂	Nitrogen	-195.8
N _e	Neon	-246.1
H ₂	Hydrogen	-252.9
H _e	Helium	-268.9

Table 2. Boiling Point of Substances and Compounds at atmospheric pressure. Adapted [5].

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 worthy choice for use in space simulators in liquid and gaseous state [5]. 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 from -180°C to 150°C. In addition, nitrogen is a relatively cheap and is commonly used in cryogenic processes. Figure 15 shows temperature levels that can be reached using nitrogen in two phases through a cryoshroud.

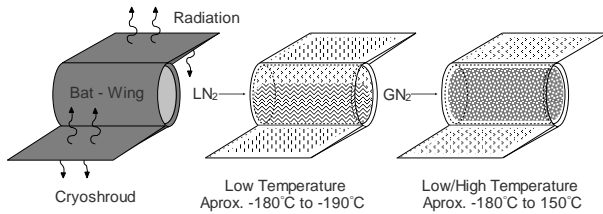


Fig. 15. Range of temperatures in a cryoshroud using LN₂ or GN₂.

It should be noted that the nitrogen temperature ranges and the thermal load transmitted by the shroud to the test object basically depend on the thermal control efficiency of the cryogenic substance and shroud performance in terms of heat transfer.

8.4 Generation of Temperatures

By controlling the temperature that the fluid travels inside the shrouds, it is possible to produce high and low temperatures in function of time following a test profile (see Fig. 16).

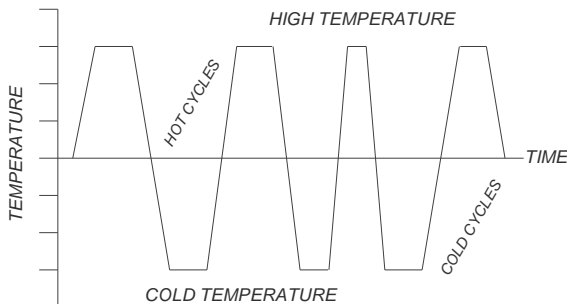


Fig. 16. Typical thermal cycling profile. Adapted [7].

These profiles are designed according to the nature of the spacecraft's mission and the type of test: Thermal Balance Test, Vacuum Bake out Test, Thermal Vacuum Test, and Functional Performance Test [2, 7].

During cycles, the distribution of heat transfer surfaces (shrouds and platens) generates a series of desirable and undesirable thermal phenomena inside the chamber.

The surfaces transfer heat to the specimen inside the chamber. The shrouds do this transfer through radiation, and platens through conduction. In Figure 17, the basic components, forms of heat transfer and other phenomena generated are identified.

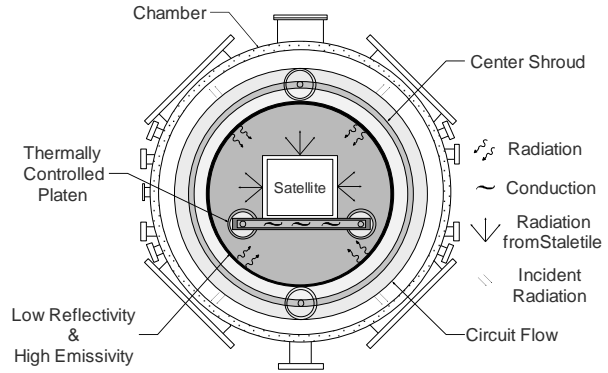


Fig. 17. Basic components and heat transfer in the phenomena generated in the chamber.

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

8.5 Considerations for Simulation & Surface Finishes

To simulate space 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 shrouds area exposed by the satellite is coated with black paint, which has low reflectivity in the visible spectrum, with a high capacity of radiation absorption [5]. The paintings 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 shroud usually has a natural shine because of its manufacturing material. The amount of radiation between this surfaces is cancelled by the surfaces finishes (emissivity between two walls).

8.6 Control Temperature Systems

The shrouds installed inside the chamber recreate the conditions of the space environment, interchanging heat from the specimen under test. To produce temperature changes within the chamber, a variety of forms of control substances circulate through the internal shrouds ducts. Right below some early and current thermal vacuum chambers control methods are described.

8.6.1 Gas-Bypass Flow System

This system uses GN2 as heat transfer fluid. It comprises the shrouds installed inside the vacuum chamber, a blower that circulates GN2 through the system, a cooler, a heat exchanger, a LN2 tank, a heat chamber and a flow control valves installed in the piping circuit [28]. Figure 18 depicts the distribution of devices in the system and bypass gas-flow direction in GN2.

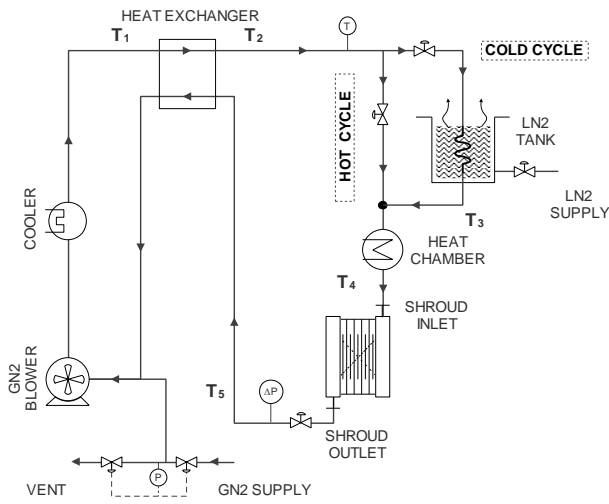


Fig. 18. Gas Bypass Flow System. Adapted [28].

In the cold cycle (-100.15°C to 26.85°C), the GN2 circulated by the blower passes through the cooler and the heat exchanger, where its temperature is decreased. Then the current is divided into two, where one of them passes through LN2 bath, decreasing its temperature. This resulting stream is mixed with the other that has a higher temperature. Then the resulting flow enters into the chamber's shroud [28].

The stream exiting the shroud then passes through heat exchanger, pre-cooling the stream that is running on the system. After that, the flux is sucked into the blower, where the cycle begins again. The proper flow control of both streams that branch, permits to reach the desired temperature at the shroud inlet [28].

In the hot cycle, (26.85°C to 99.85°C), the total gas flow from the heat exchanger passes only through the heat chamber, then enters the shroud. The gas

temperature before entering the shroud is controlled by the power supplied to electrical heaters. The gas stream leaving the shroud first passes through the heat exchanger, pre-heating the gas stream that will flow through the system, and then is sucked into the blower, where the cycle begins again [28].

8.6.2 Liquid Nitrogen Injection System

This system uses gaseous and liquid nitrogen as heat transfer vehicle. It comprises a blower GN2, coolers cooled by water, a heat exchanger, an injection chamber of LN2, the shrouds installed inside the vacuum chamber, and control flow valves installed in the circuit. Figure 19 illustrates the distribution of mechanisms in the described system.

Before and after the blower there are two water-cooled coolers. In the first cooler, the heat acquired by GN2 is eliminated, resulted by its compression in the blower. In the second cooler, GN2 is stabilized at room temperature for admission into the blower. This latter process temperature stabilization is necessary to ensure that the gas is sucked by the blower at room temperature, both to the cold and hot cycles [28].

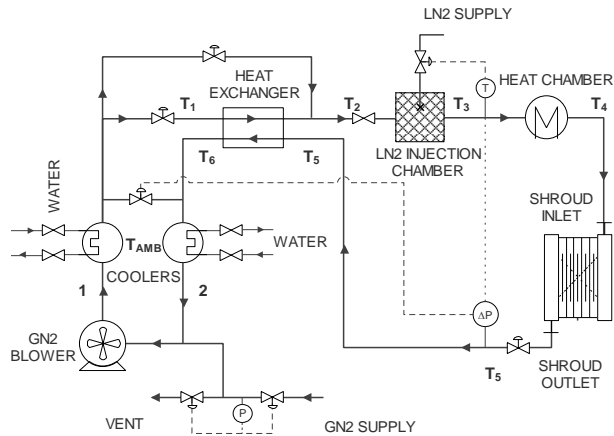


Fig. 19. Liquid Nitrogen Injection System. Adapted [28].

In the Cold Cycle (-100.15°C to 26.85°C), the compressed GN2 driven from the blower passes through the first cooler, and the heat exchanger where it is pre-cooled. Then GN2 enters the injection chamber, where liquid nitrogen is supplied in its current. The combined flow of GN2/LN2, result from injection (which has a low temperature), enters the shroud attached to the chamber, passing through the heat chamber without suffering changes in their status, since the latter remains inactive during this cycle. Finally the GN2 stream exiting the shroud passes through the heat exchanger, where the temperature of the other current that is available to run on the system decreases. The original current stabilizes its temperature in the second cooler to subsequently be sucked into the blower, where the cycle begins again. It should be noted that the entering shroud

GN2 temperature is controlled by the injection rate of LN2 in its flow [28].

In the hot cycle (26.85°C to 99.85°C) the LN2 injection chamber remains inactive, then all GN2 from heat exchanger passes through the heat chamber, where its temperature rises, later accessing the shroud installed in the vacuum chamber. The gas stream exiting the shroud then passes through the heat exchanger, the other pre-heating gas stream available to circulate in the system. Finally the original gas stream stabilizes its temperature as it passes through the second cooler, later to be sucked into the blower, where the cycle begins again. It is important to state that the GN2 temperature is controlled by the power supplied by the electrical heaters installed in the heat chamber.

8.6.3 Considerations

For Hot Cycle in the Gas-bypass flow system, and Liquid Nitrogen injection system, the heat exchange in the heat exchanger made between the output current of the shroud that has a high temperature, and the flow entering the system with environment temperature, determines the efficiency of this process in terms of consumption. Given that the inflow of GN2 that is conditioned in the heat exchanger, having the wrong temperature to enter the heat chamber will require greater power to the gas reach the needed temperature to enter the shroud [28].

8.6.4 Liquid and Gaseous Nitrogen System

This system uses gaseous and liquid nitrogen as heat transfer vehicle. It consists of two independent lines of LN2 supply, a liquid nitrogen spray nozzle, electric immersion heater, storage LN2 tank, the shrouds, control valves, ventilation valve, pressure gauge, temperature and level sensors, which are installed on the extension of the piping circuit. In Figure 20 the distributing devices that integrate the system are illustrated.

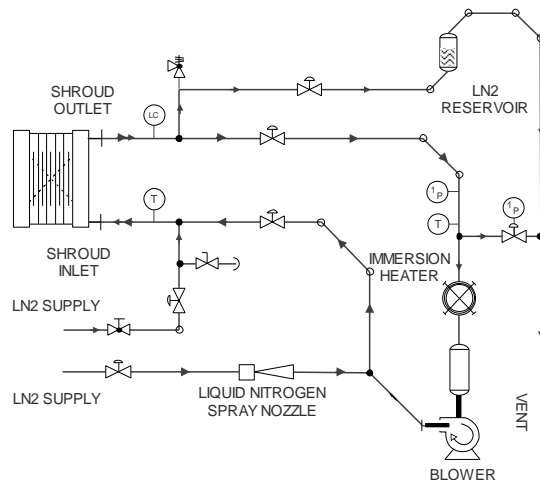


Fig. 20. Liquid and Gaseous Nitrogen System.

This type of system has two modes of operation:

Gaseous Nitrogen mode: In this mode, the shrouds are flooded with pulverized LN2, allowing the execution of cold and hot cycles by controlling the temperature of the dense gas flowing in the system.

Liquid nitrogen is supplied at a specific pressure by a control valve, which injects amounts of LN2 through a nozzle spray where the liquid is atomized, dispersing thereby the particles to finish transforming it into a stream of dense gas, which is then sucked into the circuit and driven by a blower flow.

Controlling the temperature of the gas stream traveling through the pipes depends on three factors: electric power supplied to the heater; the injection pressure of pulverized nitrogen in a flowing current; and effective ventilation of gas flowing in the system. Thus the system can produce temperatures from -180°C to 150°C.

Liquid Nitrogen Mode: In this mode, the shrouds are totally flooded only with LN2, allowing only cold cycle production.

To carry out the cold cycle by using LN2, the system has a supply line that is connected to the gas circulating circuit, which in turn is connected to the chamber shroud. The system has control valves that prevent access of LN2 in the lines of the flow gaseous system. A level controller (LC) of LN2 measures the required amount of liquid to fill the shroud. After completely fill the internal volume of the shroud with LN2, 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.

8.6.5 Gaseous Nitrogen System.

This system comprises a LN2 supply line, a spray nozzle, an electrical immersion heater, a blower, pressure sensors, temperature sensors, the shrouds and control valves installed in the flow pipes. This type of system operates on the same principle as the previous one in its nitrogen gaseous mode. The Figure 21 shows the gaseous nitrogen system.

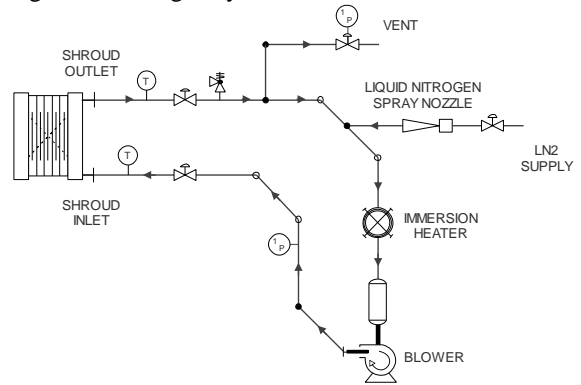


Fig. 21. Gaseous Nitrogen System

8.6.6 Considerations

The systems described above are classified as mechanical refrigeration systems, which use a closed-loop structure for recycling the substances used as heat transfer vehicle in the shrouds.

These systems are able to maintain the properties of heat transfer almost constant in all operating temperature ranges, while retaining the constant density of gas in the circulation circuit, which is possible by adjusting the pressure in the GN₂ circulation system in direct relation with temperature. This means that to produce a specific temperature in the system, the gas must flow at a given pressure.

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, it is commonly used a mechanical or vacuum jacketed insulation pipes.

8.6.7 GN₂ Thermal Conditioning Unit (TCU)

Considering modern control systems, such units are generally comprised of a GN₂ circulator blower, a variable frequency drive (VFD) to control the blower speed, an inline heater, pressure gauges, LN₂ and GN₂ supply lines, control valves, and mechanical or vacuum jacketed insulation. These units are used to operate programmable logic controller (PLC) and Human-Machine Interface (HMI). In Figure 22, the connection system is illustrated. Such systems keep the gas density constant by controlling the power supplied to the inline heater; LN₂ and GN₂ injection control; LN₂ and GN₂ ventilation control. The substances temperature control and the system pressure is controlled through the PLCs installed in the unit [29].

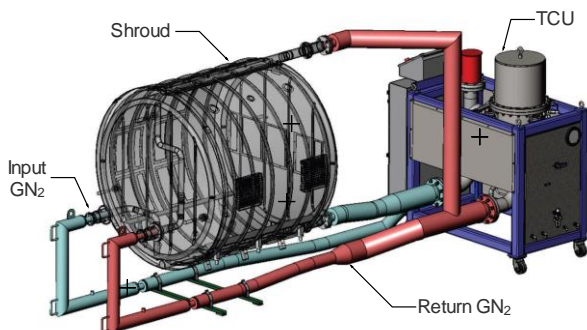


Fig. 22. Illustration of a TCU connected to a cylindrical shroud [29].

These units are compact high performance and low consumption of LN₂ [29].

9. Solar Simulator

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 need to align with sunlight. Collimation also influences the behavior of spacecraft parts reflection [5]. 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 Fig.23). After that, the collimator mirror reflects the light to the test area in order to simulate the sun's natural collimation and light intensity [4]. The light source used by solar simulators is a set of lamps usually of Carbon-Arc, Xenon or Mercury-Xenon Compact-Arc types [5]. 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. [4]

Solar simulators can be classified in "modular type" or "simple reflector type" [5]. Both types of simulators have a set of mirrors that may be disposed as off-axis or on-axis position. (See Fig.23)

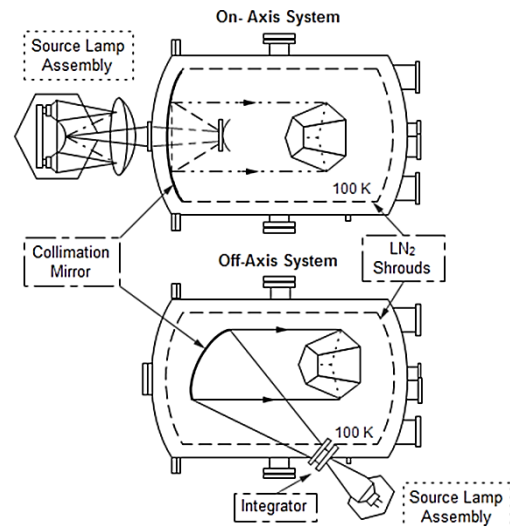


Fig. 23. Two types of solar simulator positions.

The difference between them is that the test specimen emitted radiation doesn't returns directly to an Off-axis type simulators, decreasing the source of error [5].

9.1 Motion Simulator

A motion simulator allows to guide the spacecraft with respect to artificial solar beam [4]. As space simulation chamber with solar simulator may have a motion simulator system attached with external mechanisms or installed within the chamber (see fig. 2). Such system provides rotation (vertical or 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 [4]. In order to avoid undesirable thermal effects during tests, the motion simulator structure has the same temperature and optical characteristics than chamber shrouds (see section 9.1). The actuators and interior simulator mechanical components are maintained at atmospheric pressure through an air venting system [4].

9.2 Considerations

The Space Simulation Chambers with solar simulators have their vacuum chamber dimensions determined by solar simulation optical geometry, motion simulation size and the volume used by heat sink simulation mechanisms, including its supply connections. [2]. Recently, solar simulation is becoming less used due to high costs [4]. This trend is supported by the quality and reliability of the current simulation softwares, that are capable of predicting the solar radiation with a high accuracy [4].

10. 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.

10.1 Primitive Control Systems

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. Figure 24 depicts a thermal vacuum control panel.

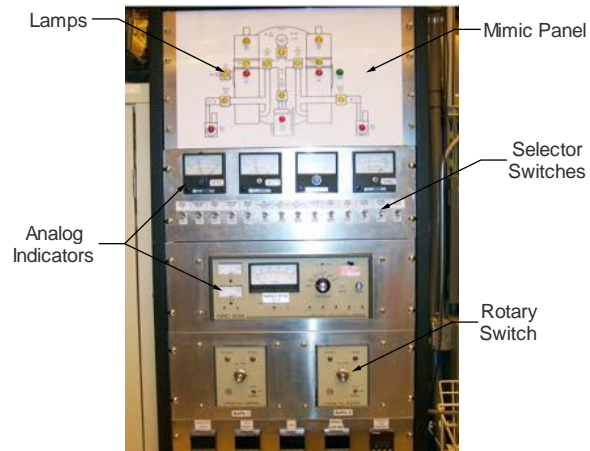


Fig. 24. Thermal Vacuum controls. Adapted [25].

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 PID (Proportional - Integral - derivative), and I/O modules.

In general, the control system performs actions through signal processing in I/O modules of discrete and analog data.

The I/O modules allow discrete data processing signals generated by the buttons/switches on mimic panels, and transform these signals into decisions to electro-pneumatic and electromechanical devices that are hosted on the extension of thermal and vacuum systems.

The control system uses I/O module analog data which allows process variables, such as pressure and temperature captured by the sensors of the systems, and represent them in voltage signals, current and electrical resistance. These signals are used for their own processing or to attribute any specific action to electro-pneumatics and electromechanical devices that integrate thermal-vacuum systems.

In these control systems, data acquisition of temperature and internal pressure of the chamber is regularly transmitted to a processor coupled to the control racks. Temperature measurements are performed by a set of sensors connected in the shrouds, which are generally type "T" thermocouples. Various types of sensors for reading different pressure ranges perform the chamber's internal pressure data acquisition. They are installed on specific connections of the chamber structure. For the system pressure data, pressure gauges are installed in the flow lines of cryogenic substances and adjacent units pumping sensors.

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. The alarm system comprises temperature sensors, pressure sensors, transmitters, flow switches, etc., which are installed in system physical extent, and interconnected to control racks.

10.2 Actual Control System

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 that 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) [25].

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. In Figure 25 circuits are represented in the HMI.

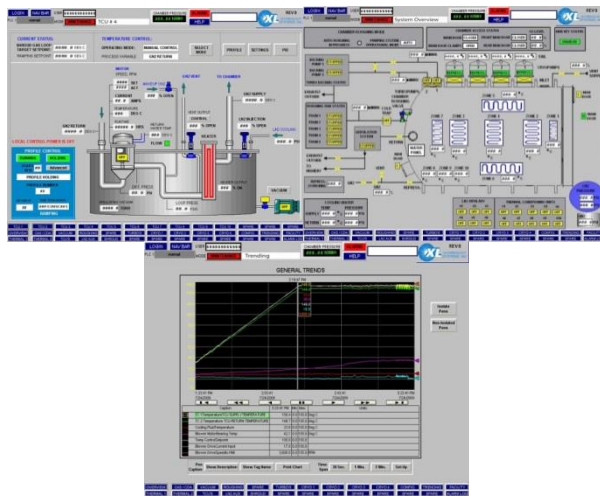


Fig. 25. Actual control system HMI screens [25].

In the graphical interfaces, the general conditions of the systems are displayed in real time, alarms and data acquisition of environmental status of the chamber are also shown. The components coupled to the system extension communicate via integrated sensors their status and operation mode. These systems record each control decisions implemented by operators.

11. Supply System

This system manages the necessary supplies for the operation of each of the devices in thermal vacuum chamber systems. The supply systems usually control water, compressed air, LN₂, GN₂ and electric. The table 3 indicates the type of consumable that each of the systems uses.

The supply system consists of pneumatic and hydraulic lines, where are installed flow control valves, relief valves, filters, lubricators, pressure regulators and different gauges.

For the power supply management, the system has switches, transformers, regulators, fuses, circuit breaker, and uninterruptible power supply (UPS), among others, which are usually integrated into consoles for their control with power distribution lines in the extension of thermal-vacuum system.

SYSTEMS	
UTILITIES	Vacuum System Thermal System Solar Simulation Controls System Structure of the Chamber
Water	X X X
Compressed Air	X X X
Liquid Nitrogen	X X X
Gaseous Nitrogen	X X
Electrical	X X X X

Table 3. Type of supply used by each system.

Vacuum system generally uses water for cooling each of the pumping units as well as their support modules (compressors), in case of having them. The vacuum system uses compressed air at a specified pressure operate the various pneumatic control valves. This allows to seal the vacuum chamber and connection lines between the pumping units. The vacuum system uses GN₂ to return to ambient pressure, LN₂ for decontamination plates, and electricity to power pumping units and control valves.

The thermal system usually uses water for cooling gas recirculation mechanisms. It consumes LN₂ and GN₂ to produce thermal cycles and power electricity to energize recirculation mechanisms, as well as electric resistance heaters, flow control valves, injection valves and ventilation valve. Air is supplied to the system to operate with multipurpose proportional valves.

The solar simulation system uses electricity to power its light sources and control mechanisms, and also uses water and/or nitrogen to refrigerate its components.

The chamber structure as means of conservation of thermal vacuum environment does not use any consumables. The instrumentation and control system only uses electricity to operate, which is distributed among its measuring, monitoring and control devices.

12. Environmental considerations for Space Simulation Chambers Facilities

In the design of a thermal-vacuum chamber, one of the first requirements one must consider is the environment in which the chamber will be installed. There are no general rules for a Space Simulation Chamber (SSC) environment; therefore each case shall be particularly analyzed. The environmental requirements may vary depending on the chamber characteristics and the kind of specimens that will be tested.

In a way to prevent specimen and chamber damage, as well as the test development itself, the SSC shall be placed in an environment that meets some environmental requirements. Most of them are derivative from specimens' type requirements.

SSC's specimens are usually very sensitive, and require temperature, humidity and contamination control. The SSC shall as well meet the same requirements in order to prevent specimen damage.

The correct temperature and humidity level shall maintain the ideal environment for the chamber functioning.

The temperature ranges will depend on the type of space specimens being tested. As a general rule, a temperature of $22^{\circ}\text{C} \pm 3^{\circ}\text{C}$ may be applied [30].

The humidity control becomes detrimental due to electrostatic charging and surface corrosion, which may also affect the chamber structure. As a general rule for space systems, the room shall have a relative humidity of $55 \pm 10\%$ [30].

A contamination controlled environment is required in order to prevent damages to specimens and contamination to the chamber interior caused by airborne particles. This internal chamber contamination 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 [31]. As a minimum for general space products, the chamber (or at least the chamber's door) shall be placed in a 100,000 Federal Standard 209E (equivalent to ISO 8) class clean room. Otherwise, in a case where the specimens use optical lenses for example, the minimum may be increased to a 10,000 Federal Standard 209E (equivalent to ISO 7) class clean room. [32, 33].

The physical space requirements for SSC are not usually a problem, since they are generally placed on large buildings such as integration and testing

laboratories, which have sufficient space and access for all pumping ports, diagnostics equipments and supports.

The chamber base structure shall be 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. For SSCs which test specimens that vibrate or need a precise vibration control during test, such as optical equipments, the chamber shall be installed on the basis of a seismic block.

13. Conclusions

The Space Simulation Chambers are used to simulate as closely as possible the space environment conditions experienced by spacecrafts.

Space simulation chambers play a key role to spacecraft systemic models qualification.

The space environment main characteristics experienced by spacecraft orbiting the Earth are: high vacuum, cold space environment and different sources of radiation. These phenomena are transformed into function assigned to systems or a set of systems that will permit their generation. The basic systems that compose the space simulation chambers are: *Structure of the Chamber, Vacuum System, Thermal System, Solar Simulator, Controls and Instrumentation System and Supply System.*

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*

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.

This study allowed a comprehensive understanding on the state-of-the-art of space simulation chambers, depicting all the phenomena involved in the process of testing and showing the technological evolution of these systems from conception to present moment. The work also identified the definition and classification of operation, states, modes, passive and active operations and control monitoring philosophy of a set of chambers. Another contribution of this paper is the definition of the conventional operational requirements of various state-of-the-art commercial chambers.

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