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Space systems — Development technology of a thermal vacuum chamber

Systèmes spatiaux — Technologie de développement d'une chambre thermique sous vide

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Foreword

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Introduction

Since the first artificial satellite was launched into space successfully in 1957, space activities have been developed over the decades. The large amount of experience collected during that period demonstrates that a significant number of failures or defects appearing during spacecraft in-orbit operation were induced by space environment factors. These factors include space vacuum, cold black background, solar radiation, and also albedo and eigenradiation of the Earth. Therefore, thermal balance tests and thermal vacuum tests for spacecraft are performed in a simulated environment generated by ground simulation facilities in order to evaluate spacecraft performance, to verify thermal analysis models, and to discover early failures and defects in the spacecraft design and manufacturing process.

Countries engaged in spacecraft development have established several thermal test facilities, known as thermal vacuum chambers. They also have standardized requirements for thermal vacuum tests and thermal balance tests. These efforts greatly improved spacecraft reliability and played an important role in space activities.

A thermal vacuum chamber is designed to simulate vacuum, cold black and heat flux environment that a spacecraft experiences during its mission in space. It is composed of vacuum vessel, shroud, nitrogen system, vacuum system, heat flux simulation system, specimen support mechanism, measurement and control system, etc. Based on the state-of-the-art simulation technology, the relevant test standards and experiences accumulated from facilities development, this document provides development technology of a thermal vacuum chamber.

Space systems — Development technology of a thermal vacuum chamber

1 Scope

This document describes the technology for simulating space environments such as vacuum, cold black, and heat flux, as well as the compositions and functions of a thermal vacuum chamber (TVC). This kind of facility defined in this document is suitable for thermal vacuum tests (TVT) and thermal balance tests (TBT) on spacecraft-system level as well as on large-spacecraft-component level.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
thermal vacuum chamber
TVC
space environment simulator
facility to simulate the space vacuum, cold black, and heat flux environment on the ground

Note 1 to entry: It is used for *thermal vacuum tests (TVT)* (3.4) and *thermal balance tests (TBT)* (3.5) of spacecraft.

3.2
shroud
subsystem of a *thermal vacuum chamber (TVC)* (3.1) to simulate the *cold black environment* (3.3) in space

Note 1 to entry: It is cooled by liquid nitrogen or gaseous nitrogen to simulate the cold black environment in space. It is also called heat sink.

3.3
cold black environment
space environment without considering the solar and Earth radiation and the Earth's atmospheric albedo

Note 1 to entry: The radiated energy from spacecraft under cold black environment will be completely absorbed.

3.4
thermal vacuum test
TVT
test which is conducted to demonstrate the capability of the test item and to operate according to requirements in vacuum at predefined temperature conditions

Note 1 to entry: A spacecraft is validated by a *thermal balance test (TBT)* (3.5) and a thermal vacuum test (TVT) in a similar environment provided by a *thermal vacuum chamber (TVC)* (3.1) prior to launch.

3.5
thermal balance test
TBT
test which is conducted to verify the adequacy of the thermal model and the adequacy of the thermal design

Note 1 to entry: A spacecraft is validated by a thermal balance test (TBT) and a *thermal vacuum test (TVT)* (3.4) in a similar environment provided by a *thermal vacuum chamber (TVC)* (3.1) prior to launch.

3.6
simulation chamber
main body of a *thermal vacuum chamber (TVC)* (3.1)

Note 1 to entry: It includes vacuum vessel and *shroud* (3.2) and provides test space for spacecrafts.

4 Symbols and abbreviated terms

B/S	browser/server
C/S	client/server
DCS	distributed control system
FCS	field bus control system
GN_2	gas nitrogen
HMI	human-machine interface
LAN	local area network
LN_2	liquid nitrogen
NPSH	net positive suction head
PLC	programmable logic controller
SCADA	supervisory control and data acquisition
SS	stainless steel
TVC	thermal vacuum chamber
TBT	thermal balance test
TCU	thermal conditioning unit
TVT	thermal vacuum test

5 Vacuum and thermal environment simulation

5.1 General

Spacecrafts in-orbit are exposed to high vacuum, cold black and heat flux radiation environment. Therefore, a spacecraft is validated by TBT and TVT in a similar environment provided by a TVC prior to launch. This allows to evaluate the thermal control system's performance, to verify the thermal analysis model, to discover early failures and defects in spacecraft design and manufacturing process, and to check the performance of spacecraft in extreme high and low temperatures. With decades of technical development and the establishment of testing standards, the simulation methodology for the three environmental factors (vacuum, cold black and heat flux) tends to be mature.

5.2 Vacuum environment simulation technology

The pressure in space varies with the orbital altitude of the spacecraft. The higher the orbital altitude is, the lower the pressure would be. The pressure at the Earth's sea level is about $1{,}013\times10^{5}$ Pa, and the pressure in the flight orbit of Earth spacecrafts is between 10^{-2} Pa and 10^{-12} Pa. According to the heat exchange theory, under the condition that the pressure is lower than 10^{-2} Pa, heat exchange between spacecrafts and space environment is mainly radiation, and conduction and convective heat transfer is negligible. According to the purpose and standards of TVT and TBT of spacecraft, the vacuum environment simulation is satisfied when the test specimen is under test condition with not higher than $1{,}33\times10^{-2}$ Pa. According to the development of vacuum acquisition technology, Roots pump-dry pump unit, molecular pump and cryopump are generally combined for obtaining an ultimate pressure about 10^{-5} Pa under non-load condition, so as to ensure that the pressure is not higher than $1{,}33\times10^{-2}$ Pa with load and meet the test for spacecrafts.

5.3 Cold black environment simulation technology

Without considering the solar radiation and earth (or other planet) albedo and eigenradiation, deep space is similar to an infinite dissipation black body. Under such conditions a passive body experiences a balance temperature between −270,15 °C (3 K) and −269,15 °C (4 K), and the black body energy density is about 5×10^{-6} W/m^2. This concept, known as cold black environment, implies that the heat emitted by a spacecraft will be absorbed completely. The device on the ground which simulates this environment is called shroud. However, to generate the exact space environment on the ground is economically unviable and proved to be unnecessary. Based on the error analysis, generating an environment of below 100 K, shroud absorptivity of about 0,95, and shroud emissivity of no less than 0,9 can reduce the temperature error on the spacecraft to less than 1 % under vacuum environment. Therefore, the state-of-the-art simulation requirement for cold black environment requires a balance of performance, cost and schedule that can be achieved in the design and production of thermal systems. Typically shroud consists of SS or aluminium. Its surfaces facing towards the test volume are coated with black paint to obtain high absorptivity (α) and high emissivity (ε). The volume inside of the shroud is part of a cooling circuit with fluids that are capable of cooling down the shroud to a temperature of approximately −173,15 °C (100 K). Nitrogen with a boiling point at 77 K is widely used for that purpose since it is relatively cheap compared to hydrogen, oxygen or helium.

5.4 Space heat flux simulation technology

5.4.1 General

The external heat flux experienced by spacecrafts in Earth orbit comes from solar radiation, albedo and eigenradiation of the earth. The space heat flux is simulated in two different ways, the incident heat flux simulation and the absorbed heat flux simulation.

5.4.2 Incident heat flux simulation technology

The incident heat flux method is used to simulate the effect of solar radiation only. For the incident heat flux method, the heat flux is generated by a solar simulator.

A predefined volume of the thermal vacuum chamber is exposed to solar type energetic illumination which complies in each respect with the basic parameters of the sun: irradiance, spectrum, divergence, illumination stability, and spatial uniformity. This is typically achieved by collect light from xenon lamps through an arrangement of lenses and mirrors. The light beam is focused and superimposed to the predefined volume. Typically, a solar simulator provides the range of irradiance from 0,5 to 1,3 solar constant and collimation angle of no more than ±2°. A solar simulator provides an accurate simulation of the actual solar spectrum. A solar simulator is restricted in application due to high-cost, complicated system and fixed illumination surface. In addition, when using a solar simulator, the satellite can be installed on the motion simulator which guides the spacecraft with respect to artificial solar beam.

5.4.3 Absorbed heat flux simulation technology

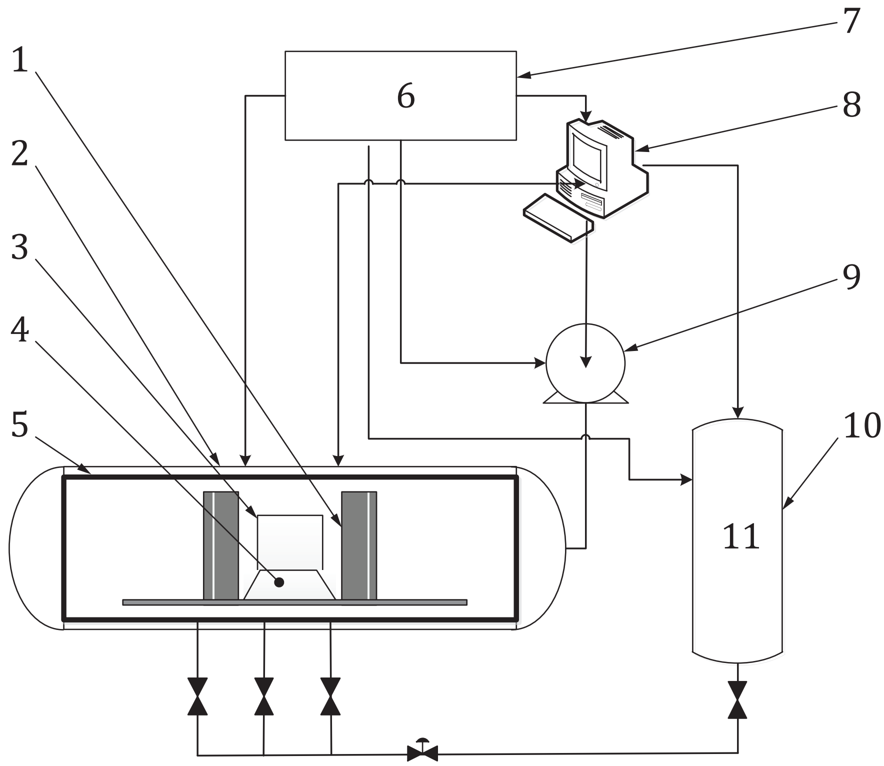
For the absorbed heat flux simulation technology, the heat flux is generated by heat sources within the test volume. State-of-the-art, there are three ways to generate absorbed heat flux. The first way is using infrared heat flux simulator, such as infrared lamps, infrared cage, or thermal controlled panel, to generate infrared radiation to simulate the absorbed heat flux. The second way is using resistive film heater attached to the specimen surface with the absorbed heat flux controlled by electrical power. The third way is using a temperature-adjustable shroud to simulate the absorbed heat flux. It requires a set of GN_2 thermal conditioning unit (TCU).

The first two ways are widely used due to the characteristics of low-cost, flexible combination and simple system configuration. However, the equipment used for these two ways will partially block the radiation of the shroud to the specimen during the test, which brings difficulties to the realization of low-temperature conditions for the specimen. In addition, due to poor versatility, infrared heat flux simulators and resistive film heaters must be designed and manufactured according to the structural dimensions and heat flux requirements of spacecrafts. When the third way is adopted, there is no need to develop extra heat flux simulator for thermal test, which saves preparation time and cost. However, it has low simulation accuracy and slow heat reflection.

6 Design of TVC

6.1 Configuration of TVC

A thermal vacuum chamber is designed to simulate vacuum, cold black and heat flux environment that a spacecraft experiences during its mission in space. It is composed of vacuum vessel, shroud, nitrogen system, vacuum system, heat flux simulation system, specimen support mechanism, measurement and control system, etc. The heat flux simulation system can consist of any combination of the different heat flux simulation technology: solar simulator, infrared flux simulator and temperature-adjustable shroud. The system composition of TVC is shown in Figure 1.



Key

1 vacuum vessel
2 shroud
3 test specimen
4 specimen support mechanism
5 heat flux simulator
6 cooling circulating water, equipment electricity, compressed air, liquid nitrogen
7 logistic support system
8 measurement and control system
9 vacuum system
10 nitrogen system
11 LN_2 tank

Figure 1 — Schematic diagram of a typical TVC

The simulation chamber composed of vacuum vessel and shroud is the main body of TVC, in which the specimen and its support mechanism are fixed during the test. The nitrogen system provides liquid nitrogen or gas nitrogen for the shroud to simulate cold black environment. The vacuum system provides the required vacuum environment for the simulation chamber. The heat flux simulation system provides the heat flux environment for the specimen. The measurement and control system realizes the operation control of the whole system and data acquisition.

6.2 General design

Firstly, the test requirements are analysed, including the maximum weight, the maximum structural dimensions, the attitude regulation, and the method of heat flux simulation of the test specimen, etc.

Secondly, the design standards are selected from the relevant international, national, industrial and enterprise standards.

Thirdly, the overall scheme is determined, including equipment configuration, the structural type of the simulation chamber, the way the specimen access to the simulation chamber, and the overall equipment layout, etc.

Then, technical specifications are determined, including the size of the simulation chamber, the maximum weight and the attitude regulation of the specimen, the vacuum degree with load and the pumping time, ways of heat flux simulation, the shroud temperature, the cleanliness requirement of simulation chamber, the measurement and control requirements, the reliability, safety and maintainability requirements. In order to diminish the simulation error brought by the limited volume of simulation chamber to be acceptable, the space between the specimen and the shroud is at least 1/3 of a characteristic dimension of the test specimen.

Finally, the executive plan of TVC is determined, including the development period, transportation, assembly, commissioning, and cost.

7 Vacuum vessel

7.1 Composition and function

The vacuum vessel is the main body of the TVC and provides a benchmark for other subsystem equipment installation. It houses the test specimen and the shroud. The vacuum vessel provides interfaces for nitrogen system, vacuum system, heat flux simulation system, specimen support mechanism, measurement and control system. The vacuum vessel is composed of cylinder, door, flanges, and support as shown in Figure 2.

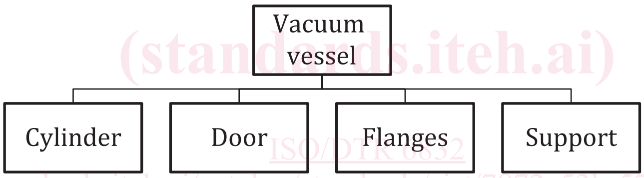


Figure 2 — Block diagram of vacuum vessel

7.2 Vessel design

7.2.1 Structure shape

The size of the vacuum vessel is determined together by the size of the test specimen, the room size and the other test requirements.

There are several structural shapes available for vacuum vessel, e.g. cylinder, sphere, and box. The most common shape of TVC is a cylinder vessel. Although its stress state is not as good as that of a spherical vessel, it has the advantages of simple structure and convenient manufacturing. Compared with the box-shaped vessel, its rigidity is much better. Table 1 shows structural shapes of vacuum vessel.

Table 1 — Structural shapes of vacuum vessel

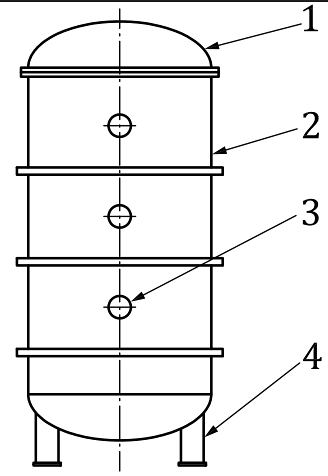
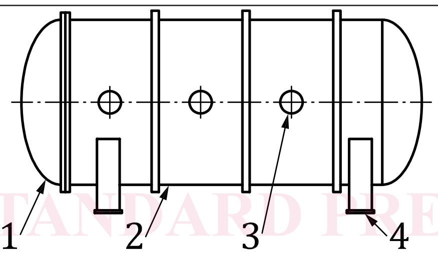
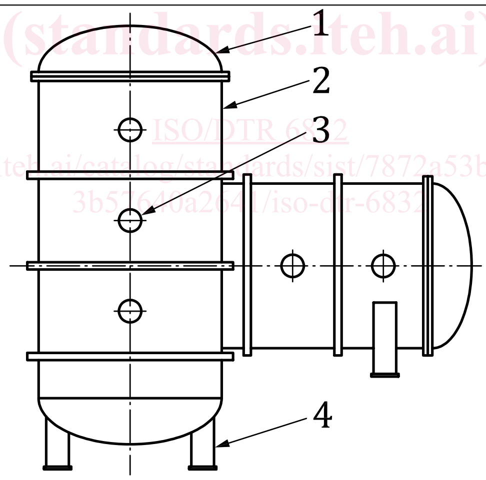
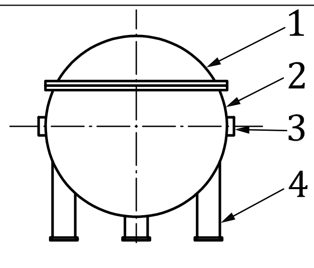
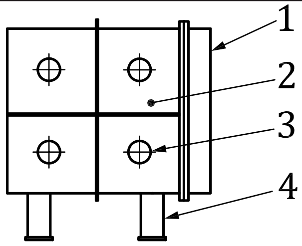
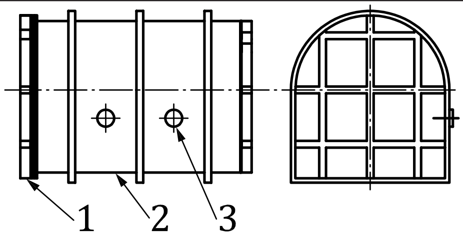
Name		Diagram	Notes
Cylinder	Vertical type		This type vessel occupies small floor area and has high height. The sealing ring is compressed by the weight of the door itself, so no preload mechanism is required.
	Horizontal type		This type vessel is easy and safe access to the vessel for specimen. The self-weight of the vessel produces a bending moment.
	T type		This type vessel combines the features of vertical and horizontal type, but is complex and expensive to build. This type vessel is often used along with solar simulator and motion simulator.
Sphere			Under the same external pressure condition, the sphere type vessel has the best stress state and the minimum wall thickness required, which means saving the material. But it is complex to manufacture and expensive to build. It's not widely used due to the low effective space.
Key 1 door 2 cylinder 3 flange 4 support			

Table 1 *(continued)*

Name		Diagram	Notes
Box	Cube		This type vessel is easy and safe access to the vessel for specimen, and high effective space. But it has poor stress state.
	Mailbox		This type vessel has similar features to the cube vessel with better stress state.
Key 1 door 2 cylinder 3 flange 4 support			

7.2.2 Material

The vacuum vessel is placed indoor. Its external environment is ambient temperature and atmospheric pressure, and the internal environment is vacuum and cryogenic temperature. The material of the vacuum vessel not only bears low temperature and air corrosion, but also has low outgassing rate under vacuum environment.

The stainless steel is often used for the cylinder, dome ends, flanges, and inner parts of the vessel. Because it has many advantages, such as good rigidity, easy processing, easy welding, high chemical stability, oxidation resistance, corrosion resistance, cryogenic environment resistance, good air tightness, low outgassing rate, etc. Other components use in ambient environment, such as the support and stiffening ring etc. These components use carbon steel to reduce the consumption of stainless steel and reduce the manufacturing cost. The performance of the stainless steels commonly used in vacuum vessel are shown in Table 2.

Table 2 — Performance of stainless steel

No.	Performance	Name			
		SS 304	SS 304L	SS 316	SS 316L
1	Mass density/g·cm^{-3}	7,93	7,93	7,98	7,98
2	Yield strength/MPa (20 °C)	205	180	205	180
3	Allowable stress/MPa	137	120	137	120
4	Modulus of elasticity/10^3 MPa (20 °C)	195			
5	Outgassing rate/ × 133,3 Pa·L·s^{-1}·cm^{-2} (Pump 1 h to 25 h)	2,1 × 10^{-9} to 1,7 × 10^{-10}			

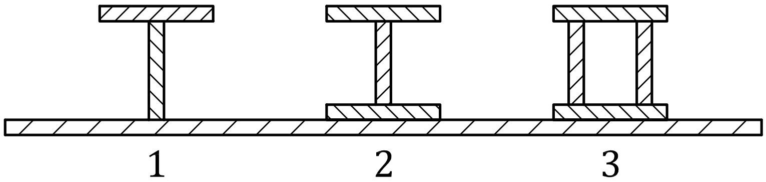
7.2.3 Structure design

7.2.3.1 Cylinder

The cylinder, the main body of the vacuum vessel, mainly includes the straight cylinder, the end, and the flanges. Refer to 7.2.1 for the structure shape of the cylinder.

The end shape is categorized into spherical, spherical crown, ellipse, disc, cone, flat etc. The spherical crown, ellipse and disc end are preferred for vacuum vessel because of their good stress state.

In order to increase the rigidity and minimize the thickness of vessel, the stiffening ring is designed on the outer wall of the vessel. By this way, the consumption of stainless steel is reduced, saving manufacturing cost. Common shapes of stiffening rings include T type, H type and II type as shown in Figure 3.



Key

1 T type

2 H type

3 II type

Figure 3 — Types of stiffening ring

7.2.3.2 Door mechanism

The door provides the access way for test specimen and personnel. The type of door mechanism depends on the vessel shape and the room layout. Table 3 shows the types of door mechanism.