
**Space systems — Thermal vacuum
environmental testing**

Systèmes spatiaux — Essais environnementaux sous vide thermique

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The on-orbit environments of spacecraft, with their vacuum state, cryogenic and black background, and complex heat transfer, are harsher and more complex than the ground environment. They have a strong impact on the success of spacecraft mission. Thermal balance tests (TBT) and thermal vacuum tests (TVT) at spacecraft level are conducted to ensure the units in spacecraft operate normally in specified pressure and thermal range.

This document provides methods and specifies general requirements for spacecraft level thermal balance tests and thermal vacuum tests. However, the technical requirements in this document can be tailored by the parties for some special spacecraft, such as manned vehicle, deep space explorer, extra-terrestrial body lander or the satellites with emphasis on low-cost and fast delivery, which are characterized by extensive use of non-space-qualified commercial-off-the-shelf (COTS) units.

This document acts as a supplement to ISO 15864 and ISO 19683. It is applicable to test project designers and test organizations. It also serves as a reference for spacecraft designers and test facility manufacturers.

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Space systems — Thermal vacuum environmental testing

1 Scope

This document provides methods and specifies general requirements for spacecraft level thermal balance tests (TBT) and thermal vacuum tests (TVT). It also provides basic requirements for test facilities, test procedures, test malfunction interruption emergency handling and test documentation. The methods and requirements can be used as a reference for subsystem-level and unit-level test article.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 15864:2021, *Space systems — General test methods for spacecraft, subsystems and units*

ISO 17566:2011, *Space systems — General test documentation*

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

maximum predicted temperature

highest temperature that can be expected to occur during the entire life cycle of the *subsystem* (3.4)/*unit* (3.8) in all operational modes plus an uncertainty factor

3.2

minimum predicted temperature

lowest temperature that can be expected to occur during the entire life cycle of the *subsystem* (3.4)/*unit* (3.8) in all operational modes plus an uncertainty factor

3.3

spacecraft

integrated set of *subsystems* (3.4) and *units* (3.8) designed to perform specific tasks or functions in space

3.4

subsystem

assembly of functionally related *units* (3.8), which is dedicated to specific functions of a system

3.5

thermal balance test

test conducted to verify the adequacy of the thermal model and the adequacy of the thermal design

3.6

thermal uncertainty margin

temperature margin included in the thermal analysis of *units* (3.8), *subsystems* (3.4) and *spacecraft* (3.3) to account for uncertainties in modelling parameters such as complex view factors, surface properties, contamination, radiation environments, joint conduction and interface conduction and ground simulation

3.7

thermal vacuum test

test conducted to demonstrate the capability of the test item to operate according to requirements in vacuum at predefined temperature condition

Note 1 to entry: Temperature conditions can be expressed in terms of temperature level, gradient, variation and number of high-low temperature cycles.

3.8

unit

lowest level of hardware assembly that works with specified complex electrical, thermal and/or mechanical functions

4 Symbols and abbreviated terms

AT	acceptance test
EGSE	electrical ground support equipment
FM	flight model
IR	infrared
MGSE	mechanical ground support equipment
OSR	optical solar reflector
PFT	proto-flight test
QT	qualification test
TBT	thermal balance test
TQCM	temperature-controlled quartz crystal microbalances
TVT	thermal vacuum test
UPS	uninterruptible power supply
UV	ultraviolet

5 Test purpose

5.1 Thermal balance test

The purpose of the thermal balance test is to provide the data necessary to verify the analytical thermal model and demonstrate the ability of the spacecraft thermal control subsystem to maintain the specified operational temperature limits of the units throughout the entire spacecraft.

5.2 Thermal vacuum test

5.2.1 General purpose

The purpose of the thermal vacuum test is to demonstrate the ability of the test item and its units to meet the design requirements under vacuum conditions and temperature extremes that simulate those predicted for flight. TVT detects material, process and workmanship defects that would respond to vacuum and thermal stress conditions.

The test level and test duration are described in [6.2.2.1](#) and [6.2.2.2](#) respectively.

5.2.2 Qualification test

During the qualification test (QT), the thermal vacuum test serves to validate the performance of the qualification model (QM) in the intended environments with the specified qualification margins.

5.2.3 Proto-flight test

During the proto-flight test (PFT), the thermal vacuum test serves to validate the performance of the proto-flight model (PFM) on the first flight in the intended environments with the specified proto-flight margins.

5.2.4 Acceptance test

During the acceptance test (AT), the thermal vacuum test serves to validate the performance of the flight model (FM), except the one used as pro-flight, in the intended environments with the specified acceptance margins.

6 Test methods

6.1 Thermal balance test

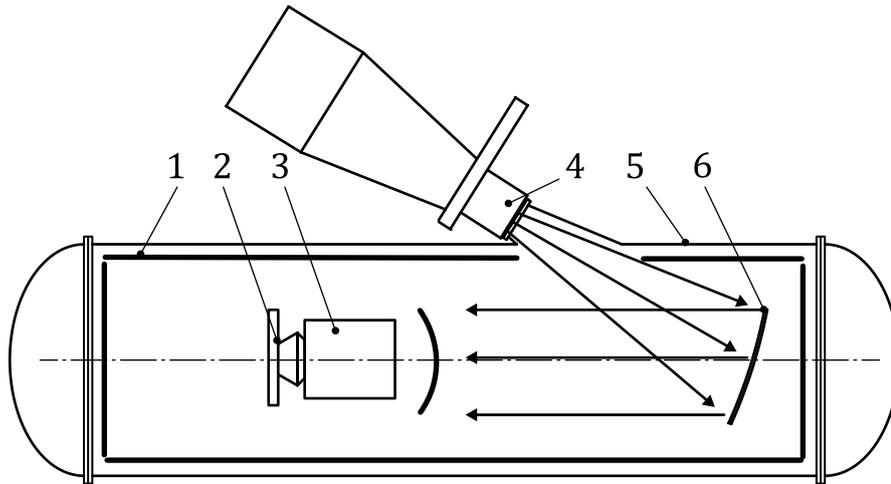
6.1.1 Test description

The on-orbit external thermal flux simulation can be conducted by one of the following methods:

a) Incident flux method

The intensity, spectral content and angular distribution of the incident solar, albedo and planetary irradiation encountered by on-orbit spacecraft are simulated by using solar simulator system, shown in [Figure 1](#) or using the other method (e.g. with axial location of solar simulator).

The solar simulator is composed of the xenon lamp, the filter and the collimator. Generally, the test article is installed on a motion simulator (rotating platform) to simulate the different attitudes on orbit. For the requirements of a solar simulation system, see [7.3.4.5](#). For the main characteristic of a solar simulator, see [Annex A](#).



Key

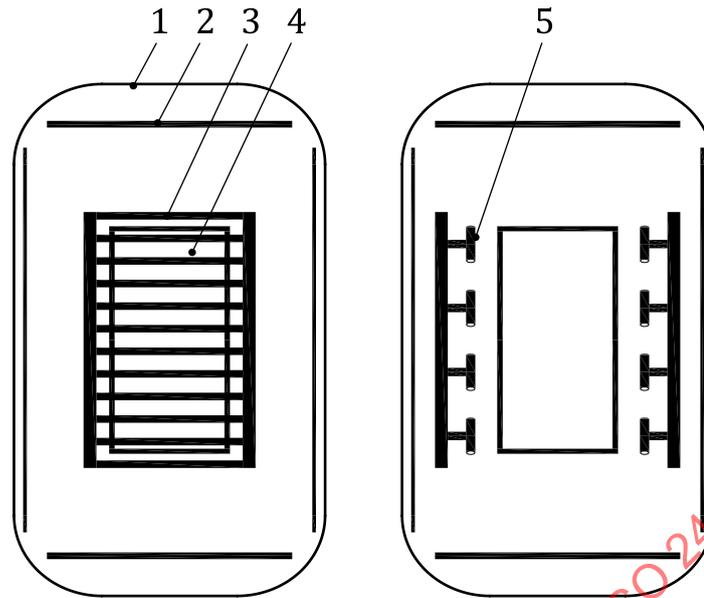
- | | | | | | |
|---|-----------------|---|------------------|---|--------------|
| 1 | shroud | 2 | motion simulator | 3 | test article |
| 4 | solar simulator | 5 | vacuum chamber | 6 | collimator |

Figure 1 — Solar simulation method

This method is suitable for spacecraft with complex shapes and large differences in surface thermal characteristics. It can provide incident illumination with matching spectral, uniformity and stability of irradiance, divergence angle for the thermal test of the spacecraft. However, it is difficult to simulate the effects for performance degradation of thermal control coatings at end of lifetime. This method may be restricted for the effect of reflection light or heat from surfaces of shroud and MGSE, large operating cost and heat pipes on-board normally working horizontally.

b) Absorbed flux method

The absorbed solar, albedo and planetary irradiation for on-orbit spacecraft, are simulated by using infrared (IR) heaters (cage, lamps, calrods and thermal plate) with their spectrum adjusted to the external thermal coating properties, or by using film heaters attached to spacecraft surfaces with the absorbed heat flux controlled by electrical power, shown in [Figure 2](#). For the requirements for IR heater and film heater, see [7.3.4.3](#) and [7.3.4.4](#). [Annex B](#) describes the design flow of an IR heater in the absorbed flux method in TBT.

**Key**

- | | | | | | |
|---|----------------|---|----------------------|---|-----------------------------|
| 1 | vacuum chamber | 2 | shroud | 3 | IR cage or IR thermal plate |
| 4 | test article | 5 | IR lamp/calrod array | | |

Figure 2 — Absorbed flux method

This method is suitable for spacecraft with simple shapes and similar in surface thermal characteristics. It has the advantage of high reliability, low manufacturing and operation cost. It may be restricted for the containment released from MGSE, limited temperature ramp and the numbers of heating loops or electrical power.

c) The combination of methods a) and b)

The combination of the methods a) and b) can be used for heat flux simulation of different surfaces of the test article in TBT.

Generally, the following shall be considered during test article design:

- The profile, structures, materials, instrument and device layout, cable network, various thermal control measures, envelop dimension, surface state, installation and connection mode, internal heat sources, thermal capacity shall meet the requirements of thermal design and simulation.
- The thermal simulation model of spacecraft or its units may be designed specially, whose thermal capacity and heat consumption are in accord with that on orbit.
- The large antenna, solar array and other external components may not participate in the test, but their radiation heat effects shall be evaluated. Conduction heat shall be simulated on installation interfaces by proper heat insulation, heat leakage compensation, or constant temperature.
- Additional radiation flux created by thermal vacuum chamber, MGES and heating devices frames shall be taken into account.
- If the natural convection effects cannot be ignored under the ground gravitation condition, pressurized cabin convection boundary shall be simulated by adjusting the gas temperature, pressure and velocity on the units' surface to ensure the heat transfer is equivalent.
- The propellant tank is filled with protective gas.

6.1.2 Test conditions

6.1.2.1 Test cases design

TBT cases depend on the mission, spacecraft design, spacecraft operational modes, and times required to reach stabilization. According to the internal heat source heating mode, orbital heating mode and other thermal boundary conditions, there are four types of operating cases.

a) Case 1

Internal heat source, simulative orbital heating and other thermal boundary conditions are constant;

b) Case 2

Internal heat source works in a set periodic change mode, while the simulative orbital heating and other thermal boundary conditions are constant;

c) Case 3

Internal heat source works in a set periodic change mode; the simulative orbital heating and other thermal boundary conditions are in the periodic orbit change mode;

d) Case 4

Internal heat source, simulative orbital heating mode or other thermal boundary conditions are in the aperiodic change during the specified phase.

For b) and c), the cyclic test for several periods can be repeated either with the heat source operating mode and simulative orbital heating mode in one orbit period until the temperature of test model is steady periodically, or with several orbit periods as one test period until the temperature of test model is steady periodically.

The design principles of the test cases are as follows.

- Test phases shall simulate cold and hot conditions to verify all aspects of the thermal hardware and software, including heater operation, radiator sizing, and critical heat transfer paths.
- Test cases shall obtain sufficient critical parameters required for thermal analytical model verification and flight mission indication.
- To validate the adequacy of the thermal control design, the cases shall contain hot case and cold case at least. Consideration should be given for testing an “off-nominal” case such as a safehold or a survival mode.
- Generally, the test for the only purpose of verifying thermal analytical model shall contain transient case.
- Transient case shall be set when the influence of on-orbit heat flux or other thermal boundary conditions on spacecraft temperature increases with time.

6.1.2.2 Temperature stabilization

The exposure shall be long enough for the test article to reach temperature stabilization so that temperature distributions are ensured in the steady-state conditions. The test temperature shall be considered as stabilized, in case that

- a) temperature monitored at the test article is within the allowed tolerance around the specified test temperature;
- b) temperature change rate is lower than the value allowed for stable conditions.

Steady-state conditions shall be defined in test specification. The temperature fluctuation should be within $\pm 0,5$ °C over 4 h; or monotonous change should be less than $0,1$ °C/ h over 4 h. Meanwhile the fluctuation of other temperature points can be used as a reference.

6.1.3 Basic requirements of test facilities

- a) The test pressure should be no higher than $1,33 \times 10^{-2}$ Pa.
- b) The shroud surface temperature should be no higher than 100 K.
- c) The distance between testing equipment and a test item shall ensure:
 - convenience while performing preparation and completion operations with a test item;
 - availability of required uniformity of heat fluxes, incident on a test item surface when performing tests.
- d) The shroud surface shall be painted with high-emissivity black coating whose solar absorption ratio shall be higher than 0,95 and hemispheric emissivity shall be higher than 0,9.
- e) The recommendations in a) and b) should be reassessed according to the specified elements such as external and internal thermal and pressure environment, operational modes of spacecraft and its units, and flight mission.

6.1.4 Monitoring during TBT

The test article shall be operated and monitored throughout the test. Functional tests shall be conducted before, during, and after the test for flight model. Sufficient and timely measurements shall be made on the major internal and external units to verify the major units' thermal design, hardware, and analyses. The heat flux, temperature, unit's operation mode and other performance parameters shall be controlled to meet the requirements of the specified case.

The modification of the thermal analytical model is applicable to all test cases. The modification parameters shall be within the acceptable range. After modification of the thermal analytical model, the modification parameters shall be configured to the thermal analytical model to indicate the temperature of spacecraft flying on orbit.

After the test, a comprehensive analysis shall be made on energy balance in test cases for test error sources. The absorbed and irradiated heat by the test model shall be compared, whose difference is generally controlled within ± 10 %. Test errors generally are derived from limitations of the heat flux simulation mode, deviation between the test model and actual spacecraft, measurement accuracy of heat flux and temperature.

6.2 Thermal vacuum test

6.2.1 Test description

Spacecraft shall be placed in a thermally controlled vacuum chamber having the capability to expose the test article at or beyond the minimum and maximum test temperatures.

The following should be considered.

- a) Units of spacecraft should be flight products (except qualification test).
- b) Some units may be replaced by qualification parts, process parts or simulation parts with their thermal performance and electrical performance parameters conforming to the test requirements.
- c) Large units such as large antenna and solar array may not participate in the test, or may be set apart from spacecraft in test with cable connection.
- d) The propellant tank is generally filled with protective gas.

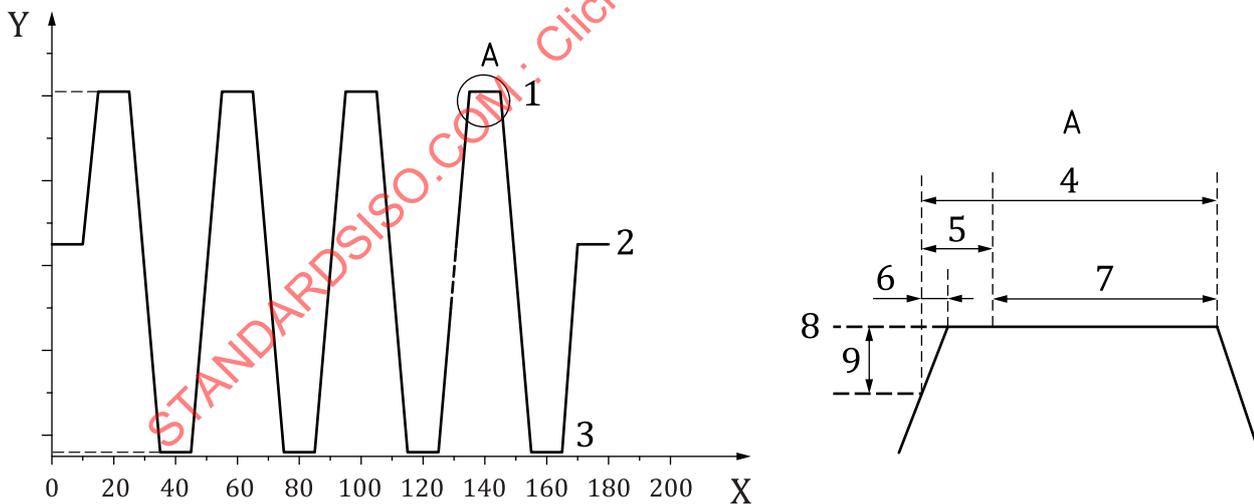
The temperature can be controlled by the following two measures.

- Controlled by test facility
 - 1) Temperatures of shroud and heating devices shall be controlled by adjusting the flow of gas/liquids or the electrical power to assure that the test article reaches the required temperature.
 - 2) The temperature on main functional areas (e.g. light entrance, OSR radiation surface) should be consistent with the extreme external temperature on orbit.
 - 3) The surface protrusion, surface coating, cables temperature change shall be taken into consideration during adjusting to prevent the test article from being damaged.
- Controlled by inner heat source

Internal heat sources include heat consumption of active units or active control heaters.

- 1) In cooling down the test article, its units may be powered off or work in a minimum power consumption state.
- 2) In heating up the test article, its units may be powered on and work in a maximum power consumption state.
- 3) Temperature control thresholds of the active temperature controller should be extended at both ends when the unit temperature is required to be reached faster.
- 4) Temperature should be monitored for temperature-sensitive units during the thermal cycling process.

The temperature profile for TVT is shown in [Figure 3](#). The durations of thermal soak, thermal stabilization and thermal dwell for different units of spacecraft depend on their operation modes, heat inertia characteristics, lifetime, etc. Functional performance testing should be performed after adequate thermal stabilization during thermal soak.

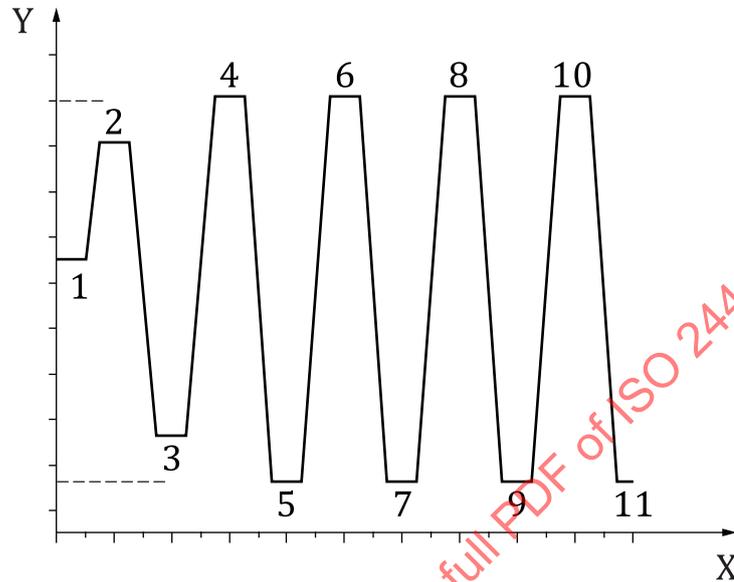


Key

X	time	Y	temperature	1	hot case
2	ambient temperature	3	cold case	4	thermal soak
5	thermal dwell	6	thermal stabilization	7	functional/performance testing
8	hot test temperature	9	within test tolerance		

Figure 3 — Temperature profile for testing

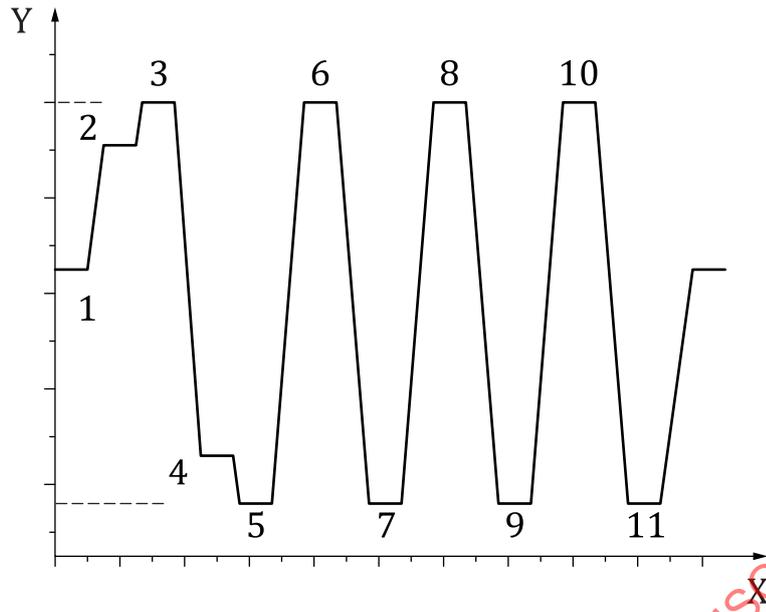
Consideration should be given to conducting the thermal balance test in conjunction with the thermal vacuum test program. A combined test is often technically and economically advantageous. It shall, however, satisfy the requirements of both tests. Examples for combined test temperature profiles are shown in [Figure 4](#), where TBT and TVT are performed in sequence, and in [Figure 5](#), where TBT hot and cold cases are integrated into the first TVT cycle. TBT may be performed after TVT in order to test the thermal-cycling effect on thermal interfaces.



Key

X	time	Y	temperature	1	ambient temperature
2	TB hot case	3	TB cold case	4	TV hot case1
5	TV cold case1	6	TV hot case2	7	TV cold case2
8	TV hot case3	9	TV cold case3	10	TV hot case4
11	TV cold case4				

Figure 4 — TBT and TVT are carried out successively



Key

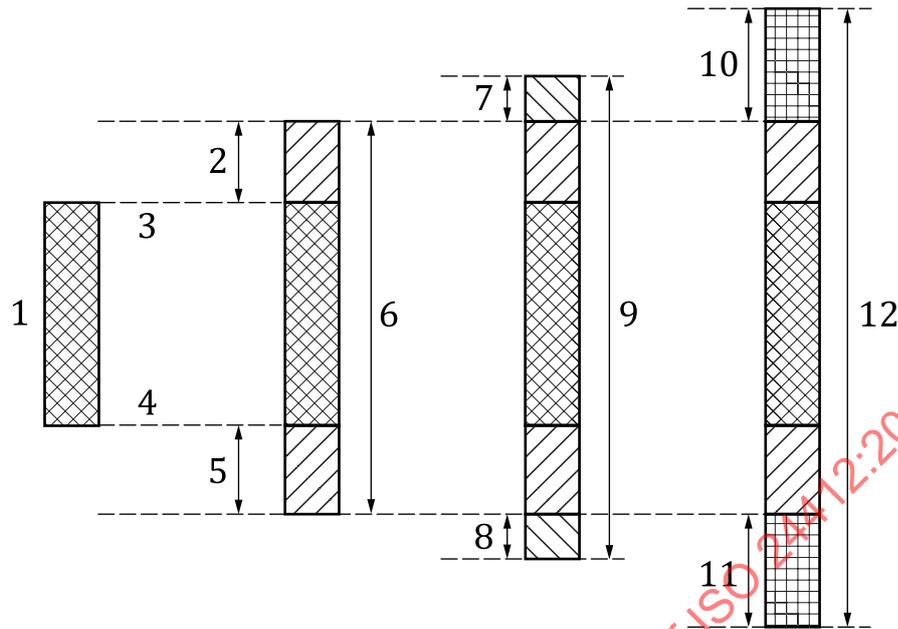
X	time	Y	temperature	1	ambient temperature
2	TB hot case	3	TV hot case1	4	TB cold case
5	TV cold case1	6	TV hot case2	7	TV cold case2
8	TV hot case3	9	TV cold case3	10	TV hot case4
11	TV cold case4				

Figure 5 — TBT is integrated in first TVT cycle

6.2.2 Test conditions

6.2.2.1 Test levels

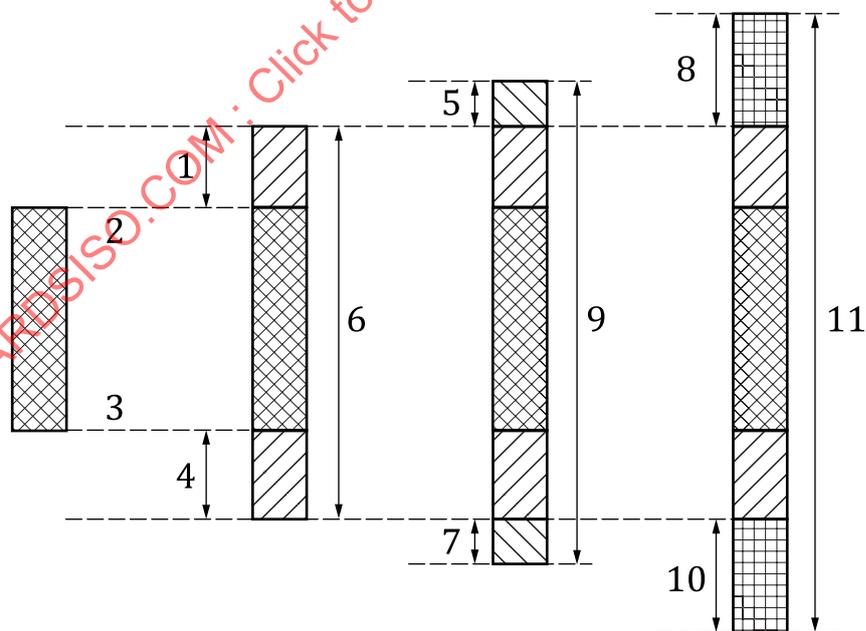
In TVT, the temperature of all units to be verified can be confirmed on the basis of the temperature result from TBT, or the temperature result predicted by the thermal model analysis, as shown in [Figures 6](#) and [7](#). TVT temperature margin of unit is determined in [Table 1](#) according to the test level.



Key

- | | | | | | |
|----|-------------------------|----|------------|----|-------------------------|
| 1 | TBT result | 2 | AT margin | 3 | maximum TBT temperature |
| 4 | minimum TBT temperature | 5 | AT margin | 6 | AT temperature range |
| 7 | PFT margin | 8 | PFT margin | 9 | PFT temperature range |
| 10 | QT margin | 11 | QT margin | 12 | QT temperature range |

Figure 6 — Temperature range and margin of TVT based on TBT result



Key

- | | | | | | |
|----|------------|----|-------------------------------|---|-------------------------------|
| 1 | AT margin | 2 | maximum predicted temperature | 3 | minimum predicted temperature |
| 4 | AT margin | 5 | PFT margin | 6 | AT temperature range |
| 7 | PFT margin | 8 | QT margin | 9 | PFT temperature range |
| 10 | QT margin | 11 | QT temperature range | | |

Figure 7 — Temperature range and margin of TVT based on predicted temperature analysis

Table 1 — Determination of TVT temperature margin

Test level	Margin based on TBT result	Margin based on predicted temperature analysis
QT	5 °C to 10 °C beyond acceptance temperature	5 °C to 10 °C beyond acceptance temperature
PFT	0 °C to 5 °C beyond acceptance temperature	0 °C to 5 °C beyond acceptance temperature
AT	0 °C to 5 °C beyond the maximum and minimum temperatures of TBT	3 °C to 11 °C as thermal uncertainty margin beyond thermal model analysis

The thermal uncertainty margin shall be evaluated by importance, complexity, type, operation temperature of units, and whether the TBT has been carried out or not.

For passive thermal control, the thermal uncertainty margin is a temperature added to worst-case temperature predictions. For active thermal control, the thermal uncertainty margin is a power margin to ensure thermal control stability. When the margin is added to worst-case temperature predictions, the resulting temperature forms the basis for the acceptance temperature range.

Generally, for units that adopt active thermal control, the minimum thermal uncertainty margin can be reduced to ± 3 °C to ± 5 °C. For units that meet more uncertain operational or environmental conditions, the thermal uncertainty margin may be larger than ± 7 °C to ± 11 °C. Lower thermal margins may be adopted for units with an allowable operating temperature below -170 °C or above 120 °C. Specific estimated uncertainty values are set in a spacecraft thermal system specification. For active thermal control units at the cold extreme, 25 % excess heater control authority is used in lieu of 11 °C temperature margins. For unit controlled by heat pipes, the heat transfer margin should be considered if one of the heat pipes fails.

Test temperatures are restricted as follows.

- a) The temperature of the working units should not exceed the temperature range for the corresponding test levels; and the temperature range of the non-working units should not exceed the storage temperature range.
- b) The upper and lower temperature limits in the same thermal control zone shall be within the temperature envelope of the test units.
- c) The temperature ramp rate should be equal to or higher than the maximum predicted ramp rate. In case that the test system is not capable to achieve the ramp rates, rates may be lower at no expense of the test objective and test validity.

6.2.2.2 Test duration

The number of thermal cycles and the duration of thermal soak shall be specified with consideration of mission requirements.

Generally, the numbers of cycles for spacecraft are:

- a) QT: 8 cycles;
- b) PFT: 4 cycles;
- c) AT: 4 cycles.

The thermal soak is suggested to be over 8 h at each temperature extreme during the first and last cycle, and over 4 h for the intermediate cycles.

Test temperature shall be considered as stabilized, in case:

- the test article temperature is within the allowed test tolerance at the specified test temperature;

- the temperature change rate is less than 3 °C per hour.

It is allowed to shorten the measure time or reduce the cycles for some special units such as short-time or disposable products. Their temperatures are not required to reach the stability value. They shall be sufficiently tested before the subsystem TVT or unit TVT.

6.2.3 Basic requirements for test facilities

- a) The test pressure shall be no higher than $1,33 \times 10^{-2}$ Pa.
- b) The shroud temperature and heating devices shall be controlled to meet the requirements for the maximum and minimum temperature and ramp rate of the test article.
- c) The size of the thermal vacuum chamber shall be sufficient to safely perform installation activities of the test article and MGSE.
- d) For spacecraft with high-voltage and high-power units, the test pressure should be at 10^{-4} Pa level due to the internal and external pressure difference.
- e) For some special spacecraft such as Mars lander, the test pressure shall be redetermined according to specified mission environment.

6.2.4 Monitoring during TVT

- a) The performance and function of the test article shall be tested in hot and cold temperature stabilization.
- b) Before, during and after the TVT, functional tests shall be conducted and the results meet its specification.
- c) Within thermal soak at cold and hot test temperature of each cycle, the performance of the test article shall be tested in each operational mode that is foreseen during its service life.
- d) If parts of units are sensitive to vacuum environment, vacuum gauges shall be mounted inside the spacecraft. These units shall not be powered unless pressure is within acceptable range.
- e) Low-pressure discharge testing (to simulate the pressure decrease during launch) should be conducted during the pumping or pressurization process.
- f) Temperatures of high-power units during test deserve special attention to avoid damage from excessive temperature.
- g) Thermal sensors for testing shall be installed as indicated by the thermal analysis for monitoring and acquiring thermal data.
- h) Backup units and redundant circuits shall be tested at hot and cold temperature. Their test duration shall be the same as that of the primary units and shall be equally distributed in each cycle.
- i) Collect and analyse the test environment data, including vacuum degree, shroud temperature, composition and content of released gas, contamination fluctuation.
- j) If required, the motion property or thermal deformation should be measured or monitored when checking mechanism or thermal structure.

7 Test facility

7.1 Laboratory environment

The laboratory environment shall meet the requirements of the specified test article, which include temperature, humidity, cleanliness, etc.

7.2 Laboratory infrastructure

The laboratory infrastructure supports the test system operation and test article handling by providing e.g. water, pressurized air, power, lifting and transport means and communication interfaces.

The laboratory infrastructure shall provide all means to safely:

- a) operate the test system;
- b) handle the test article;
- c) conduct tests.

7.3 Test system

7.3.1 Overview

TBT and TVT shall be performed in a thermal vacuum chamber.

An example for a typical composition of a thermal vacuum chamber is shown in [Figure 8](#). A thermal vacuum chamber usually includes:

- a) chamber system;
- b) vacuum system;
- c) thermal system (cryogenic/heating);
- d) data acquisition system;
- e) mechanical spacecraft ground support equipment (MGSE);
- f) contamination measurement and control equipment.

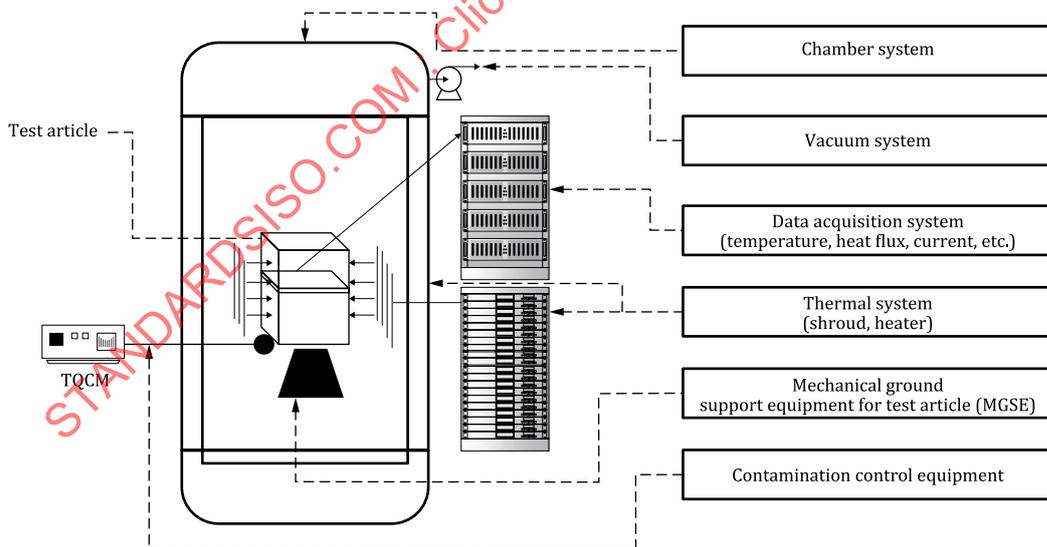


Figure 8 — Typical composition of a test system

7.3.2 Chamber system

- a) The chamber shall provide sufficient number and performance of feedthrough connectors for measurement channels, power supply, EGSE communication, to comply with test requirements.

- b) Cables and connectors permanently used inside the chamber shall be suitable for use in extreme high and low temperature, and vacuum environment.
- c) Leakage of flanges and connector/pipe feedthroughs shall be minimized.
- d) Temperature sensors on shrouds shall be sufficient and distributed uniformly to ensure temperature measurement accuracy. The measurement acquisition period for chamber parameters should not exceed 1 min.
- e) Heat flux from sink background shall be less than 10 W/m² to 30 W/m² based on the relative sizes of the tested articles and a vacuum chamber.
- f) The chamber shall provide a test article grounding interface. The grounding resistance should be less than 1,0 Ohm.

7.3.3 Vacuum system

- a) The vacuum system shall be capable of achieving and maintaining the vacuum pressure required for testing under consideration of leakage, heat devices, MGSE, test article. Pressures as low as 10⁻³ Pa to 10⁻⁴ Pa are readily obtainable. The vacuum system should be entirely dry and should have “dry” vacuum pumps both in its fore-vacuum part (e.g. dry screw and mechanical booster roots-type vacuum pumps) and high-vacuum part (e.g. turbomolecular and cryogenic vacuum pumps).
- b) The pressure change rates should simulate the pressure environment change during the spacecraft ascent and descend.
- c) the vacuum system should provide turbomolecular pumps to evacuate some released gas during testing like hydrogen and helium, provide mass spectrometer to measure the partial pressures of each composition.
- d) Pressurization of the chamber is accomplished with dry nitrogen. This allows the chamber to be returned to ambient pressure at any time that the contaminant cleaning equipment and all major equipment in the chamber are above the minimum allowable temperature of the satellite. Moisture condensation is prevented with this method.
- e) Equipment shall be above the dew point if ambient air is pumped into the chamber. The rate should be controllable.
- f) Vacuum gauges shall be selected in accordance with the test pressure range. Pressure acquisition period shall not exceed 5 s.

7.3.4 Thermal system

7.3.4.1 General requirements

The thermal system shall be able to provide the required thermal conditions both in the volume and on the surface of test article. Thermal conditions typically are generated by:

- a) shroud system;
- b) film heaters;
- c) IR heaters;
- d) solar simulation system;
- e) others or combinations of above.

7.3.4.2 Shroud system

The shroud system generates the required thermal conditions in the vacuum chamber.

Generally, the following apply to the shroud system.

- a) The shroud system shall have the ability to maintain the shroud temperatures within the required range during test. For any temperature zones of shroud required by the test specification, they should be controlled independently. Usually, an independent special shroud is used as a decontamination panel, which is filled with liquid nitrogen during testing and shall be wiped more often.
- b) If required, the shroud system should be able to provide hot gas to bake contamination off the shroud surface.
- c) If required, the shroud system may provide independent cooling panels inside the chamber for large chambers.
- d) The shroud temperature acquisition period should not exceed 1 min.
- e) Liquid nitrogen is the usual cryogenic fluid. When necessary, gaseous helium can be used for lower temperatures.
- f) When the incident flux method is applied in TBT, TVT or combined TVT, the ratio of characteristic dimensions (e.g. length, diameter) of the shroud to the test article should be no less than 3.
- g) When the absorbed flux method is applied in TBT, TVT or combined TVT, the ratio of characteristic dimensions (e.g. length, diameter) of the shroud to the test article should be no less than 2.

NOTE f) and g) describe an ideal case to define a cryogenic shroud inner dimension. In some cases, the characteristic dimensions ratio requirement is not fulfilled as a result of the specific geometry of the thermal vacuum chamber or the testing cost.

7.3.4.3 Film heater

Film heaters are composed of a resistor film and an insulation film. Film heaters are attached directly to surfaces of spacecraft and units, offer minimal test equipment blockage and in many cases are used with specific heating methods, such as appendages (booms, antennas, etc.).

Generally, the following apply to film heaters.

- a) The working temperature in whole test conditions shall not exceed the allowed temperature.
- b) The heating power shall be sufficient to meet the maximum temperature requirements of the test article.
- c) The quantity of adhesives shall be minimized to avoid additional contamination.
- d) When used in serial connection and parallel connection, heat flux consistency shall be considered; and heater resistance matching performance shall be checked.
- e) To increase heating accuracy, a large heating zone should be divided into several individually controlled heating circuits.
- f) Film heaters should be outgassed before installation on the test article to avoid contamination.

7.3.4.4 Infrared heater

An IR cage is made up of a series of metal strips creating heat from an electrical current, and it is designed as the same shape as the spacecraft. An IR cage is divided into different isothermal zones according to different heat flux of spacecraft surface on orbit. The electrical current of each zone is controlled to simulate the heat flux absorbed by the spacecraft.

An IR lamp/calrod array is made up of a series of IR lamps or IR rods. It can be divided into several isothermal zones. The electrical current of each lamp and rod is controlled to simulate the heat flux absorbed by the spacecraft.

A thermal plate is a plate and its temperature is controlled according to the required radiant heat flux, either by electrical power or by fluid flowing in internal tubes.

Generally, the following apply to infrared heaters.

- a) Heating power shall be sufficient to meet the maximum temperature requirements of units.
- b) IR heaters shall be thermally and electrically insulated from test article and chamber.
- c) IR heaters and its accessories (e.g. fasteners, slings, structural frame) shall be clean and oil-free.
- d) The heater and its supporting structure shall contain sufficient rigidity and strength, and shall adapt to the test environment.
- e) The distance from the test article and IR heater shall be suitable to ensure heat flux uniformity and avoid collision damage and local overheating.
- f) Outgassing from the structure frame and materials in vacuum environment shall be performed before the test to avoid contamination.
- g) Uniformity of heat-flux shall be evaluated or measured before testing.
- h) Surfaces of the structure facing towards the test article should be high-reflective to minimize heat reflection. The heater structure shall be designed to minimize shading of the shroud.
- i) To increase accuracy, a large heating zone should be divided into several individually controlled heating circuits.

7.3.4.5 Solar simulation system

Solar simulation is the preferred method of space external heat flux, because it allows the natural occlusion and cavity effects to occur, while imposing direct and reflected solar heat flux with motion simulator. The test article can pitch and roll under test. The solar simulator heats the test article with solar-wavelength rays that simulate the sun. Normally, the solar simulator should be used with the motion simulator.

Generally, the following apply to the solar system.

- a) The illumination area of the optical beam shall cover the test article.
- b) Nonconformity of the optical beam irradiance should be within $\pm 5\%$.
- c) The optical beam shall simulate the thermal environment on orbit.
- d) The created spectrum approximates a 3 000 K blackbody, so with the sun more nearly like a 5 800 K blackbody, augmenting xenon short-arc lamps are used to improve spectral matching.
- e) The collimation angle of the optical beam shall meet the uniformity requirement.
- f) The solar simulation spectrum shall meet the test requirements (see [Annex A](#)).
- g) The load capacity and the number of slip-rings of the motion simulator shall comply with the test specification.
- h) The motion simulator spin speed and pitch angle shall be suitable to simulate the spacecraft attitude change. If not specified otherwise, it should be in the range of:
 - 1) spin speed: 0 to 10 rounds per minute;

- 2) pitch angle: -90° to $+90^{\circ}$.

7.3.5 Data acquisition system

The data acquisition system shall be able to measure and acquire the status parameters of the test article and MGSE, such as temperature, heat flux, current and power.

Generally, the following apply to the data acquisition system.

- a) The data acquisition system shall provide anti-interference.
- b) The data acquisition system shall allow visualization (e.g. curve plotting), processing and storage of the data.
- c) The data acquisition system shall allow setting alarms (e.g. minimum/maximum temperatures).
- d) All data acquisition instruments and computers shall use a synchronized time base throughout the test.
- e) The acquisition period should be no more than 1 min.
- f) In case that a cable/connector is sensitive to temperature (e.g. for electrical performance testing), it shall be controlled within a suitable temperature range.
- g) Instruments used for tests shall be calibrated and used within the valid calibration period.

7.3.6 MGSE

The MGSE is used to support the test article and the test facility (e.g. test bracket).

Generally, the following apply to the MGSE.

- a) The MGSE shall adapt to the working environment temperatures.
- b) The strength and stiffness of the test bracket shall be sufficient to support the test article during test.
- c) The MGSE and its accessories (e.g. fasteners, slings, tools) shall be clean and oil free.
- d) The test bracket mechanical and thermal interface shall be designed to protect the bracket and test article from extra force and thermal effects in the required temperature conditions.
- e) The MGSE outgassing in vacuum environment shall be minimized to avoid chamber or test article contamination.

7.3.7 Contamination measurement and control system

- a) An independent cold panel (decontamination plate) should be fixed inside the chamber to absorb the condensable volatiles during test.
- b) The contamination from organic substance generated from the chamber should be as low as possible.
- c) The contamination from particles brought in the chamber should be as low as possible.
- d) Temperature-controlled quartz crystal microbalances (TQCM), mass spectrometer, wipe samples and witness plates should lie in a suitable position near the units sensitive to pollution to collect, measure or analyse the contamination.
- e) During the chamber pressurization process after the vacuum test, dry nitrogen should be filled first to about 500 Pa to 1 000 Pa to prevent the releasing of absorbed coagulable volatile matter from the decontamination plate.

- f) Before opening the chamber after the test, check that the temperature of the shroud and MGSE shall be above the dew point of the ambient air pumped into the chamber to avoid water condensing on the test article surface and major equipment in the chamber.
- g) The number of staff inside the chamber should be as small as possible. Active movement of the staff inside the chamber should be avoided.

8 Test requirements

8.1 Test tolerance and accuracy

The values for allowed tolerance and the allowed accuracy shall be defined in the test specification according to the different categories of the test article. If not otherwise specified the maximum allowable test tolerance listed in [Table 2](#) should apply.

Table 2 — Maximum allowable test tolerance

Test parameters	Test tolerance
Temperature:	
— Above -193 °C:	— $T_{\min} +0/-4$ °C, $T_{\max} -0/+4$ °C
— Below -193 °C:	— Defined case by case
Atmospheric pressure:	
— Above 133 Pa	— ±15 %
— 133 Pa to 0,133 Pa	— ±30 %
— Below 0,133 Pa	— ±80 %
Solar flux:	
— In reference plane	— ±5% of the set value
— In reference volume	— ±5 % of the set value
IR flux:	
— Mean value	— ±3 % on reference plane

If not otherwise specified, the measurement accuracy listed in [Table 3](#) shall apply.

Table 3 — Test accuracy

Test parameters	Accuracy
Temperature:	
— Above -193 °C	— ±2 °C
— Below -193 °C	— Defined case by case
Atmospheric pressure:	
— Above 133 Pa	— ±15 %
— 133 Pa to 0,133 Pa	— ±30 %
— Below 0,133 Pa	— ±80 %

8.2 Test configuration

The test configuration should be defined taking the following into consideration.

- a) The thermal vacuum chamber shall be able to receive the test article by shape and size.

- b) The thermal, electrical and mechanical interfaces of the test facility and test articles shall match each other.
- c) The thermal boundary simulation method should take into account the configuration of heat pipes, and the orientation and main radiating surfaces of the test article.
- d) The test system shall meet the spacecraft operational modes requirements.
- e) The volume and leakage rate of the sealed cabin shall be determined before TBT and TVT.

8.3 Temperature and heat flux measurement

8.3.1 General

In the thermal vacuum environment test:

- a) temperatures are measured by sensors like thermocouple, thermal resistor and thermistor;
- b) heat flux is measured by:
 - 1) radiation intensity meter or Wattmeter (radiometer) for IR heating;
 - 2) calorimeter (absolute radiometer) and solar cell for solar simulator.

In order to minimize thermal leakage, the temperature of the sensor wiring shall be kept close to the temperature of the controlled object.

If only one heat flux sensor is installed in a heated area, it should be arranged in the average heat flux line of this area.

8.3.2 Location of temperature monitoring point for test article

The monitoring point locations for the test article shall be defined considering:

- a) computational nodes for the thermal analysis model;
- b) telemetry points for the flight model.

8.3.3 Location of temperature monitoring point for test equipment

Monitoring sensors for the test equipment shall be:

- a) placed in different positions on the shroud surface allowing for backup;
- b) on the interfaces between the MGSE and the test article;
- c) other test devices as required by the test specification.

8.4 Heating device selection

Heating devices of thermal system can be used alone or coherently for TBT or TVT. The following factors should be considered in selection:

- a) the specified purpose of TBT or TVT;
- b) thermal parameters of the simulated environment (e.g. the uniformity or heat flux, control range of temperature and power);
- c) status and stage of the product (qualification model, proto-flight model, acceptance model, thermal dummy);
- d) influence of gravity (e.g. heat pipes or other equipment susceptible to the direction of gravity);

- e) impact on the test article (e.g. contaminants or remainders from the film heaters attached to the test article);
- f) facility capacities (e.g. chamber volume, shroud temperature, cable channel, power supply);
- g) verification means on the capacities of the heating device;
- h) convenience and safety for production and installation;
- i) cost of operation, storage and reusing or reproduction.

8.5 Safety requirements and recommendations

The following safety requirements and recommendations apply.

- a) Test facilities shall be equipped with uninterruptible power supply (UPS) for critical instruments.
- b) Security-related parameters like nitrogen pressure and vacuum degree shall be continuously monitored.
- c) Sufficient measures shall be adopted at high-risk areas against accidents or damages, such as caution signs, safety fences, cable coverers, electrostatic release and measurement devices.
- d) Critical electrical interface relationship and relevant parameters such as electrical power load, phase sequence and ground insulation, shall be confirmed before the test.
- e) If risky operation has to be performed high above the ground or in narrow space, protection measures such as using aerial working platforms and safety belts shall be adopted.
- f) While the solar simulator is active, operators that can be exposed to the beam shall wear protection apparatus, such as protective clothing, masks and gloves with UV-protection and goggles.
- g) An emergency response procedure to handle interruptions or anomalies of participating systems shall be established and practiced before test. Procedures shall address test article, power supply, heating and cooling devices, measuring and control instruments.

9 Test procedure

9.1 Test flow

A typical test flow for TBT and TVT is shown in [Figure 9](#).

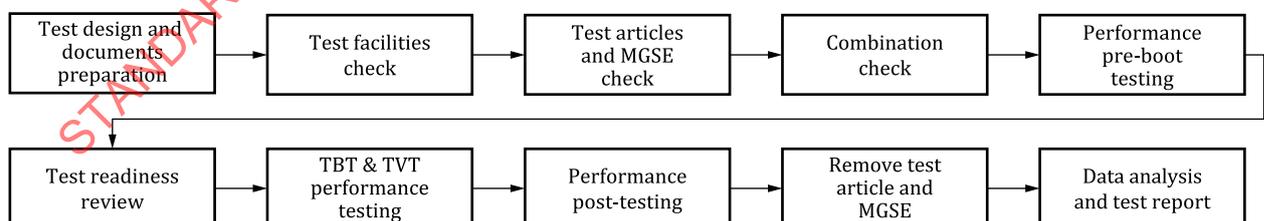


Figure 9 — Typical test flow

9.2 Test procedure

9.2.1 General

If no otherwise specified, the procedures specified in [9.2.2](#) to [9.2.4](#) should be applied.

9.2.2 Before test

9.2.2.1 Test design and documents preparation

- a) Select the test method and make the test plan according to experimental resources and mission.
- b) Carry out the thermal and mechanical design, develop the heating device and other relevant facilities required.
- c) Prepare the test documents according to ISO 15864:2021, 4.9. Test documents should be reviewed by the customer.

9.2.2.2 Test facilities check

- a) All test facilities shall work steadily, safely and reliably, and be examined before test to conform to test equipment requirements. Sometimes, electromechanical and thermal properties of IR heaters and its supporting structure may be checked under vacuum environment before test. If necessary, test facilities and MGSE can be checked combined with a dummy of the test article.
- b) Measuring instruments shall be calibrated in a valid period.

9.2.2.3 Test article check

- a) The test article configuration and condition shall be examined.
- b) The leakage rates required for sealed cabin, propellant tank and pipelines and so on shall be verified.
- c) Mechanical and electrical functions and performances shall be tested.
- d) The conductivity and insulation of cables for measurement, heating and signal transmission shall be inspected.
- e) Heating devices and temperature sensors shall be examined.

9.2.2.4 Combination state check

- a) The status of connection between cables and the test article shall be verified; insulation and conductivity of all cables shall be tested.
- b) Measuring instruments shall be well grounded. The grounding resistance of the test article shall be controlled within the acceptable level.
- c) IR radiation heater circuits shall be corresponding to relevant temperature measuring points. Heater circuits shall not interfere with each other, when IR radiation heaters are used for simulation of orbital heating in TBT.
- d) The electromagnetic interference between the test article and the test equipment shall be tested.

9.2.2.5 Test readiness review

The test readiness review shall verify that:

- a) the configuration of all systems participating in test have finished and the clock synchronization on software and hardware have been checked out without abnormality according to test documents;
- b) operation handbooks on software, equipment, instrument have been prepared properly;
- c) the emergency response procedure is ready and necessary exercises for emergency handling and recovery activities have been performed;

- d) The staff are in position.

9.2.3 Test implementation

The main steps are as follows.

- a) Set up the initial operating state of the test article.
- b) Power on the data acquisition system, vacuum system, thermal system and contamination control equipment, and so on.
- c) During the vacuum pumping process, in TVT, for the units working in the launching stage, inspect the low-pressure discharge and multipacting. The test pressure reduction rate should not exceed the actual pressure reduction rate in the rising process of the carrier rocket to ensure enough time for monitoring the low-pressure discharge phenomenon. Units not working during the launch phase shall be powered on after reaching the specified test pressure.
- d) Pay attention to the heating device and MGSE sensitive to rapid pressure changes.
- e) Measure and control the temperature, heat flux, vacuum degree, contaminate and other parameters, monitor the performance of units under specified operation conditions.
- f) Power off the thermal system, vacuum system, and contamination control equipment, data acquisition system after confirming that all test cases or units have been verified and the test purpose has been achieved.
- g) Avoid contamination to the test article, moisture condensation on test article and low-pressure discharge during shroud temperature and chamber pressure recovery.

9.2.4 After test

The main steps are as follows.

- a) The chamber door shall not be opened unless the chamber is pressurized to laboratory pressure.
- b) Health protection measures shall be taken in view of potential harmful gas inside the chamber, for example, gas composition measurement, oxygen concentration check, ventilation strengthening, or inserting appropriate delay in operation.
- c) The status and appearance of the test article and MGSE shall be checked and compared with that before test. Especially, the abnormalities occurred during testing shall be identified. Take detailed videos and photos for abnormal sites when necessary.
- d) The testing on performance and functionality inside the chamber under atmospheric pressure may be performed for data comparison, interpretation.
- e) The test article and the MGSE shall be removed safely from the vacuum chamber following the lifting procedure.
- f) The acquired data test data shall be evaluated; and final test reports shall be issued.

10 Test interruption and handling

10.1 Interruption

10.1.1 Test facility malfunction

A test should be interrupted in the following case.

- a) After pump-down and building of the cold environment, the pressure of the vacuum chamber rises above the set value (generally, $1,3 \times 10^{-2}$ Pa) or a specified value for a predefined time. The pressure and time shall be defined before test depending on test documents and be different due to TVT and TBT.
- b) Thermal shroud temperatures are too high to meet the requirements of cold conditions, for example, affect units heat dissipation in TVT or cause unacceptable extra background heat flux in TBT.
- c) Some of heating devices or its control system is broken and unable to meet test requirements.
- d) The data acquisition system (sensor, measuring and processing device) cannot work as specified, which affects the judgment of test conclusion and test validity.
- e) Safety accident occurs.

10.1.2 Test article malfunction

Testing shall be interrupted in case that:

- a) some of the key on-board units do not work as specified, such as power source and computer, which affects the judgment of test conclusion and test validity;
- b) safety accident occurs.

10.2 Interruption handling

- a) If malfunctions or abnormalities occur only on a few of on-board units during test, and the faulty or abnormal unit effect on test purpose can be ignored, the test may be continued.
- b) In case that failures coming from the test facility are dealt with in a timely manner and abnormalities are eliminated, testing may be continued.
- c) In TBT, in case that some of lamps/calrods or fluid circuits are invalid, testing may be continued on the basis of the thermal non-uniformity analysis to guarantee the test objective and test validity.
- d) The contamination control procedure should be conducted in the case that the vacuum chamber has to be opened in an emergency.
- e) According to the severity analysis of the malfunction or abnormality, adopt some improvement countermeasures after the test.

11 Test documentation

Test documentation shall conform to ISO 17566:2011, 3.4.