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Space systems — Space environment simulation for material tests — General principles and criteria

Systèmes spatiaux — Simulation de l'environnement spatial pour les essais de matériaux — Principes généraux et critères

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Contents

Page

Foreword

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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).

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The committee responsible for this document is ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

In outer space environment, spacecraft materials are subjected to various factors that may cause damage and deterioration of their service properties. In addition, there are several objective reasons to require improvements in the forecasting of spacecraft material durability in relation to outer space environment impact. The most important reasons are the following:

— increase of spacecraft lifetime;

— development of new spacecraft designs (non-hermetic spacecraft, microsatellites, etc.);

— application of new materials, including nanomaterials;

— complexity and sensitivity improvement of spacecraft on-board equipment;

— development of new orbits in the near-Earth space;

— implementation of new space projects (manned flight to Mars, building of manned bases on the Moon, etc.).

Material durability forecast in relation to space environment impact is based on results of ground tests and mathematical modelling of processes of space environment effects on materials and on-board experiments. For high-precision forecasts, it is necessary

— to choose correctly the set of space environment components which affect a spacecraft in various space regions, and to define their characteristics authentically,

— to select the principle and minor physical and chemical processes causing the material degradation under the space environment impact, including possible synergistic effects,

— to define the requirements to conditions of the ground-based material tests and to applied physical and mathematical models,

— to define the criteria for structural and functional material durability to the space environment impact, and

— to select the correct methods of material durability forecasting for different spacecraft lifetimes in various space regions.

This International Standard considers the items above as a unified system. It does not detail specific questions but only determines general principles and criteria for space environment simulation during material tests. Thus, this International Standard does not replace existing International Standards on specific types of space material tests. The basic purpose of this International Standard is to describe the general test methodologies using the most correct and full initial data on the space environment. Development of a general methodology will

— determine the role of each existing International Standard on space materials tests more precisely,

— help understand how existing International Standards provide the general system of space materials tests, and

— determine tests types for which development of new International Standards is necessary.

Space systems — Space environment simulation for material tests — General principles and criteria

1 Scope

This International Standard provides a general description of the whole set of space environment components which affect spacecrafts in various outer space regions, and the physical and chemical processes causing material degradation in a space environment, including synergistic effects. This International Standard defines the most important general principles and criteria of space environment simulation during material tests, and formulates the general requirements to laboratory test facilities and to physical and mathematical models that are applied to the research of the space environment impact on materials. The basic purpose of this International Standard is to

— provide a general description of the methodology in selecting a set of space environment components and their characteristics during spacecraft material tests, and

— determine general principles and criteria for the tests.

Additionally, such methodology will help in the understanding of the degree of coverage of space materials tests with existing International Standards on the specific test types, and help define the actual directions in developing new International Standards.

This International Standard can be applied as a reference document in designing spacecrafts, forecasting spacecraft lifetime, conducting ground-based tests, and analyzing changes in material properties during operation.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 11227, *Space systems — Test procedure to evaluate spacecraft material eject upon hypervelocity impact*

ISO 15856, *Space systems — Space environment — Simulation guidelines for radiation exposure of non-metallic materials*

ECSS-Q-ST-70-02C, *Thermal vacuum outgassing test for the screening of space materials*

ECSS-Q-ST-70-04C, *Thermal testing for the evaluation of space materials, processes, mechanical parts and assemblies*

ECSS-Q-ST-70-06C, *Particle and UV radiation testing for space materials*

IEC 60068–2-14, *Environmental testing — Part 2-14: Tests — Test N: Change of temperature*

ASTM E512, *Standard practice for combined, simulated space environment testing of thermal control materials with electromagnetic and particulate radiation*

ASTM E595, *Standard test method for total mass loss and collected volatile condensable materials from outgassing in a vacuum environment*

ASTM E1559, *Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials*

ASTM E2089–00, *Standard practices for ground laboratory atomic oxygen interaction evaluation of materials for space applications*

JERG-2-143, *Design standard — Space environment effect mitigation*

GOST R 50109, *Nonmetallic materials test method for mass loss and content of volatile condencable substances under vacuum-thermal effect*

MIL-STD-202–107, *Test method standard for electronic and electrical component parts — Test method 107: Thermal shock*

3 Terms and definitions

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

NOTE Common terms are defined according to ISO 10795.

3.1 Terms related to regions in space

3.1.1
near-Earth space
region of space limited by sphere with radius equal to the average distance from the Moon to the Earth (380 000 km)

3.1.2
Earth's magnetosphere
region of the near-Earth space occupied by the Earth's magnetic field where physical conditions are determined by its interaction with solar wind

3.1.3
Earth's ionosphere
region of the Earth's atmosphere at 50 km to 1 500 km height containing partially ionized cold plasma

3.1.4
interplanetary space
region of space limited by sphere with radius equal to average distance of the most remote from the Sun planet

3.2 Terms related to orbits

3.2.1
low Earth Orbits
orbits with altitude up to 2 000 km

3.2.2
low polar (Sun synchronous) orbits
orbits with the altitude of 600 km to 800 km and the inclination of 85° to 97°

3.2.3
mid-Earth orbits
intermediate circular orbits with an altitude h = 2 000 km to 36 000 km:

— GPS orbit h = 20 200 km, inclination (i) = 55°

— GLONASS orbit h = 19 100 km, i = 64,8°

— GALILEO orbit h = 23 222 km, i = 56°

— BeiDou orbit h = 21 528 km, I = 55°

3.2.4
geosynchronous orbit
orbit around the Earth with an orbital period of one sidereal day, matching the Earth's sidereal rotation period

3.2.5
geostationary orbit
circular orbit with the altitude of ~36 000 km in the Earth's equatorial plane. Geostationary orbit is a special case of a geosynchronous orbit

3.2.6
high elliptical orbits
perigee of approximately 1 000 km and apogee of approximately 36 000 km

3.3 Terms related to space environment factors affecting spacecrafts

3.3.1
primary factors
factors existing in space and affecting spacecraft (i.e. space environment components)

— vacuum

— neutral particles of the Earth's upper atmosphere (including atomic oxygen)

— plasma (cold plasma with particle energy up to 10 eV, hot plasma with particle energy of 10 eV to 10^5 eV)

— solar electromagnetic radiation: X-rays, vacuum ultraviolet radiation, ultraviolet radiation, visible light, infrared radiation

— charged particles of high energy: Earth's radiation belts, solar energetic particles, galactic cosmic rays

— meteoroids (micrometeoroids), ejecta (for Moon), lunar dust

— space debris (microparticles)

3.3.2
secondary (induced) factors
space factors appearing as a result of the impact of primary factors on materials but possessing of their own characteristics and physical mechanisms of the impact on materials

— spacecraft own atmosphere

— surface charging

— internal charging

— thermal cycling

— spacecraft operation factors: plasma sources (plasma contactors), electric propulsion engines and others

3.4 Terms related to penetration depth of affecting space factors

3.4.1
surface impact factors
space factors which impact changes in the characteristics or properties of near-surface layers of materials (with depth of less than ~100 µm)

EXAMPLE Plasma, ultraviolet (UV) and vacuum ultraviolet (VUV), and hard microparticles.

3.4.2
volume impact factors
space factors causing changes in bulk materials (in depths more than 0,1 mm to 1 mm)

EXAMPLE Particles of Earth's radiation belts, galactic cosmic rays, solar energetic particles, meteoroids and others.

3.5 Terms related to physical and chemical mechanisms of space environment effects on materials

3.5.1
mechanisms of space environment effects on materials
totality of physical and chemical phenomena causing the changes in material properties under the influence of primary and secondary space environment factors

— evaporation, sputtering, surface erosion

— surface contamination

— charge accumulation on the surface (surface charging)

— charge accumulation in the volume of dielectrics (bulk charging)

— formation of structural radiation defects

3.5.2
synergistic effects
effects appearing with the simultaneous or sequential impact of several space environment factors when the final effect is not equal to the sum of the effects from the individual factors

3.5.3
durability criteria
maximum permissible changes in operational parameters of spacecraft materials and equipment causing by the impact of primary and secondary space environment factors when a material or an equipment element can perform the given function

— radiation hardness

— durability to surface and internal charge accumulation

— mass losses and surface erosion

— surface contamination

— thermal stability

Note 1 to entry: In determining durability criteria, mechanical, thermal, electrical and optical properties of materials are to be considered.

4 Abbreviated terms and symbols

4.1 Abbreviated terms

AO atomic oxygen

ERB Earth's radiation belts

GCR galactic cosmic rays

GEO geostationary Earth orbit

GSO	geosynchronous orbit
LEO	low Earth orbit
MEO	mid-Earth orbit
MLI	multi-layer insulation
MMOD	micrometeoroids and orbital debris
SEP	solar energetic particles
UV	ultraviolet
VUV	vacuum ultraviolet

4.2 Symbols

E	energy, eV
F	flux density, $m^{-2} \cdot s^{-1}$
l	energy flux density, $J \cdot m^{-2} \cdot s^{-1}$
n	concentration, m^{-3}
P	pressure, Pa
T	temperature, K
v	velocity, $m \cdot s^{-1}$
φ	electrostatic potential, V

5 Choice of sets of space environment components for typical orbits and regions of space

The sets of the most important space environment components affecting spacecraft materials and equipment in different space regions required to simulate in on-ground tests are given below.

5.1 LEO, including polar (Sun synchronous) orbits

— vacuum

— solar UV and VUV radiation

— neutral particles of the Earth's upper atmosphere (including atomic oxygen)

— cold ionosphere plasma

— auroral radiation

— GCR, SEP, protons of ERB

— meteoroids, space debris

5.2 MEO

— vacuum

— solar UV and VUV radiation

— hot magnetosphere plasma

— electrons, protons of ERB

— GCR, SEP

— meteoroids

5.3 GSO/GEO

— vacuum

— solar UV and VUV radiation

— hot magnetosphere plasma

— electrons of ERB

— GCR, SEP

— meteoroids

5.4 Interplanetary space

— deep vacuum

— solar UV and VUV radiation

— GCR, SEP

— solar wind

— meteoroids

5.5 Moon

— vacuum

— solar UV and VUV radiation

— GCR, SEP

— meteoroids

— solar wind

— Earth's magnetosphere plasma (the magnetosphere tail)

— neutrons produced by energetic particles of GCR and SEP

— thermal cycling

— secondary particles of Lunar regolith (ejecta)

— lunar dust

5.6 Mars

— Martian atmosphere

— GCR, SEP

— meteoroids

— solar UV and VUV radiation

— secondary neutrons on Martian surface

— Martian dust storms

5.7 Jupiter

— vacuum

— GCR, SEP

— Jovian radiation belts

— meteoroids

— Jovian magnetosphere plasma

— solar UV and VUV radiation

— conditions on satellites of Jupiter

5.8 Mercury

— solar UV and VUV radiation

— GCR, SEP

— thermal cycling

— meteoroids

5.9 Venus

— Venusian atmosphere

— high temperature and high pressure

— GCR, SEP

— solar UV and VUV radiation

6 General processes for simulation of space environment impact on materials

6.1 Processes for simulation

Physical and chemical processes, which shall be taken into account during simulation of space environment impact on materials, are considered in this subclause.

The choice of processes is determined by the set of primary and secondary space factors affecting spacecraft in regions shown in Clause 5.

The main processes that shall be taken into account for assessing the durability of materials and simulating the space environment impact on spacecraft materials and equipment are given below.

6.1.1 LEO including polar orbits

— material sublimation

— erosion and mass losses by atomic oxygen of the upper Earth's atmosphere
— optical degradation under the influence of UV and VUV radiation
— charging in the polar regions
— radiation damage in South Atlantic anomaly
— surface erosion under the impact of space debris

6.1.2 MEO

— material sublimation
— optical degradation under the influence of UV and VUV radiation
— charging in the hot magnetosphere plasma
— internal charging by electrons of ERB
— radiation damage by electrons and protons of ERB, GCR and SEP
— surface erosion under the impact of meteoroids

6.1.3 GSO/GEO

— material sublimation
— optical degradation under the influence of UV and VUV radiation
— charging in the hot magnetosphere plasma
— internal charging by electrons of ERB
— radiation damage by electrons of ERB, GCR and SEP
— surface erosion under the impact of meteoroids

6.1.4 Interplanetary space

— material sublimation
— optical degradation under the influence of UV and VUV radiation
— radiation damage of materials by charged particles of GCR and SEP
— sputtering by protons of the solar wind
— surface erosion under the impact of meteoroids

6.1.5 Near-Moon space and on the Moon surface

— material sublimation
— optical degradation under the influence of UV and VUV radiation
— radiation damage of materials by charged particles of GCR, SEP, and secondary neutrons
— sputtering by protons of the solar wind
— surface erosion under the impact of meteoroids and secondary particles of lunar regolith
— surface contamination by lunar dust

6.1.6 Near-Mars space and on the Martian surface

— material sublimation

— optical degradation under the influence of UV and VUV radiation

— radiation damage of materials by charged particles of GCR, SEP, and secondary neutrons

— sputtering by protons of the solar wind

— surface erosion under the impact of meteoroids and particles of Martian dust storms

6.1.7 Near-Jupiter space

— radiation damage of materials by charged particles of Jovian radiation belts, GCR and SEP

— charging in the Jovian magnetosphere plasma

— surface erosion under the impact of meteoroids

6.1.8 Near-Mercury and on its surface

— optical degradation under the influence of UV and VUV radiation

— radiation damage of materials by charged particles of GCR, SEP

— surface erosion under the impact of meteoroids

— material destruction due to thermal cycling

6.1.9 Near-Venus space and on the Venusian surface

— radiation damage of materials by charged particles of GCR, SEP

— optical degradation under the influence of UV and VUV radiation

— degradation due to the influence of Venusian atmosphere and high temperature

6.2 Setting a problem of simulation of space environment on spacecraft materials

When analysing the impact of primary and secondary space environment factors on spacecraft materials, the three groups of methods are used:

— ground-based laboratory experiments and tests of material samples;

— theoretical studies and computer modelling;

— flight experiments in space.

These methods are closely related and shall be applied together. This is illustrated in Figure 1 as an example of the study on the effects of the space radiation environment on spacecraft materials and devices.

The starting points for problem setting and choice of the research methods are:

— models and standards of space radiation (1);

— types of orbits and the spacecraft lifetimes (2);

— spacecraft design, applied materials and on-board devices (3).

In relation to the starting points above, requirements for laboratory testing equipment, mathematical models and software tools to be used for space radiation effects simulation are formulated (4). Then, the most suitable experimental methods and equipment (5) and/or mathematical models and software tools (6) are chosen, taking into account the requirements.

Mathematical modelling of the space environment impact processes can be done using analytical and numerical computation methods. Recommended mathematical models for study of spacecraft/environment interaction are given in Annex B.

The complex experiments in space (7) in which the features of the space environment, radiation condition inside the spacecraft and radiation effects in various materials are studied simultaneously, are organized taking into account the results of both laboratory testing and mathematical simulation. MISSE (USA) and KOMPLAST (Russia-USA) are the examples of complex space experiments on space environment impact on various spacecraft materials.

The database obtained using all methods is used for creation of models of material and device degradation in various conditions (8), and for development of spacecraft reliability and lifetime forecasting methods (9) and recommendations on spacecraft protection against the radiation effects (10).

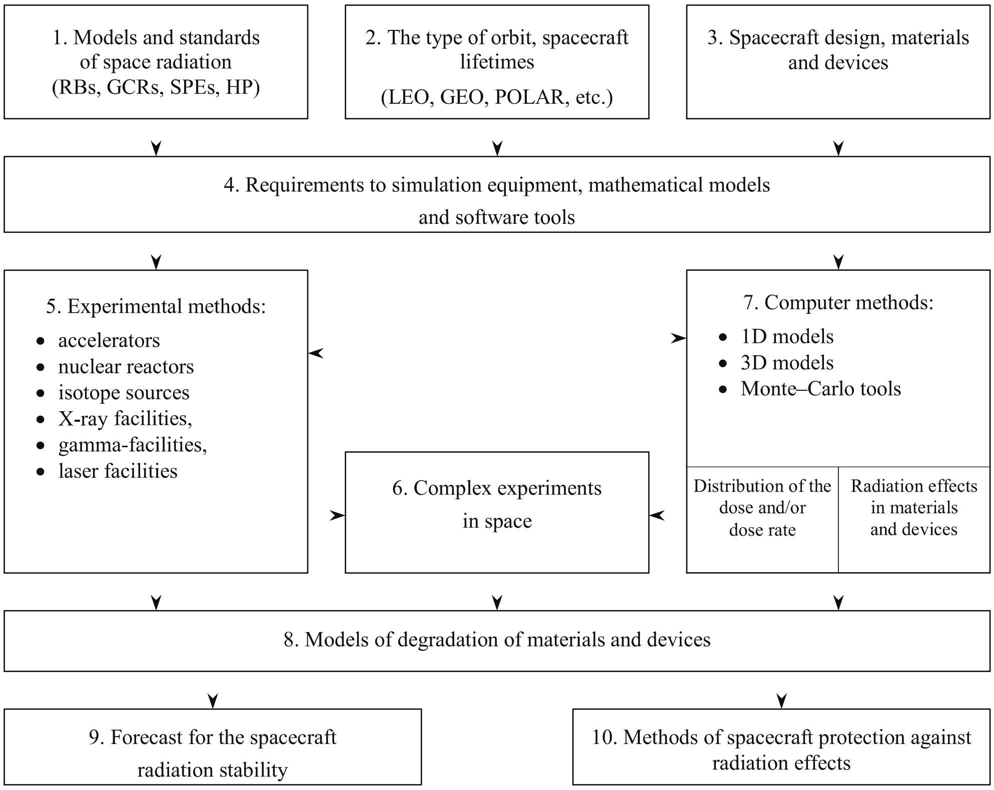

Figure 1 — Study of space radiation environment effects on the spacecraft materials and devices scheme

6.3 Principles of ground-based tests

In the definition of principles of ground-based tests, recommendations and mandatory requirements shall be marked out.

The following are marked out first:

— increase of the test rate (duration);

— selection of impact energy of charged particles;

— replacement of one radiation by another, etc.

Then, the following are noted:

— maintenance of the correct physical and chemical mechanisms of the space factor impact on the materials;

— achievement of the correct quantitative results, etc.

During ground-based tests of materials, two principle approaches are applied. The first approach implies the reproduction of the characteristics of the space environment at laboratory facilities in the full correspondence with space conditions and requires no initial assumption or additional data on the nature and type of processes under investigation. However, in laboratory conditions, it is practically impossible to reproduce characteristics of certain space environment components (e.g. space radiation component because of the complexity of energy spectra and composition of cosmic rays) and to provide simultaneous impact of the whole set of space environment components.

For these reasons, the second approach to the simulation of the space environment impact on spacecraft materials is used more frequently. In this case, the choice of one or several space factors that have the most damaging effects is made on the basis of certain assumptions and the data of physical mechanisms of degradation of objects under study.

As a rule, within this approach, the duration of accelerated tests is substantially shorter with respect to the period of material usage in space. The monoenergetic sources and the replacement of certain types of radiation with other ones are often applied. However, this approach requires the detailed knowledge of physical mechanisms of space environment component impact on objects under study, because the insufficient scientific validity of accelerated tests and indicated replacements may lead to false results. It shall also be noted that degradation rate may not be linearly related with the acceleration ratio.

Taking into account the variety of environment factors affecting spacecraft and complexity of processes, happening in tested materials and elements of spacecraft, testing is conducted with following special techniques:

a) the most weak segment which defines the limit of the durability is noted in the material or device under investigation;

b) one (sometimes two to three) space factors causing most critical damages to objects under investigation are selected taking into account the spacecraft orbit type and lifetime;

c) the most important physical processes causing the material and equipment degradation are revealed;

d) criteria of replacement of certain space factors with other ones are chosen (e.g. the uniform distribution of the absorbed dose on thickness of irradiated material sample, similar type and concentration of radiation defects appearing in the material, etc.).

6.4 Requirements to physical and mathematical models

The methods of the experimental and mathematical simulation of the space environment impact on spacecraft materials are based on physical and mathematical models including the description of the space environment and the research methodology. The general scheme of such models is given in Figure 2.

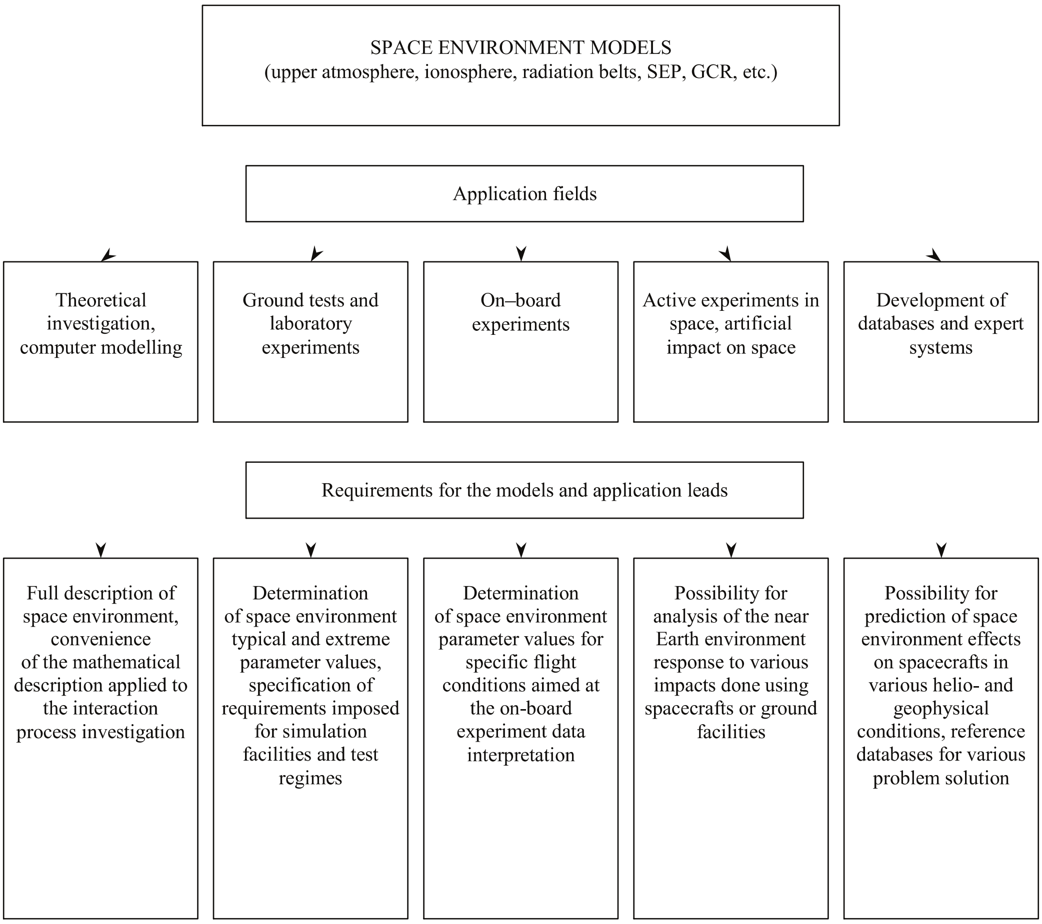

Figure 2 — Requirements to the space environment models

Models of the space environment are used for solving all the totality of tasks of studying the space environment impact on spacecraft with experimental and theoretical methods. The important request is the development of universal models with the full set of data and functionality for solving all the tasks. For applied problems, it is very promising to create computerized expert systems including complex models of the space environment along with databases on various effects of the spacecraft/environment interaction. Requests to these expert systems shall be realized in technical terms, such as orbit parameters, duration of spacecraft flight, etc. Higher-level expert systems may obtain online data on the current state of the near-Earth space using communication channels with Earth's satellites (e.g. velocity of the solar wind, interplanetary magnetic field, charged particles fluxes, etc.) and ground-based observation centres (e.g. geomagnetic indices, solar electromagnetic radiation, neutron monitor data, and so on). In this case, expert systems can operate in real time, and this will enable to predict the possible adverse effects of space environment components on spacecraft and to develop recommendations on the spacecraft operation to prevent these unfavourable effects.

6.5 Choice of parameters of laboratory facilities

When choosing parameters of laboratory facilities, it shall be taken into account the possibility of conducting accelerated testing as well as the possible replacement of certain types of radiation with the other ones, of particle fluxes with distributed energy spectra with monoenergetic beams, etc.

It is necessary to take into account undesirable side effects, which can occur in laboratory facilities (e.g. the generation of UV radiation by atomic oxygen source, heating of material samples by a beam of charged particles, etc).

7 General criteria of material resistance to space environment

The criterion for applicability of a material in a spacecraft is the amount of change of its performance property as a result of exposure to space environment during spacecraft service life.

When determining material resistance, one shall consider the following:

a) radiation situation in working orbit from the beginning to the end of spacecraft service life;

b) location of the material in spacecraft;

c) temperatures that will exert influence on the material during spacecraft service life;

d) volume charging, discharge behaviour and ways to prevent it, for dielectric materials;

e) changes of optical properties and mass loss of external non-metallic materials and assemblies being subjected to UV/VUV and AO;

f) possible synergetic effects.

7.1 General regulations on testing materials to space environment

Materials are tested in a space environment to determine their ability to keep key characteristics during spacecraft service life stated in their design documentation.

Materials intended for use in a particular spacecraft shall be tested if there are no data, or they are insufficient, on their resistance to corresponding levels of damaging conditions.

Test requirements are set in the test program that is being worked out by the executor and approved by customer.

The model test program shall contain the following:

— material (test object);

— quantitative and qualitative indicators to be assessed;

— criteria according to which, if matched, the material is considered to have passed tests;

— test sequences, modes, and conditions;

— permitted deviation values;

— calculations and equations by which the indicators are to be calculated;

— test methods (a catalogue of standard methods);

— available measuring tools and facilities to carry on tests;

— test result processing methods.

The extent of tests is determined by functional purpose of the material and variety and level of damaging factors. In tests, one can simulate damaging factors acting separately, damaging factors acting in sequence, combined action of several factors, and full-scale action of space environment.

Test results prescribe possible use of a material in dependence on the limits imposing on changes of its properties. Service properties of the material under study shall be measured in the process of action and in environment corresponding with service conditions.

By agreement with Customer, the properties may be measured before and after action, or the action itself or measurements of properties may be performed in environment different from the service conditions.

7.2 Functional purpose of spacecraft materials

All materials may be grouped according to their function as follows:

— structural;

— insulating;

— sealants;

— adhesives;

— coatings;

— optical;

— thermo-insulating and heat-protecting;

— ion-exchange, etc.

Some materials may have different functional purposes. Ground test and criteria shall be selected according to their functional purposes.

7.3 UV tests

UV-radiation tests shall be carried out for coatings and optical materials located on the exterior of spacecraft and subjected to solar radiation.

A UV source with spectral distribution of radiation density within the 200 nm to 400 nm wavelength range, as close as possible to the solar spectrum, is used for tests. Optical properties of samples are measured inside the vacuum chamber in the course of irradiation, without removal of samples into air (*in situ* measurement). When optical properties are only measured outside of the vacuum chamber (*ex situ* measurement), ambient air exposure time shall be minimized to reduce post-test oxidization. Dependence of optical properties on duration of exposure is determined. Forecast of optical values is calculated based on mathematical models.

7.3.1 Degradation mechanism

UV irradiation cuts crosslink of polymers. In other cases, UV accelerates cross-linking. These processes are caused by a certain wavelength light in accordance with bonding energy.

Most polymers optical properties change under UV irradiation due to darkened colour. Hardness of polymers increase, so polymers become brittle.

7.3.2 UV sensitive materials

Polymers directly exposed to UV irradiation are affected. Total fluence is defined by attitude of spacecraft and material location due to shadowing. UV only affects the surface of material. Materials deep inside, MLI covered or box contained material are not affected.

Metal is not affected. When chemical treatments or oxidized surfaces are used in thermally critical places, change in optical properties shall be evaluated.

NOTE MLI or thermal control coatings are usually applied on the thermally critical area. Metal is directly exposed to space environment only where not thermally sensitive.

7.3.3 Limitations of ground test

Test sample shall be cooled to remove heat from UV lamp. But sample surface temperature may differ from cooling plate temperature. It is recommended to measure sample temperature directly on the surface of reference sample.

7.3.4 Typical test apparatus

Set samples on a cooling plate in a vacuum chamber. Radiate UV light through a window. Xenon lamp, which closely imitates sun light from 250 nm to 1 100 nm range, is widely used.

7.3.5 Reference test standards

— ASTM E512

— ECSS-Q-ST-70–06C

— JERG-2-143

7.4 VUV tests

VUV-radiation tests shall be carried out for coatings and optical materials located on the exterior of spacecraft and subjected to solar radiation.

A VUV source with spectral distribution of radiation density within 10 nm to 200 nm wavelength range, as close as possible to the solar spectrum, is used for tests. By agreement with the customer, a VUV line spectrum source may be used. Optical properties of samples are measured inside the vacuum chamber in the course of irradiation, without removal of samples into air. Dependence of optical properties on duration of exposure is determined. Forecast of optical values is calculated based on mathematical models.

7.4.1 Degradation mechanism

Same with UV (see 7.3.1).

7.4.2 VUV sensitive materials

Same with UV (see 7.3.2).

Some materials show bigger change in thermo-optical properties under VUV irradiation than UV.

7.4.3 Limitations of ground test

Same with UV (see 7.3.3).

7.4.4 Typical test apparatus

Set samples on a cooling plate in a vacuum chamber. D_2 lamp which produces light of 120 nm to 400 nm wavelength range is widely used.

7.4.5 Reference test standards

— ASTM E512

— ECSS-Q-ST-70–06C

— JERG-2-143

7.5 AO tests

AO tests shall be carried out for coatings, optical materials, thermal-insulation and heat-protecting non-metallic materials located on the exterior of spacecraft.

7.5.1 Degradation mechanism

High speed atomic oxygen bombardment induces material mass loss due to chemical erosion.

7.5.2 AO sensitive materials

Polymers directly exposed to AO irradiation are affected. Since a spacecraft hits AO by its movement, the ram-facing surface suffers the highest fluence. AO also reflects on surfaces. AO only affects the surface of material. Materials deep inside, MLI covered or box contained material are not affected. However, AO sneak into covered area via multiple reflections. Areas around an opening, close to MLI rim or hole are eroded.

Silver and Osmium shall not be used where exposed to AO irradiation because they are rapidly oxidized. Other metals are not affected.

7.5.3 Limitations of ground test

Test sample shall be cooled to remove heat from AO source.

Laser detonation type AO generator produces UV as by-product. Metal contamination caused by AO nozzle erosion could occur.

Plasma asher does not replicate the on-orbit condition such as AO flux or speed. Impact of the difference in irradiation condition on material degradation shall be assessed.

Simulation test for long term flight takes time due to limited acceleration ratio.

7.5.4 Typical test apparatus

Laser detonation type equipment simulates AO irradiation of 8 km/s speed on LEO spacecraft.

Plasma asher enables AO irradiation with limited similarity using more simple apparatus.

7.5.5 Reference test standards

— ASTM E2089–00

— JERG-2-143

7.6 Outgassing tests

Outgassing tests shall be carried out for all non-metallic polymeric materials subjected to elevated temperatures (>80 °C), located outside the pressurized moduli and being a potential contamination source for spacecraft optical-sensitive surfaces and avionics.

Outgassing tests are performed in accordance with

a) ASTM E595, GOST R 50109 and ECSS-Q-ST-70-02C, to choose materials suitable for use in the as-delivery conditions, and

   NOTE Materials that did not pass may be used in spacecrafts after degassing, if required, outgassing values are ensured, or if its substitution is impractical or allowable.

b) ASTM E1559 to determine kinetics of material mass loss in order to predict changes in material mass, assess composition of spacecraft’s own atmosphere, calculate deposition of CVCM and contamination of spacecraft optical-sensitive surfaces.

7.6.1 Degradation mechanism

Under vacuum environment, surface absorbed molecule and volatile molecule contained in polymer are effused. Gas effusion is accelerated at higher temperature.

7.6.2 Thermal vacuum sensitive materials

Every polymer effuse outgas. Softer, lower melting point, lower limited temperature polymers effuse more outgas in general. A material produce more outgas at higher temperature.

Metal of high vapour pressure such as mercury or cadmium produce outgas by evaporation.

7.6.3 Limitations of ground test

Outgassing test based on ASTM E595 or ECSS-Q-ST-70-02C present mass loss after 24 h of thermal vacuum exposure. Data obtained by these tests are not applicable for long term contamination prediction.

It is possible to perform non-standard test with different sample temperature or heating time.

7.6.4 Typical test apparatus

Outgassing test apparatus conforming to ASTM E595 and ECSS-Q-ST-70-02C requirements are widely used.

Outgassing rate test according to ASTM E1559 measures real time molecular deposition on Quartz Crystal Microbalance (QCM). Obtained data are used for long term contamination prediction.

7.6.5 Reference test standards

— ASTM E595

— GOST R 50109

— ECSS-Q-ST-70-02C

— ASTM E1559

7.7 Thermal cycling tests

Thermal cycling tests shall be carried out according to ECSS-Q-ST-70-04C for non-metallic materials located on the exterior of spacecraft and subjected to cyclical temperature changes occurring in the course of spacecraft orbital motion.

Temperature boundaries in tests shall be established with consideration of material location in spacecraft. Cycle duration is defined by spacecraft orbital period. By agreement with the customer, the tests may be accelerated and/or carried out in other medium (inert gas, air) rather than in vacuum.

7.7.1 Degradation mechanism

Where two materials with different coefficient of thermal expansion are attached, thermal strain causes distortion, peeling and flaking.

Temperature higher than glassy-transition point soften the material.

7.7.2 Thermal cycling sensitive materials

Polymers that use close-to-their-lowest or -highest temperature limit will be affected.

Mechanically fasten or adhere materials. Connection of far different coefficient of thermal expansion shall be avoided by design.

7.7.3 Limitations of ground test

Thermal shock test cannot be performed under vacuum condition though it simulates rapid temperature change.

Thermal vacuum test with big cycle number will take long time due to its limited temperature change speed.

7.7.4 Typical test apparatus

7.7.4.1 Change of temperature test (Thermal shock test)

A test apparatus has two chambers of extreme cold and hot temperatures. Test specimen is transferred between the two chambers. Rapid temperature change enables short cycle time and many cycle numbers. This test is performed under ambient pressure. Oxidation may occur on some materials.

7.7.4.2 Thermal vacuum test

Put the test specimen in a vacuum chamber. Heat the specimen using heat source such as solar simulator, IR panel, IR lamp or shroud. Cold temperature is achieved by a cold plate or shroud.

Since radiation is the dominant heat transfer pass, temperature change speed is limited.

7.7.5 Reference test standards

— MIL-STD-202–107

— IEC 60068–2-14

7.8 Radiation tests

Ionizing radiations of the Van Allen belts are electron and proton flows with energies from several hundred eVs to several hundred MeVs. As a result of different penetrability and energy, ionizing particles exert influence on all materials independent of their location, both on the exterior of spacecraft (coatings, blankets) and inside it. The protons act mainly on surface materials whereas the electrons, on surface and internal materials.

Radiation tests are carried out with consideration to the purpose and location of materials.

Thus, when testing thermal control coatings, simulating the low-energy part of the electronic spectrum (up to 100 keV to 200 keV) and protons with energies up to 1 MeV is needed, because changes of the near-surface layers with thickness of tens to hundreds of microns are significant. Such materials are tested in vacuum.

In contrast, volume properties (tensile strength, breaking elongation, volume resistivity, etc.) which are changed by electrons are the most important for structural materials. Therefore, such materials shall be tested using electron accelerators or gamma sources. As far as the volume properties that are essential for such materials, their tests can be done either in vacuum or in air.

7.8.1 Degradation mechanism

Radiation cuts crosslink of polymers. In other cases, radiation accelerates cross-linking. These processes cause decomposition, embrittlement, yellowing, change in electrical resistivity, mechanical strength degradation, etc.

A wire insulator enables decrease in breakdown voltage or cracks. The dominant degradation mechanism depends on the type of material, LET, type of ray, etc.

Most polymers show no or slight change in thermo-optical properties except for thermal control coatings. However, radiation accelerates thermo-optical property change by UV.

7.8.2 Radiation sensitive materials

Any material can be affected. Ionized particles penetrate the shield with the interaction and absorption with the shielding material. The total dose of shielded material is generally provided by the Dose-Depth Curve.

As a rule, metals are significantly more durable to space radiation influence in comparison with dielectrics.

7.8.3 Limitations of ground test

Few facilities perform ionized particle irradiation tests. Electron beam irradiation often represents other particles.

Test samples shall be cooled, if necessary, to remove heat from interaction with radiated particles.

Typical test apparatuses give big acceleration ratio, while flux dependency of material deterioration has not been observed.

7.8.4 Typical test apparatus

— Electron beam: Electron accelerator

— Proton beam: Cyclotron, Tandem accelerator

— γ-particles: Co^{60} source

— Heavy ion

— Tandem accelerator (heavy ions are not the dominant degradation source for material due to their relatively small fluence)

7.8.5 Reference test standards

— ISO 15856

— JERG-2-143

7.9 Micrometeoroid tests

Micrometeoroid tests shall be performed in accordance with ISO 11227 for thermal control coatings and optical materials located on the exterior of spacecraft.

7.9.1 Degradation mechanism

MMOD mechanically perforates or erodes material by hypervelocity impact. Major parameters of perforation are: Impact speed, projectile mass, materials strength, heat capacity, thickness, multi-layered structure, etc.

7.9.2 Hypervelocity impact sensitive materials

All materials used on the exposed surface of spacecraft. After the outermost layer perforation, all or a part of MMOD is considered to be plasma by impact energy. Layers under the top are damaged by heat in addition to mechanical impact.

7.9.3 Limitations of ground test

Test apparatus limits impact speed and projectile size.

One shot of test takes a couple of hours including preparation.

7.9.4 Typical test apparatus

— Light gas gun, consists of a powder gun that compresses low-density gas to accelerate a projectile up to hypervelocity (two or three stage light gas gun accelerates projectile up to about 9 km/s)

— Plasma gun, produces an accelerated plasma flow compressed in a coil and then drags a projectile up to hypervelocity

— Electrostatic accelerator

7.9.5 Reference test standards

There are no test standards for hypervelocity impact test.

8 Recommendations for simulating action of space environment on materials

When simulating, the effect of separate factors (protons, electrons, UV), combined action (protons + electrons + UV; UV + AO; debris/micrometeoroids + thermal cycling, etc.), consequent and/or simultaneous actions shall be considered.

It is necessary to investigate the following synergistic effects:

— protons + electrons;

— protons + electrons + UV;

— UV, VUV + atomic oxygen;

— radiation + thermal cycling;

— hard microparticles + thermal cycling;

— hard microparticles + atomic oxygen, etc.

The simultaneous and sequential impact of several space factors shall be taken into account.

9 Outlook for usage of this International Standard

This International Standard may be applied for the following:

a) development of engineer mathematical models and software for the computer modelling of processes of the spacecraft / environment interaction;

b) creation of expert systems for forecasting and analysis of spacecraft operation, including online systems;

c) development of principles and methods of design and construction of next generation laboratory testing facilities;

d) development of optimal methods of conducting combined in-flight experiments on studying space environment conditions and the impact of space environment components on spacecraft materials and equipment.

Annex A
(informative)

Space environment factors, their main parameters and effects

Table A.1 — Main parameters of particle fluxes of cosmic rays, radiation belts of the Earth and hot magnetosphere plasma

Type of corpuscular radiation	Composition	Energy of particles MeV	Flux density $m^{-2} \cdot s^{-1}$
Galactic cosmic rays	protons He nuclei heavy nuclei	10^2 to 10^{15} (for all nuclei)	$1,5 \times 10^4$ 1×10^3 $1,2 \times 10^1$
Solar cosmic rays	protons	1 to 10^4	10^7 to 10^8
Earth's radiation belts	protons electrons	1 to 30 >30 0,1 to 1,0 >1,0	3×10^{11} 2×10^8 1×10^{12} 1×10^{10}
Hot magnetosphere plasma	protons electrons	10^{-3} to 10^{-1}	10^{11} to 10^{14}

Table A.2 — Space environment factors and their effects

Space environment factors	Space region, radiation origin	Phenomena induced
Neutral atoms (O): F approximately 10^{18} $m^{-2} \cdot s^{-1}$ to 10^{20} $m^{-2} \cdot s^{-1}$ Vacuum, P, approximately 10^{-4} Pa to 10^{-11} Pa	Earth's upper atmosphere, interplanetary space	— Erosion and mass losses of polymeric materials — Sublimation of materials
Solar electromagnetic radiation: $I = 1,4 \cdot 10^3$ $J \cdot m^{-2} \cdot s^{-1}$	Interplanetary space, near-Earth space	— Mass loss enhancement — Modification of mechanical, optical and electrical properties of materials — Photoemission — Heating, thermal cycling
Cold plasma: T approximately 10^3 K to 10^5 K n approximately 10^6 m^{-3} to 10^{12} m^{-3}	Earth's ionosphere and plasmosphere	— Material charging: φ approximately 0,1 V to 10 V — Leakage currents. — Glow in the spacecraft vicinity
Interplanetary space plasma: T approximately 10^5 K n approximately 10^7 m^{-3} v approximately 5×10^5 $m \cdot s^{-1}$	Solar wind	— The same phenomena as cold plasma — Radiation effects on surface layers of materials
Hot plasma: T approximately 10^3 eV to 10^5 eV n approximately 10^6 m^{-3}	Earth's magnetosphere, GEO, plasma sheath, auroral regions	— Material charging: φ approximately 1 kV to 30 kV. — Radiation effects

Table A.2 *(continued)*

Space environment factors	Space region, radiation origin	Phenomena induced
Electrons and ions of Earth's radiation belts: *E* approximately 0,1 MeV to 30 MeV *F* approximately 10^8 m^{-2}·s^{-1} to 10^{12} m^{-2}·s^{-1}	Trapped radiation zone inside the Earth's magnetosphere	— Radiation effects (dose and dose rate effects): modification of mechanical, optical and electrical properties
Protons of solar flares: *E* approximately 1 MeV to 10^4 MeV *F* approximately 10^7 m^{-2}·s^{-1} to 10^8 m^{-2}·s^{-1}	Solar cosmic rays	— Radiation effects — Danger for crew
High energy nuclei: *E* approximately 10^3 MeV to 10^{14} MeV *F* approximately 10^2 m^{-2}·s^{-1} to 10^4 m^{-2}·s^{-1}	Galactic cosmic rays	— Local radiation damage. — Single event upsets. — Light flashes
Hard particles and fragments: *F* approximately 10^{-4} m^{-2}·s^{-1} to 10^{-2} m^{-2}·s^{-1} *v* approximately 10^3 m·s^{-1} to 10^5 m·s^{-1}	Meteoroids, comet dust sheath, space debris near the Earth	— Crater formation, surface erosion, puncture of walls. — Secondary product formation, emission, electric discharge initiation
Secondary (induced) factors: — spacecraft charging φ approximately 0,1 B to 10^4 B; — embedded charging of dielectrics; — spacecraft own atmosphere — thermal cycling	Area near spacecraft	— Electric discharges: electromagnetic noise, destruction of equipment and construction elements — Surface pollution light scattering near the spacecraft, reduction of equipment electrical strength — Oxidation and corrosion of elements of electronics

Annex B
(informative)

Mathematical models for research of spacecraft/environment interaction

This Annex provides information on the most important mathematical models used in the research on spacecraft-environment interaction.

The following models can be used for modelling

- radiation impact on materials:
  - GEANT III, IV;
  - TRIM/SRIM;
  - TIGER;
- radiation impact on materials in the design of spacecraft:
  - NASCAP;
  - SPIS;
  - MUSCAT;
  - COULOMB-2;
- internal charging:
  - GEANT III, IV;
  - RDOSE;
  - DICTAT;
- radiation dose distribution:
  - GEANT III, IV;
  - RDOSE;
  - SHIELDOSE 2;
- hard particles impact:
  - MASTER;
  - ORDEM;
  - SDPA;
  - BUMPER II.

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