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Space systems — Space environment — Simulation guidelines for radiation exposure of non-metallic materials

Systèmes spatiaux — Environnement spatial — Lignes directrices de simulation pour l'exposition aux radiations des matériaux non métalliques

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 15856 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

The purpose of this International Standard is to establish guidelines for designing space systems that are highly reliable and will have long mission life spans. It is impossible to reproduce the space environment for ground testing of space system elements because of the variety and complexity of the environments and the effects on materials. The reliability of the test results depends on simulating the critical effects of the space environments for a particular mission. The main objectives of the simulation are to get test results that are satisfactory for the material behaviour in a space environment and to use existing radiation sources and methods available in the test laboratory.

Non-metallic materials used in space systems are affected by electrons and protons in a broad energy interval, electromagnetic solar radiation (both the near and the far ultraviolet radiation) and X-ray radiation. The response of non-metallic materials to radiation depends on the type of radiation and energy that defines the ionization losses density, and the radiation response of materials depends on these losses. The radiation spectrum and chemical composition of materials define the absorbed dose distribution, especially in the near-the-surface layers.

During the design of the space system, it is necessary to simulate long mission time in reasonable ground time. For this reason, it is necessary to perform accelerated radiation tests requiring the use of dose rates that may be of an order of magnitude greater than in the natural space environment. These high dose rates can influence the effects on the properties of materials. Therefore, the main requirement for the correct simulation in radiation tests involves simulating the correct effects of materials in space by considering the type, spectrum (energy), and absorbed dose rate of the radiation. Simulation is complex because the various properties of materials may respond differently to the approximations of the natural space environment used for testing. In addition, various materials may respond differently to the same simulated space radiation environment. This is valid for different classes of materials such as polymeric and semiconductor materials.

The space engineering materials in space environment are exposed not only to charged particles and electromagnetic solar radiation but also to a number of other environmental factors, e.g. atomic oxygen, deep vacuum, thermocycling, etc. Synergistic interactions can significantly increase the material degradation, i.e. decrease the time of operation, but in certain cases (like solar absorptance variation under UV and protons) synergistic interaction can decrease the degradation. These effects are not well understood and have to be simulated as far as possible. Space environment simulation at the combined exposure is a much more complicated procedure than the simulation of each factor separately. Development of corresponding standards, both for different factors and different classes of materials, will be provided in the following stages of the standard set preparation for space environment simulation at on-ground tests of materials.

This International Standard contains normative statements, recommended practices and informative parts. The term “shall” indicates a normative statement.

Space systems — Space environment — Simulation guidelines for radiation exposure of non-metallic materials

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This International Standard is the first part of a series on space environment simulation for on-ground tests of materials used in space. This International Standard covers the testing of non-metallic materials exposed to simulated space radiation. Non-metallic materials include glasses, ceramics and polymer-metal composite materials such as metal matrix composites and laminated materials. This International Standard does not cover semiconductor materials used for electronic components. The types of simulated radiation include charged particles (electrons and protons), solar ultraviolet radiation and soft X-radiation of solar flares. Synergistic interactions of the radiation environment are covered only for these natural, and some induced, environmental effects.

This International Standard outlines the recommended methodology and practices for the simulation of space radiation effects on materials. Simulation methods are used to reproduce the effects of the space radiation environment on materials that are located on surfaces of space vehicles and behind shielding.

This methodology involves:

a) the definition of the environment to be simulated using commonly accepted space environment models;

b) the definition of the material properties under test or of concern in accordance with the specificity of degradation in the space environment, satellite-specific constraints determination, temperature conditions (constant values or cycled temperature mode), mechanical stress, charging, contamination, etc.;

c) the selection of laboratory radiation simulation sources, energies and fluences that will be used to reproduce the kind of orbital radiation and mimic the orbital dose profiles;

d) the exposure techniques and procedures used to perform the laboratory simulation including contamination control, acceleration factors (dose rates), temperature control, vacuum levels and atmospheric effects.

An alternative method using standard spacecraft orbits and environments is included.

This International Standard does not specify the design of material specimens, methods of measuring the properties of materials and characteristics of radiation sources, the design of vacuum systems and the preparation of test reports. The user should select designs and measurement methods based on the state of the art and the requirements of specific space systems and contracts.

This International Standard does not include a list of hazards and safety precautions. The users are responsible for providing safe conditions based on national and local regulations.

2 Normative references

The following referenced documents are indispensable for the application 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.

IEC 60544-2, *Guide for determining the effects of ionizing radiation on insulating materials — Part 2: Procedures for irradiation and test*

ASTM E490, *Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables*

ASTM E512, *Standard Practice for Combined, Simulated Space Environment Testing of Thermal Control Materials with Electromagnetic and Particulate Radiation*

3 Terms, definitions, abbreviated terms and acronyms

3.1 Terms and definitions

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

3.1.1
absorbed dose
D
amount of energy imparted by ionizing radiation per unit mass of irradiated matter

NOTE 1 The quotient of $\mathrm{d}\bar{\varepsilon}$ by $\mathrm{d}m$, where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter of mass $\mathrm{d}m$, is

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}$$

NOTE 2 The special name of the unit for absorbed dose is the gray (Gy). $1\ \mathrm{Gy} = 1\ \mathrm{J{\cdot}kg^{-1}}$.

3.1.2
acceleration factor
ratio of dose rate between simulation and expectation at space application for the same type of radiation

3.1.3
bremsstrahlung
brake radiation
photon radiation, continuously distributed in energy up to the energy of the incident particle radiation, emitted from a material due to deceleration of incident particle radiation within the material, mainly due to electrons

3.1.4
depth distribution criterion of absorbed dose
ratio of the exponent index, μ, of the absorbed dose depth profile curve to the material density, ρ

NOTE The depth distribution criterion of absorbed dose is measured in square centimetres per gram.

3.1.5
depth dose profile
distribution of the absorbed dose through the depth of material

3.1.6
energy fluence
total energy of ionizing radiation per unit area of the irradiated surface

NOTE Energy fluence is measured in joules per square metre.

3.1.7
galactic cosmic rays
GCR
high-energy-charged particle fluxes penetrating the heliosphere from local interstellar space

[ISO 15390, definition 2.1]

3.1.8
heliosphere
region surrounding the sun where the solar wind dominates the interstellar medium

NOTE Also known as solar cavity.

3.1.9
ionizing radiation
any type of radiation consisting of charged particles or uncharged particles or both, that, as a result of physical interaction, creates ions of opposite signs by either primary or secondary processes

NOTE Charged particles could be positive or negative electrons, protons or other heavy ions, and uncharged particles could be X-rays, gamma rays, or neutrons.

3.1.10
linear energy transfer
LET
energy delivered by a charged particle passing through a substance and locally absorbed per unit length of path

NOTE It is measured in joules per metre. Other dimensions are $\text{keV}\cdot\mu\text{m}^{-1}$, $\text{J}\cdot\text{m}^2\cdot\text{kg}^{-1}$, $\text{MeV}\cdot\text{cm}^2\cdot\text{g}^{-1}$, $\text{MeV}\cdot\text{cm}^2\cdot\text{mg}^{-1}$.

3.1.11
mean free path
average distance that a subatomic particle, ion, atom or molecule travels between successive collisions with ions, atoms or molecules

3.1.12
natural space environment
environment that exists in space without a spacecraft system present

NOTE This includes radiation, vacuum, residual atmosphere, plasmas, magnetic fields and meteoroids.

3.1.13
near ultraviolet radiation
NUV radiation
solar electromagnetic radiation with a wavelength in the range of 300 nm to 400 nm

3.1.14
radiation action measure
energetic characteristic of radiation action on a material

NOTE The radiation action measure for non-metallic materials is an absorbed dose or energy fluence.

3.1.15
radiation belt
electrons and protons trapped by the geomagnetic (planetary magnetic) field

3.1.16
radiation scale effect
dependence of the material degradation on the thickness ratio of irradiated and unirradiated layers

3.1.17
surface properties
properties of a material which are defined by the physico-chemical and morphological structure of its surface

NOTE The depth or thickness that constitutes surface properties depends upon the type of material and particular property.

3.1.18
synchrotron radiation
continuous radiation created by the acceleration of relativistic charged particles, as in a synchrotron or storage ring

NOTE Synchrotron radiation is a practical energy source of photons.

3.1.19
volume properties
bulk properties
properties that are determined by characteristics averaged through the volume of a product

3.1.20
irradiance
⟨at a point on a surface⟩ quotient of the radiant flux incident on an element of the surface containing the point, by the area of that element

3.1.21
vacuum ultraviolet radiation
VUV radiation
solar electromagnetic radiation with a wavelength in the range from 10 nm to 200 nm

3.1.22
X-rays
irradiances with a wavelength in the range from 0,001 nm and 10 nm

3.2 Abbreviated terms and acronyms

Al	aluminium
ASTM	(now ASTM International) American Society for Testing and Materials
ECSS	European Cooperation for Space Standardization
ESA	European Space Agency
EUV	extreme ultraviolet
FEP	fluorinated ethylene propylene
VUV	vacuum ultraviolet
GCR	galactic cosmic rays
GEO	Geosynchronous orbit
GLON	GLONASS navigation spacecraft (Russian Federation)
GOST R	Federal Agency on Technical Regulating and Metrology (Russian Federation)
GPS	Global Positioning Satellite (U.S.A.)
HEO	highly elliptical orbit

ISS	International Space Station
LEO	low Earth orbit
LET	linear energy transfer
MeV	megaelectronvolt
Mg	magnesium
MUV	middle ultraviolet
NUV	near ultraviolet
POL	Standard polar orbit
PTFE	polytetrafluoroethylene

4 Space environment radiation characteristics

4.1 Sources of radiation in space

The main sources of radiation in space are galactic and solar particle radiation (solar wind), solar X-radiation in the 1 nm to 10 nm wavelength band, vacuum ultraviolet radiation and trapped charged particles of low energy in radiation belts around the planets (e.g. Earth, Jupiter and Saturn).

4.2 Radiation levels for Earth orbits

4.2.1 General

The specified radiation levels for the various standard orbits are based on generally accepted, published models that are, in turn, based on measurements. Work is in progress for improving and standardizing the models. Space Environment Information System (SPENVIS) provides standardized access to models of the hazardous space environment through the following website: http:/www.spenvis.oma.be/spenvis/.

4.2.2 Electron irradiation

The electron irradiation environment is based on the best available model to date, the AE-8 model. The AE-8 model describes spectra of electrons with minimal energy 40 keV (see Clause A.1 and Reference [23]).

There are no similar models for lower-energy electrons. Energy characteristics of low-energy particles for a geosynchronous orbit are presented in References [25] and [28].

For the LEO and POL orbits, the energy ranges are 40 keV to 5 MeV for electrons. For the GEO, GLON and HEO orbits, the energy ranges are 1 keV to 5 MeV for electrons.

4.2.3 Proton irradiation

The proton irradiation environment is based on the best AP-8 model available now. The AP-8 model describes spectra of protons with minimal energy 100 keV (see Clause A.1 and Reference [24]).

There are no similar models for low-energy protons. Energy characteristics of such particles for a geosynchronous orbit are presented in Reference [26].

For the LEO (ISS) and POL orbits, the energy ranges are 100 keV to 200 MeV for protons. For the GEO, GLON and HEO orbits, the energy ranges are 1 keV to 100 MeV for protons.

4.2.4 X-radiation

The main part of the solar X-ray radiation in the energy range of 0,1 keV to 10 keV corresponds to the solar flares. See Reference [29]. The predominant energy contribution comes from photons with energies between 1 keV and 3 keV.

4.2.5 Bremsstrahlung (brake radiation)

Bremsstrahlung is produced from the deceleration of particulate radiation inside matter. Bremsstrahlung contributes to the radiation damage in materials with thicknesses greater than several grams per square centimetre or in shielded materials.

4.2.6 Ultraviolet radiation

Solar spectral irradiances in the VUV and NUV are specified in ASTM E490.

Irradiance of the VUV in low Earth orbits is about 0,1 $W \cdot m^{-2}$ or 0,007 % of the total solar electromagnetic irradiance. Irradiance of the NUV for the same conditions is about 118 $W \cdot m^{-2}$ or 8,7 % of the total solar electromagnetic irradiance.

The VUV energy spectrum with wavelength lower than 50 nm is specified in ASTM E512.

4.3 Methods for charged particle and photon irradiation

Use the dose and energy fluence calculation made for a typical mission (for specific environmental conditions and place of the material on the spacecraft, taking into account all the shielding effects). Examples of the most commonly used codes are presented in Clause A2.

An alternative method to obtain such information is based on the standard spacecraft orbits and environments (see Clause 8).

Take into account that the contribution of each type of space radiation into the total absorbed dose depends on the shielding depth (see, for example, Table A.1). Sometimes the space radiation (i.e. Bremsstrahlung, high-energy electrons) may be simulated by ^{60}Co gamma rays (see References [14], [15] and [18] for simulation methods). See ASTM E512 and Reference [21] for UV radiation simulation methods.

5 Properties of spacecraft materials

5.1 General

Various regions of radiation spectra are responsible for the degradation of different properties when materials are irradiated in the space environment. The properties are divided into surface properties and volume (bulk) properties.

5.2 Surface properties

Surface properties are determined by the nature of the material at or near the surface. The surface of a material is defined as that part of the material exposed directly to the space environment in the spacecraft application. “Near the surface” is considered to be approximately 4 $mg \cdot cm^{-2}$ or less (see Figures B.1 to B.3). The surface properties include surface electrical conductivity, optical properties (reflectance, absorptance, emittance), adhesive properties (adhesion, adhesive strength), tribotechnical characteristics (coefficient of friction, friction durability, wear resistance) and surface electrical charging.

The low-energy part of the corpuscular radiation spectrum (no more than 50 keV for electrons and 1,0 MeV for protons) and VUV are primarily responsible for the degradation of surface properties.

The whole spectrum of the solar X-radiation and UV affect the surface properties of non-metallic materials. Most materials have a high absorption of VUV, and some materials will be affected by near UV-radiation depending on absorption characteristics and energies required to break molecular bonds.

5.3 Volume (bulk) properties

Volume properties are determined by the average properties of the material through the bulk of a product. Degradation of the volume material properties is determined by the high-energy parts of the charged particle spectrum. The radiation damage to materials located behind shielding of more than 5 $mg \cdot cm^{-2}$ to 10 $mg \cdot cm^{-2}$ thickness is also caused by the high-energy parts of the spectrum.

Composite materials consisting of layers of thin films may require additional analyses to determine the depth dose distribution from the natural space radiation.

5.4 Measure of radiation action

To study the surface properties, a measure of radiation action should be taken equal to the energy fluence of corpuscular radiation, J/m^2, resulting from the absorption of more than 90 % exposure energy in tens of microns thick near-the-surface layers and neglecting the absorption of Bremsstrahlung energy in the same layers in comparison with that of corpuscular radiation (see Table A.1).

The absorbed dose averaged over the product thickness is taken to be a measure of radiation action to analyse the volume properties and it practically relates to a high-energy part of the spectrum. The same measure is applied to shielded materials.

This approach to selecting the radiation action measure is influenced by a radiation scale effect, i.e. dependence of the material degradation on the thickness ratio of irradiated and unirradiated layers (see References [31] and [32]). The two-measure approach of radiation action is applicable to the layers with more than 4 mg/cm^2 thickness on the space vehicle surface. The energy fluence is an only measure of radiation action on the layers of less than 4 mg/cm^2 thickness.

6 Requirements for simulation of space radiation

6.1 Objective

The objective is to simulate the effects of the space environment on materials and not necessarily duplicate the space environment.

6.2 Methodology (test)

The following methodology is suggested for organizing space simulation tests.

a) Select the space environment factors for the specific mission and properties that are critical for performance and reliability of the material to be tested.

b) Consider the induced environment factors that can influence the effects that are under investigation (radiation-induced outgassing, contamination of samples, etc.).

c) Determine the environment acceptable acceleration rates that will not adversely affect the results.

d) Select the environments to be simulated for on-ground tests.

e) Select the radiation sources for ground simulation.

f) Determine the energies and fluences for the radiation sources to closely simulate the depth dose profile that would occur in space. A detailed analysis of the space radiation environment and absorbed dose profile for the given orbit, mission lifetime and material shall be performed. Various mathematical models are available to perform this type of analysis.

g) For simulation, calculate the depth dose profile for the tested material for both the space environment and test conditions. It is necessary to perform the calculations using the same mathematical code and taking into account the geometries of particle incidence for both the space and simulated space radiation environments.

6.3 Methodology for simulation that involves simulation of the type of radiation, its spectrum, and intensity

6.3.1 Type of radiation

The effects of each type of radiation on non-metallic materials at the same values of absorbed energy and dose rate differ both quantitatively and qualitatively. Effects are based on radiation-chemistry processes operating in a material. The lack of experimental and theoretical data on specific effects of low-energy protons and electrons as well as of X-radiation and UV, at the same absorbed dose, makes it difficult to replace one kind of radiation by another.

As a rule, it is desirable to conduct the tests of materials using the same type of radiation to which the material would be exposed in the natural space environment. First of all, it concerns the tests for stability of surface properties.

For protons and electrons of high energy, which cause degradation of the material volume properties, it is possible to replace one kind of radiation by another if it is technically more feasible and the effects can be duplicated (e.g. when there are reliable experimental data demonstrating the suitability of such a replacement for the similar material and the same property; see Reference [15]). Replacement of the UV radiation by other radiation cannot be done. It is not recommended to replace one kind of radiation by another through the tests of reversible changes of properties.

6.3.2 Ionizing radiation spectrum

6.3.2.1 The ionizing radiation spectrum can affect the degradation of non-metallic materials in two ways:

a) different depth dose distribution in a material;

b) dependence of radiation-chemical yield on the LET value of radiation.

As the difference in LET values for actual operational spectra of the same kind of radiation is small, item a) is more important.

6.3.2.2 Two methods for simulating the radiation spectrum of charged particles are recommended.

a) Use several beams of quasimonoenergetic, charged particles with various energies. The spectrum is adjusted by proper choice of fluences of the separate radiation sources.

Also, (quasi)monoenergetic spectra can be used to simulate most effects; for some others, such as induced conductivity or recovery, a broad spectrum radiation is to be preferred.

b) Convert a monoenergetic beam to a number of quasimonoenergetic beams using a sectioned foil with the thickness varying from point to point. The thickness of the foil is about the size of the free path of the particles and is determined by the scattering and absorption characteristics of the foil.

6.3.2.3 The largest drop in the dose depth profile occurs in the near-the-surface layers (see Figures B.1 and B.2). Therefore, the simulation of corpuscular ionizing radiation of the space environment based on its spectrum is primarily recommended for radiation tests of material surface properties.

6.3.2.4 Calculate the fluxes and the energy spectra of particles according to the mission using the best available codes; transport these fluxes and spectra to the material (taking into account the shielding) and calculate the dose profile with the available codes (referenced in Clause A.2). This profile shall be reproduced by the proper choice of the energy and fluences of the charged particles from the selected accelerators.

6.3.2.5 The assessment of reliable simulation of the radiation spectrum may be made, for example, by introducing a numerical characteristic of the depth dose profile in a material. For a description of a possible assessment, see Clause B.2.

6.3.2.6 Mg and Al soft photon sources can be used for simulation of soft X-ray.

6.3.3 Dose rates

6.3.3.1 As a rule, it is necessary to perform tests at dose rates substantially above those that would occur while being exposed to the natural space environment. The increased dose rates at irradiation *in vacuo* create additional radiation and induced environmental effects in materials, and these can have synergistic effects on the materials, thus complicating the simulation process.

6.3.3.2 It is desirable to verify the validity of reciprocity in the range of dose rates, defined by the acceleration factor, for each type of radiation using a representative material of the series to be studied. For an example of such verification, see Annex C. Sealed radio-isotope sources may be used to validate the reciprocity at low dose rates.

6.3.3.3 The range of operating temperatures on a surface of a space vehicle is generally assumed to vary from −150 °C to +150 °C. The actual or predicted operating temperatures of the material should be considered when selecting test temperature requirements.

6.3.3.4 It is necessary to conduct accelerated radiation tests *in vacuo* with a recommended residual pressure no higher than 10^{-2} Pa to 10^{-3} Pa depending on dose rate and specific property. However, for certain properties and tests it may be possible to conduct tests in an atmosphere of inert gas. The value of maximum dose rate (or an energy flux on a material surface) is determined both by the allowable temperature increase of a sample and the admissible acceleration factor. Take into account that the mean free path of the residual atmosphere may have an effect on desorption of gases from the material.

6.3.3.5 Water desorption is an important concern for composite materials. Dissolved oxygen can react with materials to produce chemical changes that are different from the material experiences in space when irradiated. Radiolysis products (broken chemical bonds and free radicals) may react with the oxygen. IEC 60544-2 discusses this subject.

In connection with the aforesaid, the accelerated radiation tests are only possible when preceded by a conditioning of the material samples in a vacuum in order to remove dissolved oxygen. Heating of a material in vacuum (vacuum bakeout) will increase the outgassing rate thereby reducing the conditioning time. However, the material should not be heated to a temperature where thermal damage occurs.

6.3.3.6 The dose rate effect on radiation-induced outgassing is most significant. To take it into account in accelerated tests, it is advisable to increase the value of the absorbed dose. A recommendation of the factor of an adsorbed dose reserve is given in Annex C based on a accelerated tests.

6.3.3.7 It is permissible to conduct accelerated tests for the effects of VUV exposure of non-metallic materials at acceleration factors up to 10^3 (see Reference [21]). NUV exposure acceleration factors of up to 7 have been used. Acceleration factors should be carefully considered and verified for acceptable simulation of space radiation effects in the particular material being tested. Additional information is given in Annex C.

6.3.3.8 Electron irradiation can result in a negative charge build-up in dielectric materials. At accelerated dose rates, this charge build-up will result in effects that are different from those when the materials are exposed in space.

An increase of a negative charge on the surface of the material will repel incident low-energy electrons, thereby reducing the net irradiance of the material. This effect can be reduced by neutralizing the charge with proton irradiation or earthing of the material at on-ground testing.

High-energy electrons depositing within a dielectric material may build up a high bulk voltage charge that can discharge within the material or to the surface and damage the material. This effect limits the maximum dose rates at on-ground tests.

7 Radiation sources for simulation

7.1 Sources

Charged particle sources typically produce quasimonoenergetic beams. Low-energy sources are used to simulate the absorption of the low-energy space radiation in the near-the-surface layers of materials. The high-energy particle sources are used to simulate the absorption of space radiation in the volume of thick materials.

7.2 Low-energy protons

Low-energy protons can be produced using accelerators in the energy range of 10 keV to 1 MeV. It is possible to decrease the minimum energy but reliable data for such protons do not exist. To obtain a broad spectrum of protons with mean energies of 0,5 MeV to 1 MeV in the hydrogen-rich materials, it is possible to use a neutron beam from a nuclear reactor. The neutron beam should be filtered from the accompanying gamma-radiation and thermal neutrons.

7.3 Low-energy electrons

Low-energy electrons can be produced using accelerators in the energy range of 10 keV to 0,5 MeV. It is possible to decrease the minimum energy, but reliable data for such electrons do not exist.

7.4 High-energy proton accelerators

High-energy proton accelerators operate in the energy range of 2 MeV to 200 MeV.

7.5 High-energy electron accelerators

High-energy electron accelerators provide particles with energies $> 0{,}5$ MeV.

7.6 Ultraviolet radiation

7.6.1 General

Ultraviolet radiation is the main part of the solar radiation causing the degradation of non-metallic materials. It consists of vacuum ultraviolet (VUV) and near ultraviolet (NUV). In any case, the solar energy spectrum shall be followed as closely as possible.

7.6.2 Vacuum UV

For the simulation of vacuum ultraviolet radiation effects, sources of optical radiation in the wavelength range of 10 nm to 200 nm shall be used. Hydrogen and deuterium discharge lamps and similar lamps filled with helium can be used. It is also possible to use resonant gas lamps filled with krypton ($\lambda = 123{,}6$ nm) and xenon ($\lambda = 147$ nm). Gas-jet sources and synchrotron radiation sources have also been used.

7.6.3 Near UV

For the simulation of near ultraviolet radiation effects in the range of wavelength of 300 nm to 400 nm, it is desirable to utilize xenon arc lamps. It is also possible to use mercury arc, mercury-xenon arc, and carbon arc lamps. When using all these sources, it is usually necessary to filter the simultaneously generated visible and infrared radiation to reduce heating of materials. This is especially important when using high irradiances to accelerate the test. Heating may cause a different type of damage in the material than would be caused by radiation.

7.6.4 Monochromatic sources

Monochromatic sources (line sources) of UV radiation do not match the continuum radiation spectrum of the sun, but these sources are convenient for many simulation tests. Monochromatic sources may be used if it can be demonstrated that the effects in the material are equivalent to those from the continuum radiation. Preliminary tests on the material and understanding of the radiation chemistry of the material may be used to verify equivalency.

8 Alternate simulation method

8.1 Methodology

The dose and energy fluence data for a typical mission may be obtained without detailed calculation on the base of standard orbits. The standard orbits in Table 1 and the standard radiation environments in Tables 2 and 3 should be considered for the selection of the applicable space environments for testing.

If the standard orbits and radiation environments are not applicable to the mission under consideration, it is necessary to perform analyses to determine the applicable environments to be used in accordance with 4.3.

A standard orbit and radiation environment that is more severe than the actual environment may be used based on the concept that if the materials are satisfactory for the more severe environment, they will be satisfactory for the actual environment.

A detailed analysis of the space radiation environment and absorbed dose profile for a particular orbit, mission lifetime, and material should be performed if the mission and system require a better fidelity of simulation. Various mathematical models are available to perform this type of analysis.

8.2 Standard spacecraft orbits

In order to provide a uniform methodology for space environment simulation, five standard Earth orbits are specified in Table 1. The designations are the International Space Station (ISS), Geosynchronous orbit (GEO), GLONASS navigation spacecraft (Russian Federation) (GLON), highly elliptical orbit (HEO), and Standard polar orbit (POL).

Table 1 — Standard spacecraft orbits

Standard orbit	Designation	Orbit	Altitude km	Inclination °	Type of orbit
1	ISS	Low Earth orbit of ISS	426	51,6	Circular
2	GEO	Geosynchronous orbit	35 790	0	Circular
3	GLON	GLONASS/GPS vehicles	19 100	64,8	Circular
4	HEO	Highly elliptical orbit	500 to 39 660	65	Elliptical
5	POL	Standard polar orbit	600	97	Circular

For the orbits not included in Table 1 (such as higher Earth orbits, interplanetary missions and other deep space flights), it is necessary to make special calculations of energy fluences and dose rates. The relevant codes are indicated as examples in Clause A.2.

Table 2 — Energy fluence of corpuscular radiation

Standard orbit	Designation	Energy fluence J·m^{-2} per year		
		Electrons	Protons	Total
1	ISS	$8,6 \times 10^2$	36	$8,6 \times 10^2$
2	GEO	$9,8 \times 10^5$	$3,8 \times 10^4$	$1,0 \times 10^6$
3	GLON	$8,3 \times 10^5$	$2,6 \times 10^5$	$1,1 \times 10^6$
4	HEO	$4,9 \times 10^5$	$6,8 \times 10^4$	$5,6 \times 10^5$
5	POL	$2,3 \times 10^3$	$1,0 \times 10^2$	$2,4 \times 10^3$

Table 3 — Absorbed dose of corpuscular radiation in aluminum at a depth of 1 mg/cm^2

Standard orbit	Designation	Absorbed dose Gy per year		
		Electrons	Protons	Total
1	ISS	$1,2 \times 10^3$	$4,8 \times 10^1$	$1,2 \times 10^3$
2	GEO	$5,4 \times 10^5$	$8,3 \times 10^6$	$8,8 \times 10^6$
3	GLON	$3,8 \times 10^5$	$2,0 \times 10^6$	$2,4 \times 10^6$
4	HEO	$2,6 \times 10^5$	$3,1 \times 10^5$	$5,7 \times 10^5$
5	POL	$2,5 \times 10^3$	$3,0 \times 10^2$	$2,8 \times 10^3$

Annex A
(informative)

Additional information

A.1 Space radiation environment

The absorbed dose in the vehicle near-the-surface layers is determined mainly by low-energy types of radiation (protons with energies up to 1,0 MeV, electrons with energies up to 500 keV, solar X-radiation, VUV and NUV).

Spectra of electrons, with a minimum energy of 40 keV, and protons, with a maximum energy of 100 keV, in the trapped radiation belts of the Earth, are described in the AE-8 and AP-8 models (see References [23] and [24]). Validity of the AE-8 and AP-8 models is limited to solar minimum or solar maximum and to certain orbits.

There are no similar models for low-energy electrons and protons. Energy characteristics of low-energy electrons and protons for a geosynchronous orbit are presented in References [25] and [26] respectively. References [27] and [28] present data on low-energy electrons for a geosynchronous orbit. POLE model developed by ONERA-LANL may be used for geosynchronous orbits in the electron 30 keV to 5,2 MeV range.

Space Environment Information System (SPENVIS) provides standardized access to models of the hazardous space environment through a WWW interface (http://www.spenvis.oma.be/spenvis/). The following models of radiation environments are evaluated over a user-defined orbit:

a) Trapped particles: AE-8 and AP-8, CRRESPRO and CRRESELE;

b) TREND models;

c) Solar protons: JPL-91, JPL-85 and King;

d) CRÈME for cosmic rays.

A.2 Most used codes

After transporting specified values of fluences and spectra (AE-8 and AP-8 models are recommended for electrons and protons accordingly) to a space material, the following codes for calculation of absorbed doses are now most famous: CREME, SPACERAD, NOVICE, Tiger-P, ESABASE, RADMOLDS and others. The Tiger-P code is found in the code package ITS 3,0 Sandia National Laboratories (see Reference [36]). Vampola A.L. RADMODLS, Version 4.20/1994 may be found at the following adress: http://modelweb.gsfc.nasa.gov/magnetos/radmodls.html

The aforementioned system SPENVIS includes for this aim SHIELDOSE and SHIELDOSE-2 (calculation of ionizing dose) and NIEL (calculation of non-ionizing energy loss).

Table A.1 shows the percentage of absorbed doses of space radiation for various shielding depths calculated for the Cosmos 1887 spacecraft. Cosmos 1887 was at an altitude of 406 km apogee and 224 km perigee, at an inclination of 62,8°.

Table A.1 — Space radiation absorbed dose at various shielding depths on satellite Cosmos 1887

Values expressed as a percentage of the total dose

Type of radiation	Shielding depth g·cm^{-2}					
	0,1	**0,5**	**1,0**	**1,5**	**2,0**	**3,0**
Electrons	99,2	95,6	79,0	42,8	13,7	2,2
Protons of radiation belts	0,6	2,7	11,8	30,0	42,5	34,0
Protons of GCR	0,2	1,7	9,2	27,2	43,8	63,8
NOTE Reproduced with permission from Reference [30].						

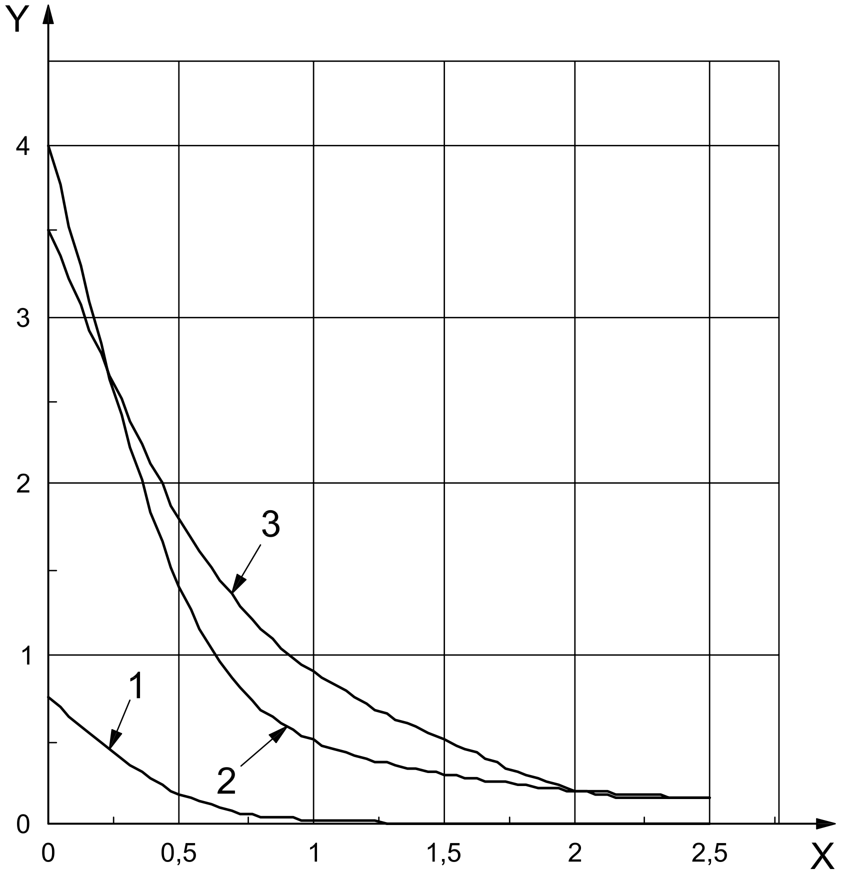
Annex B
(informative)

Depth dose

B.1 Depth dose distribution

The largest drop in the dose depth profile occurs in the near-the-surface layers. Examples of such a drop are presented on Figures B.1 and B.2.

Figure B.1 (see Reference [31]) shows depth dose profiles for three types of space radiation in FEP exposed in a standard GEO orbit. The radiation consists of galactic cosmic rays, charged particles in the radiation belt (electrons and protons), and far ultraviolet (Ly-a at 121,6 nm). The larger depth dose profiles occur from the VUV and the lower-energy charged particles.



Key

Y depth, in micrometres

X dose rate, in gray per second

1 soft X-ray background

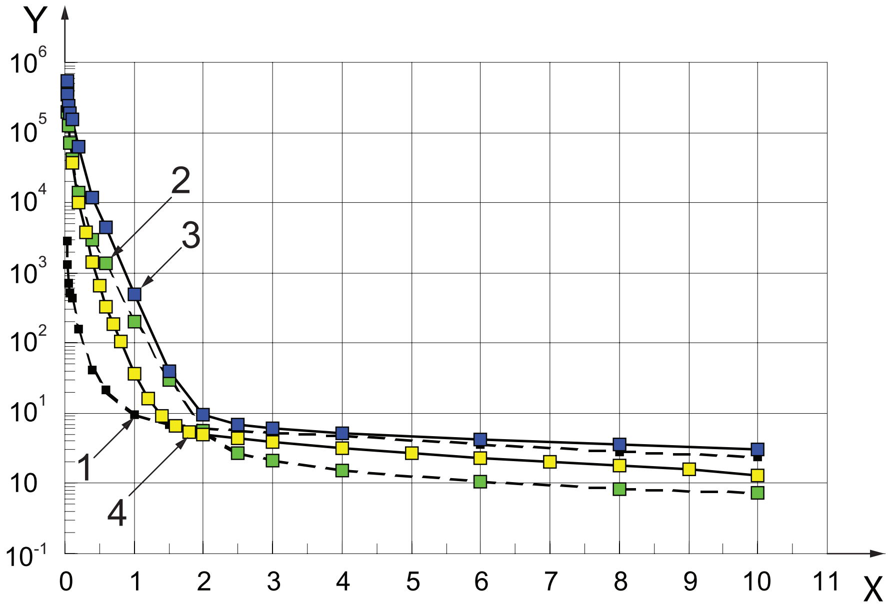
2 charged particles in GEO

3 VUV, L_{α} at 121,6 nm

NOTE Reproduced with permission from Reference [31].

Figure B.1 — Depth dose profile in FEP

Figure B.2 (see References [40] and [42]) shows depth dose profiles in Al exposed in three types of heliosynchronous orbits and in a standard GEO orbit.



Key

X	Al thickness, in grams per square centimetre
Y	dose Al, in grays per year

1	—■—	heliosynchronous, 770 km
2	—🟩—	10 400 km, 55°
3	—🟦—	20 000 km, 55°
4	—🟨—	GEO orbit

NOTE Provided by ONERA/DESP, France. Reproduced with permission from References [40] and [42].

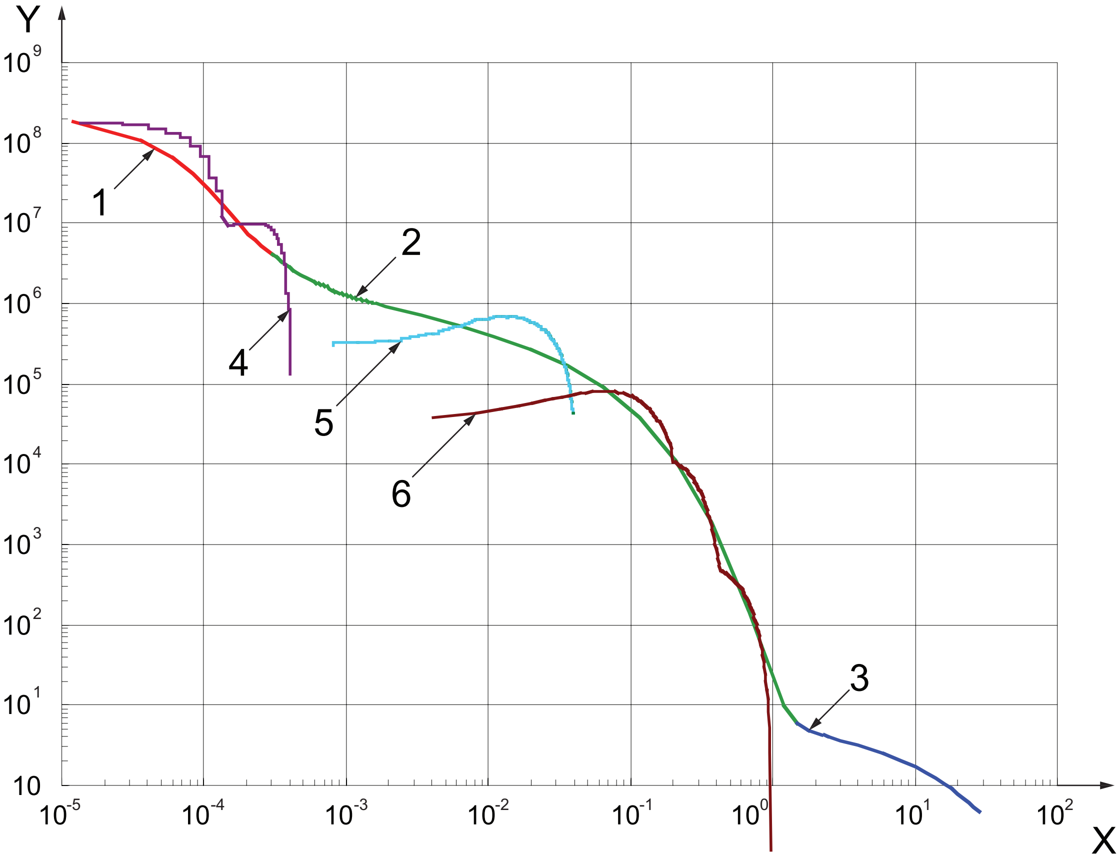
Figure B.2 — Depth dose profile in Al for different orbits

B.2 Simulation of depth dose profile

It is customary to simulate the depth dose profile for space environment conditions by several monoenergetic beams of charged particles. Examples of such simulation are presented on Figures B.3 and B.4.

Figure B.3 (References [40] and [42]) shows depth dose profiles in Al for GEO orbit and six beams of protons and electrons of different energy.

Figure B.4 (Reference [34]) shows depth dose profiles in cerium glass for POL orbit (800 km) and three beams of protons and electrons of different energy.



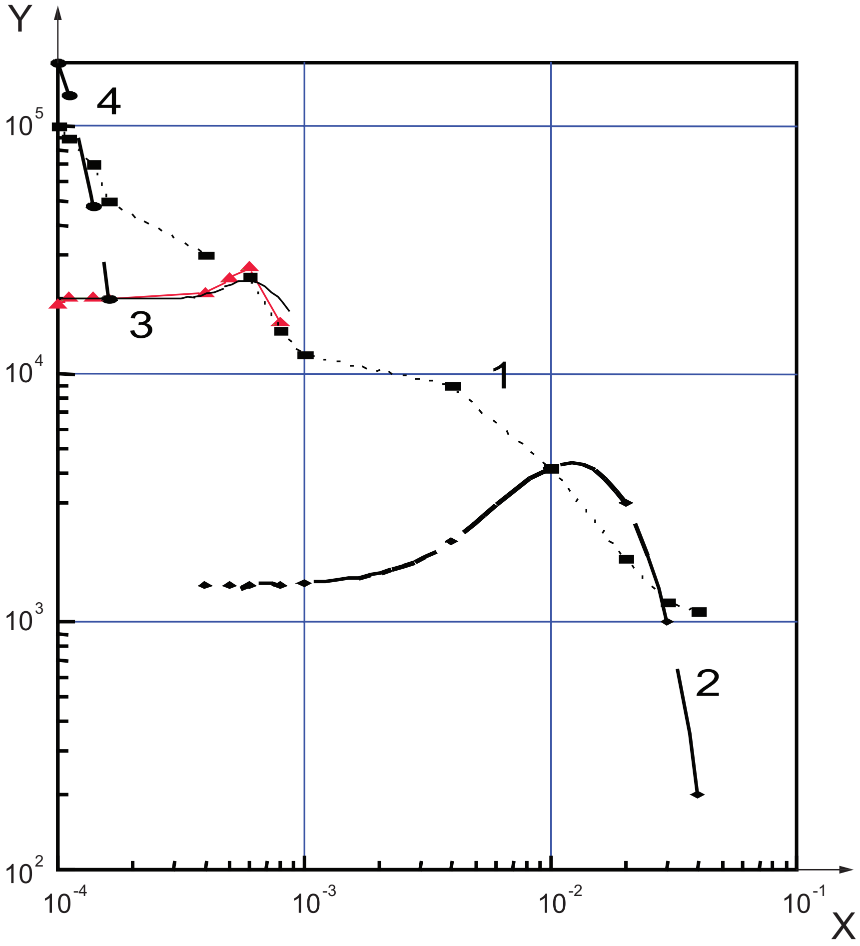
Key

X	Al thickness, in grams per centimetre
Y	dose, in grays per year

1	—	dose due to trapped protons
2	—	dose due to trapped electrons
3	—	dose due to Bremsstrahlung
4	—	2,5 × 10^{15} protons/cm^2 (30 KeV) and 1,2 × 10^{14} (150 KeV)
5	—	6 × 10^{14} electrons/cm^2 (200 KeV)
6	—	1 × 10^{14} electrons/cm^2 (0,6 MeV) + 2 × 10^{13} (1 MeV) + 1 × 10^{12} (2 MeV)

NOTE Provided by ONERA/DESP, France. Reproduced with permission from References [40] and [42].

Figure B.3 — Dose profile in Al for GEO orbit and monoenergetic simulation beams



Key

X depth, in grams per square centimetre

Y absorbed dose, in grays per year

1 total spectrum

2 electrons, $E = 200$ keV, fluence $= 3 \times 10^{12}$ cm^{-2}

3 protons, $E = 300$ keV, fluence $= 3,5 \times 10^{11}$ cm^{-2}

4 protons, $E = 50$ keV, fluence $= 3,2 \times 10^{12}$ cm^{-2}

NOTE Reproduced with permission from Reference [34].

Figure B.4 — Depth dose profile in cerium glass for POL orbit (800 km) **and monoenergetic simulation beams**

B.3 Reliability of radiation spectrum simulation

The assessment of reliable simulation of the radiation spectrum may be made, for example, by introducing a special numerical characteristic of the depth dose profile in a material – depth dose criterion (see Reference [41]).

For this purpose, it is recommended that the ratio of the exponent index of the depth dose profile, μ, to the density of the material, ρ, be used. In the simplest form, the depth dose profile can be represented as a sum of two exponents (see Figure B.5).

$$D = D_1 \times \exp\left[\left(\frac{-\mu}{\rho}\right)_1 X\right]_{0<X<\Delta}$$

and

$$D = D_2 \times \exp\left[\left(\frac{-\mu}{\rho}\right)_2 X\right]_{X>\Delta}$$

where

D is the absorbed dose;

X is the thickness of the material, in grams per square centimetre;

Δ is the point of intersection of the two exponents.

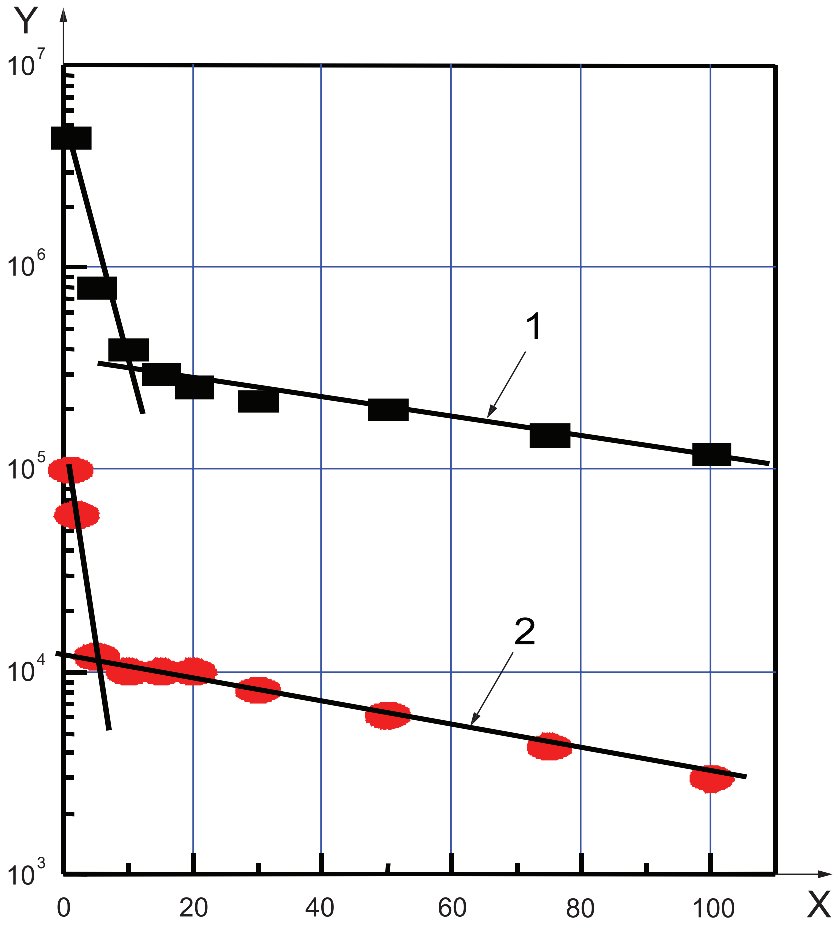
The values of Δ, D_1 and D_2 are defined at graphical data handling.

The first depth dose profile applies to a near-the-surface layer of 5 µm to 10 µm in thickness, and the second to a layer of 10 µm to, as a minimum, 100 µm in thickness. The reference values of μ/ρ, calculated for standard spectra of ionizing radiation, are given in Table B.1.

The depth dose profiles may be presented in the form of two exponents.

The next step is to find the values of depth distribution criterion for both types of conditions and then to adjust the values of μ/ρ by varying the radiation source energy and the particle fluences.

Permissible difference between the depth dose profile criteria for orbit flight and ground test is a complex function of material properties, values of absorbed dose and dose rate. For optical properties, for example, in a majority of non-metallic materials, a linear response results, except at high doses, and this response, in a broad range of dose rates with irradiation in vacuum, changes not more than two times (see Reference [35]). The recommended permissible difference between the μ/ρ values for the adjustment process is about 30 %.



Key

X depth, in micrometres
Y absorbed dose, in grays per year

1 polyimide film, GEO orbit, 0° inclination, 160° western longitude (see Reference [33])
2 cerium glass, POL orbit, 800 km altitude (see Reference [34])

Figure B.5 — Simulated depth dose profiles

Table B.1 shows examples of the depth distribution criterion, μ/ρ, for various standard orbits and three materials.

Table B.1 — Depth distribution criterion of absorbed dose (see Reference [42])

Orbit	**Standard orbit**	$(\mu/\rho)_1$ cm^2/g	$(\mu/\rho)_2$ cm^2/g
1	LEO[a]	$4,0 \times 10^3$	$1,30 \times 10^2$
2	GEO[b]	$3,0 \times 10^3$	$1,22 \times 10^2$
3	GLON[a]	$3,1 \times 10^3$	$0,53 \times 10^2$
4	HEO[a]	$4,6 \times 10^3$	$0,46 \times 10^2$
5	POL[c]	$4,2 \times 10^3$	$1,46 \times 10^2$
6	GEO[a]	$2,5 \times 10^3$	$0,41 \times 10^2$

[a] For aluminum, assuming normal incidence.

[b] For polyimide, assuming isotropic incidence.

[c] For cerium glass, assuming isotropic incidence.

Annex C
(informative)

Accelerated tests

It is desirable to verify the validity of reciprocity in the range of dose rates, defined by the acceleration factor, for each type of radiation using a representative material of the series to be studied. An example of such verifying is presented here.

For this purpose the radiation tests of the material are carried out at various values of dose rate (no less than three values differing from each other by an order of magnitude beginning, at the least, from 1 mGy/s). The absorbed dose and temperature of the sample should be identical in all cases. The permissible degree of acceleration is taken to be equal to the value at which the difference for measured irreversible effect in comparison with a previous one is higher than the total measurement error of a property and dosimetry (see Reference [42]).

To measure the radiation-induced outgassing in accelerated tests with the acceleration factor up to 10^3, the factor of an absorbed dose reserve, equal to five, was established at a dose rate of no more than 1 mGy/s under operating conditions. This recommendation is based on the results of investigations of radiation-chemical yield for species of chemical stage of radiolysis for a number of polymers irradiated in a vacuum (see References [35], [37], [38] and [39]).

The maximum increase of the sample temperature during accelerated tests for the effects of VUV and NUV due to radiation heating (including the IR and visible regions of spectrum) should not be greater than 30 K, if a phase transition of the material does not fall in this temperature interval (see Reference [21]).

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[5] IEC 60544-5, *Electrical insulating materials — Determination of the effects of ionizing radiation — Part 5: Procedures for assessment of ageing in service*

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