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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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DRAFT

Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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.

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

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Introduction

This International Standard is necessary to design 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 adequate to the material behavior in a space environment and to use existing radiation sources and methods available in the test laboratory.

Nonmetallic 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 nonmetallic materials to radiation depends on the type of radiation and its energy that define 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 surface layers.

During the design of space system, it is necessary to simulate long mission time in reasonable ground time. For this reason, it is necessary to perform accelerated tests. With the need for conducting accelerated radiation tests, it is necessary to use dose rates that may be orders 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 complicated 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, first of all, valid for different classes of materials, such as, for example, 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 on the following stages of the standard set preparation for space environment simulation at on-ground tests of materials.

This 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

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 nonmetallic materials to simulated space radiation. Nonmetallic materials includes glasses, ceramics, and polymer-metal composite materials such as metal matrix composites and laminated materials. The standard does not cover semiconductor materials used for electronic components. The types of simulated radiation includes 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 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:

- 1) The definition of the environment to be simulated using commonly accepted space environment models;
- 2) The definition of the material properties under test or of concern in accordance with specificity of degradation in the space environment; satellite specific constraints determination: temperature conditions (constant values or cycled temperature mode), mechanical stress, charging, contamination etc.
- 3) 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;
- 4) 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 Publication 544 (Parts 1-4), *Electroinsulating materials; determination of ionizing radiation influence*

ISO 15390, *Space environment (natural and artificial) — Galactic cosmic ray model*

ASTM E 490, *Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables*

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 equivalence coefficient, k

the ratio of the absorbed doses for two different types of radiation to provide the same radiation effect in a material

3.1.2

absorbed dose, D

the amount of energy imparted by ionizing radiation per unit mass of irradiated matter

NOTE 1 The quotient of $d\bar{\epsilon}$ by dm , where $d\bar{\epsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm . $\{D = \frac{d\bar{\epsilon}}{dm}\}$

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

3.1.3

acceleration factor

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

3.1.4

bremsstrahlung

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. It is mainly due to electrons

3.1.5

depth distribution criterion of absorbed dose

the ratio of the exponent index (μ) of the absorbed dose depth profile curve to the material density (ρ). Dimensions - $\text{cm}^2\cdot\text{g}^{-1}$

3.1.6

depth dose profile

distribution of the absorbed dose through the depth of material

3.1.7

energy fluence

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

NOTE Dimensions - $\text{J}\cdot\text{m}^{-2}$

3.1.8

far ultraviolet (FUV) radiation

solar electromagnetic radiation with the wavelength in the range from 10 to 200 nm. This is also called vacuum ultraviolet.

NOTE Another structure of electromagnetic solar radiation short-wave range is proposed in the draft of ISO standard DIS 21348 "Solar Irradiances ": the XUV (soft X-rays line emission) extends from 1 nm to 30 nm, the EUV (extreme ultraviolet lines, continua emission) extends from 30 nm to 120 nm, FUV extends from 120 nm to 208 nm, the MUV (middle ultraviolet lines, continua) extends from 208 nm to 300 nm, and the UV (ultraviolet lines, continua) extends from 300 nm to 400 nm.

3.1.9

galactic cosmic rays (GCR)

high-energy charged particle fluxes penetrating the heliosphere from local interstellar space

3.1.10

heliosphere

the region surrounding the sun where the solar wind dominates the interstellar medium; also known as solar cavity

3.1.11

induced space environment

the environmental factors that result from interactions of the space system with the natural space environment or the factors that are produced by the space system. They include thermocycling, ambient atmosphere, electrical charging, etc.

3.1.12

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. (For example, charged particles could be positive or negative electrons, protons, or other heavy ions, and uncharged particles could be X-rays, gamma rays, or neutrons.)

3.1.14

linear energy transfer (LET)

the energy delivered by a charged particle passing through a substance and locally absorbed per unit length of path

NOTE Dimensions - $\text{J}\cdot\text{m}^{-1}$ (often - $\text{keV}/\mu\text{m}$)

3.1.18

mean free path

the average distance that a subatomic particle, ion, atom, or molecule travels between successive collisions with ions, atoms, or molecules

3.1.19

natural space environment

the environment that exists in space without a spacecraft system present

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

3.1.20

near ultraviolet (NUV) radiation

solar electromagnetic radiation with the wavelength in the range from 200 up to 400 nm

NOTE See the note to item 3.1.9.

3.1.21

radiation action measure

energetic characteristic of radiation action on a material

NOTE The radiation action measure for nonmetallic material is an absorbed dose or energy fluence.

3.1.22

radiation belt

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

3.1.23

radiation scale effect

dependence of the material degradation on the thickness ratio of irradiated and unirradiated layers

3.1.24

reciprocity law

the statement that the observed property change depends only on the applied dose and is independent of the dose rate

3.1.26

surface properties

properties of a material that are defined by physico-chemical and morphological structure of its surface in a product

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

3.1.27

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.

3.1.28

synergism

the joint action of two or more stimuli whose combination elicits a level or sensation different (greater or less) than the result of combining the effects of each stimulus taken separately

3.1.29

teflon[®]

DuPont trade name for polytetrafluoroethylene (PTFE) and fluorinated ethylene propylene (FEP) fluoropolymers

3.1.30

volume properties (bulk properties)

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

3.1.31

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.

NOTE 1 Symbol: E_e , E , $E_e = d\Phi_e/dA$

NOTE 2 Dimensions - $W \cdot m^{-2}$

3.1.32

reversible radiation change of material property

radiation change of a material that arises through the process of radiation exposure and reverses after its stoppage

3.1.33**irreversible radiation change of material property**

radiation change of a material that is accumulating through the process of radiation exposure and remains after irradiation stoppage.

3.2 Abbreviated terms and acronyms

ASTM Now ASTM International, was American Society for Testing and Material

ECSS European Cooperation for Space Standardization

ESA European Space Agency

EUV extreme ultraviolet

FEP fluorinated ethylene propylene

FUV far ultraviolet

GCR galactic cosmic rays

GEO GEosynchronous Orbit

GLON GLONASS navigation spacecraft (Russian Federation)

GOST Russian Federation Standard

GPS Global Positioning Satellite (U.S.A.)

HEO high-elliptical orbit

ICRU International Commission on Radiation and Units

ISS International Space Station

keV kiloelectronvolt

LEO low Earth orbit

LET linear energy transfer

MeV megaelectronvolt

MUV middle ultraviolet

nm nanometer

NUV near ultraviolet

POL Standard POLar Orbit

PTFE polytetrafluoroethylene

4 Space environment radiation characteristics

4.1 Sources of ionizing radiation in space

The main sources of ionizing radiation in space are galactic and solar particle radiation (solar wind), solar X-radiation in the 1-10 nm wavelength band (see the note to definition 3.1.9), far 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 on 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.spennis.oma.be/spennis/>.

4.2.2 Electron irradiation

The electron irradiation environment is based on the best available now AE-8 model. The AE-8 model describes spectra of electrons with minimal energy 40 keV (Annex A.1, Reference 2.1).

There are no similar models for lower-energy electrons. Energy characteristics of low-energy particles for a geosynchronous orbit are presented in References 2.6 and 2.7.

For the low Earth orbit (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 available now AP-8 model. The AP-8 model describes spectra of protons with minimal energy 100 keV (Annex A.1, Reference 2.2).

There are no similar models for low-energy protons. Energy characteristics of such particles for a geosynchronous orbit are presented in References 2.3 and 2.4.

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 - 10 keV corresponds to the solar flares, Reference 2.7. The predominant energy contribution comes from photons with energies between 1 and 3 keV.

4.2.5 Bremsstrahlung

Bremsstrahlung is produced from the deceleration of particulate radiation inside of matter. Bremsstrahlung contributes to the radiation damage in materials with thickness more than several g/cm^2 or in shielded materials.

4.2.6 Ultraviolet radiation

Solar spectral irradiances in the FUV and NUV are specified in ASTM E 490

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

The FUV energy spectrum with the lower wavelength 50 nm is specified in ASTM E 512 (Reference 1.1.1)

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 used codes are presented in the Annex A2.

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

Take into account that contribution of each type of space radiation into total absorbed dose depends on the shielding depth (see an example - Table A.2). Sometimes the space radiation (i.e. bremsstrahlung, high-energy electrons) may be simulated by ^{60}Co gamma rays (see References 1.2.4, 1.3.1 and 1.3.4 for simulation methods). See References 1.1.1 and 1.3.7 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 $4 \text{ mg}\cdot\text{cm}^{-2}$ or less (see Fig. B1 - B3). The surface properties include surface electrical conductivity, optical (reflectance, absorptance, emittance), adhesive (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 FUV are primarily responsible for the degradation of surface properties.

The whole spectrum of the solar X-radiation and UV affect the surface properties of nonmetallic materials. Most materials have a high absorption to FUV, 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 $5\text{-}10 \text{ mg}\cdot\text{cm}^{-2}$ 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 micron 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 in Annex A).

The absorbed dose averaged over the product thickness is taken to be a measure of radiation action to analyze 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 selection of 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 (Reference 2.9). The two-measure approach of radiation action is applicable to the layers with more than 4 mg/cm² thickness on the space vehicle surface. The energy fluence is an only measure of radiation action on the layers of less than 4 mg/cm² 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

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 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, depth dose profile for the tested material shall be calculated 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 nonmetallic 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. This includes differences in ionization characteristics. 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 ionizing 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 that cause degradation of the material volume properties, it is possible to replace one kind of ionizing radiation by another radiation if it is technically more feasible and the effects can be duplicated (e.g. when there are reliable experimental data of adequacy of such replacement for the similar material and the same property – see Reference 1.3.1). 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 nonmetallic 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, the way a) is most 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 free path of the particles and is determined by 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 Figs. B.1 and B.2 in Annex B). 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 Annex A2). This profile has to 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 a possible assessment, see Annex B.2.

6.3.2.6 Mg and Al soft photon sources can be used for simulation of soft X-ray (see Reference 2.21)

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 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 radioisotope 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 up 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 not 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 an 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 the connection with aforesaid the accelerated radiation tests are only possible when preceded by conditioning the material samples in a vacuum 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 outgassing is most significant. To take it into account in accelerated tests it is advisable to increase the value of absorbed dose. An example of such dose reserve factor is given in Annex C.

6.3.3.7 It is permissible to conduct accelerated tests for the effects of FUV exposure of nonmetallic materials at acceleration factors up to 10^3 (see Reference 1.3.7). 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 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 grounding 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 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 don't exist.

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 don't exist.

7.4 High-energy proton accelerators

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

7.5 High-energy electron accelerators

High-energy electron accelerators provide particles with energies greater than 0.5 MeV.

7.6 Bremsstrahlung

Bremsstrahlung can be simulated using gamma-radiation emitted by cobalt-60, an artificial isotope. The predominant gamma-radiation energies are 1.33 MeV and 1.17 MeV.

7.7 Neutron beam

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.

7.8 Ultraviolet radiation

Ultraviolet radiation is the main part of the solar radiation in degradation of nonmetallic materials. It consists from far ultraviolet (FUV) and near ultraviolet (NUV). In any case the solar energy spectrum has to be followed as closely as possible.

7.8.1 Far UV

For the simulation of far 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.

7.8.2 Near UV

For the simulation of near ultraviolet radiation effects in the range of wavelength from 200 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 the 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.

7.8.3 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 the clause 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), high elliptical orbit (HEO), and standard Polar Orbit (POL).

Table 1 — Standard spacecraft orbits

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

For the orbits not included in the 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 according codes are indicated as examples in the Annex A2.

Table 2 — Energy fluence of corpuscular radiation

| Standard Orbit | Designation | Energy fluence ($\text{J}\cdot\text{m}^{-2}$ 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 the depth 1 mg/cm²

| 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 | $2,5 \times 10^3$ | $3,0 \times 10^2$ | $2,8 \times 10^3$ |

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Annex A (informative)

Additional Information

A.1 Space radiation environment

The absorbed dose in the vehicle near-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, FUV, and NUV).

Spectra of electrons with minimal energy 40 keV and protons with minimal energy 100 keV, in the trapped radiation belts of the Earth, are described in the AE-8 and AP-8 models, References 2.1 and 2.2. Validity of the AE-8 and AP-8 models is limited to Solar min or Solar max 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 2.3 and 2.4, respectively. References 2.5 and 2.6 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.spenvjs.oma.be/spenvjs/>). 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, RADMODLS and others. The Tiger-P code is found in the code package ITS 3,0 Sandia National Laboratories (Reference 2.14). Vampola A.L. RADMODLS, Version 4.20/ 1994 may be found on the Web-site:

<http://nssdc.gsfc.nasa.gov/space/model/magnetos/radmodls.html>

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

Table A.1 shows the percent 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, inclination of 62,8 degrees.

Table AA.1 — Space radiation absorbed dose at various shielding depths on satellite Cosmos 1887 (% 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 taken from reference 2.8 | | | | | | |

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Annex B
(informative)

Depth dose

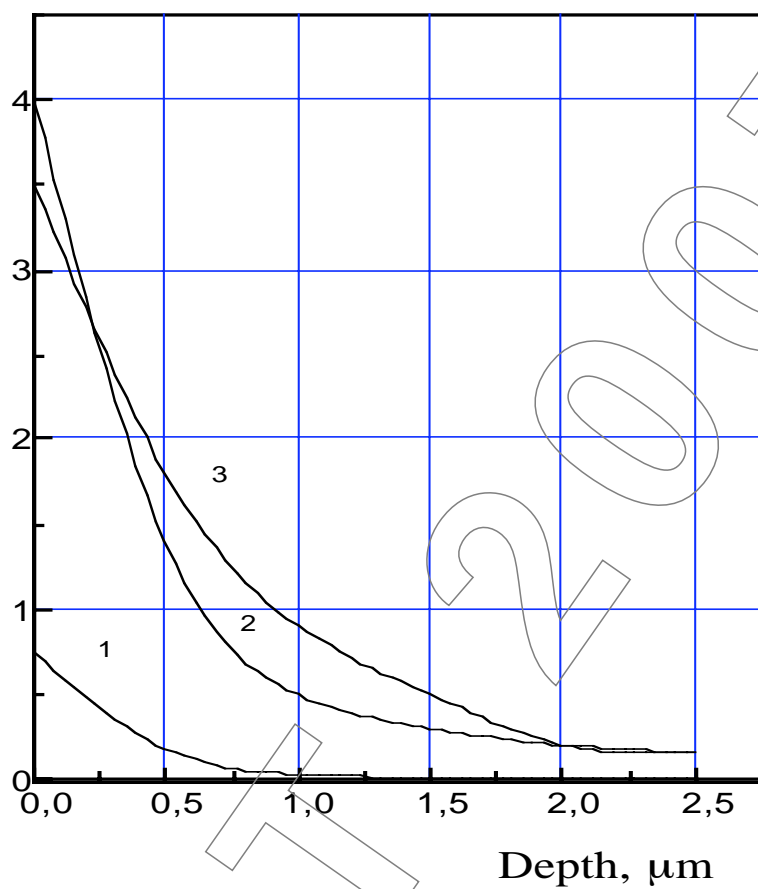
B.1 Depth dose distribution

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

Figure B.1 (Reference 2.9) 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- α at 121,6 nm). The larger depth dose profiles occur from the FUV and the lower energy charged particles.

Figure B.2 (Reference 2.21) shows depth dose profiles in Al exposed in three types of heliosynchronous orbits and in a standard GEO orbit.

Dose rate, Gy/sec



- 1) Soft X-ray background
- 2) Charged particles in GEO
- 3) FUV, L_α at 121.6 nm

Figure BB.1 — Depth dose profile in FEP (Reference 2.9)

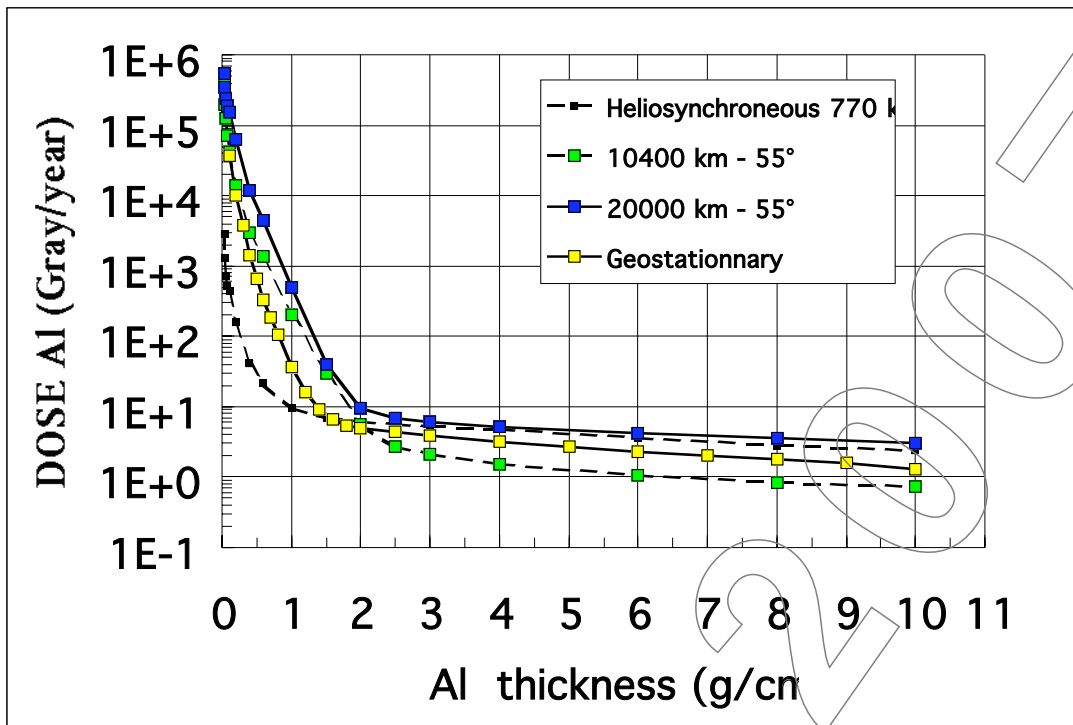


Figure BB.2 — Depth dose profile in Al for different orbits (Provided by ONERA-CERT, France)

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 Figs. B.3 and B.4.

Figure B.3 (Reference 2.21) shows depth dose profiles in Al for GEO orbit and six beams of protons and electrons of different energy.

Figure B.4 (Reference 2.18) shows depth dose profiles in cerium glass for POL orbit (800 km) and three beams of protons and electrons of different energy

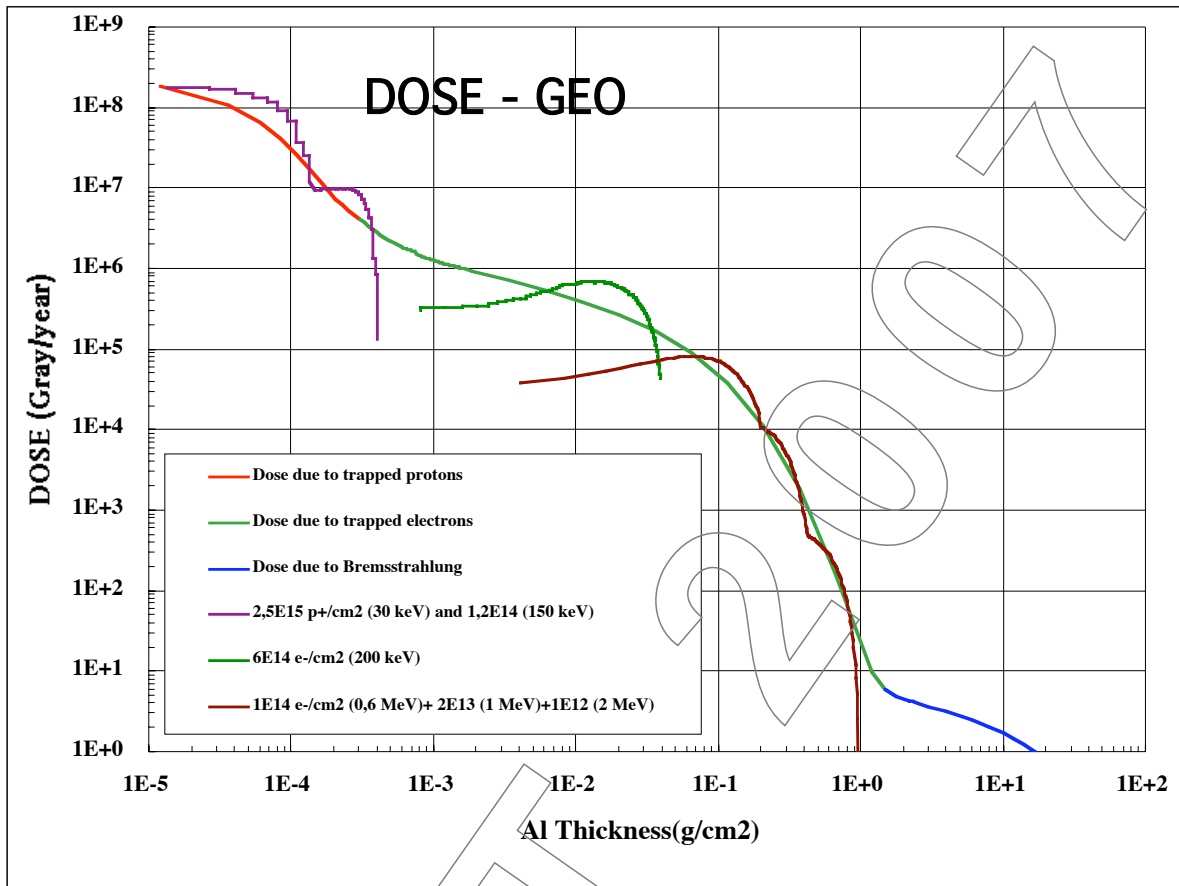
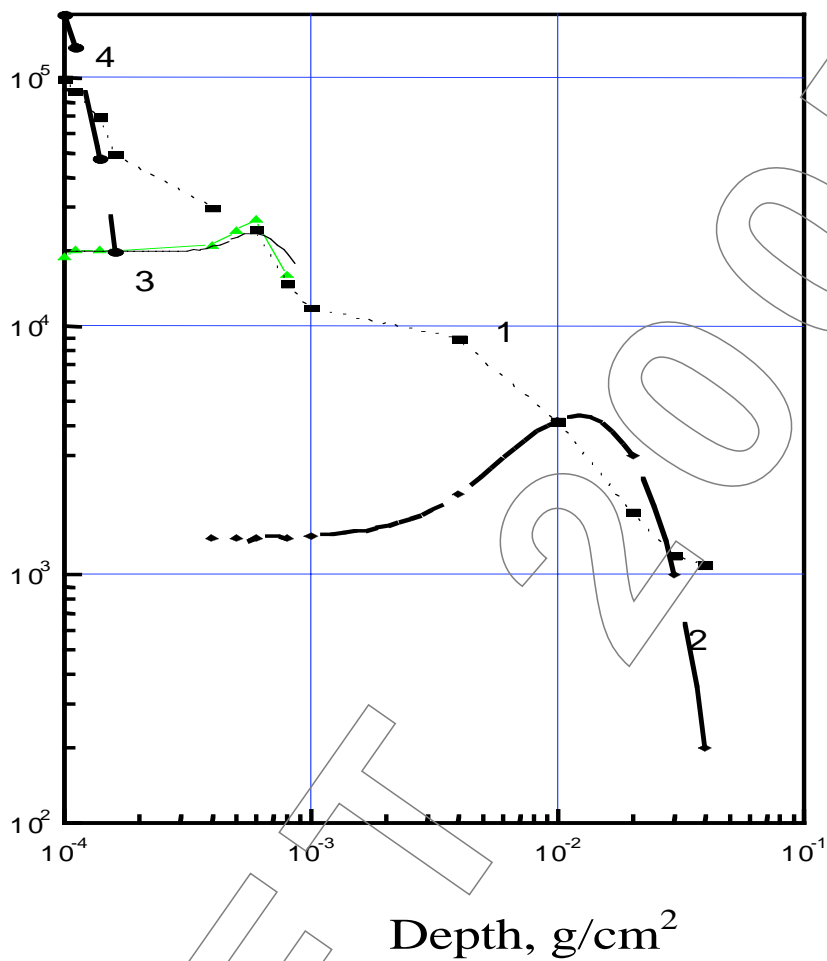


Figure BB.3 — Dose profile in Al for GEO orbit and monoenergetic simulation beams (Provided by ONERA-CERT, France)

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Absorbed dose, Gy per year



- 1) Total spectrum
- 2) Electrons, $E = 200 \text{ keV}$,
fluence = $3 \times 10^{12} \text{ cm}^{-2}$
- 3) Protons, $E = 300 \text{ keV}$,
fluence = $3,5 \times 10^{11} \text{ cm}^{-2}$
- 4) Protons, $E = 50 \text{ keV}$,
fluence = $3,2 \times 10^{12} \text{ cm}^{-2}$

Figure BB.4 — Depth dose profile in cerium glass for POL orbit (800 km) and monoenergetic simulation beams (Reference 2.18)

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 (Reference 2.19).

For this purpose, it is recommended to use the ratio of the exponent index of the depth dose profile (μ) to the density of the material (ρ). 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, g/cm^2 ; 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.

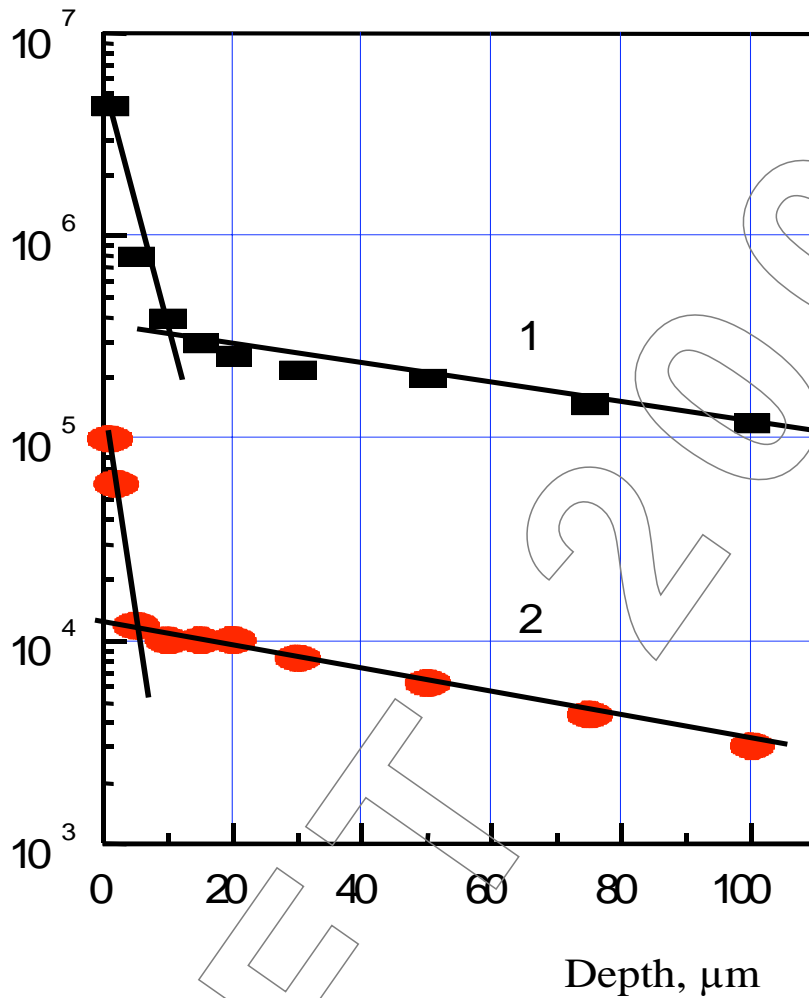
The first depth dose profile applies to a near-the-surface layer of 5 to 10 μm in thickness, and the second to a layer of from 10 μm up to, as a minimum, 100 μm in thickness. The reference values of \square/\square , calculated for standard spectra of ionizing radiation, are given in Table B.3.

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 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 nonmetallic materials, a linear response results except at high doses, and this response in broad range of dose rates with irradiation in vacuum changes not more than two times (Reference 2.13). The recommended permissible difference between the \square/\square values for the adjustment process is about 30%.

Absorbed dose, Gy per year



- 1) Polyimide film, GEO orbit, 0° inclination, 160° western longitude (Reference 2.11)
- 2) Cerium glass, POL orbit, 800 km altitude (Reference 2.12)

Figure BB.5 — Simulated depth dose profiles

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

Table BB.1 — Depth distribution criterion of absorbed dose (Reference 2.20)

| Orbit | Standard orbit | (μ/ρ) (cm ² /g) | $(\mu/\rho)_2$ (cm ² /g) |
|---|-----------------------|--------------------------------------|--|
| 1 | LEO ^a (2) | $4,0 \cdot 10^3$ | $1,30 \cdot 10^2$ |
| 2 | GEO ^b (1) | $3,0 \cdot 10^3$ | $1,22 \cdot 10^2$ |
| 3 | GLON ^a (2) | $3,1 \cdot 10^3$ | $0,53 \cdot 10^2$ |
| 4 | HEO ^a (2) | $4,6 \cdot 10^3$ | $0,46 \cdot 10^2$ |
| 5 | POL ^c (3) | $4,2 \cdot 10^3$ | $1,46 \cdot 10^2$ |
| 6 | GEO ^a (2) | $2,5 \cdot 10^3$ | $0,41 \cdot 10^2$ |
| <p>^a For aluminum, assuming normal incidence.</p> <p>^b For Kapton^{®1}, assuming isotropic incidence.</p> <p>^c For cerium glass, assuming isotropic incidence.</p> | | | |

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¹ DuPont trade name for polyimide polymer.

Annex C (informativ)

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 below.

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. Permissible degree of acceleration is taken 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 (Reference 2.20).

To measure radiation 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 investigation of radiation-chemical yield for species of chemical stage of radiolysis for a number of polymers at irradiation *in vacuo* and is not connected with oxidation (Reference 2.13).

The maximum increase of the sample temperature during accelerated tests for the effects of FUV 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 (Reference 1.3.7).

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[1.1.3] E 491, *Standard Practice for Solar Simulation for Thermal Balance Testing of Spacecraft.*

[1.1.4] E 170, *Standard Terminology Relating to Radiation Measurements and Dosimetry.*

[1.1.5] E 1027, *Standard Practice for Exposure of Polymeric Materials to Ionizing Radiation.*

[1.1.6] E 1420, *Standard Practice for Specifying Polymeric Materials for Service in Ionizing Radiation Environments.*

1.2 ECSS/European Space Agency standards

[1.2.1] ESA PSS-01-70, *Material and Process Selection and Quality Control for ESA Spacecraft and Associated Equipment.*

[1.2.2] ESA PSS-01-702, *A Thermal Vacuum Test for the Screening of Space Materials.*

[1.2.3] ESA PSS-01-704, *A Thermal Cycling Test for the Screening of Space Materials and Processes.*

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