

KARPOV INSTITUTE OF PHYSICAL CHEMISTRY

OBNINSK BRANCH

FINAL REPORT

ON THE CONTRACT F61775-99-WE022:

"Research program for radiation stability of the aerospace materials – development of ISO standards for space environment simulation at material tests"

The detailed work plan consisted of:

1. Verifying calculations of the surface energy fluence and absorbed doses of electrons and protons in near-surface layers of the materials for six standard orbits of space vehicles. Selecting typical calculation examples and introducing them in the standard draft.
2. Sustaining the main principles used for the dose rate simulation and reviewing a corresponding section of the standard.
3. More precise defining of the terms, in particular, specification of the vacuum ultraviolet radiation range and agreement of the energy range limits with the experts involved.
4. Getting approval of the whole document contents from the interested specialists in the ISO member-countries.
5. Preparing the document at the ISO Committee stage.

As a result, the CD (Committee Document) ISO 15856 "Space Environment Simulation at Radiation Tests of Materials. I. Nonmetallic Materials" is developed and discussed at the last meeting of ISO TC14/SC20/WG4 in London. This document is integral with the report.

Resolution #86 recommended to correct the 1st version of CD 15856 in accordance with experts previous comments (Japan, USA, France, ESA) and with this aim in mind to organize a special meeting of experts in the field of space material science.

A paper with the similar title, based on the standard draft, was presented on the 8th International Symposium "Materials in a Space Environment", Arcachon, France, June 2000.

Principal Investigator

Dr. Boris. A. Briskman

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June 15, 2000

INTERNATIONAL STANDARD

**ISO
CD 15856**

**Space Systems and Operations
Space Environment (Natural and Artificial)
Space Environment Simulation for Radiation Tests of Materials.
Part I: Nonmetallic Materials**

COMMITTEE DRAFT

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Foreword

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

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 percent of the member bodies casting a vote.

International standard ISO 15856 was prepared by the Technical Committee ISO/TC 20, Aircraft and Space Vehicles; Sub-Committee SC 14, Space Systems and Operations, Working Group WG4, Space Environment (Natural and Artificial).

Users should note that all international standards undergo revision from time to time and that any reference made herein to any other international standard implies its latest edition, unless otherwise stated.

Annex A is for information only. Annex B is a bibliography for information only.

Introduction

The specification of standard space environment characteristics and standard methods for testing materials in laboratory environments is necessary for the design of space systems and the achievement high reliability and long mission life times. It is impossible to reproduce exactly the space environment for ground testing of space system elements because of the variety and complexity of the environments and 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: a) getting of the test results that are adequate to the material behavior in space environment; b) using of to-day 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 the last. 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 times in reasonable ground times. 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 in the materials. Therefore, the main requirement for the correct simulation in radiation tests involves simulating the correct effects 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, different 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 factors - atomic oxygen, deep vacuum, thermocycling, etc. Synergistic interactions can significantly increase the material degradation, i.e., decrease the time of operation. Space environment simulation at the combined exposure is 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.

Space Systems and Operations

Space Environment Simulation for Radiation Tests of Materials —

Part 1: Nonmetallic Materials

1. Scope

1.1. This standard is the first part of an international standards series on space environment simulation for on-ground tests of materials used in space. This standard covers the testing of nonmetallic materials to simulated space radiation. 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.

1.2. Standard orbits are specified to provide recommended approximate levels of absorbed doses and energy fluences.

1.3. Simulation methods are used to reproduce the effects of the space radiation environment on nonmetallic materials that are located on surfaces of space vehicles and behind shielding.

1.4. The standard does not specify the design of material specimens, methods of measuring properties of materials and radiation, components of radiation sources and vacuum systems, and the preparing of test reports. The users should select designs and measurement methods based on the current state-of-the-art and the requirements of space systems and contracts.

1.5. The standard does not include hazards and safety precautions. The users are responsible for providing safe conditions based on national and local regulations.

2. Normative References

2.1. The following normative documents contain provisions, which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to apply. Members of ISO and IEC maintain registers of currently valid International Standards.

2.2. IEC (International Electrotechnical Commission) standards

2.2.1. IEC 544, Electroinsulating materials. Determination of ionizing radiation influence. Parts 1-4.

2.3. ISO standards

2.3.1. CD 15390, Space environment (natural and artificial) - Galactic cosmic ray model.

2.3.2. CD 15391, Space environment (natural and artificial) - Probabilistic model of fluences and peak fluxes in solar energetic particles.

3. Terms and definitions

4.1. 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.

4.2. Absorbed dose, D

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

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 . $\{D = \frac{d\bar{\epsilon}}{dm}\}$

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

4.3. Acceleration factor

Ratio between the dose rate used in simulation and the one expected in space for the same type of radiation.

4.4. 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.

4.5. 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 - $\text{cm}^2\cdot\text{g}^{-1}$

4.6. Depth dose

The variation of absorbed dose with distance from the incident surface of a material exposed to radiation.

4.7. Depth dose profile

Distribution of the absorbed dose through the depth of material

4.8. Energy fluence

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

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

4.9. 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 "Solar Extreme Ultraviolet": the XUV (soft X-rays line emission) extends from 1-30 nm, the EUV (extreme ultraviolet lines, continua emission) extends from 30-120 nm, FUV extends from 120-208 nm, the MUV (middle ultraviolet lines, continua) extends from 208-300 nm, and the UV (ultraviolet lines, continua) extends from 300-400 nm.

4.10. Galactic cosmic rays (GCR)

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

4.11. Heliosphere

The region surrounding the sun where the solar wind dominates the interstellar medium. Also known as solar cavity.

4.12. 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.

4.13. 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.)

4.14. Kapton®,

DuPont trade name for polyimide polymer.

4.15. Linear energy transfer, LET

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

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

4.16. Mean free path

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

4.17. Natural space environment

The environment that exists in space without a space system present. This includes radiation, vacuum, residual atmosphere, and meteoroids.

4.18. 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 3.9

4.19. 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

4.20. Radiation belt

Electrons and protons around the Earth, trapped by the geomagnetic field.

4.21. Radiation scale effect

Dependence of the material degradation on the thickness ratio of irradiated and unirradiated layers.

4.22. Ram direction

The surface of a spacecraft that looks in the positive orbital velocity vector direction.

4.23. Reciprocity law

The statement that in radiation-chemical or photochemical reactions, a constant effect is produced if the product of time and dose rate is a constant.

4.24. Surface properties

Properties of a material that are defined by physico-chemical and morphological structure of its surface in a product. The depth or thickness that constitutes surface properties depends upon the type of material and particular property but can be considered to be approximately $4 \text{ mg}\cdot\text{cm}^{-2}$

4.25. 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.

4.26. Synergism

The joint action of two or more stimuli whose combination elicits a level or sensation greater than the result of combining the effects of each stimulus taken separately.

4.27. Teflon®,

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

4.28. Volume properties (bulk properties)

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

4.29. 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.

Symbol: E_e , E $E_e = d\Phi_e/dA$. Dimensions - $W \cdot m^{-2}$

4.30. Low energy radiation

Space environment radiation including protons with maximum energy 1 MeV and electrons with maximum energy 50 keV.

4.31. Reversible radiation change of material property

Radiation change of a material that arises through the process of radiation exposure and disappears after its stoppage.

4.32. Irreversible radiation change of material property

Radiation change of a material that is accumulating through the process of radiation exposure and last out after its stoppage.

- 4. Symbols and abbreviated terms**
- 4.1. ASTM: American Society for Testing and Materials**
- 4.2. ECSS European Cooperation for Space Standards**
- 4.3. ESA: European Space Agency**
- 4.4. FEP Fluorinated Ethylene Propylene**
- 4.5. GEO: GEOsynchronous Orbit**
- 4.6. GLON: GLONASS navigation spacecraft (Russian Federation)**
- 4.7. GOST Russian Federation Standard**
- 4.8. GPS: Global Positioning Satellite (U.S.A.)**
- 4.9. HEO: High Elliptical Orbit**
- 4.10. ICRU: International Commission on Radiation and Units**
- 4.11. ISS: International Space Station**
- 4.12. LEO: Low Earth Orbit**
- 4.13. MIR: Russian Federation Space Station**
- 4.14. POL: Standard POLar Orbit**
- 4.15. PTFE PolyTetraFluoroEthylene**

5. Standard Spacecraft Orbits

5.1. In order to provide an uniform methodology for space environment simulation, six standard earth orbits are specified in Table 1.

Table 1. Standard spacecraft orbits

Std. Orbit	Designation	Orbit	Altitude km	Inclination degrees	Type of orbit
1	MIR	Low Earth Orbit of MIR station	350	51,6	Circular
2	ISS	Low Earth Orbit of ISS	426	51,6	Circular
3	GEO	Geostationary	35 790	0	Circular
4	GLON	GLONASS/GPS vehicles	19 100	64,8	Circular
5	HEO	High-elliptic orbit	500-39 660	65	Elliptical
6	POL	Standard polar orbit	600	97	Circular

5.2. The orbits in Table 1 shall be used in conjunction with Table 3 for the specification of the radiation environments for materials to be used in the specified orbits.

5.3. 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 requirements are stated in Section 6.

6. Space environment radiation characteristics

6.1. Sources of ionizing radiation in space

The main sources of ionizing radiation in space are galactic and solar particle radiation, solar X-radiation in the 1-10 nm wavelength band (see the note to item 3.9), far ultraviolet radiation (FUV), and trapped charged particles of low energy in radiation belts around the Earth.

6.2. Radiation levels for Earth orbits

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.

6.2.1. Electron irradiation

6.2.1.1. The electron irradiation environment is based on the AE-8 model. The AE-8 model describes spectra of electrons with minimal energy 40 keV (Reference B2.2).

6.2.1.2. There are no similar models for low energy electrons. Energy characteristics of low energy particles for a geosynchronous orbit are presented in References B2.6 and B2.7.

6.2.1.3. For the LEO (MIR, ISS) and POL orbits, the energy ranges are 40 keV to 5 MeV for electrons.

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

6.2.2. Proton irradiation

6.2.2.1. The proton irradiation environment is based on the AP-8 model. The AP-8 model describes spectra of protons with minimal energy 100 keV (Reference B2.3).

6.2.2.2. There are no similar models for low energy protons. Energy characteristics of such articles for a geosynchronous orbit are presented in References B2.4 and B2.5.

6.2.2.3. For the LEO (MIR, ISS) and POL orbits, the energy ranges are 100 keV to 200 MeV for protons.

6.2.2.4. For the GEO, GLON and HEO orbits, the energy ranges are 1 keV to 100 MeV for protons.

6.2.3. 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 B2.8. The predominant energy contribution comes from photons with energies between 1 and 3 keV.

6.2.4. Bremsstrahlung radiation

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

6.2.5. Ultraviolet radiation

6.2.5.1. Solar spectral irradiances in the FUV and NUV are specified in Table 2. This is based on the information in ASTM E 490 (Reference B1.1.3). The FUV energy spectrum with the lower wave length 50 nm is specified in ASTM E 512 (Reference B 1.1.1).

6.2.5.2 Irradiance of the far ultraviolet (FUV) in low earth orbits is about $0,1 \text{ W}\cdot\text{m}^{-2}$ or 0,007 % of the total solar electromagnetic irradiance.

6.2.5.3. Irradiance of the near ultraviolet (NUV) for the same conditions is about $118 \text{ W}\cdot\text{m}^{-2}$ or 8,7 % of the total solar electromagnetic irradiance.

Table 2 Standard solar UV spectral irradiance λ = wavelength, μm , E_{λ} = solar spectral irradiance averaged over small bandwidth centered at λ ,
 $\text{W}\cdot\text{m}^{-2}\cdot\mu\text{m}^{-1}$, $E_{0-\lambda}$ = integrated solar irradiance in the wavelength range from 0 to λ , $\text{W}\cdot\text{m}^{-2}$, $D_{0-\lambda}$ = percentage of solar constant associated with wavelengths shorter than λ ,
and solar constant = $1353 \text{ W}\cdot\text{m}^{-2}$.

Note-Lines indicate change in wavelength interval of integration.

λ	E_{λ}	$E_{0-\lambda}$	$D_{0-\lambda}$
0.115	0.007	0.0025	0.0001
0.120	0.900	0.0048	0.0003
0.125	0.007	0.0070	0.0005
0.130	0.007	0.0071	0.0005
0.140	0.030	0.0073	0.0005
0.150	0.070	0.0078	0.0005
0.160	0.230	0.0093	0.0006
0.170	0.630	0.0136	0.0010
0.180	1.250	0.0230	0.0016
0.190	2.710	0.0428	0.0031
0.200	10.7	0.1098	0.0081
0.210	22.9	0.2778	0.0205
0.220	57.5	0.6798	0.0502
0.225	64.9	0.9858	0.0728
0.230	66.7	1.3148	0.0971
0.235	59.3	1.6298	0.1204
0.240	63.0	1.9356	0.1430
0.245	72.3	2.2738	0.1680
0.250	70.4	2.6306	0.1944
0.255	104.0	3.0666	0.2266
0.260	130	3.6516	0.269
0.265	185	4.4391	0.328
0.270	232	5.4816	0.405
0.275	204	6.5716	0.485
0.280	222	7.6366	0.564
0.285	315	8.9791	0.663
0.290	482	10.9716	0.810
0.295	584	13.6366	1.007
0.300	514	16.3816	1.210
0.305	603	19.1741	1.417
0.310	689	22.4041	1.655
0.315	764	26.0366	1.924
0.320	830	30.0216	2.218
0.325	975	34.5341	2.552
0.330	1059	39.6191	2.928
0.335	1081	44.9691	3.323
0.340	1074	50.3566	3.721

l	E_l	E_{0-l}	D_{0-l}
0.345	1069	55.7141	4.117
0.350	1093	61.1191	4.517
0.355	1083	66.5591	4.919
0.360	1068	71.9366	5.316
0.365	1132	77.4366	5.723
0.370	1181	83.2191	6.150
0.375	1157	89.0641	6.582
0.380	1120	94.7566	7.003
0.385	1098	100.3016	7.413
0.390	1098	105.7916	7.819
0.395	1189	111.5091	8.241
0.400	1429	118.0541	8.725

6.3. Total particulate irradiation

6.3.1. For corpuscular radiation, reference values of the energy fluences for each of the specified orbits are listed in Table 3. These values are independent of the origin of the charged particles. The energy fluence for each type of radiation is specified in $\text{J}\cdot\text{m}^2$.

Table 3 Energy fluence of corpuscular radiation

Std Orbit	Designation	Energy fluence, $\text{J}\cdot\text{m}^2$ per year		
		Electrons	Protons	Total
1	MIR	$4.6\cdot 10^2$	11	$4.7\cdot 10^2$
2	ISS	$8.6\cdot 10^2$	36	$8.6\cdot 10^2$
3	GEO	$9.8\cdot 10^5$	$3.8\cdot 10^4$	$1.0\cdot 10^6$
4	GLON	$8.3\cdot 10^5$	$2.6\cdot 10^5$	$1.1\cdot 10^6$
5	HEO	$4.9\cdot 10^5$	$6.8\cdot 10^4$	$5.6\cdot 10^5$
6	POL	$2.3\cdot 10^3$	$1.0\cdot 10^2$	$2.4\cdot 10^3$

Note. Electrons with energy lower than 100 keV and protons with energy lower than 500 keV were not taken into account for MIR, ISS and POL orbits.

6.3.2. For corpuscular radiation reference values of absorbed doses in aluminium at the depth 1 mg/cm^2 for each of the specified orbits are listed in Table 4. These values are independent of the origin of the charged particles. The absorbed dose for each type of radiation is specified in Gy per year.

Table 4 Absorbed dose of corpuscular radiation in aluminium at the depth 1 mg/cm^2

Std Orbit	Designation	Absorbed dose, Gy per year		
		Electrons	Protons	Total
1	MIR	$6.4\cdot 10^2$	$1.5\cdot 10^1$	$6.6\cdot 10^2$
2	ISS	$1.2\cdot 10^3$	$4.8\cdot 10^1$	$1.2\cdot 10^3$
3	GEO	$5.4\cdot 10^5$	$8.3\cdot 10^6$	$8.8\cdot 10^6$
4	GLON	$3.8\cdot 10^5$	$2.0\cdot 10^6$	$2.4\cdot 10^6$
5	HEO	$2.6\cdot 10^5$	$3.1\cdot 10^5$	$5.7\cdot 10^5$
6	POL	$2.5\cdot 10^3$	$3.0\cdot 10^2$	$2.8\cdot 10^3$

6.3.3 Simulation of space environment at radiation tests of the materials should take into account the characteristics of the orbits from the Tables 1, 3 and 4, which are the closest to the actual orbit of a particular space vehicle.

6.3.4 For the orbits not included in Tables 1, 3 and 4 (such as higher Earth orbits, interplanetary missions, and other deep space flights), it is necessary to make special calculations of energy fluences.

7 Properties of spacecraft materials

7.1. 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.

7.2. Surface properties

7.2.1. Surface properties are determined by the nature of the material at or near the surface. Near the surface is considered to be approximately $4 \text{ mg}\cdot\text{cm}^{-2}$ or less. 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.

7.2.2. 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.

7.2.3. 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.

7.3. Volume (bulk) properties

7.3.1. 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.

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

7.4. Measure of radiation action

7.4.1. To study the first group of properties a measure of radiation action should be taken equal to the energy fluence of corpuscular radiation, J/m^2 , proceeding 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 Fig. A1 of the Annex A).

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

7.4.3. 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 B 2.10). The two measure approach of radiation action is applicable to the layers with more than $4 \text{ mg}/\text{cm}^2$ thickness on the space vehicle surface. The energy fluence is an only measure of radiation action on the layers of less than $4 \text{ mg}/\text{cm}^2$ thickness.

8 Requirements for simulation of space radiation

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

8.2. The following methodology is suggested for organizing space simulation tests:

8.2.1. Select the space environment factors for the specific mission and effects that are critical for performance and reliability of the material to be tested based on expected radiation effects on the material and depth dose profile.

8.2.2. Consider the induced environment factors that can influence the effects that are under investigation.

8.2.3. Determine the environments that must be accelerated and the acceptable acceleration rates that will not adversely affect the results.

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

8.2.5. Select the radiation sources for ground simulation.

8.2.6. Determine the energies and fluences for the radiation sources to closely simulate the depth dose profile that would occur in space.

8.2.7. The standard orbits in Table 1 and the standard radiation environments in Table 3 should be considered first for the selection of the applicable space environments for testing.

8.2.8. 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.

8.2.9. 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.

8.2.10. A detailed analysis of the space radiation environment and absorbed dose profile for a particular orbit, mission life time, 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.

8.3. Methodology for simulation involves simulation of the type of radiation, its spectrum and intensity.

8.3.1. 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.

8.3.1.1. 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.

8.3.1.2. For protons and electrons of high energy that cause degradation of the material volume properties, it is permissible to replace one kind of ionizing radiation by another if technically more feasible and the effects can be duplicated. This approach is based on the examination of radiation-chemical yields dependence on the effects of various types of ionizing radiation on different organic materials.

8.3.1.3. Such replacement is possible by introducing special absorbed dose equivalence coefficient independent of the property of a material. The absorbed dose equivalence

coefficient, k , relates the absorbed dose of one type of radiation with that of another. In the course of simulation, the absorbed dose, D_1 , of simulated radiation is k times higher than a specific absorbed dose of natural radiation in space, D_2 . The relationship is defined in the following equation:

$$D_1 = kD_2$$

Table 5 shows the absorbed dose equivalence coefficient for various types of radiation.

Table 5 Absorbed Dose Equivalence Coefficient

Type of Simulated Radiation	Coefficient k for Simulated Radiation			
	Bremsstrahlung	Gamma	Electrons	Protons
Bremsstrahlung ($E \leq 100$ keV)	1.0	1.5	1.5	2.0
Gamma or bremsstrahlung ($E \geq 100$ keV)	1.5	1.0	1.0	2.0
Electrons ($E \geq 100$ keV)	1.5	1.0	1.0	2.0
Protons ($E \geq 1.0$ MeV)	1.5	2.0	2.0	1.0

8.3.1.4. At simulation of mixed radiation consisting of n components by one monoenergetic kind of radiation, a maximum absorbed dose of the simulating radiation is established from the following expression

$$D_1 = \sum_{i=1}^n k_i D_{2,i} ,$$

where D_{2i} is the absorbed dose from the i -th component of the simulated radiation; k_i are the appropriate absorbed dose equivalence coefficients from the Table 5.

8.3.1.5 Such way of ionizing radiation simulation is only applicable when maximum permissible irreversible changes of the material properties under radiation exposure are not less than the values, listed in the table 6 for various classes of non-metallic materials.

Table 6. Maximum permissible changes, d , of the properties of polymeric materials as a percentage of the initial value

Property of material	Value of d , %
Structural materials	
Strength at a break (bending, compression, shear)	-50
Relative elongation at a rupture	from -50 up to +100
Modulus of elasticity at tension	-50
Impact viscosity	-50
Electrical insulation materials	
Specific volume and surface electrical resistance	-90
Tangent of dielectric loss angle in the range of frequencies 10^3 - 10^{10} Hz	From +50 up to +100
Permeability of dielectric in the range of frequencies 10^3 - 10^{10} Hz	From ± 10 up to ± 30
Electric strength	-50

8.3.1.6. It is not permitted to replace one kind of radiation by another through the tests of reversible changes of properties.

8.3.2. 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 first way is most important.

8.3.2.1. The largest drop in the dose depth profile occurs in the near-the-surface layers (see Figure. A1 in Annex A). 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.

8.3.2.2. The assessment of reliable simulation of the radiation spectrum is made by introducing a numerical characteristic of depth dose profile in a material.

8.3.2.3. 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 A2 of Annex A).

8.3.2.4. 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 μ/ρ , calculated for standard spectra of ionizing radiation, are given in Table A3 of Annex A.

8.3.2.5. For simulation, depth dose profile for the tested material shall be calculated up to the depth of 100 to 150 μm for both the space environment and test conditions. The depth dose profiles shall be presented in the form of two exponents, as described in items 8.3.2.3 and 8.3.2.4.

8.3.2.6. 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.

8.3.2.7. 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 (Ref. B2.14). The recommended permissible difference between the μ/ρ values for the adjustment process is about 30%.

8.3.2.8. It is necessary to perform the calculations using the same mathematical code and the same geometry of particle incidence for both the space and simulated space radiation environments.

8.3.2.9. For electrons, the Tiger-P code is recommended. The Tiger-P code is found in the code package ITS 3.0 Sandia National Laboratories (Ref. B2.15) and is based on the Monte-Carlo method.

8.3.3. 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.

8.3.3.1. 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 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.

8.3.3.2. The range of operating temperatures on a surface of a space vehicle are 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.

8.3.3.3. It is permissible to conduct accelerated radiation tests *in vacuo* with a recommended residual pressure not higher than 10^{-2} to 10^{-3} Pa. However, 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, defined in item 8.3.3.1.

8.3.3.4. Dissolved oxygen can react with materials to produce chemical changes that are different from the material experiences in space when irradiated. Radiolysis products resulting from irradiation may react with the oxygen. IEC 544.2 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.

8.3.3.5. 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, should be 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.

8.3.3.6. It is permissible to conduct accelerated tests for the effects of FUV exposure of nonmetallic materials at acceleration factors up to 10^3 . The maximum increase of the sample temperature 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.

8.3.3.7. 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.

8.3.3.8. 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.

8.3.3.9. 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 from above the dose rates at on-ground tests.

9. Radiation sources for simulation

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

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

9.1.2. 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.

9.2. 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.

9.3. Low energy protons can be produced using accelerators in the energy range of 10 keV to 2 MeV.

9.4. Low energy electrons can be produced using accelerators in the energy range of 10 keV to 1 MeV.

9.5. High-energy proton accelerators operate in the energy range of 20 to 400 MeV.

9.6. High-energy electron accelerators provide particles with energies greater than 1 MeV.

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

9.8. To obtain a uniform field of protons with mean energies of 0,5 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.

9.9. Ultraviolet radiation

9.9.1. For the simulation of far ultraviolet radiation effects, sources of optical radiation in the wavelength range of 10 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.

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

Annex A
Additional Information
(Informative)

A1. Space radiation environment

A1.1. 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 50 keV, solar X-radiation, FUV, and NUV).

A1.2. 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 (B2.2) and (B2.3).

A1.3. There are no similar models for low energy electrons and protons. Energy characteristics of low energy protons for a geosynchronous orbit are presented in References B2.4 and B2.5. References B2.6 and B2.7 present data on low energy electrons for a geosynchronous orbit.

A1.4. Absorbed doses on the surface of a vehicle and behind a shield ($1 \text{ g}\cdot\text{cm}^{-2}$) are listed in Table A1, Reference (B2.1).

Table A1. Absorbed Doses from Space Sources of Ionizing Radiation for Earth Orbits

Type of radiation	Energy, MeV	Annual dose, Gy (1 J/kg)	
		on surface	behind shield, 1 g/cm ²
Galactic Cosmic Rays (GCR)			
Protons	10 ² - 10 ³	0,01 - 0.1	0,01 - 0,1
Solar Particle Radiation			
Protons	20 - 10 ³	10 - 10 ²	1 - 10
Electrons	0,05	10 ² - 10 ⁵	0
Bremsstrahlung	0,05	0,01- 1	0,01 - 1
Inner Radiation Belt			
Protons	10 ⁻³ - 7•10 ²	10 ⁸	10 ³
Electrons	0,02 - 1	10 ¹⁰	0
Bremsstrahlung	0,02 - 1	10 ³	10 ³ - 10 ⁴
Outer Radiation Belt			
Protons	up to 60		
Electrons	0,02 - 5	10 ⁹ - 10 ¹¹	10
Bremsstrahlung	0,02 - 5	10 ³ - 10 ⁵	10 ² - 10 ⁴

A2. Dose depth profile

A2.1. Table A2 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 A2. Space Radiation Absorbed Dose at Various Shielding Depths on Satellite Cosmos 1887 (%) (from Ref. B2.9)

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

A2.2. Table A3 shows examples of the depth distribution criterion, μ/ρ , for various standard orbits and three materials.

Table A3 Depth Distribution Criterion of Absorbed Dose

Orbit	Standard Orbit	(m/r) ₁ , cm ² /g	(m/r) ₂ , cm ² /g
1	LEO (2)	$4,0 \cdot 10^3$	$1,30 \cdot 10^2$
2	GEO (1)	$3,0 \cdot 10^3$	$1,22 \cdot 10^2$
3	GLON (2)	$3,1 \cdot 10^3$	$0,53 \cdot 10^2$
4	HEO (2)	$4,6 \cdot 10^3$	$0,46 \cdot 10^2$
5	POL (3)	$4,2 \cdot 10^3$	$1,46 \cdot 10^2$
6	GEO (2)	$2,5 \cdot 10^3$	$0,41 \cdot 10^2$

Notes:

- (1) For kapton, assuming isotropic incidence.
- (2) For aluminum, assuming normal incidence.
- (3) For cerium glass, assuming isotropic incidence.

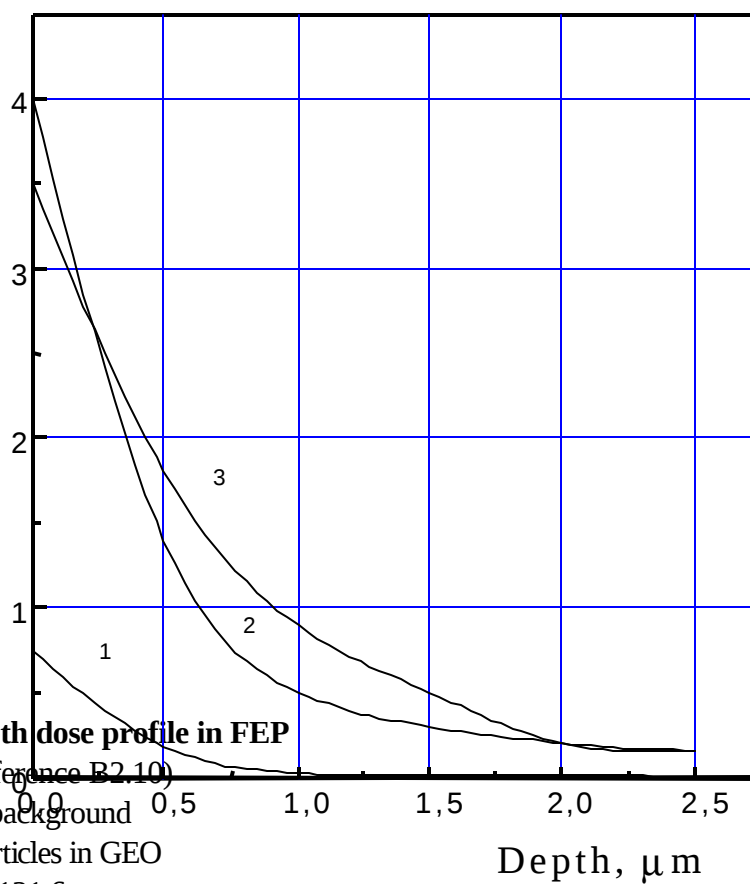
A2.3. Figure A1 (Ref. B2.10) shows depth dose profiles for three types of space radiation in FEP exposed in a standard GEO orbit. The radiation consists of galactic cosmic rays (GCR), charged particles in the radiation belt (electrons and protons), and far ultraviolet (Ly- α at 121.6 nm). The larger depth dose profiles occur from the FUV and the lower energy charged particles.

A2.4. Figure A2 (Ref. B2.19) shows the simulated depth dose profile for cerium glass in a POL orbit with altitude 800 km (opposite to the standard orbit POL). The depth dose profile is simulated using three different radiation sources: 200 keV electrons, 300 keV protons, and 50 keV protons. Curve 1 is the depth dose profile for the total spectrum in the POL orbit.

A2.5. Figure A3 shows the simulated depth dose profiles for two standard orbits, GEO and POL (800 km altitude), and for two materials, kapton film (Ref. B2.12) and cerium glass (Ref. B2.13).

The depth dose profiles can be approximated by a sum of two exponential depth dose profiles using the ratio of the depth distribution criterion, μ , to the material density, ρ .

Dose rate, Gy/sec

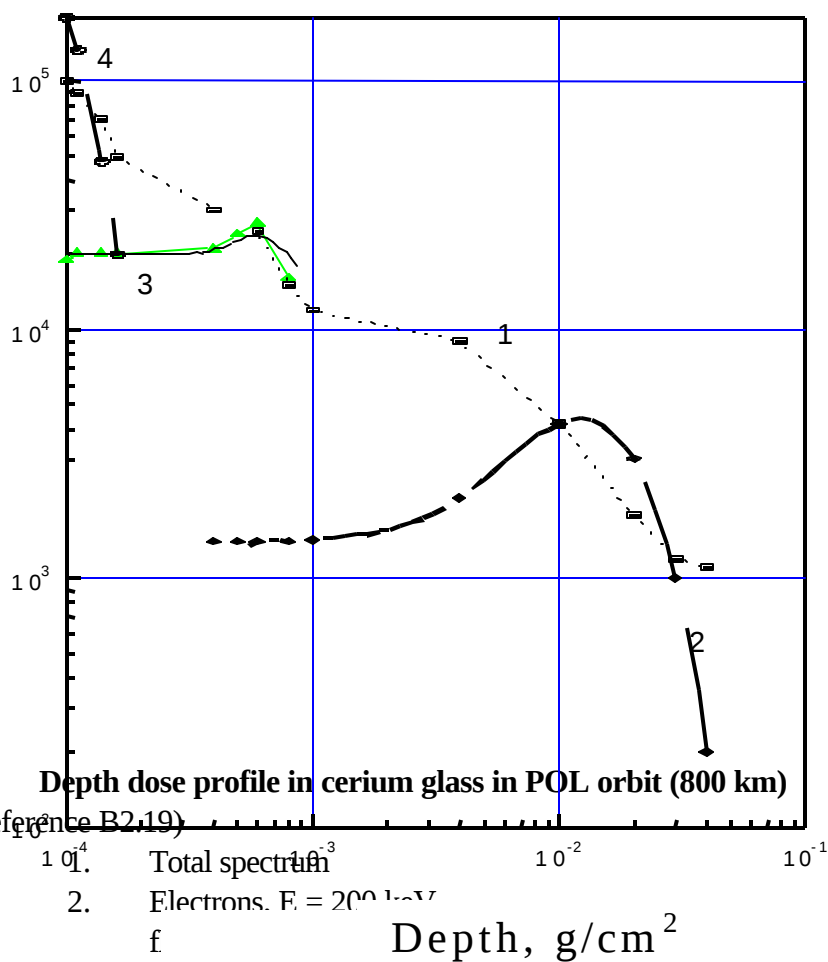
**Figure A1.****Depth dose profile in FEP**

(Reference B2.10)

- 1 Soft X-ray background
- 2 Charged particles in GEO
- 3 FUV, L_{α} at 121.6 nm

Depth, μm

Absorbed dose, Gy per year



Absorbed dose, Gy per year

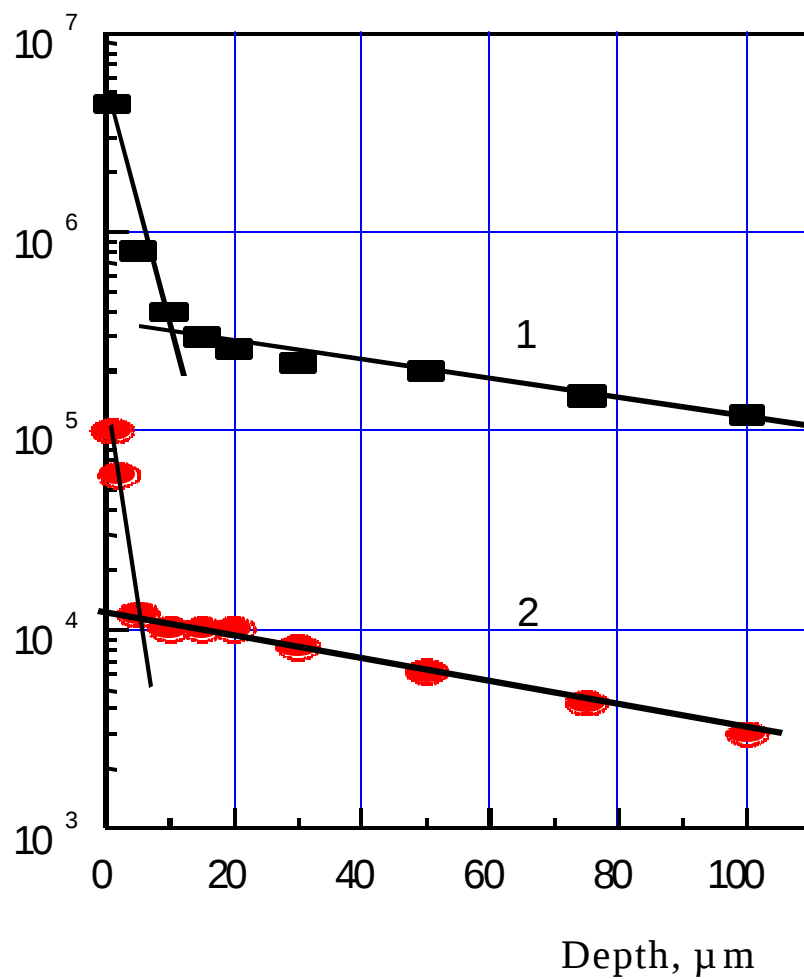


Figure A3. Simulated depth dose profiles

- 1 Polyimide film, GEO orbit, 0° inclination, 160° western longitude (Ref. B2.12)
- 2 Cerium glass, POL orbit, 800 km altitude (Ref. B2.13)

Annex B (Informative) Bibliography

B1. Standards

B1.1. ASTM standards

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B1.1.2. E 349, *Terminology Relating to Space Simulation.*

B1.1.3. E 490, *Solar Constant and Air Mass Zero Solar Spectral Irradiance Tables,*

B1.1.4. E 491, *Practice for Solar Simulation for Thermal Balance Testing of Spacecraft.*

B1.1.5. E 170, *Standard Terminology Relating to Radiation Measurements and Dosimetry.*

B1.1.6. E 1027, *Standard Practice for Exposure of Polymeric Materials to Ionizing Radiation.*

B1.1.7. E 1420, *Standard Practice for Specifying Polymeric Materials for Service in Ionizing Radiation Environments.*

B1.2. ECSS/European Space Agency Standards

B1.2.1. ESA PSS-01-70, *Material and Process Selection and Quality Control for ESA Spacecraft and Associated Equipment.*

B1.2.2. ESA PSS-01-702, *A Thermal Vacuum Test for the Screening of Space Materials.*

B1.2.3. ESA PSS-01-704, *A Thermal Cycling Test for the Screening of Space Materials and Processes.*

B1.2.4. ESA PSS-01-706, *The Particle and Ultraviolet (UV) Radiation Testing of Space Materials.*

B1.3. Russian standards

B1.3.1. GOST 9.706, *Polymeric materials. Test methods for resistance to radiation aging.*

B1.3.2. GOST 9.711, *Polymeric materials for technical elements in conditions of radiation aging. General demands for selection.*

B1.3.3. GOST 25645.321, *Radiation resistance of polymeric materials. Terms and definitions.*

B1.3.4. GOST 25645.323, *Polymeric materials. Radiation test methods.*

B1.3.5. GOST 25645.331, *Polymeric materials. Demands to estimation of radiation resistance.*

B1.3.6. GOST R 25645.332, *Polymeric materials for spacecraft with nuclear reactor. Requirements for radiation tests.*

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