EUROPEAN COOPERATION FOR SPACE STANDARDIZATION

Space Engineering

Methods for the calculation of radiation received and its effects, and a policy for design margins

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This Standard is one of the series of ECSS Standards intended to be applied together for the management, engineering and product assurance in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards.

Requirements in this Standard are defined in terms of what shall be accomplished, rather than in terms of how to organize and perform the necessary work. This allows existing organizational structures and methods to be applied where they are effective, and for the structures and methods to evolve as necessary without rewriting the standards.

The formulation of this Standard takes into account the existing ISO 9000 family of documents.

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Change log

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1. Scope

This standard is a part of the System Engineering branch of the ECSS engineering standards and covers the methods for the calculation of radiation received and its effects, and a policy for design margins. Both natural and man-made sources of radiation (*e.g.* radioisotope thermoelectric generators, or RTGs) are considered in the standard.

This standard applies to the evaluation of radiation effects on all space systems.

This standard applies to all product types which exist or operate in space, as well as to crews of on manned space missions. The standard aims to implement a space system engineering process that ensures common understanding by participants in the development and operation process (including Agencies, customers, suppliers, and developers) and use of common methods in evaluation of radiation effects.

This standard is complemented by ECSS-E-HB-10-12A "Radiation received and its effects and margin policy handbook".

2. Normative references

The following dated normative documents are called by the requirements of this ECSS Standard and therefore constitute requirements to it. Subsequent amendments to, or revisions of any of these publications do not apply.

NOTE However, parties to agreements based on this ECSS Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated be-low.

ECSS-P-001A	ECSS – Glossary of terms
ECSS-E-10-04	Space engineering - Space Environment
ECSS-E-10-11A	Space engineering - Human Factors engineering
ECSS-E-20B	Space engineering – Electric and electronic
ECSS-E-20-08	Space engineering - Photovoltaic Assemblies and Components
ECSS-E-30 Part 4A	Space engineering - Mechanical – Part 4 Environmental control and life support
ECSS-E-30 Part 8A	Space engineering - Mechanical – Part 8 Materials
ECSS-Q-30-01A	Space product assurance - Worst case circuit performance analysis
ECSS-Q-60A	Space product assurance - Electronic Components
ECSS-Q-60-XX[1]	Space product assurance - Radiation Hardness Assurance
ECSS-Q-60-11A	Space product assurance - Derating and end-of-life parameter drifts

[1] To be published

3. Terms, definitions and abbreviated terms

3.1. Terms from other standards

The following terms and definitions are specific to this Standard in the sense that they are complementary or additional to those contained in ECSS-P-001.

Derating

Subsystem

3.2. Terms and definitions specific to the present Standard

3.2.1. absorbed dose

energy absorbed locally per unit mass as a result of radiation exposure which is transferred through ionisation, displacement damage and excitation and is the sum of the ionising dose and non-ionising dose.

NOTE 1 It is normally represented by D, and in accordance with the definition, it can be calculated as the quotient of the energy imparted due to radiation in the matter in a volume element and the mass of the matter in that volume element. It is measured in units of gray, Gy (1 Gy = 1 J kg^{-1} (= 100 rad)).

NOTE 2 The absorbes dose is the basic physical quantity that measures radiation exposure.

3.2.2. air kerma

energy of charged particles released by photons per unit a mass of dry air

NOTE It is normally represented by K.

3.2.3. ambient dose equivalent, H*(d)

dose at a point equivalent to the one produced by the corresponding expanded and aligned radiation field in the ICRU sphere at a specific depth on the radius opposing the direction of the aligned field

NOTE 1 It is normally represented by H*(d), where d is the specific depth used in its definition, in mm.

NOTE 2 $H^*(d)$ is relevant to strongly penetrating radiation. The value normally used is 10 mm, but dose equivalent at other depths can be used when the dose equivalent at 10 mm provides an unacceptable underestimate of the effective dose.

3.2.4. bremsstrahlung

high energy electromagnetic radiation in the X-ray energy range emitted by charged particles slowing down by scattering of atomic nuclei

NOTE The primary particle is ultimately absorbed while the bremsstrahlung can be highly penetrating. In space the most common source of bremsstrahlung is electron scattering.

3.2.5. component

device that performs a function and consists of one or more elements joined together and which cannot be disassembled without destruction

3.2.6. continuous slowing down approximation range (CSDA)

integral pathlength travelled by charged particles in a material assuming no stochastic variations between different particles of the same energy, and no angular deflections of the particles

3.2.7. COTS

commercial electronic component readily available off-the-shelf, and not manufactured, inspected or tested in accordance with military or space standards

3.2.8. critical charge

minimum amount of charge collected at a sensitive node due to a charged particle strike that results in a SEE

3.2.9. cross-section

<single event phenomena>

probability of a single event effect occurring per unit incident particle fluence

NOTE This is experimentally measured as the number of events recorded per unit fluence.

<nuclear or electromagnetic physics>

probability of a particle interaction per unit incident particle fluence

NOTE It is sometimes referred to as the *microscopic cross-section*. Other related definition is the macroscopic cross section, defines as the probability of an interaction per unit path-length of the particle in a material.

3.2.10. directional dose equivalent

dose at a point equivalent to the one produced by the corresponding expanded radiation field in the ICRU sphere at a specific depth d on a radius on a specified direction

NOTE 1 It is normally expressed as $H'(d, \Omega)$, where d is the specific depth used in its definition, in mm, and Ω is the direction.

NOTE 2 $H'(d,\Omega)$, is relevant to weakly-penetrating radiation where a reference depth of 0,07 mm is usually used and the quantity denoted $H'(0,07, \Omega)$.

3.2.11. displacement damage

crystal structure damage caused when particles lose energy by elastic or inelastic collisions in a material

3.2.12. dose

quantity of radiation delivered at a position.

NOTE 1 In its broadest sense this can include the flux of particles, but in the context of space energetic particle radiation effects, it usually refers to the energy absorbed locally per unit mass as a result of radiation exposure.

NOTE 2 If "dose" is used unqualified, it refers to both ionising and non-ionising dose. Non-ionising dose can be quantified either through energy deposition via displacement damage or damage-equivalent fluence (see Clause 8).

3.2.13. dose equivalent

absorbed dose at a point in tissue which is weighted by quality factors which are related to the LET distribution of the radiation at that point

3.2.14. dose rate

rate at which radiation is delivered per unit time

3.2.15. effective dose

sum of the equivalent doses for all irradiated tissues or organs, each weighted by its own value of tissue weighting factor.

NOTE 1 It is normally represented by E, and in accordance with the definition it is calculated with the equation (1) below, and the w_T is specified in the ICRP-92 standard [RDH.22] (For further discussion on E, see ECSS-E-HB-10-12A Clause 10.2.2:

$$E = \sum w_T \cdot H_T \qquad (1)$$

NOTE 2 Effective dose, like organ equivalent dose, is measured in units of sievert, Sv. Occasionally this use of the same unit for different quantities can give rise to confusion.

3.2.16. energetic particle

particle which, in the context of space systems radiation effects, can penetrate outer surfaces of spacecraft.

3.2.17. equivalent dose

See 3.2.36 (organ equivalent dose)

3.2.18. equivalent fluence

quantity which represents the damage at different energies and from different species by a fluence of monoenergetic particles of a single species

NOTE 1 These are usually derived through testing.

NOTE 2 Damage coefficients are used to scale the effect caused by particles to the damage caused by a standard particle and energy.

3.2.19. extrapolated range

range determined by extrapolating the line of maximum gradient in the intensity curve until it reaches zero intensity

3.2.20. fluence

time-integration of flux

NOTE It is normally represented by Φ.

3.2.21. flux

<unidirectional incident particles>

number of particles crossing a surface at right angles to the particle direction, per unit area per unit time

<arbitrary angular distributions>

number of particles crossing a sphere of unit cross-sectional area (*i.e.* of radius $1/\sqrt{\pi}$) per unit time.

NOTE 1 For arbitrary angular distributions, it is normally known as omnidirectional flux.

NOTE 2 Flux is often expressed in "integral form" as particles per unit time (*e.g.* electrons cm^{-2} s^{-1}) above a certain energy threshold.

NOTE 3 The directional flux is the differential with respect to solid angle (*e.g.* particles-cm^{-2}steradian^{-1}s^{-1}) while the "differential" flux is differential with respect to energy (*e.g.* particles-$cm^{-2}$$MeV^{-1}$$s^{-1}$). In some cases fluxes are treated as a differential with respect to linear energy transfer rather than energy.

3.2.22. ICRU sphere

sphere of 30 cm diameter made of tissue equivalent material with a density of 1 g/cm^3 and a mass composition of 76.2 % oxygen, 11.1 % carbon, 10.1 % hydrogen and 2.6 % nitrogen.

3.2.23. ionising dose

amount of energy per unit mass transferred by particles to a target material in the form of ionisation and excitation

3.2.24. ionising radiation

transfer of energy by means of particles where the particle has sufficient energy to remove electrons, or undergo elastic or inelastic interactions with nuclei (including displacement of atoms), and in the context of this standard includes photons in the X-ray energy band and above

3.2.25. isotropic

property of a distribution of particles where the flux is constant over all directions

3.2.26. L or L-shell

parameter of the geomagnetic field often used to describe positions in near-Earth space

NOTE L or L-shell has a complicated derivation based on an invariant of the motion of charged particles in the terrestrial magnetic field. However it is useful in defining plasma regimes within the magnetosphere because, for a dipole magnetic field, it is equal to the geocentric altitude in Earth-radii of the local magnetic field line where it crosses the equator.

3.2.27. linear energy transfer (LET)

rate of energy deposited through ionisation from a slowing energetic particle with distance travelled in matter, the energy being imparted to the material

NOTE 1 LET is normally used to describe the ionisation track caused by passage of an ion. LET is material dependent and is also a function of particle energy and charge. For ions involved in space radiation effects, it increases with decreasing energy (it also increases at high energies, beyond the minimum ionising energy). LET allows different ions to be considered together by simply representing the ion environment as the summation of the fluxes of all ions as functions of their LETs. This simplifies single-event upset calculation. The rate of energy loss of a particle, which also includes emitted secondary radiations, is the stopping power.

NOTE 2 LET is not equal to (but is often approximated to) particle electronic stopping power, which is the energy loss by ionisation and excitation per unit pathlength.

3.2.28. margin

factor or difference between the design environment specification for a device or product and the environment at which unacceptable behaviour occurs

3.2.29. mean organ absorbed dose

energy absorbed by an organ by ionising radiation divided by its mass

NOTE It is normally represented by DT, and in accordance with the definition, it is calculated with the equation (35) in ECSS-E-HB-10-12A Clause 10.2.2. The unit is the gray (Gy), being 1 Gy = 1 joule / kg.

3.2.30. mean range

integral pathlength travelled by particles in a material after which the intensity is reduced by a factor of two

NOTE In accordance with the above definition, it is not the range at which all particles are stopped.

3.2.31. multiple bit upset (MBU)

set of bits corrupted in a digital element that have been caused by direct ionisation from a single traversing particle or by recoiling nuclei from a nuclear interaction

NOTE MCU and SMU are special cases of MBU.

3.2.32. multiple cell upset (MCU)

set of physically adjacent bits corrupted in a digital element that have been caused by direct ionisation from a single traversing particle or by recoiling nuclei from a nuclear interaction

3.2.33. (total) non-ionising dose, (T)NID, or non-ionising energy loss (NIEL) dose

energy absorption per unit mass of material which results in damage to the lattice structure of solids through displacement of atoms

NOTE Although the SI unit of TNID or NIEL dose is the gray (see 3.2.29), for spacecraft radiation effects, MeV/g(material) is more commonly used in order to avoid confusion with ionising energy deposition, *e.g.* MeV/g(Si) for TNID in silicon.

3.2.34. NIEL or NIEL rate or NIEL coefficient

rate of energy loss in a material by a particle due to displacement damage per unit pathlength

3.2.35. omnidirectional flux

scalar integral of the flux over all directions

NOTE This implies that no consideration is taken of the directional distribution of the particles which can be non-isotropic. The flux at a point is the number of particles crossing a sphere of unit cross-sectional surface area (*i.e.* of radius $1/\sqrt{\pi}$) per unit time. An omnidirectional flux is not to be confused with an isotropic flux.

3.2.36. organ equivalent dose

sum of each contribution of the absorbed dose by a tissue or an organ exposed to several radiation types, weighted by the each radiation weighting factor for the radiations impinging on the body.

(ICRP-60-defined quantity.)

NOTE 1 The organ equivalent dose is normally represented by H_T, and usually shortened to **equivalent dose.** In accordance with the definition, it is calculated with the equation (2) below (for further discussion, see ECSS-E-HB-10-12A Clause 10.2.2):

$$H_T = \sum w_R \cdot D_{T;R} \qquad (2)$$

NOTE 2 The organ equivalent dose is measured in units of sievert, Sv, where 1 Sv = 1 J/kg. The unit rem (roentgen equivalent man) is still used, where 1 Sv = 100 rem.

3.2.37. personal dose equivalent (individual dose equivalent)

dose equivalent in ICRU soft tissue at a depth in the body.

NOTE 1 It is normally represented by $H_P(d)$ for strongly penetrating radition at a depth d in millimetres that is appropriate for strongly penetrating radiation. A reference depth of 10 mm is usually used. It varies both as a function of individuals and location and is appropriate for organs and tissues deeply situated in the body.

NOTE 2 It is normally represented by $H_s(d)$ for weakly penetrating radiation (superficial) at a depth d in millimetres that is appropriate for weakly penetrating radiation. A reference depth of 0,07 mm is usually used. It varies both as a function of individuals and location and is appropriate for superficial organs and tissues which will be irradiated by both weakly and strongly penetrating radiation.

3.2.38. plasma

partly or wholly ionised gas whose particles exhibit collective response to magnetic or electric fields

NOTE The collective motion is brought about by the electrostatic Coulomb force between charged particles. This causes the particles to rearrange themselves to counteract electric fields within a distance of the order of the Debye length. On spatial scales larger than the Debye length plasmas are electrically neutral.

3.2.39. projected range

average depth of penetration of a particle measured along the initial direction of the particle

3.2.40. quality factor

factor accounting for the different biological efficiencies of ionising radiation with different LET, and used to convert the absorbed dose to operational parameters (ambient dose equivalent, directional dose equivalent and personal dose equivalent)

NOTE 1 Quality factor, normally represented by *Q*, are used (rather than radiation or tissue weighting factors) to convert the absorbed dose to dose equivalent quantities described above (ambient dose equivalent, directional dose equivalent and personal dose equivalent). Its actual values are given by ICPR (see 11.2.3.2).

NOTE 2 Prior to ICRP-60, quality factors were synonymous to radiation weighting factors.

3.2.41. radiation

transfer of energy by means of a particle (including photons)

NOTE In the context of this Standard, electromagnetic radiation below the X-ray band is excluded. This therefore excludes UV, visible, thermal, microwave and radiowave radiation.

3.2.42. radiation design margin (RDM)

<cumulative process>

ratio of the radiation tolerance or capability of the component, system or protection limit for astronaut, to the predicted radiation environment for the mission or phase of the mission

NOTE The component tolerance or capability, above which its performance becomes non-compliant, is project-defined.

<non-destructive single event>

ratio of the design SEE tolerance to the predicted SEE rate for the environment

NOTE The design SSE tolerance is the acceptable SEE rate which the equipment or mission can experience while still meeting the equipment reliability and availability requirements.

<destructive single event>

ratio of the acceptable probability of component failure by the SEE mechanism to the calculated probability of failure

NOTE the acceptable probability of component failure is based on the equipment reliability and availability specifications.

<biological effect>

ratio of the protection limits defined by the project for the mission to the predicted exposure for the crew

3.2.43. radiation weighting factor

factor accounting for the different levels of radiation effects in biological material for different radiations at the same absorbed dose

NOTE It is normally represented by w_R. Its value is defined by ICPR (see 11.2.2.2).

3.2.44. relative biological effectiveness (RBE)

inverse ratio of the absorbed dose from one radiation type to that of a reference radiation that produces the same radiation effect

NOTE 1 The radiation type is usually ^{60}Co or 200-250 keV X-rays.

NOTE 2 In contrast to the weighting or quality factors, RBE is an empirically founded measurable quantity. For additional information on RBE, see ECSS-E-HB-10-12A Clause 10.2.2.

3.2.45. sensitive volume (SV)

charge collection region of a device

3.2.46. single event burnout (SEB)

destructive triggering of a vertical n-channel transistor accompanied by regenerative feedback

3.2.47. single event dielectric rupture (SEDR)

formation of a conducting path triggered by a single ionising particle in a high-field region of a dielectric

NOTE For example, in linear devices, or in FPGAs.

3.2.48. single event disturb (SED)

momentary voltage excursion (voltage spike) at a node in an integrated circuit, originally formed by the electric field separation of the charge generated by an ion passing through or near a junction

NOTE SED is similar to SET, but used to refer to such events in digital microelectronics.

3.2.49. single event effect (SEE)

effect caused either by direct ionisation from a single traversing particle or by recoiling nuclei emitted from a nuclear interaction

3.2.50. single event functional interrupt (SEFI)

interrupt caused by a single particle strike which leads to a temporary non-functionality (or interruption of normal operation) of the affected device

3.2.51. single event gate rupture (SEGR)

formation of a conducting path triggered by a single ionising particle in a high-field region of a gate oxide

3.2.52. single event hard error (SEHE)

unalterable change of state associated with semi-permanent damage to a memory cell from a single ion track

3.2.53. single event latch-up (SEL)

potentially destructive triggering of a parasitic PNPN thyristor structure in a device

3.2.54. single event snapback (SESB)

event that occurs when the parasitic bipolar transistor that exists between the drain and source of a MOS transistor amplifies the avalanche current that results from a heavy ion

3.2.55. single event transient (SET)

momentary voltage excursion (voltage spike) at a node in an integrated circuit, originally formed by the electric field separation of the charge generated by an ion passing through or near a junction

3.2.56. single event upset (SEU)

single bit flip in a digital element that has been caused either by direct ionisation from a traversing particle or by recoiling nuclei emitted from a nuclear interaction

3.2.57. single word multiple bit upset (SMU)

set of logically adjacent bits corrupted in a digital element caused by direct ionisation from a single traversing particle or by recoiling nuclei from a nuclear interaction

NOTE SMU are multiple bit upsets within a single data word.

3.2.58. solar energetic particle event (SEPE)

emission of energetic protons or heavier nuclei from the Sun within a short space of time (hours to days) leading to particle flux enhancement

NOTE SEPE are usually associated with solar flares (with accompanying photon emission in optical, UV and X-Ray) or coronal mass ejections.

3.2.59. stopping power

average rate of energy-loss by a given particle per unit pathlength traversed through a given material

NOTE The following are consequence of the above definition:

- **collision stopping power**: (electrons and positrons) average energy loss per unit pathlength due to inelastic Coulomb collisions with bound atomic electrons resulting in ionisation and excitation.
- **radiative stopping power**: (electrons and positrons) average energy loss power unit pathlength due to emission of bremsstrahlung in the electric field of the atomic nucleus and of the atomic electrons.

- * **electronic stopping power**: (particles heavier than electrons) average energy loss per unit pathlength due to inelastic Coulomb collisions with atomic electrons resulting in ionisation and excitation.
- * **nuclear stopping power**: (particles heavier than electrons) average energy loss per unit pathlength due to inelastic and elastic Coulomb collisions with atomic nuclei in the material.

3.2.60. tissue weighting factor

factor that accounts for the different sensitivity of organs or tissue in expressing radiation effects to the same equivalent dose

NOTE It is normally represented by w_T, and its actual values are defined by ICPR (see 11.2.2.3).

3.2.61. total ionising dose

energy deposited per unit mass of material as a result of ionisation

NOTE The SI unit is the gray (see 3.2.29). However, the deprecated unit rad (radiation absorbed dose) is still used frequently (1 rad = 1 cGy).

3.3. Abbreviated terms

The following abbreviated terms are defined and used within this Standard:

Abbreviation	Meaning
ADC	analogue-to-digital converter
ALARA	as low as reasonably achievable
AMPTE	
APS	active pixel sensor
ASIC	application specific integrated circuit
BFO	blood-forming organ
BiCMOS	bipolar complementary metal oxide semiconductor
BJT	bipolar junction transistor
BRYNTRN	Baryon transport model
BTE	Boltzmann transport equation
CAM/CAF	computerized anatomical man/male / computerized anatomical female
CCD	charge coupled device
CCE	charge collection efficiency
CDR	critical design review
CEPXS/ONELD	One-dimensional Coupled Electron-Photon Multigroup Discrete Coordinates Code System
CERN	European Organisation for Nuclear Research
CGRO	Compton Gamma Ray Observatory

CID	charge injection device
CMOS	complementary metal oxide semiconductor
COMPTEL	CGRO Compton Telescope
COTS	commercial off-the-shelf
CREAM	Cosmic Radiation Effects and Activation Monitor (Space Shuttle experiment)
CEASE	compact environmental anomaly sensor
CREME	cosmic ray effects on microelectronics
CSA	Canadian Space Agency
CSDA	continuous slowing down approximation range
CTE	charge transfer efficiency
CTI	charge transfer inefficiency
CTR	current transfer ratio
CZT	cadmium zinc telluride (semiconductor material)
DAC	digital-to-analogue converter
DD	displacement damage
DDEF	displacement damage equivalent fluence
DDREF	dose and dose rate effectiveness factor
DNA	deoxyribonucleic acid
DOSRAD	software to predict space radiation dose at system and equipment level
DRAM	dynamic random access memory
DSP	digital signal processing
DUT	device under test
EEE	electrical and electronic engineering
EEPROM	electrically erasable programmable read only memory
EGS	Electron Gamma Shower Monte Carlo radiation transport code
ELDRS	enhanced low dose-rate sensitivity
EM	engineering model
EPIC	European Photon Imaging Camera on the ESA X-ray Multi-Mirror (XMM) mission
EPROM	erasable programmable read only memory
ESA	European Space Agency
ESABASE	engineering tool to support spacecraft mission and spacecraft platform design
ESD	electrostatic discharge
EVA	extravehicular activity
FASTRAD	sectoring analysis software for space radiation effects
FLUKA	Fluktuierende Kaskade (Fluctuating Cascade) Monte Carlo radiation transport code

FPGA	field programmable gate array
FM	flight model
GEANT	Geometry and Tracking Monte Carlo radiation transport code
GEO	geostationary Earth orbit
GOES	Geostationary Operational Environment Satellite
GRAS	Geant4 Radiation Analysis for Space
HERMES	3-D Monte Carlo radiation transport simulation code developed by Institut für Kernphysik Forschungszentrum Jülich GmbH
HETC	High Energy Transport Code
hFE	current gain of a bipolar transistor in common-emitter configuration
HPGe	high-purity germanium
HZE	particle of high atomic mass and high energy
IBIS	Imager on Board the INTEGRAL Satellite
IC	integrated circuit
ICRP	International Commission on Radiobiological Protection
ICRU	International Commission on Radiation Units and Measurements
IGBT	insulated gate bipolar transistor
IML1	International Microgravity Laboratory 1
INTEGRAL	International Gamma Ray Astrophysical Laboratory
IR	infrared
IRPP	integrated rectangular parallelepiped
IRTS	Integrated Radiation Transport Suite
ISO	Infrared Space Observatory
ISOCAM	ISO infrared Camera
ISS	International Space Station
ISSP	International Space Station Program
ITS	Integrated Tiger Series coupled electron-photon radiation transport codes
JAXA	Japan Aerospace Exploration Agency
JFET	junction field effect transistor
LDEF	Long Duration Exposure Facility
LEO	low Earth orbit
LED	light emitting diode
LET	linear energy transfer
LHI	Light Heavy Ion Transport code
LISA	Laser Interferometer Space Antenna
LNT	linear no-threshold

LOCOS	local oxidation of silicon
LWIR	long-wavelength infrared
MCP	microchannel plate
MCNP	Monte Carlo N-Particle Transport Code
MCNPX	Monte Carlo N-Particle Extended Transport Code
MCT	mercury cadmium telluride
MCU	multiple-cell upset
MEMS	micro-electromechanical structure
MEO	medium (altitude) Earth orbit
MICAP	Monte Carlo Ionization Chamber Analysis Package
MMOP	Multilateral Medical Operations Panel
MORSE	Multigroup Oak Ridge Stochastic Experiment – coupled neutron-g-ray Monte Carlo radiation transport code
MOS	metal oxide semiconductor
MOSFET	metal oxide semiconductor field effect transistor
MRHWG	Multilateral Radiation Health Working Group
MULASSIS	Multi-Layered Shielding Simulation Software
MWIR	medium-wavelength infrared
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection and Measurements
NID	non-ionising dose (identical to TNID)
NIEL	non-ionising energy loss
NMOS	N-channel metal oxide semiconductor
NOVICE	3-D Radiation transport simulation code developed by Experimental and Mathematical Physics Consultants, Gaithersburg, USA
NPN	bipolar junction transistor with P-type base
NUREG	Nuclear Regulatory Commission Regulation
OMERE	Radiation environment and effects code developed by TRAD with the support of CNES
OSSE	CGRO Oriented Scintillator Spectrometer Experiment
PCB	printed circuit board
PCC	part categorization criterion
PDR	preliminary design review
PIXIE	particle-induce X-ray emission
PLL	phase-locked loop
PMOS	P-channel metal oxide semiconductor
PMT	photomultiplier tube
PNP	bipolar junction transistor with N-type base

PNPN	deliberate or parasitic thyristor-like semiconductor structure (containing four, alternating P-type and N-type regions)
PPAC	parallel plate avalanche counter
PSR	Pacific-Sierra Research Corporation
PSTAR	stopping power and range tables for protons
PWM	pulse-width modulator
RBE	relative biological effectiveness
RC	resistor-capacitor
RDM	radiation design margin
RGS	reflection grating spectrometer
RHA	radiation hardness assurance
RPP	rectangular parallelepiped
RSA	Russian Space Agency
RTG	radio-isotope thermoelectric generator
RTS	random telegraph signal
SBD	surface barrier detector
SDRAM	synchronous dynamic random access memory
SHIELDOSE	space shielding radiation dose calculations
SEB	single event burnout
SED	single event disturb
SEDR	single event dielectric rupture
SEE	single event effect
SEFI	single event functional interrupt
SEGR	single event gate rupture
SEHE	single event hard error
SEL	single event latch-up
SEPE	solar energetic particle event
SESB	single event snapback
SET	single event transient
SEU	single event upset
SMART-1	Small Mission for Advanced Research and Technology
SMU	single word multiple-bit upset
SOHO	Solar and Heliospheric Observatory
SOI	silicon-on-insulator
SOS	silicon-on-sapphire
SPE	sole particle event
SPENVIS	Space Environment Information System
SPI	Spectrometer on INTEGRAL
SRAM	static random access memory

SREM	Standard Radiation Environment Monitor
SRIM	Stopping Power and Range of Ions in Matter
SSAT	Sector Shielding Analysis Tool
STRV	Space Technology Research Vehicle
SV	sensitive volume
SWIR	short wavelength infrared
TID	total ionising dose
TNID	total non-ionising dose
UNSCEAR	United Nation's Scientific Committee on the Effects of Atomic Radiation
USAF	United States Air Force
UV	ultraviolet
VLSI	very large scale integration
WCA	worst-case analysis
XMM	X-ray Multi Mirror Mission (also known as Newton)

4. Principles

4.1. Radiation Effects

This standard is applicable to all space systems. There is no space system in which radiation effects can be neglected.

In this section the word “component” refers not only to electronic components but also to other fundamental constituents of space hardware units and sub-systems such as solar cells, optical materials, adhesives, polymers, *etc*.

Survival and succesful operation of space systems in the space radiation environment, or the surface of other solar system bodies cannot be ensured without careful consideration of the effects of radiation. A comprehensive compendium of radiation effects is provided in ECSS-E-HB-10-12A Clause 3. The corresponding engineering process, including design of units and sub-systems, involves several trade-offs, one of which is radiation susceptibility. Some radiation effects can be mission limiting where they lead to a prompt or accumulated degradation which results in subsystem or system failure, or catastrophic system anomalies. Examples are damage of electronic components due to total ionising dose, or damaging interaction of a single heavy ion (thermal failure following "latch-up"). Others effects can be a source of interference, degrading the efficiency of the mission. Examples are radiation "background" in sensors or corruption of electronic memories. Biological effects are also important for manned and some other missions where biological samples are flown.

The correct evaluation of radiation effects occurs as early as possible in the design of systems, and is repeated throughout the development phase. A radiation environment specification is established and maintained as a mandatory element of any procurement actions from the start of a project (Pre-Phase A or other orbit trade-off pre-studies). The specification is specific to the mission and take account of the timing and duration of the mission, the nominal and transfer trajectories, and activities on non-terrestrial solar system bodies, employing the methods defined in ECSS-E-10-04. Upon any update to the radiation environment specification (*e.g.* as a result of orbit changes), a complete re-evaluation of the radiation effects calculations arising from this standard is performed.

In order to make a radiation effects evaluation, test data are used, both to confirm the compatibility of the component with the environment it is intended to operate in, and to provide data for quantitative analysis of the radiation effect. In general there is one effects parameter for each radiation effect. Severe engineering, schedule and cost problems can result from inadequate anticipation of space radiation effects and preparation of the engineering options and solutions.

In some cases, knowledge about the radiation effects on a particular component type can be found in the published literature or in databases on radiation effects. It is important to use these data with extreme caution since verifying that data are relevant to the actual component being employed is often very difficult. For example in evaluating electronic components, consideration is given to:

- variations in sensitivity between manufacturers' "batches";
- variations in sensitivity within a nominally identical manufacturing "batch";
- changes in manufacturing, processes, packaging;
- correlation of measurements made on the ground and in-flight experience is far from complete.

As a consequence, and to account for accumulated uncertainties in testing procedures, component-to-component variations and environmental uncertainties, margins are usually applied to the radiation effects parameters for the particular mission. This document also seeks to provide specification for when and how to apply such margins.

Application of margins can have important effects on the engineering. Too high a level, implying a severe environment, can imply change of components (leading to increased cost or degradation of performance), application of additional shielding or even orbit changes. On the other hand, too low a margin can result in compromised mission performance or premature failure.

Table 1: Stages of a project when radiation effects analysis shall be performed.

Phase	Activity
Pre-phase A	Environment specification for each mission option; Preliminary assessment of sensitivities and availability of components
A	Environment specification for baseline mission and options where they are retained for consideration Preliminary assessment of sensitivities and availability of components
B	Environment specification update; Space radiation hardness assurance requirements including detailed analysis of component requirements and identification of availability of susceptibility data; Establishment and execution of component test plan
C & D	Accurate shielding and radiation effects analysis (including component-specific analysis)[a] Consolidation of test results; augmented testing
E	Investigation of radiation effects; consideration of radiation effects in anomaly investigation; feedback to engineering groups of lessons learned including *e.g.* radiation related anomalies.
[a] If mission assumptions change in this phase, such as the proposed orbit, a complete re-evaluation of the radiation environment specification is performed.	

4.2. Radiation effects evaluation activities

Table 1 summarises the activities to be undertaken during a project. Effects on electrical and electronic systems, and materials are considered in terms of total ionising dose (TID), displacement damage, and single event effects (SEE). For spacecraft sensors, whether as part of the platform or payload, radiation-enhanced background levels are also considered. The user can find a general description of these radiation effects in ECSS-E-HB-10-12A Clause 3. Table 2 provides a summary, identifying the parameters used to quantify radiation effects, units and space radiation sources which induce those effects, whilst Table 3 identifies the effects as a function of component technology.

Table 2: Summary of radiation effects parameters, units and examples.

Effect	Parameter	Typical units	Examples	Particles
Total ionising dose (TID)	Ionising dose in material	grays (material) (Gy(material)) or rad(material) 1 Gy = 100 rad	Threshold voltage shift and leakage currents in CMOS, linear bipolar (note dose-rate sensitivity)	Electrons, protons, bremsstrahlung
Displacement damage	Displacement damage equivalent dose (total non-ionising dose) Equivalent fluence of 10 MeV protons or 1 MeV electrons	MeV/g cm^{-2}	All photonics, eg CCD transfer efficiency, optocoupler transfer ratio Reduction in solar cell efficiency	Protons, electrons, neutrons, ions
Single event effects	Events per unit fluence	cm^2 versus $MeV \cdot cm^2/mg$	Memories, microprocessors.	Ions Z>1

from direct ionisation	from linear energy transfer (LET) spectra & cross-section versus LET		Soft errors, latch-up, burn-out, gate rupture, transients in op-amps, comparators.	
Single event effects from nuclear reactions	Events per unit fluence from energy spectra & cross-section versus particle energy	cm^2 versus MeV	As above	Protons, neutrons, ions
Payload-specific radiation effects	Energy-loss spectra, charge-deposition spectra charging	counts s^{-1} MeV^{-1}	False count rates in detectors, false images in CCDs Gravity proof-masses	Protons, electrons, neutrons, ions, induced radioactivity (α, $\beta\pm$, γ)
Biological damage	Dose equivalent = Dose(tissue) x Quality Factor; equivalent dose = Dose(tissue) x radiation weighting factor; Effective dose	sieverts (Sv) or rems 1 Sv = 100 rem	DNA rupture, mutation, cell death	Ions, neutrons, protons, electrons, γ-rays, X-rays
Charging	Charge	coulombs (C)	Phantom commands from ESD	Electrons

Table 3: Summary of radiation effects and cross-references to other chapters (part 1 of 2)

Sub-system or component	Technology	Effect	Main Section Cross-reference	ECSS-E-HB-10-12A Cross-reference
Integrated circuits	Power MOS	TID SEGR SEB	Clause 7 Clause 9.4.1.6 Clause 9.4.1.6	Clause 6 Clause 8.6.2 Clause 8.6.3
	CMOS	TID SEE (generally)	Clause 7 Clause 9	Clause 6 Clause 8
	bipolar	TNID SEU SET TID	Clause 8 Clauses 9.4.1.2, 9.4.1.3 Clause 9.4.1.7 Clause 7	Clause 7.4.2 Clause 8.7.1 Clause 8.7.5 Clause 6
	BiCMOS	TID TNID SEE (generally)	Clause 7 Clause 8 Clause 9	Claise 6 Clause 7.4.2 Clause 8
	SOI	TID SEE (generally exc. SEL)	Clause 7 Clause 9	Clause 6 Clause 8
Optoelectronics and sensors (1)	MEMS [a]	TID	Clause 7	Clause 6
	CCD	TNID TID Enhanced background (SEE)	Clause 8 Clause 7 Clauses 10.4.2, 10.4.3, 10.4.5	Clause 7.4.3 Clause 6 Clauses 9.2, 9.4
	CMOS APS	TNID TID SEE (generally) Enhanced background	Clause 8 Clause 7 Clause 9 Clauses 10.4.2, 10.4.3, 10.4.5	Clause 7.4.4 Clause 6 Clause 8 Clauses 9.2, 9.4,
	Photodiodes	TNID TID SET	Clause 8 Clause 7 Clause 9.4.1.7	Clause 7.4.5 Clause 6 Clause 8.7.5
	LEDs	TNID	Clause 8	Clause 7.4.7
	laser LEDs	TNID	Clause 8	Clause 7.4.6
	Opto-couplers	TNID SET	Clause 8 Clause 9.4.1.7	Clause 7.4.8 Clause 8.7.5
	γ-ray or X-ray scintillator	TNID (alkali halides) Enhanced background	Clause 8 Clauses 10.4.2, 10.4.3, 10.4.4	Clause 7.4.11 Clause 9.5
	γ-ray semiconductor	TNID Enhanced background	Clause 8 Clauses 10.4.2, 10.4.3, 10.4.4	Clause 7.4.10 Clause 9.5
	charge particle detectors	TNID (scintillator & semiconductor) Enhanced background TID (scintillator & semiconductors)	Clause 8 Clause 10.4.2, 10.4.3 Clause 7	Clause 9.5 Clause 9.3 Clause 6
	microchannel plates	Enhanced background	Clause 10.4.6	Clause 9.6
	photomultiplier tubes	Enhanced background	Clause 10.4.6	Clause 9.6

[a] MEMS refers to the effects on the microelectromechanical structure only. Any surrounding microelectronics are also subject to other radiation effects identified in “Integrated circuits” row

Table 3: Summary of radiation effects and cross-references to other chapters (part 2 of 2)

Sub-system or component	Technology	Effect	Main Section Cross-reference	ECSS-E-HB-10-12A Cross-reference
Optoelectronics and sensors (2)	Other imaging sensors (*e.g.* InSb, InGaAs, HgCdTe, GaAs and GaAlAs)	TNID Enhanced background	Clause 8 Clauses 10.4.2, 10.4.3	Clause 7 Clause 9.3
	gravity wave sensors	Enhanced background	Clause 10.4.7	Clause 9.7
Solar cells	cover glass & bonding materials	TID	Clause 7	Clause 6
	cell	TNID	Clause 8	Clause 7.4.9
Non-Optical materials	crystal oscillators	TID	Clause 7	Clause 6
	polymers	TID (radiolysis)	Clause 7	Clause 6
Optical materials	silica glasses	TID	Clause 7	Clause 6
	alkali halides	TID TNID	Clause 7 Clause 8	Clause 6 Clause 7.4.11
Radiobiological effects		Early effects	Clause 11	Clauses 10.3.3, 10.4.4
		Stochastic effects	Clause 11	Clauses 10.3.4, 10.4.4
		Deterministic late effects	Clause 11	Clauses 10.3.4, 10.4.4

4.3. Relationship with other standards

There are important relationships between this standard and others in the ECSS system and elsewhere. While these are referred to in the relevant parts of the standard, and referenced as mandatory references, some of the important complementary resources are briefly described here:

- ECSS-E-10-04 “Space environment”

  This standard describes the environment and specifies the methods and models to be employed in analysing and specifying the model.

- ECSS-Q-60A “Electronic components”

  This standard identifies the requirements related to procurement and testing of electronic components, excluding solar cells.

- ECSS-E-20 “Electrical and electronic”

  This standard describes and sets up rules and regulations on generic system testing.

- ECSS-E-10-11 “Human factors engineering”

  This standard addresses all aspects relevant to assure a safe and comfortable environment for human beings undertaking a space mission. When other forms of life are accommodated on board, this standard also ensures the appropriate environmental conditions to those living organisms.

- ECSS-E-30 Part 4A “Space engineering - Mechanical - Part 4: Environmental control and life support”

- ECSS-E-30 Part 8A “Space engineering - Mechanical – Part 8: Materials”

This standard defines the mechanical engineering requirements for materials. It also encompasses the effects of the natural and induced environments to which materials used for space applications can be subjected.

- ECSS-Q-60-11A "Derating and end-of-life parameter drifts"

  This standard specifies derating requirements applicable to electronic, electrical and electro-mechanical components and end-of-life drifts in component parameters to be used in worst-case analyses.

- ECSS-E-20-08 "Photovoltaic assemblies and components"

  This standard outlines the requirements for the qualification, procurement, storage and delivery of the main assemblies and components of the space solar array electrical layout: photovoltaic assemblies, solar cell assemblies, bare solar cells and cover-glasses. It does not outline requirements for the qualification, procurement, storage and delivery of the solar array structure and mechanism.

5. Radiation design margin

5.1. Overview

5.1.1. Radiation environment specification

The radiation environment specification forms part of the product requirements. Qualification margins (the minimum RDM specified) are part of the specification, since the objective of the qualification process is to demonstrate whether an entity is capable of fulfilling the specified requirements, including the qualification margin in ECSS-P-001B. As a result of this qualification process, the achieved RDM is established, to be compared with the specified RDM.

This Clause specifies requirements for addressing and establishing RDMs. Margins are closely related to hardness assurance as well as to environment uncertainties. Hardness assurance is covered by ECSS-Q-60-XX, and environment uncertainties and worst-case scenarios are specified in ECSS-E-10-04.

5.1.2. Radiation margin in a general case

RDM can be specified at system level down to subsystem, board or component level, depending upon the local radiation environment specification at different components, and the effects analysis methodology adopted for the equipment.

Requiring the RDM to exceed a minimum value ensures that allowance is made for the uncertainties in the prediction of the radiation environment and damage effects, these arising from:

- Uncertainties in the models and data used to predict the environment;
- The potential for stochastic enhancements over the average environment (such as enhancements of the outer electron radiation belt);
- Systematic and statistical errors in models used to assess the influence of shielding, and determine radiation parameters (*e.g.* TID, TNID, particle fluence) at components' locations;
- Uncertainties in the radiation tolerance of components, established by irradiation tests, due to systematic testing errors;
- Uncertainties as a result of relating test data to the actual parts procured, and variability of measured radiation tolerance within the population of parts.

An appropriate selection of the radiation design margin takes into account:

- the criticality of the component, subsystem or system to the success of the mission, imposed through equipment reliability and availability requirements, and
- the type of mission (*e.g.* scientific, commercial, "low-cost", an optional mission extension).

Margins are also achieved by application of worst-case analyses. The quantification of the margins achieved is a good engineering practice. However, it is recognized that such a quantification is sometimes difficult or impossible.

5.1.3. Radiation margin in the case of single events

RDMs are usually related to cumulative degradation processes although within this document they are also used in the context of single event effects. In such context, the definition of RDM is particularized for the case of destructive or non-destructive single events (see 3.2.42).

Since in the case of single event the RDM definition is linked to the SSE prediction, the RDM can change depending upon the phase of the mission (*e.g.* whether a payload system is intended to be operational at particular times) and local environment or space weather conditions (*e.g.* if the spacecraft is passing through the South Atlantic Anomaly or during a solar particle event). Since SEE prediction is based on use of test data and simplifying assumptions on the geometry and interactions, it is important to take into account the potential for large errors in predicting SEE rates when establishing the reliability requirements for equipment, and specially for critical equipment.

5.2. Margin approach

a. The customer shall specify an overall minimum RDM (MRDM).

b. The customer may specify separate MRDMs to differentiate between components without test data but with evaluation data, and those with test data, MRDM1 and MRDM2, respectively.

NOTE These minimum RDMs can be established directly by the customer, or based on a proposal made by the supplier and approved by the customer.

c. If the differentiation specified in 5.2 NOTE is not provided, then the following shall apply: MRDM1=MRDM2=MRDM.

d. The RDM for components, etc. shall be established by analysis and a justification provided.

e. The analysis specified in 5.2 d shall include the following elements, and the associated uncertainties and margins, either hidden or explicit:

1. Space radiation environment, evaluated as specified in 5.3.

2. Deposited dose, calculated as specified in 5.4, and including:

(a) Shielding and

(b) Calculation of effects parameters

EXAMPLE Ionising dose, displacement dose, SEE rate, instrumental background, and biological effects.

3. Radiation effect behaviour of entities (including components, payloads, and humans), evaluated as specified in 5.5.

NOTE Hidden margins appear in many aspects of the hardness assurance process (see ECSS-Q-60-XX) and they can compensate for uncertainties in other elements of the assessment process. The hardness assurance plan can consider:

* Part type sensitivity evaluation.
* Lot-to-lot variation.
* Minimum considered radiation level (since dose-depth curves are often asymptotic to a dose value for thick shielding due to bremsstahlung or high energy protons, a minimum qualification dose can be specified)

f. Further design margin need not be applied for calculations where the elements of the calculation assume the following worst-case conditions:

1. For environment, those specified in ECSS-E-10-04A

2. For other than environment, those specified in clauses 5.4 and 5.5, below.

g. It shall be ensured that the qualification process demonstrates that the RDMs are met for the design adopted.

NOTE With this objective, the radiation design margins specified for the equipment are established based on the reliability and availability requirements, and on the methodologies adopted for calculating the radiation environment and effects.

5.3. Space radiation environment

a. When using the AE-8 model for electrons at the worst-case longitude on geostationary orbit for long-term exposure (greater than 11 years), no additional margin shall be applied.

b. When using AE-8 model under conditions other than specified in 5.3 a, or using standard models of the particle environment other than AE-8, it shall be demonstrated that the establishment of the RDM includes the model uncertainties.

c. Where models are worst-case, as specified in ECSS-E-10-04A, further margin need not be applied.

d. Where models are of a probabilistic nature, the process specified in ECSS-E-10-04A shall be used to establish an acceptable level of risk.

NOTE Example of models of probabilistic nature are statistical solar proton models. Example of an acceptable level of risk are worst case and specific percentiles.

e. Where models are of a probabilistic nature further margin need not be applied if it is demonstrated that the intrinsic uncertainties in the instrument data underlying the model as provided in ECSS-E-10-04 are included in the model's probabilistic formulation.

NOTE Any margin associated with the environment prediction is strongly dependent on the available knowledge and is used to mitigate against the uncertainties in the environment. Clearly, experience with certain types of Earth orbit is extensive; giving rise to smaller margins, but uncertainties for others, and for example other planets, necessitate careful consideration of uncertainties.

5.4. Deposited dose calculations

a. One of the three following methods are used to evaluate the deposited dose and are progressively more accurate or rigorous:

- abstract simple shielding such as planar or spherical shell geometry, as specified in 6.2.2.1;
- 3-D sector shielding, as specified in 6.2.3;
- 3-D physics-based Monte-Carlo analysis, as specified in 6.2.4.

In establishing the shielding contribution to a component's RDM, the following shall be included:

b. Since it is known to be conservative, when doses in geometries are computed with the 3-D sector shielding method specified in 6.2.3, additional margin need not be applied.

NOTE This is particularly true when approximate geometry models are used which are demonstrably conservative (e.g. lacking modelling of some units, harness, and fuel).

c. When 3-D physics based Monte-Carlo analysis specified in 6.2.4 is used for electron-bremsstrahlung dominated environments, it shall be demonstrated that the establishement of the RDM includes the uncertainties (including the level of conservatism in the shielding and the systematic and statistical errors in the calculation.

NOTE 1 Example of electron-bremsstrahlung dominated environments are geostationary or MEO orbits.

NOTE 2 When 3-D Monte Carlo analysis is used for ion-nucleon shielding in heavily shielded situations (*e.g.* ISS and other manned missions) greater margins are used.

5.5. Radiation effect behaviour

5.5.1. Uncertainties associated with EEE component radiation susceptibility data

a. It shall be demonstrated that the establishment of the RDM includes the uncertainties that arise in component susceptibility data, including:

1. In the results from irradiation: the beam characterization and dosimetry, and the subsequent statistical errors in the measured or derived results such as SEE cross-sections;
2. differences between the test circuit and the application circuit, such as bias conditions, opportunities for annealing or ELDRS;
3. differences in the radiation susceptibility of different components within the same batch, or collection of batches selected for testing;
4. differences between part batches or collection of batches, where errors arise from relating the results from component irradiations to devices employed in the final application.

NOTE 1 In the absence of contemporaneous beam characterisation, quoted particle accelerator characteristics are assumed to be no better than ±30 % accurate in beam intensity.

NOTE 2 For γ-ray sources such as ^{60}Co, uncertainties in the total ionising dose delivered are typically better than ±10 %.

b. It should be demonstrated that the establishment of the RDM includes the possible effects of packaging on low-energy proton beams (<30 MeV).

NOTE The reason is that this packaging can affect the penetration and energy (LET) of the particles.

c. The stated accuracy of the facility shall be used together with the uncertainties in 5.5.1 a, taking into account position, attenuation, *etc*.

d. The RDM associated with the variations in performance within a device population should be determined from statistical techniques defined in ECSS-Q-60-XX.

5.5.2. Component dose effects

a. In assessment of a part's total dose behaviour, the following shall be performed in establishing the margin:

1. Ensure that the test conditions lead to worst-case

EXAMPLE Choice of static bias and of dose rate.

2. Measure key parameters for worst-case analysis.

NOTE This can imply also measurement of other parameters in the specification or datasheet.

3. Include in the assessment the lot-to-lot variability as follows: if a flight part is from a different lot, then either perform testing or evaluate other test data to demonstrate that the tested part is representative.

NOTE This cannot be done without good statistics across lots including information such as process and technology variations between lots.

4. Include in the assessment the variability within one lot by using a statistical tool defined in ECSS-Q-60-xxA Clause xxxx.

5. Establish the implications of the final total dose effect on the part via the equipment worst-case analysis as specified in ECSS-Q-30-01A clause XXXX;

6. Detect the lots where behaviour is not consistent with previous behaviour *i.e.* containing a part with total drifts higher than observed previously in evaluation or testing according to ECSS-Q-60-xxA clause XXXX.

NOTE If a part has unexpectedly high sensitivity and this is discovered late in a project, corrective actions in terms of e.g. additional shielding, or part substitution, are very costly, particularly if units are already integrated.

b. It shall be demonstrated that the potential sensitivity of a device to both TID and TNID is included in the establishment of an overall RDM.

NOTE The main margin in radiation dose assessment is provided through the radiation hardness assurance plan. As specified in ECSS-Q-60-xx, a radiation hardness assurance plan is prepared, agreed and reviewed at all mission phases.

5.5.3. Single event effects

5.5.3.1. General single event

It shall be demonstrated that the equipment reliability requirements include the potential for large errors in predicting SEE.

NOTE 1 For a rationale, see 5.1.3.

NOTE 2 It is common practice in SEE evaluation to use worst-case environmental assumptions and perform worst-case analysis of system impacts. As indicated in Clause 5.2, when such worst-case analysis is performed, additional margins are not applied.

NOTE 3 Prediction errors of a factor 10 are possible in some circumstances.

5.5.3.2. Destructive single event

a. In the case of destructive single event effect, the acceptable probability of component failure by the SEE mechanism, and the calculated probability of failure used to determine the RDM, shall relate to performance of the component for the environment over the specified period of operation, rather than simply the worst-case environment condition.

NOTE However, in many cases it can be demonstrated that environment contributions other than worst case environment are negligible compared with the worst-case environment, in which case the use of one or the other is irrelevant.

b. Where the SEE calculation is based on an environment prediction which includes the confidence level for the environment not being exceeded, the confidence level should be quoted with the statement of the RDM for destructive SEEs.

c. Radiation effects calculation and design margin need not be performed for a component and SEE process if:

   1. the threshold energy (for protons or neutrons) or LET (for ions) for destructive SEE is greater than that identified in the radiation environment specification, and

   2. the electrical operational conditions for a component have been derated to levels where the device is shown by testing not to suffer that particular SEE mechanism.

d. Furthermore, margin shall be guaranteed through application of the hardness assurance process defined in ECSS-Q-60-XX.

5.5.4. Radiation-induced sensor background

a. The radiation metric used in the radiation design margin for sensor background calculations shall be agreed with the customer.

b. The radiation metric used in the RDM shall be chosen as representative of the sensor bandwidth critical to the mission objectives.

   NOTE 1 It is highly dependent upon the sensor design and application. It can be provided by the customer in the equipment requirements.

   NOTE 2 As with single event effects, the RDM applied can be dependent upon the phase of the mission, and local environment.

c. Where the background has been simulated, a comparison between simulations and irradiation results for the sensor (or a representation of the sensor) shall be performed in order to gauge the level of error in the modelling process.

   NOTE The uncertainties associated with the calculation of the background are very much dependent upon the sensor or instrument design and method for calculating detector background, including, where appropriate, the use of experimental data.

5.5.5. Biological effects

The protection limits and predicted exposure used to determine the RDM for biological effects shall be defined in terms of one or more of the following variables:

a. effective dose;

b. organ equivalent dose;

c. ambient dose equivalent;

d. directional dose equivalent;

e. personal dose equivalent.

   NOTE 1 For requirements on radiation effects in biological material, see Clause 11. For background on limit exposure policies of the different Space Agencies, see ECSS-E-HB-10-12A Clause 10.4.4.

   NOTE 2 For interplanetary missions, exposure limits are not currently defined.

5.6. Establishment of margins at project phases

5.6.1. Mission margin requirement

At this stage, the customer shall specify a minimum radiation design margin (MRDM) depending on mission-specific constraints as specified in 5.2 a.

EXAMPLE Mission specific constraints: reliability, cost, and lifetime.

5.6.2. Pre-PDR

a. Before PDR, a worst-case assessment of unit shielding shall be made (*i.e.* minimum shielding thickness)

NOTE Before PDR an accurate geometrical model of a satellite is not generally available. As a consequence it is not possible to estimate the dose level expected at a part and so the final RDM cannot be accurately assessed.

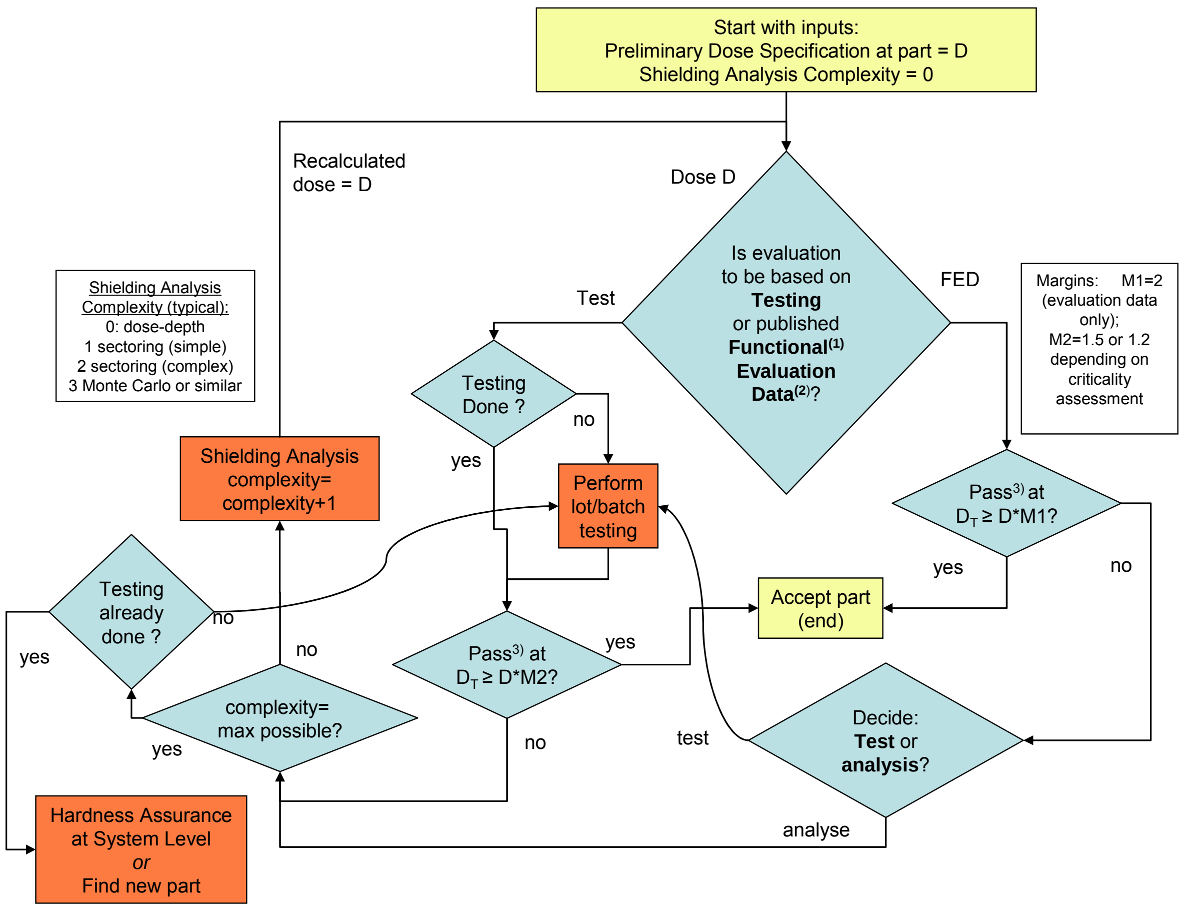
b. Other than the environmental margin, additional margin shall not be applied to the dose calculation at this stage.

c. For parts whose RDM determined from the worst-case assessment specified in 5.6.2 a and b falls below the MRDM specified in 5.2 a or b, and where information is available, the worst case assessment shall be augmented by geometrical (sector-shielding) analysis.

d. The analysis procedure described in Figure 1 shall be followed with the derived dose value from 5.6.2 a and c being the “preliminary dose specification” and the margin M1 being MRDM1, and margin M2 being MRDM2 from 5.2 b.

e. Parts whose RDM falls below the MRDM shall either be replaced or identified at PDR as candidates for subsequent iteration post-PDR.

Component evaluation:



Notes
1) "Functional" refers to degradation of a parameter to a specified level and may not closely correspond to a failure or condition where the operation is unacceptable
2) "Evaluation Data" refers to data available for the same component type but which may not be related to the flight lot or batch
3) Pass/fail criteria: parameter shifts may be far from problematic = hidden margin

Figure 1: Parts dose (ionising, non-ionising) hardness evaluation

5.6.3. At PDR

a. For parts failing the parts selection test in 5.6.2 e, the process shown in Figure 1 shall be applied using the Preliminary Dose Specification (the dose-depth curve from clause 6.2.2.1) with complexity "1" at the part location.

b. A more accurate RDM may be derived from a complex sectoring analysis at equipment level using the sectoring technique specified in XXXX, if the geometry data are available.

NOTE The shielding analysis specified in b. above is based on evaluation of the basic spacecraft and unit geometries, with sufficient detail of major local spacecraft elements which can provide shielding. Monte-Carlo techniques can also be attempted at this stage. The RDM is evaluated considering the environmental and shielding uncertainties and possible conservatism.

5.6.4. Between PDR and CDR

a. Parts that fail the parts selection test in 5.6.3 shall be dealt with through the process identified in Figure 1, with the shielding calculation being a full and detailed sectoring (complexity 2 as specified in clause 6.2.3) or Monte-Carlo analysis as specified in clause 6.2.4, including a geometrical analysis of the unit, its surroundings, and the spacecraft structure (complexity 3).

NOTE The RHA process defines the reporting expected at this stage (normally radiation analysis, including shielding).

b. At this stage, it shall be verified that the final radiation values, considering the uncertainties and conservatism in environment, shielding and parts evaluation are compatible with the specified project-specific overall MRDM.

NOTE The MRDM requirement can be established by the customer, or by the supplier in negotiation with the customer.

5.6.5. Hardness assurance post-CDR

Remaining problems close to or following CDR are clearly expensive to rectify. Solutions to be investigated may include additional “spot” shielding or other mitigation techniques, and analysis of the function of the part in the context of the WCA and system level implication analysis.

NOTE The pass/fail criteria in testing can be unrelated, or not closely related, to functional failure. If a part’s parameter is out of spec after testing, it can be that the parameter is not important in the equipment worst-case analysis.

5.6.6. Test methods

The test method, including frequency and sample sizes, is described in ECSS-Q-60-xx. The test frequency is a direct function of the knowledge gained from previous testing and application of hardness assurance processes.

6. Radiation shielding

6.1. Overview

The assessment of the amount, type and energy of radiation arriving at any component location cannot be performed without an accurate knowledge of the external environment and also an understanding of the attenuating effect of any material between the location and the external environment. This attenuation is commonly known as shielding.

Shielding occurs in two ways; "built-in" shielding, that is the fortuitous shielding afforded by materials already included in the design, and "add-on" shielding, which is added specifically for the purposes of attenuating radiation. This section identifies the standard approaches to be used when calculating the effects of shielding on the radiation environment experienced by a component, system or astronaut.

6.2. Shielding calculation approach

6.2.1. General

6.2.1.1. Process

a. A first-order estimate of the influence of shielding shall be made by determining the dose or particle fluence corresponding to the most lightly shielded part of the subsystem under evaluation using the simplified approaches specified in 6.2.2.

b. If the particle environment (including secondary as a result of additional shielding) behind that shielding is tolerable, further analysis need not be performed.

NOTE 1 Example of secondary radiation is bremsstrahlun.

NOTE 2 In some special circumstances (*e.g.* for galactic cosmic rays in high-Z materials) enhancement in radiation levels from secondary particles as a result of additional shielding can take place.

c. In case other than 6.2.1.1 b, one of the following analysis of the shielding shall be performed:

- a sector-analysis, as specified in in clauses 6.2.2 and 6.2.3, or
- a detailed radiation transport simulation of the whole or a part of the spacecraft, as specified in clause 6.2.4.
- shielding analysis as part of a simultaneous complete analysis with all sensitive locations defined, irrespective of whether problems are apparent or not.

6.2.1.2. Secondary radiation

The shielding analysis specified in 6.2.1.1 shall include

a. the secondary radiation effects in accordance with the mission types identified in Table 4.

b. for specialised instrumentation agreed with the customer (such as astrophysics radiation detectors), all prompt and delayed radioactive emissions which have the potential to produce background signals.

NOTE This can be done either by including them in the calculations, or by demonstrating that the effect is negligible.

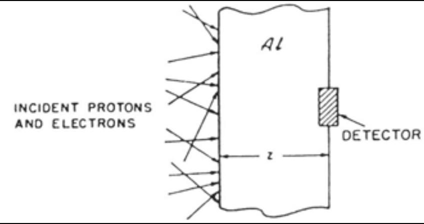
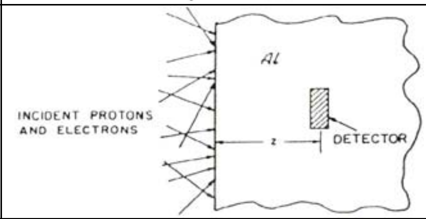
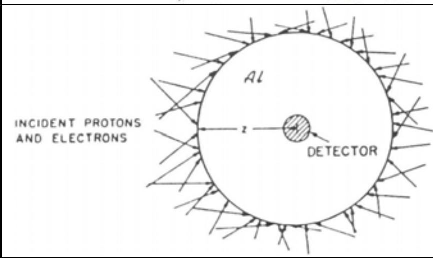
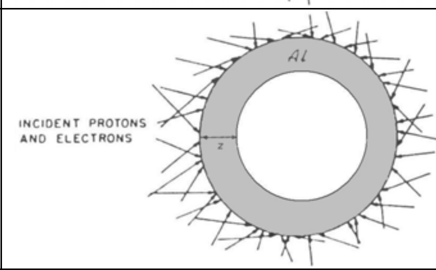
Table 4: Summary table of relevant primary and secondary radiations to be quantified by shielding model as a function of radiation effect and mission type (part 1 of 2).

Radiation effect	Mission type	Important primary radiations	Important secondary radiations
Total ionising dose	LEO	trapped protons trapped electrons solar protons	X-rays from electrons
	"high MEO" (*e.g.* navigation constellation)"	trapped electrons solar protons	X-rays from electrons
	"low MEO" (*e.g.* low altitude communications constellations such as ICO)	trapped protons trapped electrons solar protons	X-rays from electrons
	GEO	low energy trapped protons trapped electrons solar protons	X-rays from electrons
	Interplanetary space	cosmic rays solar energetic particles other planetary trapped-belts (*e.g.* Jovian)	X-rays from electrons (Jovian)
	Planetary lander	solar energetic particles	secondary protons and neutrons
	Missions involving RTGs or strong radioactive sources	γ-rays neutrons	electrons
Displacement damage	LEO	trapped protons trapped electrons solar protons	secondary neutrons (special susceptibilities and heavily shielded situations; not typically a concern for commercial missions)
	MEO	trapped protons (low MEO) trapped electrons solar protons	
	GEO	trapped protons (very low energy) trapped electrons solar protons	
	Interplanetary space	cosmic rays solar energetic particles other planetary trapped-belts (*e.g.* Jovian)	
	Planetary lander	cosmic rays solar energetic particles	secondary protons and neutrons
	Missions involving RTGs or strong radioactive sources	neutrons	

Table 4: Summary table of relevant primary and secondary radiations to be quantified by shielding model as a function of radiation effect and mission type (part 2 of 2).

Radiation effect	Mission type	Important primary radiations	Important secondary radiations
Single event effects	LEO	trapped protons solar energetic particles cosmic rays	secondary neutrons (special susceptibilities or heavily shielded situations; not typically a concern for commercial missions)
	MEO	trapped protons (low –MEO) solar energetic particles cosmic rays	
	GEO	solar energetic particles cosmic rays	
	Interplanetary space	cosmic rays solar energetic particles other planetary trapped-belts (*e.g.* Jovian)	
	Planetary lander	cosmic rays solar energetic particles	secondary protons and heavier ions, secondary neutrons
	Missions involving RTGs or strong radioactive sources	neutrons	
Radiation-induced backgrounds	(See tables in Clause 10)		
Radiobiological effects	LEO	trapped protons trapped electrons solar protons cosmic rays	X-rays from electrons Secondary protons and neutrons
	Interplanetary space	cosmic rays solar energetic particles other planetary trapped-belts (*e.g.* Jovian) solar X-rays	secondary protons and heavier ions, secondary neutrons
	Planetary lander	cosmic rays solar energetic particles	secondary protons and heavier ions, secondary neutrons
	Missions involving RTGs or strong radioactive sources	γ-rays and neutrons	neutrons

Table 5: Description of different dose-depth methods and their applications.

Shielding Geometry	Description of Source		Application
Finite slab shielding	Isotropically incident over 2π steradians		Used to quantify effects of spot shielding on components and self-shielding in active antenna arrays.
Semi-infinite slab shielding	Isotropically incident over 2π steradians		Used to quantify radiation dose to components near to the surface of a spacecraft (the majority of the spacecraft provides effectively an infinite shield over 2π steradians).
Solid spherical shielding	Isotropically incident over 4π steradians		Used for conditions where components are shielded to a finite level over all solid angles. Most common geometry used for the dose-depth curve of sector shielding analyses.
Spherical shell shielding [a]	Isotropically incident over 4π steradians of shell of user specified thickness and inner radius		Used for components shielded to a finite level over all solid angles and sometimes in sector shielding analysis.

[a] When using the solid spherical shielding method, the inner radius of the shell can be difficult to quantify precisely.

6.2.2. Simplified approaches

6.2.2.1. Planar and spherical geometries

For the first-order estimate of the influence of shielding, the analysis shall be performed as follows:

a. Assume that the influence of material type is negligible, and the different materials can be approximated to the equivalent mass of a single material type (such as aluminium) by a proportional change in density.

b. approximate the shielding geometry to one of the geometries shown in Table 5, as follows:

   1. Approximate a configuration with two opposing lightly shielded directions to the summed effects of two finite slab shown in Table 5.

   2. Approximate a configuration with a light shielding in one direction with heavy rear-side shielding to a semi-infinite planar geometry.

   3. Approximate a configuration with uniform shielding in all directions to the

solid sphere;

4. Approximate a configuration with a large cavity and uniform shielding in all directions (thickness < 0.5 cavity diameter) and no significant material local to the dose point to the spherical shell geometry;

c. Obtain the effect-versus-depth information (the so called “dose-depth curve” and/or comparable information for particle fluence or other radiation effects parameters as a function of shielding).

d. Assess the minimum shielding quantity provided by the spacecraft to be used in conjunction with a the effect-versus-depth.

e. If the shielding conditions do represent a worst-case analysis, and the component, subsystem or system performs to within the specified RDM for those shielding conditions, consider the the result of the analysis as acceptable.

f. In case other than 6.2.2.1 e, apply the detailed shielding calculation method specified in 6.2.2.2 or 6.2.3.

NOTE The first order approximation of the influence of shielding could result in an overestimation of the radiation effects, and a more detailed analysis could indeed show that the component, subsystem or system performs to within the specified RDM. This can be a worst-case estimation and so can indicate a requirement for more detailed analysis.

6.2.2.2. Simple sectoring based on solid angles

The sectoring method based on solid angles takes account of the fact that generally shielding around a point of interest is heterogeneous. For this second-order estimate of the influence of shielding, the analysis shall be performed by using the method in 6.2.2.1 and accounting for heterogeneous shielding by estimating the percentage of the overall solid angle (4π) subtended by the major elements of the configuration viewed from the shielded point.

6.2.3. Detailed sector shielding calculations

For detailed sector shielding calculations, the following shall be done:

a. Assume that the influence of material type is negligible, and the different materials can be approximated to the equivalent mass of a single material type (such as aluminium) by a proportional change in density.

b. Agree with the customer the specific sector shielding calculation method to use.

NOTE A summary of possible methods to use is presented in ECSS-E-HB-10-12A Clause 5.

c. If sectoring calculation is applied, assess if one of the following cases is present:

1. Performance of graded shields, dose enhancement in a silicon die close to gold contacts, or high-Z packaging materials, or X-ray bremsstrahlung dose in a location shielded by tantalum.

NOTE The reason is that sector shielding approach does not consider the physics involved in these phenomena. For graded shields see ECSS-E-HB-10-12A Clause 5.

2. The calculation includes assessment of secondary hadron levels from materials with significantly different (atomic) mass number from the original target material.

EXAMPLE Neutrons generated by high-energy proton interactions in lead.

NOTE This is particularly important for neutron fluxes or cosmic-ray fragments in heavily shielded manned missions or in sensitive scientific instruments.

d. If the assessment specified in 6.2.3 c is positive then either:

1. analyse the case ensuring conservatism in the sector shielding evaluation, or

2. perform the shielding calculation based on a radiation transport model in accordance with 6.2.4, which use the characterisitics of the actual materials employed.

e. If the detailed sector shielding method specified in XX is used, use one of the following approaches for the calculation:

1. Agree with the customer the method for the particulat sector shielding evaluation, or

2. use the “SLANT” approach for calculating the amount of material along a path, and the solid sphere geometry for production of the dose-depth or fluence-versus-depth curve, or

3. use the the “NORM” technique for estimating the amount of material along a path, and the spherical shell geometry for production of the dose-depth or fluence-versus-depth curve.

NOTE The transport model specified in 6.2.4 considers the actual materials employed. Such calculations can be performed using, for example, a finite-difference coupled electron-photon simulation or a Monte Carlo simulation for nuclear and electron-photon interactions.

4. Provide to the customer a description of the calculation techniques used, including:

(a) The description of the sector shielding simulation method used.

(b) The number of directional rays sampled

(c) The dose-depth geometry type.

(d) The results of the calculations

f. For protons and heavier ions, use the projected particle range for low-energy particles for the calculation of the attenuation of the particle flux, and the extrapolated particle range for high-energy particles.

NOTE This is in order to prevent underestimating the influence of particle straggling (ECSS-E-HB-10-12A Clause 5.2.3).

g. For sector shielding calculations, use a minimum of 1800 rays evenly distributed over 4π steradians.

NOTE Sector shielding can be used to compute a shield distribution, rather than direct computation of radiation effects parameters. This can be a useful way of using shielding information for a number of subsequent analyses. Therefore it is important to ensure sufficient resolution of the shielding distribution (which is dependent upon the geometry and the specified precision). In such a situation, the considerations outlined above apply also for the subsequent analyses.

6.2.4. Detailed 1-D, 2-D or full 3-D radiation transport calculations

For detailed radiation transport calculations, the following shall be done:

a. Use for the calculation the characterisitics of the actual materials used in the final structure or subsystem, or materials with similar electromagnetic (electron-photon) and nuclear cross-sections.

NOTE Detailed radiation “transport” calculations provide a more accurate treatment of the radiation interaction processes in which the particle numbers, species, energy, and direction of propagation can change in a complex manner according to the

Boltzmann transport equation. This type of calculation approach is used where aspects of the equipment orcomponent performance and the influence of shielding cannot be adequately treated within a sector shielding analysis.

b. If undertaken, agree with the customer the level of physics simulation to use.

NOTE The objective is to ensure accurate treatment of the production of secondary particles which can affect the component, system or human, as well as the attenuation and scattering of the primary radiation (see ECSS-E-HB-10-12A Clause 5.6).

c. Agree with the customer the number of dimensions (1-D. 2-D or 3-D) to use in the simulation.

NOTE The objective is to ensure that geometries are well represented and the analysis is conservative.

d. Use a number of primary particle simulations such that the statistical errors for the results used to infer component response are within the project's design margins for the radiation shielding model.

NOTE Radiation simulations employing Monte Carlo models carry both statistical and systematic errors, the latter as a result of uncertainties in the physics models and geometry approximations.

6.3. Geometry considerations for radiation shielding model

6.3.1. General

a. Except in the case specified in 6.3.1 b, the radiation shielding model shall include in the calculations the following geometry elements:

1. Parts packaging, as specified in 6.3.2.1.

NOTE Since it is the one that is the closest to the sensitive portion of the part (the die), the influence of packaging on the radiation received by the component can be very important, especially for electron or low-energy (up to a few 10's MeV) protons.

2. Equipment, as specified in 6.3.2.2.
3. Spacecraft, as specified in 6.3.2.3.
4. Interfaces between spacecraft and (sub)system, as specified in 6.3.2.4.

b. If it is demonstrated that omission of geometry elements does not result in radiation effect enhancements, these geometry elements may be omitted in the calculations.

NOTE Normally, these omissions lead to a conservative approaches, with higher radiation effect predictions.

6.3.2. Geometry elements

6.3.2.1. Parts packaging

The effect of the parts packaging in the radiation shielding model shall be assessed as follows:

a. Place the target point inside the package, located on top or slightly inside the active region of the volume

NOTE The objective is to get the best possible estimate of the deposited dose at die level, the target point. The active region is typically a silicon chip.

b. For hybrid devices containing several sensitive dies, use one target point per die.

NOTE The reason is that the calculated dose level can vary significantly depending on the die location.

c. For situations where the total ionising dose from X-ray or γ-ray fields is the largest contribution, assess the influence of local high-Z materials and include it in the calculations.

NOTE Example of high-Z materials are gold contacts or tungsten silicide layers and vias.

6.3.2.2. Equipment

The effect of the equipment in the radiation shielding model shall be assessed as follows:

a. Include in the equipment model (at least) the subsystem enclosure and printed circuit boards (PCBs), unless

1. worst-case calculations in which they are excluded show the component can tolerate the environment to within the RDM, and

2. it is demonstrated that the enclosure and PCB materials do not lead to radiation enhancement.

b. Either surround the target points by the actual parts package model, or use a worst case parts package.

NOTE Example of worst case parts package is an aluminium sphere with a thickness of 0.6 mm.

c. In order to get a better estimate of the radiation level, include in the model any passive element providing shielding to active elements.

NOTE Example of passive elements that can provide shielding are transformers, capacitors, and connectors.

6.3.2.3. Spacecraft

The effect of the spacecraft in the radiation shielding model shall be assessed as follows:

a. Include in the spacecraft radiation model a representation of the structure and the boxes for equipments.

b. Include in the model the material, as follows:

1. Where the dominant material used in the spacecraft is aluminium, or material of similar Z, model the spacecraft as aluminium boxes of the thickness having the size of actual enclosures, containing a reduced density of aluminium to provide the equivalent mass of the actual contents.

2. Otherwise, model the spacecraft with the precise material and contents as for the actual subsystem.

c. Approximate the walls of the satellite to those of an aluminium box providing the equivalent areal mass.

d. Assess the shielding afforded by the satellite structure for an internal subsystem either by

1. Using a worst-case calculation, and assuming normal incidence of radiation on each of the faces of the satellite box, or

2. Perform a sector shielding analysis for each subsystem location to better determine the shielding distribution.

e. If the spacecraft surface includes honeycomb panels, for worst case calculations, either:

1. Incorporate in the radiation model only the face-panels of the honeycomb, or

2. Agree with the customer the model to use to include the actual geometry and materials.

6.3.2.4. Interfaces between spacecraft and (sub)system

a. If the internal arrangement of (sub)systems are not be available when sectoring is made of the spacecraft geometry,

1. the environment at (sub)system level shall be specified in a way that the analysis of the (sub)system shielding and radiation effects can be made.

2. If the (sub)system has a box shape, either:

(a) Provide the dose or fluxes to each surface, or

(b) Mesh the surfaces and provide the values for each mesh element.

NOTE While useful for engineering purposes, it is important to recognise the uncertainties in this method. It can happen that the propagation directions of the radiation and possibly the type and energy of the radiation are not retained. Nevertheless, this is generally a conservative approach.

b. Otherwise, the actual internal arrangements of (sub)systems shall be provided by the customer and used by the supplier.

NOTE The satellite geometry and subsystem geometry can be exchanged between contractors and customers using available geometry exchange formats or tools.

6.4. Uncertainties

The use of simplified approaches for shielding analysis geometries gives rise to uncertainties. As described above, shielding material effects, scattering and secondary radiation production are only approximately handled in “sectoring” types of calculation. Investigations of resulting uncertainties are in progress but results are not yet available.

7. Total ionising dose

7.1. Overview

Ionisation induced in semiconductor materials or associated insulators, such as silicon dioxide layers, can lead to charge trapping or the formation of interface states at the semiconductor-insulator boundary, affecting component behaviour or material properties. In MOS devices, the trapped charge can lead to a shift in the gate threshold voltage, and for semiconductors in general, interface states can significantly increase device leakage currents. Materials such as polymers and glasses are also susceptible to total ionising dose (TID) effects and can suffer degradation in mechanical, electrical and optical properties.

The purpose of this clause is to give an overview of total ionising dose (TID) effects and specify the requirements for calculating the TID threat to spacecraft systems in terms of the technologies which are susceptible, and standard methods of calculation.

Radiation dose is the amount of energy per unit mass transferred by particles to a target material, in this case from ionisation and excitation. The International System unit is the gray: 1 Gy = 1 J/kg, but a deprecated unit, the rad (radiation absorbed dose), is still widely used: 1 rad = 1 cGy.

Total ionising dose is included in the overall radiation assessment process diagram shown in Figure 1.

7.2. General

The target material shall be indicated in the results.

EXAMPLE For expressing TID effects in silicon, the unit of dose commonly used are Gy(Si) or rad(Si).

NOTE The reason is that dose is dependent also on the target material.

7.3. Relevant environments

Total ionising dose effects **shall** be analysed for spacecraft and planetary-mission systems to be operated within any of the following radiation environments:

a. Trapped proton and electron belts.

EXAMPLE Terrestrial and other planetary belts, such as Jovian.

b. Solar protons;

c. Secondary particles, except secondary neutrons

NOTE This includes bremsstrahlung from electrons, and protons generated in atmospheric showers in the planetary environment or within large spacecraft or planetary-lander structure.

d. Local sources of radiation

EXAMPLE In close proximity to radioactive or nuclear-energy sources, e.g. RTGs generating γ radiation.

7.4. Technologies sensitive to total ionising dose

If one of the technologies identified in Table 6 is used in spacecraft and planetary-mission systems, the potential TID level and effects shall be analysed.

NOTE 1 Technologies in Table 6 are susceptible to TID. This is not exhaustive and other parameters can be important and result from worst-case analysis.

NOTE 2 As specified in Clauses 8, 9 and 10, calculation of cumulative damage due to non-ionising energy loss and single event effects and detector background is also mandatory for many of these components, such as those based on bipolar junction transistors or optoelectronics .

Table 6: Technologies susceptible to total ionising dose effects.

Technology category	Sub categories	Effects
MOS	NMOS PMOS CMOS CMOS/SOS/SOI	Threshold voltage shift Decrease in drive current Decrease in switching speed Increased leakage current
BJT		hFE degradation, particularly for low-current conditions
JFET		Enhanced source-drain leakage currents
Analogue microelectronics (general)		Changes in offset voltage and offset current Changes in bias-current Gain degradation
Digital microelectronics (general)		Enhanced transistor leakage Logic failure from (1) reduced gain (BJT), or (2) threshold voltage shift and reduced switching speeds (CMOS)
CCDs		Increased dark currents Effects on MOS transistor elements (described above) Some effects on CTE
APS		Changes to MOS-based circuitry of imager (as described above) – including changes in pixel amplifier gain
MEMS		Shift in response due to charge build-up in dielectric layers near to moving parts
Quartz resonant crystals		Frequency shifts
Optical materials	Cover glasses Fibre optics Optical components, coatings, instruments and scintillators	Increased absorption Variation in absorption spectrum (coloration)
Polymeric surfaces (generally only important for materials exterior to spacecraft)		Mechanical degradation Changes to dielectric properties

7.5. Radiation damage assessment

7.5.1. Calculation of radiation damage parameters

a. The radiation damage assessment shall use the total ionising dose due to charged particles and X-rays, calculated as specified in 7.5.2.

b. The influence of shielding in attenuating the primary particle environment and modification to its spectrum at the component location shall be analysed, including the effects of the component packaging, as specified in Clause 6.

c. The influence of secondary particles on TID shall be analysed.

NOTE The analysis can conclude that their contribution is negligible compared with the residual primary radiation components. This secondary radiation is typically electron-induced bremsstrahlung but in some circumstances secondary protons, electrons and neutrons can also have an important contribution.

d. For items in unshielded or lightly shielded locations, the energy spectrum at low energy shall be as specified in ECSS-E-10-04A clause XXXX.

7.5.2. Calculation of the ionizing dose

a. The calculation of the ionising dose in the target should used the particle fluxes at the surface of the TID-sensitive elements of the component or material.

b. At a point or in a finite volume, the dose should be calculated as follows:

1. Calculate charged particle ionisation restricted stopping power (or LET) in the material, or in the case of photons, mass energy absorption coefficients, or

2. Calculate particle ionisation energy deposition in small (i.e. a volume where the radiation field suffers negligible change, either by attenuation or multiple scattering, traversing the volume) or extended volumes

NOTE Monte-Carlo methods can be used for this purpose.

3. Use tabulations of dose versus flux and shielding information.

NOTE This is the case of SHIELDOSE and SHIELDOSE-2, based on Monte-Carlo calculation and energy loss functions.

c. Analyse dose enhancement effects due to changes in material composition in the vicinity of, or within a target, as a result of using high-Z materials.

NOTE See ECSS-E-HB-10-12A Clause 5 for more details on dose enhancement phenomena.

7.6. Experimental data used to predict component degradation

The use of component test data used in conjunction with total ionising dose results to predict degradation shall be agreed with the customer.

NOTE The objective is that these data are based on irradiations performed using particles with sufficient energies to traverse the sensitive part of the device and doses defined through application of the methods defined in Clause XXXX. It is important that the testing conditions are appropriate to the final operating conditions, for example:

* That the electrical and environmental test conditions (*e.g.* voltage bias, temperature) are equivalent to the expected operating environment for the device, or be such as to give rise to more severe TID effects.

* That the time period over which the radiation dose is delivered is considered when comparing the dose received in the operational environment and under test conditions. Some bipolar devices (*e.g.* bipolar linear integrated circuits) exhibit greater radiation sensitivity when exposed to ionising radiation at lower TID rates, whilst others such as MOS-based devices suffer lower radiation effects if exposure takes place over a longer time.

* That the irradiation by different radiation types is equivalent. For example, dose enhancement effects can be experienced in the shielded bremsstrahlung field in electron-rich orbits due to presence of high-Z materials close to sensitive volumes, whereas these are not represented in a proton or ^{60}Co irradiation.

7.7. Experimental data used to predict material degradation

The dose deposition from the source used to assess material degradation shall be calculated through application of the methods specified in clause 7.5.2.

NOTE Refer to ECSS-Q-70-06 and ISO/DIS 15856 for further details.

7.8. Uncertainties

Refer to Clause 5, and ECSS-E-HB-10-12A Clauses 4 and 5.8.

8. Displacement damage

8.1. Overview

This chapter explains the displacement damage (DD) effect, identifies technologies and components susceptible to DD, and specifies the requirements for calculating the DD threat to spacecraft systems, and standard methods of calculation.

Displacement damage (also referred to as non-ionising dose damage) is a cumulative damage process induced by energetic particles and which affect components such as opto-electronics, bipolar devices, and solar cells. The damage mechanism is as a result of collisions with atoms to displace them from lattice positions creating interstitials and vacancies. These interstitials and vacancies are mobile and can cluster together or react with impurities in the lattice structure creating stable defect centres. The overall effect of displacement damage (DD) is a change in the minority carrier lifetimes of semiconductors, and increased light absorption and coloration in crystalline optical materials.

Displacement damage is sometimes quantified in terms of component degradation as a function of particle fluence for a specific particle spectrum (with units, for example, or protons/cm^2 or electrons/cm^2). However, since the level of degradation varies with spectrum shape as well as intensity, such a definition has limited applications, and for general applications, in this Standard DD is expressed as specified in 8.2.

Total non-ionising dose is included in the overall radiation assessment process diagram shown in Figure 1.

8.2. Displacement damage expression

The displacement damage should be expressed either by:

- Displacement damage equivalent particle fluence (DDEF) for mono-energetic spectra,

  EXAMPLE Damage induced as a function of fluence from 10 MeV protons, 1 MeV neutrons or 1 MeV electrons, identified by DDEF(particle, energy, material).

- The non-ionising energy loss (NIEL) dose or (total) non-ionising dose ((T)NID), *i.e.* the energy deposition in a material per unit mass by radiation through displacements

  NOTE 1 This is better than expressing it by excitation or ionisation.

  NOTE 2 Units of TNID are Gy(material) or rad(material), but for space radiation effects analysis, MeV/g is more commonly used to avoid confusion with TID-related quantities.

8.3. Relevant environments

a. Displacement damage effects shall be analysed for spacecraft and planetary mission systems to be operated within any of the following radiation environments:

   1. Trapped proton belts

EXAMPLE Terrestrial and other planetary belts, such as Jovian.

2. Solar protons.

3. Secondary protons and neutrons

NOTE They can be generated in atmospheric showers in the planetary environment or within the spacecraft or planetary-lander structure.

4. In close proximity to radioactive or nuclear-energy sources

EXAMPLE RTGs generating thermal or fission-spectrum neutrons.

5. Trapped electrons (when considering solar cell degradations and opto-electronic devices).

b. Displacement damage from cosmic ray primary and secondary radiation shall be agreed with the customer.

NOTE It is normally neglected for effects in microelectronics, but it can be important for special or novel scientific instruments and sensors. While NIEL increases with atomic number of the projectile, the reducing fluence of ions with Z means that cosmic-ray heavy ion contribution to TNID is not normally significant.

8.4. Technologies susceptible to displacement damage

If one of the technologies identified in Table 7 is used in spacecraft and planetary-mission systems, the potential TNID level and effects shall be analysed.

NOTE As specified in Clauses 7, 9 and 10, calculation of total ionising dose effects and single event effects or detector background, including potential synergistic effects of DD and other effects, is also a requirement for many of these components.

8.5. Radiation damage assessment

8.5.1. Calculation of radiation damage parameters

a. The radiation damage assessment should (shall?) use either the DDEF of mono-energetic protons, electrons, or neutrons calculated as specified in 8.5.2.1, or the TNID, calculated as specified in 8.5.2.2.

b. The influence of shielding in attenuating the primary particle environment and modifying its spectrum shall be analysed,

c. The influence of secondary protons, electrons and neutrons on displacement damage shall be analysed.

NOTE In many cases the analysis can conclude that their contribution is negligible, but in some circumstances secondary protons, electrons and neutrons can have an important contribution.

8.5.2. Calculation of the DD dose

8.5.2.1. Calculation of the DDEF

a. DDEF shall be calculated from the environmental proton, electron or neutron spectra and the conversion factors for the device type being assessed as described in ECSS-E-HB-10-12A Clause 7.5.1:

b. The decrease in the component performance shall then be based on experimental performance test data collected on the component at these mono-energetic energies.

8.5.2.2. Calculation of the NIEL

a. NIEL shall be calculated by one of the following procedures:

1. If the NIEL function of energy, particle type and target material is known, calculate the TNID through the integration over energy of the NIEL function (multiplied by fluence) for each particle species on the target material.

2. Otherwise, calculate NIEL following the methodologies described by Jun *et al* or Messenger *et al* [3] [4].

b. Conversion from TNID to component parameter degradation shall be obtained by testing the component at different NIEL values.

c. The same NIEL function shall be used in converting the test particle fluence to the test TNID in 8.5.2.2 a and in 8.5.2.2 b, and the calculation and approach shall be specified.

Table 7: Summary of displacement damage effects observed in components as a function of component technology.

Technology category	Sub-category	Effects
General bipolar	BJT Integrated circuits	hFE degradation in BJTs, particularly for low-current conditions (PNP devices more sensitive to DD than NPN)
	diodes	Increased leakage current increased forward voltage drop
Electro-optic sensors	CCDs	CTE degradation Increased dark current Increased hot spots Increased bright columns Random telegraph signals
	APS	Increased dark current Increased hot spots Random telegraph signals Reduced responsivity
	Photo diodes	Reduced photocurrents Increased dark currents
	Photo transistors	hFE degradation Reduced responsivity Increased dark currents
Light-emitting diodes	LEDs (general)	Reduced light power output
	Laser diodes	Reduced light power output Increased threshold current
Opto-couplers		Reduced current transfer ratio
Solar cells	Silicon GaAs, InP, *etc.*	Reduced short-circuit current Reduced open-circuit voltage Reduced maximum power
Optical materials	Alkali halides Silica	Reduced transmission
Radiation detectors	Semiconductor γ-ray & X-ray detectors: Si, HPGe, CdTe, CZT	Reduced charge collection efficiency (calibration shifts, reduced resolution) Poorer timing characteristics HPGe show complex variation with temperature
	Semiconductor charged-particle detectors	Reduced charge collection efficiency (calibration shifts, reduced resolution)

Table 8: Definition of displacement damage effects.

Parameter	Phenomenology and observation	Technologies affected
Charge-transfer efficiency (CTE)	Creation of traps in active volume of CCD – reduced charge collection from each pixel, also streaking observed due to the delayed release of trapped charge.	CCD
Dark current	Excess charge from electro-optic sensor due to charge collection from radiation-induced defects.	CCD APS photo-diodes photo-transistors
Hot spots	Defect-induced charge generation in specific pixels which become brighter than the average dark current. These are usually defined in the context of the application and identified by the image-processing software as “bad pixels”. Very bright spots can result from field-enhanced emission mechanisms.	CCD APS
Random telegraph signals (RTS)	Two or more multi-level dark-current states with random switching between the dark current states from seconds (for imager at room temperature) to hours (if operated at reduced temperatures)	CCD APS
Bright columns	Defect-induced dark current can saturate a pixel with a time-constant comparable to or longer than device read-out times. Information from one or more pixels after the damaged pixel are this rendered unreadable.	CCD
Reduced photo-current / Pixel responsivity	Reduced charge collection as a result of decreased minority carrier life-times	APS photo-diodes photo-transistors
Threshold current		
Light output	Increase in charge traps result in greater non-radiative recombination of electron-hole pairs and hence reduced radiation power efficiency	LED laser diodes
h_{FE}	Reduced minority carrier life-times in BJT base result in lower currents between the collector and emitter, and hence reduced transistor gain.	BJT
Open-circuit voltage	The open circuit voltage is reduced by introduction of recombination centres in the depletion region which increase the dark current.	Solar cell
Short-circuit current	Recombination centres reduceminority carrier life-time in the neutral regions of the device resulting in reduced quantum efficiency (*i.e.* reduced charge collection).	Solar cell
Power output	See open circuit voltage and short circuit current.	Solar cell
Energy calibration Detector resolution	Reduced charge collection efficiency (CCE) results in less signal from detector per unit energy deposition, and greater statistical errors in the signal (hence reduced resolution). For cryogenic detectors, these parameters show complex behaviour with changes in temperature.	Semiconductor radiation detectors

8.6. Prediction of component degradation

Prediction of component degradation as a function of NIEL shall be performed by one of the following approaches:

a. Calculate the degradation from the total TNID damage predicted considering both elastic and inelastic processes, or

b. By using experimental degradation data for high energy protons, accepted by the customer.

NOTE 1 It is important that the testing conditions are appropriate to the final operating conditions, for example:

* That the component test data used in conjunction with radiation damage parameters to predict degradation are based on tests performed with particle species and

energy that are representative of the environment, taking account of the appropriate NIEL conversion data.

* That contamination of the TNID effects data by TID effects are be minimised and taken into account.
* That the particle energies for the tests are sufficient to allow particles to traverse the sensitive part of the device.
* For solar cells, that normal incidence data are converted to represent the expected in-flight distribution (normally assumed isotropic – see ECSS-E-10-04) and cover glass shielding effects.
* That mono-energetic particle tests are permitted provided there is a consistent one-to-one correspondence between the device degradation and TNID, or if the particle energy chosen for testing leads to worst-case degradation of the device.

NOTE 2 For guidelines on prediction of predicting component degradation as a function of NIEL, see ECSS-E-HB-10-12A Clause 7.3.

8.7. Uncertainties

Refer to Clause 5, and ECSS-E-HB-10-12A Clauses 4, 5.8 and 7.

9. Single event effects

9.1. Overview

This Clause provides an explanation of single event effects, identifies technologies and components susceptible to the SEEs, and specifies the methods to be used to calculate single event rates for spacecraft systems.

Single event effects are a collection of phenomena whereby microelectronics can be disrupted or permanently damaged by single incident particles (as opposed to effects like total ionising dose where cumulative damage occurs from many particles). Protons and heavier ions, and neutrons can induce such effects: in the case of heavy ions, this occurs by direct ionisation of sensitive regions of the semiconductor, and for protons and neutrons, their nuclear interactions within or very near to the active semiconductor can produce localised charge generation.

SEE phenomena can be divided into two sub-groups:

- destructive effects, where high-current conditions are induced which have the potential to destroy the device. SEE examples include single event latch-up (SEL), single event gate rupture (SEGR), single event burn-out (SEB), and single event snap-back (SESB) (see ECSS-E-HB-10-12A Clause 8.6).
- non-destructive effects, in which data are corrupted or the device is placed in a different operational state (*e.g.* a diagnostic mode) or power cycling is employed to return the state of the device to its normal condition. Examples of such effects include single event upset (SEU), multiple-bit upset (MBU), multiple-cell upset (MCU), single-word multiple-bit upsets[2] (SMU), single event functional interrupt (SEFI), single event hard error (SEHE), single event disturb (SED), and single event transient (SET) (see ECSS-E-HB-10-12A Clause 8.7).

Radiation susceptibility of a device is expressed as a cross-sectional area, usually in units of cm^2/device or cm^2/bit (the latter being used for single event upset analysis). The cross-section is a function of incident particle species and energy. However, for ions heavier than protons, the cross-section can be expressed as a function of linear energy transfer (LET), which is the energy deposition per unit pathlength of the ion, often expressed in units of $MeV{\cdot}cm^2/g$ or $MeV{\cdot}cm^2/mg$.

9.2. Relevant environments

a. Single event effects shall be analysed for spacecraft and planetary-mission systems to be operated within any of the following radiation environments:

1. trapped proton belts (terrestrial and other planetary belts, such as Jovian);
2. solar protons and heavier ions;
3. galactic cosmic-ray protons and heavier ions;

[2] Here, the term multiple-cell upset (MCU) refer to events in which several memory cells are corrupted, whether they form part of the same word (as in SMU) or not.

b. The mission environmental specifications shall define all the relevant environments to be analysed.

NOTE In some special circumstances, the following environments can also make an important contribution to SEE:

* secondary protons and neutrons, which are generated in atmospheric showers in the planetary environment or within massive spacecraft or planetary-lander structures.
* neutron environment in close proximity to radioactive or nuclear-energy sources, *e.g.* RTGs generating thermal or fission-spectrum neutrons.

9.3. Technologies susceptible to single event effects

If one of the technologies identified in Table 9 is used in spacecraft and planetary-mission systems, the SEE probability and effects shall be analysed.

NOTE 1 As specified in Clauses 7, 8 and 10, the susceptibility of many of these components is also analysed for other radiation effects (such as total ionising dose and displacement damage).

NOTE 2 As technologies evolve and new phenomena are identified, it can be the case that this table does not fully represent the technologies and effects.

Table 9: Possible single event effects as a function of component technology and family.

Component type	Technology	Family	Function	SEL	SESB	SEGR	SEB	SEU	MCU/SMU	SEDR	SEHE	SEFI	SET	SED
Transistors	Power MOS					X	X							
ICs	CMOS or BiCMOS or SOI	Digital	SRAM	X*				X	X		X			
			DRAM/ SDRAM	X*	X			X	X		X	X		
			FPGA	X*				X		X		X		X
			EEPROM/ Flash EEPROM	X*						X		X		X
			µP/ µcontroller	X				X			X	X		X
		Mixed Signal	ADC	X*				X				X	X	X
			DAC	X*				X				X	X	X
		Linear		X*						X			X	
	Bipolar	Digital						X					X	
		Linear						X					X	
Opto-electronics			Opto-couplers										X	
			CCD										X	
			APS (CMOS)	X									X	
*except SOI														

9.4. Radiation damage assessment

9.4.1. Prediction of radiation damage parameters

9.4.1.1. General

When predicting component SEE rates, the following shall be assessed:

a. The probability of SEE occurrence for the environments as specified in 9.2, using the methods specified in 9.4.1.2 to 9.4.1.8.

NOTE 1 More information on this method is available in ECSS-E-HB-10-12A Clause 8.2.

NOTE 2 Total ionising dose induced in semiconductors can increase sensitivity to single event effects. Therefore, potential SEE/TID synergy can be important in special cases, both in estimating single event rate for the operating environment, as well as assessing the suitability of data collected from proton and ion beam irradiations.

b. The influence of shielding in attenuating the primary particle environment and modification to its spectrum, as specified in Clause 6.

NOTE The effects of the component packaging (as described in Clause 6.3) can be considered.

9.4.1.2. Heavy ion-induced SEU, MCU (including SMU), and SEFI

a. The probability of single event transients, upsets, functional interrupts and multiple-cell upsets due to ions heavier than protons should be determined as follows:

1. If the variation of the ion cross-section with LET is known, by using the Integrated RPP (IRPP) approach described in ECSS-E-HB-10-12A Clause 8.5.2.

2. Otherwise, using either of the following RPP methods:

(a) The incident particle differential LET spectrum, integrated over the integral chord-length distribution in the sensitive volume for which the energy deposition is above that corresponding to the experimentally-determined LET threshold of the device, and using the formulation of Bradford specified in ECSS-E-HB-10-12A Clause 8.5.2 .

(b) The differential chord-length distribution integrated over the incident particle integral LET spectrum, for which the LET corresponds to energy deposition above the experimentally-determined threshold of the device, and using the formulation of Bradford or Pickel, Blandford and Adams specified in ECSS-E-HB-10-12A Clause 8.5.2.

b. SEFI analysis shall

1. assess the range of internal operating modes that complex digital devices used by the intended application, and

2. use only test data which cover these modes.

9.4.1.3. Proton- and neutron-induced SEU, MCU (including SMU), and SEFI

a. The probability of single event transients, upsets, functional interrupts and multiple-cell upsets due to protons or neutrons should be determined as follows:

1. If the variation of the cross-section with LET is known,

(a) Calculate the probability by integration of the incident differential proton or neutron spectrum over the experimentally determined cross-section of the device as specified in ECSS-E-HB-10-12A Clause 8.5.5.

(b) If experimental data from ion beam irradiations indicate the threshold for SEU, MCU or SEFI for ions is ≥15 MeV·cm^2/mg, assume that the device has negligible susceptibility to that effect from protons and neutrons.

2. Otherwise, perform the following:

(a) determine the SEE rate from calculation of the energy-deposition spectrum from proton-nuclear or neutron-nuclear interactions within the representation of the sensitive volume, and

(b) integrate this spectrum with cross-section data from ion-beam irradiations as specified in ECSS-E-HB-10-12A Clause 8.5.5, and

(c) analyse potential problems arising from use of the device, along with appropriate margins.

NOTE The reason is that this method is not as accurate as direct calculation based on proton data.

b. SEFI analysis shall

1. assess the range of internal operating modes that complex digital devices used by the intended application, and

2. use only test data which cover these modes.

9.4.1.4. Heavy ion-induced SEL and SESB

a. For SEL and SESB experimental data shall be used to determine the LET threshold for susceptibility to SEL or SESB.

b. Where experimental data indicate that the normal incidence LET threshold for susceptibility to single event latch-up or single event snapback for ions is ≥60 MeV·cm^2/mg, it shall be assumed that the device has negligible probability of SEL or SESB respectively to heavy ions., when subjected to the electrical and temperature conditions under which the device is operated in the test and intended application, as specified in 9.4.2.

c. For devices with lower thresholds than those specified in a. above, one of the following two methods shall be used:

1. Determine the probabilities for SEL and SESB due to heavy ions from the integration of the incident differential ion LET spectrum over the experimentally-determined cross-section of the device, as specified in ECSS-E-HB-10-12A Clause 8.5.2.

2. worst case analysis based on experimental data

NOTE alternative testing methods (laser or proton irradiation), combined with a cross-section equivalent to the device surface can be used with worst case analysis.

d. If a worst-case analysis is performed in accordance with 9.4.1.4 c.2, and the probability is unacceptable to the customer, the cross-section shall be determined experimentally.

9.4.1.5. Proton- and neutron-induced SEL and SESB

a. For SEL and SESB experimental data shall be used to determine the LET threshold for susceptibility to SEL or SESB.

b. Where experimental data indicate that the LET threshold for susceptibility to single event latch-up or single event snapback for ions is ≥15 MeV·cm^2/mg, or proton or neutron data indicate that the energy threshold for proton/neutron SEE is ≥150 MeV, it shall be assumed that the device has negligible probability of SEL or SESB respectively for protons and neutrons. when subjected to the electrical and temperature conditions under which the device is operated in the test and intended application, as specified in 9.4.2.

c. For devices with lower thresholds that the ones specified in a. above, the probabilities for SEL and SESB due to protons or neutrons shall be determined by one of the following methods:

1. by integration of the incident differential proton or neutron spectrum over the experimentally determined cross-section of the device, as specified in ECSS-E-HB-10-12A Clause 8.5.5.

2. by worst case analysis

NOTE Alternative testing methods (laser irradiation), combined with a cross-section equivalent to the device surface can be used with worst case analyses.

9.4.1.6. Heavy ion-, proton- and neutron-induced SEGR, SEDR and SEB

a. For single event gate/dielectric rupture and single event burnout, experimental data shall be used to determine the electrical operational conditions of the device under which neither SEGR nor SEB occurs

NOTE ECSS-E-HB-10-12A Clause 8.5.8 describes derating and mitigation techniques for defining electrical operational conditions.

b. Where experimental data show that the threshold for single event gate/dielectric rupture or single event burnout in a device for ions is ≥60 MeV·cm^2/mg, it shall be assumed that the device has negligible probability of SEGR, SEDR or SEB respectively for operation in heavy-ion, proton and neutron fields, when it is subjected to the electrical and temperature conditions under which the device is operated in the test and intended application in accordance with 9.4.2.

c. Where experimental data show that the threshold for SEGR, SEDR or SEB for ions is ≥15 MeV·cm^2/mg, or proton or neutron data indicate that the energy threshold for proton/neutron SEGR, SEDR or SEB is ≥ 150 MeV, it shall be assumed that the device has negligible probability of SEGR, SEDR or SEB respectively when operated in either a proton or neutron field. when it is subjected to the operating conditions or the test and application.

d. In the case specified in 9.4.1.6 c, the device's susceptibility to heavy-ion induced SEGR, SEDR and SEB should be analysed.

9.4.1.7. Heavy ion-, proton- and neutron-induced SET and SED

a. If SET is mitigated by circuit design, the effects of spurious pulses shall be minimized as follows:

1. Test the equipment performance under different filter conditions for SET and SED effects by propagating a perturbation signal in the final electrical design of the hardware itself to study its influence at the system level.

NOTE This approach is used when there is sufficient access to inject test pulses to the range of circuit nodes, or using a circuit simulation mode.

2. Use a circuit simulation model, and verify the accuracy of the different components in the circuit model for propagating large amplitude signals (*i.e.* up to the maximum amplitude expected from the SET/SED).

NOTE Typical applied amplitudes and signal durations are provided in ECSS-E-HB-10-12A Clause 8.5.9 (Table 9) as a function of semiconductor family type. Note, however, that these are not the only devices to be tested for SET/SED.

b. In case other than a. above, the SET/SED rate should be predicted using the same methods as for SEU, as specified in 9.4.1.2 and 9.4.1.3, including ion or proton test.

9.4.1.8. Heavy ion-, proton- and neutron-induced SEHE

The probability of single hard errors due to ions, protons or neutrons shall be determined by integration of the incident particle differential energy spectrum and over the experimentally determined cross-section of the device, as a function particle species and angle of incidence

NOTE ECSS-E-HB-10-12A Clause 8.7.4 provides a description of SEHE and considerations that can be significant for the test procedure.

9.4.2. Experimental data and prediction of component degradation

a. Experimental data used to calculate single event rates shall cover a LET range (for heavy-ion induced SEEs) or energy range (for proton and neutron-induced effects) capable to ensure that:

1. The lower LET or energy is the threshold for the onset of the single event effect.

2. For heavy ions, the upper LET threshold corresponds either to:

(a) the maximum LET expected for the environment, or

(b) 60 MeV·cm^2/mg.

3. For nucleons, the maximum energy corresponds either to:

(a) the maximum energy for the predicted environment, or

(b) 200 MeV for all SEE phenomena.

b. The experimental data used for device conditions shall be either those expected for operational conditions, or such that the experiment provide worse SEE-susceptibility data, as follows:

1. For SRAMs and DRAMs, SEU-dependent electrical conditions are voltage, clock frequency and refresh rate.

2. For SEL, tests are for the maximum power and maximum temperature conditions expected for space application.

3. For SEB, tests correspond to the minimum operating temperature for the application, as this corresponds to maximum SEB susceptibility of the device.

c. For SEL, SEGR, and SEB, the potential inaccuracy of LET cross-section data obtained using obliquely incident heavy-ion beams shall be analysed and the results used to establish an additional margin.

NOTE 1 The reason is that the concepts of sensitive volume and effective LET are not strictly valid (see ECSS-E-HB-10-12A Clauses 8.6.1 to 8.6.3).

NOTE 2 In some special cases, single event effect rates due to protons have been shown to vary significantly depending upon the angle of incidence.

NOTE 3 SEHE cross-section can be a function of particle species and energy (*i.e.* not just LET) and angle of incidence (see ECSS-E-HB-10-12A Clause 8.7.4).

NOTE 4 It is important that the ion track width of the particles used in the irradiations is sufficient to cover a significant fraction of the gate region.

d. SEHE cross section data shall be based on particles with sufficient range for the technology.

NOTE The reason is that many modern devices (including power semiconductors) have significant vertical structure and very thick epitaxial layers and sufficient range of the incident test particle is required to adequately penetrate through the entire sensitive volume of the device.

e. SEHE cross-section data should be obtained from analyses which include the TID contribution.

NOTE The reason is that stuck-bits can result from cumulative dose (TID) as well as microdose effects.

9.5. Calculation procedure flowchart

The assessment of single event effects and the suitability of the proposed hardware and mission design shall be performed as specified in Figure 2.

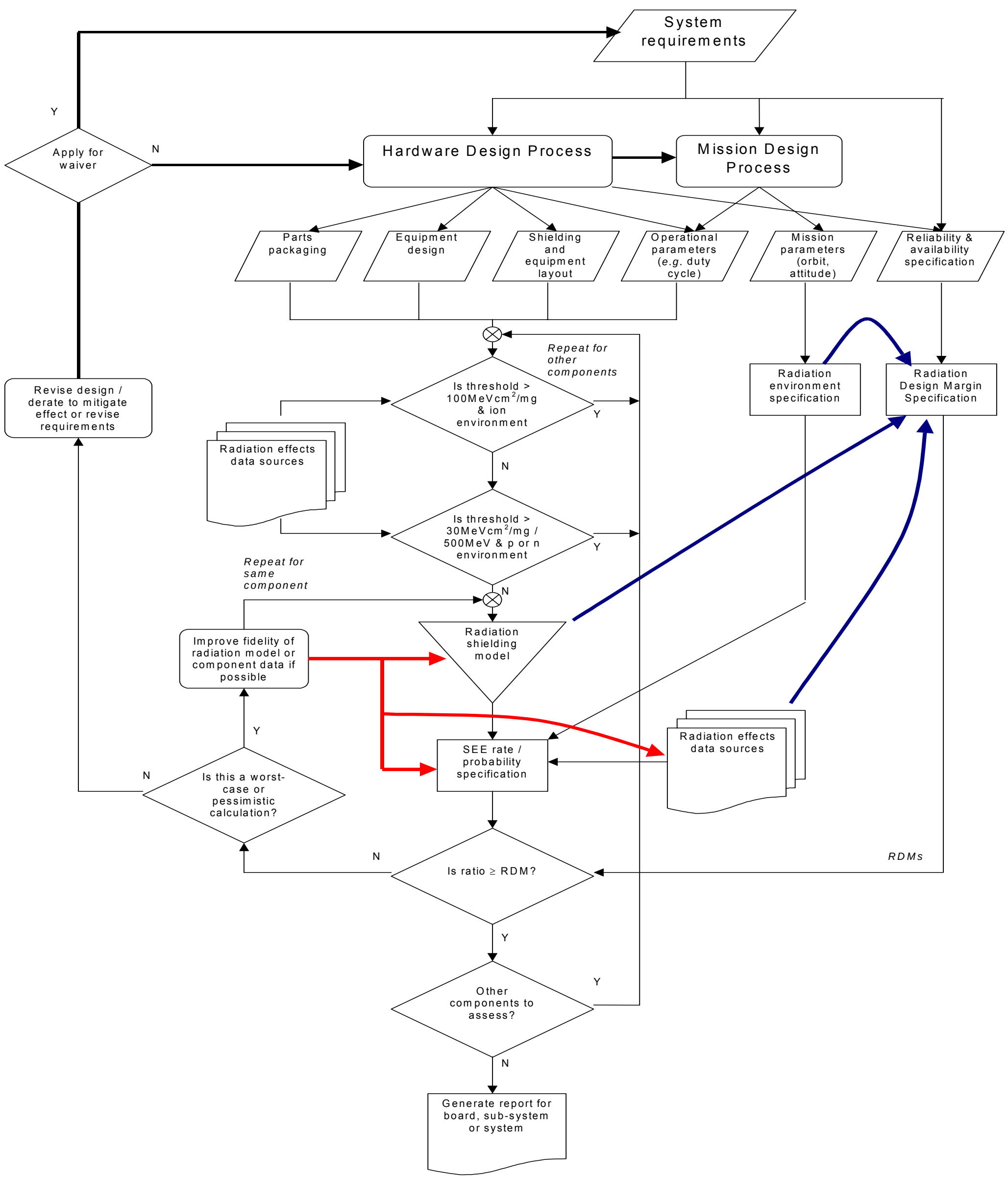


Figure 2: Procedure flowchart for hardness assurance for single event effects.

10. Radiation-induced sensor backgrounds

10.1. Overview

This clause provides an explanation of radiation-induced sensor backgrounds, identifies technologies and components susceptible to this phenomenon, and specifies the general approaches for assessing background rates in susceptible sensors.

Radiation-induced sensor backgrounds described in this section refer to enhanced noise levels in detectors such as:

- IR, optical, UV, X-ray and γ-ray photon detectors, including those comprising single detector elements, as well as imaging arrays;
- detectors for other particle radiations;
- gravity wave detectors;

as a result of the incident radiation environment other than those components of the environment the sensor is attempting to detect. As well as signal production in these sensors from direct ionisation by charged primary particles and secondaries, delayed effects can result such as from the build-up of radioactivity in materials of the spacecraft and instrument. The effects observed (and therefore the approach for calculating background rates) are highly dependent upon the instrument design and operating conditions.

10.2. Relevant environments

a. Radiation-induced backgrounds shall be analysed for spacecraft and planetary-missions where there is the potential for energy deposition events within the bandwidth of the sensor from the radiation environment, whether from a single event or accumulation of interaction of events.

NOTE Example of accumulation is a pile-up.

b. The analysis specified in 10.2 a shall include all components of the environment that have the potential to affect the instrument, including secondary particles from the spacecraft structure and local planetary bodies, and man-made radiation sources

NOTE Example of man-made radiation sources are radioactive calibration sources, and radio-isotope thermoelectric generators.

Table 10: Summary of possible radiation-induced background effects as a function of instrument technology (part 1 of 3).

Application	Instrument / technology type	Example System	Effect	Radiation sources	Comments
γ-ray detection	Semiconductor / scintillator No anti-coincidence (veto) shield		Direct ionisation Ionisation from neutron-nuclear elastic and inelastic interactions Induced radioactivity	Protons & heavier nuclei Electrons Gammas Secondary neutron-emission from spacecraft / nearby planetary atmosphere Protons & heavier nuclei	Induced radioactivity remains important after exiting intense proton regimes or following solar particle events
	Semiconductor / scintillator with anti-coincidence (veto shield)		Direct ionisation events below the veto threshold Ionisation from neutron-nuclear elastic and inelastic interactions Induced radioactivity	Protons & heavier nuclei Electrons Gammas Secondary neutron-emission from spacecraft / nearby planetary atmosphere Protons & heavier nuclei	
	Semiconductor / scintillator with active collimation	CGRO/OSSE, INTEGRAL /SPI	As above + induced radioactivity from events in active collimator which are too low to trigger collimator but do affect primary detector Gamma-ray leakage through collimator	Secondary gamma emission from spacecraft / nearby planetary atmosphere	

Table 10: Summary of possible radiation-induced background effects as a function of instrument technology (part 2 of 3).

Application	Instrument / technology type	Example System	Effect	Radiation sources	Comments
X-ray detection		XMM, Chandra	Direct ionisation	Protons & heavier nuclei Electrons	
			Elastic & inelastic interactions	Protons and neutrons	
			Induced X-ray emission	Charged-particle induced X-ray emission (PIXE) Protons, heavier nuclei producing secondary electromagnetic cascades, and gammas from nuclear interactions	Discrete line emission
				Electron bremsstrahlung	
	Grazing-incidence mirrors	XMM, Chandra	Firsov scattering of protons off mirrors into detector	Typically low-energy, high flux protons	
Charged particle detectors		CREAM, SREM, CEASE	Direct ionisation	Protons & heavier nuclei Electrons	
UV, optical and IR imaging detectors	Silicon CCD and APS, InSb, InGaAs, GaAs/GaAlAs, HgCdTe, PtSi		Particle tracks from direct ionisation and nuclear-interactions	Protons & heavier nuclei Electrons	

Table 10: Summary of possible radiation-induced background effects as a function of instrument technology (part 3 of 3).

Application	Instrument / technology type	Example System	Effect	Radiation sources	Comments
UV, optical and IR detectors	Photomultipliers and micro-channel plates		Direct ionisation of the cathode or dynode by a particle producing secondary electrons Scintillation in optical components of the PMT Cerenkov radiation induced in optical components, or above Cerenkov threshold of other materials	Protons & heavier nuclei Electrons	Discrete line emission
gravity-wave detectors	Free-floating test mass interferometer	LISA	Charging of test mass by ionising particles, including secondary electron emission Energy deposition leading to thermal changes to test-mass or superconducting materials	Protons & heavier nuclei, including secondary nucleons	Electrons usually ignored due to high shielding conditions

10.3. Instrument technologies susceptible to radiation-induced backgrounds

a. If one of the technologies or instruments identified in Table 10 is used in spacecraft or planetary-mission systems, the potential radiation-induced background effects shall analysed.

b. The mechanisms shall be analysed by which the energetic radiation environment can deposit energy in the instrument so as to register as a sensor event.

NOTE The reason is that spacecraft scientific payloads are often unique.

c. The analysis specified in 10.3 b shall include:

1. Events from prompt ionisation by primary particles and all prompt secondaries

EXAMPLE X-ray fluorescence.

2. The potential "pile-up" of such ionising events, within the temporal-resolution of the sensor, which results in higher-than-expected energy deposition.

3. Delayed ionisation effects from induced radioactivity.

NOTE As specified in Clauses 7, 8 and 9, calculation of susceptibility to other radiation effects (total ionising dose, displacement damage, and single event effects) is also normative.

10.4. Radiation background assessment

10.4.1. General

a. Radiation shielding calculations shall be performed to determine the radiation environment at the instrument after passing through the spacecraft structure.

b. Background effects in instruments shall be analysed using:

1. calculations or simulations of the energy-deposition processes in sensitive volumes, or

2. results from particle accelerator irradiations of the instrument or its sensitive components, or

3. a combination of both of the above.

c. Where experimental results from component tests are used, or simulations based on components of the instrument, one of the following shall be performed:

1. shielding calculations for the instrument, to determine the incident particle spectrum on the sensitive volume(s) of the instrument, or

2. an analysis demonstrating that instrument structure has a negligible perturbing effect on the radiation field.

d. Where grazing-incidence mirrors are used, the calculation of the radiation environment at the sensitive volumes of the instrument shall include the effects of Firsov scattering and shallow angle multiple scattering of protons in the grazing-incidence mirrors

NOTE See ECSS-E-HB-10-12A Clause 9.4 for the reasons for including Firsov scattering in the simulation.

10.4.2. Prediction of effects from direct ionisation by charged particles

a. The energy deposition spectrum by direct ionisation shall be calculated by one of the following methods:

1. By using the formula of ECSS-E-HB-10-12A Clause 9.2, if both of the following conditions are met:

   (a) the sensitive volume of the sensor is so small that the incident particle spectrum does not change significantly in either intensity or energy after passing through the volume;

   (b) the pathlength distribution is not change significantly as a result of multiple scattering.

2. By a radiation transport simulation agreed with the customer.

NOTE For guidelines, see ECSS-E-HB-10-12A Clause 5.7.

b. If method specified in 10.4.2 a.1 is used, the following shall be performed:

1. An estimation of the combined effects of the maximum change in energy, intensity and pathlength on the energy deposition, and

2. A demonstration that the error produced is within the accepted margins defined for the project.

10.4.3. Prediction of effects from ionisation by nuclear interactions

Prediction of energy deposition spectra initiated by nuclear interactions event shall be performed by a method agreed with the customer.

NOTE Prediction of energy deposition spectra initiated by nuclear interactions event are usually performed using detailed radiation transport simulations (see ECSS-E-HB-10-12A Clause 5.7). However, where simplifications in the interactions and energy deposition processes permit, simplified analytical solutions are applied, provided the combined effects of the approximations produce an error within the accepted margins defined for the project.

10.4.4. Prediction of effects from induced radioactive decay

a. Nuclear interaction rates in the sensitive volume and surrounding materials (the radioactive decay products from which can affect the sensitive volume) shall be calculated by one of the following methods:

1. By using the formula of ECSS-E-HB-10-12A Clause 9.5, if all of the following conditions are met:

   (a) the sensitive volume of the sensor and surrounding material producing background in the sensor are so small that the incident particle spectrum does not change significantly in either intensity of energy after passing through the volume;

   (b) the pathlength distribution in the sensitive volume and surrounding material is not changed significantly as a result of multiple scattering;

   (c) the probability of secondary nuclear interactions is much lower than the primary interaction rate.

2. By a radiation transport simulation agreed with the customer.

NOTE For guidelines, see ECSS-E-HB-10-12A Clause 5.7.

b. If method spacified in 10.4.4 a.1 is used, the following shall be performed:

1. An estimation of the combined effects of the maximum change in energy, intensity and pathlength, and the influence of secondaries on the energy deposition, and

2. A demonstration that the error produced is within the accepted margins defined for the project.

c. The nuclear interaction rate shall be convolved with relevant response function spectra to radioactive decay in the sensitive volume and surrounding materials, to determine the background count rate in the sensor.

10.4.5. Prediction of fluorescent X-ray interactions

The analysis for the prediction of fluorescent X-ray interactions shall include the induced continuum and discrete X-ray emission spectrum from materials surrounding X-ray detector.

10.4.6. Prediction of effects from induced scintillation or Cerenkov radiation in PMTs and MCPs

a. The method used for predicting the fluorescence or Cerenkov radiation production shall either:

1. use a radiation transport calculation that includes Cerenkov and fluorescence physics models and the instrument shielding geometry, or

2. use a simplified method and shall demonstrate that the level of error in the prediction is within the accepted margins defined for the project.

b. The prediction shall assess the effects of:

1. Direct ionisation of the cathode or dynode of a PMT by a particle, or direct ionisation of the walls of a MCP, in either case producing secondary electrons.

2. Scintillation of optical components of the PMT/MCP.

3. Cerenkov radiation induced in any optical components of the instrument from particles above the Cerenkov threshold.

10.4.7. Prediction of radiation-induced noise in gravity-wave detectors

a. The method adopted for predicting the influence of the radiation environment on gravity-wave interferometric experiments shall be agreed with the customer.

NOTE The method adopted for predicting the influence of the radiation environment on gravity-wave interferometric experiments is normally based on a detailed radiation transport calculation, or if a simplified approach is used, the level of error in the prediction is be estimated in order to ensure that it is within the accepted margins defined for the project.

b. The prediction shall be used to assess the noise introduced into the instrument as a result of the incident radiation:

1. changing the charge of the free-floating test mass;

2. acting as a source of energy to change the thermal conditions of the cryogenically cooled test mass;

3. changing the critical temperature of superconducting materials.

10.4.8. Use of experimental data from irradiations

a. Experimental data from irradiations should be used to validate prediction techniques.

b. If experimental data are used in place of elements of the prediction process, the parameter-space covered by experiment shall ensure that the data can be interpolated to operational environment conditions within the error limits specified by the project.

NOTE 1 This is especially important in assessing the response of the instrument to the local radiation environment.

NOTE 2 Examples of parameter space covered by the experiment are incident particle species and energy, angle of incidence, flux (to allow for effects of pulse pile-up).

11. Effects in biological material

11.1. Overview

The effects that ionising radiation produces in living matter result from energy transferred from radiation into ionisation (and excitation) of the molecules of which a cell is made. The primary effects start with physical interactions and energy transfer, after which changed molecules interact by chemical reactions and interfere with the regulatory processes within the cell.

The resulting radiobiological effects in man can be divided into two different types:

- stochastic effects, where the probability of manifestation is a function of dose rather than the magnitude of the radiobiological effect, and
- deterministic effects, where the severity of the effect depends directly on dose, with a lower threshold dose below which no response occurs.

Symptoms of radiation exposure are classified as either early or late effects, with early effects relating to symptoms that occur within 60 days of exposure, and late effects usually become manifest many months or years later.

This chapter summarises the radiation quantities used to define the environment relevant to radiation effects in biological materials, and specifiies the requirements for quantifying radiobiological effects for space missions.

Note that the discussions in this chapter are aimed at radiation effects on man. Effects on other biological materials (*e.g.* animals or plants flown as test subjects for experiment) on unmanned or manned missions can also be assessed, based on the principles discussed here.

11.2. Parameters used to measure radiation

11.2.1. Basic physical parameters

The following basic parameters shall be used to measure the radiation environment:

a. The absorbed dose, D

b. The air kerma, K,

c. The fluence, Φ, and

d. The linear energy transfer, LET.

11.2.2. Protection quantities

11.2.2.1. General

The following protection quantities shall be used when relating the basic physical parameters to biological systems:

a. The mean organ absorbed dose, D_T

b. The relative biological effectiveness, RBE

c. The radiation weighting factor, w_R

d. The organ equivalent dose, H_T

e. The tissue weighting factor, w_T, and

f. The effective dose, E.

NOTE 1 Protection quantities are defined by the International Commission on Radiobiological Protection (ICRP).

NOTE 2 The mean organ dose, organ equivalent dose, and effective dose are not directly measurable, but are essential for assessing risk due to a radiation environment.

11.2.2.2. Value of the radiation weighting factor, w_R

a. The values of the radiation weighting factor shall be as specified in Table 11.

b. Values for the radiation weighting factor of particles not specified in Table 11 shall be derived by dividing the ambient dose equivalent for the particle H*(10) by the dose at 10 mm depth in the ICRU sphere.

NOTE 1 The radiation weighting factor, w_R, accounts for the different levels of biological effects resulting from different particle types, although they can produce the same mean organ dose. For further discussion on w_R see ECSS-E-HB-10-12A Clause 10.2.2.

NOTE 2 The values in Table 11 are defined and maintained by ICRP. The users are encouraged to consult (WHICH REFERENCE?) for the more recent updates.

Table 11: Radiation weighting factors.

Type and energy range		Radiation weighting factor, w_R
Photons, all energies		1
Electrons and muons, all energies		1
Neutrons, energy	<10 keV	5
	10 keV to 100 keV	10
	100 keV to 2 MeV	20
	2 MeV to 20 MeV	10
	>20 MeV	5
Protons, other than recoil protons, energy >2 MeV		5
Alpha particles, fission fragments, heavy nuclei		20

11.2.2.3. Value of the tissue weighting factor, w_T

The values of the tissue weighting factor shall be as specified in Table 12.

NOTE 1 The tissue weighting factor takes into account the variability in sensitivity of different organs and tissue subject to the same equivalent dose.

NOTE 2 The values in Table 12 are defined and maintained by ICRP. The users are encouraged to consult (WHICH REFERENCE?) for the more recent updates.

Table 12: Tissue weighting factors for various organs and tissue.

Organ or Tissue	Tissue Weighting Factor w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Other tissues and organs	0.05

11.2.3. Operational quantities

11.2.3.1. General

The following operational quantities shall be used for the assessment of radiation exposure:

a. The ambient dose equivalent, H*(d)

b. The directional dose equivalent, $H'(d,\Omega)$

c. The personal dose equivalent, H_P

d. The quality factor, Q

NOTE Operational quantities are measurable. They are defined by the International Commission on Radiation Units and Measurements (ICRU) with the aim of never underestimating the relevant protection quantities, in particular the effective dose, E, under conventional normally-occurring exposure conditions.

11.2.3.2. Value of the quality factor, Q

The values of the quality factors given in Table 13 shall be used.

NOTE This values, related to the unrestricted LET in water, correspond to the ones given by equation (3) below, which is established by ICRP-60.

$$Q(L) = \begin{cases} 1 & : L \le 10 keV/\mu m \\ 0.32L - 2.2 & : 10\ keV/\mu m \le L \le 100\ keV/\mu m \\ 300/\sqrt{L} & : L > 100\ keV/\mu m \end{cases}$$

(3)

Table 13: Specified *Q*–*L* relationship.

Unrestricted linear energy transfer, *L* in water (keV/μm)	*Q*(*L*)
< 10	1
10 – 100	0.32 L –2.2
>100	300/ √L

11.3. Relevant environments

Radiobiological effects shall be analysed for manned spacecraft and planetary-mission systems to be operated within any of the following radiation environments:

a. trapped proton and electron belts (terrestrial and other planetary belts);

b. solar protons and ions;

c. cosmic ray protons and heavier nuclei;

d. bremsstrahlung produced as secondaries from electrons;

e. secondary protons, neutrons and other nuclear fragments which can be generated in atmospheric showers in the planetary environment or within the spacecraft or planetary-habitat structure, including the body itself.

NOTE This contribution is particularly important for cosmic-ray induced secondaries.

f. in close proximity to radioactive or nuclear-energy sources.

EXAMPLE RTGs generating γ-ray and neutron radiation.

11.4. Establishment of radiation protection limits

a. The project shall establish the radiation protection limits to be applied to the mission.

NOTE These limits are established based on the policies and standards defined by the space agency for manned space flight (see ECSS-E-HB-10-12A Clause 10.4 and ECSS-E-10-11A). Where there is more than one space agency involved, the radiation protection limits to be adopted by the project are normally agreed through consensus (*e.g.* through a working group of radiation effects experts from the different partner agencies).

b. The radiation protection limits shall be defined in terms of the protection quantities in Clause 11.2.2 and the operational quantities in 11.2.3.

NOTE These limits can vary between different space agencies.

c. Synergistic effects between radiobiological damage and other environmental stressors (such as microgravity, vibration, acceleration, hypoxia) and the radiation protection limits specified in a. above shall be analysed.

NOTE For guidelines on the influence of spaceflight environment, see ECSS-E-HB-10-12A Clause 10.5.7.

d. The quality factors, radiation weighting factors and tissue weighting factors identified in Table 11 to Table 13 shall be used to determine dose equivalent, organ equivalent dose and effective dose.

NOTE It is the responsibility of the project manager to perform the trade-off between spacecraft and mission design and operation, and their effects on predicted crew exposure, in order to:

* achieve the defined protection limits, and
* ensure radiation protection is managed according to the ALARA (as low as reasonably achievable) principle.

11.5. Radiobiological risk assessment

a. A radiobiological risk assessment shall be performed by comparing the protection and operational quantities calculated according to the definitions in Clause 11.2 with the protection limits defined for the project in accordance with 11.4 a.

b. When calculating the protection and operational quantities as specified in a. above, the influence of shielding in attenuating the primary particle environment and modification to its spectrum at the location of the astronaut **shall** be evaluated as follows:

1. Perform initial calculations as specified in 6.2.2 to assess the influence of shielding for worst-case shielding, environment and secondary production.

2. If these indicate that the protection limits are exceeded, perform more detailed calculations using a detailed sector shielding calculation or Monte-Carlo analysis,calculation, as specified in Clauses 6.2.3 and 6.2.4, respectively .

c. The evaluation specified in b. above shall include the potential variations in radiation exposure as a function of shielding material and its configuration.

d. Scaling to the equivalent areal mass shall not be performed, unless an analysis is performed that demonstrates that the scaling provides an overestimate of the severity of the environment.

e. Shielding issues shall be considered in the context of mission phases and the associated crew activities within the spacecraft habitats, lunar or planetary habitats, or extra-vehicular activities.

f. The crew exposure shall be assessed for both

1. the nominal environment, and

2. conditions when there is exceptional enhancement in the external radiation environment

EXAMPLE A solar particle event or transition through the South Atlantic anomaly.

g. The linear, no threshold (LNT) hypothesis shall be applied extrapolating high-dose-rate data in order to quantify the risk of radiobiological effects.

NOTE For long-term missions the doses are likely to attain values where extrapolation can be replaced by a look up into epidemiological data.

h. If shielding simulations are performed which include self-shielding (*i.e.* treatment of radiation transport in the body), the simulation shall include the variations in a build-up of high LET particles, including the nuclear interactions (“star” events) of these particles.

i. Self shielding should be included for simulations where the shielding afforded is less than provided by the self shielding.

EXAMPLE Astronauts during an EVA.

j. For simulation of the effects of self-shielding, secondary radiation generated within an organ shall not be included in the calculation of the equivalent dose to that organ.

NOTE 1 The reason is that radiation weighting factors already include secondary particle contribution.

NOTE 2 For extremely densely ionising radiation like HZE (high mass and energy) particles and nuclear disintegration stars the concept of absorbed dose can break down and has therefore become inapplicable, but not having better concepts it is the only one used to calculate effective dose or dose equivalent.

11.6. Uncertainties

Analysis of the uncertainties in the exposure calculation shall incorporate the uncertainties in the source data identified in Table 14 (from the atomic bomb data) and Table 15 (from the space radiation field).

NOTE 1 The uncertainties in risk estimates have been evaluated in detail in 'NCRP 1997' [10]. The risk estimates are presented in a distribution that ranges from 1.15 to 8.1×10^{-2} Sv^{-1} for the 90 % confidence interval for the nominal value of 4 % per Sv for an adult US population.

NOTE 2 Uncertainties also arise from systematic errors (and potentially statistical errors in the case of Monte Carlo simulation) in the radiation shielding calculation – see ECSS-E-HB-10-12A Clause 5.8.

Table 14: Sources of uncertainties for risk estimation from atomic bomb data

Uncertainties		Approximate Contribution
Supporting higher risk estimates	Dosimetry bias errors	+10 %
	Under-reporting	+13 %
	Projection directly from current data	+? %
Supporting lower risk estimates	Dosimetry: more neutrons at Hiroshima	-22 %
	Projection, i.e., by using attained age (?)	-50 %
Either way	Transfer between populations	? ±25-50 %
	Dose response and extrapolation	? ±50 %
Source: [11]		

Table 15: Uncertainties of risk estimation from the space radiation field

Source		R_γ	$Q(L)$
Biological	DDREF[3], extrapolation across nationalities, risk projection to end-of-life, dosimetry, etc.	200-300% (mult.)	
	Radiation quality dependence of human cancer risk		200-500% (mult.)
Source: [12]			

[3] DDREF is the Dose and Dose Rate Effectiveness Factor. (NCRP deliberately described only a DREF -a low dose-rate-reduction factor - without including a low dose factor)

Annex A (informative) References

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