



BSI Standards Publication

Space engineering — Calculation of radiation and its effects and margin policy handbook

National foreword

This Published Document is the UK implementation of CEN/CLC/TR 17603-10-12:2021.

The UK participation in its preparation was entrusted to Technical Committee ACE/68, Space systems and operations.

A list of organizations represented on this committee can be obtained on request to its committee manager.

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

This publication is not to be regarded as a British Standard.

© The British Standards Institution 2021
Published by BSI Standards Limited 2021

ISBN 978 0 539 16241 7

ICS 49.140

Compliance with a Published Document cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 November 2021.

Amendments/corrigenda issued since publication

Date	Text affected
------	---------------

English version

Space engineering - Calculation of radiation and its effects and margin policy handbook

Ingénierie spatiale - Manuel de calcul du transport des
radiations et de leurs effets, et politique des marges

Raumfahrttechnik - Handbuch zur Berechnung von
Strahlung, Strahlungseffekten und Marginregeln

This Technical Report was approved by CEN on 19 March 2021. It has been drawn up by the Technical Committee CEN/CLC/JTC 5.

CEN and CENELEC members are the national standards bodies and national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom.



CEN-CENELEC Management Centre:
Rue de la Science 23, B-1040 Brussels

Table of contents

European Foreword	9
1 Scope	10
2 Terms, definitions and abbreviated terms	11
2.1 Terms from other documents	11
2.2 Terms specific to the present handbook	11
2.3 Abbreviated terms.....	11
3 Compendium of radiation effects.....	12
3.1 Purpose	12
3.2 Effects on electronic and electrical systems.....	14
3.2.1 Total ionising dose	14
3.2.2 Displacement damage	14
3.2.3 Single event effects.....	15
3.3 Effects on materials	16
3.4 Payload-specific radiation effects.....	16
3.5 Biological effects.....	17
3.6 Spacecraft charging.....	17
3.7 References	17
4 Margin	19
4.1 Introduction.....	19
4.1.1 Application of margins.....	19
4.2 Environment uncertainty	20
4.3 Effects parameters' uncertainty.....	21
4.3.1 Overview	21
4.3.2 Shielding	21
4.3.3 Ionising dose calculation	22
4.3.4 Non-ionising dose (NIEL, displacement damage).....	22
4.3.5 Single event effects.....	22
4.3.6 Effects on sensors.....	23
4.4 Testing-related uncertainties.....	23

CEN/CLC/TR 17603-10-12:2021 (E)	
4.4.1	Overview23
4.4.2	Beam characteristics.....23
4.4.3	Radioactive sources.....23
4.4.4	Packaging24
4.4.5	Penetration24
4.4.6	Representativeness24
4.5	Procurement processes and device reproducibility24
4.6	Project management decisions25
4.7	Relationship with derating.....25
4.8	Typical design margins25
4.9	References25
5	Radiation shielding26
5.1	Introduction.....26
5.2	Radiation transport processes26
5.2.1	Overview.....26
5.2.2	Electrons.....26
5.2.3	Protons and other heavy particles28
5.2.4	Electromagnetic radiation – bremsstrahlung.....32
5.3	Ionising dose enhancement33
5.4	Material selection.....33
5.5	Equipment design practice.....33
5.5.1	Overview33
5.5.2	The importance of layout.....34
5.5.3	Add-on shielding34
5.6	Shielding calculation methods and tools – Decision on using deterministic radiation calculations, detailed Monte Carlo simulations, or sector shielding analysis36
5.7	Example detailed radiation transport and shielding codes.....45
5.8	Uncertainties.....45
5.9	References46
6	Total ionising dose.....48
6.1	Introduction.....48
6.2	Definition48
6.3	Technologies sensitive to total ionising dose48
6.4	Total ionising dose calculation50
6.5	Uncertainties.....50

7 Displacement damage	51
7.1 Introduction	51
7.2 Definition	51
7.3 Physical processes and modelling	51
7.4 Technologies susceptible to displacement damage	55
7.4.1 Overview	55
7.4.2 Bipolar	56
7.4.3 Charge-coupled devices (CCD)	57
7.4.4 Active pixel sensors (APS)	57
7.4.5 Photodiodes	58
7.4.6 Laser diodes	58
7.4.7 Light emitting diode (LED)	58
7.4.8 Optocouplers	58
7.4.9 Solar cells	59
7.4.10 Germanium detectors	59
7.4.11 Glasses and optical components	60
7.5 Radiation damage assessment	60
7.5.1 Equivalent fluence calculation	60
7.5.2 Calculation approach	60
7.5.3 3-D Monte Carlo analysis	60
7.5.4 Displacement damage testing	60
7.6 NIEL rates for different particles and materials	61
7.7 Uncertainties	68
7.8 References	68
8 Single event effects	70
8.1 Introduction	70
8.2 Modelling	71
8.2.1 Overview	71
8.2.2 Notion of LET (for heavy ions)	71
8.2.3 Concept of cross section	71
8.2.4 Concept of sensitive volume, critical charge and effective LET	72
8.3 Technologies susceptible to single event effects	73
8.4 Test methods	73
8.4.1 Overview	73
8.4.2 Heavy ion beam testing	73

CEN/CLC/TR 17603-10-12:2021 (E)	
8.4.3	Proton and neutron beam testing74
8.4.4	Experimental measurement of SEE sensitivity74
8.4.5	Influence of testing conditions75
8.5	Hardness assurance77
8.5.1	Rate prediction77
8.5.2	Prediction of SEE rates for ions77
8.5.3	Improvements79
8.5.4	Method synthesis80
8.5.5	Prediction of SEE rates of protons and neutrons80
8.5.6	Method synthesis82
8.5.7	Calculation toolkit82
8.5.8	Applicable derating and mitigating techniques82
8.5.9	Analysis at system level82
8.6	Destructive SEE83
8.6.1	Single event latch-up (SEL) and single event snapback (SESB)83
8.6.2	Single event gate rupture (SEGR) and single event dielectric rupture (SEDR)85
8.6.3	Single event burnout (SEB)86
8.7	Non-destructive SEE87
8.7.1	Single event upset (SEU)87
8.7.2	Multiple-cell upset (MCU) and single word multiple-bit upset (SMU)87
8.7.3	Single event functional interrupt (SEFI)89
8.7.4	Single event hard error (SEHE)90
8.7.5	Single event transient (SET) and single event disturb (SED)91
8.8	References92
9	Radiation-induced sensor backgrounds96
9.1	Introduction96
9.2	Background in ultraviolet, optical and infrared imaging sensors96
9.3	Background in charged particle detectors100
9.4	Background in X-ray CCDs100
9.5	Radiation background in gamma-ray instruments101
9.6	Photomultiplier tubes and microchannel plates104
9.7	Radiation-induced noise in gravity-wave detectors105
9.8	Other problems common to detectors105
9.9	References106
10	Effects in biological material108
10.1	Introduction108

10.2	Quantities used in radiation protection work.....	108
10.2.1	Overview.....	108
10.2.2	Protection quantities.....	109
10.2.3	Operational quantities	111
10.3	Radiation effects in biological systems.....	113
10.3.1	Overview.....	113
10.3.2	Source of data.....	114
10.3.3	Early effects	114
10.3.4	Late effects	115
10.4	Radiation protection limits in space.....	117
10.4.1	Overview.....	117
10.4.2	International agreements.....	117
10.4.3	Other considerations in calculating crew exposure.....	118
10.4.4	Radiation limits used by the space agencies of the partners of the International Space Station (ISS)	118
10.5	Uncertainties.....	122
10.5.1	Overview.....	122
10.5.2	Spacecraft shielding interactions.....	122
10.5.3	The unique effects of heavy ions.....	122
10.5.4	Extrapolation from high-dose effects to low-dose effects.....	123
10.5.5	Variability in composition, space and time.....	123
10.5.6	Effects of depth-dose distribution	123
10.5.7	Influence of spaceflight environment	123
10.5.8	Uncertainties summary	125
10.6	References	125

Figures

Figure 1: CSDA range of electrons in example low- and high-Z materials as a function of electron energy	27
Figure 2: Total stopping powers for electrons in example low- and high-Z materials	28
Figure 3: Intensity of mono-energetic protons in a beam as a function of integral pathlength,	29
Figure 4: Projected range of protons in example low- and high-Z materials as a function of proton energy.....	30
Figure 5: Total stopping powers for protons in example low- and high-Z materials.....	30
Figure 6: Stopping power for electrons from collisions with atomic electrons and bremsstrahlung production, and from bremsstrahlung production alone.....	32

CEN/CLC/TR 17603-10-12:2021 (E)

Figure 12: Five electric effects due to defects in the semiconductor band gap [RDE.4]	56
Figure 13: SEE initial mechanisms by direct ionisation (for heavy ions) and nuclear interactions (for protons and neutrons)	70
Figure 22: ISOCAM images for quiet conditions (top) and during solar flare event of November 1997	98
Figure 23: Predicted and measured background spectra observed in OSSE instrument on Compton Gamma-Ray Observatory 419 days after launch [RDG.10]	102
Figure 25: Relationship of quantities for radiological protection.	113

Tables

Table 1: Summary of radiation effects parameters, units and examples.	12
Table 2: Summary of radiation effects and cross-references to other chapters (part 1 of 2)	13
Table 2: Summary of radiation effects and cross-references to other chapters (part 2 of 2)	14
Table 3: Description of physics models (part 1 of 4)	37
Table 3: Description of physics models (part 2 of 4)	38
Table 3: Description of physics models (part 3 of 4)	39
Table 3: Description of physics models (part 4 of 4)	40
Table 4: Example radiation transport simulation programs which are applicable to shielding and effects analysis.	44
Table 5: NIEL rates for electrons incident on Si (from Summers <i>et al</i> based on Si threshold of 21 eV [RDE.11])	61
Table 6: NIEL rates for protons incident on Si (part 1 of 2). This is a subset of NIEL data from Huhtinen and Aarnio [RDE.12].	62
Table 6: NIEL rates for protons incident on Si (part 2 of 2). This is a subset of NIEL data from Huhtinen and Aarnio [RDE.12].	63
Table 7: NIEL rates for neutrons incident on Si (part 1 of 2). This is a subset of NIEL from Griffin <i>et al</i> [RDE.13].	64
Table 7: NIEL rates for neutrons incident on Si (part 2 of 3). These data are from Konobeyev <i>et al</i> [RDE.14].	65
Table 7: NIEL rates for neutrons incident on Si (part 3 of 3). This is a subset of NIEL from Huhtinen and Aarnio [RDE.12].	66
Table 8: NIEL rates for electrons in Si and GaAs (Akkerman <i>et al</i> [RDE.15])	67
Table 9: NIEL rates for protons in Si	67
Table 10: NIEL rates for protons in GaAs.	68
Table 11: Typical materials for UV, visible and IR sensors, with band-gap and electron-hole production energies (e-h production energy for MCT is based on Klein semi-empirical formula.	97
Table 12: Lifetime mortality in a population of all ages from specific cancer after exposure to low doses	116
Table 13: Estimates of the thresholds for deterministic effects in the adult human testes, ovaries, lens and bone marrow.	116

Table 14: CSA career ionising radiation exposure limits.	119
Table 15: ESA ionising radiation exposure limits.	119
Table 16: NCRP-132 recommended RBEs.....	119
Table 17: NCRP-132 Deterministic dose limits for all ages and genders (Gy-Eq.).	120
Table 18: NCRP-132 career ionising radiation exposure limits.	120
Table 19: NCRP-132 career effective dose limits for age and gender specific ionising radiation exposure for 10-year careers.	120
Table 20: JAXA short-term ionising exposure limits.....	120
Table 21: JAXA career ionising radiation exposure limits (Sv).	121
Table 22: JAXA current career exposure limits by age and gender	121
Table 23: RSA short-term ionising exposure limits.	121
Table 24: Russian career ionising radiation exposure limits	122

European Foreword

This document (CEN/CLC/TR 17603-10-12:2021) has been prepared by Technical Committee CEN/CLC/JTC 5 “Space”, the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-10-12.

This Technical report (CEN/CLC/TR 17603-10-12:2021) originates from ECSS-E-HB-10-12A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

1

Scope

This handbook is a part of the System Engineering branch 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 handbook.

This handbook can be applied to the evaluation of radiation effects on all space systems.

This handbook can be applied to all product types which exist or operate in space, as well as to crews of on manned space missions.

This handbook complements to EN 16603-10-12 “Methods for the calculation of radiation received and its effects and a policy for the design margin”.

Terms, definitions and abbreviated terms

2.1 Terms from other documents

For the purpose of this document, the terms and definitions from ECSS-S-ST-00-01 and ECSS-E-ST-10-12C apply.

2.2 Terms specific to the present handbook

None.

2.3 Abbreviated terms

The abbreviated specified in ECSS-E-ST-10-12C apply to this handbook.

Compendium of radiation effects

3.1 Purpose

This clause provides a brief summary of the various mechanisms for radiation damage and effects, and is summarised in the context in Table 1, which identifies important parameters to quantify effects, and gives units and examples. Table 2 can be used by the reader to cross-reference component/instrument technology to radiation effects discussed in detail elsewhere in this document.

Table 1: 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, e.g. CCD transfer efficiency, optocoupler transfer ratio Reduction in solar cell efficiency	Protons, electrons, neutrons, ions
Single event effects from direct ionisation	Events per unit fluence from linear energy transfer (LET) spectra & cross-section versus LET	cm ² versus MeV·cm ² /mg	Memories, microprocessors. Soft errors, latch-up, burn-out, gate rupture, transients in op-amps, comparators.	Ions Z>1
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, β±, 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 2: Summary of radiation effects and cross-references to other chapters (part 1 of 2)

Sub-system or component	Technology	Effect	ECSS-E-ST-10-12C 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	Clause 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 2: 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

3.2 Effects on electronic and electrical systems

3.2.1 Total ionising dose

Total ionising dose (TID) effects in semiconductor devices depend on the creation of electron-hole pairs within dielectric layers (oxides, nitrides, *etc.*) by the incident radiation and subsequent generation of:

- traps at or near the interface with the semiconductor;
- trapped charge in the dielectric.

This can produce a variety of device effects such as flatband and threshold voltage shifts, surface leakage currents, and noise [RDA.1].

TID effects in semiconductors are discussed further in Clause 7 of ECSS-E-ST-10-12C, and Clause 6 of the present handbook.

3.2.2 Displacement damage

Energetic particles such as neutrons, protons, electrons, α -particles and heavy ions can create damage in semiconductor materials by displacing atoms in the crystal lattice. Secondary electrons produced by high-energy photons also produce displacement effects. The result is that stable defect states are created within the bandgap that can

give rise to a variety of effects depending on the temperature, carrier concentration and the location of the defect site [RDA.2]:

- Generation of electron-hole pairs (leading to thermal dark current in detectors).
- Recombination of electron-hole pairs (leading to reduction of minority carrier lifetime and effects in LEDs and laser diodes).
- Trapping of carriers, leading to loss in charge transfer efficiency in CCDs (minority carrier trapping) or carrier removal (majority carrier trapping).
- Compensation of donors or acceptors, also leading to carrier removal in some devices (for example the resistance in a lightly doped collector in a bipolar transistor can increase).
- Tunnelling of carriers (leading to increased current in reverse biased junctions – particularly for small bandgap materials and high electric fields).

Displacement damage effects in semiconductors is discussed further in Clause 8 of ECSS-E-ST-10-12C and Clause 7 of the present handbook.

3.2.3 Single event effects

Single event effects (SEEs) arise from the interaction of single particles (*e.g.* protons, neutrons or heavy ions) with the semiconductor causing either destructive (or potentially destructive) effects or transient effects.

- Destructive
 - Single event latch-up (SEL) in CMOS circuits – a potentially destructive triggering of a real or parasitic pnpn thyristor structure in the device;
 - Single event snapback (SESB) in NMOS devices, particularly in SOI devices – a destructive triggering of a lateral NPN transistor accompanied by regenerative feedback [RDA.3];
 - 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 [RDA.4];
 - Single event dielectric rupture (SEDR) – destructive rupture of dielectric triggered by a single ionising particle in a high-field region of a dielectric *e.g.* in linear devices, FPGAs;
 - Single event burnout (SEB) in power transistors – a destructive triggering of a vertical n-channel transistor accompanied by regenerative feedback.
- Non-destructive
 - Single event upset (SEU) in memories and registers – *i.e.* bit-flips leading to change of stored information [RDA.5];
 - Multiple-cell upsets (MCU) in memories and registers (including single-word multiple-bit upsets (SMU)) – single particle impacts affecting several adjacent bits due to large particle ranges [RDA.6][RDA.7][RDA.8];
 - Several logically 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, *i.e.* multiple bit upsets within a single data word.
 - Single event functional interrupt (SEFI) in control circuitry, *e.g.* in processors, memories or ADCs – transient corruption of a control path [RDA.9];

- Single event hard errors (SEHE) in SRAM and DRAM devices – where semi-permanent damage is sustained by the memory cell due to micro-dose effect from the ionising particle;
- Single event transients (SET) in linear circuits – *i.e.* a current transient which can be interpreted as a false signal [RDA.10][RDA.11][RDA.12];
- Single event disturb (SED) in digital circuits – *i.e.* a signal transient that is propagated to cause an output error in combinatorial logic.

Further information on single event effects is presented in Clause 9 of ECSS-E-ST-10-12C and Clause 8 of the present handbook.

3.3 Effects on materials

Although TID effects are usually considered in the context of microelectronics or active sensors, exposure to ionising radiation at high doses can also degrade polymers (including those used in thermal blankets) and optical materials. In the case of the former, radiolytic reactions occur in which the bonds in the polymer chains are broken and formed with other reactive fragments. The result can be degradation of mechanical and dielectric properties, coloration, and production of gases that can contaminate and corrode nearby materials. Other optical materials such as silica glasses can also suffer coloration and therefore degradation of their optical properties, depending upon the purity of the material. These effects, together with TID effects in microelectronics, are discussed further in Clause 7 of ECSS-E-ST-10-12C and Clause 6 of the present handbook.

As with TID effects, displacement damage can also have deleterious effects on the properties of passive materials. Atomic displacements in optical materials based on alkali halides result in the production of colour centres (charge traps in the band-gap), and therefore darkening of the crystal. This is discussed further in Clause 8 of ECSS-E-ST-10-12C and Clause 7 of the present handbook.

3.4 Payload-specific radiation effects

Payloads can incorporate instruments which can suffer detrimental effects under irradiation, in the main resulting in enhanced background levels, *e.g.*:

- Direct ionisation from primary or prompt secondary particles (*e.g.* in CCDs);
- Added background noise in sensors due to the various mechanisms, *e.g.* random telegraph signals (RTS) discussed in Clause 8 of ECSS-E-ST-10-12C and Clause 7 of the present handbook;
- Gamma-ray detectors are sensitive to radioactive decays even outside regimes of intense particle radiation [RDA.13][RDA.14];
- It is known that high temperature superconductors, proposed for gravity-wave missions, can suffer a reduction in critical temperature under irradiation [RDA.15]. Intense radiation regimes can lead to macroscopic temperature changes in cryogenically cooled materials [RDA.16].

The use of high-mass spacecraft and detector systems necessitates the accurate computation of secondary radiation and its spectrum to the point of energy/charge deposition within the detector bandwidth.

Radiation background effects are discussed further in Clause 10 of ECSS-E-ST-10-12C and Clause 9 of the present handbook.

3.5 Biological effects

Ionisation produces free hydroxyl radicals which compromise one or more of the functions of the cell, this cellular damage becoming apparent after several cycles, or even resulting in immediate cell death. The effects of this can be deterioration of tissue or organ function, presenting within a matter of minutes to 30-60 days after exposure (early radiobiological effects). Stochastic radiobiological effects can occur over the duration of the life of the individual exposed and appears in the form of neoplastic diseases (tumours). These are very probably the results of DNA damage to, and subsequent mutation of, a single cell. In addition to long-term stochastic effects, deterministic late effects are possible, such as the development of eye cataracts, which definitely occur beyond a threshold dose. Individual relativistic high-Z particles can also produce light flashes in the retina. These effects are discussed further in Clause 11 of ECSS-E-ST-10-12C and Clause 10 of the present handbook.

3.6 Spacecraft charging

Spacecraft charging can arise from energetic plasmas (10s of keV), leading to surface charging, or from energetic electrons (MeV), which can penetrate the spacecraft skin and collect in insulators leading to deep dielectric charging. The subsequent discharges can couple into spacecraft systems leading to anomalies and damage. Spacecraft charging is not discussed further in this document, but the reader is referred to a separate ECSS standard (ECSS-E-ST-20-06) for detailed information [RDA.17][RDA.18][RDA.19].

3.7 References

- [RDA.1] P V Dressendorfer, "Basic mechanisms for the New Millennium," IEEE Nuclear and Space Radiation Effects Conference, Short Course, Session III, 1998.
- [RDA.2] P W Marshall and C J Marshall, "Proton effects and test issues for satellite designers," IEEE Nuclear and Space Radiation Effects Conference, Short Course, Norfolk, VA, 1999.
- [RDA.3] P E Dodd, M R Shaneyfelt, D S Walsh, J R Schwank, G L Hash, R A Loemker, B L Draper, P S Winokur, "Single-event upset and snapback in silicon-on-insulator devices and integrated circuits," *IEEE Trans Nucl Sci*, **47**, No 6, pp2165-2174, December 2000.
- [RDA.4] G K Lum, H O'Donnell and N Boruta, "The impact of single event gate rupture in linear devices," *IEEE Trans Nucl Sci*, **47**, pp2373-2379, 2000.
- [RDA.5] A H Johnston, "Radiation effects in advanced microelectronics technologies," *IEEE Trans Nucl Sci*, **45**, pp1339-1353, 1998.
- [RDA.6] G M Swift and S M Guertin, "In-flight observations of multiple-bit upset in DRAMs," *IEEE Trans Nucl Sci*, **47**, pp2386-2391, 2000.
- [RDA.7] A Makiyara, H Shindou, N Nemeto, S Kuboyama, S Matsuda, T Oshima, T Hirao, H Itoh, S Buchner and A B Campbell, "Analysis of single-ion multiple-bit upset in high density DRAMs," *IEEE Trans Nucl Sci*, **47**, pp2400-2404, 2000.
- [RDA.8] C S Dyer, C Comber, P R Truscott, C Sanderson, C Underwood, M Oldfield, A Campbell, S Buchner, T Meehan, "Microdosimetry code simulation of charge-deposition spectra, single-event upsets and

- multiple-bit upsets,” *IEEE Trans Nucl Sci*, **46**, No 6, pp1486-1493, December 1999.
- [RDA.9] S Bee, G R Hopkinson, R Harboe-Sørensen, L Adams and A Smith, “Heavy-ion study of single event effects in 12- and 16-Bit ADCs,” Workshop Record 1998 IEEE Radiation Effects Data Workshop, pp 58-67, 1998.
- [RDA.10] A H Johnston, G M Swift, T Miyahira, S Guertin and L D Edmonds, “Single-event upset effects in optocouplers,” *IEEE Trans Nucl Sci*, **45**, pp2867-2875, 1997.
- [RDA.11] R Koga, S H Penzin, K B Crawford, W R Crain, S C Moss, S D Pinkerton, S D LaLumondiere and M C Maher, “Single event upset (SEU) sensitivity dependence of linear integrated circuits (Ics) on bias conditions,” *IEEE Trans Nucl Sci*, **44**, pp2325-2332, 1997.
- [RDA.12] R Harboe-Sorenson, F X Guerre, H Constans, J van Dooren, G Berger, W Hajdas, “Single Event Transient characterisation of analog IC's for ESA's satellites,” Proceedings of RADECS99 Conference, IEEE 998471, pp 573-581, 1999.
- [RDA.13] C S Dyer, J I Trombka, S M Seltzer and L G Evans, “Calculation of radioactivity induced in gamma-ray spectrometers during spaceflight,” *Nucl Instrum Meth*, **173**, pp 585-601, 1980.
- [RDA.14] C S Dyer, P R Truscott, H E Evans, N D A Hammond, C Comber, and S J R Battersby, “Calculations and observations of induced radioactivity in spaceborne materials,” Proceedings of the 2nd European Conference on Radiation and its Effects on Components and Systems (RADECS) 1993, St Malo, France, IEEE Conference Proceedings 93TH0616-3, pp 77-83, 1993.
- [RDA.15] G P Summers, D B Chrisey, W G Maisch, G H Stauss, E A Burke, M Nasatasi, J R Tesmer, “Electron and proton radiation effects on high temperature superconductor YBa₂Cu₃O₇₋₈,” *IEEE Trans Nucl Sci*, **36**, pp1840, 1989.
- [RDA.16] A L Vampola, R D Jiminez, J E Cox, “Heat loads due to the space particle environment,” *J Spacecraft and Rockets*, **26**, pp474-476, 1989.
- [RDA.17] Carolyn K Purvis, Henry B Garrett, A C Whittlesey and N John Stevens, “Design guidelines for assessing and controlling spacecraft charging effects,” NASA Technical Paper 2361, 1984.
- [RDA.18] “Avoiding problems caused by on-orbit internal charging effects,” NASA-HDBK-4002.
- [RDA.19] ECSS-E-ST-20-06 "Space engineering – Spacecraft charging" (equivalent EN = 16603-20-06:2014)

4

Margin

4.1 Introduction

4.1.1 Application of margins

The application of a margin is ultimately a project management decision, but is based on consideration of a number of uncertainties in the radiation hardness analysis of a particular device or product.

Several issues contribute to the margin, and projects often adopt a “lumped” approach to margins in the domain by assuming that a single margin covers all the issues.

Applying a margin can result in problems for spacecraft development, including:

- The present component class can be unsuitable, and this can imply the use of a different one.
- COTS components can become unusable.
- The present shielding can be insufficient, and this can imply the use of additional shielding.
- Alternative, it can imply the use of lower performance components.
- Conformity to the requirements cannot be ensured without additional and costly testing.

There is often pressure to reduce the margin. However, a margin should not be reduced without a risk analysis. Situations can result in which a mission becomes unfeasible with application of “standard” margins.

It is also important to consider the following issues:

- Criticality

A target (component, experiment, astronaut) can be critical to mission success in which case it is important that the margin guarantees a high probability of survival, functioning, or both. Less critical functions (experiment mass storage, for example) can be affected in such a way as to represent a “nuisance”, and so a less stringent margin can be employed.

- Immunity

If a target can be shown to be immune to radiation to a degree where the most conservative simplified assessment of the effects parameter(s) is considerably below the expected problem threshold, assuming worst-case margins, little further analysis is warranted.

This clause discusses the contributions to the margin and identifies ways in which the risk associated with the margins can be assessed. The domain is the subject of on-going

research and understanding is limited in many areas. Therefore the advice provided is less solid than desired. Where possible normative requirements are indicated in Clause 5 of ECSS-E-ST-10-12C and expanded upon in this clause.

The contributors to the margin are:

- environmental uncertainty (models or other data);
- uncertainty in predicting effects parameters (shielding uncertainty, uncertainty in parameter prediction *e.g.* dose, SEU rate, *etc.*);
- testing: testing is complex and subject to both systematic and statistical uncertainties;
- procurement processes;
- project management decisions.

Each of these is treated below. They are also addressed in the individual clauses.

4.2 Environment uncertainty

ECSS-E-ST-10-04 space environment standard [RDB.1] is the formal location for information on the uncertainties and margins associated with the environment of a space system and related models and data. The standard models contained therein are based on satellite data. It is typically said that the models are accurate to “within a factor 2” as a consequence of uncertainties in these measurements due to:

- instrument calibration and characterisation difficulties;
- extrapolation and interpolation procedures employed in constructing models;
- representativity of the periods measured.

There is strong evidence that the AE-8 models for the electron radiation belts are compatible with the worst case, at least for the long-term average geostationary environment. In addition, geostationary environments are often specified for a “worst longitude” since there is arguably a dependence on longitude and in AE-8 this is a factor of two. The AE-8 models for the electron belts are only intended as long-term averages and the environment over short periods, months or various phases of the solar cycle can be considerably milder or more severe than the average model value. Evaluation of transient effects relates to extremes of the environment rather than the long-term averages represented by the models.

Radiation effects due to solar protons can be due to accumulated exposure or to transient effects. Certainly for the former and often with the latter, the environment is specified through use of statistical models. It is important to appreciate that when such models are employed *a margin is implicitly included*. Nevertheless, the same potential problems with instrumentation apply to solar particle measurements so a design margin can be appropriate. For example, for solar proton induced solar array degradation or total dose, the JPL-91 model can be employed [RDB.2], with a “90 % confidence level”. It is often not appreciated that the environment specified is not a prediction but is rather a risk-level, or budget. A project can relax the specified confidence level, take a greater risk and “achieve” a lower dose.

A similar situation can arise with other environmental aspects when applying “worst case” methodologies – for example with the worst-case fluxes expected in the (dynamic) electron radiation belt.

Accuracy of environmental estimates are provided in the ECSS-E-ST-10-04 space environment standard [RDB.1].

4.3 Effects parameters' uncertainty

4.3.1 Overview

The process of deriving the radiation effects parameter (e.g. absorbed dose, SEE rate, dose equivalent, and background rates) are often complex and often the subject of simplification. In addition, calculation of shielding and interactions with materials around or within the target can be uncertain. As a result some margin are assumed and used for such calculations.

4.3.2 Shielding

For engineering purposes, three, progressively more detailed, levels of radiation shielding assessment are possible:

- Basic use of the “dose-depth” curve

A mission environment specification usually specifies the dose (ionising, non-ionising), or particle fluence as a function of shield thickness (usually assumed to be aluminium). The minimum shielding between the target and space can be established by examining the actual configuration of the system under analysis. The “dose-depth” curve, usually representing a spherical model of the shielding, indicates the dose through this minimum, and a worst-case dose can be estimated assuming all directions experience such minimum levels. Further, if other directions are particularly heavily shielded, they can be attributed a lower dose (according to the dose-depth curve) and the fraction of the total solid angle subtended used to weight the contribution (see ECSS-E-ST-10-12C Clause 6.2.2.2).

- Sectoring

“Sectoring” (see ECSS-E-ST-10-12C Clause 6.2.3) is a method of estimating the effect of shielding surrounding a point of interest taking account of the complexity of the geometry. It samples all directions from the point and finds the total shielding in each direction. Each shielding value in the distribution corresponds to a dose in a “dose-depth curve” (see ECSS-E-ST-10-12C Clause 6.2.3). As a result, the total dose is found through integration of all contributions (weighted by the solid angle represented by the individual values). It is only an approximation in that the dose-depth curve is derived assuming the shielding is spherical (or sometimes planar). In reality, as radiation propagates through the spacecraft structure, it is scattered in direction and generates secondary radiation. Sectoring generally converts all materials to an equivalent amount of aluminium, thereby ignoring the differences in shielding, scattering and secondary production of materials. Slowing down behaviour also has a statistical scatter. Furthermore the environment is generally assumed isotropic. This is a reasonable assumption in most cases but can be incorrect in some circumstances.

The error inherent in sectoring calculations depends on the environment, since electrons scatter more than protons and also generate significant bremsstrahlung – which also scatters. So in electron-dominated environments such as GEO and MEO, or close to Jupiter, it is important to consider the error.

- Monte-Carlo & finite difference models

The full tracking of particles of representative type and energy through a 3-D model of the geometry, with correct attribution of material type, gives the best estimated (see ECSS-E-ST-10-12C Clause 6.2.4).

4.3.3 Ionising dose calculation

Ionising dose is calculated according to the methods defined in ECSS-E-ST-10-12C Clause 7, and Clause 6 of the present handbook. The dose is an integral of the product of the differential fluence of particles and the ionisation energy loss:

$$\int f(E) \cdot \left(\frac{dE}{dx} \right)_i \cdot dE \quad (1)$$

The main uncertainties relate to the use of the appropriate energy loss for the correct material. Uncertainties are usually quite minor.

For thick materials, the dose deposition profile is important to consider, rather than the surface dose.

Some shielding calculations tend to generate TID predictions directly by computing local energy deposit through ionisation, whilst others convert estimates of particle fluence through a material into ionising dose (see Clause 4.5.1 of ECSS-E-ST-10-12C and Clause 6.4 of the present handbook). For the former, RDM factors associated with the TID can be assumed to be taken into consideration in the shielding calculation, whilst for the latter, the additional uncertainty associated with the conversion is very small compared to those incurred in from the fidelity of the shielding calculation and can in any case be neglected.

4.3.4 Non-ionising dose (NIEL, displacement damage)

By analogy with ionising dose, this is an integral involving the non-ionising energy-loss and so includes elastic and inelastic scattering from atoms. The main uncertainty is the non-ionising energy-loss function in a given material. This is often best derived from testing of individual materials or devices.

Solar cell assessment methods have been based in the past on a “damage-equivalence” methodology where extensive testing of cell types was used to derive the behaviour in space. With more complex cell types this approach is not suitable, and a more general approach, utilising direct calculation of the non-ionising dose in the cell materials, and an assessment of cell structure, is used.

4.3.5 Single event effects

Calculation of single event effects (see ECSS-E-ST-10-12C Clause 10 and in Clause 8 of the present handbook) often assumes that all the sensitive parts of “bits” on a chip are well approximated by identical rectangular parallelepipeds. This considerably simplifies the prediction of single event upset rates since a component can be characterised by a single “path-length distribution”. Modern electronics have many different logical elements on the chip and these are often not parallelepipeds. Memories often include control logic that can be susceptible to upsets, “locking” the component, or to latch-up. Consequently many of the assumptions made in the traditional prediction break down. Furthermore, many of the assumptions made in interpreting accelerator test data also break down. Tilting a component with respect to the accelerator ion beam is a common way of trying to mimic ions that produce greater ionisation, but this is only true for flat two-dimensional structures.

The single event transient (SET), which is an upset in analogue electronics – is also a complex problem to deal with. Generally the seriousness of the SET depends on where in the linear circuit the ion strikes, on the settings of the circuit, on the filtering of the signal and on the way in which the signal is used. So evaluation is very application-specific.

4.3.6 Effects on sensors

Radiation background in detectors is a related phenomenon, but is often much more complex to analyse because the specific sensitivity of a payload system depends on its application, what background event rates can be coped with, and whether there are specific energy (or energy-deposit) thresholds in play. Analysis depends increasingly on application of Monte-Carlo simulation to treat the passage of the radiation through the spacecraft and detector and of the interaction with detector elements.

4.4 Testing-related uncertainties

4.4.1 Overview

Testing has clear uncertainties related to systematic and random errors. The source of radiation, preparation of the device or sample, and means of measuring the effects all play a role.

The good calibration of radiation sources, as well as the availability of both the calibration data and estimates of systematic and statistical uncertainties, are fundamental issues. Equally important is a good understanding of the characteristics of the source.

Statistical analysis of results is important and if a limited sample size or number of single event effects observed in a test (or both) is not properly and rigorously accounted for, a good estimation of the measurement error cannot be established.

It is important that the outcome of testing includes a quantitative error estimate, which can be used to demonstrate that the part or product satisfied the requirements that include a specified margin.

4.4.2 Beam characteristics

For particle beam sources, it is important to know:

- energy;
- energy spread;
- flux;
- beam size and uniformity;
- composition.

Beams used for total ionising dose, total non-ionising dose and SEU simulation can pass through “degraders” to reduce the energy and as a consequence what began as a well-defined mono-energetic beam can become broad in energy. Such energy spreading is taken into account in interpretation because effects can be energy dependent.

4.4.3 Radioactive sources

For radioactive sources, such as ^{60}Co , commonly used for total dose testing, the emission is normally characterised by a total ionising dose measurement. Account should be taken of the dose variation with location with respect to the source. Sources can emit a spectrum of (mainly) photons and electrons and it is important to take this into account.

^{252}Cf used for single event effects screening is a special case. In addition to its main emission (96.9 %) of alpha particles, it emits neutrons (2.3×10^9 neutron/s/mg) and a range of ions that have rather low energy. The source is usually used in a rough vacuum

to ensure sufficient particle range. Nevertheless, the penetration capabilities of the ions are poor.

4.4.4 Packaging

The effect that electronic component packaging has in modifying the source environment should be appreciated. Preparation of the sample can include removal of the lid of electronic components, *etc.* The purpose of this is often to ensure that particle from a source of low energy can reach the sensitive zones of a device. But such preparation can be difficult and residual layers can still obstruct the sensitive device regions under test.

4.4.5 Penetration

In electronic components, apart from problems of packaging in degrading low-energy sources, low-energy ions can slow significantly in the device and as a result their LETs, NIELs or dose profiles are not those of ideal un-slowed primaries.

For materials and solar cells, it is important to consider also the penetration behaviour. The profile of deposited dose (ionising or non-ionising) depends on the energy distribution and particle type of the radiation. While the “surface dose” can correspond to the in-orbit dose, if the spectrum of energies or particle types is very different, the resulting dose profile in the material can be very different from that in space. For example in optical materials, the resulting distribution of colour centres can be unrepresentative.

4.4.6 Representativeness

Space radiation is usually characterised by high energy and (relatively) low flux. Ground tests attempt to simulate this in a cost-effective and time-compressed manner. As a result, energies and particles are used which often do not correspond to space conditions. As mentioned in 4.4.5, particle penetration sometimes is not as desired and in addition, other properties of particle propagation and damage can come into play. Direct ionisation single event effects are assumed to be characterised by particle LET, independent of particle species and energy. However, there is evidence that different ion species possessing the same LET can give rise to different effects because of the details of the ionisation track structure. Tilting devices to change the “apparent LET” can cause range effects to come into play, invalidating the “non-slowing” assumption.

Dose rates in testing are generally different from in space and it is known that some devices respond differently to low and high dose rates.

While SEU testing devices with protons, a significant dose can be imparted to the device, degrading its behaviour and modifying its response. In order to achieve a statistically meaningful number of single event errors, this degradation can be difficult to avoid.

4.5 Procurement processes and device reproducibility

The device being flown should be as identical as possible to the one(s) tested. However, this is becoming more difficult to achieve as device manufacturing is a worldwide process, part codes do not guarantee the same manufacturing batch, and physical examination of devices is becoming very difficult.

4.6 Project management decisions

The ultimate authority to decide margins and margin policy is the project manager. In such decision making, it is important to clearly understand an analysis of the risks to the project as a result of changing the margins. Such decision-making cannot be supported if the analysis of the criticality and mission impact of a device or product, and of the uncertainties related to environment, and testing, are not available.

4.7 Relationship with derating

Derating is the “process of designing a product such that its components operate at a significantly reduced level of stress to increase reliability.” Reference ECSS-Q-ST-30-11 [RDB.3]) discusses in detail the derating methods for a wide range of components.

If it can be demonstrated that de-rating improves the ability of the component to withstand radiation effects, it can usefully be employed. Nevertheless, it does not affect the margin to be used – it rather allows a component to comply with the specification, including the margin.

System de-rating can also be useful. For example, in the presence of single event transients (SET, see Clause 9.4.1.7 of ECSS-E-ST-10-12C, and Clause 8.7.5 of the present handbook), filtering and slowing the response of the circuit or system to analogue signals can protect the system against invalid responses to erroneous analogue signals induced by SET.

4.8 Typical design margins

A minimum RDM for long-duration operational geostationary missions where there is a lot of experience, and the environment is predicted on the basis of AE-8, is typically 1.2. However, certain assumptions are made on shielding and parts conservatism and this margin is established on a case-by-case basis.

For other missions the RDM can vary between 1.2 and 2 depending on mission reliability requirements.

Short duration missions or applications subject to episodic increases (*e.g.* SMART-1) should generally consider the risk of encountering a period of enhanced radiation (*e.g.* recurrent electron radiation belt enhancements due to coronal hole co-rotating region triggered storms).

4.9 References

- [RDB.1] ECSS-E-ST-10-04 "Space engineering – Space environment" (*equivalent EN = EN 16603-10-04:2015*)
- [RDB.2] J Feynman, G Spitale, J Wang and S Gabriel, “Interplanetary proton fluence model: JPL 1991,” *J Geophys Res*, **98(A8)**, pp13281-13294, 1993.
- [RDB.3] ECSS-Q-ST-33-11 "Space product assurance – Derating EEE components" (*equivalent EN = EN 16602-30-11:2014*)

5 Radiation shielding

5.1 Introduction

In this clause we outline the interaction processes of particles found in the space environment, and trends in the importance of these processes as a function particle energy and target material. Key terms used, such as particle range and stopping power, are defined, shielding calculation approaches are described together with typical models used for these applications, and the standard techniques for mitigating radiation effects by radiation shielding are identified.

5.2 Radiation transport processes

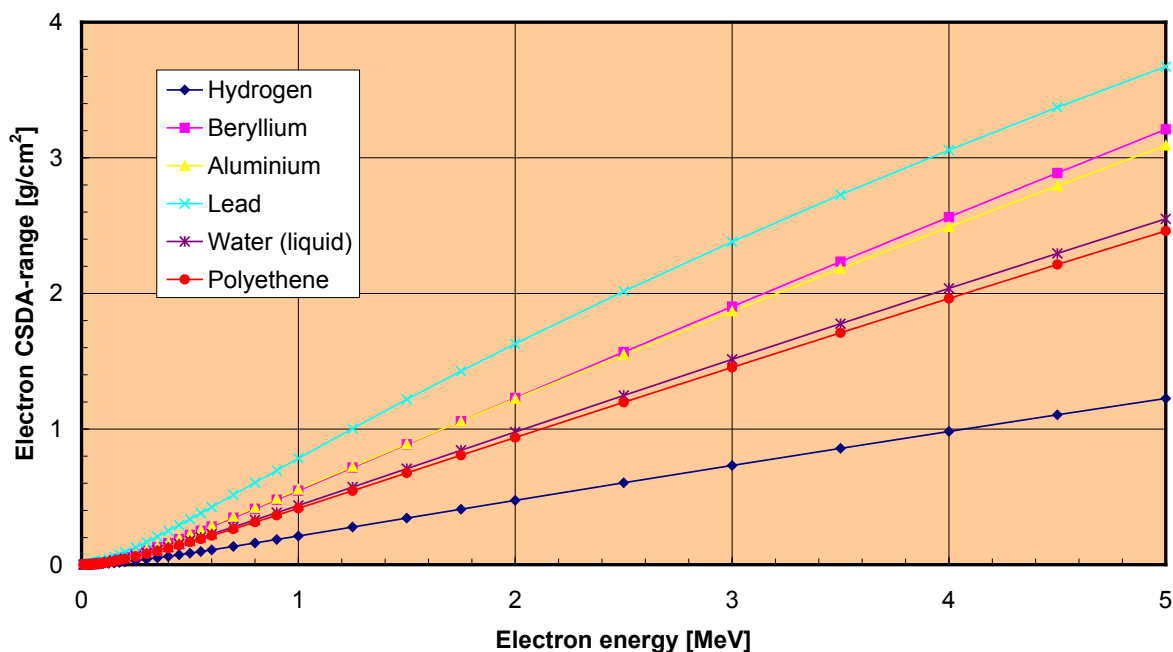
5.2.1 Overview

There are many texts describing the transport of energetic particles through materials and it is not the intention of this clause to repeat this work. Instead this clause intends to highlight the main interaction mechanisms of electrons, protons, heavy ions, and electromagnetic radiation.

5.2.2 Electrons

Electrons interact with material mainly at the atomic level, producing excitation and ionisation, losing energy and being scattered in the process. Such scattering can lead to highly convoluted electron paths in the material. Electron acceleration in the strong electric field of the atomic nucleus results in the generation of energetic photons known as ‘bremsstrahlung’ (braking radiation). For electrons in the energy range less than 5 MeV (typical of the Earth’s radiation belts) almost all energy loss during passage through a material is by bremsstrahlung and by interaction methods resulting in atomic excitation and ionisation of the material, *i.e.* the creation of electron-hole pairs with no momentum transfer to the atom.

The rate of loss of energy with distance traversed is known as the stopping power of the material. The amount of data available on stopping power for various materials at different incident particle energies is considerable. The range of an electron of a given energy is clearly an important parameter to understand in calculating the dose received by a component. Figure 1 and Figure 2 show the *continuous slowing down approximation* (CSDA) range and stopping powers for electrons in hydrogen,

CSDA range of electrons in various materials

NOTE: CSDA refers to the average integral pathlength of the electrons in the material rather than penetration.

Figure 1: CSDA range of electrons in example low- and high-Z materials as a function of electron energy

¹ Also known as polyethylene or polythene.

Total stopping-powers for electrons in various materials

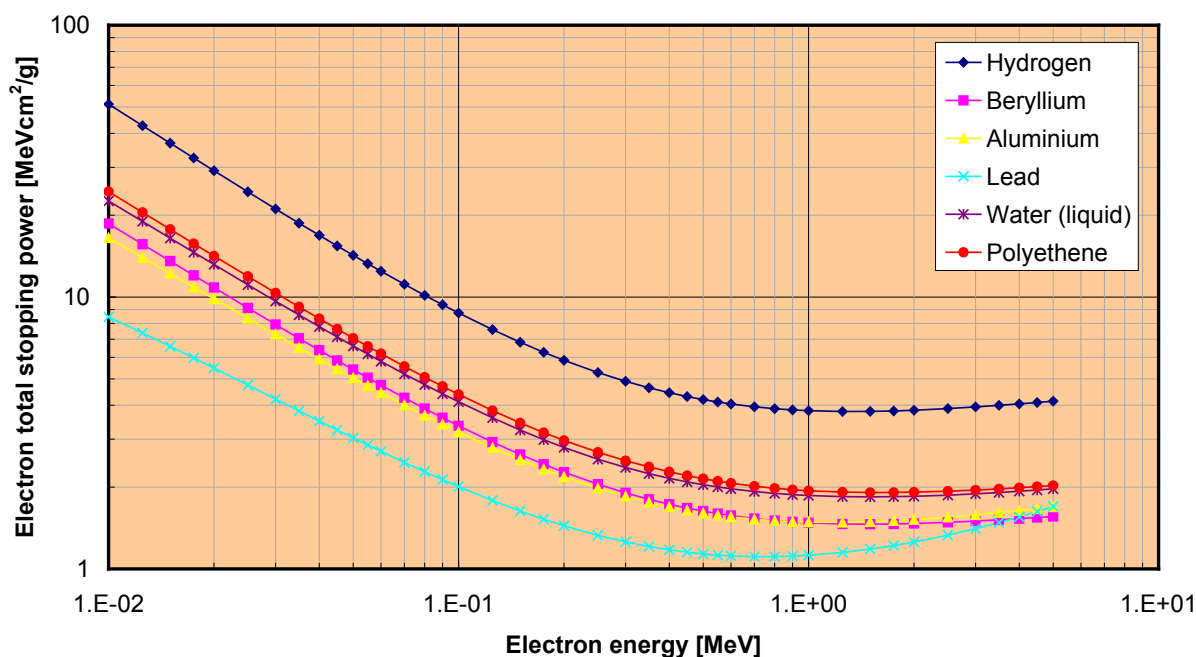


Figure 2: Total stopping powers for electrons in example low- and high-Z materials

available from the US National Institute of Standards and technology website [RDC.1]). The CSDA range corresponds to the integral pathlength travelled by electrons assuming no stochastic variations between different electrons of the same energy (see Clause 5.2.3). As already mentioned, electrons can suffer considerable multiple scattering, therefore, the *depth of penetration* is for most cases shorter than the CSDA range (depending upon the electron energy and material).

Typically for electrons in the space environment, the Z/A factor in the Bethe formula for the collision stopping power dominates [RDC.2]. Therefore, since there are fewer target electrons per unit mass in high-Z materials, the electron range (in units of g/cm^2) is greater in high-Z materials, such as lead, than in lower-Z materials, such as aluminium and silicon. This is illustrated in Figure 1. However for dose behind a shield, the increased scattering in high-Z materials reduces the dose more for thin high-Z shields than for thin low-Z shields. For thicker shields the bremsstrahlung becomes important, and low-Z shielding is more efficient than high-Z. An optimum shield employs a low-Z layer followed by a high-Z layer (discussed further in Clause 5.4). Such graded shields against electrons can give weight or dose advantages of as much as a factor of ten, depending upon the electron spectrum, and the degree of the dose attenuation to be achieved. It cannot be optimized without a careful application of radiation transport simulation codes.

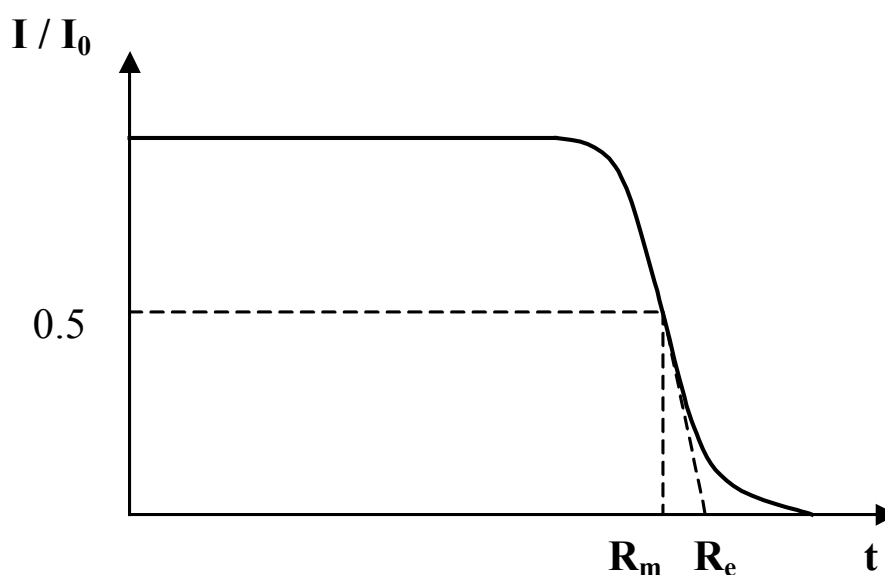
5.2.3 Protons and other heavy particles

Inelastic collision with atomic electrons is the main mechanism of energy dissipation for protons and heavy ions in matter. Being heavier particles, these are not subject to the range of scattering experienced by electrons and their paths through materials are thus easier to compute. However, care should still be taken in interpreting published range data for protons and heavier ions, since particle range can be defined in several ways:

- **CSDA range** assumes no stochastic variations in the interactions for different protons of the same initial energy, and no angular deflections of the particles. In reality, the probabilistic nature of the interaction process gives rise to straggling, in which some protons have slightly longer pathlengths whilst others have shorter pathlengths. This is depicted in Figure 3, which shows the variation in intensity of a mono-energetic proton source as it passes through material. The *mean range* R_m is to a good approximation equal to the CSDA range and represents the integral pathlength after which the intensity is reduced by a factor of two, *i.e.* it is not the range at which all particles are stopped.
- **Extrapolated range** (R_e in Figure 3) attempts to compensate for range straggling, and is determined by extrapolating the line of maximum gradient in the intensity curve (Figure 3) until it reaches zero intensity.
- **Projected range** is the *average depth of penetration* of a particle measured along the initial direction of the particle. This value takes into consideration the deflection of the protons/ions due to multiple scattering.

The projected range (for low-energy protons/ions) or the extrapolated range (for higher energy protons/ions) are more appropriate quantities for assessing radiation-shielding effects.

Figure 4 and Figure 5 show the projected ranges and stopping powers for protons as a function of energy in hydrogen, beryllium, aluminium, lead, water and polythene. Due to the smaller scattering of heavy particles, the Z/A term in the Bethe-Bloch equation always means that low- Z materials provide more mass-efficient shields, as indicated in Figure 4.



NOTE: This range curve demonstrates the distinction between mean range R_m (almost exactly equal to CSDA range) and extrapolated range R_e .

Figure 3: Intensity of mono-energetic protons in a beam as a function of integral pathlength,

Projected range of protons in various materials

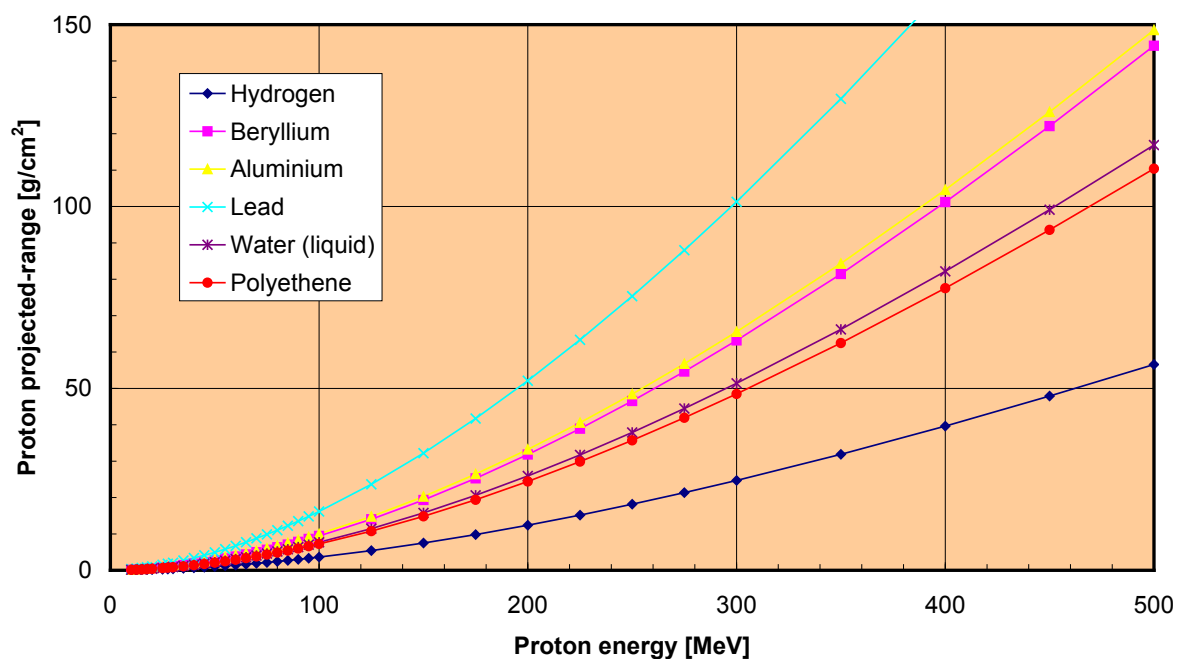


Figure 4: Projected range of protons in example low- and high-Z materials as a function of proton energy.

Total stopping-powers for protons in various materials

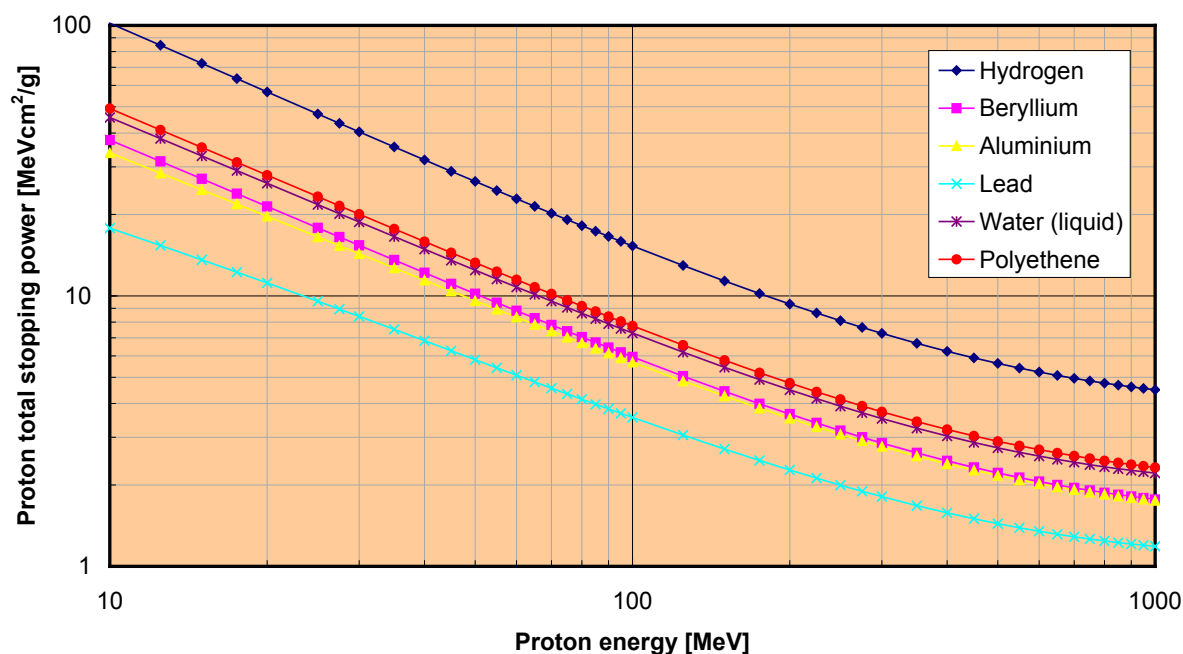


Figure 5: Total stopping powers for protons in example low- and high-Z materials.

The ranges and stopping powers for ions heavier than protons can be estimated based on the following approximate formulae:

$$S_i(E_i) = z_i^2 S_p \left(E_i \frac{M_p}{M_i} \right) \quad (2)$$

$$R_i(E_i) = \frac{M_i}{M_p z_i^2} R_p \left(E_i \frac{M_p}{M_i} \right)$$

where:

$S_i(E)$	= stopping power for ion with energy E;
$S_p(E)$	= stopping power for proton with energy E;
$R_i(E)$	= range of ion with energy E;
$R_p(E)$	= range of proton with energy E;
z_i	= charge number of ion;
M_i	= mass of ion;
M_p	= mass of proton.

In addition to interactions with electrons, there is however a small, but not negligible, chance of protons and other ions interacting with atomic nuclei, causing excitation and fragmentation of the nucleus or the emission of secondary neutrons, protons, α -particles and other light nuclear fragments, as well as γ -rays. The probability of such processes taking place depends on the charge, mass and energy of the incoming particle, and on the properties of the target material. The fragments and secondaries produced in this manner are hazards that cannot be ignored in some circumstances such as manned missions or applications sensitive to single-event processes. Secondary neutrons produced in spacecraft materials contribute significantly to the radiation exposure to astronauts on large structures such as the Shuttle and Space Station, and can significantly enhance background rates in some sensitive scientific equipment. The secondary neutron flux produced by cosmic radiation and solar event particle interactions in planetary atmospheres or the surfaces of solar system bodies can also be important when considering radiation exposure for manned interplanetary missions, or enhanced background in specialised instrumentation such as radiation monitors.

The reader should note that in addition to being more efficient at slowing down ions through ionisation, low-Z materials produce fewer secondary products. Hydrogen is the optimum material on a mass basis, but is rarely practical. However, polythene is used extensively on the ISS.

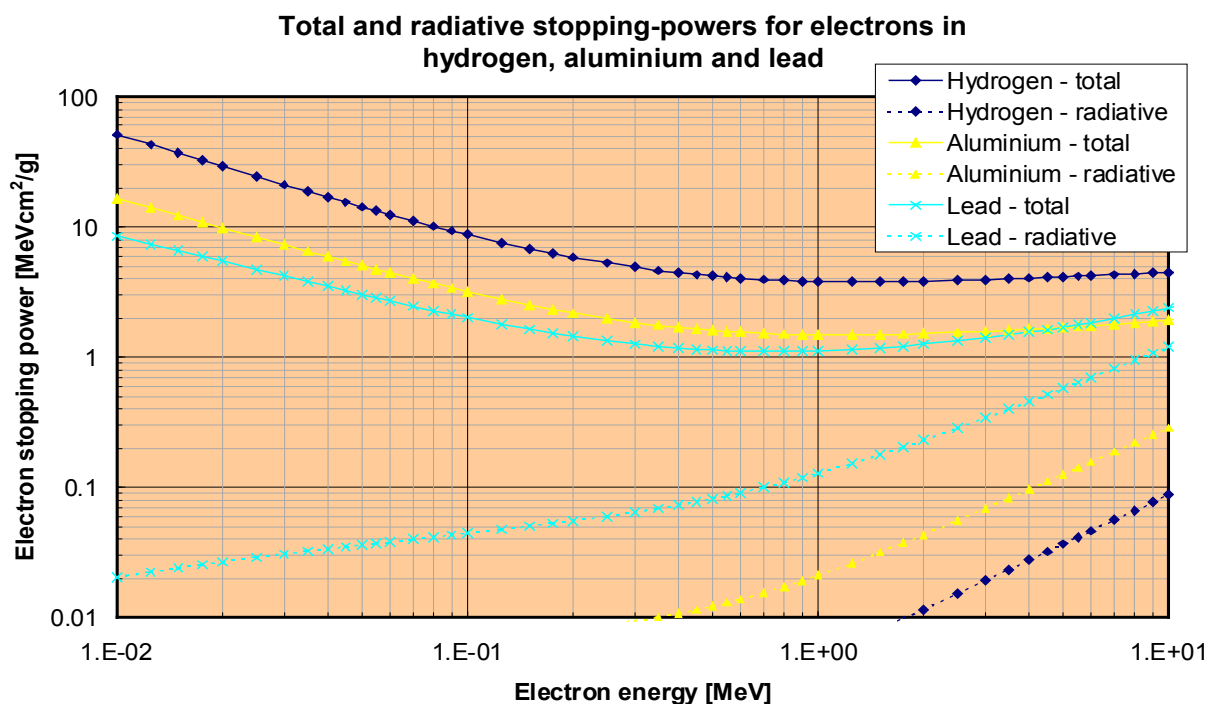


Figure 6: Stopping power for electrons from collisions with atomic electrons and bremsstrahlung production, and from bremsstrahlung production alone.

5.2.4 Electromagnetic radiation – bremsstrahlung

As electrons slow down in material, they generate “braking radiation,” or bremsstrahlung, photons with a distribution of photon energies and directions. These photons subsequently interact through a number of processes (Rayleigh scattering, photoelectric effect, Compton effect and pair-production), resulting in the loss or scattering of the incident photon, and for the three latter processes, the production of electrons or positrons that can induce further ionisation or bremsstrahlung.

Photons generated by electron bremsstrahlung are the main concern from a space radiation perspective although ambient X-rays and gamma rays can also affect sensitive scientific payloads. Bremsstrahlung production allows energetic electrons to deposit energy significantly beyond the range of electrons in materials due to the longer average ranges of the photons.

The fraction of energy loss by bremsstrahlung production is highly dependent upon the material, varying as the square of the atomic number. Figure 6 shows the stopping power for electrons from collisions with atomic electrons and bremsstrahlung production, and from bremsstrahlung production alone (the latter is identified as the *radiative stopping power* in the figure). It can be seen that for energetic electrons in higher-Z material, such as aluminium and especially lead, a greater fraction of energy loss occurs by the bremsstrahlung process than for low-Z materials.

5.3 Ionising dose enhancement

It is important to realise that simply adding more shielding does not always lead to reduced dose at the sensitive target. Depending on the radiation environment and on the local spacecraft and instrument geometry, there are cases where this can rather lead to more secondary particles or to undesirable changes in the incident particle energy spectrum, hence actually enhancing the dose. In particular, the high-energy cosmic rays are difficult to shield against, and nuclear interactions in the shield give rise to a significant multiplicity of secondary particles, the lower-energy charged particles producing more ionisation than the original cosmic ray. Additionally, dose enhancement can be seen at boundaries between high-Z and low-Z materials. This implies paying special attention in optimising the shielding structures.

5.4 Material selection

Higher-Z materials are more effective at shielding electrons as more electrons are scattered than in lower-Z materials. However, bremsstrahlung photon production increases with increasing Z number. As indicated above, it is therefore possible to create ‘sandwich’ composite shields, which balance the benefits of electron stopping power of high-Z materials along with the lower bremsstrahlung production of lower-Z materials.

To shield against electrons, the first layer facing space is a low-Z material that attenuates the high-energy electrons whilst minimising bremsstrahlung production, while the next, high-Z layer scatters lower-energy electrons and attenuates any bremsstrahlung created by earlier interactions. For X-rays, the shield is reversed (high-Z material first) to attenuate photons and then absorb secondary electrons in the lower-Z material.

Although there are occasions where such sandwich shields are desirable, the standard engineering approach is to calculate the shield thickness that achieves the required dose attenuation in aluminium and if possible to realise the shield in aluminium. Where housing issues arise the general approach is to convert the thickness of aluminium into that of a higher-Z material. As has been discussed previously higher-Z materials are more effective at attenuating electrons although they produce bremsstrahlung more effectively. It is important, when applying sector shielding analysis (which approximates all materials to aluminium), to ensure the result is still conservative. More accurate results imply considering such effects using, for example, Monte Carlo coupled electron-photon simulation codes..

5.5 Equipment design practice

5.5.1 Overview

The most common starting-point for equipment radiation effects and shielding analysis is the:

- ionising dose-depth curve;
- information on NIEL as a function of depth;
- LET spectrum (or for protons-induced SEEs, the proton flux) as a function of shielding.

A first-cut at the shielding analysis can be made by determining the dose or particle flux corresponding to the most lightly shielded part of the subsystem under evaluation. If the dose is tolerable then clearly no further analysis is performed. However, the identification of a problem implies a more extensive analysis of shielding be performed,

possibly including a sector-analysis or even 3-D radiation transport simulation of the whole or a part of the spacecraft (see Clause 5.6).

5.5.2 The importance of layout

When optimising the configuration of equipment in a spacecraft, it is important that the designer always attempts to put equipment boxes containing the more sensitive devices in protected locations; to surround them with structures containing less sensitive materials. The ultimate aim of this design practice is to use "built-in" shielding such that the need for "add-on" shielding is minimised. Layout therefore has a fundamental importance in the design of a radiation-tolerant spacecraft. Considerations include, for example:

- If the spacecraft is spin-stabilised, the solar array is wrapped-around at least part of the spacecraft providing the equivalent of 3 to 4 mm of aluminium. This is a significant addition (possibly 30 kg) to the built-in shielding provided by platforms, box covers and circuit boards.
- Microelectronics in the centre of a stack of printed circuit boards can be exposed to only one-tenth of the dose received by the same circuits on the uppermost board of a stack. Similarly, equipment boxes near the edge of a platform receive greater dose than those near the centre.
- Many equipment boxes designed by European industry are made up of sections milled out of solid aluminium with certain parts milled very thin as a weight-saving measure. Such an absorber array gives less protection than the uniform sheet-metal enclosures more common in the USA. This is a case of the general rule that good built-in protection from radiation is a matter of total mass as well as efficient mass distribution. This same rule applies not only to box structures, but also to the arrangement of masses around a box containing sensitive devices.
- The mass of the spacecraft structure can be misleading when assessing radiation shielding. Often the mass is concentrated in struts, attachment points, mechanical connectors and stiffeners. The facings ("shims") of a carbon fibre honeycomb can be very thin (a few hundred micrometers), and the honeycomb structure can contain more mass but presents a smaller solid angle to interior objects.
- Other large subsystems, such as batteries, propellant tanks and apogee boost motor can provide significant shielding. Future missions can use lithium-ion battery technologies, which can make feasible the use of thin, large area cells that can also act as an absorber to the incident radiation.
- Clearly, all the above points are subject to other design issues such as spacecraft mass balance, thermal behaviour of subsystems and the overall spacecraft, and other threats to spacecraft operation such as from hypervelocity impact from debris or meteoroids.

5.5.3 Add-on shielding

5.5.3.1 Introduction

If built-in mass on the spacecraft cannot be arranged so as to protect all sensitive components, the solution can be to judiciously add some "add-on". Given the mass penalty from adding shielding, other options for protecting the component or subsystem should also be assessed from the point of view of impact on cost and system/mission performance.

The choices to be made when considering add-on shielding include:

- the elemental composition;

- the location;
- the method of attachment.

The question of material composition has been discussed earlier, and in the following sections, which consider shield location and method of attachment, the reader should bear in mind the possible use of high- or low-Z materials (or combinations of both) for the particular radiation environment.

Added shielding can be considered as either "local" or "whole box". If the array of devices to be shielded is small, we can save weight by enclosing the array in a compact shield rather than build the same thickness onto the outside of the equipment. This is the idea of "local" shielding: simply to obtain a given dose or particle flux reduction in a given volume for the minimum weight penalty. For instance, a single integrated circuit is best protected by a blob of filled plastic applied directly to the package or by using thicker Kovar for the covers. This type of shield is called a "spot shield".

When adding shielding, it should be borne in mind that for the same thickness and mass of planar material added, the radiation dose/fluence from residual primary particles at a point behind the shield is reduced more if the shield is closer. This is as a result of the increased mean pathlength of the radiation as well as the increased solid angle subtended by the shield.

5.5.3.2 On-PCB shielding

5.5.3.2.1 Spot shielding

The simplest type of shield is one totally surrounding the device and lying close to it. Alumina-filled plastic has a good insulating power and can be given suitable mechanical strength to resist vibration. With ICs, shielding is sometimes performed in two parts: one above and one below the board. Screw-on fins have been designed for ICs, so screw-on shields can also be designed. The USAF has successfully procured CMOS devices with Kovar lids about twice the usual thickness.

A design of package incorporating radiation shielding was developed for the USAF [RDC.3] for the UK AMPTE satellite, tantalum spot-shielding was applied to the lids of certain CMOS circuits. Calculations of layered shield have shown that the dose in geosynchronous orbit can be reduced to 200 rad(Si) for 10 years.

5.5.3.2.2 Edge of board

Under the heading of "Efficient Use of Built-in Mass" comes the use of other active components on the same board. These, if arranged properly, can supply absorber mass in exactly the most critical direction - the line of view through the thin box walls. However, only the middle area of the board gets full benefit of this mode of shielding. On the other hand, if we put add-on shielding around the edge of the device area, the whole of the board gains full benefit.

5.5.3.2.3 Internal slabs

The types of shield so far described protect only one plane of a single component. If a whole plane or several planes are sensitive to radiation, then the region involved can be sandwiched between slabs of material. Such a slab is bolted onto the lower frame element where the clearance with respect to the next board allows this. In certain cases, foam sheets can be inserted or potting compound can be poured into the module after fabrication. In extreme cases, an empty module - carrying only the add-on absorber- can be inserted.

5.5.3.3 Whole box shielding

5.5.3.3.1 Bolt-on slabs

The simplest way of adding mass to a box can appear to be by bolting a slab of plastic or metal to the outside. In fact, this is rarely convenient because:

- Suitable bolting can be unavailable on the outside of the box and
- The shield can foul other boxes or cables lying close to the sensitive box.

The latter difficulty can sometimes be dealt with by using a very dense material such as lead, tungsten or tantalum, but these can generate excessive bremsstrahlung if the low-energy electron fluxes from space impinge directly. As already mentioned, high-Z materials perform best once an initial few millimetres of lower-Z material (*e.g.* aluminium or polyethene) has removed these electrons so that bremsstrahlung generation is minimised.

5.5.3.3.2 Thickened walls

If the precise amount of shielding to be used is known at the beginning of the design, then box walls can be designed to the thickness over and above the thickness that meets the mechanical strength requirements. Many boxes are milled out of solid metal and hence this does not present mechanical difficulties. It has already been noted that, for radiation-sensitive boxes, thin areas of box wall are to be avoided. Such thin areas are sometimes produced when mechanically unnecessary material is milled away. As discussed, the thickening of a whole box is likely to be uneconomical in weight unless shielding of every component in the box is a requirement.

5.6 Shielding calculation methods and tools – Decision on using deterministic radiation calculations, detailed Monte Carlo simulations, or sector shielding analysis

Modelling of the effects of built-in or add-on shielding is strongly advisable, unless it can be shown by simple calculation that for the thinnest (worst-case) shielding condition, the radiation environment at component level is negligible, and the effects of secondary particle build-up can also be ignored.

The above sections show that the interaction processes of radiation in spacecraft materials can often be very complex and therefore non-trivial to quantify. A full treatment implies the solution of the Boltzmann transport equation (BTE). Deterministic methods apply numerical techniques to integrate the finite difference form of the Boltzmann equation. Although these are computationally efficient and accurate, deterministic methods are often limited to simulation of 1-D or 2-D geometries. Complex 3-D geometries are more often simulated using Monte Carlo solutions of the BTE, which involves simulating individual particle trajectories by the systematic sampling of probability distributions derived from cross-sections. Clause 5.7 provides a list of example radiation transport codes based on deterministic or Monte Carlo solutions to the BTE, applicable to coupled electron-gamma transport, coupled low-energy neutron-gamma transport, energetic nucleon-meson transport, or even comprehensive treatment of almost all hadronic and electromagnetic interactions of a wide variety of particles. The physics models which should be included in the simulation are identified in ECSS-E-ST-10-12C Table 6 as a function of source radiation and application.

Table 3: Description of physics models (part 1 of 4)

#	Primary Particle	Energy range	Target/geometry considerations	Application considerations	Physical processes treated
1	electrons	< a few 100s keV			Direct ionisation Multiple scattering
2	electrons	>100's keV <1.022 MeV	δ -rays important if their ranges are similar to or greater than geometry feature sizes bremsstrahlung increasingly important for high- Z materials (varies as Z^2)		Direct ionisation (including δ -ray electron production) Multiple scattering Bremsstrahlung production Transport of secondary electrons using above physics Transport of bremsstrahlung (photoelectric effect, Compton scattering)
3	electrons	>1.022 MeV	δ -rays important if their ranges are similar to or greater than geometry feature sizes Bremsstrahlung increasingly important for high- Z materials (varies as Z^2)		Direct ionisation (including δ -ray electron production) Multiple scattering Bremsstrahlung Photoelectric effect Compton scattering Pair-production Annihilation
4	electrons			Important if angular distribution of photon spectrum is a requirement.	Rayleigh scattering
5	protons and other ions	up to a few 10's MeV/nuc			Direct ionisation Multiple scattering Elastic scattering