TECHNICAL REPORT

RAPPORT TECHNIQUE

TECHNISCHER BERICHT

CEN/CLC/TR 17603-10-12

September 2021

ICS 49.140

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

Ref. No. CEN/CLC/TR 17603-10-12:2021 E

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

4.4.1 Overview 23
4.4.2 Beam characteristics 23
4.4.3 Radioactive sources 23
4.4.4 Packaging 24
4.4.5 Penetration 24
4.4.6 Representativeness 24
4.5 Procurement processes and device reproducibility 24
4.6 Project management decisions 25
4.7 Relationship with derating 25
4.8 Typical design margins 25
4.9 References 25

5 Radiation shielding 26

5.1 Introduction 26
5.2 Radiation transport processes 26
5.2.1 Overview 26
5.2.2 Electrons 26
5.2.3 Protons and other heavy particles 28
5.2.4 Electromagnetic radiation – bremsstrahlung 32
5.3 Ionising dose enhancement 33
5.4 Material selection 33
5.5 Equipment design practice 33
5.5.1 Overview 33
5.5.2 The importance of layout 34
5.5.3 Add-on shielding 34
5.6 Shielding calculation methods and tools – Decision on using deterministic radiation calculations, detailed Monte Carlo simulations, or sector shielding analysis 36
5.7 Example detailed radiation transport and shielding codes 45
5.8 Uncertainties 45
5.9 References 46

6 Total ionising dose 48

6.1 Introduction 48
6.2 Definition 48
6.3 Technologies sensitive to total ionising dose 48
6.4 Total ionising dose calculation 50
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

8.4.3 Proton and neutron beam testing 74
8.4.4 Experimental measurement of SEE sensitivity 74
8.4.5 Influence of testing conditions 75
8.5 Hardness assurance 77
8.5.1 Rate prediction 77
8.5.2 Prediction of SEE rates for ions 77
8.5.3 Improvements 79
8.5.4 Method synthesis 80
8.5.5 Prediction of SEE rates of protons and neutrons 80
8.5.6 Method synthesis 82
8.5.7 Calculation toolkit 82
8.5.8 Applicable derating and mitigating techniques 82
8.5.9 Analysis at system level 82
8.6 Destructive SEE 83
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 SEE 87
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 References 92

9 Radiation-induced sensor backgrounds 96
9.1 Introduction 96
9.2 Background in ultraviolet, optical and infrared imaging sensors 96
9.3 Background in charged particle detectors 100
9.4 Background in X-ray CCDs 100
9.5 Radiation background in gamma-ray instruments 101
9.6 Photomultipliers tubes and microchannel plates 104
9.7 Radiation-induced noise in gravity-wave detectors 105
9.8 Other problems common to detectors 105
9.9 References 106

10 Effects in biological material 108
10.1 Introduction 108

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

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 *et al* 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 *et al* [RDE.13]. 64
Table 7: NIEL rates for neutrons incident on Si (part 2 of 3). These data are from Konobeyev *et al* [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 *et al* [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”.