

Contents

Preface	iii
1. Summary	1
1.1 Background	1
1.2 Reasons for a Reappraisal of Radiation Protection Standards	1
1.3 Radiation Environments	2
1.4 Radiation Effects	4
1.5 Acute Effects	4
1.6 Cancer Risks	4
1.7 Genetic Effects	5
1.8 Nonstochastic Late Effects	6
1.9 Career Exposure Limits	7
1.10 Uncertainties in the Risk Estimates	8
1.11 Impact of Career Limits on Space Activities	9
1.12 Future Research	9
2. Introduction	10
2.1 Background of Space Radiation Safety Standards	10
2.2 Spaceflight Exposures: Relationship to Guidelines	11
2.3 Reason for a Reappraisal	12
2.4 Objectives of this Report	13
3. Radiation Environment in Space	15
3.1 Introduction	15
3.2 Radiation Belts	16
3.2.1 The Electron Belts	16
3.2.2 Trapped Protons	16
3.2.3 Typical Energy Spectra of the Trapped Particles	17
3.3 Galactic Cosmic Rays	18
3.4 Solar Particle Events (SPE)	19
3.4.1 Predictions of Solar Particle Events (SPE)	25
4. Radiation Exposure to Personnel	27
4.1 Introduction	27
4.1.1 Absorbed Dose	27
4.1.2 Dose Equivalent	28
4.2 Measured Radiation Doses and Dose Components on Manned Missions	29

4.2.1	Introduction	29
4.2.2	Early Information on Doses in Space Vehicles	29
4.2.3	HZE Particle Measurements	33
4.2.4	Dosimetric Results on Space Transport Shuttle Flights	35
4.2.5	Measured and Calculated LET Spectra	38
4.3	Mission Scenarios	42
4.3.1	Introduction	42
4.3.2	Low Orbital Inclination Space Station Orbit	44
4.3.3	Medium Orbital Inclination Orbit	45
4.3.4	High Orbital Inclination (Polar) Orbit	45
4.3.5	Sortie to Geostationary Earth Orbit (GEO)	46
4.3.6	Lunar Mission	48
4.3.7	Mission to Mars	48
5.	Radiobiological Features of the Space Radiation Environment	50
5.1	Introduction	50
5.1.1	Biological Effects of Electrons	51
5.1.2	Biological Effects of Protons	52
5.1.3	Biological Effects of Neutrons	54
5.1.4	Biophysical Characteristics of Heavy Ions	57
5.1.5	Biological Effects of Heavy Ions	61
5.1.6	Special Features of Effects of HZE Particles	65
5.1.6.1	The Microlesion Concept	65
5.1.6.2	Visual Effects of Individual Cosmic-Ray HZE Particles	66
5.1.6.3	HZE Effects on the Brain	67
5.1.6.4	Critique of Evidence Concerning Microlesions	67
5.2	Health Effects of the Space Radiation Environment	69
5.2.1	Introduction	69
5.2.2	Early Organ Effects	69
5.2.3	Late Organ Effects	74
5.2.4	Fertility	77
5.2.5	Effects on Lifespan	80
5.2.6	Radiation Quality	81
5.2.7	Preventive and Therapeutic Measures	82
5.3	The Effects of Radiation on the Eye	85
5.3.1	Introduction	85
5.3.2	The Lens of the Eye	85
5.3.3	Radiation Effects	87
5.3.4	Cataract	88

5.3.5	Radiation-Induced Cataracts	90
5.3.6	High-LET Radiation and the Lens	95
5.3.7	Heavy Ions and the Lens	96
5.3.8	Radiation-Induced Effects on the Cornea	101
5.3.9	Radiation-Induced Effects on the Retina	103
5.4	Radiation Carcinogenesis	105
5.4.1	Introduction	105
5.4.2	Dose-Response Models	106
5.4.3	The Evidence for Radiation Carcinogenesis	107
5.4.4	An Approach to Estimate Cancer Risk	118
5.4.5	Risks of Radiation Carcinogenesis	121
5.5	Genetic Risks Associated with Manned Space Flight Operations	122
5.6	Radiation Risks to the Embryo and Fetus	141
5.7	Interactions with Other Agents	143
6.	Radiation Protection Standards in Space: Evaluation and Recommendation	145
6.1	Introduction	145
6.1.1	Early Experience	145
6.1.2	Stochastic and Non-Stochastic Effects	146
6.1.3	Risk Estimation	147
6.1.4	Risk Estimation and Radiation Protection	147
6.1.5	Present Status of Risk Estimates	149
6.1.6	Uncertainties in Risk Estimates	150
6.1.7	High-LET Radiation	150
6.2	Terrestrial Exposures	152
6.2.1	Occupational Exposure	152
6.2.2	Public Exposure Levels	155
6.2.3	Protection Limits (for External and Internal Radiation)	155
6.3	Criteria for Limiting Radiation Exposures in Space	157
6.3.1	Dose Equivalents for Specific Scenarios in Space	157
6.3.2	Limiting Biological Effects	157
6.4	Space Exposure Limits	159
6.4.1	Earlier Experience	159
6.4.2	Current Considerations	159
6.4.3	Recommended Limits	162
6.5	Recommendations for NASA Sponsored Research	163
6.5.1	Physics and Dosimetry Research for Missions in Low Earth Orbit (LEO) for Shuttle and Space Station	165

x / CONTENTS

6.5.2 Physics and Dosimetry Research for Missions in Geosynchronous Earth Orbit (GEO) and Outer Space	165
6.5.3 Research in Radiobiology and Health Effects	166
6.5.4 Summary and Conclusions of Research that is Needed	168
Glossary	169
References	174
The NCRP	206
NCRP Publications	213
Index	222

