

Table of Contents

1	Introduction	1
2	History and Current Development	7
2.1	Visions, Concepts and Early Designs of Space Stations (1865–1957)	7
2.2	US Space Station Studies (1957–1985) and Skylab	11
2.3	Russian Space Stations: Salyut (1971–1991) and Mir (Development until 1994)	25
2.4	The European Space Laboratory Spacelab and the US Module Spacehab	30
2.4.1	The European Spacelab Program	30
2.4.2	The US Spacehab Module	38
2.5	From Mir to the International Space Station ISS (1994–2004)	39
2.5.1	Phase 1 (1994–1998): Further Expansion and Operation of Mir	41
2.5.2	Phase 2 (1998–2000): Start of Assembly of the International Space Station	46
2.5.3	Phase 3 (2000–2004): Operation of the International Space Station and Further Expansion	48
2.5.4	General Description of the International Space Station	50
2.6	Space Station Comparison	53
3	Orbital Environment	57
3.1	Gravitational Fields	58
3.1.1	Gravitational Field at Large Distances from a Central Body	58
3.1.2	Gravitational Field Near a Central Body	59
3.2	Magnetic Fields	60
3.2.1	The Earth's Magnetic Field	60
3.2.2	The Magnetic Field of the Sun	64
3.3	Radioactive Radiation	65
3.3.1	Fundamentals	65
3.3.2	Low-Energy Particles of Solar Origin: Solar Wind	65
3.3.3	High-Energy Particles of Solar Origin: Solar Flares	67
3.3.4	Particles of Galactic Origin	67
3.3.5	Radiation Belts within the Earth's Magnetic Field	68
3.3.6	Radiation Effects on Materials and on the Human Organism	70
3.3.7	Protective Measures	72
3.4	Electromagnetic Radiation (EMR)	73
3.4.1	Galactic Radiofrequency (RF) Noise	75
3.4.2	Solar Radiation	76
3.4.3	Solar Radiation Pressure	78
3.4.4	Albedo Radiation	79
3.4.5	Thermal Radiation	80
3.5	Natural and Other Radiation Sources	81

VI Table of Contents

3.6	The Atmosphere	82
3.6.1	Composition	82
3.6.2	Atomic Oxygen (AO)	86
3.7	The Ionosphere	89
3.7.1	Ionosphere Models	89
3.7.2	Variations in the Ionosphere	90
3.7.3	Behavior of Radio Waves in the Ionosphere	91
3.8	Solid Matter	92
3.8.1	Meteoroids	92
3.8.2	Sporadic Flux	93
3.8.3	Showers of Meteoroids	93
3.8.4	Space Debris	95
3.8.5	Occurrence of Space Debris	95
3.8.6	The Development of Space Debris-Caused Risk	98
3.8.7	Protection against Space Debris and Implications for Space Stations	100
3.9	Induced Environment – Contamination	103
4	Environmental Control and Life Support System	109
4.1	ECLSS: Environmental Protection for the Crew	109
4.1.1	Physiological Boundary Conditions	109
4.1.2	Metabolic Boundary Conditions	112
4.1.3	Additional Boundary Conditions	113
4.2	Tasks of an ECLSS	113
4.2.1	Overview and Classification	113
4.2.2	Atmosphere Management	115
4.2.3	Water Management	129
4.2.4	Waste Management	136
4.2.5	Food Supply	137
4.2.6	Crew Safety	138
4.3	Outlook on Bioregenerative ECLSS	139
4.4	Summary	143
5	Power and Thermal Control System	147
5.1	Power Supplies	148
5.1.1	Characteristics of Space Stations	148
5.1.2	Energy Sources and Storage Systems	150
5.2	Technology	154
5.2.1	Photovoltaic Solar Generators	154
5.2.2	Solar Dynamic Generators	163
5.2.3	Influence of Shadow Period on the Design of Solar Power Systems	166
5.2.4	Comparison of Photovoltaic and Solar Dynamic Systems	170
5.2.5	Energy Distribution and Processing	173
5.3	Examples of Overall Systems	176
5.4	The Tasks of the Thermal Control System	179
5.4.1	Mechanisms of Heat Transfer	182

5.5	Thermal Control Systems	184
5.5.1	Passive Thermal Control Systems	184
5.5.2	Active Thermal Control Systems	185
5.5.3	Performance and Technological Data of TCS Hardware	189
5.5.4	Boundary Conditions for the Design of Thermal Control Systems	190
5.5.5	Radiators	192
5.6	System Examples	195
5.7	The Thermal Control System of the International Space Station	196
5.7.1	Passive Thermal Control	197
5.7.2	Active Thermal Control	198
6	Attitude and Orbit Control System	205
6.1	The Attitude and Orbit Control Problem	205
6.2	Perturbations	207
6.2.1	Aerodynamic Drag	208
6.2.2	Aerodynamic Torque	210
6.2.3	Gravity Gradient	211
6.2.4	Operational Influences	214
6.3	Flight Strategies	215
6.3.1	Strategies for Attitude Control	215
6.3.2	Orbit Control Strategies	221
6.4	Propulsion System Technology	227
6.4.1	Thrusters	228
6.4.2	Generation of Control Torques	232
6.4.3	Sensors	236
6.5	Overall System	237
7	Utilization	239
7.1	Environmental Conditions and User Disciplines	239
7.1.1	Weightlessness and Microgravity	240
7.1.2	Vacuum	243
7.1.3	Space Radiation	244
7.1.4	Overview of User Disciplines	245
7.2	Physics and Materials Science	247
7.2.1	Results Obtained and Areas for Future Research	247
7.2.2	Summary of Prospects for the International Space Station	267
7.3	Life Sciences and Biotechnology	268
7.3.1	Results Obtained and Areas for Future Research	268
7.3.2	Emphasis on Further Research in the Field of Life Sciences	278
7.4	Space Sciences	282
7.4.1	Typical Disciplines of Space Sciences: Astrophysics and Radiation Physics	282
7.4.2	What does ISS Offer in the Way of Benefits for Space Sciences?	285
7.5	Earth Observation	286
7.6	Engineering Sciences and Development of Technology	290
7.6.1	Validation of New Technologies	291
7.6.2	Examples of the Development of Systems and Components	291

VIII Table of Contents

7.7	Outlook for Industrial and Commercial Applications	294
7.7.1	Fluid and Materials Sciences	295
7.7.2	Biotechnology and Medicine	296
7.7.3	Summary of Industrial Applications	297
8	Microgravity	299
8.1	Microgravity as a Locational Advantage	299
8.2	Ways to Obtain Microgravity	300
8.2.1	Drop Tower	301
8.2.2	Parabolic Flights	303
8.2.3	Sounding Rockets	304
8.2.4	Space Capsules	305
8.2.5	Flight Opportunities	305
8.2.6	SPAS	307
8.2.7	EURECA	308
8.2.8	Spacelab	308
8.2.9	Space Stations	308
8.2.10	Comparison of Flight Opportunities	309
8.3	Perturbing Accelerations aboard Space Stations	311
8.3.1	Atmospheric Drag	312
8.3.2	Tidal Forces	314
8.3.3	The g-Jitter	318
8.3.4	Solar Radiation Pressure	322
8.4	Perturbation Compensation and Levitation	323
9	System Engineering	329
9.1	The Life Cycle of a Space Project	329
9.2	The Conceptual Design Problem	334
9.3	Methods and Tools for Conceptual Design	338
9.3.1	Conceptual Design Methodology	339
9.3.2	Characterization of System Elements	345
9.3.3	Conceptual Design Tools	358
9.4	Space Station Architectures	362
9.4.1	CDG and “Freedom” Concepts	362
9.4.2	The Mir Configuration	366
9.4.3	The Columbus Free Flying Laboratory	367
9.4.4	The International Space Station (ISS)	368
10	Synergisms	371
10.1	Terms and Concepts	371
10.2	Coupling of Subsystems	372
10.3	System Balances	373

10.4 Examples for Synergistic Linkages	375
10.4.1 Non-Integrated System	376
10.4.2 Regenerative Fuel Cells for Energy Storage	380
10.4.3 Regenerative Fuel Cell for Pollutant Filtering	384
10.4.4 Electrolytically Produced Propellants	387
10.4.5 Safety and Reliability	389
10.5 Summary	390
11 Human Factors	393
11.1 Terms and Historical Development	393
11.2 Humans in Space	395
11.3 Human Factors Engineering (HFE)	398
11.3.1 Organization and Integration	398
11.3.2 Methods of HFE	399
11.3.3 Means of HFE Support	402
11.4 Design of a Workstation	406
11.5 Habitability and Crew Performance	412
11.6 Astronaut Selection	414
11.6.1 Astronaut Tasks and Duties	415
11.6.2 Selection Criteria	415
11.6.3 Rejection Criteria	416
11.6.4 Selection Process	417
12 Logistics, Communications and Operation	419
12.1 Logistics	419
12.1.1 Transportation Requirements	420
12.1.2 Launch Systems and Transportation Capabilities	423
12.1.3 The Automated Transfer Vehicle (ATV)	425
12.1.4 Return Vehicles	429
12.1.5 Extravehicular Activities	432
12.2 Data and Communication Systems	433
12.2.1 The Data Management System	434
12.2.2 Transmission Paths to Space Stations	435
12.2.3 Distributed Data Systems	438
12.2.4 Radio Communication System Design	442
12.2.5 Antennas	445
12.2.6 Modulation and Coding	448
12.2.7 The Tracking and Data Relay Satellite System (TDRSS)	450
12.2.8 Data and Communication Systems for the ISS	452
12.3 Automation and Maintenance	452
12.3.1 Payload Operation aboard a Space Station	453
12.3.2 Design of Payloads that are Subject to Maintenance and Repair	456
12.3.3 Automation of Payload Operation	457
12.3.4 Testing and Verification	463
12.3.5 Summary	463
12.4 Telescience	464
12.4.1 Crew Time – A Critical Resource	465
12.4.2 Teleoperation and Telepresence	467

13 The International Space Station	471
13.1 Station and Mission Elements	471
13.1.1 Characteristics of ISS	472
13.1.2 The Gradual Assembly of ISS	474
13.1.3 Mission Characteristics	475
13.2 Pressurized Modules and Payload Structures	477
13.2.1 The US Laboratory Modules	478
13.2.2 The Columbus Orbital Facility (COF)	480
13.2.3 The Japanese Experiment Module (JEM)	482
13.2.4 The Russian Laboratory Modules	483
13.3 Accommodation Sites for External Payloads	484
13.3.1 The US Truss Structure ITA (Integrated Truss Assembly)	484
13.3.2 The Japanese Experiment Module Exposed Facility (JEM-EF)	486
13.3.3 Russian External Payload Attachment Sites	486
13.3.4 The Station's External Robotic Systems	486
13.3.5 External Environmental Monitoring	488
13.4 Transportation Systems and Logistics Containers	488
13.5 Payloads and Payload Selection	491
13.5.1 Typical Payloads: Experiment Facilities and Experiments	491
13.5.2 Selection of Class 1 Payloads and Users	492
13.5.3 Access for Commercial Users	495
13.5.4 Utilization Planning	496
13.5.5 International Coordination of Space Station Utilization	498
13.5.6 From Conceptual Design to Qualification	499
13.5.7 Development Support	500
13.5.8 The User Support and Operations Centers	501
13.5.9 From Ground Verification to Launch	503
13.5.10 Performance of Experiments: From On-Orbit Installation to Return of Results to Earth	504
13.6 Preparation for ISS Utilization	506
13.6.1 Present NASA and ESA Early Utilization Plans	506
13.6.2 European Facilities for the Early Utilization Phase	508
13.6.3 ESA's Preparation for the Early Utilization Phase	509
13.6.4 European Utilization Plans for the Initial Utilization Phase	516
13.6.5 Outlook on the Routine Phase and User Acquisition	517
13.6.6 Preparation of Future Payloads	519
References	521
Fundamental Constants	535
Glossary	537
Index	551