Contents

Tara Ruttley

Nicol Caplin

Masaki Fujimoto

Introductory Statement xv

Introductory Statement xvii

Introductory Statement xix

	Introductory Statement xxi Enrico Palermo Preface xxiii	
	Part I Space Medicine and Human Health 1	
1	Human Health in Space 3	
	Jennifer Fogarty	
1.1	Introduction 3	
1.2	Preflight Determination of Health and Performance Risk 4	
1.3	Physiologic Responses to Spaceflight 6	
1.4	Vestibular and Sensorimotor Disruption and Adaptation 6	
1.5	Cardiovascular Adaptation 9	
1.6	Musculoskeletal Adaptation a Tale of Disuse Atrophy and	
	Remodeling 12	
1.7	Multisystem Effects 14	
1.8	Vehicle-Induced Effects 16	
1.9	Conclusions 16	
	References 17	
2	Space Medicine and Countermeasures 21	
	Philip M. Williams, Tejasvi Shivakumar, and Valentine Anyanwu	
2.1	Introduction 21	
2.2	Medicines for Space 22	
2.2.1	Stability and Shelf-life 24	
2.2.2	Changes in Pharmacokinetics (PK) and Pharmacodynamics (PD) 26	5

Contents	
2.2.3	The Vascular Echo Study: The Case for On-site Manufacture and Telepharmacy 27
2.3	Medicines in Space 28
2.3.1	Toward Chemical Synthesis in Space 30
2.3.2	Drugs from Plants in Space 31
2.3.3	Cell-Based Systems for Biopharmaceutical Manufacture 31
2.3.3.1	Cell-Free Systems for Biopharmaceutical Manufacture 33
2.3.4	On-site Formulation of the Drug 35
2.4	Medicines from Space 36
2.4.1	Accelerated Aging 37
2.4.2	Crystal Studies 37
2.5	Conclusions 40
	References 40
3	Frontier Medical Technologies to Support Space
	Exploration 47
	Quy D. Tran, Nam N. Tran, and Volker Hessel
3.1	Introduction 47
3.2	Health Risks of Space Flights 48
3.3	Pathogenic and Immunogenic Studies 50
3.3.1	Genome Sequencing 50
3.3.2	Microbiology Studies of Pathogens 50
3.3.3	Vaccination in Space 51
3.3.4	New Formulations for Medication in Space 51
3.4	Organ-on-Chip Microfluidics 53
3.4.1	Cardiovascular System 53
3.4.2	Blood-Brain Barrier (BBB) 54
3.4.3	Musculoskeletal Organ 55
3.4.4	Lung 56
3.4.5	Kidney 56
3.5	Telemedicine for Space Exploration 58
3.5.1	Point-of-Care (POC) Diagnostic Device 58
3.5.2	Handheld Ultrasound Devices in Emergency Medicine 59
3.5.3	VisualDx 61
3.5.4	Bio-Monitor 62
3.6	Conclusion 62
	References 63
	Part II Space Biology 67
4	Digut Dialogy and a New Approach to Sance Forming 60
4	Plant Biology and a New Approach to Space Farming 69
4.1	Natasha Haveman, Anna-Lisa Paul, and Robert Ferl
4.1	Introduction 69 Historical Context of Plant Selections 60
4.2	Historical Context of Plant Selections 69

4.3 4.4 4.5 4.6 4.7 4.8 4.9	Resistance to Biotic or Abiotic Stresses 72 Improving Crop Yield and Nutritional Value 72 Transgenic Plants as Bioreactors for Recombinant Proteins 73 Plant Products for Manufacturing 73 Synthetic Plant Biology 75 Engineering Plants for Spaceflight Application 77 Discussion 81 Conclusion 82 References 83
5	Stem Cell Biology and Tissue Engineering in Space 89 Madelyn Arzt, Amelia Jenkins, and Arun Sharma
5.1	Historical Context 89
5.2	Stem Cells and Space Flight 90
5.3	Expansion of Select Cell Types 94
5.4	Altering Differentiation Capacity 96
5.5	Altering Stem Cell Potency and Progenitor Cell Function 97
5.6	Commercial Opportunities for Stem Cells and their Derivatives in LEO 98
5.7	Tissue Engineering 100
5.8	Conclusion 102
	Part III Space Chemistry 109
6	Part III Space Chemistry 109 Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111
6	Chemistry-Related Innovations in Space, Benefits of Flow
6.1	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111
6.1 6.2	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111 Challenges of Chemistry Realized in Space 111
6.1	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111 Challenges of Chemistry Realized in Space 111 Unique Features of Space: Lack of Directionality (Cosmic Rays, Microgravity) 112
6.1 6.2	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111 Challenges of Chemistry Realized in Space 111 Unique Features of Space: Lack of Directionality (Cosmic Rays, Microgravity) 112 Theoretical Aspects: Quantum Chemistry Approach 113
6.1 6.2 6.2.1	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111 Challenges of Chemistry Realized in Space 111 Unique Features of Space: Lack of Directionality (Cosmic Rays, Microgravity) 112
6.1 6.2 6.2.1	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111 Challenges of Chemistry Realized in Space 111 Unique Features of Space: Lack of Directionality (Cosmic Rays, Microgravity) 112 Theoretical Aspects: Quantum Chemistry Approach 113 Space Chemistry – Concept, Historical Summary, and Current
6.1 6.2 6.2.1 6.2.2 6.3 6.3.1 6.3.2	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111 Challenges of Chemistry Realized in Space 111 Unique Features of Space: Lack of Directionality (Cosmic Rays, Microgravity) 112 Theoretical Aspects: Quantum Chemistry Approach 113 Space Chemistry – Concept, Historical Summary, and Current Efforts 114 Foundation of the Space Chemistry Consortium 115 Recent Activities and Successes in Space Chemistry 116
6.1 6.2 6.2.1 6.2.2 6.3	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111 Challenges of Chemistry Realized in Space 111 Unique Features of Space: Lack of Directionality (Cosmic Rays, Microgravity) 112 Theoretical Aspects: Quantum Chemistry Approach 113 Space Chemistry – Concept, Historical Summary, and Current Efforts 114 Foundation of the Space Chemistry Consortium 115
6.1 6.2 6.2.1 6.2.2 6.3 6.3.1 6.3.2	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111 Challenges of Chemistry Realized in Space 111 Unique Features of Space: Lack of Directionality (Cosmic Rays, Microgravity) 112 Theoretical Aspects: Quantum Chemistry Approach 113 Space Chemistry – Concept, Historical Summary, and Current Efforts 114 Foundation of the Space Chemistry Consortium 115 Recent Activities and Successes in Space Chemistry 116 Space Chemistry Results: Life Sciences, Pharma Industry, Agro Industry,
6.1 6.2 6.2.1 6.2.2 6.3 6.3.1 6.3.2 6.4	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111 Challenges of Chemistry Realized in Space 111 Unique Features of Space: Lack of Directionality (Cosmic Rays, Microgravity) 112 Theoretical Aspects: Quantum Chemistry Approach 113 Space Chemistry – Concept, Historical Summary, and Current Efforts 114 Foundation of the Space Chemistry Consortium 115 Recent Activities and Successes in Space Chemistry 116 Space Chemistry Results: Life Sciences, Pharma Industry, Agro Industry, Cosmetics, and Others 118
6.1 6.2 6.2.1 6.2.2 6.3 6.3.1 6.3.2 6.4	Chemistry-Related Innovations in Space, Benefits of Flow Chemistry 111 Ferenc Darvas, Paul G. Mezey, György Dormán, Balázs Buchholcz, Csaba Janáky, Richard V. Jones, Gellért Sipos, Tamás Peidl, and Gergo Mezohegyi Introduction 111 Challenges of Chemistry Realized in Space 111 Unique Features of Space: Lack of Directionality (Cosmic Rays, Microgravity) 112 Theoretical Aspects: Quantum Chemistry Approach 113 Space Chemistry – Concept, Historical Summary, and Current Efforts 114 Foundation of the Space Chemistry Consortium 115 Recent Activities and Successes in Space Chemistry 116 Space Chemistry Results: Life Sciences, Pharma Industry, Agro Industry, Cosmetics, and Others 118 Investigating and Exploiting Microgravity Effects 118

viii	Contents	
	6.5.2	Nanoformulation in Space 122
	6.6	Electrochemical CO ₂ Conversion in Space: a Key Step to <i>In Situ</i> Resource Utilization 123
	6.7	Synthetic Chemistry, Purification, and Analytics in Space 126
	6.7.1	Synthetic Efforts in Space 126
	6.7.2	Purification and Analysis in Space 128
	6.8	Flow Instruments for Space Chemistry 130
	6.8.1	The Flow Chemistry Advantage in Space 130
	6.8.2	Flow Reactors for Space Applications 131
	6.9	Conclusions 133
		References 133
	7	Catalysis in Space Environments 141
		Shaumica Saravanabavan, Manpreet Kaur, Claire T. Coulthard, and
		Katharina Brinkert
	7.1	Introduction 141
	7.2	Physical Fundamentals of Catalysis in Space Environments 141
	7.3	The Application of Catalysis in Atmosphere Revitalization – Catalytic
	7.3.1	Oxygen Generation and Carbon Dioxide Reduction for Life Support 144
	7.3.1	Current Research and Developments within the ECLS System 147
	7.3.2	Oxygen Generation from Lunar Regolith 147 Oxygen Generation via MOXIE on the Mars 2020 Perseverance
	7.3.3	Rover 148
	7.3.4	(Photo-)electrocatalytic Devices for Oxygen and Fuel Generation 150
	7.3.5	(Photo-)electrocatalytic Hydrogen Production in Microgravity
	,	Environment 150
	7.4	Catalytic Waste Recycling on the International Space Station 151
	7.4.1	Wastewater Treatment – the Water Recovery System (WRS) 151
	7.4.2	Removal of Trace Contaminants 153
	7.5	Enzyme Catalysis for Space Applications 155
	7.5.1	Enzyme Kinetics in Reduced Gravitation 156
	7.6	Conclusions 158
		References 158
		Part IV Space Mining 163
	8	Mining and Microbiology for the Solar System Silicate and
	0	Basalt Economy 165
		Charles S. Cockell and Rosa Santomartino
	8.1	Introduction 165
	8.2	The Silicate and Basalt Economies 166
	8.2.1	Rationale for Opening the Silicate Economy 166
	8.2.2	Elements of the Silicate Economy 168
	8.3	Processing in the Silicate Economy 171
		•

8.4	The Use of Biology in the Silicate Economy 172		
8.4.1	General Observations on Silicate Biomining 172		
8.4.2	Using Biomining in Space 173		
8.4.3	Demonstrating Biological Access to the Silicate Economy on the		
	International Space Station 174		
8.4.4	Using Synthetic Biology to Enhance Access to the Silicate Economy 179		
8.4.5	Some Conceptual Novelties in Extraterrestrial (Bio)mining 180		
8.5	The Circular Silicate Economy 181		
8.6	Conclusion 182		
0.0	References 182		
9	Near-Earth Asteroids as Promising Candidates for Space		
•	Resources 187		
	Hideaki Miyamoto		
9.1	Introduction 187		
9.2	Materials in the Solar System 188		
9.3	Asteroids as Extraterrestrial Resources 189		
9.4	Overview of Asteroids 192		
9.5	Findings Through <i>In Situ</i> Explorations of Small Asteroids 195		
9.6	Mars, the Moon, and Asteroids 198		
9.7	Future View 199		
9.8	Conclusion 200		
9.0	Acknowledgment 201		
	References 201		
	References 201		
10	Mining of Phosphorus from Moon Crust – Spillover of		
10	Learning from Earth 205		
	Changping Zhuang, Daniel Kinasz, Nam N. Tran, and Volker Hessel		
10.1	Introduction 205		
10.1	Phosphorus Geomineral Sources 205		
10.2.1	Sources of Phosphorus on Earth 205		
10.2.1	Phosphorus Mining Sites 206		
10.3.1	Mining Sites of Phosphorus on Earth 206		
10.3.1	Mining Sites of Phosphorus on the Moon 206		
10.3.2	Phosphorus Industrial Production from Mined Resources 208		
10.4.1	Industrial Production of Phosphorus on Earth 208		
10.4.1	Phosphorus Cycle to Ensure Circularity of P Provision vs.		
10.5	Consumption 210		
10 5 1	*		
10.5.1	Land-Based Cycle of Phosphate 210 Phosphorus Extraction Technologies 210		
10.6	Phosphorus Extraction Technologies 210		
10.6.1	Total Process Technology Overview 210		
10.7	Lunar Biomining of Phosphorus as Integrating Minerals Processing and		
1071	Space Horticulture 215		
10.7.1	Bio-Extractants for Phosphorus Minerals Processing 215		

x Cont	ents
10.8	Moon Phosphate Circular Process Based on Microfluidic Biomining 216
10.9	
10.1	•
	References 220
11	Lunar Resources in Support of Human Interplanetary Settlement and Limitations 223 Zoe Nunn, Samantha Smith, and John Culton
11.1	
11.2	
	2.1 Settlement Uses 224
11.2	2.2 Limitations 226
11.3	Regolith 226
11.3	3.1 Settlement Uses 227
11.3	3.2 Limitations 227
11.4	Sunlight 228
11.4	8.1 Settlement Uses 229
11.4	Limitations 229
11.5	
11.6	
	References 231
	Part V Space Farming and Food 235
12	PONDS: A New Method for Plant Production in Space 237 Howard G. Levine, Jeffrey T. Richards, Lawrence L. Koss, Mark Weislogel, David Reed, Anna Nguyen, Hector Barea, and David Kusuma
12.1	Vegetable Production System (Veggie) 237
12.2	J1 1
12.3	Growth of Outredgeous Lettuce Within KSC PONDS Prototype #1 240
12.4	71
12.5	Growth of Zinnia and <i>Arabidopsis thaliana</i> Within KSC PONDS Prototypes #2 and #3 242
12.6	• •
12.7	
12.8	3 Conclusions 246
	Acknowledgments 248 References 249

13	Space Food for the Future: Nutritional Challenges and Technological Strategies for Healthy and High-Quality Products 251 Paola Pittia and Martina Heer
13.1	Introduction 251
13.2	Nutritional and Metabolic Challenges of Astronauts 253
13.2.1	Energy Expenditure, Exercise, and the Musculoskeletal System: Find a Good Balance 253
13.2.2	Immune 254
13.2.3	Microbiota 254
13.3	Space Missions and Food Supply 255
13.4	Space Food Types: Processing Aspects and Storability 255
13.5	Safety Management, Quality, and Stability of Space Food Systems 260
13.6	Future Trends in Food Supply to Meet Nutritional Challenges 262
13.7	Food Processing and Design for Future Space Food 263
13.8	Conclusion 264
	References 265
	Part VI Advanced Materials 269
14	Metal Alloy Synthesis in Microgravity 271
1.4.1	Jessica J. Frick and Debbie G. Senesky
14.1	Historical Context 271
14.2	Metal Alloy Synthesis on the International Space Station (ISS) 273
14.3	Metal Alloy Synthesis on the Tiangong-2 (TG-2) Space
144	Laboratory 279
14.4	Future Outlook 281
	References 281
15	Layer-by-Layer Deposition in Microgravity for Enhanced
	Thin-Film Production 285
	Daniel B. Lawrence, Jordan A. Greco, Robert R. Birge, and Nicole L. Wagner
15.1	Background 285
15.2	Layer-by-Layer Applications 287
15.2.1	Terrestrial Applications of Significance 287
15.2.2	Potential Microgravity Applications 287
15.2.3	Benefits of Microgravity 288
15.2.4	Considerations for Microgravity LBL Manufacturing 288
15.3	Bacteriorhodopsin-Based Artificial Retinas and Other Biophotonic Technologies 290

xii	Contents
	J

15.3.1	Significance of Protein-Based Artificial Retinas 290		
15.3.2	Bacteriorhodopsin-Based Artificial Retinas 290		
15.3.2.1			
15.3.2.2	_		
15.3.3	Artificial Retina Manufacturing 293		
15.3.4	LBL-Assembled Artificial Retinas in Microgravity 294		
15.3.5	Other Bacteriorhodopsin-Based Biophotonic Applications 294		
15.3.5.1	Thin-Film Applications 294		
15.3.5.2	Protein-Based Volumetric Memories and Associative Processors 295		
15.4	Future Directions in LEO Commercialization 297		
	References 298		
16	3D Bioprinting Aboard the International Space Station Using the Techshot BioFabrication Facility 303 Carlos C. Chang and Eugene D. Boland		
16.1	Introduction 303		
16.2	Engineering a 3D Bioprinter for Use in Microgravity 303		
16.3	Bioink Development 304		
16.4	Print Testing in Zero-G 306		
16.5	Launching to ISS 311		
16.6	Containers and Containment 311		
16.7	Bioink Packaging 312		
16.8	In-Flight 313		
16.9	Bioprinting Preparation 313		
16.10	Bioprinting in Microgravity on the ISS 314		
16.11	Post-Print Activities and Conditioning on ISS 316		
16.12	Return of 3D Bioprinted Tissues from the ISS 316		
16.13	Future Considerations 317		
	Part VII Space Construction 319		
17	Beyond the ISS: The World's First Commercial Space Station 321		
	Christian Maender, Jason Aspiotis, Rachel Clemens, Anjali Gupta,		
	Divya Panchanathan, David Zuniga, and Jana Stoudemire		
17.1	Historical Context 321		
17.2	The World's First Commercial Space Station 321		
17.3	Construction and Assembly of the Axiom Station 323		
17.3.1	First Module (AxH1) 323		
17.3.2	Second Module (AxH2) 324		
17.3.3	Third Module (AxRMF) 324		
17.3.4 17.3.5	The Power and Thermal Tower 325		
1/35	Common Systems 326		

17.4	Preparing for the Axiom Station: A New Era of Human
17 4 1	Spaceflight 327
17.4.1	Building a Robust and Sustainable Commercial Space Economy in Low-Earth Orbit 328
17.5	Emerging Market Sectors: In-Space Manufacturing of Advanced
17.5	Materials 328
17.5.1	Optical Fibers and Exotic Glasses 330
17.5.2	Industrial Crystals 330
17.5.3	Metal Alloys 330
17.5.4	Thin-Layer Deposition 331
17.6	Emerging Market Sectors: In-Space Production Biomedical
	Products 331
17.6.1	Flow Chemistry (Active Pharmaceutical Ingredient Production) 332
17.6.2	Biologics 332
17.6.3	Layer-by-Layer Deposition 332
17.6.4	Drug Delivery 333
17.6.5	Regenerative Medicine 333
17.6.6	Disease modeling 333
17.6.7	Stem Cells 334
17.6.8	3D Bioprinting 334
17.7	Conclusion 334
	References 335
18	Leveraging Open Innovation to Incentivize Advances in
18	Leveraging Open Innovation to Incentivize Advances in Additive Construction in Space and on Earth 339
18	Additive Construction in Space and on Earth 339
	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk
18.1	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339
18.1 18.2	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340
18.1 18.2 18.3	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341
18.1 18.2	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342
18.1 18.2 18.3 18.4	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344
18.1 18.2 18.3 18.4 18.5 18.6	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344 How 3DPH Attracted Nontraditional Participants 345
18.1 18.2 18.3 18.4 18.5	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344
18.1 18.2 18.3 18.4 18.5 18.6 18.7	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344 How 3DPH Attracted Nontraditional Participants 345 How 3DPH Advanced Planetary Additive Construction 346
18.1 18.2 18.3 18.4 18.5 18.6 18.7	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344 How 3DPH Advanced Planetary Additive Construction 346 Conclusions and Future Outlook 348
18.1 18.2 18.3 18.4 18.5 18.6 18.7	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344 How 3DPH Advanced Planetary Additive Construction 346 Conclusions and Future Outlook 348
18.1 18.2 18.3 18.4 18.5 18.6 18.7	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344 How 3DPH Attracted Nontraditional Participants 345 How 3DPH Advanced Planetary Additive Construction 346 Conclusions and Future Outlook 348 References 349
18.1 18.2 18.3 18.4 18.5 18.6 18.7 18.8	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344 How 3DPH Attracted Nontraditional Participants 345 How 3DPH Advanced Planetary Additive Construction 346 Conclusions and Future Outlook 348 References 349 Part VIII Space Policy, Law, and Economics 351
18.1 18.2 18.3 18.4 18.5 18.6 18.7 18.8	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344 How 3DPH Attracted Nontraditional Participants 345 How 3DPH Advanced Planetary Additive Construction 346 Conclusions and Future Outlook 348 References 349 Part VIII Space Policy, Law, and Economics 351 The Impact of the Artemis Accords on Resource
18.1 18.2 18.3 18.4 18.5 18.6 18.7 18.8	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344 How 3DPH Attracted Nontraditional Participants 345 How 3DPH Advanced Planetary Additive Construction 346 Conclusions and Future Outlook 348 References 349 Part VIII Space Policy, Law, and Economics 351 The Impact of the Artemis Accords on Resource Extraction 353
18.1 18.2 18.3 18.4 18.5 18.6 18.7 18.8	Additive Construction in Space and on Earth 339 Monsi Roman, Christopher Frangione, and Ademir Vrolijk Background and Overview 339 Historical Context: What are prize challenges? 340 Prize Challenges at NASA 341 NASA's Additive Construction Challenge: 3D-Printed Habitat 342 How 3DPH Raised Awareness of Planetary Additive Construction 344 How 3DPH Attracted Nontraditional Participants 345 How 3DPH Advanced Planetary Additive Construction 346 Conclusions and Future Outlook 348 References 349 Part VIII Space Policy, Law, and Economics 351 The Impact of the Artemis Accords on Resource Extraction 353 Melissa de Zwart

xiv	Contents	
	19.4	Issues for Australia as a Signatory to the Moon Agreement 363
	19.5	Recent Developments: Purchase of Lunar Regolith 364
	19.6	Conclusions: Where to from Here for International Space Law? 365
		References 366
	20	Space Resources: Physical Constraints, Policy Choices, and Ethical Considerations 369 Martin Elvis, Alanna Krolikowski, and Tony Milligan
	20.1	Introduction and Outline 369
	20.2	Economic Prospects and Strategic Resources 370
	20.2.1	The Moon 371
	20.2.2	Asteroids 373
	20.2.2.1	Near-Earth Asteroids 373
	20.2.2.2	Main Belt Asteroids 374
	20.2.3	Mars 374
	20.3	Policy Choices and the Emergence of Markets for Space Resources 376
	20.3.1	Government Programs that Create Anchor Demand 377
	20.3.2	Government Support to Emerging Firms 378
	20.3.3	Trade-Offs in the Design of New Regimes 378
	20.3.4	The Collective Management of Crowding and Interference 380
	20.3.5	Unfolding Policy Developments 380
	20.4	Two Problems of Ethics for an Expanding Space Economy 381
	20.4.1	The "Tenure and Entitlement" Problem 382
	20.4.2	The Near-Term Justice Problem 383
	20.5	Conclusions 385
		References 386

The Future Of Space Exploration: A Young Perspective 389 Index 391