

Contents

1	The Development of Nuclear Energy in the World	1
1.1	History of Development and Projections	1
1.2	Status of Nuclear Energy Generation in 2008.	2
1.3	Technical Applications of Nuclear Fission Energy	4
1.3.1	Nuclear Power for Electricity and Process Heat Generation	4
1.3.2	Nuclear Ship Propulsion	6
1.3.3	Nuclear High Temperature Process Heat	6
1.3.4	Nuclear Power for Hydrogen Generation	6
1.4	Economic Aspects of Nuclear Energy	7
1.4.1	Electricity Generating Costs by Nuclear Power Reactors.	7
1.4.2	Example for Projected Nuclear Electricity Generating Costs of a 1.6 GW(e) PWR	8
1.4.3	Cost Comparison for Nuclear Energy, Coal and Gas	9
1.5	Comparison of Environmental Impacts of Nuclear Energy	10
1.5.1	Carbon Dioxide Emissions	10
1.5.2	Particulate Emissions.	10
1.5.3	SO ₂ Emissions	11
1.5.4	NO _x Emissions	11
1.5.5	Radioactive Gas and Liquid Emission	11
1.6	Sustainability of Nuclear Energy	13
	References	13
2	Nuclear Fuel Supply	15
2.1	The Nuclear Fuel Cycle.	15
2.2	Uranium Resources and Requirements.	17
2.2.1	Uranium Consumption in Various Reactor Systems	17

2.3	Worldwide Available Uranium Reserves	19
2.3.1	Unconventional Uranium Resources	20
2.3.2	Uranium Production	21
2.4	Worldwide Available Thorium Reserves	21
2.5	Concentration, Purification and Conversion of Uranium	22
	References	24
3	Some Basic Physics of Converters and Breeder Reactors	25
3.1	Basic Nuclear and Reactor Physics	25
3.1.1	Elastic Scattering	25
3.1.2	Inelastic Scattering	26
3.1.3	Neutron Capture	26
3.1.4	Nuclear Fission.	27
3.1.5	Energy Release in Nuclear Fission	28
3.1.6	Decay Constant and Half-Life	29
3.1.7	Prompt and Delayed Neutrons	30
3.1.8	Afterheat of the Reactor Core.	30
3.2	Neutron Flux and Reaction Rates	31
3.3	Spatial Distribution of the Neutron Flux in the Reactor Core.	33
3.4	Fuel Burnup, Fission Product and Actinide Buildup	38
3.5	Conversion Ratio and Breeding Ratio	41
3.6	Conversion Ratio and Fuel Utilization.	44
3.7	Radioactive Inventories in Fission Reactors	46
3.8	Inherent Safety Characteristics of Converter and Breeder Reactor Cores	48
3.8.1	Reactivity and Non-Steady State Conditions.	48
3.8.2	Temperature Reactivity Coefficients	50
3.8.3	Reactor Control and Safety Analysis	52
	References	56
4	Uranium Enrichment	59
4.1	Introduction	59
4.2	Elements of Enrichment Plants.	60
4.3	World Uranium Enrichment Plant Capacities	61
4.4	Uranium Enrichment by Gaseous Diffusion	63
4.5	Gas Centrifuge Process	64
4.6	Aerodynamic Methods.	67
4.7	Advanced Separation Processes	68
4.8	Effects of Tails Assay and Economic Optimum	68
4.9	Fuel Fabrication	69
	References	70

5	Converter Reactors With a Thermal Neutron Spectrum	73
5.1	Light Water Reactors	73
5.1.1	Pressurized Water Reactors	75
5.1.2	Boiling Water Reactors	88
5.2	Gas Cooled Thermal Reactors	101
5.2.1	Advanced Gas Cooled Reactors	101
5.2.2	High Temperature Gas Cooled Reactors	102
5.3	Heavy Water Reactors	107
5.3.1	CANDU Pressurized Heavy Water Reactor	108
5.4	Near Breeder and Thermal Breeder Reactors	115
5.4.1	Homogeneous Core Thermal Breeders	115
5.4.2	Light Water Breeder Reactors (LWBRs)	115
5.5	Accelerator Driven Systems	117
5.5.1	Spallation Process, Breeding and Transmutation	117
5.5.2	Design Concept for ADS	118
	References	119
6	Breeder Reactors With a Fast Neutron Spectrum	123
6.1	The Potential Role of Breeder Reactors With a Fast Neutron Spectrum	123
6.2	Brief History of the Development of Fast Breeder Reactors	124
6.3	The Physics of SFBR Cores	127
6.3.1	SFBR Core Design	127
6.3.2	Energy Spectrum and Neutron Flux Distribution	128
6.3.3	Breeding Ratio	129
6.3.4	Reactivity Coefficients and Control Stability	130
6.3.5	The Doppler Coefficient	131
6.3.6	The Coolant Temperature Coefficient	132
6.3.7	Fuel and Structural Temperature Coefficients	133
6.3.8	Delayed Neutron Characteristics and Prompt Neutron Lifetime	133
6.3.9	Masses of Fuel, Fission Products and Actinides	135
6.4	Technical Aspects of Sodium Cooled FBRs	136
6.4.1	Sodium Properties and Design Requirements	136
6.4.2	Sodium Cooling Circuits and Components	137
6.4.3	Control and Shutdown Systems	138
6.4.4	Afterheat Removal and Emergency Cooling of SFBR Cores	140
6.4.5	Sodium Fires	141
6.4.6	Sodium-Water Reactions in Steam Generators	142
6.5	BN 800: A Near Commercial Size Demonstration SFBR	142
6.5.1	Reactor Core and Blankets	144
6.5.2	Reactor Tank and Primary Coolant Circuits	145
6.5.3	Commercial Size SFBR Designs	146

6.6	Lead-Bismuth Cooled FBRs.	148
6.6.1	Lead-Bismuth Coolant Properties	149
6.6.2	Design Proposals for Lead-Bismuth FRs	150
6.7	The Integral Fast Reactor (IFR)	154
6.8	Structural Materials for LMFBRs	155
6.8.1	Steels for Coolant Pipes, Pumps, Intermediate Heat Exchangers and Steam Generators.	155
6.8.2	Steels for Claddings and Subassembly Ducts	157
6.8.3	The Different Time Phases of Steel Development for LMFBR Cores.	158
6.8.4	Conclusions on Cladding and Subassembly Duct Material Development	159
6.9	LMFBR Cores With Advanced Oxide, Carbide, Nitride and Metallic Fuels	160
6.9.1	Mixed Oxide PuO_2/UO_2 Fuel	160
6.9.2	Mixed Carbide PuC/UC Fuel	161
6.9.3	Mixed Nitride PuN/UN Fuel.	161
6.9.4	Metallic U/Pu Fuel	161
	References	162
7	Technical Aspects of Nuclear Fuel Cycles	165
7.1	Discharge and Storage of Spent Fuel Elements.	166
7.1.1	Shipping Spent Fuel Elements	166
7.1.2	Interim Storage of Spent Fuel Elements.	168
7.2	The Uranium-238/Plutonium Fuel Cycle	169
7.2.1	Reprocessing of Spent UO_2 Fuel Elements.	170
7.2.2	Recycling of Plutonium and Uranium	178
7.2.3	Status of Uranium Fuel Reprocessing Technology	179
7.2.4	Status of Experience in MOX Fuel Fabrication and Reprocessing	180
7.2.5	Safety of Reprocessing and MOX Re-Fabrication Plants.	181
7.3	The Thorium/Uranium-233 Fuel Cycle	183
7.3.1	Fuel Element Disassembly	183
7.3.2	THOREX Process	183
7.3.3	Uranium-233/Thorium Fuel Fabrication.	185
7.4	The Uranium/Plutonium Fuel Cycle of Fast Breeder Reactors	186
7.4.1	Ex-Core Time Periods of LMFBR Spent Fuel	186
7.4.2	Mass Flow in a Model LMFBR Fuel Cycle	188
7.4.3	LMFBR Fuel Reprocessing	189
7.4.4	LMFBR Fuel Fabrication.	190
7.4.5	Status of LMFBR Fuel Reprocessing and Refabrication	191

7.4.6	Radioactive Inventories of Spent LWR Fuel.	191
7.4.7	Decay Heat of Spent Fuel	191
7.5	Conditioning of Waste from Spent LWR	
	Fuel Reprocessing.	192
7.5.1	Classification of Radioactive Waste	192
7.5.2	Solidification and Storage of Liquid High Level Waste	194
7.5.3	Radioactive Waste from Uranium-233/Thorium Fuel Reprocessing.	202
7.5.4	Radioactive Waste from Reprocessing Plutonium/Uranium Fuel of LMFBRs	203
7.5.5	Wastes Arising in Other Parts of the Fuel Cycle. . .	203
7.6	Nuclear Waste Repositories	204
7.6.1	Disposal of Short Lived MLW/LLW.	204
7.6.2	Direct Disposal of Spent Fuel Elements.	210
7.6.3	Health and Safety Impacts of Radioactive Waste Disposal.	212
	References	218
8	Nuclear Fuel Cycle Options	221
8.1	Fuel Cycle Options for Reactors with Thermal Neutron Spectrum.	221
8.1.1	The Once-Through Fuel Cycle	221
8.1.2	Closed Nuclear Fuel Cycles	224
8.2	Fuel Cycle Options for Liquid Metal Cooled Fast Breeder Reactors	236
8.2.1	The Uranium-Plutonium Fuel Cycle for LMFBRs.	238
8.2.2	The Thorium/Uranium-233 Fuel Cycle	238
8.3	Natural Uranium Consumption in Various Reactor Scenarios	239
	References	240
9	Minor Actinides: Partitioning, Transmutation and Incineration.	243
9.1	Introduction	243
9.2	Worldwide Inventories in Spent Fuel Elements of Uranium, Plutonium, Neptunium, Americium.	245
9.3	Radiotoxicity of HLW.	247
9.4	Various Strategies of Partitioning and Transmutation with Incineration of Actinides	248
9.5	Chemical Separation of Actinides.	249
9.5.1	Joint Chemical Separation of Plutonium and Neptunium from Spent Fuel.	249

9.5.2	Separation of Americium and Curium together with the Lanthanides	250
9.5.3	Chemical Separation of Actinides from the Lanthanides.	252
9.5.4	Chemical Separation of Americium from Curium	253
9.6	Pyrochemical Methods of Separating Minor Actinides	254
9.6.1	The Integral Fast Reactor Pyroprocessing Process	254
9.6.2	Electro-Reduction and Refining of Spent UOX and MOX Fuel to Metallic Fuel	255
9.6.3	Actinide/Lanthanide Separation Using Aluminum.	256
9.6.4	Pyro-Processing of Fast Reactors PuO ₂ /UO ₂ Fuel in Russia.	256
9.7	Fuel Fabrication for Transmutation and Incineration of Actinides in Nuclear Reactors	256
9.7.1	Pellet Fabrication with SOL-GEL Microspherical Particles.	257
9.7.2	Fuel Fabrication by Vibrocompaction	257
9.7.3	Inert-Matrix Fuel	258
9.7.4	Infiltration Method	258
9.7.5	Metallic Fuel	258
9.7.6	Intermediate Storage of Curium	259
9.7.7	Irradiation Experience with Fuel Containing High Plutonium Contents or Neptunium and Americium.	259
9.8	Incineration of Minor Actinides in Nuclear Reactors.	260
9.8.1	Introduction	260
9.8.2	Transmutation and Incineration of Neptunium and Americium.	261
9.8.3	Neutronic Analysis for Potential Destruction Rates of Neptunium and Americium in PWRs and FRs (One Cycle Irradiation).	261
9.8.4	Multi-Recycling of Plutonium, Neptunium and Americium in PWRs	262
9.8.5	Recycling of Plutonium and Minor Actinides in ADSs.	266
9.8.6	Plutonium Incineration by Multi-Recycling in MOX-PWRs, FR-Burners and ADSs	266
9.8.7	Influence of the Transmutation of Actinides on the Fuel Cycle and on the Waste Repository . . .	268
9.8.8	Transmutation of Long-Lived Fission Products. . . .	273

9.8.9	Comparison of Possible Radiation Exposure Rates from Drinking Water in the Vicinity of a Deep Geological Repository for Different Incineration Schemes.	277
9.8.10	Influence of the Transmutation of I-129 and Tc-99 on the Radiation Exposure from Drinking Water in the Vicinity of a Deep Geological Repository. . .	278
References		278
10	Radioactive Releases from Nuclear Power Plants and Fuel Cycle Facilities During Normal Operation.	283
10.1	Radioactive Releases and Exposure Pathways	283
10.1.1	Exposure Pathways of Significant Radionuclides	285
10.2	Radiation Dose	287
10.3	Natural Background Radiation	289
10.3.1	Natural Background Exposure from Natural Sources in Germany	290
10.4	Radiation Exposure from Man-Made Sources.	290
10.4.1	Nuclear Weapons Tests	290
10.4.2	Chernobyl Reactor Accident.	291
10.4.3	Nuclear Installations	291
10.4.4	Medical Applications.	292
10.4.5	The Handling of Radioactive Substances in Research and Technology.	292
10.4.6	Occupational Radiation Exposure	292
10.5	Radiobiological Effects	292
10.5.1	Stochastic Effect.	293
10.5.2	Deterministic Effects of Radiation.	294
10.5.3	Acute Radiation Syndrome.	294
10.6	Permissible Exposure Limits for Radiation Exposures.	295
10.6.1	Limits of Effective Radiation Dose from Nuclear Installations in Normal Operation	295
10.6.2	Radiation Exposure Limit for the Population	295
10.6.3	Exposure Limits for Persons Occupationally Exposed to Radiation.	295
10.6.4	Exposure Limits for Persons of Rescue Operation Teams During a Reactor Catastrophe.	296
10.6.5	Life Time Occupational Exposure Limit	296
10.6.6	The ALARA Principle.	297
10.7	Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle	297
10.7.1	Uranium Mining and Milling	297

10.7.2	UF ₆ Conversion, Enrichment, and Fuel Fabrication	299
10.7.3	Nuclear Power Plants	300
10.7.4	Spent Fuel Reprocessing and Waste Treatment Centers	304
10.8	Summary of Radiation Exposures Caused by the Nuclear Fuel Cycle	309
	References	310

11 Safety and Risk of Light Water Reactors and their

	Fuel Cycle Facilities	313
11.1	Introduction	314
11.2	Goals of Protection for Nuclear Reactors and Fuel Cycle Facilities	314
11.3	Safety Concept of Nuclear Reactor Plants	315
	11.3.1 Containment by Radioactivity Enclosures	315
	11.3.2 Multiple Level Safety Principle	316
11.4	Design Basis Accidents	318
	11.4.1 Events Exceeding the Design Basis	318
	11.4.2 Probabilistic Safety Analyses	318
11.5	Atomic Energy Act, Ordinances, Regulations	319
11.6	Detailed Design Requirements at Safety Level 1	319
	11.6.1 Thermodynamic Design of LWRs	320
	11.6.2 Neutron Physics Design of LWRs	321
	11.6.3 Instrumentation, Control, Reactivity Protection System (Safety Level 2).	325
	11.6.4 Mechanical Design of a PWR Primary Cooling System	326
	11.6.5 Reactor Containment	330
	11.6.6 Analyses of Operating Transients (Safety Level 3, Design Basis Accidents).	332
	11.6.7 Transients with Failure of Scram (Safety Level 3)	335
	11.6.8 Loss-of-Coolant Accidents	336
11.7	Probabilistic Analyses and Risk Studies	340
	11.7.1 General Procedure of a Probabilistic Risk Analysis	340
	11.7.2 Event Tree Method	342
	11.7.3 Fault Tree Analysis	344
	11.7.4 Releases of Fission Products from a Reactor Building Following a Core Meltdown Accident	344
	11.7.5 External Events	349
	11.7.6 Results of Reactor Safety Studies	352
	11.7.7 Results of Event Tree and Fault Tree Analyses for BWRs	355

11.7.8	Release of Radioactivity as a Consequence of Core Melt Down	356
11.7.9	Accident Consequences in Reactor Risk Studies . . .	357
11.8	Historical Occurrence of Severe Core Melt Accidents in Commercial Nuclear Power Plants	362
11.8.1	Three Mile Island Accident	362
11.8.2	Chernobyl Accident.	364
11.8.3	The Fukushima Reactor Accident in Japan.	369
11.9	Assessment of Risk Studies and Severe Nuclear Accidents.	376
11.9.1	Principles of the KHE Safety Concept for Future LWRs.	376
11.10	New Findings in Safety Research	378
11.10.1	Steam Explosion (Molten Fuel–Water Interaction)	378
11.10.2	Hydrogen Detonation.	384
11.10.3	Break of a Pipe of the Residual Heat Removal System in the Annulus.	386
11.10.4	Core Meltdown after an Uncontrolled Large Scale Steam Generator Tube Break	387
11.10.5	Core Meltdown Under High Primary Coolant Pressure	387
11.10.6	Medium-Term Pressure Buildup in the Outer Containment.	389
11.10.7	Molten Core Retention and Cooling Device (Core Catcher)	396
11.10.8	Direct Heating Problem	397
11.10.9	Summary of Safety Research Findings About the KHE Safety Concept	398
11.11	The Safety of Facilities of the Nuclear Fuel Cycle	399
11.11.1	In-Pile Fuel Element Storage Pool	399
11.11.2	Wet and Dry Fuel Element Intermediate Stores . . .	400
11.11.3	Safety Concept of Reprocessing Facilities	402
11.11.4	Safety Concept of MOX Fuel Refabrication Plants	404
11.11.5	Safety Design Concept of HAW Vitrification Plants	405
11.11.6	Risk Studies of Fuel Cycle Plants	407
	References	408
12	Safety Design Concept of Liquid Metal Cooled Fast Breeder Reactors (LMFBRs)	417
12.1	Introduction	417
12.2	Basic Principles of the Safety Design Concept of LMFBRs.	418

12.3	Reactor Physics and Safety Related Characteristic	
	Data of LMFR Cores	418
12.3.1	Safety Characteristics of LMFRs	419
12.3.2	Reactivity Coefficients of the LMFR Core.	421
12.4	LMFR Plant Protection System (PPS)	427
12.5	Design Basis for the Plant Protection System and Related Safety Systems	428
12.5.1	Design Basis Accidents Initiated by Positive Reactivity Input	428
12.5.2	Design Criteria for Shutdown Systems.	429
12.6	Mechanisms Leading to Impairment of Heat Removal	431
12.7	Instrumentation and Monitoring of the Protection System	431
12.8	Analysis of Design Basis Accidents	433
12.8.1	Power Transients.	433
12.8.2	Positive Reactivity and Power Transients.	433
12.8.3	Loss of Primary Flow	434
12.8.4	Transient Events in Sodium Steam Circuits	435
12.9	Decay Heat Removal in LMFRs.	435
12.10	Anticipated Transients with Failure to Scram.	437
12.10.1	Phase from 1970–1990	438
12.10.2	The Phase from 1985–2010	439
12.11	Local Melting in Fuel Assemblies.	442
12.12	Molten Core Cooling Device (Core Catcher) for LMFRs	444
12.13	Sodium Fires	444
12.13.1	Sodium Spray Fires.	446
12.13.2	Double Walled Piping	447
12.13.3	LBE as Coolant	447
12.14	Sodium-Water Interactions in Steam Generators.	447
12.14.1	Instrumentation of Steam Generators.	449
12.14.2	Double Walled Steam Generator Tubes	449
12.14.3	Steam Generators with LBE Coolant.	450
12.15	Containment Safety Design Concept	450
12.16	Core Melt Down and Core Disruptive Accidents in LMFRs	452
12.16.1	Core Melt Down and Core Disruptive Accidents for the Early Prototype Power LMFRs	452
12.16.2	Core Melt Down and Core Disruptive Accidents for Future LMFRs.	454
	References	454
	Index	459

Sustainable and Safe Nuclear Fission Energy
Technology and Safety of Fast and Thermal Nuclear
Reactors

Kessler, G.

2012, XXVI, 466 p., Hardcover

ISBN: 978-3-642-11989-7