

	Title pages, Contributors, Preface, Table of contents	
	Title pages	
	Contributors	
	Preface	
	Table of contents	
0	Introduction to nuclear fission and fusion energy technologies (K. HEINLOTH)	1
1	Nuclear fission energy (K. KUGELER, E. KUGELER, N. PÖPPE, Z. ALKAN, W. GRÄTZ)	3
1.1	Principles of fission reactors	3
1.1.1	The fission process	3
1.1.2	The controlled chain reaction and the critical arrangement	7
1.1.3	Principle of a nuclear reactor	11
1.1.4	Some necessary fundamentals	13
1.1.4.1	Cross sections	13
1.1.4.2	Neutron flux and reaction rates	16
1.1.4.3	Neutron spectrum	16
1.1.4.4	Diffusion of neutrons	17
1.1.4.5	Slowing down of neutrons	21
1.1.4.6	Resonance escape probability	25
1.1.5	Reactor equations and critical reactors	27
1.1.5.1	Reactor equations	27
1.1.5.2	Aspects of criticality	31
1.1.6	Neutron balance and heat production in an LWR core	33
1.1.6.1	Neutron balance of the core	33
1.1.6.2	Heat production in the core	37
1.1.7	Some aspects of reactor physics	37
1.1.7.1	Burn-up of fissile materials and build-up of higher isotopes	37
1.1.7.2	Building up of fission product inventory	39
1.1.7.3	Xenon and samarium poisoning	42
1.1.7.4	Reactivity coefficients	47
1.1.7.5	Time behavior of reactors, kinetic equations	49
1.1.7.6	Dynamic equations	54
1.1.7.7	On the importance of fission products in nuclear technology	58
1.2	Nuclear power plants	61
1.2.1	Overview of different reactor types	61
1.2.2	Pressurized water reactors	65
1.2.2.1	Plant overview	65

1.2.2.2	Components of the core	68
1.2.2.3	Components of the primary system	70
1.2.2.4	Reactor containment	73
1.2.2.5	Reactor safety systems	74
1.2.2.6	Auxiliary systems	76
1.2.2.7	Steam turbine plant	76
1.2.3	Thermohydraulic aspects of the core and of the fuel elements	79
1.2.4	Operating experience	86
1.2.4.1	Availability of power plants	86
1.2.4.2	Release of radioactivity to the environment	87
1.2.4.3	Radiation inside nuclear power plants	88
1.2.4.4	Fuel handling	90
1.2.4.5	Control	93
1.2.5	Accidents in the design area	94
1.2.5.1	Overview	94
1.2.5.2	Loss of coolant	97
1.2.5.3	Break of steam generator pipe	99
1.2.5.4	Loss of power and failure of turbine	100
1.2.5.5	Break of pipes in the secondary system	101
1.2.5.6	Loss of a control rod	103
1.2.5.7	External events	103
1.2.6	Other types of nuclear reactors	108
1.2.6.1	Boiling water reactors	108
1.2.6.2	CANDU reactors	111
1.2.6.3	RBMK reactors	113
1.2.6.4	Advanced gas-cooled reactors (AGR)	116
1.2.6.5	High temperature reactors	117
1.2.6.6	Liquid metal cooled fast breeder reactors (LMFBR)	123
1.2.6.7	New concepts in nuclear technology	125
1.3	Economic aspects	129
1.3.1	Calculation formula for the generating costs of electricity	129
1.3.2	Investment costs	131
1.3.3	Capital factors	132
1.3.4	Hours of full-power operation	134
1.3.5	Efficiencies of plants	135
1.3.6	Burn-up of nuclear fuel	136
1.3.7	Costs of nuclear fuel	137
1.3.8	Costs of intermediate storage and final storage of spent fuel or high-level radioactive waste	139
1.3.9	Overall nuclear fuel cycle costs	140
1.3.10	Personnel costs and costs for auxiliary materials	142
1.3.11	Total generating costs of electricity in nuclear power plants	142
1.3.12	Comparison of generating costs	143

1.3.13	External costs	145
1.4	Safety questions	147
1.4.1	Core melt incidents in light water reactors	147
1.4.2	Consequences of core melt accidents	152
1.4.3	New safety requirements for future nuclear power plants	157
1.4.4	Paths of development of new reactor systems	159
1.4.5	Reactor system with retention of the molten core	160
1.4.6	Principles of inherently safe reactors without core melt	164
1.4.7	Inherently safe high temperature reactors without core melt	173
1.5	References for 1	182
2	Risk analyses and protection strategies for the operation of nuclear power plants (W. KRÖGER, WITH CONTRIBUTIONS FROM J. MERTENS, D. KOGELSCHATZ, S. CHAKRABORTY)	186
2.1	Introduction	186
2.2	Technical fundamentals	187
2.3	Protection strategies	188
2.3.1	Basic philosophy	188
2.3.2	Commonly shared principles and future requirements	190
2.3.3	Future role of probabilistic safety analysis (PSA)	192
2.4	Methodology of PSA	193
2.4.1	Structure and scope	193
2.4.2	Basic mathematical techniques	194
2.4.3	Fundamentals of Level-1 PSA	196
2.4.3.1	Selection of initiating events	196
2.4.3.2	Event sequence and system modeling	196
2.4.3.3	Data for assessment of frequencies	198
2.4.3.4	Treatment of dependences	198
2.4.3.5	Human actions and reliability	200
2.4.4	Level-2 PSA	202
2.4.5	Level-3 PSA	205
2.4.6	PSA codes	208
2.4.7	Treatment of uncertainties	209
2.4.8	Expert judgment	209
2.4.9	Team expertise and quality assurance issues	209
2.4.10	Data collection	210
2.5	PSA applications and results	211
2.5.1	Status of PSA activities	211
2.5.2	Results and insights from Level-1 PSA	212
2.5.3	Results and insights from Level-2 PSA	215
2.5.4	Results from Level-1 and -2 PSA from a country perspective	217
2.5.5	Results from Level-3 PSA	218
2.6	Approaches and results of risk comparisons of different electricity-producing systems	219
2.7	Outlook	222
2.8	Appendix	223

2.8.1	Appendix for 2.4	223
2.8.2	Appendix for 2.5	225
2.9	References for 2	232
3	Nuclear fuel and fuel cycle (B. BARRÉ)	236
3.1	The nuclear fuel cycle(s)	236
3.2	Fissile and fertile materials procurement	238
3.2.1	Uranium and thorium	238
3.2.2	Exploration	241
3.2.3	Mining and concentration (milling)	242
3.2.4	Sites rehabilitation	243
3.2.5	Plutonium	244
3.2.6	World uranium resources and market	246
3.3	Uranium enrichment	247
3.3.1	Principle, cascade, SWU, HEU, LEU	248
3.3.2	Enrichment technologies	250
3.3.2.1	Gaseous diffusion	251
3.3.2.2	Ultra centrifugation	253
3.3.2.3	Laser isotopic separation (AVLIS)	254
3.3.3	World enrichment capacities and market	255
3.3.4	Conversion	256
3.4	Fuel fabrication	256
3.4.1	Elements of fuel design	256
3.4.1.1	Fissile/fertile couple	257
3.4.1.2	Fuel material	258
3.4.1.3	Cladding materials	258
3.4.1.4	Absorber materials	259
3.4.1.5	PWR and BWR fuel assemblies	259
3.4.2	LWR fabrication technology	260
3.4.2.1	Fuel pellet production	260
3.4.2.2	Fuel rod fabrication	261
3.4.2.3	Assembly	261
3.4.2.4	MOX fuel	261
3.4.3	LWR fuel fabrication capacity and market	263
3.4.4	Other fuel	264
3.4.4.1	CANDU	264
3.4.4.2	FBR	264
3.4.4.3	HTR	265
3.5	In-reactor PWR fuel behavior	266
3.6	Spent-fuel management	268
3.6.1	Disposal or reprocessing and recycle	268
3.6.2	Reprocessing technology	269
3.6.2.1	PUREX	269

3.6.2.2	Waste management	271
3.6.2.3	Other processes	272
3.6.3	Reprocessing capacities and market	272
3.6.4	Final repository	273
3.6.5	Partitioning and transmutation	274
3.7	Economics	275
3.8	References for 3	277
4	Radionuclides in the environment (H.G. PARETZKE, J.E. TURNER)	278
4.1	Introduction	278
4.2	Radioactivity and radionuclides	278
4.2.1	Atoms and energy	278
4.2.2	Transitions of atoms: radioactivity	279
4.2.3	Radiation emitted in transitions	279
4.2.4	General relevancy of radionuclides in the environment	280
4.3	Natural radionuclides in the environment	281
4.3.1	Cosmogenic isotopes	281
4.3.2	Primordial isotopes	282
4.3.3	Technical radionuclides in the environment	285
4.3.3.1	Nuclear fuel cycles	285
4.3.3.2	Fossil fuel	286
4.4	Major radioactive releases	286
4.5	Interactions of ionizing radiation with matter	290
4.5.1	Photons	290
4.5.2	Beta particles	291
4.5.3	Alpha particles	291
4.5.4	Neutrons	291
4.5.5	Dosimetry	292
4.6	Radiation exposures from natural and artificial radiation sources	293
4.7	Radiation measurements	295
4.7.1	General methods	295
4.7.2	Alpha particles	295
4.7.3	Beta particles	296
4.7.4	Photons	296
4.7.5	Neutrons	297
4.8	Biological radiation effects on humans	298
4.8.1	Acute and teratogenic radiation effects	298
4.8.2	Stochastic late and genetic effects	299
4.9	Biological radiation effects on biota	300
4.9.1	Historical development	300
4.9.2	Effects on plants	301
4.9.3	Effects on animals	302
4.10	References for 4	302

5	Controlled nuclear fusion: general aspects (E. REBHAN, D. REITER, R. WEYNANTS, U. SAMM, W.J. HOGAN, J. RAEDER, T. HAMACHER)	304
5.1	Fusion processes (E. Rebhan)	304
5.1.1	Introduction	304
5.1.2	Binding energy of nuclei	304
5.1.3	Fusion reactions	306
5.1.4	Reaction cross-sections and reaction rates	307
5.2	Operational conditions and balances (D. Reiter)	310
5.2.1	Introduction	310
5.2.2	Fusion power density	310
5.2.3	The fusion energy gain factor G and the power gain factor Q	310
5.2.4	Break-even, ignition	311
5.2.5	Power balances for magnetically confined plasmas	312
5.2.6	The Lawson criterion	312
5.2.7	Power balances for inertial confinement systems	313
5.2.8	Burn-up fraction	313
5.2.9	ICF reactor balance	314
5.2.10	Spark ignition	314
5.3	Main principles of a fusion reactor (R. Weynants)	315
5.3.1	Introduction	315
5.3.2	Magnetic confinement fusion (MCF)	316
5.3.2.1	Principles of confinement by magnetic fields	316
5.3.2.2	Main magnetic confinement configurations	317
5.3.2.3	Outline of an MF reactor	319
5.3.3	Inertial confinement fusion (ICF)	321
5.3.3.1	Main inertial confinement principles	321
5.3.3.2	Main inertial confinement configurations	322
5.3.3.3	Outline of an inertial confinement reactor	323
5.4	Reactor technology for magnetic confinement (U. Samm)	324
5.4.1	First wall and high heat flux components	325
5.4.2	Systems for heating, current drive, profile control and refueling	328
5.4.3	Blanket, shield, and energy conversion system	331
5.4.4	Fuel cycle	333
5.4.5	Magnet systems	333
5.4.6	Remote handling	335
5.5	Reactor technology for inertial confinement (W.J. Hogan)	336
5.5.1	Introduction	336
5.5.2	Targets	337
5.5.3	Drivers	340
5.5.4	Target fabrication and positioning systems	341
5.5.5	Reaction chamber systems	343
5.5.6	Balance-of-plant systems	346

5.5.7	Special design issues	347
5.6	Safety and environmental aspects of magnetic confinement systems (J. Raeder)	348
5.6.1	Introduction	348
5.6.2	The safety characteristics of magnetic confinement fusion	349
5.6.3	Safety concept	349
5.6.3.1	Safety objectives	349
5.6.3.2	Safety principles	350
5.6.3.3	Criteria and guidelines	350
5.6.3.4	Implementation of safety	351
5.6.4	Plant models	352
5.6.5	Safety-relevant inventories	352
5.6.6	Normal operation effluents	353
5.6.7	Personnel safety	353
5.6.8	Accidents	353
5.6.9	Radioactive materials	355
5.6.10	Proliferation	356
5.6.11	Conclusions	357
5.7	Fusion resources (T. Hamacher)	357
5.7.1	Introduction	357
5.7.2	Fusion plant material requirement	359
5.7.3	Fusion fuels	360
5.7.3.1	Deuterium	360
5.7.3.2	Lithium	360
5.7.4	Construction materials	361
5.7.4.1	Neutron multipliers (beryllium and lead)	361
5.7.4.2	Niobium for magnets	361
5.7.4.3	Vanadium as structural material	361
5.7.4.4	Wall armors	361
5.7.4.5	Copper	362
5.7.5	Operation materials	362
5.7.6	Energy requirements	363
5.7.7	Summary and conclusions	363
5.8	References for 5	364
6	Magnetic confinement fusion: tokamak (D. CAMPBELL)	369
6.1	Introduction	369
6.2	The tokamak configuration	371
6.2.1	Tokamak equilibrium	371
6.2.2	Plasma equilibrium parameters	373
6.2.3	Particle orbits	375
6.2.4	Plasma resistivity	376
6.3	Auxiliary systems	378
6.3.1	Heating and current drive systems	378
6.3.2	Fueling and exhaust	380
6.3.3	Diagnostics	382

6.4	Transport and confinement	382
6.4.1	Elementary transport processes	382
6.4.2	Plasma confinement modes	384
6.5	Magnetohydrodynamic (mhd) stability	388
6.5.1	Essential principles	388
6.5.2	Vertical instability	388
6.5.3	Disruptions	389
6.5.4	Operational limits	390
6.5.5	Mhd instabilities	392
6.6	Plasma-surface interactions	393
6.6.1	Power and particle control	393
6.6.2	Plasma boundary issues	394
6.6.3	Divertor experiments	396
6.7	Steady-state operation	397
6.8	Energetic particle physics	399
6.8.1	Energetic particle confinement	399
6.8.2	Energetic particle interactions with mhd instabilities	401
6.9	Tokamak experiments	402
6.9.1	Present status	402
6.9.2	Deuterium-tritium experiments	405
6.10	ITER and tokamak power plants	407
6.10.1	ITER	407
6.10.2	Tokamak power plants	410
6.11	References for 6	414
7	Magnetic confinement fusion: stellarator (H. WOBIG, F. WAGNER)	418
7.1	Introduction	418
7.2	Survey of stellarator reactor studies	419
7.3	Coil configurations	423
7.3.1	Continuous coil stellarators	424
7.3.2	Torsatron configurations	425
7.3.3	The Helic concept	426
7.3.4	Modular coil systems	427
7.4	Physics basis of the stellarator reactor	428
7.4.1	Requirements on reactor physics	428
7.4.2	Plasma equilibrium	430
7.4.3	The role of Pfirsch-Schlüter currents	432
7.4.4	Classical diffusion and Pfirsch-Schlüter currents	433
7.4.5	Stability of stellarator equilibria	433
7.4.6	Particle orbits in stellarators	434
7.4.7	Neoclassical transport in stellarators	435
7.4.8	The bootstrap current	437
7.4.9	Principles of optimization in stellarators	437

7.4.10	Alpha-particle confinement	438
7.4.11	Distortion of the magnetic field	439
7.4.12	The divertor in the stellarator reactor	439
7.4.13	Anomalous transport in stellarator reactors	440
7.4.14	Empirical scaling laws and ignition	441
7.5	Economic aspects of a stellarator reactor	443
7.5.1	Wall loading	443
7.5.2	Blanket systems in stellarator reactors	445
7.5.3	Thermal cycle	445
7.5.4	Safety of stellarator reactors	447
7.5.4.1	Energy reservoir	447
7.5.4.2	Tritium inventory	448
7.5.4.3	Decay heat	448
7.5.5	Balance of mass and cost analysis	449
7.6	References for 7	450
8	Inertial confinement fusion: laser (W.J. HOGAN)	453
8.1	Introduction	453
8.2	Target types most suitable for laser drivers	457
8.3	Laser drivers: KrF, solid state	461
8.3.1	KrF lasers	461
8.3.1.1	Timescale issues	462
8.3.1.2	Beam smoothing	462
8.3.1.3	Pulse shaping and zooming	463
8.3.1.4	Electron beam propagation and energy deposition efficiency	463
8.3.1.5	Advanced pulsed power development	465
8.3.1.6	Gas recirculation system	465
8.3.1.7	Platforms for KrF laser research and development	466
8.3.1.8	System efficiency	466
8.3.2	Diode-pumped solid state lasers (DPSSL)	468
8.3.2.1	Timescale issues	469
8.3.2.2	Beam smoothing issues	470
8.3.2.3	Two approaches to DPSSL design and development	471
8.3.2.4	Diode array development and cost reduction issues	472
8.3.2.5	Laser medium growth	474
8.3.2.6	Repetition rate and amplifier cooling issues	475
8.3.2.7	Test beds for DPSSL development	475
8.4	Fast ignition lasers for laser-driven IFE	478
8.5	Reaction chamber and target positioning issues for laser IFE	480
8.6	Final optics issues for laser IFE	483
8.7	Development path for laser IFE	490
8.8	References for 8	492
9	Inertial confinement fusion: z-pinch (C.L. OLSON)	495
9.1	Introduction	495
9.2	Pulsed power drivers for z-pinch IFE	497

9.2.1	Marx generator/water line pulsed power technology	497
9.2.2	RHEPP (magnetic switching, inductive voltage adder) technology	499
9.2.3	Linear Transformer Driver technology	501
9.2.4	Z-pinch drivers for high-yield (~ 0.5 GJ) facilities	503
9.3	Standoff: Recyclable Transmission Lines	504
9.3.1	MITL (Magnetically-Insulated Transmission Line)	504
9.3.2	RTL (Recyclable Transmission Line)	505
9.4	Z-pinch targets	509
9.4.1	Fast z-pinch as intense soft X-ray radiation sources	510
9.4.2	Z-pinch driven targets	513
9.5	Z-pinch power plant concept for IFE	516
9.6	IFE materials testing on pulsed power facilities	520
9.7	Status and development plans for z-pinch IFE	522
9.8	References for 9	526
10	Inertial confinement fusion: heavy ions (R.M. BOCK, I. HOFMANN, D.H.H. HOFFMANN, G. LOGAN)	529
10.1	Introduction	529
10.2	Target physics	530
10.2.1	Interaction of heavy ions with matter	530
10.2.2	Basic issues of IFE target development for heavy ion beams	532
10.2.3	Physics of dense plasmas and fast ignition	533
10.2.4	Conclusions	534
10.3	Heavy ion driver concepts	535
10.3.1	Introduction	535
10.3.2	Basic principles	535
10.3.2.1	Requirements for fusion energy production	535
10.3.2.2	Intense heavy ion beams	536
10.3.3	Driver scenarios	537
10.3.3.1	RF linac and storage ring systems	537
10.3.3.2	Induction linac scenario and component development	539
10.4	The inertial fusion reactor	543
10.4.1	Introduction	543
10.4.2	Systems overview	544
10.4.3	Reactor chamber design	545
10.4.3.1	Chamber and jet array system, clearing and condensation	545
10.4.3.2	Target injection	547
10.4.3.3	Tritium technology and facilities	547
10.4.3.4	Materials and molten-salt technology	547
10.4.4	Neutronics and activation of materials, safety aspects	548
10.4.5	Power plant parameters and economic analysis	550
10.4.6	Conclusions	550
10.5	References for 10	552

11	Muon-catalyzed fusion (μ CF) (K. NAGAMINE)	555
11.1	Introduction	555
11.2	Basic properties of muons	555
11.3	Accelerator-produced muons	556
11.4	Muons inside matter and muonic atoms	560
11.5	Basic concept of muon catalysis of nuclear fusion	562
11.6	Experimental arrangements	565
11.7	Fusion reaction in a small muonic molecule	567
11.8	Muonic atom thermalization and muon transfer among hydrogen isotopes	570
11.9	Formation of muonic molecules	572
11.10	Muon sticking and regeneration in the μ CF cycle	578
11.11	The He impurity effect	584
11.12	Applications of μ CF	587
11.12.1	A practical energy source using μ CF	587
11.12.2	A 14 MeV neutron source using μ CF	591
11.12.3	Slow- μ^- generation via μ CF	591
11.12.4	Power generation at the kW level before 2010	592
11.13	Conclusions and future perspectives	592
11.14	Concluding remarks on a possible μ CF power plant	593
11.15	Appendix	594
11.15.1	Numerical data on D-T μ CF	594
11.15.1.1	($d\mu$) formation rate	594
11.15.1.2	Muon loss rate and X-rays from sticking	595
11.15.2	Numerical data on D ₂ μ CF	598
11.15.2.1	($dd\mu$) formation rate and hyperfine transition rate λ_{hf}	598
11.16	References for 11	599

Nuclear Energy

2005, XVIII, 604 p. With online files/update., Hardcover

ISBN: 978-3-540-42891-6