

Contents

Preface *xxv*

1	Characteristics of the Fusion Reactor	1
1.1	The Fusion Reactor as an Energy Source	1
1.1.1	Trends in World Energy Consumption	1
1.1.2	Energy Classification	1
1.1.3	Nuclear Fusion Power Generation	2
1.2	Nuclear Fusion Reaction	3
1.2.1	Nuclear Reaction Used in the Fusion Reactor	3
1.2.2	Cross Section of the Fusion Reaction	4
1.2.3	Fusion Reaction Rate	5
1.3	Plasma Confinement Concept	7
1.3.1	Magnetic Confinement	7
1.3.1.1	Linear System (Open-End System)	7
1.3.1.2	Toroidal System	9
1.3.2	Inertial Confinement	13
	References	15
2	Basis of the Fusion Reactor	17
2.1	Power Flow	17
2.2	Fusion Reactor Structure	19
2.3	Power Generation Conditions of the Fusion Reactor	20
2.3.1	Power Flow of the Power Plant	20
2.3.2	Plant Efficiency	21
2.3.3	Fuel Supply Scenario	22
2.4	Core Plasma Conditions	22
2.4.1	Break-Even Condition and Self-Ignition Condition	22
2.4.2	Lawson Criterion	22
2.4.3	Typical Reactor Concepts	24
2.5	Requirements of Plasma in the Fusion Reactor	24
2.5.1	Fusion Triple Product	25
2.5.2	β Value	25
2.5.3	Current Drive Efficiency	25

2.6	Operation Scenario	26
2.6.1	Pulse Operation	26
2.6.2	Quasi-steady-state Operation	27
2.6.3	Steady-state Operation	28
2.7	Stepwise Development Research of the Fusion Reactor	28
2.7.1	Experimental Reactor	29
2.7.2	Prototype Reactor	29
2.7.3	Demonstration Reactor/Commercial Reactor	29
	References	29
3	Basics of Plasma Analysis	31
3.1	Boltzmann Equation	31
3.2	Plasma Analysis	32
3.2.1	Velocity Information	33
3.2.2	Nonlinear Effects	33
3.2.3	External Electromagnetic Field	33
3.2.4	Numerical Simulation	33
3.2.5	Main Plasma Theories	33
3.3	Magnetohydrodynamic Equation	35
3.3.1	Macroscopic Physical Quantity	35
3.3.1.1	Momentum Flow Tensor $P(r, t)$	36
3.3.1.2	Pressure Tensor $p(r, t)$	36
3.3.1.3	Energy Density $\epsilon(r, t)$	36
3.3.1.4	Internal Energy Density $U(r, t)$	36
3.3.1.5	Energy Flux Vector $Q(r, t)$	36
3.3.2	Particle Number Conservation Law (Equation of Continuity)	37
3.3.3	Momentum Conservation Law	38
3.3.4	Energy Conservation Law	39
3.4	Kinetic Equation	39
3.5	Linearized Kinetic Analysis (One Dimension)	41
3.6	Linearized Kinetic Analysis (Three Dimensions)	43
3.7	Quasi-Linear Theory	46
3.8	Turbulence Theory	49
3.8.1	Weak Turbulence Theory	49
3.8.1.1	Wave-Particle Interaction	51
3.8.1.2	Wave-Wave (3 Waves) Interaction	52
3.8.1.3	Nonlinear Wave-Particle Interaction	52
3.8.1.4	Wave-Wave (4 Waves) Interaction	52
3.8.2	Strong Turbulence Theory	53
3.9	Neutron Transport Analysis	53
3.9.1	Transport Equation	53
3.9.2	Interaction Between Neutrons and Materials	54
	References	55

4	Plasma Equilibrium and Stability	57
4.1	Plasma Equilibrium	57
4.1.1	Plasma Pressure	57
4.1.2	Equilibrium Equation	59
4.1.3	Tokamak Equilibrium	61
4.1.4	Plasma Cross Section	63
4.2	MHD Stability	64
4.2.1	Energy Principle	64
4.2.1.1	MHD Equation	64
4.2.1.2	Linearized Ideal MHD Equation	66
4.2.1.3	Energy Principle	67
4.2.2	Energy Integral	68
4.2.3	MHD Instability	69
4.2.4	MHD Mode and Resonant Surface	69
4.3	Plasma Positional Instability	71
4.4	Kink Instability	74
4.4.1	Characteristics	74
4.4.2	Dispersion Relation	74
4.4.3	Stabilization Method	76
4.5	Interchange Instability	77
4.6	Ballooning Instability	78
4.6.1	Characteristics	78
4.6.2	Energy Integral	79
4.6.3	Stabilization Method	81
4.7	Resistive Instability	82
4.7.1	Tearing Mode	83
4.7.1.1	Characteristics	83
4.7.1.2	Basic Equations	84
4.7.1.3	Magnetic Island Width	85
4.7.1.4	Magnetic Island Evolution Equation	86
4.7.1.5	Stabilization Method	88
4.7.2	Neoclassical Tearing Mode	88
4.7.2.1	Characteristics	88
4.7.2.2	Difference in the Logarithmic Derivative Due to Bootstrap Current	89
4.7.2.3	Magnetic Island Evolution Equation	89
4.7.2.4	Stabilization Method	89
4.8	Drift Instability	90
4.8.1	Density Gradient	90
4.8.2	Density Gradient and Temperature Gradient	90
4.8.3	Resistive Drift Mode	92
4.8.4	Influence of Drift Wave on Plasma Transport	95
4.9	Resistive Wall Instability	96
4.9.1	Characteristics	96
4.9.2	Stabilization Method	97

4.10	Instability Due to High Energy Particles	98
4.10.1	Alfvén Eigenmode	98
4.10.1.1	Characteristics	98
4.10.1.2	Dispersion Relation	99
4.10.1.3	Instability Condition and Stabilization Method	100
4.10.2	Fishbone Oscillation	102
4.11	Sawtooth Oscillation	102
4.12	Edge Localized Mode	102
4.13	Locked Mode	103
4.14	Future Challenges	103
	Appendix 4A	103
	Appendix 4B	107
	References	111
5	Plasma Transport and Confinement	113
5.1	Confinement Time	113
5.2	Plasma Transport	114
5.2.1	Diffusion by Collision	114
5.2.2	Diffusion by Turbulence	116
5.2.2.1	Bohm Diffusion	116
5.2.2.2	Gyro-Bohm Diffusion	118
5.2.2.3	Energy Confinement	119
5.3	Scaling Law of Energy Confinement	119
5.3.1	Parameter Dependence of Energy Confinement Time	119
5.3.2	Scaling Law	120
5.3.3	L–H Transition Threshold Power	122
5.3.4	Improved Confinement Mode	122
5.4	Edge Localized Mode	124
5.4.1	Types of Edge Localized Mode	124
5.4.2	Energy Released by ELM	125
5.4.3	Measures Against ELM	127
5.5	β Limit	127
5.5.1	Plasma Current Profile	128
5.5.2	Plasma Pressure Profile	128
5.5.3	Shape of Plasma Cross Section	129
5.5.4	Neoclassical Tearing Mode	129
5.6	Density Limit	129
5.7	Confinement of High-Energy Particles	129
5.8	Disruption	130
5.8.1	Plasma Behavior in Disruption and Cause of the Occurrence	131
5.8.1.1	Plasma Behavior	131
5.8.1.2	Causes of Disruption	133
5.8.2	Effect on Equipment	133
5.8.2.1	Thermal Load	133
5.8.2.2	Electromagnetic Force	134

5.8.3	Countermeasures Against Disruption	135
5.9	Future Challenges	137
	References	137
6	Plasma Design	141
6.1	Particle and Energy Balances of Plasma (One Dimension)	141
6.1.1	Thermal Conduction Loss Power	143
6.1.2	Convection Loss Power	143
6.1.3	α Heating Power	143
6.1.4	Additional Heating Power	144
6.1.5	Joule (Ohmic) Heating Power	144
6.1.6	Electron-Ion Energy Transfer	144
6.1.7	Radiation Loss Power	145
6.2	Particle and Energy Balances of Plasma (Zero Dimension)	145
6.2.1	Zero-Dimensional Particle and Energy Balances	145
6.2.2	Plasma Temperature and Density in Steady-State Operation	146
6.3	Burn-Up Fraction	148
6.4	Plasma Circuit	150
6.5	Reactor Structure	152
6.5.1	Radial Build	152
6.5.2	Magnetic Flux Required for Operation	153
6.5.3	Magnetic Flux to Be Supplied	154
6.6	Future Challenges	155
	References	156
7	Blanket	157
7.1	Functions Required for the Blanket	157
7.2	Tritium Production	157
7.2.1	Necessity of Tritium Production	157
7.2.2	Tritium Breeding Ratio	159
7.2.3	Tritium Doubling Time	159
7.2.4	Improvement of Tritium Breeding Ratio	160
7.2.4.1	${}^6\text{Li}(n, T)\alpha$ Reaction Cross Section	161
7.2.4.2	${}^7\text{Li}(n, n'T)\alpha$ Reaction Cross Section	161
7.2.4.3	Tritium Breeding Material	161
7.2.4.4	Neutron Flux	163
7.2.4.5	Blanket Coverage	164
7.2.5	Recovery of Tritium	165
7.3	Taking Out of Thermal Energy	165
7.3.1	Energy Multiplication Factor of the Blanket	165
7.3.2	Power Generation Efficiency and Coolant Temperature	166
7.3.2.1	Temperature of Breeder and Multiplier Materials	166
7.3.2.2	Temperature of the Blanket Structural Material	167
7.3.2.3	Coolant	167
7.3.3	Temperature Profile	168

7.3.4	Power Generation Method	170
7.3.4.1	Power Generation Methods of Fission Reactor and Thermal Power Plant	171
7.3.4.2	Characteristics of Fusion Power Generation	172
7.3.4.3	Combination of Coolants	173
7.3.4.4	Fusion Power Generation	175
7.4	Radiation Shielding Function	175
7.4.1	Blanket Thickness	175
7.4.2	Low Radioactivation	176
7.5	Maintenance	176
7.5.1	Extension of Life	176
7.5.1.1	Wear Amount of Lithium by Burning of Tritium Breeding Material	177
7.5.1.2	Wear Amount of Beryllium by Burning of Neutron Multiplier Material	178
7.5.1.3	Wear Amount of First Wall	179
7.5.1.4	Nuclear Damage Due to Displacement Damage, Hydrogen and Helium Productions, Swelling, etc.	179
7.5.1.5	Change in Thermal Life of Structural Materials Due to Cycle Thermal Fatigue	179
7.5.2	Maintenance Method	179
7.5.2.1	Wear Amount and Replacement Frequency	179
7.5.2.2	Remote Maintenance Method	180
7.6	Blanket Design	181
7.6.1	Blanket Classification	181
7.6.2	Design Conditions	181
7.6.3	Blanket Concept	181
7.6.3.1	Blanket Configuration	181
7.6.3.2	Size of a Blanket	183
7.6.4	Design Example	185
7.7	Future Challenges	187
	References	189
8	Plasma-Facing Components	191
8.1	Functions Required for Plasma-Facing Components	191
8.1.1	Required Functions	191
8.1.1.1	Impurity Control	191
8.1.1.2	Plasma Particle Control	191
8.1.1.3	Thermal Treatment of Plasma Thermal Energy	192
8.1.2	Limiter and Divertor	192
8.2	Divertor Characteristics (in Steady State)	193
8.2.1	Basic Characteristics of Divertor Plasma	193
8.2.2	Two-Point Model	194
8.2.3	Attached State and Detached State	196
8.2.4	Two-Dimensional Divertor Analysis Model	197
8.2.5	Measures for Reducing Particle and Thermal Loads	200

8.2.5.1	Impurity Control	200
8.2.5.2	Particle Control	200
8.2.5.3	Average Heat Flux to the Divertor Plate	200
8.3	Divertor Characteristics (in Non-steady State)	201
8.3.1	ELM	201
8.3.2	Disruption	202
8.3.2.1	Thermal Load	202
8.3.2.2	Electromagnetic Force	203
8.4	Structures of Limiter and Divertor	203
8.4.1	Shape and Type of Limiter and Divertor	203
8.4.1.1	Trends in Impurity Control Research	203
8.4.1.2	Limiter and Pumped Limiter	204
8.4.1.3	Divertor	204
8.4.1.4	Comparison of Pumped Limiter and Divertor	205
8.4.2	Comparison of Single Null Divertor and Double Null Divertor	206
8.4.3	Shape of Divertor	206
8.5	Divertor Design	208
8.5.1	Design Conditions and Design Items	208
8.5.2	Material Selection	210
8.5.3	Structural Concept	212
8.5.3.1	Heat Receiving Plate Structure	212
8.5.3.2	Eddy Current Suppression Structure	213
8.5.3.3	Reduction of Stress and Strain	213
8.5.3.4	Cooling Tube	213
8.5.4	Design Example	214
8.6	First Wall	217
8.6.1	Particle Load and Thermal Load	217
8.6.2	First-Wall Structure	218
8.6.2.1	Overall Structure	218
8.6.2.2	Protection Structure	218
8.6.2.3	Flow Path Cross Section	218
8.6.2.4	Amount of Wear	220
8.6.3	Design Example	220
8.7	Future Challenges	222
	References	222
9	Coil System	227
9.1	Fusion Reactor Coils	227
9.1.1	Types of Coils	227
9.1.2	Necessity of Superconducting Coil	227
9.2	Basics of Superconducting Coils	228
9.2.1	Characteristics of Superconductivity	228
9.2.2	Superconducting Materials	228
9.2.3	Manufacturing Methods for Superconducting Wires	229
9.2.3.1	NbTi	229

- 9.2.3.2 Nb₃Sn 230
- 9.2.3.3 Nb₃Al 230
- 9.2.3.4 MgB₂ 231
- 9.2.3.5 Bismuth-Based Oxide 231
- 9.2.3.6 Yttrium-Based Oxide 231
- 9.2.4 Superconducting Wires 231
 - 9.2.4.1 Hysteresis Loss 231
 - 9.2.4.2 Stabilizing Materials (Stabilizers) 232
 - 9.2.4.3 Twist 232
 - 9.2.4.4 Cooling Performance 232
 - 9.2.5 Thermal Load and Cooling Methods 232
 - 9.2.5.1 Thermal Load 232
 - 9.2.5.2 Cooling Methods 233
 - 9.2.6 Conductor Structure 234
 - 9.2.6.1 Critical Current 235
 - 9.2.6.2 Limited Current 236
 - 9.2.6.3 Stability Margin 236
 - 9.2.6.4 Coil Average Current Density 237
 - 9.2.6.5 Conductor Design 237
 - 9.2.7 Coil Structure 237
 - 9.2.7.1 Structure 237
 - 9.2.7.2 Structural Material 238
- 9.3 Basics of Toroidal Magnetic Field Coil 238
 - 9.3.1 Functions for Toroidal Magnetic Field Coil 239
 - 9.3.2 Coil Current and Number of Coils 239
 - 9.3.2.1 Coil Current 239
 - 9.3.2.2 Number of Coils 239
 - 9.3.2.3 Stored Energy 241
 - 9.3.3 Electromagnetic Force Generated in Coil 241
 - 9.3.3.1 Extensional Force 241
 - 9.3.3.2 Centering Force 242
 - 9.3.3.3 Overturning Force 242
 - 9.3.4 Coil Shape 242
 - 9.3.4.1 Shape 242
 - 9.3.4.2 Three-Arc Approximation 243
 - 9.3.5 Maximum Magnetic Field 245
- 9.4 Design of Toroidal Magnetic Field Coil 245
 - 9.4.1 Conductor Design 246
 - 9.4.1.1 Selection of Superconducting Material 246
 - 9.4.1.2 Cooling Method 246
 - 9.4.2 Design of Coil Structure 246
 - 9.4.2.1 Coil Structure 246
 - 9.4.2.2 Selection of Structural Materials 246
 - 9.4.3 Support Structure 247
 - 9.4.3.1 Support Structure for the Centering Force 247

9.4.3.2	Support Structure for the Overturning Force	249
9.4.3.3	Support Structure of Own Weight	249
9.4.4	Design Example	249
9.5	Basics of Poloidal Magnetic Field Coil	254
9.5.1	Functions of Poloidal Magnetic Field Coil	254
9.5.2	Waveform Pattern of Coil Current for Control of Plasma Position and Shape	255
9.5.3	Position of Poloidal Magnetic Field Coil	256
9.6	Current Control of Poloidal Magnetic Field Coil	256
9.6.1	Magnetic Field Configuration to Determine the Plasma Shape	256
9.6.2	Control of Plasma Position and Shape	257
9.6.3	Generation Types of Poloidal Magnetic Field	258
9.6.4	Function-Specific Coil System	259
9.6.5	Hybrid Coil System	260
9.6.5.1	Number of PF Coils	260
9.6.5.2	Determining the PF Coil Position	260
9.6.5.3	Determining the PF Coil Current	260
9.7	Design of Poloidal Magnetic Field Coil	263
9.7.1	Conductor Design	263
9.7.1.1	Selection of Superconducting Material	263
9.7.1.2	Cooling Method	263
9.7.2	Design of Coil Structure	263
9.7.2.1	Coil Structure	263
9.7.2.2	Selection of Structural Materials	263
9.7.2.3	Support Structure	264
9.7.3	Design Example	264
9.8	Basics of Central Solenoid Coil	265
9.8.1	Functions of Central Solenoid Coil	265
9.8.2	Magnetic Field of Central Solenoid Coil	266
9.8.3	Supplied Magnetic Flux	266
9.9	Design of Central Solenoid Coil	267
9.9.1	Conductor Design	267
9.9.1.1	Selection of Superconducting Material	267
9.9.1.2	Cooling Method	268
9.9.2	Design of Coil Structure	268
9.9.2.1	Coil Structure	268
9.9.2.2	Selection of Structural Materials	268
9.9.2.3	Support Structure	268
9.9.3	Design Example	268
9.10	Future Challenges	270
	References	271
10	Plasma Heating and Current Drive	273
10.1	Necessity of Plasma Heating and Current Drive	273
10.1.1	Plasma Heating	273

10.1.2	Current Drive	274
10.2	Basics of NBI Heating	275
10.2.1	Ionization of Neutral Particle Beam	275
10.2.2	Trajectory of Ion Beam	276
10.2.2.1	Direction of Injection	276
10.2.2.2	Trapped Condition	277
10.2.2.3	Trajectory of Beam Ion	278
10.2.3	Plasma Heating by Energy Relaxation	279
10.3	Basics of NBI Current Drive	281
10.3.1	Driven Current	281
10.3.2	Current Drive Efficiency	282
10.3.3	Shine Through Rate	284
10.3.4	Current Drive Efficiency Obtained by Experiments	284
10.4	Bootstrap Current	285
10.4.1	Trapped Electron Orbit and Bootstrap Current	285
10.4.2	Ratio of the Bootstrap Current	286
10.5	Basics of Radio Frequency Heating	287
10.5.1	Dispersion Relation	287
10.5.2	Dispersion Relation of Cold Plasma	288
10.5.3	Dispersion Relation of Hot Plasma	289
10.5.4	Dispersion Relation of Plasma with Maxwell Distribution	290
10.5.5	Characteristics of RF Waves	291
10.5.5.1	Phase Velocity and Group Velocity	291
10.5.5.2	Cutoff and Resonance	292
10.5.5.3	Polarization	292
10.5.6	Propagation Characteristics of RF Waves	293
10.5.6.1	When the Wave Number Vector is Parallel to the Magnetic Field	294
10.5.6.2	When the Wave Number Vector is Perpendicular to the Magnetic Field	296
10.5.7	Principles of Plasma Heating	297
10.5.7.1	Landau Damping	298
10.5.7.2	Transit Time Damping	298
10.5.7.3	Cyclotron Damping	299
10.5.7.4	Absorption Power	299
10.5.8	Propagation in Nonuniform Plasma	300
10.6	Various RF Waves	301
10.6.1	Alfvén Wave	301
10.6.2	Ion Cyclotron Wave	303
10.6.2.1	Right-handed Cut Off and Left-handed Cut Off	304
10.6.2.2	Density at Which the Wave can Propagate	305
10.6.2.3	Characteristics of the Slow Wave	305
10.6.2.4	Characteristics of the Fast Wave	305
10.6.3	Lower Hybrid Wave	307
10.6.3.1	Resonance and Cut Off	307
10.6.3.2	Accessibility Condition	309

10.6.4	Electron Cyclotron Wave	310
10.6.4.1	Absorption Power	311
10.6.4.2	Resonance and Cut Off	311
10.6.4.3	Propagation Path	311
10.7	Basics of RF Current Drive	313
10.7.1	General Theory of RF Current Drive	313
10.7.1.1	Various Noninductive Current Drive Methods	313
10.7.1.2	Normalized Current Drive Efficiency	314
10.7.1.3	Current Drive Using Momentum of the Wave	315
10.7.1.4	Current Drive Using Anisotropy of the Velocity Space	316
10.7.1.5	Current Drive Efficiency	316
10.7.2	Current Drive Using Momentum of the Wave	316
10.7.2.1	Fokker–Planck Equation in One and Two Dimensions	316
10.7.2.2	Driven Current Density and Current Drive Power Density	318
10.7.2.3	LHCD (One-Dimensional Analysis)	318
10.7.2.4	DC Electric Field	318
10.7.2.5	LHCD (Two-Dimensional Analysis)	320
10.7.3	Current Drive with Anisotropy of the Velocity Space	321
10.7.3.1	Two-Dimensional Fokker–Planck Equation	321
10.7.3.2	Relativistic Effect	323
10.7.3.3	Trapped Effect	324
10.7.4	Current Drive Efficiency Obtained by Experiments	327
10.7.4.1	Fast Wave Current Drive (FWCD)	327
10.7.4.2	LHCD	328
10.7.4.3	ECCD	329
10.8	NBI System Design	330
10.8.1	Design Requirements	330
10.8.1.1	Required Functions	330
10.8.1.2	Design Requirements	330
10.8.1.3	System Efficiency	330
10.8.2	System Configuration	331
10.8.2.1	Positive-ion NBI	331
10.8.2.2	Negative-ion NBI	332
10.8.3	Negative-ion Source	332
10.8.3.1	Negative-ion Generator	332
10.8.3.2	Accelerator	334
10.8.4	Beam Transport System	334
10.8.4.1	Beam Profile Control Unit	334
10.8.4.2	Neutralization Cell (Neutralizer)	334
10.8.4.3	Residual Ion Bending Magnet and Residual Ion Dump	335
10.8.4.4	Vacuum Exhaust System	335
10.8.5	Design Example	335
10.8.6	Future Challenges	336
10.9	System Design of the Ion Cyclotron Wave	337
10.9.1	Design Requirements	337

10.9.1.1	Required Functions	337
10.9.1.2	ICRF Excitation Method	338
10.9.1.3	System Efficiency	338
10.9.2	System Configuration	339
10.9.2.1	RF Source	339
10.9.2.2	Transmission System	339
10.9.2.3	Injection System	340
10.9.3	Design Example	340
10.9.4	Future Challenges	342
10.10	System Design of the Lower Hybrid Wave	342
10.10.1	Design Requirements	342
10.10.1.1	Required Functions	342
10.10.1.2	LHW Excitation Method	343
10.10.1.3	Plasma Density in Front of the Launcher	344
10.10.1.4	System Efficiency	344
10.10.2	System Configuration	344
10.10.2.1	RF Source	345
10.10.2.2	Transmission System	345
10.10.2.3	Injection System (Launcher)	346
10.10.2.4	Phase Shifter	347
10.10.3	Design Example	348
10.10.4	Future Challenges	350
10.11	System Design of the Electron Cyclotron Wave	350
10.11.1	Design Requirements	350
10.11.1.1	Required Functions	350
10.11.1.2	ECW Excitation Method	351
10.11.1.3	System Efficiency	352
10.11.2	System Configuration	353
10.11.2.1	Various System Configurations	353
10.11.2.2	RF Source	354
10.11.2.3	Transmission System	355
10.11.2.4	Injection System (Launcher)	355
10.11.3	Design Example	356
10.11.4	Future Challenges	357
	Appendix 10A	358
	Appendix 10B	363
	Appendix 10C	369
	Appendix 10D	373
	Appendix 10E	377
	References	380
11	Vacuum Vessel	385
11.1	Functions Required for Vacuum Vessel	385
11.2	Holding Ultra-High Vacuum and High-Temperature Baking	385
11.2.1	Degree of Vacuum in the Vacuum Vessel	385

11.2.2	Holding the Ultra-high Vacuum	386
11.2.3	High-Temperature Baking	387
11.3	Ensuring Electrical Resistance, Plasma Position Control, and Toroidal Field Ripple	387
11.3.1	Electrical Resistance of the Vacuum Vessel	387
11.3.2	Ensuring Electrical Resistance	390
11.3.3	Plasma Position Control	391
11.3.4	Toroidal Field Ripple	391
11.4	Supporting the Electromagnetic Force and In-Vessel Equipment	392
11.4.1	Supporting the Electromagnetic Force	392
11.4.2	Supporting the Vacuum Vessel	392
11.5	Cooling Performance, Radiation Shielding, Confinement, Assembly, and Maintenance	394
11.5.1	Cooling Performance	394
11.5.2	Radiation Shielding	394
11.5.3	Confinement of Radioactive Material	394
11.5.4	Assembly and Maintenance	395
11.5.4.1	Assembly	395
11.5.4.2	Maintenance	395
11.6	Design of Vacuum Vessel	396
11.6.1	Structural Standard	396
11.6.2	Design Items	396
11.6.3	Design Example	398
11.6.3.1	Holding Ultra-high Vacuum	398
11.6.3.2	Surface Cleaning System	399
11.6.3.3	Ensuring Electrical Resistance, Plasma Position Control, and Toroidal Field Ripple	400
11.6.3.4	Supporting Electromagnetic Force and In-vessel Equipment	400
11.6.3.5	Cooling of Vacuum Vessel, Radiation Shielding, and Confinement	400
11.6.3.6	Assembly	401
11.6.3.7	Maintenance	401
11.7	Future Challenges	402
	References	402
12	Fuel Cycle System	405
12.1	Functions Required for the Fuel Cycle System	405
12.2	Configuration of the Fuel Cycle System	405
12.3	Fueling System	407
12.3.1	Fueling Method	407
12.3.2	Fueling Amount	407
12.4	Gas Exhaust System	408
12.4.1	Exhaust Gases by Source	408
12.4.2	Plasma Vacuum Exhaust System	408
12.4.2.1	Types of Vacuum Exhaust Pump	408
12.4.2.2	Configuration	409

- 12.4.2.3 Initial Ultimate Pressure 409
- 12.4.2.4 Helium Pumping Speed 411
- 12.4.2.5 Cryopanel Area 412
- 12.4.2.6 Helium Accumulation on the Cryopanel 412
- 12.4.2.7 Exhaust Time 413
- 12.5 Fuel Clean-up System 414
 - 12.5.1 Kinds of Recovered Gas and Amount of Exhaust Gas 414
 - 12.5.2 Configuration of the Fuel Clean-Up System 414
- 12.6 Hydrogen Isotope Separation System 416
- 12.7 Atmosphere Detritiation System 418
- 12.8 Water Detritiation System 418
- 12.9 Fuel Storage System 419
- 12.10 Material Accountancy of Tritium 420
- 12.11 Design Example 420
 - 12.11.1 Fuel Cycle System 420
 - 12.11.2 Fueling System 421
 - 12.11.3 Tokamak Exhaust Processing System 422
 - 12.11.4 Hydrogen Isotope Separation System 422
 - 12.11.5 Atmosphere Detritiation System 422
 - 12.11.6 Water Detritiation System 423
 - 12.11.7 Fuel Storage System 423
- 12.12 Future Challenges 423
 - References 424

- 13 Cryostat 425**
 - 13.1 Functions of Cryostat 425
 - 13.2 Cryostat Structure 425
 - 13.3 Thermal Shield 425
 - 13.3.1 Design Requirements 427
 - 13.3.2 Structure 428
 - 13.4 Design Example 429
 - 13.5 Future Challenges 432
 - References 433

- 14 Nuclear Design 435**
 - 14.1 Items Required for Nuclear Design 435
 - 14.2 Radiation Shielding 437
 - 14.2.1 Main Shield 437
 - 14.2.1.1 Equipment Shielding and Biological Shielding 437
 - 14.2.1.2 Installation Position of Shields 438
 - 14.2.1.3 Activation of Air and Cooling Water 439
 - 14.2.2 Evaluation Method of Radiation Shielding 440
 - 14.2.2.1 Intensity of Neutron Source 440
 - 14.2.2.2 Nuclear Data 440

14.2.2.3	Analysis Code	440
14.2.2.4	Analysis Procedure	440
14.3	Dose Rate	441
14.4	Nuclear Heating	441
14.5	Radiation Damage	442
14.5.1	Surface Damage	442
14.5.1.1	Sputtering	442
14.5.1.2	Blistering	444
14.5.2	Bulk Damage	444
14.5.2.1	Displacement Damage	444
14.5.2.2	Damage Due to Nuclear Transmutation	445
14.6	Radioactive Waste	447
14.7	Design Example	448
14.7.1	Neutron Flux	449
14.7.2	dpa Distribution	449
14.7.3	Helium Production	450
14.7.4	Dose Rate	450
14.7.5	Dose Rate by Skyshine	452
14.7.6	Nuclear Heating and So on	452
14.8	Future Challenges	453
	References	453
15	Operation and Maintenance	457
15.1	Functions Required for Operation and Maintenance	457
15.1.1	High Plant Availability	457
15.1.2	Maintenance Method Consistent with the Reactor Structure	457
15.1.3	Remote Maintenance with High Efficiency and High Reliability	458
15.2	Operation Period	458
15.3	Equipment to be Inspected and Maintained	459
15.4	Frequency of Maintenance	461
15.5	Remote Maintenance Methods	461
15.6	Process of Remote Maintenance	463
15.7	In-Vessel Transport System	465
15.8	Design Example	466
15.8.1	Frequency of Maintenance and Maintenance Period	466
15.8.2	In-Vessel Transport System	466
15.8.2.1	Maintenance of Blanket Module	466
15.8.2.2	Maintenance of Divertor	467
15.8.3	Ex-Vessel Transport System	468
15.8.4	Piping Cutting/Welding Tool	469
15.8.5	Failure of Maintenance Device	469
15.8.6	Hot Cell Building	469
15.9	Future Challenges	470
	References	471

16	Cooling System	473
16.1	Functions of Cooling System	473
16.2	Configuration of Cooling System	473
16.2.1	Operation Mode	473
16.2.2	Cooling Method	474
16.2.3	Heat Reservoir	474
16.3	Cooling Performance	476
16.4	Design Example	478
16.4.1	Configuration of Cooling System	478
16.4.1.1	Tokamak Cooling Water System	478
16.4.1.2	Component Cooling Water System	479
16.4.1.3	Chilled Water System	480
16.4.1.4	Heat Rejection System	480
16.4.2	Decay Heat Removal in Emergency	480
16.4.2.1	Emergency Power Supply	480
16.4.2.2	Natural Circulation Mode	480
16.5	Future Challenges	480
	References	481
17	Power Supply System	483
17.1	Functions Required for the Power Supply System	483
17.2	Characteristics of the Power Supply System	483
17.2.1	Power Supply Capacity	483
17.2.2	Equipment and Facilities to Which Power Is Supplied	484
17.2.3	Technologies to Reduce Coil Power Supply Capacity	485
17.2.3.1	Hybrid Coil System	485
17.2.3.2	Superconductivity	485
17.2.3.3	Steady-state Operation	486
17.2.4	Configuration of Power Supply	488
17.3	Power Supply for Toroidal Magnetic Field Coil	489
17.3.1	Self-inductance	489
17.3.2	Power Supply Voltage	490
17.3.3	Stored Energy and Coil Protection	491
17.3.4	Protection Resistor	491
17.4	Power Supply for Poloidal Magnetic Field Coil	492
17.4.1	Inductance	492
17.4.1.1	Mutual Inductance	492
17.4.1.2	Self-inductance of PF Coil	492
17.4.1.3	Self-inductance of CS Coil	493
17.4.2	Power Supply Voltage	494
17.4.3	Power Supply Capacity	494
17.4.4	Stored Energy	495
17.4.5	Coil Protection	495
17.4.5.1	At the Time of Quench	495

- 17.4.5.2 At the Time of Plasma Disruption 495
- 17.5 Design Example 495
- 17.5.1 Coil Power Supply 496
- 17.5.2 Power Supply of Plasma Heating and Current Drive System (H&CD) 497
- 17.6 Future Challenges 498
- References 498

- 18 Operation Control and Diagnostic Systems 501**
- 18.1 Functions of Operation Control and Diagnostic Systems 501
- 18.2 Basics of Control 502
- 18.2.1 Control Method 502
- 18.2.2 Transfer Function 503
- 18.2.3 Transient Response of a System 504
- 18.2.4 Feedback Control 504
- 18.2.5 PID Controller 505
- 18.2.5.1 Ideal PID Controller 505
- 18.2.5.2 Practical Noninterference-Type PID Controller 505
- 18.3 Operation Control System 507
- 18.3.1 Central Control System 507
- 18.3.2 Plasma Control 507
- 18.3.2.1 Control of Fusion Power 508
- 18.3.2.2 MHD Control 509
- 18.3.2.3 Disruption Control 509
- 18.4 Diagnostic Systems 511
- 18.4.1 Passive and Active Measurements 511
- 18.4.2 Probe Measurement 512
- 18.4.2.1 Electrostatic Probe 512
- 18.4.2.2 Magnetic Probe, Magnetic Loop, and Rogowski Coil 513
- 18.4.2.3 Diamagnetic Coil 513
- 18.4.3 Electromagnetic Wave Measurement 514
- 18.4.3.1 Passive Electromagnetic Wave Measurement 514
- 18.4.3.2 Active Electromagnetic Wave Measurement 518
- 18.4.4 Particle Measurement 522
- 18.4.4.1 Passive Particle Measurement 522
- 18.4.4.2 Active Particle Measurement 528
- 18.5 Design Example 529
- 18.5.1 Operation Control System 529
- 18.5.1.1 Plant Control System 530
- 18.5.1.2 Interlock Level 530
- 18.5.1.3 Plasma Operation 531
- 18.5.2 Diagnostic System 533
- 18.6 Future Challenges 535
- References 536

19	Safety	539
19.1	Requirements for Safety	539
19.2	Radioactive Materials	540
19.2.1	Radioactivity	540
19.2.2	Exposure Dose	541
19.2.3	Absorbed Dose	541
19.2.4	Dose Equivalent/Effective Dose Equivalent	541
19.2.5	Equivalent Dose/Effective Dose	542
19.2.6	Committed Effective Dose	543
19.2.7	Tritium Concentration Limit	544
19.2.8	Biological Hazard Potential	544
19.3	How to Ensure Safety	545
19.3.1	Safety Features	545
19.3.2	Goal of the Safety	546
19.3.2.1	In Normal Time	546
19.3.2.2	In Emergency	547
19.3.3	Basic Concept of Ensuring the Safety	547
19.3.3.1	Basic Concept	547
19.3.3.2	Implementation of Ensuring Safety	548
19.3.4	Basic Concept of the Safety Design	548
19.3.5	Evaluation of the Safety Design	550
19.3.6	Waste Disposal	550
19.4	Design Example	551
19.4.1	Dose Limit	551
19.4.2	Basic Concept of Ensuring the Safety	552
19.4.3	Implementation of Ensuring the Safety	552
19.4.3.1	Reduction of Radioactive Materials	552
19.4.3.2	Confinement Barrier of Radioactive Materials	552
19.4.3.3	Energy That Damages the Confinement Barriers	553
19.4.3.4	Zoning Management	555
19.4.4	Safety Design	555
19.4.5	Event Analysis	556
19.4.5.1	Events for Analysis	556
19.4.5.2	Safety Analysis Code	558
19.5	Future Challenges	558
	References	560
20	Analysis Code	563
20.1	How to Design	563
20.1.1	Design Flow	563
20.1.2	Flow of Reactor Design	563
20.1.2.1	Requirements as Power Reactor	564
20.1.2.2	Construction of Reactor Concept	564
20.1.2.3	Clarification of Constraints	565
20.1.2.4	Plasma Design	565
20.1.2.5	Design of Reactor Structure	566
20.1.2.6	Plant Design, Safety, and Economic Evaluations	566

20.2	Various Types of Analysis Codes	566
20.2.1	Plasma Analysis Code	566
20.2.2	Equipment Analysis/Design Code	567
20.2.3	Safety Analysis Code	567
20.2.4	Detailed Analysis Code	567
20.3	Reactor Design System Code	567
20.3.1	Role of the Code	567
20.3.2	Various System Codes	568
20.4	System Code for Reactor Conceptual Design	570
20.4.1	Power Balance (Energy Balance per Unit Time)	570
20.4.2	Radial Build	571
20.4.3	Volt-Second	572
20.4.4	Shape of TF Coil	573
20.4.5	Electromagnetic Force Acting on the TF Coil	573
20.4.5.1	Tensile Stress Due to Vertical Force	574
20.4.5.2	Bending Stress Due to Centering Force	575
20.4.5.3	Bending Stress Due to Overturning Force	575
20.4.6	Bucking Cylinder	575
20.4.7	Radiation Shield	577
20.4.8	Vertical Build	577
20.4.9	Power Supply Capacity	578
20.4.9.1	TF Coil	578
20.4.9.2	PF Coil	578
20.5	System Codes for Economic Evaluation	579
20.5.1	Cost of Electricity	579
20.5.2	Initial Capitalized Investment	580
20.5.3	Direct Cost of Construction	580
20.5.4	Annual Cost of Component Replacement at Specific Intervals	581
20.5.5	Annual Cost of Operation and Maintenance	581
20.5.6	Annual Fuel Cost and Annual Cost of Waste Disposal and Decommissioning	581
20.6	System Codes for Plasma Dynamics Evaluation	582
20.6.1	Particle Balance and Energy Balance	582
20.6.1.1	Particle Balance Equation	582
20.6.1.2	Energy Balance Equations	583
20.6.2	β Limit	584
20.6.3	Density Limit	584
20.6.4	Thermal Load on Plasma-Facing Wall	585
20.6.5	Distribution of Nuclear Heating Rate	586
20.6.6	Impurity Contamination Model in Plasma	586
20.6.7	Heat Transfer Model of Reactor Structure	587
20.6.8	Analysis Example	588
20.7	Future Challenges	590
	References	590

