Contents

	Preface		page xiii
	Acknowledgements		
	Units		
Pa	Part I Fusion power		
1	Fusion and world energy		3
	1.1	Introduction	3
	1.2	The existing energy options	4
	1.3	The role of fusion energy	16
	1.4	Overall summary and conclusions	19
		Bibliography	20
2	The fusion reaction		21
	2.1	Introduction	21
	2.2	Nuclear vs. chemical reactions	21
	2.3	Nuclear energy by fission	23
	2.4	Nuclear energy by fusion	24
	2.5	The binding energy curve and why it has the shape it does	29
	2.6	Summary	35
		Bibliography	35
		Problems	36
3	Fusion power generation		37
	3.1	Introduction	37
	3.2	The concepts of cross section, mean free path, and collision	
		frequency	38
	3.3	The reaction rate	42
	3.4	The distribution functions, the fusion cross sections, and the fusion	
		power density	46
	3.5	Radiation losses	51
	3.6	Summary	56
		Bibliography	57
		Problems	58

viii Contents

1	Dar	wan balan as the Control of	
4		wer balance in a fusion reactor	60
	4.1	Introduction The O.D.	60
	4.2	and the second s	60
	4.3	1 magnetic rusion	62
	4.4	1	62
	4.5	Power balance in the plasma	65
	4.6	Power balance in a reactor	69
	4.7	Time dependent power balance in a fusion reactor	74
	4.8	Summary of magnetic fusion power balance	82
		Bibliography	82
_	ъ	Problems	83
5	Design of a simple magnetic fusion reactor		
	5.1	Introduction	85
	5.2	A generic magnetic fusion reactor	85
	5.3	The critical reactor design parameters to be calculated	86
	5.4	Design goals, and basic engineering and nuclear physics constraints	88
	5.5	Design of the reactor	91
	5.6	Summary	105
		Bibliography	106
		Problems	106
Part II The plasma physics of fusion energy			109
6		rview of magnetic fusion	111
	6.1	Introduction	111
	6.2	Basic description of a plasma	113
	6.3	Single-particle behavior	113
	6.4	Self-consistent models	114
	6.5	MHD equilibrium and stability	115
	6.6	Magnetic fusion concepts	116
	6.7	Transport	117
	6.8	Heating and current drive	118
	6.9	The future of fusion research	120
		Bibliography	120
7	Definition of a fusion plasma		
	7.1	Introduction	121 121
	7.2	Shielding DC electric fields in a plasma – the Debye length	122
	7.3	Shielding AC electric fields in a plasma – the plasma frequency	126
	7.4	Low collisionality and collective effects	130
	7.5	Additional constraints for a magnetic fusion plasma	133
	7.6	Macroscopic behavior vs. collisions	135
	7.7	Summary	135
		Bibliography	136
		Problems	137

Contents ix

8	Singl	e-particle motion in a plasma – guiding center theory	139
	8.1	Introduction	139
	8.2	General properties of single-particle motion	141
	8.3	Motion in a constant B field	143
	8.4	Motion in constant B and E fields: the $\mathbf{E} \times \mathbf{B}$ drift	148
	8.5	Motion in fields with perpendicular gradients: the ∇B drift	151
	8.6	Motion in a curved magnetic field: the curvature drift	156
	8.7	Combined $V_{\nabla B}$ and V_k drifts in a vacuum magnetic field	159
	8.8	Motion in time varying E and B fields: the polarization drift	160
	8.9	Motion in fields with parallel gradients: the magnetic moment and	
		mirroring	167
	8.10	Summary – putting all the pieces together	177
		Bibliography	179
		Problems	179
9	Singl	e-particle motion – Coulomb collisions	183
	9.1	Introduction	183
	9.2	Coulomb collisions – mathematical derivation	185
	9.3	The test particle collision frequencies	191
	9.4	The mirror machine revisited	198
	9.5	The slowing down of high-energy ions	201
	9.6	Runaway electrons	207
	9.7	Net exchange collisions	212
	9.8	Summary	219
		Bibliography	220
		Problems	221
10	A self-consistent two-fluid model		223
	10.1	Introduction	223
	10.2	Properties of a fluid model	224
	10.3	Conservation of mass	227
	10.4	Conservation of momentum	229
	10.5	Conservation of energy	234
	10.6	Summary of the two-fluid model	241
		Bibliography	242
		Problems	243
11	MHD – macroscopic equilibrium		245
	11.1	The basic issues of macroscopic equilibrium and stability	245
	11.2	Derivation of MHD from the two-fluid model	246
	11.3	Derivation of MHD from guiding center theory	252
	11.4	MHD equilibrium – a qualitative description	258
	11.5	Basic properties of the MHD equilibrium model	261
	11.6	Radial pressure balance	264
	11.7	Toroidal force balance	271

	11.8	Summary of MHD equilibrium	292
		Bibliography	293
		Problems	293
12	MHD	– macroscopic stability	296
	12.1	Introduction	296
	12.2	General concepts of stability	297
	12.3	A physical picture of MHD instabilities	302
	12.4	The general formulation of the ideal MHD stability problem	307
	12.5	The infinite homogeneous plasma – MHD waves	313
	12.6	The linear θ -pinch	317
	12.7	The $m = 0$ mode in a linear Z-pinch	320
	12.8	The $m = 1$ mode in a linear Z-pinch	324
	12.9	Summary of stability	329
		Bibliography	329
		Problems	330
13	Magn	etic fusion concepts	333
	13.1	Introduction	333
	13.2	The levitated dipole (LDX)	335
	13.3	The field reversed configuration (FRC)	344
	13.4	The surface current model	350
	13.5	The reversed field pinch (RFP)	358
	13.6	The spheromak	373
	13.7	The tokamak	380
	13.8	The stellarator	423
	13.9	Revisiting the simple fusion reactor	437
	13.10	Overall summary	441
		Bibliography	443
		Problems	445
14	Transp		449
	14.1	Introduction	449
	14.2	Transport in a 1-D cylindrical plasma	451
	14.3	Solving the transport equations	465
	14.4	Neoclassical transport	478
	14.5	Empirical scaling relations	497
	14.6	Applications of transport theory to a fusion ignition experiment	513
	14.7	Overall summary	529
		Bibliography	529
		Problems	531
15	_	g and current drive	534
	15.1	Introduction	534
	15.2	Ohmic heating	537
	15.3	Neutral beam heating	540

	15.4	Basic principles of RF heating and current drive	551
	15.5	The cold plasma dispersion relation	569
	15.6	Collisionless damping	571
	15.7	Electron cyclotron heating (ECH)	586
	15.8	Ion cyclotron heating (ICH)	597
	15.9	Lower hybrid current drive (LHCD)	609
	15.10	Overall summary	624
		Bibliography	625
		Problems	627
16	The future of fusion research		633
	16.1	Introduction	633
	16.2	Current status of plasma physics research	633
	16.3	ITER	637
	16.4	A Demonstration Power Plant (DEMO)	642
		Bibliography	644
App	endix A	Analytical derivation of $\langle \sigma v \rangle$	645
App	endix B	Radiation from an accelerating charge	650
App	endix C	Derivation of Boozer coordinates	656
App	endix D	Poynting's theorem	664
- •	Index		666