



# Contents

<i>Acknowledgments</i>		<i>page x</i>
1	Extreme environments: What, where, how	1
1.1	Background, definitions, and assumptions	1
1.1.1	Background	2
1.1.2	Definitions	3
1.1.3	Assumptions	5
1.2	Elements of the extreme physics environment	6
1.2.1	Classifications	6
1.2.2	Environments	9
1.3	Scope of the physics	11
1.4	How to achieve extreme conditions	16
1.4.1	Lasers and accelerators	17
1.4.2	Z-pinches, flyers, rail guns, and gas guns	23
1.5	Example problems and exercises	28
2	Properties of dense and classical plasma	29
2.1	Kinetic theory	30
2.1.1	The distribution function	31
2.1.2	The Maxwell–Boltzmann distribution function	33
2.1.3	Electron degeneracy and the Fermi–Dirac distribution function	36
2.2	Electron–ion collisions	40
2.2.1	Coulomb collisions	40
2.2.2	Relaxation times	46
2.3	Collective plasma effects	51
2.3.1	Debye shielding and quasi-neutrality	51
2.3.2	Electron plasma frequency and plasma waves	55
2.4	Example problems and exercises	58

3	Laser energy absorption in matter	60
3.1	Maxwell's equations and electromagnetic wave propagation	60
3.2	Laser energy deposition at high laser intensities	66
3.2.1	Inverse bremsstrahlung absorption	66
3.2.2	Resonance absorption	69
3.2.3	Ponderomotive force and ablation pressure	72
3.3	Laser energy deposition at low laser intensities	73
3.4	Laser energy deposition at very low laser intensities	74
3.4.1	Conductivity and skin depth	75
3.4.2	Electromagnetic wave absorption in metals	76
3.4.3	Absorption in dielectrics and tamped ablation	80
3.5	Example problems and exercises	85
4	Hydrodynamic motion	88
4.1	Derivation of Navier–Stokes equations	88
4.1.1	Continuum flux	88
4.1.2	Conservation relations	89
4.1.3	Lagrangian derivative	94
4.1.4	Scaling and self-similarity	95
4.2	Compression and rarefaction waves	97
4.2.1	Acoustic waves, sound speed	97
4.2.2	Characteristics of the flow	98
4.2.3	Compression waves and shock fronts	100
4.2.4	Rarefaction waves and rarefaction shocks	101
4.3	Hydrodynamic instabilities	104
4.3.1	Rayleigh–Taylor instability	105
4.3.2	Stabilization mechanisms	108
4.3.3	Kelvin–Helmholtz and Bell–Plesset	113
4.3.4	Non-linear growth and turbulence	117
4.4	Example problems and exercises	119
5	Shocks	123
5.1	Rankine–Hugoniot equations	124
5.1.1	Jump conditions	124
5.1.2	Shocks in an ideal gas	127
5.2	Shocks at boundaries and interfaces	132
5.2.1	Reflected shocks and Mach stems	132
5.2.2	Shocks at interfaces and the Richtmyer–Meshkov instability	134
5.2.3	Emergence of shocks at a free surface	137

5.3	Structure of the shock front	138
5.3.1	Entropy and adiabaticity	138
5.3.2	Viscosity and heat conduction	139
5.4	Blast waves	142
5.5	Shocks in solids	146
5.5.1	Elastic–plastic behavior and material strength	146
5.5.2	Material constitutive models	150
5.5.3	Solid-state Rayleigh–Taylor instability	154
5.6	Example problems and exercises	157
6	Equation of state	159
6.1	Basic thermodynamic relations	159
6.2	EOS for gases and plasmas	161
6.2.1	EOS for monatomic gases	161
6.2.2	Two-temperature EOS for plasmas	162
6.2.3	Thomas–Fermi model	165
6.3	EOS for solids and liquids	167
6.3.1	Grüneisen EOS	167
6.3.2	EOS for porous solids	173
6.3.3	Phase transitions	176
6.4	Example problems and exercises	180
7	Ionization	183
7.1	Electron structure of atoms	183
7.1.1	The Bohr atom	184
7.1.2	Quantum electronic energy levels	188
7.2	Ionization models	193
7.2.1	Saha	197
7.2.2	Pressure ionization and continuum lowering	204
7.2.3	Thomas–Fermi	208
7.2.4	Hydrogenic average-atom	212
7.3	Example problems and exercises	217
8	Thermal energy transport	219
8.1	Thermal energy transport equation	219
8.1.1	Linear heat conduction	221
8.1.2	Non-linear heat conduction	223
8.2	Conductivity coefficients	227
8.3	Inhibited thermal transport	233
8.4	Electron–ion energy exchange	241
8.5	Electron degeneracy effects	242

8.6	Coulomb logarithms	247
8.7	Example problems and exercises	250
9	Radiation energy transport	252
9.1	Radiation as a fluid and the Planck distribution function	252
9.2	Radiation flux	258
9.2.1	The equations of motion with radiation flux	259
9.2.2	Absorption and emission	261
9.2.3	Principle of detailed balance	262
9.2.4	The radiation transfer equation	263
9.3	Solutions of the radiation transfer equation	265
9.3.1	$P_n$ and $S_N$	265
9.3.2	The diffusion approximation	267
9.3.3	Marshak waves and hohlraums	270
9.4	Material opacity	274
9.4.1	Models for material opacity	274
9.4.2	Averaging over photon frequencies	281
9.5	Non-LTE radiation transport	283
9.6	Radiation-dominated hydrodynamics	288
9.7	Example problems and exercises	292
10	Magnetohydrodynamics	294
10.1	Plasma electrodynamics	296
10.2	Equations of magnetohydrodynamics	298
10.2.1	Induction equation	298
10.2.2	Momentum equation	301
10.2.3	Thermal conduction equations	303
10.2.4	1D cylindrically symmetric equations	305
10.2.5	Magnetic energy	306
10.3	Generalized Ohm's law	307
10.4	Magnetic reconnection	307
10.5	Magnetic confinement	311
10.5.1	The Z-pinch	311
10.5.2	The $\theta$ -pinch	319
10.5.3	The screw pinch	319
10.6	Example problems and exercises	320
11	Considerations for constructing radiation-hydrodynamics computer codes	323
11.1	Radiation-hydrodynamics computer codes	323
11.2	Code development philosophy and architecture	325

11.3	Structure of PDEs	329
11.3.1	Hyperbolic equations	330
11.3.2	Parabolic equations	330
11.3.3	Elliptic equations	331
11.4	Finite-difference approximation	331
11.4.1	Computational grid	332
11.4.2	Partial derivatives	333
11.4.3	Partial differential equations	335
11.4.4	Solution of tridiagonal systems	338
11.4.5	Accuracy, convergence, consistency, and stability	339
11.4.6	Operator splitting	348
11.5	Example problems and exercises	351
12	Numerical simulations	353
12.1	Lagrangian hydrodynamics	353
12.1.1	Momentum equation	355
12.1.2	Stability of the momentum equation	356
12.1.3	Shocks and artificial viscosity	357
12.1.4	The energy equation and thermal transport	361
12.2	Code verification	364
12.2.1	Non-linear electron thermal transport	364
12.2.2	Shock propagation	366
12.3	Code validation	374
	<i>Appendix I Units and constants, glossary of symbols</i>	384
	<i>Appendix II The elements</i>	389
	<i>Appendix III Physical properties of select materials</i>	393
	<i>References</i>	396
	<i>Further reading</i>	400
	<i>Index</i>	403