3.6 P-u Diagram for a Shock Crossing a Boundary into a Material of Higher Impedance .............................................. 37
3.7 Impedance Matching Treatment of Rarefaction Waves ....... 38
3.8 Impedance Matching for a Shock Reaching a Free Surface .... 39
3.9 Impedance Matching for a Flyer Plate Hitting a Stationary Plate of the Same Material ......................................... 41
3.10 Disturbance Velocity in a 1-D Eulerian Cartesian Coordinate System Fixed in Space .............................................. 42
3.10.1 Symmetric Impact Example .................................... 42
3.10.2 Disturbance Velocity for General Case ...................... 44
3.11 Impedance Matching for Four Basic Cases ..................... 45
3.12 Impedance Matching for Thin Foils ............................ 48
3.12.1 Summary of the Practical Lessons for Thin Foils ......... 49
3.13 Impedance Matching for Multiple Waves Is an Approximation ................................................................. 52
3.14 Wave-Wave Interaction and Contact Discontinuity .......... 53
References ........................................................................ 57

4 Experimental Techniques .............................................. 59
4.1 Selected Experimental Techniques to Measure Shock Wave Parameters .............................................................. 59
4.2 Explosive and Flyer Plate Shock Driver Systems .............. 59
4.3 Laser Shock Drivers .................................................... 62
4.4 Early Impedance Matching Experiments ......................... 63
4.5 Shock Velocity Measurements ....................................... 64
4.6 Free Surface Velocity Measurement Using a Streak Camera . 66
4.7 Electromagnetic Particle Velocity Gauge ....................... 67
4.8 Laser Velocity Interferometry ....................................... 68
4.9 VISAR ......................................................................... 68
4.10 ORVIS ....................................................................... 69
4.11 Fabry-Perot .............................................................. 70
4.12 Heterodyne System .................................................... 71
4.13 Optical Windows on Test Samples ................................. 72
4.14 Quartz Stress Gauge .................................................. 72
4.15 Quartz Gauge Technique for Measuring Low Pressure Hugoniot ............................................................... 74
4.16 Quartz Gauge Technique for Measuring the Hugoniot of a Thin Material ......................................................... 75
4.17 Manganin Stress Gauge ............................................. 75
4.18 Other Stress Gauges ..................................................... 78
4.19 Proton Radiography for Accurate Density Measurements of Shock Wave ......................................................... 80
4.20 Issues for Making Temperature Measurements Behind Shock Waves ........................................................... 80
4.21 Error Analysis for Experiments .................................... 82
4.22 Random Errors .......................................................... 83
4.23 Systematic Errors .................................. 85
4.24 Combining Random and Systematic Errors to Get Final Error ... 86
4.25 Example of Errors in Measurement of a Cylinder’s Density . . . . 86
4.26 Error Analysis for a Rotating Mirror Streak Camera Measurement of Free Surface Velocity .................................. 88
4.26.1 Sources of Various Errors .......................... 89
4.26.2 Errors in Trace Angle γ and Wave Tilt Angle ω ........... 90
References ............................................ 94

5 Thermodynamics of Shock Waves ........................................ 101
5.1 Thermodynamics Review ........................................ 101
5.2 Fundamental Thermodynamic Relation .......................... 102
5.3 Equations of State ........................................... 103
5.4 Hugoniot Is Steeper than Isentrope from Same Initial State . . . . 105
5.5 Isentrope is Steeper than Isotherm from Same Initial State . . . . 106
5.6 Entropy Along Hugoniot ...................................... 107
5.7 Isentrope and Hugoniot Are Same to Second Order in Compression at a Common (P, v) Point .......................... 109
5.8 Differential Equation for Hugoniots .......................... 110
5.9 Temperature at an Isentrope Point with C_vγ/v Constant ......... 111
5.10 Temperature at a Hugoniot Point for C_vγ/v Constant .......... 112
5.11 Calculation of Gruneisen Parameter at (P = 0, v_o) from Thermodynamic Parameters and Sound Speed Values .......... 114
5.12 Determination of Gruneisen Parameter from Shock Wave Release Velocity Measured at Peak Shock Pressure ......... 115
5.13 Numerical Calculations of Isentropes and Isotherms from Hugoniot Data for C_v and γ/v Assumed Constant .......... 116
5.14 Thermodynamic Consistent Surface .................................... 118
5.15 Complete Consistent Equation of State for Materials with a Constant C_v ........................................ 120
5.16 Thermodynamic Surface Defined by Isotherm with a Constant C_v ........................................ 122
5.17 Isentrope and Isotherm on the Thermodynamic Surface with C_v and γ/v Constant and Principal Hugoniot as the Reference Curve ........................................ 130
5.18 Mie-Gruneisen Equation of State ............................ 133
5.19 Mie-Gruneisen Equation of State with C_vγ/v Constant and Principal Hugoniot as the Reference Curve .................. 134
5.20 Thermodynamics Impose Stringent Constraints on Use of the Gruneisen Equation of State With Hugoniot as Thermodynamic Reference Curve .................................... 135
5.21 Calculation of Hugoniot Where Initial Temperature Is Different than Principal Hugoniot’s with C_v and γ/v Assumed Constant ... 136
5.22 Recentered Hugoniots Using Gruneisen Equation of State with C_v and γ/v Constant .................................... 137
5.23 Determination of Volume Dependence of ∂P/∂T)_v or γ(v) .... 139
References ............................................ 144
### 6 Solids

6.1 Compression of Solids .................................................. 147  
6.2 Hooke's Tensor Law for Elastic Isotropic Solids .................. 147  
6.3 Uniaxial Stress ............................................................ 149  
6.4 Hydrostatic Pressure on a Solid .................................... 151  
6.5 Uniaxial Strain ............................................................. 151  
6.8 Impedance Matching Issues for Elastic–Plastic Material with a Free Surface .................................................. 157  
6.9 Material Strength at High Stress Hugoniot States ................. 163  
6.10 Porous Materials .......................................................... 164  
6.11 Simple Model for Totally Compacted Porous Material When Strength Can Be Ignored ................................................. 166  
6.12 Gruneisen EOS for Porous Material with Principal Hugoniot as Reference and \( \gamma/v \) Constant ............................................. 167  
6.13 Temperature for a Shocked Porous Material with \( C_v \) Constant and Pores Are Totally Compacted with Strength Ignored ..... 168  
6.14 Phenomenological P-\( \alpha \) Model for Porous Material Not Totally Compacted .................................................. 170  
6.15 Snowplow Model for Shock Wave Attenuation in Porous Solids ................................................................. 173  

References ........................................................................... 177

### 7 Differential Conservation Equations and Time-Dependent Flow

7.1 Mass, Momentum and Internal Energy Fluxes for 1-D Flow ...... 179  
7.2 Mass Differential Conservation Equation ............................. 180  
7.3 Momentum Differential Conservation Equation .................... 182  
7.4 Rayleigh Line Is Compression Path for a Steady Shock Wave ... 183  
7.5 Energy Differential Conservation Equation ........................... 184  
7.6 Summary of Eulerian Differential Conservation Equations ...... 186  
7.7 Rise-Time and Shape of a Steady Shock Wave Due to Viscosity ................................................................. 186  
7.9 Time-Dependent Material Properties Overview .................. 192  
7.9.1 Elastic–Plastic Solids .................................................... 192  
7.9.2 Elastic–Plastic Solid that Undergoes a Phase Transition .................................................................................. 193  
7.9.3 Initiating High Explosive ................................................. 195  
7.10 Time and Spatial Scales Affect Dynamic Material Response ... 196  
7.11 Elastic Wave Stress Decay Described by a Maxwell-Like Material Model .......................................................... 197  

References ........................................................................... 199
8 First-Order Polymorphic and Melting Phase Transitions Under Shock Loading ........................................ 201
8.1 Introduction ........................................ 201
8.2 General Background of Polymorphism Under Shock Compression .................................................... 203
8.3 Select Observed Transitions in Shocked Materials ............. 203
8.4 Fast Reversible Phase Transition in Iron .................... 206
8.4.1 Evidence for Non-equilibrium Behavior in Mixed Phase Region of Iron .................................... 208
8.4.2 Martensitic Phase Transition..................................... 209
8.5 Steady Shock Wave Profiles for Shock Compressed Thick Iron Samples ............................................ 210
8.6 Experimental Rise-Time Measurements of the Steady Plastic II Shock in Polycrystalline Iron .................. 212
8.7 Permanent Regime Theory for Rise-Time of a Steady Transmitted Shock Wave Front Where the Phase Transition Occurs and Material Strength Is Ignored .......................... 213
8.8 Time-Dependent Flow for Transmission Shock Waves in Iron for Thin Samples ................................ 217
8.9 Kinetics of Plastic I Shock Decay ................................ 222
8.10 Reverse Impact Experiments of Iron onto a VISAR Window . 225
8.11 Fast Shock Induced Phase Transition in KCL with Two Measured Rates from Reverse Impact Experiments ... 226
8.12 Polymorphic Phase Transitions with Slow Transition Rates . 228
8.13 Nucleation of Phase Transitions Under Shock Loading . . 229
8.14 Solid and Liquid Phase Thermodynamic Surface for Aluminum ..................................................... 232
8.15 Melting in Shocked Porous Aluminum ...................... 234
8.16 Shock Loading Porous Aluminum Along Metastable Extension of Solid Hugoniot Above the Solid Melt Line .......................... 236
8.17 Determination if Fully Compacted Aluminum Can Melt Under Pressure Release Down an Isentrope After Being Shock Loaded ..................................................... 237
References ............................................... 238

9 Secondary Ideal High Explosives Non-steady Initiation Process and Steady Detonation Wave Models .............. 243
9.1 Explosives ............................................ 243
9.2 Secondary Explosives Initiation ............................ 245
9.3 High Pressure Shock Initiation of Homogeneous Explosives . . . 247
9.4 Low Pressure Shock Initiation of Heterogeneous Explosives .......................... 247
9.5 High Pressure Shock Initiation of Heterogeneous Explosives ........................................ 250
9.6 Phenomenological Energy Fluence Initiation Model ......... 250
9.7 Phenomenological Reactive Flow Reaction Rate Models for Heterogeneous HE Initiation ...................... 252
9.8 Shock Sensitivity Tests .................................. 255
9.9 Steady 1-D Detonation Shock Waves in Near-Ideal Explosives ........................................... 259
9.10 Chapman-Jouget (CJ) Detonation Model for Near Ideal High Explosives ........................................ 261
  9.10.1 Case 1 Initiation by Thick Driver Plate ............ 262
  9.10.2 Case 2 Initiation by Very Thin Flyer or a Booster HE with Its Initial Surface Free ..................... 262
9.11 CJ Detonation Model with Polytropic Equation of State for Gas Products ........................................ 264
9.12 Peak Pressure Induced in Material by Explosive Using CJ Detonation Model ..................................... 267
9.13 P-u Curves for Comp B Explosive Products Using Polytropic Gas Equation of State .............................. 269
9.14 Explosive Product Curves from JWL Equation of State ........ 271
9.15 ZND Detonation Model .................................................. 274
9.16 Detonation Spike Pressure Estimates ............................... 276
9.17 Pressure Drop Behind Detonation Spike ......................... 277
9.18 Thermal Initiation of Explosives ................................. 278
9.19 Adiabatic or Instantaneous Volume Thermal Explosion .... 282
References ................................................................ 285

10 Steady Detonation Waves in Right Circular Cylinders of Non-ideal Explosives .......................................... 291
  10.1 Non-ideal Explosives .................................................. 291
  10.2 Non-ideal Explosive’s Evidence of Late-Time Energy Release ...................................................... 294
  10.3 Summary of Key Detonation Properties Due to Two Dimensional Flow in Right Circular Cylinders of Explosives .......... 296
  10.4 Detonation Wave Velocity, Curvature and Failure Diameter Measurement Techniques ............................. 297
  10.5 Thin Foil Velocity Technique for Measuring CJ State of a Near-Ideal HE ........................................... 303
  10.6 Navy Impedance Matching Technique for Measuring CJ State ......................................................... 305
    10.6.1 Simple Approximate Solution for Polytropic Parameter G from Navy Technique ...................... 307
  10.7 CJ States Defined by Determining JWL Equation of State for Near Ideal HE’s ........................................... 309
  10.8 Orvis Line VISAR Technique with Very Good Temporal Resolution to Measure CJ Reaction Zone Length of a Near-Ideal HE ................................................................. 310
  10.9 1-D Experimental Technique for Determining Sonic Plane ............................................................. 316
  10.10 Significance of Experimental Measurements of Detonation Wave Properties ........................................... 317
10.11 Curved Front Detonations in Right Circular High Explosive Cylinders ................................................................. 318
10.12 Calculated PBXN-111 Detonation Sonic Zone Lengths as a Function of Cylinder Diameter ......................... 321
10.13 2D Flow Across Curved Shock Front ........................................ 323
References ........................................................................... 326

11 Special Topics: Lagrangian Coordinates, Spall, and Radiation Induced Shocks ......................................................... 329
11.1 Lagrangian Coordinates ...................................................... 329
11.2 Steady Flow of Two Forward Facing Shock Waves in Eulerian and Lagrangian Coordinates ......................... 330
11.3 Conservation Equations for Two Steady Forward Facing Shocks in Lagrangian Coordinates ......................... 333
11.4 Relief Wave Speeds ............................................................ 334
11.5 Sound Speed Determined from Symmetric Impact .............. 335
11.6 Lagrangian Differential Conservation Equations ............... 337
11.7 Planar Spall of Materials Under Dynamic Loading .............. 338
11.8 Dynamic Method of Detecting Spalling ............................... 341
11.9 Spall Strength of Condensed Matter ..................................... 343
11.10 Smooth Planar Spall Due to a Fast Reversible Phase Transition ................................................................. 344
11.11 Radiation Induced Shocks .................................................... 346
References ........................................................................... 352

Appendix 1: Symbols, Useful Conversion Factors, and Some Basic Equations for Steady Shock Waves ................. 355
Appendix 2: Hugoniot for Some Materials ................................. 359
Appendix 3: One-Dimensional Steady Shock Conservation Equations ................................................................. 361
Appendix 4: Impedance Matching Rule and Four Basic Examples .... 363
Appendix 5: Analytical Impedance Matching for Two Most Common Cases ......................................................... 365
Appendix 6: Thermodynamic Parameter Definitions and Relationships ................................................................. 367
Erratum to: Shock Wave Compression of Condensed Matter ...... E1
Index ...................................................................................... 371
Shock Wave Compression of Condensed Matter
A Primer
Forbes, J.W.
2012, XIV, 374 p. 211 illus., 11 illus. in color., Hardcover
ISBN: 978-3-642-32534-2