

INDEX

- Abbreviations and acronyms for
 chemical ingredients of solid
 propellants, 511–513
- Ablative cooling and materials, 274,
 215, 573, 576–578
- Acceleration of vehicle, terminal,
 110–113
- Acoustic velocity, *see* velocity of sound
- Acoustic absorbers, cavities, 360, 361
- Action time, *see* Burning time and
 action time
- Additive manufacturing, 310
- Aerodynamic forces, *see* Drag; Lift
- AJ -10- 118I rocket engine, for Delta 2
 launch vehicle upper stage,
 274–275
- Aerospike engine, *see* Nozzle,
 aerospike, 77
- Aging of solid propellant, 499, 506
- Air launched rocket, 144–147
- Altitude,
 test facilities, 731
 variation of atmospheric air
 properties, 747 (Appendix 2)
 variation of thrust with, 33
- Aluminum or aluminum powder, 250,
 499, 526, 573, 606
- Ammonium nitrate (AN), 181, 185, 500,
 514–517, 520, 524, Tab. 13–19
- Ammonium perchlorate (AP), 181, 538,
 539, 540, *see* Particle size.
- Apogee, definition, 117
- Applications of plume technology, 704
- Applications of rocket propulsion,
 4–21, 231, 436–438, 595–600,
 621–626, 658–663
- Apsidal drift, Fig. 4–12
- Arcjet, *see* Electric propulsion
- Area ratio of nozzle, *see* Nozzle
- Atlas space launch vehicle, 17, 18,
 Fig. 12–2
- Atmospheric properties, 747 (*see*
 Appendix 2)
- Attitude control, *see* Reaction control
- Attitude control rocket propulsion or
 attitude
 control systems (ACS), *see* Auxiliary
 rockets

- Automatic engine controls, 419–427
- Auxiliary rocket propulsion systems,
also called: Reaction Control
 Systems
 or Attitude Control Systems, *see also*
 thrusters, 196–198, 229–232,
 300–309
 for electric propulsion, 661–663
 with liquid propellants, 232
 with pulsing, 212, 229, 301, 658
 with solid propellants, 483–485
 for orbital maintenance, 124
- Back-flow barrier *see* Thermal
 shield, 684
- Baffles, injector, 358–359
- Ballistic missile (ICBM), 22,
 Fig. 4–10
- Battery, *see* electric power, 661
- Bearings (turbopump), 374, 375
- Bell-shaped nozzle, *see* Nozzle
- Beryllium, 250, 516
- Binder, *see* Solid propellants; Grain
- Bipropellant, 8, 173, 193, 231, 244,
 274–275, Fig. 6–6
- Blast tube, *see* Nozzle
- Blow-back gas barrier, *see* thermal
 shield
- Blow-down pressurized gas feed
 system, 206–207
- Bonding of solid propellant grains, *see*
 Grain, solid propellant
- Booster pump, *see* Pump
- Boron, 516
- Boundary layer, 82–83, 708
- Budget for liquid propellants,
 399–402
- Burning rate or burn rate, solid
 propellant, 439–457; *see also*
 grain; solid propellant rocket
 motors 447, 465
 burning surface contour, 439–457
 with catalyst or burning rate modifier,
 440, 517
 with acceleration effect, 455–456
 as function of chamber pressure,
 Fig. 12–6, Fig. 12–7, 455–456
 with erosive burning, 454–456, 590
 exponent or pressure exponent, 452
 temperature sensitivity of, 449–451
- Burning time and action time, 458, 459,
 464, Fig. 12–13
- Burning surface of grain, 443, 444, 445
- c^* *see* characteristic velocity
- Carbon-carbon, 292, 305, 443,
 573, 574
- Carbon deposit in cooling jackets, 319
- c^* (cee star), *see* Characteristic velocity
- Carbon-carbon, 275, 288, 292, 310, 443,
 573, 574, 680
- Carbon phenolic, 443, 569, 574,
 575, 576
- Case or solid rocket motor case, 436,
 438, 555–563, 587; *see also*
 Nozzle; Solid propellant rocket
 motor
 case of filament-wound fiber
 reinforced plastic, 442, 561–563
 loads or forces on case, 556
 materials for case, 462, 557,
 561–564, Tab. 15–2
 metals of, 441, 559–561
 stresses and elongation of, 558
- Cathode, Fig. 17–5, 647, 648, 650
- Catalyst, 255, 264–266, Fig. 8–14,
 Fig. 17–4, Fig. 17–6
- Cavitation, *see* Pump 375, 382, 383
- Chamber (combustion), 285–288. *see*
 heat transfer; thrust chamber,
 chamber pressure, Fig. 2–1 of
 combustion gas
 geometry/volume of, 285–288
 pressure loss in narrow chamber, *see*
 Table 3–2, 72
 wall loads and stresses of, 296–300
- Characteristic chamber length,
 (L^*), 287
- Characteristic speed (electric
 propulsion), 628

- Characteristic velocity or characteristic exhaust velocity or c^* , 34, 63, 66, 181, 274, 441, 608
- c^* efficiency, 66, 86
- Chemical equilibrium, 46, 158
- Chemical reaction:
 - in chamber or in motor case, 161–170, 344–348
 - free energy or chemical potential, 163–164
- Chemical propellant combustion, 344–364
- Chemical rocket propellant performance analysis, 39, 40, 154–185
- Chemical rocket propulsion systems, 5, 9
- Choked flow condition, 58–59
- Chugging combustion instability, 350, 611–615
- Classification of:
 - electric thrusters, 620–625
 - hazards, 250–252, 505–512
 - liquid propellant feed systems, 203–204
 - liquid propellants, 193–194
 - rocket propulsion systems, 1–14,
 - of solid propellants, 437–458, 492–494
 - turbines (turbopumps), 387–388
 - thrust vector controls, 673–675
 - valves, 235–237
- Cold gas propellants and thrusters, 42, 266–267, 301–303
- Combustion; *see also* Temperature; Solid propellant rocket motors; thrust chambers, analysis/simulation of, 161–166
 - efficiency of, 35–37, 346
 - gas processes during, 172–185,
 - instability of, 349–361, 543–552, 611–615,
 - control of instabilities, 358–362, 547
 - rating techniques, 357
 - remedy and design, 360–363, 550
 - of hybrid propulsion, 611–615
 - of liquid propellants, 254–255, 346–352, 422
 - process of, 160, 346–350, 537–541; *see* Stay time
 - with solid propellants, 537–554
 - stability assessment or rating technique 359–360, 550–552
 - vibration: longitudinal, radial or tangential, 350, 354–357
 - vibration frequency of, 352–356, 358–359, 548, 615–616
- Communication signal attenuation, 720–722
- Composite propellant, *see* Solid propellant(s)
- Computers programs for:
 - combustion analysis, 171–172, 348–349, 548
 - exhaust plume analysis, 723–724
 - grain strain analysis, 478
 - heat transfer, 288, 310–322
 - nozzle contour, 568–570
 - rocket engine control, 421–423
- Conical/bell shaped nozzle, 73–81, *see also* Nozzle
- Continuum flow regime, 710
- Controls for rocket engines, 412–422
- Conversion factors and constants, (Appendix 1), 743–746
- Cooling with liquid propellant, 289–295 *see also* radiation
 - cooling, regenerative cooling,
 - thrust chamber, in cooling jackets, 289–290, 306, 310–322
 - heat transfer, 311–322
- Copper alloy, Table 8–3
- Correction factors: 85–88
 - for exhaust velocity, 87
 - for thrust, 86
- Cost savings or reduction, 701–702
- Cracks in grain, *see* Failure modes
- Criteria for selection of optimum propulsion system, 697–699
- Cryogenic liquid propellants, 194, 197–198

- Cumulative damage of solid propellants, 481–483
- Curing agents for solid propellant, 512
- Cut-off, *see* thrust termination
- Deep space flight, 120–121, 130
- Deflagration, 464, 507–508
- Delivered performance parameters, four sets of, 89–91
- Delta space launch vehicle, 16, 18, *see also* RS-68
- Density of air at altitude, 747; *see* Appendix 2, Specific gravity of atmosphere
- Density specific impulse, 253 *see also* specific impulse
- Desaturation of flywheels (gyroscopes) 230
- Design calculation examples for:
 hybrid propellant rocket, 607–611
 liquid propellant thrust chamber, 328–337
 solid propellant motor, 586–589
- Detonation, *see* Solid propellant, detonation
- Discharge:
 coefficients for injectors, 278–283
 correction factor for propulsion system, 85–89
- Double base propellant, 492–498
- Drag coefficient, 104–105
- Drag force, 104–109, 138
- Ducted rocket, 2
- Duty cycle, *see also* pulsing, 137, 651–652
- Earth's atmosphere, Appendix 2
- Earth's parameters, 115
- Effective exhaust velocity: *see* Exhaust velocity
- Electric propulsion, 10–12, 30, 620–667, Fig. 2–5, Tab. 2–1, Tab. 17–1, 17–2, 17–7
 applications and missions of, Fig. 17–1
- arcjet, 10–12, Fig. 1–8, Tab. 17–7, 634–637,
 electromagnetic or magnetoplasmadynamic thruster, Tab. 2–1, Tab. 17–1, Tab. 17–7
- electrostatic or ion thruster, 12, 30, Fig. 1–9, Tab. 2–1, Tab. 17–1, 17–7, 638–646, 656
- ionization schemes, 645–646, Tab. 17–5
- electrothermal, 622, 631–637
- flight performance, 626–630, 654–658
- Hall effects thrusters, 30, 622, 624, 650–654
- performance data 30, 39, 622, 656
- power (magnitude), 30, 39–40, 627–628, 656
- power conditioning/conversion, 664–666
- power supply and power sources, 661–664
- pulsed plasma, 11, 13, 32, 42, 626, 648–649
- resistojet, 32, 42, 622, 624, 631–634
- thruster types. 621–624
 typical propellants for, Tab. 17–1
- Electrostatic discharge, 505
- Elliptical orbit, 116–120
- Energy and Efficiencies, 35–37
 energy balance, Fig. 2–2
 of orbiting satellite, 114
 combustion efficiency, 164
- Engine, *see* Liquid Propellant Rocket engine
- Engine cycles, 221–228
- Enthalpy, chemical reaction, 47–48, 158–159
- Environment, 267–268, 731–735 *see* Hazards; Rocket exhaust plumes
- Equation summary, 749–750, (Appendix 3)
- Erosive burning, *see* Burning rate
- Escape from solar system, 115

- Escape velocity from earth, 113–115
- Exhaust gas, exhaust jet, flame, *see*
 Rocket
- exhaust plume, Chapter 20
- Exhaust nozzle, *see* Nozzle
- Exhaust velocity, *see* Nozzle, effective
- exhaust velocity; Nozzle, exit velocity
- Expander engine cycle, 224
- Expansion-deflection nozzle, 77, 85
- Explosive ingredients of solid
 propellants, 518–519, *see also*
 HMX, Nitrocellulose,
 Nitroglycerine
- Expulsion efficiency, 196
- Extendible nozzle, 79–80, 311, 439
- Failure modes of solid rocket motors
 (cracks and debonding), 472–473
- Failure sensing, 739
- Failures, post-accident procedures,
 740–741
- Falcon space launch vehicle, propulsion
 system *see* front cover, 131
- Feed systems, liquid propellants, 198,
 208–210, 213, *see also* tanks
 electric propulsion, 633–634
 gas pressurized, with pressure
 regulator, 6, 214–216, 217–221, 274,
 331; *see also* blow-down
 feed system 210–212
 turbopump feed system 7, 197,
 221–228, 274, 331
- Filaments for motor cases, 557, 564
- Filament wound cases, 561–563
- Film coefficient (heat transfer):
 gas, 311–315
 liquid, 311, 312
- Film cooling with liquid propellants,
 293–295
- Finite element analysis 310, 478
- Flame, *see* Combustion; Rocket exhaust
 plume
- Flap in liner (also called boot), 480; *see*
also Grain, Solid propellant rocket
 motors
- Flexible nozzle bearing, *see* Thrust
 vector control
- Flexible pipe joint, 237, 238
- Flight, 99–153; *see also* Application;
 Drag; Lift; Spacecraft; Vehicle
 velocity
 ballistic missiles, 119
 forces acting on the vehicle, 104–111
 interplanetary, 117–120, 124
 maneuvers, 127–131
 motions, 106–111
 performance, chemical propulsion,
 99–153
 performance, electrical propulsion,
 620–630
 perturbations to space flight path,
 121–124
 propulsion effect on vehicle.
 133–136
 rotation maneuvers, 131–133
 in space, 113–130
 stability of, 147–148
 testing, 726–741
 vehicles, 136–139
 velocity and acceleration at burn-out,
 99–104, 106–112, Fig. 4–7,
 117, 626–629
- Flow, *see* Flow mass *below*
- Flow diagram or flow sheet: *see* 210,
 223, 226, 228,
 of manufacturing process for
 composite propellants, 529
 preliminary design, 584
 propulsion system selection, 693
- Flow, *see also* nozzle gas flow
 isentropic, 51, 52–75
 fuel mass flow (hybrid), 605–609
 mass (or weight) flow parameters, 29,
 34, 50, 60, 199, 274, 332, 409,
 444–445, 606–607
 multiphase flow (gas with liquid
 drops and/or solid particles),
 83–85
 supersonic, sonic, subsonic flow,
 Fig. 3–1, Tab. 3–1

- Flywheels, 231
- Force; *see also* Thrust
 acting on flight vehicle, 104–106
 measurement of, 735–736
 of solar radiation pressure, 13
- Free energy or chemical potential, 159–160
- Free molecular flow, 710
- Frozen and shifting chemical equilibrium, 167, 170, Fig. 5–1
- Fuel cells, 662
- Fuel, hybrid rocket, 595–596
- Fuel, liquid propellants, 259–264
- Fuel pumps, 378–387
- Fuel, solid propellants, 511–514, 518–519
- Gas constant, 48, 52, Tab. 5–10
- Gaseous propellant rocket engine, 8, Fig. 2–5, 194, 266–267
- Gas generator; *see also* Preburner, 393–395
 in engine cycles, 219
 with liquid propellant, 185, 393–395
 with solid propellant, 438, 522–524
- Gas pressurized feed system, *see* Feed system
- Gas propellants (cold), 194, 266–267
- Geosynchronous earth orbit (GEO), *see* Orbits
- Gibbs free energy, *see* Free energy
- Gimbal, bearing, 190, 674–679
- Grain, solid propellant, 462–472, *see also* Solid propellant rocket motor
 aging of, 481, 499, 506
 binder, propellant, 442, 516, 518
 bond strength, 472–476, 482
 burning surface area to nozzle throat area ratio (K) of, 447
 cartridge loaded grain, Fig. 12–14, 482
 case-bonded grain, Fig. 12–14, 482
 configuration and design of, 462–472
 definitions/terminology, 463–466
 design, 466–472
 end burning grain, 469–470
 hybrid fuel grain, 602–607
 inhibitor for, 464
 insulator, internal, thermal, 464
 liner, 464
 multiple grains (restartable), Fig. 12–20
 perforation, port, or internal cavity, 463, 467, Fig. 12–16
 regressive, neutral, or progressive burning, 463–466
 requirements for, 466
 sagging/slumping of large grains, Tab. 12–6
 sliver, 463, 471–472
 stress and strain, 472–483
 cumulative damage, 481–482
 stress relief flap or boot, 480–481
 structural design, 476–483
 surface cracks, 472
 tensile strength, 474–476
 thermal cycling, Tab. 12–6
 unbonded area, 472, 482
 volumetric loading fraction, 466
- Graphite, 572, 573
- Gravitational attraction, 105–106
- Gravity gradients, 123
- Hall thruster 652–656
- Hazards: 250–242, 505–511
 classification, 440, 508
 solid propellant explosion, detonation, 250, 440, 507
 solid propellant, fire, deflagration, 251
 health, 252, 267–268
 insensitive munitions, 509–511
 liquid propellants and engines, 252
 solid propellant, 505–511
 toxic gas exposure limits, 735
 toxicity, 510
- Health monitoring system, 428–430, 738

- Heat of formation, 158, 159, 162–163
 Heat of reaction, 158, 162
 Heat transfer, 264, 288–295, 334–336
 analysis of, 310–322
 boundary layer, 82–83
 cooling techniques; 289–295, 335;
 see also insulation-thermal;
 radiation cooling; regenerative
 cooling, film coefficient, liquid
 propellant thrust chamber
 cooling,
 film cooling, 293–295: *see* RD-191
 thrust chamber, Fig. 8–11
 radiation from exhaust plume,
 711–714
 heat transfer to coolant, 317, 320
 to liquid propellants, 253
 steady state, 290–291
 transient, 291–292
 Helium, 213, 266–267
 Helmholtz resonator. 360, 361
 Hexanitrohexaasaisowurtzitane or
 CL-20 explosive, 519
 HMX (Cyclotetramethylene
 tetranitramine), 493–495, 499,
 512, 518, 519
 Hohmann transfer orbit, 117–118,
 626, 627
 HTPB or Hydroxyl terminated
 polybutadiene, 496, 512, 514,
 516–517, 595, 604, 605, Fig.
 16–2, Tab. 16–1
 Hybrid propellant rocket propulsion, 9,
 593–619,
 advantages/disadvantages, 593–594
 applications and propellants of,
 596–600
 combustion instability of, 611–615
 design example of, 607–611
 fuel regression rate, 601–606
 performance analysis and grain
 configuration, 602–607
 Hydrazine, 247–249, 262–263,
 264–266, 320, 632–633,
 636–637, 656
 Hydrocarbon fuels, liquid, 260–261;
 see also RP-1 fuel, RP-2, *see* solid
 propellant binder, plasticizer
 Hydrogen, 173, 180, 185, 190,
 247–249, 261–262, 267, 309
 Hydrogen, peroxide, 164–166,
 248–249, 256–257
 Hydroxyl terminated polybutadiene,
 abbreviated as HTPB, 498, 500,
 502, 512, 516, 518, 595, 605–606;
 see also Polybutadiene
 Hypergolic ignition, *see* Ignition
 Ideal rocket propulsion system,
 46–47
 Ignition/igniter: analysis and design
 of, 337, 581–582, Fig. 15–16
 starting and ignition, 322–325
 hardware, 272, 438–439, 577–582
 hypergolic (spontaneous), 254, 326,
 598–599
 inadvertent ignition, 505–506
 for liquid propellants, 254, 272,
 324–325
 propellants for igniters, 324–325,
 524–525
 pyrotechnic, pyrogen, 324,
 579–581
 for solid propellants, 435, 438, 439,
 506–507, 540–541, 578–582
 Impulse, *see* specific impulse; total
 impulse
 Impulse to weight ratio, 29, 460
 Inducer (impeller), 385–386, *see* pump
 Ingredients of solid propellants,
 511–513
 Inhibitor for grain, 464, 527
 Injector, liquid propellants, 198, 272,
 276–285, 336–337; 383–385
 see also thrust chamber
 baffles of, 360–361
 effect on heat transfer, 284
 platelet injector, 273, 281
 pintle injector, 277
 pressure drop and flow, 280–283

- Injector, liquid propellants, (*continued*)
 factors influencing injector behavior
 283–285
 types of, 276–283
- Insensitive munitions, 508–510
- Instability of combustion, *see*
 Combustion Instrumentation,
 735–739
- Insulation thermal, external, 525–527
- Insulation thermal, internal, 294, 464,
 525–527
- Interfaces between propulsion system
 and vehicle, 699–700
- Internal ballistics, 457–458
- International rocket effort, 13–14;
see also LE-7; RD-120, RD-170,
 Vulcain
- Interplanetary missions, 123–124, 130,
 626–627, data on planets, 119,
 propulsion systems for space
 maneuvers 127–131
- Ion propulsion, *see* Electric propulsion
- Isonropic flow through nozzles, 50,
 51–75; *see also* Flow
- IUS (Interim Upper Stage) rocket motor
 (UTC), 438, 677
- Jet, *see* Rocket exhaust plume
- Jetavator, *see* Thrust vector control
- Jet fuel, 260
- Jet power of gas plume, 35
- Jet vane, *see* Thrust vector control
- Kerosene, 260, 329, 408; *see also* RP-1,
 RP-2 fuels
- Kinetic energy rate of exhaust, 35
- Launch vehicle, *see* Space launch
 vehicle LE-7 and LE-5A rocket
 engines (Japan)
- Latch valve, *see* footnote on page 209,
see diagram on page 210
- Life time of propulsion system in space,
 193
- Life limits for liquid propellant rocket
 engine feed system, 208
- Life of thrust chambers/thrusters,
 325–326
- Life limits of solid grain/motor, 500
see also aging
- Life time of electric propulsion, 656
- Lift, aerodynamic, *see* lift force,
 104–106
- Liner, 464, 525–527, *see* grain
- Liquid oxygen, *see* Oxygen
- Liquid propellants, 193–194, 244–270,
see also fuels: hydrazine,
 hydrogen; RP-1, kerosene,
 methane, *see also*: oxidizers:
 nitrogen tetroxide,
 oxygen, nitric acid
 bipropellant, 193,
 budget for, 399–401,
 combustion of, 344–364,
 cryogenic propellant, 194, 246–250,
 gelled propellant, 250,
 hazards of, 250–252, 267–268,
 heat transfer of, 254, 288–295,
 311–328,
 ignition/start of, 254–255, 323–326
 mixture ratio of, 180, 404, 408–409
 monopropellant, 194, 264–266,
 302–303
 performance of several bi-propellant
 combinations, 173, 180, 193,
 Fig. 5–1 until Fig. 5–6
 properties of, 246–255
 storable propellant, 194
 topping off, cryogenic propellants,
 198
- Liquid propellant rocket engines, 5–8,
 189–243, 399–412, *see also*
 auxiliary rockets, controls, engine
 cycles, feed systems, heat transfer,
 tanks: thrust chambers, turbopumps
 advantages/disadvantages of,
 695, 696
 boost propulsion, 193
 calibration of, 423–430

- chamber pressure of, 274, 404, 408–409
 control of, 206–208, 412–422
 engine cycles of, 218–228
 engine design, 403–412
 engine design, optimization, 407
 engines: multiple systems, 40–41, 401–402
 engine families, 232–235
 engine support structure, 239–240
 gas generators and preburners of, 185, 190, 223, 393–395
 inert mass and center of gravity, 407
 with pressurized gas or pump feed, 194, 197, 208–228
 starting, ignition, and thrust build-up of, 323–326, 414–419
 shut down or termination of, 416–419
 system integration and engine optimization of, 430–431
 system performance of, 401–403
 thrust chamber or thrusters of, 271–343
 variable thrust of, 40, 41, 326–328
 Lorentz force, electrical propulsion, 638, 648, 652
 Low Earth orbit (LEO), 124, 125

 Mach number, 49–51
 Magnetic field flight perturbation, 123
 Mandrel for casting solid propellant grain, 530
 Maraging steel, 561
 Masses of vehicle, definitions, 101
 Mass flow, 42, 59, 444–445, 449, 606, 644; *see also* flow of gas; flow of liquid propellant
 Mass fraction, *see* propellant mass fraction
 Mass ratio, vehicle, 28, 100–102, 110
 Materials and materials properties, 305–310, 442, 557, 572–573
 MESSENGER space probe, liquid propellant flow diagram, 210

 Metals, 442; *see also* Niobium; Rhenium; Stainless steel; Titanium
 Measurement/sensing of data, 736–738
 Methane, 184, 247–249, 261, 267
 Micrometeorology, 734
 Migration in solid propellant grain, 527
 Minimum smoke solid propellants, 523–524
 Minuteman rocket motor, 683
 Missiles, military, 21–24, 144–148, 438
 Missions, 191, 659–660, *see also* requirements
 Mission velocity, 125–127, 128–131, 133–135
 Mixing of solid propellant, 530, 531
 Mixture ratio, *see* liquid propellant rocket engine; hybrid propulsion
 Molecular mass (or weight), 52–53, Fig. 3–2, 56, 157, 180, 184, 246–247
 Monomethyl hydrazine (MMH), 247–249, 264–266, 273, 274
 Monopropellant, 42, 232, 263–265, *see also* Thrust chamber, monopropellant
 Motor, *see* Solid Propellant Rocket Motor
 Movable nozzle, *see* Nozzle, extendible or movable
 Multistage or multistep rocket vehicles, 16–17, 136–138
 Multiple propulsion systems, 38, 401–403

 Net positive suction head, 383
 Niobium, 192, 301, 305, 307–308
 Nitric acid, and inhibited red fuming nitric acid (IRFNA), 246–249, 257–258
 Nitrocellulose (NC), 511, 514, 520
 Nitrogen tetroxide, N₂O₄, 247–250, 259, 273, 274, 321, 409

- Nitrous oxide, 259
- Nitroglycerine (NG), 499, 513, 519
- Noise of exhaust plume, 719–720
- Nozzle; *see also* Flow; Mass flow; Liquid
- propellant rocket engine; Solid
- propellant rocket motor; Specific impulse
- aerospike, 74
- alignment of, 91–92
- analysis, thermochemical of, 166–171
- nozzle exit area ratio, Fig. 3–1, Fig. 3–3, 56–61, 72, 182, 274, 329–331, 404, 408–409
- with bell shape or contour exit, 73–85, 190, 329–331, 567–570, 677
- blast tube of, Fig. 12–4, 565–566
- boundary layer of, 46, 82–83
- change in gas composition of, Fig. 5–2, until Fig. 5–5; 184, 187, 188
- classification or type of, 564–565
- cone angle correction factor of, 75
- critical pressure, temperature, or velocity of, 57–58
- effective exhaust velocity of, 33–35
- energy and efficiency of, 35–37
- energy losses in, 81, 82
- erosion of, 569–570, 589
- exit or exhaust velocity, 34–36, 52–56,
- exit gas composition, 176
- extendible nozzle, 309, 438, 565–566
- flow analysis with computers, 170–172
- flow separation within, 68–71
- Gibb's free energy, 159
- gimbal or hinge mounted, 673–679
- illustrations of nozzles 8, 190, Fig. 12–1, –3, 565, 677
- insert in nozzle throat, 8, Fig. 15–7, Fig. 15–9
- losses, 81–82, 569–570
- materials, Fig. 8–13, Tab. 8–3, Fig. 8–16, 307, 571–575; *see also* ablative materials
- multi-phase flow in, 83–85
- multiple nozzles, 81
- optimum expansion thrust coefficient of, 63, 67
- over-expanded nozzle, 67–72
- performance correction of, 85–88
- performance parameters/specified conditions, 30, 89–91, 274–275
- effect of altitude, 33, 64, 70–72
- pressure drop or pressure ratio, 35, 50, 56, 59–64, 66–67
- scarfed nozzle, 92
- separation of flow in, 67–70
- shape, length, and configuration of, 73–82, 287–288, 330–331
- submerged nozzle, 565
- throat condition or diameter of, 57–61
- under-expanded nozzle, 67–71
- supersonic, sonic, and subsonic flow, 53, 60, Tab. 3–1.
- theory, 47–90
- Nuclear power generation, 663
- Nuclear rocket propulsion, 10
- Nucleate boiling heat transfer, 318–320
- Ohm's law, 635
- Optimum expansion, *see* Nozzle, optimum expansion
- Optimization studies, 407, 693
- Orbits of satellites and spacecraft:
- circular, 114, 118, 627
- deorbit, 133, 135
- elliptical, 116–117
- energy, 114
- low earth orbit (LEO), 114, 127–129
- orbit maintenance, 124
- geosynchronous earth orbit (GEO), 127, 627

- injection into orbit, orbit transfer, space maneuvers, 21–122, 127–129
 - 132, 135, Tab.17–8.
- Hohmann transfer path, 117
- low earth orbit (LEO), 128, 627, 629, 663
- orbit maintenance, station keeping
 - 124, 128, 132, 134–135, 663
- payloads for different orbits, or flight paths, Tab. 4–5, Fig. 4–16, 659
- period of orbit revolution, 114
- perturbations of orbits, 121–124
- raising orbit altitude, 117
- Oxidizer(s):
 - liquid, 256–259
 - pump for, 253, 367, 370, 374, 378–387
 - solid, 512–516, 518–522
 - particles or particulates, size parameters, 520–522
 - vibration damping, 361
- Oxygen, 173, 179, Fig. 5–6, 5–7, 5–8, 246–249, 274, 404, 408–409
 - performance data with LOX-RP-1, Fig. 5–1 to Fig. 5–6
 - performance data with hydrogen, 173
- Payload, payload mass fraction, 103, 143
- Pegasus space launch vehicle, Fig. 4–16, 304
- Perfect gas law, 48
- Performance; *see* nozzle, effective exhaust velocity; nozzle exit or exhaust velocity; propellant mass fraction; specific impulse:
 - theoretical, delivered, standard, and guaranteed performance, 89–91
 - correction factors, 85–89
- Perigee, 116, Fig. 4–8
- Perturbation of flight path, 121–124
- Pipes or flow lines, 237–238
- Piston expulsion, 202
- Pitch, yaw, and roll maneuvers, 131, 672
- Planets, sun and moon data, 115
- Plasticizers, for solid propellants, Tab. 13–6 and 13–7, 518
- Plume, *see* Chapter 20
- Plume shape versus altitude, Table 20–2
- Pogo pulsations or feed system instability, 351, 352
- Polybutadiene (various), *see* HTPB, 496, 498–499, Tab. 13–7, Tab. 13–8
- Polyether, polyester, polyurethane, 512, 516
- Port area or cavity, *see* Grain
- Positive expulsion devices, 201–203
- Power conditioning/conversion, *see* Electric propulsion
- Power of jet or plume, 35
- Preburner, *see* Liquid propellant rocket engines, gas generators, 293–294
- Pressure, atmosphere, 752
- Pressure balance (turbopump), 376–378, and (calibration), 424–426
- Pressure exponent, *see* burning rate
- Pressure oscillations, *see* Combustion instability
- Pressure regulators, Fig. 1–3, Fig. 6–3, 236–237
- Pressurized gas feed system, 6, 205–212
- Propellant, *see* Liquid propellant; Solid propellant; for Ignition; Gaseous propellant
- Propellant budget, 399–401
- Propellant mass fraction, 29, 460
- Propellant tanks, *see* Tanks
- Propellant utilization, 213, 420–421
- Propulsive efficiency, 36–37
- Pulse modulation or pulsing thruster, 212, 300, 328, 649–650
- Pump, 253, 371, 378–386, *see* turbopump, ooster pump, 374
 - cavitation, 373, 375, 382–385
 - desirable propellant properties, 246–255

- Pump, (*continued*)
 dual pump inlet, 385
 efficiency of, 380–382, 385
 head and suction head of, 380,
 383–384
 inducer pump, impeller of, 385
 shrouded impeller of, 379
 specific speed of 381–382
 suction specific speed, 383
 type or configuration of, 372, 382
- Pyrolytic graphite and other high
 temperature materials, 573, 574
- Qualification of rocket propulsion
 system:
 preliminary flight rating test, 727
 qualification test, 728
- Radiation heat transfer and cooling,
 273, Fig. 8–13, Fig. 8–16, 307,
 308, 321–322, 572–575
- Ramjet, 2–4, 9
- Radiation cooled thrusters 274, 308
- Reaction control system (RCS),
 131–133, 229–232, 300–304,
see also auxiliary rocket engine,
 Attitude Control System (ACS)
- Reduced smoke solid propellant,
 523–524
- Rendezvous or docking in space, 128,
 133–135
- Reinforced plastics case, 561–563,
 Tab.15–2, *see also* Carbon-carbon
- Reentry and landing of vehicle, 128,
 132–133
- Regenerative cooling, 274, 289–292,
 310, 311–320; *see also* Thrust
 chamber
- Requirements and constraints for solid
 propellant rocket motors, 583
- Requirements for mission, 191, 466,
 661–663, 703–705
- Residual propellant:
 liquid, 196–197, item 6 on page 400
 solid (*see* slivers), 463, 471
- Resistojet, Fig. 2–4, 624, 631–634
 658–660; *see* Electric propulsion
- Retro firing of Falcon SLV, *see* front
 cover story
- Reusability of propulsion system, 208
- Rhenium, Fig. 8–16
- RL 10 rocket engine, 225, 232–235,
 274, 404
- Rocket engine, *see* Liquid propellant
 rocket engine
- Rocket exhaust plume, 703–725
 color, luminosity, and spectral
 distribution of, 254–255, 717–721
 appearance and shape, 705–710
 noise, 719–720
 radio signal attenuation of, 720–722
 smoke of, 254, 493, 717–718
- Rocket motor, *see* Solid propellant
 rocket motor
- Rocket-assisted gun-launched
 projectiles, 147
- Rocket propulsion:
 applications, 14–24, 437, 498,
 Fig. 17–1, Tab. 17–1,
 Fig. 17–2, 658–660
 definition, 1
 exhaust gas or flame, *see* Rocket
 exhaust
 plume, Chapter 20
 for certain flight maneuvers,
 134–135
 testing, 726–750
 types of, 4–14
- Roll or roll maneuver, 672
- RP-1 fuel (kerosene), Fig. 5–1 to 5–6,
 247–250, 260, 274–275
- RP-2 fuel (more refined kerosene)
 260–261
- RS-27 rocket engine (Aerojet
 Rocketdyne), 274–275, 369
- RS-68 rocket engine, for Delta 4 Space
 Launch Vehicle (Aerojet Rocketdyne),
 221–224, 404

- Russian engines RD-120, RD-170, RD-253, *see* Tab. 11–3; for RD-191 *see* 227–228; for RD-0124 *see* 684–685
- Safe and arm device, 505, 579
- Safety, *see also* Hazards, Insensitive Munitions, 208, 267–268, 413, 493, 595–519, 579, 528–235, 728–735
- Satellite;
 - orbits/payloads of, 117–121
 - period of revolution of, 114
 - perturbing forces on, 121–124
 - velocity of, 114
- Seals of turbopumps, 374
- Selection of rocket propulsion systems, 692–697; *see also* Interfaces of, criteria for, 697–699
- Separation of nozzle flow, 69–73
- Shrouded pump impeller, 379
- Shock wave, 716–717
- Silica phenolic, 573
- Single stage to orbit, 20
- Sliver, residual solid propellant, 441, 463, 471–472
- Sloshing of liquid in tank, 199
- Smoke of plume, *see* rocket exhaust plume
- Solar cells, 662–663
- Solar heating propulsion or solar thermal propulsion, 13, 30, Fig. 2–5
- Solar propulsion (by radiation pressure) or solar sail, 13
- Solid propellant(s), 8, 435, 442, 491–535, *see* burning rate;
 - combustion of, 536–554
 - cumulative damage of, *see* aging, 481–483
 - grain, 463–472
 - ignition of, *see* igniter
 - abbreviations and acronyms for grain ingredients, 511–513
 - aging of, 499, 506
 - aluminum in, 496, 511–513
 - binder for grain, 441, 498–499, 511–513, 518
 - characteristics and behavior of, 497–504
 - chemical gas reaction products, 183–185, 504
 - exhaust plume, 711–714
 - with small solid particulates 520–522
 - comparison of different types of, 492–496, 498–500
 - composite and composite modified double base, 441–442, 447, 492–494, 498–499, 501–503, 511–513, 516
 - detonation of, 493, 507–508; *see also* deflagration, explosives
 - double base propellant, 492, 496, 498, 499, 500, 511
 - gas generator, 437, 522–524
 - hazards of, 505–511
 - high energy propellant, 493
 - ammonium nitrate, 511–512, 522–223
 - ammonium perchlorate, 495, 499, 502, 502–505, 512–513, 514, 515
 - explosives; *see* HMX, RDX, nitrocellulose; nitroglycerine
 - plateau propellants, 446
 - material characterization of, 473–477
 - migration of certain ingredients, 527
 - particle size parameters of, 520–522
 - plasticizer for, 518
 - processing or manufacturing of, 528–531, cast or extruded, 493–494
 - representative formulations, 500
 - safety, 510–511
 - rating, 493
 - smoky, smokeless, or low smoke, 494–495, 523–524
 - stress relaxation modulus of, 478–479, 497

- Solid propellant(s), (*continued*)
 testing of, 733–750
 thermal cycling of, 477, 481
 typical data regions of propellant categories, Fig. 13–1, Fig. 13–2, and Tab, 13–1
 upper pressure limit of, 510
- Solid propellant rocket motors, 8,
 434–490 *see* burning rate; case;
 grain; ignition; insulation; liner;
 nozzle; solid propellants action
 time and burn time, 458–459
 advantages and disadvantages,
 695–697
 basic performance relations and data
 for, Table 12–3, 437–458
 booster motor, strap-on 15, 19, 438
 chamber pressure, 445–452
 combustion of, 446, 536–554
 combustion instability, 543–551
 components of, 8, Figs. 12–1, –2,
 15–2
 design approach for, 581–589
 extinction, thrust termination,
 541–543
 insulators, liners, and inhibitors of,
 464, 525–527
 loads and failure modes of,
 477, 556
 materials, 443, 558, 573
 nozzles of, 8, 436, 439, 464
 performance data of, 442, 494, 496,
 498, 502–503
 requirements and constraints of,
 583, 585
 tactical missile rocket motors,
 438, 440
 temperature limits of, 438
 two-pulse motor (restartable), 471
 vortex shedding instability, 551
 weights/masses (typical), 442,
 461–462
- Spacecraft, 21–22, 23, 146; *see also*
 Orbits, Flight, Satellite, Mission
 velocity
 attitude control of, *see* reaction
 control
 system
 maneuvers of, 131–134
 perturbing forces on spacecraft,
 124–128
 surface contamination, 727
- Space flight, *see* Flight, Orbits
- Space launch vehicles, 14–22,
 145–148
 boosters, 1st stage, 14–15, 135, 438
 upper stages, 135, 438
- Space Shuttle, 19–20
 flight velocity breakdown, 129
 main engine, 20, 195, 227–228, 371,
 404, 416–418
 space shuttle start sequence, 416–419
 nozzle, of strap-on solid propellant
 booster, 288
 reaction control and orbit maneuver
 system, 19, 212–214
 solid rocket motor/nozzle of, 561,
 568–570
- Specifications for rocket propulsion
 system, 694, 699–705,
 for propellants, 255
- Specific gravity/density, 184, 247–249,
 253, 442, 497, 598
- Specific heat ratio, 50, 68, 184
- Specific impulse, 3, 29, 32, 38, 55, 173,
 177, 181, 182, 184, 185, 274, 404,
 409, 442, 460, 497, 502, 625, 658
 density specific impulse, 253
 theoretical, actual, reference, and
 guaranteed values of, 94–96, 460
- Specific power, 32, 629–630
- Specific speed (pump), 381
- Stability:
 of combustion, 352–363
 of flight, 152–153
 liquid propellant storage (chemical
 stability), 253–254, 352–363
- Staged combustion cycle, 225, 228, *see*
 RD-191
- Stage separation during flight, 142

- Staging configurations of vehicles, 131, 140–146
- Stagnation pressure and temperature, 51–52
- Standard atmosphere, 752
- Starting, 323–326, 414–418, *see also* Controls for rocket engines, Feed systems, Ignition, Thrust chamber
- Static rocket system tests, *see* Testing
- Station keeping, *see* Auxiliary rocket
- Systems, Orbits
- Stay time or residence time, 287, 350
- Stoichiometric mixture of bipropellant, 161
- Stop operations, *see* Thrust termination
- Storable liquid propellants, 199
- Strand burner for solid propellants, 444
- Strap-on motor/engine, 135, 141
- Stresses and strains, 295–299, 477–481, 557–560; *see also* Case, Grain; Liquid propellant rocket thrust chamber, Solid propellant rocket motor, Tanks
- Structure, 194; *see also* Interfaces, rocket engine support structure
- Suction specific speed, *see* pumps
- Summary of key equations, 753–754
- Sun, data, 119
- Supersonic, sonic, and subsonic nozzles, 52, 60
- Surface contamination by exhaust plume, 728
- Surface tension screens, 207
- Sweat cooling, 293–294
- Synchronous satellite, 120, 128, 627, 628, 632
- System Engineering, Ch. 18
- Tactical missile rocket motor, 21, 22, 437, 440
- Tank(s), 194, 196–208
expulsion efficiency, 196
positive expulsion during zero *g*, 200–203
pressurization, 212–214, 217–218
- Tank head start, 416
- T-burner, solid propellant, 548–550
- Temperature, 48–51, combustion chamber temperature 32, 54–56, 57, 59, 177–178, 184, 185, 312, 408
limits for solid propellant grain storage, 442, 461
sensitivity of solid propellant (coefficient), 450–452
stagnation, 48–49
variation of physical properties with, 254
- Tensile tests on propellant specimen, 443–444, 473–476
- Testing of rocket propulsion systems, *See* Chapter 21
facilities and safeguards, 728–735
flight testing, 739–740
instrumentation and data management, 735–739
post-accident procedures, 740–741
types of tests, 726–728
- Thermal shield, also called Blow-back Gas Barrier, 684
- Thermochemical data for carbon monoxide, 161
- Thermodynamic properties of chemical constituents, 159
- Thermodynamic relations and nozzle flow, 49–61
- Throttling, *see* Variable thrust
- Thrust, 5, 31–33, 39–41, 61–63, 107, 109, 274–275, 404, 622
acting on vehicle, 107–110
aerospike, 74, *see* 8th edition
altitude variation of, 33 thrust coefficient, 61–68, 182
correction factor of, 31–33, 85–89
equations, 33–34, 63, 66, 68, 642
termination, *see* Solid propellant rocket
motors, extinction
thrust level control, 208, 212, 408

- Thrust, (*continued*)
 theoretical, actual, reference, and guaranteed values of, 89–91
 variable thrust, 40–41, 326–328, 408
- Thrust chamber (small ones are called thrusters), *see also* Combustion, Heat transfer; Injection; Fig. 1–3, Fig. 1–4, 192–196, 271–343
 Chamber contraction area ratio of, (A_1/A_2), *see also* cooling, film cooling Fig. 2–1, 271–275, Regenerative cooling of, 291, 304–307
 Design of, 328–337
 Equations for ideal, 48–49
 Ignition and start up of, 322–325
 Life of, 325–226
 Low thrust (called thrusters), 229–233, 300–304; *see also* Auxiliary rockets; Electric propulsion Materials and fabrication of, 304–311
 Monopropellant, Fig. 2–4, 232, 264–266, 302–303
 Pulsed or intermittent operation, 229, 232; *see also* Duty cycle Sample design analysis of, 328–337, 607–611
 With cooling jacket, with tubes or milled channels, 272, 273, 290–291, 299, Fig. 8–15, 334–337
 Volume and shape of, 285–288
 Wall loads and stresses of, 296–300
- Thruster 229–232, 300–304
 divert force and thruster, 229
 modules of thrusters, 209
 Thrust vector control (TVC), 671–689
 alignment accuracy of, 91–92, 680
 flexible nozzle bearing for, 569, 676, 677, 679, 680
 gimbal or hinge of, 674–686 *See* RD-0124, SSME with injection
 of secondary fluid, 676, 682
 integration with vehicle, 687–688
 jet tabs, 675, 680, Fig. 18–7
 side injection, 676, 682
 jet vanes, 674, 673, 676
 with multiple thrust chambers or nozzles, 683–686
- Thrust to weight ratio, 461
 Time to target, 145–146
 Total impulse, 26–29, 441, 460
 Toxicity, 251, 267–268, 510, 735, *see also* Hazards, health
 health monitoring, 738–739
 toxic gas exposure limits, 731–732
- Toxic propellants, 251
 Turbine(s), 370, 387–390; *see* turbopump, turbojet, 2, 4
 Turbopump, *see* Pumps; Turbines, 7, 190, 199, 365–370, 371–375, 390–393
 booster pump of, 374
 design configurations of, 368–370
 feed system of, 221–228, 409
- Two-phase flow, 83–85, 459–460
- Ullage, definition, 196, 200, 202
 Unsymmetrical dimethylhydrazine (UDMH), 247–249, 263, 408
 Useful life of thrust chamber, 325–326
- Valves, 6, 7, 9, 13, 235–237, 623
 Variable thrust applications, 40–41, 326–328
- Vehicle; *see also* Missile; Satellite; spacecraft; space launch vehicle, military rockets, base geometry, recirculation of, plume gas, 715–716
 Earth escape velocity, 114
 flight performance, 99–153, 329
 forces on, 107–110
 integration with thrust vector

- control, 687–688
- satellite velocity, 114
- masses of vehicle, definition, 101
- multistage, 16, 17, 136–138
- velocity of flight, 105–109, 110, 113, 114, 117, 118
- Velocity (hot gas); *see also* Nozzle, exit or exhaust velocity; characteristic velocity; specific impulse, 28, 33–34, 52
- correction factor for, 85–87
- effective exhaust velocity, 27–28, 33
- at nozzle exist, 54–56
- of sound or acoustic velocity, 51, 60
- throat velocity, 57
- Venturi in pipe line, 238
- Vertical flight, such as sounding rocket, 109–112
- Vibration energy absorption, 547
- Vibration frequency (of chamber gas), *see* Combustion
- Volume impulse, 461
- Volumetric loading fraction, 466, 469
- Vortexing of liquid propellants, 199
- Vulcain rocket engine (France), 356, 404
- Warm gas propellant, 8, 266–267
- Water hammer, 238
- Web thickness and web fraction of grain, 441, 464, 465, 468, 469, Fig. 12–16
- Xenon (Xe), 624, 646
- Yaw maneuver, 131, 672
- YF-73, YF-75 rocket engines (China), 404

