Material property data for engineering materials

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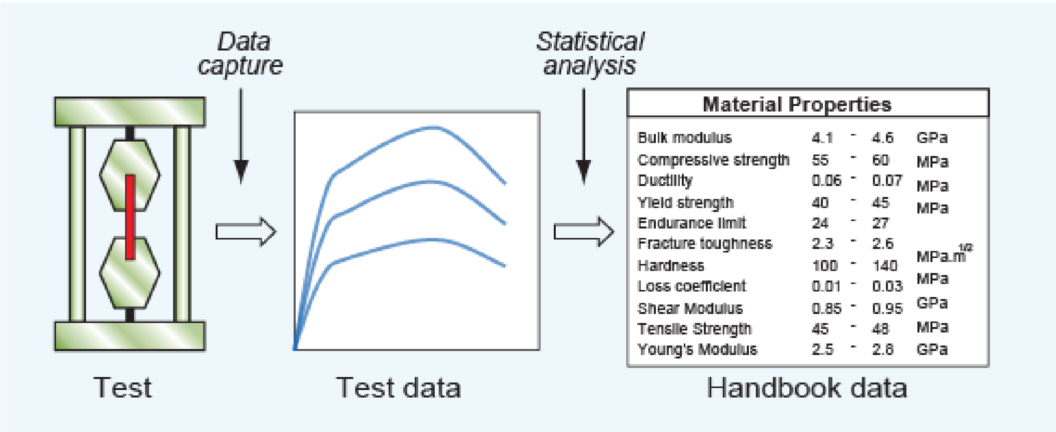

GRANTA TEACHING RESOURCES

Granta Design's Teaching Resources and website aim to support teaching of materials-related courses in Design, Engineering and Science. Resources come in various formats and are aimed primarily at undergraduate education.

Physical constants in SI units

Physical constant	Value in SI units	
Absolute zero temperature	-273.2	^oC
Acceleration due to gravity, g	9.807	m/s^2
Avogadro's number, N_A	6.022×10^{23}	-
Base of natural logarithms, e	2.718	-
Boltzmann's constant, k	1.381×10^{-23}	J/K
Faraday's constant k	9.648×10^{4}	C/mol
Gas constant, $\overline{R}$	8.314	J/mol/K
Permeability of vacuum, μ_0	1.257×10^{-6}	H/m
Permittivity of vacuum, ε_0	8.854×10^{-12}	F/m
Planck's constant, h	6.626×10^{-34}	J/s
Velocity of light in vacuum, c	2.998×10^{8}	m/s
Volume of perfect gas at STP	22.41×10^{-3}	m^3/mol

Conversion of units, general

Quantity	Imperial unit	SI unit
Angle, θ	1 rad	57.30^o
Density, ρ	1 lb/ft^3	16.03 kg/m^3
Diffusion coefficient, D	1cm^3/s	$1.0 \times 10^{-4} m^2/s$
Energy, U	See inside back cover	
Force, F	1 kgf 1 lbf 1 dyne	9.807 N 4.448 N 1.0×10^{-5}N
Length, ℓ	1 ft 1 inch 1 Å	304.8 mm 25.40 mm 0.1 nm
Mass, M	1 tonne 1 short ton 1 long ton 1 lb mass	1000 kg 908 kg 1107 kg 0.454 kg
Power, P	See inside back cover	
Stress, σ	See inside back cover	
Specific heat, Cp	1 cal/gal.^{o}C Btu/lb.^{o}F	4.188 kJ/kg.^{o}C 4.187 kg/kg.^{o}C
Stress intensity, K_{1c}	1 ksi $\sqrt{}$in	1.10 $MN/m^{3/2}$
Surface energy γ	1 erg/cm^2	1 mJ/m^2
Temperature, T	1^{o}F	0.556^{o}K
Thermal conductivity λ	1 cal/s.cm.^{o}C 1 Btu/h.ft.^{o}F	418.8 W/m.^{o}C 1.731 W/m.^{o}C
Volume, V	1 Imperial gall 1 US gall	$4.546 \times 10^{-3} m^3$ $3.785 \times 10^{-3} m^3$
Viscosity, η	1 poise 1 lb ft.s	0.1 $N.s/m^2$ 0.1517 $N.s/m^2$

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Contents

Data for engineering materials

This booklet lists the names and typical applications common engineering materials, together with data for their properties.

Table A1. Material names and applications

Polymers		Applications
Elastomers		
Butyl Rubber		Tyres, seals, anti-vibration mountings, electrical insulation, tubing
Ethylene-vinyl-acetate	EVA	Bags, films, packaging, gloves, insulation, running shoes
Isoprene	IR	Tyres, inner tubes, insulation, tubing, shoes
Natural Rubber	NR	Gloves, tyres, electrical insulation, tubing
Polychloroprene (Neoprene)	CR	Wetsuits, O-rings and seals, footware
Polyurethane Elastomers	el-PU	Packaging, hoses, adhesives, fabric coating
Silicone Elastomers		Electrical insulation, electronic encapsulation, medical implants
Thermoplastics		
Acrylonitrile butadiene styrene	ABS	Communication appliances, automotive interiors, luggage, toys, boats
Cellulose Polymers	CA	Tool and cutlery handles, decorative trim, pens
Ionomer	I	Packaging, golf balls, blister packs, bottles
Polyamides (Nylons)	PA	Gears, bearings; plumbing, packaging, bottles, fabrics, textiles, ropes
Polycarbonate	PC	Safety goggles, shields, helmets; light fittings, medical components
Polyetheretherketone	PEEK	Electrical connectors, racing car parts, fibre composites
Polyethylene	PE	Packaging, bags, squeeze tubes, toys, artificial joints
Polyethylene terephthalate	PET	Blow moulded bottles, film, audio/video tape, sails
Polymethyl methacrylate	PMMA	Aircraft windows, lenses, reflectors, lights, compact discs
Polyoxymethylene (Acetal)	POM	Zips, domestic and appliance parts, handles
Polypropylene	PP	Ropes, garden furniture, pipes, kettles, electrical insulation, astroturf
Polystyrene	PS	Toys, packaging, cutlery, audio cassette/CD cases
Polyurethane Thermoplastics	tp-PU	Cushioning, seating, shoe soles, hoses, car bumpers, insulation
Polyvinylchloride	PVC	Pipes, gutters, window frames, packaging
Polytetrafluoroethylene (Teflon)	PTFE	Non-stick coatings, bearings, skis, electrical insulation, tape
Thermosets		
Epoxies	EP	Adhesives, fibre composites, electronic encapsulation
Phenolics	PHEN	Electrical plugs, sockets, cookware, handles, adhesives
Polyester	PEST	Furniture, boats, sports goods
Polymer Foams		
Flexible Polymer Foam		Packaging, buoyancy, cushioning, sponges, sleeping mats
Rigid Polymer Foam		Thermal insulation, sandwich panels, packaging, buoyancy

Table A1. Material names and applications

Metals	Applications
Ferrous metals	
Cast Irons	Automotive parts, engine blocks, machine tool structural parts, lathe beds
High Carbon Steels	Cutting tools, springs, bearings, cranks, shafts, railway track
Medium Carbon Steels	General mechanical engineering (tools, bearings, gears, shafts, bearings)
Low Carbon Steels	Steel structures ("mild steel") – bridges, oil rigs, ships; reinforcement for concrete; automotive parts, car body panels; galvanised sheet; packaging (cans, drums)
Low Alloy Steels	Springs, tools, ball bearings, automotive parts (gears connecting rods etc)
Stainless Steels	Transport, chemical and food processing plant, nuclear plant, domestic ware (cutlery, washing machines, stoves), surgical implements, pipes, pressure vessels, liquid gas containers
Non-ferrous metals	
Aluminum alloys	
Casting alloys	Automotive parts (cylinder blocks), domestic appliances (irons)
Non-heat-treatable alloys	Electrical conductors, heat exchangers, foil, tubes, saucepans, beverage cans, lightweight ships, architectural panels
Heat-treatable alloys	Aerospace engineering, automotive bodies and panels, lightweight structures and ships
Copper alloys	Electrical conductors and wire, electronic circuit boards, heat exchangers, boilers, cookware, coinage, sculptures
Lead alloys	Roof and wall cladding, solder, X-ray shielding, battery electrodes
Magnesium alloys	Automotive castings, wheels, general lightweight castings for transport, nuclear fuel containers; principal alloying addition to aluminum alloys
Nickel alloys	Gas turbines and jet engines, thermocouples, coinage; alloying addition to austenitic stainless steels
Titanium alloys	Aircraft turbine blades; general structural aerospace applications; biomedical implants.
Zinc alloys	Die castings (automotive, domestic appliances, toys, handles); coating on galvanised steel

Natural materials	Applications
Bamboo	Building, scaffolding, paper, ropes, baskets, furniture
Cork	Corks and bungs, seals, floats, packaging, flooring
Leather	Shoes, clothing, bags, drive-belts
Wood	Construction, flooring, doors, furniture, packaging, sports goods

Composites	Applications
Aluminum/Silicon Carbide	Automotive parts, sports goods
CFRP	Lightweight structural parts (aerospace, bike frames, sports goods, boat hulls and oars, springs)
GFRP	Boat hulls, automotive parts, chemical plant

Table A1 (continued). Material names and applications

Ceramics	Applications
Glasses	
Borosilicate Glass	Ovenware, laboratory ware, headlights
Glass Ceramic	Cookware, lasers, telescope mirrors
Silica Glass	High performance windows, crucibles, high temperature applications
Soda-Lime Glass	Windows, bottles, tubing, light bulbs, pottery glazes
Technical	
Alumina	Cutting tools, spark plugs, microcircuit substrates, valves
Aluminum Nitride	Microcircuit substrates and heat sinks
Boron Carbide	Lightweight armour, nozzles, dies, precision tool parts
Silicon	Microcircuits, semiconductors, precision instruments, IR windows, MEMS
Silicon Carbide	High temperature equipment, abrasive polishing grits, bearings, armour
Silicon Nitride	Bearings, cutting tools, dies, engine parts
Tungsten Carbide	Cutting tools, drills, abrasives
Non-technical	
Brick	Buildings
Concrete	General civil engineering construction
Stone	Buildings, architecture, sculpture

Table A2 Density and Price

Metals		**Density (kg/m³)**	**Price (US$/kg)**
Ferrous metals	Cast iron, ductile (nodular)	7,100 - 7,300	0.54 - 0.6
	Cast iron, gray	7,100 - 7,300	0.45 - 0.5
	High carbon steel	7,800 - 7,900	0.52 - 0.58
	Low alloy steel	7,800 - 7,900	0.56 - 0.62
	Low carbon steel	7,800 - 7,900	0.52 - 0.58
	Medium carbon steel	7,800 - 7,900	0.52 - 0.58
	Stainless steel	7,600 - 8,100	5.9 - 6.5

Non-ferrous	Aluminum alloys	2,500 - 2,900	2.1 - 2.3
	Copper alloys	8,900	7.1 - 7.8
	Lead alloys	10,000 – 11,000	6.9 - 7.6
	Magnesium alloys	1,700 – 2,000	3.1 - 3.4
	Nickel alloys	8,800 – 9,000	17 - 19
	Silver	10,000 – 10,100	650 - 710
	Tin	7,300	23 - 25
	Titanium alloys	4,400 - 4,800	22 - 25
	Tungsten alloys	10,800 – 20,000	51 - 57
	Zinc alloys	5000 - 7000	2.4 - 2.6

Ceramics		**Density (kg/m³)**	**Price (US$/kg)**
Glasses	Borosilicate glass	2,200 - 2,300	4.5 - 7.5
	Silica glass	2,200	6.2 - 10
	Soda-lime glass	2,400 - 2,500	1.4 - 1.7

Technical ceramics	Alumina	3,800 - 400	18 - 27
	Aluminum nitride	3,300	100 - 170
	Silicon	2,300 - 2,400	9.1 - 15
	Silicon carbide	3,100 - 3,200	15 - 21
	Tungsten carbides	10,500 – 10,600	19 - 29

Non-technical ceramics	Brick	1,600 - 2,100	0.62 - 1.7
	Concrete	2,300 - 2,600	0.04 – 0.06
	Stone	2,000 - 2,600	0.41 - 0.62

Natural		**Density (kg/m³)**	**Price (US$/kg)**
	Cork	120 - 240	2.7 - 13
	Paper and cardboard	480 - 860	0.99 - 1.2
	Wood, typical across grain	660 - 800	0.66 - 0.73
	Wood, typical along grain	600 - 800	0.66 - 0.73

Table A2 (continued) Density and Price

Polymers		**Density (kg/m³)**	**Price (US$/kg)**
Elastomers	Butyl rubber (IIR)	900 - 920	3.9 - 4.5
	Ethylene vinyl acetate (EVA)	950 - 960	2.3 - 2.5
	Natural rubber	920 - 930	3.5 - 3.9
	Polychloroprene (Neoprene)	1,200 - 1,300	5.3 - 5.9
	Polyisoprene rubber	930 - 940	3.2 - 3.6
	Polyurethane	1,000 - 1,300	4.1 - 4.6
	Silicone elastomers	1,300 - 1,800	11 - 13

Thermoplastics	Acrylonitrile butadiene styrene (ABS)	1,000 - 1,200	2.4 - 2.7
	Cellulose polymers (CA)	980 - 1,300	4.1 - 4.5
	Ionomer (I)	930 - 960	3.2 - 4.2
	Polyamides (Nylons, PA)	1,100	4.1 - 4.5
	Polycarbonate (PC)	1,100 - 1,200	4.6 - 5.1
	Polyetheretherketone (PEEK)	1,300	94 - 100
	Polyethylene (PE)	940 - 960	2.1 - 2.3
	Polyethylene terephthalate (PET)	1,300 - 1,400	2.1 - 2.3
	Polymethyl methacrylate (Acrylic, PMMA)	1,200	2.7 - 3
	Polyoxymethylene (Acetal, POM)	1,400	3 - 3.3
	Polypropylene (PP)	890 - 910	2.1 - 2.4
	Polystyrene (PS)	1,000 - 1,100	2.8 - 3.5
	Polytetrafluoroethylene (Teflon, PTFE)	2,100 - 2,200	15 - 17
	Polyurethane (tpPUR)	1,100 - 1,200	4.1 - 4.6
	Polyvinylchloride (tpPVC)	1,300 - 1,600	2 - 2.2

Thermosets	Epoxies	1,100 - 1,400	2.2 - 2.5
	Phenolics	1,200 - 1,300	1.7 - 1.9
	Polyester	1,000 - 1,400	3.8 - 4.3

Foams	Flexible Polymer Foam (LD)	38 - 70	2.6 - 2.9
	Flexible Polymer Foam (MD)	70 - 120	2.8 - 3.1
	Rigid Polymer Foam (HD)	170 - 470	15 - 17
	Rigid Polymer Foam (LD)	36 - 70	15 - 17

Composites		**Density (kg/m³)**	**Price (US$/kg)**
	CFRP, epoxy matrix (isotropic)	1,500 - 1,600	37 - 42
	GFRP, epoxy matrix (isotropic)	1,800 – 2,000	24 - 34

Table A3 Young's modulus and Yield strength

Metals		**Young's modulus (GPa)**	**Yield strength (MPa)**
Ferrous metals	Cast iron, ductile (nodular)	170 - 180	250 - 680
	Cast iron, gray	80 - 140	140 - 420
	High carbon steel	200 - 220	400 - 1,200
	Low alloy steel	210 - 220	400 - 1,500
	Low carbon steel	200 - 220	250 - 400
	Medium carbon steel	200 - 220	310 - 900
	Stainless steel	190 - 210	170 - 100

Non-ferrous	Aluminum alloys	68 - 82	30 - 500
	Copper alloys	110 - 150	30 - 500
	Lead alloys	13 - 15	8 - 14
	Magnesium alloys	42 - 47	70 - 400
	Nickel alloys	190 - 220	70 - 1,100
	Silver	69 - 73	190 - 300
	Tin	41 - 45	7 - 15
	Titanium alloys	90 - 120	250 - 1,200
	Tungsten alloys	310 - 380	530 - 800
	Zinc alloys	68 - 95	80 - 450

Ceramics		**Young's modulus (GPa)**	**Elastic limit (MPa)**
Glasses	Borosilicate glass	61 - 64	22 - 32
	Silica glass	68 - 74	45 - 160
	Soda-lime glass	68 - 72	30 - 35

Technical ceramics	Alumina	340 - 390	350 - 590
	Aluminum nitride	300 - 350	300 - 350
	Silicon	140 - 160	160 - 180
	Silicon carbide	400 - 460	400 - 610
	Tungsten carbides	630 - 700	340 - 550

Non-technical ceramics	Brick	15 - 30	5 - 14
	Concrete	15 - 25	1 - 3
	Stone	20 - 60	2 - 25

Natural		**Young's modulus (GPa)**	**Yield strength (MPa)**
	Cork	0.013 – 0.050	0.3 – 1.5
	Paper and cardboard	3 – 8.9	15 - 34
	Wood, typical across grain	0.5 - 3	2 - 6
	Wood, typical along grain	6 - 20	30 - 70

Table A3 (continued). Young's modulus and Yield strength

Polymers		**Young's Modulus (GPa)**	**Yield strength (MPa)**
Elastomers	Butyl rubber (IIR)	0.001 – 0.002	2 - 3
	Ethylene vinyl acetate (EVA)	0.01 – 0.04	12 - 18
	Natural rubber	0.0015 – 0.0025	20 - 30
	Polychloroprene (Neoprene)	0.0007 – 0.002	3.4 - 24
	Polyisoprene rubber	0.0014 – 0.004	20 - 25
	Polyurethane	0.002 – 0.030	25 - 51
	Silicone elastomers	0.005 – 0.022	2.4 - 5.5
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	1.1 - 2.9	19 - 51
	Cellulose polymers (CA)	1.6 - 2	25 - 45
	Ionomer (I)	0.2 - 0.42	8.3 - 16
	Polyamides (Nylons, PA)	2.6 - 3.2	50 - 95
	Polycarbonate (PC)	2 - 2.4	59 - 70
	Polyetheretherketone (PEEK)	3.8 - 4	65 - 95
	Polyethylene (PE)	0.62 - 0.9	18 - 29
	Polyethylene terephthalate (PET)	2.8 - 4.1	57 - 62
	Polymethyl methacrylate (Acrylic, PMMA)	2.2 - 3.8	54 - 72
	Polyoxymethylene (Acetal, POM)	2.5 - 5	49 - 72
	Polypropylene (PP)	0.9 - 1.6	21 - 37
	Polystyrene (PS)	1.2 - 2.6	29 - 56
	Polytetrafluoroethylene (Teflon, PTFE)	0.4 - 0.55	15 - 25
	Polyurethane (tpPUR)	1.3 - 2.1	40 - 54
	Polyvinylchloride (tpPVC)	2.1 - 4.1	35 - 52
Thermosets	Epoxies	2.4 - 3.1	36 - 72
	Phenolics	2.8 - 4.8	28 - 50
	Polyester	2.1 - 4.4	33 - 40
Foams	Flexible Polymer Foam (LD)	0.001 – 0.003	0.02 - 0.3
	Flexible Polymer Foam (MD)	0.004 – 0.012	0.048 - 0.7
	Rigid Polymer Foam (HD)	0.2 - 0.48	0.8 - 12
	Rigid Polymer Foam (LD)	0.023 – 0.080	0.3 - 1.7

Composites		**Young's Modulus (GPa)**	**Yield strength (MPa)**
	CFRP, epoxy matrix (isotropic)	69 - 150	550 - 1,100
	GFRP, epoxy matrix (isotropic)	15 - 28	110 - 190

Table A4. Tensile strength and Fracture toughness

Metals		**Tensile strength (MPa)**	**Fracture toughness (MPa.m$^{1/2}$)**
Ferrous metals	Cast iron, ductile (nodular)	410 - 830	22 - 54
	Cast iron, gray	140 - 450	10 - 24
	High carbon steel	550 - 1,600	27 - 92
	Low alloy steel	550 - 1,800	14 - 200
	Low carbon steel	350 - 580	41 - 82
	Medium carbon steel	410 - 1,200	12 - 92
	Stainless steel	480 - 2,200	62 - 150

Non-ferrous	Aluminum alloys	58 - 550	22 - 35
	Copper alloys	100 - 550	30 - 90
	Lead alloys	12 - 20	5 - 15
	Magnesium alloys	190 - 480	12 - 18
	Nickel alloys	350 - 1,200	80 - 110
	Silver	260 - 340	40 - 60
	Tin	11 - 18	15 - 30
	Titanium alloys	300 - 1,600	14 - 120
	Tungsten alloys	720 - 300	50 - 60
	Zinc alloys	140 - 520	10 - 100

Ceramics		**Tensile strength (MPa)**	**Fracture toughness (MPa.m$^{1/2}$)**
Glasses	Borosilicate glass	22 - 32	0.5 - 0.7
	Silica glass	45 - 160	0.6 - 0.8
	Soda-lime glass	31 - 35	0.55 - 0.7

Technical ceramics	Alumina	350 - 590	3.3 - 4.8
	Aluminum nitride	300 - 350	2.5 - 3.4
	Silicon	160 - 180	0.83 - 0.94
	Silicon carbide	400 - 610	3 - 5.6
	Tungsten carbides	370 - 550	2 - 3.8

Non-technical ceramics	Brick	5 - 14	1 - 2
	Concrete	1 - 1.5	0.35 - 0.45
	Stone	2 - 25	0.7 - 1.4

Natural		**Tensile strength (MPa)**	**Fracture toughness (MPa.m$^{1/2}$)**
	Cork	0.5 - 2.5	50e-3 - 0.1
	Paper and cardboard	23 - 51	6 - 10
	Wood, typical across grain	4 - 9	0.5 - 0.8
	Wood, typical along grain	60 - 100	5 - 9

Table A4 (continued). Tensile strength and Fracture toughness

Polymers		Tensile strength (MPa)	Fracture toughness (MPa.m$^{1/2}$)
Elastomers	Butyl rubber (IIR)	5 - 10	0.07 - 0.1
	Ethylene vinyl acetate (EVA)	16 - 20	0.5 - 0.7
	Natural rubber	22 - 32	0.15 - 0.25
	Polychloroprene (Neoprene)	3.4 - 24	0.1 - 0.3
	Polyisoprene rubber	20 - 25	0.077 - 0.1
	Polyurethane	25 - 51	0.2 - 0.4
	Silicone elastomers	2.4 - 5.5	0.033 - 0.5
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	28 - 55	1.2 - 4.3
	Cellulose polymers (CA)	25 - 50	1 - 2.5
	Ionomer (I)	17 - 37	1.1 - 3.4
	Polyamides (Nylons, PA)	90 - 170	2.2 - 5.6
	Polycarbonate (PC)	60 - 72	2.1 - 4.6
	Polyetheretherketone (PEEK)	70 - 100	2.7 - 4.3
	Polyethylene (PE)	21 - 45	1.4 - 1.7
	Polyethylene terephthalate (PET)	48 - 72	4.5 - 5.5
	Polymethyl methacrylate (Acrylic, PMMA)	48 - 80	0.7 - 1.6
	Polyoxymethylene (Acetal, POM)	60 - 90	1.7 - 4.2
	Polypropylene (PP)	28 - 41	3 - 4.5
	Polystyrene (PS)	36 - 57	0.7 - 1.1
	Polytetrafluoroethylene (Teflon, PTFE)	20 - 30	1.3 - 1.8
	Polyurethane (tpPUR)	31 - 62	1.8 - 5
	Polyvinylchloride (tpPVC)	41 - 65	1.5 - 5.1
Thermosets	Epoxies	45 - 90	0.4 - 2.2
	Phenolics	35 - 62	0.79 - 1.2
	Polyester	41 - 90	1.1 - 1.7
Foams	Flexible Polymer Foam (LD)	0.24 - 2.4	0.015 – 0.05
	Flexible Polymer Foam (MD)	0.43 - 3	0.03 – 0.09
	Rigid Polymer Foam (HD)	1.2 - 12	0.024 - 0.09
	Rigid Polymer Foam (LD)	0.45 - 2.3	0.002 – 0.02

Composites		Tensile strength (MPa)	Fracture toughness (MPa.m$^{1/2}$)
	CFRP, epoxy matrix (isotropic)	550 – 1,100	6.1 - 20
	GFRP, epoxy matrix (isotropic)	140 - 240	7 - 23

Table A5. Melting temperature, Glass temperature and Specific heat

Metals		**T_m or T_g (°C)**	**Specific heat (J/kg.C)**
Ferrous metals	Cast iron, ductile (nodular)	1,100 - 1,200	460 - 500
	Cast iron, gray	1,100 - 1,400	430 - 500
	High carbon steel	1,300 - 1,500	440 - 510
	Low alloy steel	1,400 - 1,500	410 - 530
	Low carbon steel	1,470 - 1500	460 - 510
	Medium carbon steel	1,400 - 1,500	440 - 520
	Stainless steel	1,350 - 1,400	450 - 530
Non-ferrous	Aluminum alloys	470 - 680	860 - 990
	Copper alloys	980 - 1,100	370 - 390
	Lead alloys	320 - 330	120 - 150
	Magnesium alloys	450 - 650	960 - 1,100
	Nickel alloys	1,400 - 1,500	450 - 460
	Silver	960 - 970	230 - 240
	Tin	230	220 - 230
	Titanium alloys	1,500 - 1,700	520 - 600
	Tungsten alloys	3,200 - 3,400	130 - 140
	Zinc alloys	370 - 490	410 - 540

Ceramics		**T_m or T_g (°C)**	**Specific heat (J/kg.C)**
Glasses	Borosilicate glass	450 - 600	760 - 800
	Silica glass	960 – 1,600	680 - 730
	Soda-lime glass	440 - 590	850 - 950
Technical ceramics	Alumina	200 - 2,100	790 - 820
	Aluminum nitride	2,400 - 2,500	780 - 820
	Silicon	1,400	670 - 720
	Silicon carbide	2,200 - 2,500	660 - 800
	Tungsten carbides	2,800 - 2,900	180 - 290
Non-technical ceramics	Brick	930 - 1,200	750 - 850
	Concrete	930 - 1,200	840 - 1,100
	Stone	1,200 - 1,400	840 - 920

Natural		**T_m or T_g (°C)**	**Specific heat (J/kg.C)**
	Cork		
	Paper and cardboard	47 - 67	1,300 - 1,400
	Wood, typical across grain	77 - 100	1,700
	Wood, typical along grain	77 - 100	1,700

Table A5 (continued). Melting temperature, Glass temperature and Specific heat

Polymers		**T_m or T_g (°C)**	**Specific heat (J/kg.C)**
Elastomers	Butyl rubber (IIR)	-73 - -63	1,800 - 2,500
	Ethylene vinyl acetate (EVA)	-73 - -23	2,000 - 2,200
	Natural rubber	-78 - -63	1,800 - 2,500
	Polychloroprene (Neoprene)	-48 - -43	2,000 - 2,200
	Polyisoprene rubber	-83 - -78	1,800 - 2,500
	Polyurethane	-73 - -23	1,700 – 1,800
	Silicone elastomers	-120 - -73	1,100 - 1,300
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	88 - 130	1,400 - 1,900
	Cellulose polymers (CA)	-9 - 110	1,400 - 1,700
	Ionomer (I)	30 - 64	1,800 - 1,900
	Polyamides (Nylons, PA)	44 - 56	1,600 - 1,700
	Polycarbonate (PC)	140 - 200	1,500 - 1,600
	Polyetheretherketone (PEEK)	140 - 200	1,400 - 1,500
	Polyethylene (PE)	120 - 130	1,800 - 1,900
	Polyethylene terephthalate (PET)	68 - 80	1,400 - 1,500
	Polymethyl methacrylate (Acrylic, PMMA)	85 - 160	1,500 - 1,600
	Polyoxymethylene (Acetal, POM)	160 - 180	1,400
	Polypropylene (PP)	150 - 170	1,900 - 200
	Polystyrene (PS)	74 - 110	1,700 - 1,800
	Polytetrafluoroethylene (Teflon, PTFE)	110 - 120	100 - 1,100
	Polyurethane (tpPUR)	60 - 90	1,600
	Polyvinylchloride (tpPVC)	75 - 100	1,400
Thermosets	Epoxies	67 - 170	1,500 - 200
	Phenolics	170 - 270	1,500
	Polyester	150 - 210	1,500 - 1,600
Foams	Flexible Polymer Foam (LD)	-110 - -13	1,800 - 2,300
	Flexible Polymer Foam (MD)	-110 - -13	1,800 - 2,300
	Rigid Polymer Foam (HD)	67 - 170	1000 - 1,900
	Rigid Polymer Foam (LD)	67 - 170	1,100 - 1,900

Composites		**T_m or T_g (°C)**	**Specific heat (J/kg.C)**
	CFRP, epoxy matrix (isotropic)	100 - 180	900 - 100
	GFRP, epoxy matrix (isotropic)	150 - 200	100 - 1,200

Table A6. Thermal conductivity and Thermal expansion

Metals		**T-conductivity (W/m/K)**	**T-expansion (10^{-6}/C)**
Ferrous metals	Cast iron, ductile (nodular)	29 - 44	10 - 13
	Cast iron, gray	40 - 72	11 - 13
	High carbon steel	47 - 53	11 - 14
	Low alloy steel	34 - 55	11 - 14
	Low carbon steel	49 - 54	12 - 13
	Medium carbon steel	45 - 55	10 - 14
	Stainless steel	12 - 24	13 - 20
Non-ferrous	Aluminum alloys	76 - 240	21 - 24
	Copper alloys	160 - 390	17 - 18
	Lead alloys	22 - 36	18 - 32
	Magnesium alloys	50 - 160	25 - 28
	Nickel alloys	67 - 91	12 - 14
	Silver	420	20
	Tin	60 - 62	23 - 24
	Titanium alloys	7 - 14	7.9 - 11
	Tungsten alloys	100 - 140	4 - 5.6
	Zinc alloys	100 - 140	23 - 28

Ceramics		**T-conductivity (W/m/K)**	**T-expansion (10^{-6}/C)**
Glasses	Borosilicate glass	1 - 1.3	3.2 - 4
	Silica glass	1.4 - 1.5	0.55 - 0.75
	Soda-lime glass	2,400 - 2,500	1.4 - 1.7
Technical ceramics	Alumina	26 - 39	7 - 7.9
	Aluminum nitride	140 - 200	4.9 - 5.5
	Silicon	140 - 150	2 - 3.2
	Silicon carbide	80 - 130	4 - 4.8
	Tungsten carbides	55 - 88	5.2 - 7.1
Non-technical ceramics	Brick	0.46 - 0.73	5 - 8
	Concrete	0.8 - 2.4	6 - 13
	Stone	5.4 - 6	3.7 - 6.3

Natural		**T-conductivity (W/m/K)**	**T-expansion (10^{-6}/C)**
	Cork	35e-3 - 48e-3	130 - 230
	Paper and cardboard	60e-3 - 0.17	5 - 20
	Wood, typical across grain	0.15 - 0.19	32 - 43
	Wood, typical along grain	0.31 - 0.38	2 - 11

Table A6 (continued). Thermal conductivity and Thermal expansion

Polymers		**T-conductivity (W/m/K)**	**T-expansion (10^{-6}/C)**
Elastomers	Butyl rubber (IIR)	0.08 - 0.1	120 - 300
	Ethylene vinyl acetate (EVA)	0.3 - 0.4	160 - 190
	Natural rubber	0.1 - 0.14	150 - 450
	Polychloroprene (Neoprene)	0.1 - 0.12	580 - 610
	Polyisoprene rubber	0.08 - 0.14	150 - 450
	Polyurethane	0.28 - 0.3	150 - 170
	Silicone elastomers	0.3 - 1	250 - 300

Thermoplastics	Acrylonitrile butadiene styrene (ABS)	0.19 - 0.34	85 - 230
	Cellulose polymers (CA)	0.13 - 0.3	150 - 300
	Ionomer (I)	0.24 - 0.28	180 - 310
	Polyamides (Nylons, PA)	0.23 - 0.25	140 - 150
	Polycarbonate (PC)	0.19 - 0.22	120 - 140
	Polyetheretherketone (PEEK)	0.24 - 0.26	72 - 190
	Polyethylene (PE)	0.4 - 0.44	130 - 200
	Polyethylene terephthalate (PET)	0.14 - 0.15	110 - 120
	Polymethyl methacrylate (Acrylic, PMMA)	0.084 - 0.25	72 - 160
	Polyoxymethylene (Acetal, POM)	0.22 - 0.35	76 - 200
	Polypropylene (PP)	0.11 - 0.17	120 - 180
	Polystyrene (PS)	0.12 - 0.13	90 - 150
	Polytetrafluoroethylene (Teflon, PTFE)	0.24 - 0.26	130 - 220
	Polyurethane (tpPUR)	0.23 - 0.24	90 - 140
	Polyvinylchloride (tpPVC)	0.15 - 0.29	100 - 150

Thermosets	Epoxies	0.18 - 0.5	58 - 120
	Phenolics	0.14 - 0.15	120
	Polyester	0.29 - 0.3	99 - 180

Foams	Flexible Polymer Foam (LD)	0.040 – 0.059	120 - 220
	Flexible Polymer Foam (MD)	0.041 - 0.078	120 - 220
	Rigid Polymer Foam (HD)	0.034 - 0.063	22 - 70
	Rigid Polymer Foam (LD)	0.023 - 0.040	20 - 80

Composites		**T-conductivity (W/m/K)**	**T-expansion (10^{-6}/C)**
	CFRP, epoxy matrix (isotropic)	1.3 - 2.6	1 - 4
	GFRP, epoxy matrix (isotropic)	0.4 - 0.55	8.6 - 33

Table A7. Electrical resistivity and Dielectric constant

Metals		**Resistivity (μohm.cm)**	**Dielectric constant (-)**
Ferrous metals	Cast iron, ductile (nodular)	49 - 56	
	Cast iron, gray	62 - 86	
	High carbon steel	17 - 20	
	Low alloy steel	15 - 35	
	Low carbon steel	15 - 20	
	Medium carbon steel	15 - 22	
	Stainless steel	64 - 110	

Non-ferrous	Aluminum alloys	3.8 - 6	
	Copper alloys	1.7 - 5	
	Lead alloys	15 - 22	
	Magnesium alloys	5.5 - 15	
	Nickel alloys	8 - 10	
	Silver	1.7 - 1.8	
	Tin	10 - 12	
	Titanium alloys	100 - 170	
	Tungsten alloys	10 - 14	
	Zinc alloys	5.4 - 7.2	

Ceramics		**Resistivity (μohm.cm)**	**Dielectric constant (-)**
Glasses	Borosilicate glass	3.2×10^{21} - 32×10^{21}	4.7 - 6
	Silica glass	100×10^{21} - 1×10^{27}	3.7 - 3.9
	Soda-lime glass	790×10^{15} - 7.9×10^{18}	7 - 7.6

Technical ceramics	Alumina	100×10^{18} - 10×10^{21}	6.5 - 6.8
	Aluminum nitride	10×10^{18} - 1×10^{21}	8.3 - 9.3
	Silicon	1×10^{6} - 1×10^{12}	11 - 12
	Silicon carbide	1×10^{9}- 1×10^{12}	6.3 - 9
	Tungsten carbides	20 – 100	

Non-technical ceramics	Brick	100×10^{12} - 30×10^{15}	7 - 10
	Concrete	1.9×10^{12} - 19×10^{12}	8 - 12
	Stone	10×10^{9} - 100×10^{12}	6 - 9

Natural		**Resistivity (μohm.cm)**	**Dielectric constant (-)**
	Cork	1×10^{9} - 100×10^{9}	6 - 8
	Paper and cardboard	210×10^{12} - 700×10^{12}	2.5 - 6
	Wood, typical across grain	60×10^{12} - 200×10^{12}	5 - 6
	Wood, typical along grain	10×10^{12} - 1×10^{15}	5 - 6

Table A7 (continued). Electrical resistivity and Dielectric constant

Polymers		**Resistivity (μohm.cm)**	**Dielectric constant (-)**
Elastomers	Butyl rubber (IIR)	1 x10^{15} - 10 x10^{15}	2.8 - 3.2
	Ethylene vinyl acetate (EVA)	3.2 x10^{21} - 10 x10^{21}	2.9 - 3
	Natural rubber	1 x10^{15} - 10 x10^{15}	3 - 4.5
	Polychloroprene (Neoprene)	10 x10^{18} - 100 x10^{21}	6.7 - 8
	Polyisoprene rubber	1 x10^{15} - 10 x10^{15}	2.5 - 3
	Polyurethane	1 x10^{18} - 10 x10^{21}	5 - 9
	Silicone elastomers	32 x10^{18} - 10 x10^{21}	2.9 - 4
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	3.3 x10^{21} - 30 x10^{21}	2.8 - 3.2
	Cellulose polymers (CA)	100 x10^{15} - 450 x10^{18}	3 - 5
	Ionomer (I)	3.3 x10^{21} - 30 x10^{21}	2.2 - 2.4
	Polyamides (Nylons, PA)	15 x10^{18} - 140 x10^{18}	3.7 - 3.9
	Polycarbonate (PC)	100 x10^{18}8 - 1 x10^{21}	3.1 - 3.3
	Polyetheretherketone (PEEK)	3.3 x10^{21} - 30 x10^{21}	3.1 - 3.3
	Polyethylene (PE)	33 x10^{21} - 3 x10^{24}	2.2 - 2.4
	Polyethylene terephthalate (PET)	330 x10^{18} - 3 x10^{21}	3.5 - 3.7
	Polymethyl methacrylate (Acrylic, PMMA)	330 x10^{21} - 3e x10^{24}	3.2 - 3.4
	Polyoxymethylene (Acetal, POM)	330 x10^{18} - 3 x10^{21}	3.6 - 4
	Polypropylene (PP)	33 x10^{21} - 300 x10^{21}	2.1 - 2.3
	Polystyrene (PS)	10 x10^{24} - 1 x10^{24}	3 - 3.2
	Polytetrafluoroethylene (Teflon, PTFE)	330 x10^{21} - 3 x10^{24}	2.1 - 2.2
	Polyurethane (tpPUR)	3.3 x10^{18}8 - 30 x10^{18}	6.6 - 7.1
	Polyvinylchloride (tpPVC)	100 x10^{18} - 10 x10^{21}	3.1 - 4.4
Thermosets	Epoxies	100 x10^{18} - 6 x10^{21}	3.4 - 5.7
	Phenolics	3.3 x10^{18} - 30 x10^{18}	4 - 6
	Polyester	3.3 x10^{18} - 30 x10^{18}	2.8 - 3.3
Foams	Flexible Polymer Foam (LD)	100 x10^{18} - 100 x10^{21}	1.1 - 1.2
	Flexible Polymer Foam (MD)	100 x10^{18} - 100 x10^{21}	1.2 - 1.3
	Rigid Polymer Foam (HD)	10 x10^{15} - 100 x10^{18}	1.2 - 1.5
	Rigid Polymer Foam (LD)	100 x10^{15} - 1 x10^{21}	1 - 1.1

Composites		**Resistivity (μohm.cm)**	**Dielectric constant (-)**
	CFRP, epoxy matrix (isotropic)	170x10^{3} - 950x10^{3}	
	GFRP, epoxy matrix (isotropic)	2.4 x10^{21} - 19 x10^{21}	4.9 - 5.2

Table A8. Piezoelectric, pyroelectric and ferroelectric materials

Ferroelectric materials		Dielectric constant (-)	Breakdown potential (MV/m)
	Barium titanate	3,400	4.2
	PLZT	2,500	12
	PZT, hard	1,300	11
	PZT, soft	2,700	11

Piezoelectric materials		Piezo charge coefficient d_{33} (pC/N) or (pm/V)	Piezo voltage coefficient g_{33} (mV.m/N)
	Barium titanate	82 - 190	12 - 17
	Bismuth titanate	12 - 25	10 - 17
	PZT, hard	70 - 350	14 - 54
	PZT, soft	400 - 950	14 - 54
	Lithium niobate	21 - 32	19 - 28
	Lithium tantalate	6 - 8.1	17 - 26
	Quartz, device grade	2 - 2.6	47 - 71

Pyroelectric materials		Pyroelectric coefficient ($\mu C/m^2.K$)	Ferroelectric Curie temperature (C)
	Barium titanate	120 - 140	110 - 400
	Bismuth titanate	650 - 820	87 - 100
	PZT, hard	190 - 370	200 - 460
	PZT, soft	190 - 370	200 - 460
	Lithium niobate	1,100 – 1,200	83 - 95
	Lithium tantalate	600 - 660	210 - 250

Table A9. Magnetic, magnetostrictive and magnetocaloric materials

Hard magnetic materials		**Remanent induction (T)**	**Coercive force (A/m)**	**Max. energy product (MJ/m^3)**
	Alnico	0.52 - 1.4	3,600 – 6,300	9,600 - 60,000
	Ferrites, hard	0.2 - 0.46	13,000 – 35,000	6,400 – 41,000
	Neodymium iron boron	0.98 - 1.5	60,000 – 1,100,000	190,000 – 180,000
	Samarium cobalt	0.78 - 1.2	33,000 – 82,000	110,000 – 250,000

Soft magnetic materials		**Saturation induction (T)**	**Coercive force (A/m)**	**Max permeability (-)**
	Amorphous iron alloys	1.4 - 1.8	1.4 - 5.5	35,000 – 60,000
	Ferrites, soft	0.22 - 0.45	2.4 - 32	850 – 15,000
	Nickel-iron (45%)	1.5 - 1.6	2.4 - 8	60,000 - 180,000
	Nickel-iron (75%)	0.77 - 1.1	0.3 - 4	150,000 - 1,000,000
	Silicon iron	2 - 2.1	24 - 44	7,700 - 19,000

Magnetostrictive materials		**Saturation magnetostriction (μstrain)**	**Coercive force (A/m)**	**Curie temperature (C)**
	Galfenol	200 - 300	720 - 880	620
	Terfenol-D	1,400 - 2,000	5,400 - 6,400	680

Magnetocaloric materials		**Adiabatic temp change (0-2T) (^oC)**	**Entropy change (0-2T) (J/kg.C)**	**Operating temperature (C)**
	Iron-rhenium	7.6 - 9.2	12 - 15	30 - 60
	Gadolinium	5.7 - 5.8	4.5 -5.5	0 - 40
	Manganese arsenide	4.1 - 4.7	24 -32	-50 - 50

Table A10. Embodied energy, Carbon footprint and Water demand

Metals		**Energy (MJ/kg)**	**Carbon (kg/kg)**	**Water (L/kg)**
Ferrous metals	Cast iron, ductile (nodular)	18 - 22	1.7 - 1.8	43 - 47
	Cast iron, gray	17 - 21	1.7 - 1.8	42 - 46
	High carbon steel	25 - 28	1.7 - 1.9	44 - 48
	Low alloy steel	29 - 32	1.9 - 2.1	48 - 53
	Low carbon steel	25 - 28	1.7 - 1.9	43 - 48
	Medium carbon steel	25 - 28	1.7 - 1.9	44 - 48
	Stainless steel	80 - 89	4.7 - 5.2	130 - 140

Non-ferrous	Aluminum alloys	200 - 220	12 - 13	1,100 – 1,300
	Copper alloys	57 - 63	3.5 - 3.9	290 - 320
	Lead alloys	66 - 73	4.2 - 4.6	2,400 – 2,700
	Magnesium alloys	290 - 320	34 - 37	930 – 1,000
	Nickel alloys	160 - 180	11 - 12	220 - 250
	Silver	1,400 - 1,600	95 - 110	1,200 – 3,500
	Tin	220 - 240	13 - 14	10,000 - 12,000
	Titanium alloys	650 - 720	44 - 49	190 - 210
	Tungsten alloys	510 - 560	33 - 36	150 - 160
	Zinc alloys	57 - 63	3.9 - 4.3	400 - 440

Ceramics		**Energy (MJ/kg)**	**Carbon (kg/kg)**	**Water (L/kg)**
Glasses	Borosilicate glass	27 - 30	1.7 - 1.8	14 - 16
	Silica glass	37 - 41	2.2 - 2.4	1.3 - 1.5
	Soda-lime glass	10 - 11	0.72 - 0.8	14 - 15

Technical ceramics	Alumina	50 - 55	2.7 - 3	54 - 60
	Aluminum nitride	220 - 240	12 - 13	230 - 260
	Silicon	57 - 63	3.8 - 4.2	23 - 26
	Silicon carbide	70 - 78	6.2 - 6.9	34 - 100
	Tungsten carbides	82 - 91	4.4 - 4.9	48 - 140

Non-technical ceramics	Brick	2.2 - 5	0.21 - 0.23	23 - 26
	Concrete	1 - 1.3	0.09 - 0.1	34 - 100
	Stone	0.4 - 0.6	0.027 - 0.03	41 - 120

Natural		**Energy (MJ/kg)**	**Carbon (kg/kg)**	**Water (L/kg)**
	Paper and cardboard	49 - 54	1.1 - 1.2	1,600 – 1,800
	Wood, typical across grain	9.8 - 11	0.84 - 0.93	670 - 740
	Wood, typical along grain	9.8 - 11	0.84 - 0.93	670 - 740

Table A10 (continued). Embodied energy, Carbon footprint and Water demand

Polymers		**Energy (MJ/kg)**	**Carbon (kg/kg)**	**Water (L/kg)**
Elastomers	Butyl rubber (IIR)	110 - 120	6.3 - 7	64 - 190
	Ethylene vinyl acetate (EVA)	75 - 83	2 - 2.2	2.7 - 2.9
	Natural rubber	64 - 71	2 - 2.2	15,000 - 20,000
	Polychloroprene (Neoprene)	61 - 68	1.6 - 1.8	130 - 380
	Polyisoprene rubber	99 - 110	5.1 - 5.7	140 - 150
	Polyurethane	83 - 92	3.5 - 3.9	94 - 100
	Silicone elastomers	120 - 130	7.6 - 8.3	190 - 570

Thermoplastics	Acrylonitrile butadiene styrene (ABS)	90 - 100	3.6 - 4	170 - 190
	Cellulose polymers (CA)	85 - 94	3.6 - 4	230 - 250
	Ionomer (I)	100 - 110	4 - 4.4	270 - 300
	Polyamides (Nylons, PA)	120 - 130	7.6 - 8.4	180 - 190
	Polycarbonate (PC)	100 - 110	5.7 - 6.4	170 - 180
	Polyetheretherketone (PEEK)	280 - 310	22 - 24	530 – 1,600
	Polyethylene (PE)	77 - 85	2.6 - 2.9	55 - 61
	Polyethylene terephthalate (PET)	81 - 90	3.8 - 4.2	130 - 140
	Polymethyl methacrylate (PMMA)	110 - 120	6.5 - 7.1	72 - 80
	Polyoxymethylene (Acetal, POM)	85 - 94	3.9 - 4.3	140 - 410
	Polypropylene (PP)	76 - 84	3 - 3.3	37 - 41
	Polystyrene (PS)	92 - 100	3.6 - 4	130 - 150
	Polytetrafluoroethylene (Teflon, PTFE)	110 - 120	5.7 - 6.3	430 - 480
	Polyurethane (tpPUR)	83 - 92	3.5 - 3.9	94 - 100
	Polyvinylchloride (tpPVC)	55 - 61	2.4 - 2.6	200 - 220

Thermosets	Epoxies	130 - 140	6.8 - 7.6	27 - 29
	Phenolics	75 - 83	3.4 - 3.8	49 - 54
	Polyester	68 - 75	2.8 - 3.1	190 - 210

Foams	Flexible Polymer Foam (LD)	100 - 110	4.3 - 4.7	220 - 240
	Flexible Polymer Foam (MD)	100 - 110	3.4 - 3.8	170 - 180
	Rigid Polymer Foam (HD)	97 - 110	3.7 - 4.1	440 - 480
	Rigid Polymer Foam (LD)	97 - 110	3.7 - 4.1	440 - 480

Composites		**Energy (MJ/kg)**	**Carbon (kg/kg)**	**Water (L/kg)**
	CFRP, epoxy matrix (isotropic)	450 - 500	33 - 36	1,300 – 1,500
	GFRP, epoxy matrix (isotropic)	150 - 170	9.5 - 11	150 - 170

A11. Ways of checking and estimating data

The value of a database of material properties depends on its precision and its completeness – in short, on its quality. One way of maintaining or enhancing its quality is to subject its contents to validating procedures. The property range-checks and dimensionless correlations described below provide powerful tools for doing this. The same procedures fill a second function: that of providing estimates for missing data, essential when no direct measurements are available.

Property ranges. Each property of a given class of materials has a characteristic *range*. A convenient way of presenting the information is as a table in which a low (*L*) and a high (*H*) value are stored, identified by the material family and class. An example listing Young's modulus, *E*, is shown in Table A11, in which E_L is the lower limit and E_H the upper one.

All properties have characteristic ranges like these. The range becomes narrower if the classes are made more restrictive. For purposes of checking and estimation, described in a moment, it is helpful to break down the family of *metals* into classes of cast irons, steels, aluminum alloys, magnesium alloys, titanium alloys, copper alloys and so on. Similar subdivisions for polymers (thermoplastics, thermosets, elastomers) and for ceramics and glasses (engineering ceramics, whiteware, silicate glasses, minerals) increases resolution here also.

Table A11: Ranges of Young's modulus *E* for broad material classes

Material Class	E_L (GPa)	E_H (GPa)
All Solids	0.00001	1000
Classes of Solid		
Metals: ferrous	70	220
Metals: non-ferrous	4.6	570
Technical ceramics*	91	1000
Glasses	47	83
Polymers: thermoplastic	0.1	4.1
Polymers: thermosets	2.5	10
Polymers: elastomers	0.0005	0.1
Polymeric foams	0.00001	2
Composites: metal-matrix	81	180
Composites: polymer-matrix	2.5	240
Woods: parallel to grain	1.8	34
Woods: perpendicular to grain	0.1	18

* Technical ceramics are dense, monolithic ceramics such as SiC, Al_2O_3, ZrO_2 etc.

Correlations between material properties. Materials that are stiff have high melting points. Solids with low densities have high specific heats. Metals with high thermal conductivities have high electrical conductivities. These rules-of-thumb describe correlations between two or more material properties that can be expressed more quantitatively as limits for the values of *dimensionless property groups*. They take the form

$$C_L < P_1 P_2^{\,n} < C_H \qquad \text{(A1)}$$

or

$$C_L < P_1 P_2^{\,n} P_3^{\,m} < C_H \qquad \text{(A2)}$$

(or larger groupings) where P_1, P_2, P_3 are material properties, *n* and *m* are powers (usually -1, -1/2, +1/2 or +1), and C_L and C_H are dimensionless constants – the lower and upper limits between which the values of the property-group lies. The correlations exert tight constraints on the data, giving the "patterns" of property envelopes that appear on the material selection charts. An example is the relationship between expansion coefficient, α (units: K^{-1}), and the melting point, T_m (units: K) or, for amorphous materials, the glass temperature T_g:

$$C_L \leq \alpha T_m \leq C_H \quad \text{(A3, a)}$$

$$C_L \leq \alpha T_g \leq C_H \quad \text{(A3, b)}$$

a correlation with the form of equation (A1). Values for the dimensionless limits C_L and C_H for this group are listed in Table A1 for a number of material classes. The values span a factor to 2 to 10 rather than the factor 10 to 100 of the property ranges. There are many such correlations. They form the basis of a hierarchical data-checking and estimating scheme (one used in preparing the charts in this book), described next.

Table A12. Limits for the group αT_m and αT_g for broad material classes*

Correlation* $C_L < \alpha T_m < C_H$	C_L **(x 10^{-3})**	C_H **(x 10^{-3})**
All Solids	0.1	56
Classes of Solid		
Metals: ferrous	13	27
Metals: non-ferrous	2	21
Technical ceramics*	6	24
Glasses	0.3	3
Polymers: thermoplastic	18	35
Polymers: thermosets	11	41
Polymers: elastomers	35	56
Polymeric foams	16	37
Composites: metal-matrix	10	20
Composites: polymer-matrix	0.1	10
Woods: parallel to grain	2	4
Woods: perpendicular to grain	6	17

*For amorphous solids the melting point T_m is replaced by the glass temperature T_g.

Data checking. Data checks proceed in three steps. Each datum is first associated with a material class, or, at a higher level of checking, with a sub-class. This identifies the values of the property range and correlation limits against which it will be checked. The datum is then compared with the range-limits L and H for that class and property. If it lies within the range-limits, it is accepted; if it does not, it is flagged for checking.

Why bother with such low-level stuff? Because it provides a sanity-check. The commonest error in handbooks and other compilations of material or process properties is that of a value that is expressed in the wrong units, or is, for less obvious reasons, in error by one or more orders of magnitude (slipped decimal point, for instance). Range checks catch errors of this sort. If a demonstration of this is needed, it can be found by applying them to the contents of almost any standard reference data-books; none among those we have tried has passed without errors.

In the third step, each of the dimensionless groups of properties like that of Table A12 is formed in turn, and compared with the range bracketed by the limits C_L and C_H. If the value lies within its correlation limits, it is accepted; if not, it is checked. Correlation checks are more discerning than range checks and catch subtler errors, allowing the quality of data to be enhanced further.

Data estimation. The relationships have another, equally useful, function. There remain gaps in our knowledge of material properties. The fracture toughness of many materials has not yet been measured, nor has the electric breakdown potential; even moduli are not always known. The absence of a datum for a material would falsely eliminate it from a screening exercise that used that property, even though the material might be a viable candidate. This difficulty is avoided by using the correlation and range limits to estimate a value for the missing datum, adding a flag to alert the user that it is an estimate.

In estimating property values, the procedure used for checking is reversed: the dimensionless groups are used first because they are the more accurate. They can be surprisingly good. As an example, consider estimating the expansion coefficient, α, of polycarbonate from its glass temperature T_g. Inverting equation (A3b) gives the estimation rule :

$$\frac{C_L}{T_g} \leq \alpha \leq \frac{C_H}{T_g} \qquad \text{(A4)}$$

Inserting values of C_L and C_H from Table A12, and the value T_g = 420 K for a particular sample of polycarbonate gives the mean estimate

$$\overline{\alpha} = 63x10^{-3} K^{-1} \qquad \text{(A5)}$$

The reported value for polycarbonate is

$$\alpha = 54\text{–}62x10^{-3}\, K^{-1}$$

The estimate is within 9% of the mean of the measured values, perfectly adequate for screening purposes. That it is an estimate must not be forgotten, however: if thermal expansion is crucial to the design, better data or direct measurements are essential.

Only when the potential of the correlations is exhausted are the property ranges invoked. They provide a crude first-estimate of the value of the missing property, far less accurate than that of the correlations, but still useful in providing guide-values for screening.

Further reading.

Ashby M.F., (1998) "Checks and estimates for material properties" Cambridge University Engineering Department, Proc Roy Soc A **454,** 1301 – 1321. *(This and the next reference detail the data-checking and estimation methods, listing the correlations.)*

Bassetti, D. Brechet, Y. and Ashby, M.F. (1998) "Estimates for material properties: the method of multiple correlations" Proc Roy Soc A **454,** 13023 – 1336. *(This and the previous reference detail the data-checking and estimation methods, with examples.)*

Conversion of units – stress and pressure

To →	MPa	dyn/cm^2	lb/in^2	kgf/mm^2	bar	long ton/in^2
From ↓	*Multiply by*					
MPa	1	10^7	1.45 x 10^2	0.102	10	6.48 x 10^{-2}
dyn/cm^2	10^{-7}	1	1.45 x 10^{-5}	1.02 x 10^{-8}	10^{-6}	6.48 x 10^{-9}
lb/in^2	6.89 x 10^{-3}	6.89 x 10^4	1	7.03 x 10^{-4}	6.89 x 10^{-2}	4.46 x 10^{-4}
kgf/mm^2	9.81	9.81 x 10^7	1.42 x 10^3	1	98.1	63.5 x 10^{-2}
bar	0.10	10^6	14.48	1.02 x 10^{-2}	1	6.48 x 10^{-3}
long ton/ in^2	15.44	1.54 x 10^8	2.24 x 10^3	1.54	1.54 x 10^2	1

Conversion of units – energy*

To →	MJ	kWhr	kcal	Btu	ft lbf	toe
From ↓	*Multiply by*					
MJ	1	0.278	239	948	0.738 x 10^6	23.8 x 10^{-6}
kWhr	3.6	1	860	3.41 x 10^3	2.66 x 10^6	85.7 x 10^{-6}
kcal	4.18 x 10^{-3}	1.16 x 10^{-3}	1	3.97	3.09 x 10^3	99.5 x 10^{-9}
Btu	1.06 x 10^{-3}	0.293 x 10^{-3}	0.252	1	0.778 x 10^3	25.2 x 10^{-9}
ft lbf	1.36 x 10^{-6}	0.378 x 10^{-6}	0.324 x 10^{-3}	1.29 x 10^{-3}	1	32.4 x 10^{-12}
toe	41.9 x 10^3	11.6 x 10^3	10 x 10^6	39.7 x 10^6	30.8 x 10^9	1

MJ = megajoules; kWhr = kilowatt hour; kcal = kilocalorie; Btu = British thermal unit; ft lbf = foot-pound force; toe = tonnes oil equivalent.

Conversion of units – power*

To →	kW (kJ/s)	kcal/s	hp	ft lbf/s	Btu/h
From ↓	*Multiply by*				
kW (kJ/s)	1	4.18	1.34	735	4.47 x 10^4
kcal/s	0.239	1	0.321	176	1.07 x 10^4
hp	0.746	3.12	1	550	3.35 x 10^4
ft lbf/s	1.36 x 10^{-3}	5.68 x 10^{-3}	1.82 x 10^{-3}	1	
Btu/h	2.24 x 10^{-5}	9.33 x 10^{-5}	3.0 x 10^{-5}		1

kW = kilowatt; kcal/s = kilocalories per second; hp = horse power; ft lb/s = foot-pounds/second; Btu/h = British thermal units/hour

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