APPENDIX A

PHYSICAL CONSTANTS

Avogadro's number = Av = 6.022×10^{26} molecules (or atoms)/(kg · mol)
= 2.732×10^{26} molecules (or atoms)/(lbm · mol)
Boltzmann's constant = $k = 1.381 \times 10^{-23}$ J/K
= 8.618×10^{-11} MeV/K
= 4.788×10^{-11} MeV/°R
Electron charge = $e = 1.602 \times 10^{-19}$ C
= 1.602×10^{-19} J/V
Faraday's constant = $F_y = 9.649 \times 10^{7}$ C/(kg · mol of electron)
Mass-energy conversion: 1 atomic mass unit (amu) = 1.661×10^{-27} kg
= 1.492×10^{-10} J
= 931.5 MeV

Mass of the earth = $m_E = 5.979 \times 10^{24}$ kg
= 1.318×10^{25} lbm
Newton's gravitational constant = $G = 6.672 \times 10^{-11}$ N · m^2/kg^2
Permittivity of free space = $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m
Planck's constant = $h = 6.626 \times 10^{-34}$ J · s
= 4.136×10^{-21} MeV · s
Radius (average) of the earth = $r_E = 6.371 \times 10^{6}$ m
= 2.090×10^{7} ft
= 3959 mi
Rest masses: Electron: $m_e = 0.0005486$ amu = 9.110×10^{-31} kg
Neutron: $m_n = 1.0086654$ amu = 1.675×10^{-27} kg
Proton: $m_p = 1.0072766$ amu = 1.673×10^{-27} kg

Solar constant (average) $= 1.353 \text{ kW/m}^2$
$= 4871 \text{ kJ/(h} \cdot \text{m}^2)$
$= 428.9 \text{ Btu/(h} \cdot \text{ft}^2)$

Standard atmospheric pressure $= 1.013 \times 10^5 \text{ Pa} = 0.1013 \text{ MPa}$
$= 14.696 \text{ lbf/in}^2$

Standard gravitational constant $= g = \dfrac{Gm_E}{r_E^2} = 9.807 \text{ m/s}^2$
$= 32.17 \text{ ft/s}^2$

Stefan-Boltzmann constant $= \sigma = 5.670 \times 10^{-8} \text{ W/(m}^2 \cdot \text{K}^4)$
$= 0.1714 \times 10^{-8} \text{ Btu/(h} \cdot \text{ft}^2 \cdot {}^\circ\text{R}^4)$

Universal (molar) gas constant $= R_u = 8.314 \text{ kJ/(kg} \cdot \text{mol} \cdot \text{K)}$
$= 1.986 \text{ Btu/(lbm} \cdot \text{mol} \cdot {}^\circ\text{R)}$
$= 1545 \text{ ft} \cdot \text{lbf/(lbm} \cdot \text{mol} \cdot {}^\circ\text{R)}$

Velocity of light $= c = 2.998 \times 10^8 \text{ m/s}$
$= 9.836 \times 10^8 \text{ ft/s}$
$= 186{,}300 \text{ mi/s}$

APPENDIX B

CONVERSION FACTORS AND STANDARDS

FUNDAMENTAL UNITS

Length

$$
\begin{aligned}
1 \text{ meter} = 1 \text{ m} &= 10^{10} \text{ ångströms} = 10^{10} \text{ Å} \\
&= 10^{6} \text{ micrometers} = 10^{6} \ \mu\text{m} \\
&= 1000 \text{ millimeters} = 1000 \text{ mm} \\
&= 100 \text{ centimeters} = 100 \text{ cm} \\
&= 39.37 \text{ inches} = 39.37 \text{ in} \\
&= 3.281 \text{ feet} = 3.281 \text{ ft}
\end{aligned}
$$

Mass

$$
\begin{aligned}
1 \text{ kilogram} = 1 \text{ kg} &= 1000 \text{ grams} = 1000 \text{ g} \\
&= 0.001 \text{ metric ton} = 0.001 \text{ tonne} \\
&= 2.205 \text{ pounds mass} = 2.205 \text{ lbm} \\
&= 0.001102 \text{ short ton} = 0.001102 \text{ ton} \\
&= 6.022 \times 10^{26} \text{ atomic mass units (amu)}
\end{aligned}
$$

Temperature

Normal scales: Degrees Celsius = $°C = (°F - 32)/1.8$
Degrees Fahrenheit = $°F = 1.8°C + 32$

Absolute scales: Degrees Kelvin = °C + 273.16 = 1.8°R
Degrees Rankine = °F + 459.67 = K/1.8

Temperature difference = ΔT:

$$\begin{aligned}1 \text{ Celsius degree} &= 1\ \text{C}^\circ \\ &= 1 \text{ Kelvin degree} = 1\ \text{K} \\ &= 1.8 \text{ Rankine degrees} = 1.8\ \text{R}^\circ \\ &= 1.8 \text{ Fahrenheit degrees} = 1.8\ \text{F}^\circ\end{aligned}$$

Time

$$\begin{aligned}1 \text{ second} = 1\ \text{s} &= (1/3600) \text{ hour} = 2.778 \times 10^{-4}\ \text{h} \\ &= (1/86{,}400) \text{ day} = 1.157 \times 10^{-5} \text{ day} \\ &= (1/31{,}536{,}000) \text{ year} = 3.171 \times 10^{-8} \text{ year}\end{aligned}$$

SECONDARY UNITS

Area

$$\begin{aligned}1 \text{ square meter} = 1\ \text{m}^2 &= 10^{28} \text{ barns} = 10^{28}\ \text{b} \\ &= 10^4 \text{ square centimeters} = 10^4\ \text{cm}^2 \\ &= 1550 \text{ square inches} = 1550\ \text{in}^2 \\ &= 10.76 \text{ square feet} = 10.76\ \text{ft}^2 \\ &= 2.471 \times 10^{-4} \text{ acres} \\ &= 3.861 \times 10^{-7} \text{ square miles } (\text{mi}^2)\end{aligned}$$

Density

$$\begin{aligned}1 \text{ kilogram/cubic meter} = 1\ \text{kg/m}^3 &= 10^{-3}\ \text{g/cm}^3 \\ &= 0.008345 \text{ lbm/U.S. gallon (gal)} \\ &= 0.06243\ \text{lbm/ft}^3\end{aligned}$$

Electrical and Magnetic Units

$$\begin{aligned}1 \text{ ampere} &= \text{A} = 1 \text{ watt/volt} = 1\ \text{W/V} \\ &= 1 \text{ coulomb/second} = 1\ \text{C/s} \\ 1 \text{ volt} &= \text{V} = 1 \text{ watt/ampere} = 1 \text{ joule/coulomb} = 1 \text{ ampere} \cdot \text{ohm} \\ &= 1\ \text{A} \cdot \Omega \\ 1 \text{ ohm} &= \Omega = 1 \text{ volt/ampere} \\ 1 \text{ farad} &= \text{F} = 1 \text{ coulomb/volt} = 1 \text{ ampere} \cdot \text{second/volt} = 1\ \text{A} \cdot \text{s/V} \\ 1 \text{ henry} &= \text{H} = 1 \text{ volt} \cdot \text{second/ampere} = 1\ \text{V} \cdot \text{s/A} \\ 1 \text{ weber} &= 1 \text{ volt} \cdot \text{second} = 1\ \text{V} \cdot \text{s} \\ 1 \text{ weber/m}^2 &= 1 \text{ tesla} = 1 \text{ newton/ampere} \cdot \text{meter} = 10^4 \text{ gauss} = 1\text{N/A} \cdot \text{m}\end{aligned}$$

Energy

$$
\begin{aligned}
1 \text{ joule} = 1\text{ J} = 1\text{ W}\cdot\text{s} = 1\text{ N}\cdot\text{m} = 1\text{ kg}\cdot\text{m}^2/\text{s}^2 \\
&= 6.242\times10^{18} \text{ electron volts (eV)} \\
&= 6.242\times10^{12} \text{ million eV (MeV)} \\
&= 10^{7} \text{ ergs} \\
&= 200 \text{ fissions/s} \\
&= 0.2388 \text{ calorie (cal)} \\
&= 9.478\times10^{-4} \text{ British thermal unit (Btu)} \\
&= 3.725\times10^{-7} \text{ horsepower-hour (hph)} \\
&= 2.778\times10^{-7} \text{ kilowatt-hour (kWh)} \\
&= 2.381\times10^{-10} \text{ ton of TNT}
\end{aligned}
$$

Force

$$
\begin{aligned}
1 \text{ newton} = 1\text{ N} &= 1\text{ kg}\cdot\text{m/s}^2 \\
&= 7.233 \text{ lbm}\cdot\text{ft/s}^2 \\
&= 0.2248 \text{ lbf}
\end{aligned}
$$

Gravimetric (Mass) Heating Value

$$
\begin{aligned}
1 \text{ joule/gram} = 1\text{ J/g} = 1\text{ kJ/kg} &= 1000\text{ m}^2/\text{s}^2 \\
&= 0.430 \text{ Btu/lbm}
\end{aligned}
$$

Heat Flux

$$
\begin{aligned}
1\text{ W/m}^2 &= 1\text{ J/(s}\cdot\text{m}^2) = 1\text{ N/(s}\cdot\text{m}) = 1\text{ kg/s}^3 \\
&= 0.3170\text{ Btu/(h}\cdot\text{ft}^2)
\end{aligned}
$$

Power

$$
\begin{aligned}
1\text{ watt} = 1\text{ W} &= 1\text{ J/s} = 1\text{ N}\cdot\text{m/s} = 1\text{ kg}\cdot\text{m}^2/\text{s}^3 \\
&= 0.001\text{ kW} \\
&= 3.412\text{ Btu/h} \\
&= 0.001341\text{ hp} \\
&= 6.242\times10^{12}\text{ MeV/s}
\end{aligned}
$$

Power Density and Volumetric Heat Generation Rate

$$
\begin{aligned}
1\text{ watt/cubic meter} = 1\text{ W/m}^3 = 1\text{ J/(s}\cdot\text{m}^3) &= 1\text{ kg/(m}\cdot\text{s}^3) \\
&= 0.0966\text{ Btu/(h}\cdot\text{ft}^3)
\end{aligned}
$$

Pressure

$$1 \text{ pascal} = 1 \text{ Pa} = 1 \text{ N/m}^2 = 1 \text{ kg/(m} \cdot \text{s}^2)$$
$$= 9.869 \times 10^{-6} \text{ atmosphere (atm)}$$
$$= 10^{-5} \text{ bar}$$
$$= 1.45 \times 10^{-4} \text{ pound force/square inch (psi)}$$
$$= 2.953 \times 10^{-4} \text{ inch Hg (inHg)}$$
$$= 0.004018 \text{ inch } H_2O \text{ (inH}_2\text{O)}$$
$$= 0.007502 \text{ torr} = 0.007502 \text{ mmHg}$$

Absolute pressure = gage pressure + atmospheric pressure
= atmospheric pressure − vacuum pressure

Specific Heat (c)

$$1 \text{ joule/kilogram} \cdot \text{C}° = 1 \text{ J/(kg} \cdot \text{C}°)$$
$$= 1 \text{ m}^2/(\text{s}^2 \cdot \text{C}°)$$
$$= 0.2388 \text{ cal/(kg} \cdot \text{C}°)$$
$$= 2.388 \times 10^{-4} \text{ Btu/(lbm} \cdot \text{F}°)$$

Specific Power

$$1 \text{ kilowatt/kilogram} = 1 \text{ kW/kg} = 1000 \text{ m}^2/\text{s}^3$$
$$= 1548 \text{ Btu/h} \cdot \text{lbm}$$
$$= 0.6081 \text{ hp/lbm}$$

Surface Conductance (h)

$$1 \text{ W/(m}^2 \cdot \text{C}°) = 1 \text{ J/(s} \cdot \text{m}^2 \cdot \text{C}°)$$
$$= 1 \text{ kg/(s}^3 \cdot \text{C}°)$$
$$= 0.1761 \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{F}°)$$

Thermal Conductivity (k)

$$1 \text{ watt/meter} \cdot \text{Celsius degree} = 1 \text{ W/m} \cdot \text{C}° = 1 \text{ J/(s} \cdot \text{m} \cdot \text{C}°)$$
$$= 1 \text{ N/(s} \cdot \text{C}°) = 1 \text{ kg} \cdot \text{m/(s}^3 \cdot \text{C}°)$$
$$= 0.2388 \text{ cal/(s} \cdot \text{m} \cdot \text{C}°)$$
$$= 0.5778 \text{ Btu/(h} \cdot \text{ft}^2 \cdot \text{F}°/\text{ft})$$

Velocity

$$1 \text{ meter/second} = 1 \text{ m/s}$$
$$= 3.281 \text{ ft/s}$$

Viscosity

$$\begin{aligned} 1 \text{ poise} = 1 \text{ P} = 100 \text{ centipoise} &= 100 \text{ cP} \\ &= 0.1 \text{ kg/(s} \cdot \text{m)} \\ &= 241.9 \text{ lbm/(ft} \cdot \text{h)} \\ &= 0.002089 \text{ lbf} \cdot \text{s/ft}^2 \end{aligned}$$

Volume

$$\begin{aligned} 1 \text{ cubic meter} = 1 \text{ m}^3 &= 10^6 \text{ cm}^3 \\ &= 10^3 \text{ liters (L)} \\ &= 264.2 \text{ U.S. gal} \\ &= 35.31 \text{ ft}^3 \\ &= 1.308 \text{ cubic yards} \end{aligned}$$

STANDARD U.S. FUEL ENERGY VALUES

Coal

Anthracite:

$$\begin{aligned} \text{HHV} &= 12{,}700 \text{ Btu/lbm} = 29{,}540 \text{ kJ/kg} \\ &= 25.4 \times 10^6 \text{ Btu/short ton} \end{aligned}$$

Bituminous:

$$\begin{aligned} \text{HHV} &= 11{,}750 \text{ Btu/lbm} = 27{,}330 \text{ kJ/kg} \\ &= 23.5 \times 10^6 \text{ Btu/short ton} \end{aligned}$$

Lignite:

$$\begin{aligned} \text{HHV} &= 11{,}400 \text{ Btu/lbm} = 26{,}515 \text{ kJ/kg} \\ &= 22.8 \times 10^6 \text{ Btu/short ton} \end{aligned}$$

Crude Oil

$$\begin{aligned} \text{HHV} &= 18{,}100 \text{ Btu/lbm} = 42{,}100 \text{ kJ/kg} \\ &= 138{,}100 \text{ Btu/U.S. gal} \\ &= 5{,}800{,}000 \text{ Btu/barrel (bbl)} \end{aligned}$$

Natural Gas (Dry)

$$\begin{aligned} \text{HHV} &= 24{,}700 \text{ Btu/lbm} = 57{,}450 \text{ kJ/kg} \\ &= 1021 \text{ Btu/standard cubic foot (scf)} \end{aligned}$$

FUEL-ENERGY EQUIVALENTS

One barrel (42 U.S. gal) of oil = 460 lbm of coal
= 5680 scf of natural gas
= 612 kWh of electricity (assumes a conversion efficiency of 36 percent)

One short ton of coal = 4345 bbl of crude oil
= 24,682 scf of natural gas
= 2660 kWh of electricity (assumes a conversion efficiency of 36 percent)

1000 scf of natural gas = 0.176 bbl of crude oil
= 81.0 lbm of coal
= 189 kWh of electricity (assumes a conversion efficiency of 36 percent)

DECIMAL MULTIPLES AND SUBMULTIPLES

Number	Power of 10	Prefix	Symbol
0.000 000 000 000 000 001	10^{-18}	atto	a
0.000 000 000 000 001	10^{-15}	femto	f
0.000 000 000 001	10^{-12}	pico	p
0.000 000 001	10^{-9}	nano	n
0.000 001	10^{-6}	micro	μ
0.001	10^{-3}	milli	m
1	10^{0}	—	—
1,000	10^{3}	kilo	k
1,000,000	10^{6}	mega	M
1,000,000,000	10^{9}	giga	G
1,000,000,000,000	10^{12}	tera	T
1,000,000,000,000,000	10^{15}	peta	P
1,000,000,000,000,000,000	10^{18}	exa	E

APPENDIX C

ULTIMATE ANALYSIS OF BIOMASS FUELS

Material	C,†%	H_2,†%	O_2,†%	N_2,†%	S,†%	A,†%	HHV, kJ/kg‡
Agricultural wastes							
Bagasse (sugar cane refuse)	47.3	6.1	35.3	0.0	0.0	11.3	21,255
Feedlot manure	42.7	5.5	31.3	2.4	0.3	17.8	17,160
Rice hulls	38.5	5.7	39.8	0.5	0.0	15.5	15,370
Rice straw	39.2	5.1	35.8	0.6	0.1	19.2	15,210
Municipal solid waste							
General	33.9	4.6	22.4	0.7	0.4	38.0	13,130
Brown paper	44.9	6.1	47.8	0.0	0.1	1.1	17,920
Cardboard	45.5	6.1	44.5	0.2	0.1	3.6	18,235
Corrugated boxes	43.8	5.7	45.1	0.1	0.2	5.1	16,430
Food fats	76.7	12.1	11.2	0.0	0.0	0.0	38,835
Garbage	45.0	6.4	28.8	3.3	0.5	16.0	19,730
Glass bottles (labels)	0.5	0.1	0.4	0.0	0.0	99.0	195
Magazine paper	33.2	5.0	38.9	0.1	0.1	22.7	12,650

Material	C,†%	H_2,†%	O_2,†%	N_2,†%	S,†%	A,†%	HHV, kJ/kg‡
Municipal solid waste							
Metal cans (labels, etc.)	4.5	0.6	4.3	0.1	0.0	90.5	1,725
Newspapers	49.1	6.1	43.0	0.1	0.2	1.5	19,720
Oils, paints	66.9	9.6	5.2	2.0	0.0	16.3	31,165
Paper food cartons	44.7	6.1	41.9	0.2	0.2	6.9	17,975
Plastics							
General	60.0	7.2	22.6	0.0	0.0	10.2	33,415
Polyethylene	85.6	14.4	0.0	0.0	0.0	0.0	46,395
Vinyl chloride	47.1	5.9	18.6	(chlorine = 28.4%)			20,535
Rags	55.0	6.6	31.2	4.6	0.1	2.5	13,955
Rubber	77.7	10.3	0.0	0.0	2.0	10.0	26,350
Sewage							
Raw sewage	45.5	6.8	25.8	3.3	2.5	16.1	16,465
Sewage sludge	14.2	2.1	10.5	1.1	0.7	71.4	4,745
Wood and wood products							
Hardwoods							
Beech	51.6	6.3	41.5	0.0	0.0	0.6	20,370
Hickory	49.7	6.5	43.1	0.0	0.0	0.7	20,165
Maple	50.6	6.0	41.7	0.3	0.0	1.4	19,955
Poplar	51.6	6.3	41.5	0.0	0.0	0.6	20,745
Oak	49.5	6.6	43.4	0.3	0.0	0.2	20,185
Softwoods							
Douglas fir	52.3	6.3	40.5	0.1	0.0	0.8	21,045
Pine	52.6	6.1	40.9	0.2	0.0	0.2	21,280
Redwood	53.5	5.9	40.3	0.1	0.0	0.2	21,025
Western hemlock	50.4	5.8	41.4	0.1	0.1	2.2	20,045
Wood products							
Charcoal (made at 400°C)	76.5	3.9	15.4	0.8	0.0	3.4	28,560
Charcoal (made at 500°C)	81.7	3.2	11.5	0.2	0.0	3.4	31,630
Douglas fir bark	56.2	5.9	36.7	0.0	0.0	1.2	22,095
Pine bark	52.3	5.8	38.8	0.2	0.0	2.9	20,420
Dry sawdust pellets	47.2	5.5	46.3	0.0	0.0	1.0	20,500
Ripe leaves	40.5	6.0	45.1	0.2	0.1	8.1	16,400
Plant wastes							
Brush	42.5	5.9	41.2	2.0	0.1	8.3	18,370
Evergreen trimmings	49.5	6.6	41.2	1.7	0.2	0.8	6,425
Garden plants	48.0	6.8	41.3	1.2	0.3	2.4	8,835
Grass	48.4	6.8	41.6	1.2	0.3	1.7	18,520

† All percentages on moisture-free basis.
‡ 1 kJ/kg = 0.43 Btu/lbm.

MUNICIPAL SOLID WASTE

Municipal solid waste is commonly divided into seven different classes:

TYPE 0 WASTE. Trash is a mixture of highly combustible waste such as paper, cardboard, cartons, wood boxes, and combustible floor sweepings, from commercial and industrial activities. The mixtures contain up to 10 percent by weight of catalogs, magazines, or packaged paper, treated corrugated cardboard, oily rags, and plastic or rubber scraps. This type of waste contains 10 percent moisture and 5 percent incombustible solids, and has a heating value of 8500 Btu/lb, (19,770 kJ/kg) as fired.

TYPE 1 WASTE. Rubbish is a mixture of combustible waste such as paper, cardboard cartons, wood scrap, foliage, and combustible floor sweepings, from domestic, commercial, and industrial activities. This mixture contains up to 20 percent by weight of restaurant or cafeteria waste, but contains little or no treated papers, plastic, or rubber wastes. This type of waste contains 25 percent moisture and 10 percent incombustible solids, and has a heating value of 6500 Btu/lb (15,120 kJ/kg), as fired.

TYPE 2 WASTE. Refuse consists of an approximately even mixture of rubbish and garbage by weight. This type of waste is common to apartment and residential occupancy, consisting of up to 50 percent moisture and 7 percent incombustible solids, and has a heating value of 4300 Btu/lb (10,000 kJ/kg), as fired.

TYPE 3 WASTE. Garbage consists of animal and vegetable wastes from restaurants, cafeterias, hotels, hospitals, markets, and like installations. This type of waste contains up to 70 percent moisture and up to 5 percent incombustible solids, and has a heating value of 2500 Btu/lb (5815 kJ/kg), as fired.

TYPE 4 WASTE. Human and animal remains consisting of carcasses, organs, and solid organic wastes from hospitals, laboratories, slaughterhouses, animal pounds, and similar sources. This type of waste contains up to 85 percent moisture and 5 percent incombustible solids, and has a heating value of 1000 Btu/lb (2326 kJ/kg), as fired.

TYPE 5 WASTE. Byproduct wastes, gaseous, liquid, or semiliquid, are composed of tar, paints solvents, sludge, fumes, etc., from industrial operations. The energy content must be determined by the individual materials to be destroyed.

TYPE 6 WASTE. Solid byproduct waste is composed of rubber, plastics, wood waste, etc., from industrial operations. The energy content must be determined by the individual materials to be destroyed.

APPENDIX D

ASTM COAL CLASSIFICATION SYSTEM (SUMMARY OF ASTM D 388)

DEFINITIONS

Percent, dry, mineral-matter-free fixed carbon = % dry, mm-free FC:

$$\%\text{ dry, mm-free FC} = \frac{(\text{FC} - 0.15\text{S})(100)}{1 - \text{M} - 1.08\text{A} - 0.55\text{S}} = \text{D, mm} - \text{f FC}$$

Moist, mineral-matter-free Btu content of coal, Btu/lbm = moist, mm-free Btu:

$$\text{Moist, mm-free Btu} = \frac{\text{Btu} - 0.55\text{S}}{1 - 1.08\text{A} - 0.55\text{S}} = \text{M, mm} - \text{f Btu}$$

COAL CLASSIFICATIONS

Class Group	Ranking parameter	Agglomerating character
Class I: Anthracitic coals		
Group 1. Metaanthracite	Dry, mm-free FC > 98%	Nonagg.
Group 2. Anthracite	98% > D, mm-f FC > 92%	Nonagg.
Group 3. Semianthracite	92% > D, mm-f FC > 86%	Nonagg.
Class II: Bituminous coals		
Group 1. Low-volatile bituminous	86% > D, mm-f FC > 78%	Usually agg.
Group 2. Medium-volatile bituminous	78% > D, mm-f FC > 69%	Usually agg.
If dry, mm-free FC is less than 69%, rank coal according to the moist, mm-free Btu value		
Group 3. High-volatile A bituminous	M, mm-f Btu > 14,000	Usually agg.
Group 4. High-volatile B bituminous	13,000 < M, mm-f Btu < 14,000	Usually agg.
Group 5. High-volatile C bituminous	11,500 < M, mm-f Btu < 13,000	Usually agg.
	10,500 < M, mm-f Btu < 11,500	Agg.
Class III: Subbituminous coals		
Group 1. Subbituminous A	10,500 < M, mm-f Btu < 11,500	Nonagg.
Group 2. Subbituminous B	9,500 < M, mm-f Btu < 10,500	Nonagg.
Group 3. Subbituminous C	8,300 < M, mm-f Btu < 9,500	Nonagg.
Class IV: Lignitic coals		
Group 1. Lignite A	6300 < M, mm-f Btu < 8300	Nonagg.
Group 2. Lignite B	M, mm-f Btu < 6300 Btu/lbm	Nonagg.

Notes:

An agglomerating coal is one that has a caking characteristic which, during the volatile-matter determination, produces a coke residue in the form of an agglomerating button.

This classification system does not include a few coals, all of which contain less than 48% mm-free FC or have more than 15,500 Btu/lbm for moist, mm-free coal.

"Moist" refers to coal containing its inherent moisture, not liquid moisture on the coal surface.

If a Class I, Group 3 coal is agglomerating, classify it as a Class II, Group 1 coal.

APPENDIX E

TYPICAL COAL ANALYSES

States and counties	Moisture and ash-free values								As received	
	VM	FC	C	H_2	O_2	N_2	S	kJ/kg†	*M*	*A*
ALABAMA										
Jefferson, Tuscaloosa	27.7	72.3	88.1	5.2	4.2	1.7	0.8	36,340	2-5	3-10
Jefferson, Tuscaloosa	32.9	67.1	86.7	5.3	5.0	1.8	1.2	35,875	2-5	2-10
Jefferson, St. Clair	35.4	64.6	85.2	5.4	5.8	1.8	1.8	35,470	2-5	4-12
Walker, Bibb, Shelby	38.0	62.0	84.3	5.4	7.6	1.7	1.0	35,120	1-5	2-14
ARKANSAS										
Sebastian, Logan	19.0	81.0	89.3	4.4	2.0	1.8	2.5	36,040	2-4	6-12
Franklin, Johnson	16.1	83.9	89.4	4.2	2.1	1.8	2.5	35,935	2-4	6-12
COLORADO										
Las Animas	36.5	63.5	84.9	5.5	7.4	1.5	0.7	35,525	1-7	6-20
Huerfano, Gunnison, Garfield	40.7	59.3	80.6	5.5	11.6	1.6	0.7	35,575	3-10	3-12
Weld, Boulder	42.5	57.5	75.0	5.1	17.9	1.5	0.5	30,085	17-30	3-6
Routt, Fremont	43.0	57.0	76.6	5.2	16.0	1.3	0.9	31,515	10-18	3-10
El Paso	46.4	53.6	71.5	5.0	21.8	1.1	0.6	28,095	20-35	5-14
ILLINOIS										
Franklin, Williamson	39.1	60.9	81.3	5.3	9.8	1.7	1.9	33,725	8-12	8-12
Saline, Perry	39.6	60.4	80.6	5.4	10.3	1.7	2.0	33,770	6-11	7-12
Macoupin, Sangamon	46.3	53.7	77.5	5.4	10.2	1.4	5.5	32,970	12-16	8-16
Madison, St. Clair	46.7	53.3	77.0	5.4	10.6	1.3	5.7	32,865	9-16	11-20
INDIANA										
Sullivan, Greene	45.2	54.8	80.9	5.6	9.7	1.8	2.0	33,725	10-14	6-12
Vigo, Vermillion, Knox	48.0	52.0	79.6	5.6	8.8	1.5	4.5	33,750	6-12	7-12

States and counties	Moisture and ash-free values								As received	
	VM	FC	C	H_2	O_2	N_2	S	kJ/kg†	*M*	*A*
IOWA										
Appanoose, Polk, Lucas	47.9	52.1	77.0	5.5	9.7	1.5	6.3	33,155	13–19	7–15
KANSAS										
Cherokee, Crawford	39.5	60.5	83.0	5.4	6.1	1.5	4.0	34,955	2–8	9–12
Leavenworth	47.2	52.8	79.6	5.4	7.8	1.5	5.7	33,560	10–12	12–16
KENTUCKY										
Letcher, Pike	37.8	62.2	85.2	5.4	7.0	1.6	0.8	35,320	1–4	2–7
Harlan, Perry, Bell, Knox	40.2	59.8	83.5	5.6	7.9	1.9	1.1	34,785	2–6	2–8
Muhlenburg, Hopkins	44.7	55.3	80.3	5.4	8.6	1.7	4.0	33,595	4–10	5–12
Webster, Union, Butler	45.0	55.0	81.0	5.5	7.7	1.7	4.1	33,945	4–10	5–12
MARYLAND										
Alegheny, Garrett	18.2	81.8	89.3	4.7	2.7	1.7	1.6	33,400	2–4	6–14
MISSOURI										
Barton	38.0	62.0	83.0	5.5	5.1	1.4	5.0	35,165	5–7	8–13
Bates	42.3	57.7	81.0	5.5	7.5	1.5	4.5	34,190	7–12	11–15
Ray, Lafayette, Linn, Adair	46.3	53.7	78.6	5.6	9.3	1.3	5.2	33,315	11–16	7–15
Henry, Macon, Clay, Randolph	45.4	54.6	79.2	5.5	8.4	1.3	5.6	33,420	9–16	8–16
MONTANA										
Rosebud, Custer	44.4	55.6	71.7	4.4	22.0	1.1	0.8	27,980	27–30	3–15
Musselshell, Gallatin	42.8	57.2	78.5	5.4	13.6	1.4	1.1	32,365	4–14	6–30
Carbon, Fergus	40.6	59.4	76.0	5.1	14.2	1.4	3.3	31,025	8–24	8–18
Cascade	35.0	65.0	77.8	4.8	12.6	1.0	3.8	31,445	3–12	14–25
Valley	47.4	52.6	69.0	4.6	24.1	1.2	1.1	26,490	32–45	4–9
NEW MEXICO										
Colfax, Lincoln	43.1	56.9	82.6	5.7	9.3	1.5	0.9	34,560	2–5	9–17
McKinley	47.2	52.8	79.2	5.5	13.0	1.4	0.9	32,420	10–16	3–10
NORTH DAKOTA										
McLean, Morton, Stark	54.0	46.0	72.4	4.7	18.6	1.5	2.8	28,920	35–43	5–12
Williams, Ward	47.6	52.4	72.1	4.9	21.0	1.1	0.9	27,910	35–43	5–12
OHIO										
Belmont, Guernsey	46.0	54.0	80.3	5.6	8.0	1.5	4.6	34,120	3–6	9–16
Tuscarawas, Noble, Jackson	46.2	53.8	79.2	5.6	9.2	1.5	4.5	33,680	3–9	7–15
Athens, Perry, Meigs, Hocking	41.8	58.2	79.7	5.5	10.8	1.4	2.6	33,455	6–10	4–12
Jefferson, Guernsey	41.5	58.5	82.2	5.5	7.7	1.7	2.9	34,560	3–7	5–12
OKLAHOMA										
Pittsburgh, Latimer	40.0	60.0	84.0	5.5	7.4	2.0	1.1	34,990	2–10	4–8
Okmulgee, Tulsa	41.9	58.1	82.4	5.5	7.0	2.0	3.1	34,655	2–8	4–10
Coal	46.6	53.4	77.8	5.2	10.4	1.8	4.8	32,420	5–7	9–12
Haskell	23.6	76.4	89.1	4.8	3.2	1.9	1.0	36,165	2–4	3–8
LeFlore	18.2	81.8	90.4	4.6	2.2	1.9	0.9	36,190	1–3	6–12
PENNSYLVANIA										
Fayette	31.4	68.6	86.0	5.2	6.3	1.5	1.0	36,095	3–5	7–9
Fayette, Washington, Elk	37.8	62.2	84.8	5.5	5.7	1.6	2.4	35,525	2–4	6–13
Allegheny, Butler	39.6	60.4	83.7	5.5	7.1	1.7	2.0	35,050	2–5	4–13
Cambria, Center, Clearfield	24.6	75.4	88.2	5.1	3.4	1.4	1.9	36,320	1–5	5–12

States and counties	Moisture and ash-free values								As received	
	VM	FC	C	H_2	O_2	N_2	S	kJ/kg†	*M*	*A*
Somerset, Tioga	23.5	76.5	88.6	4.8	3.1	1.6	1.9	36,145	1–5	5–12
Westmoreland, Indiana	26.5	73.5	87.6	5.2	3.3	1.4	2.5	36,355	1–5	5–12
Westmoreland, Jefferson	35.4	64.6	85.0	5.4	5.8	1.7	2.1	35,550	2–4	7–15
Cambria, Bedford	19.8	80.2	89.4	4.8	2.4	1.5	1.9	36,435	1–6	5–12
Huntingdon, Somerset	17.1	82.9	90.3	4.6	2.3	1.4	1.4	36,715	1–6	5–12
Sullivan	10.6	89.4	91.6	3.8	2.5	1.2	0.9	35,925	3–4	10–15
Lackawanna, Luzerne	7.3	92.7	93.5	2.6	2.3	0.9	0.7	35,120	2–6	6–16
Schuylkill	2.0	98.0	93.9	2.1	2.3	0.8	0.9	34,585	2–3	8–13
TENNESSEE										
Campbell, Anderson	40.3	59.7	83.1	5.5	7.4	2.1	1.9	34,610	2–6	2–8
Claiborne, Overton, Scott	40.5	59.5	83.5	5.6	6.5	2.0	2.4	34,770	2–6	2–11
Morgan, Fentress, White	41.6	58.4	83.0	5.7	6.1	1.7	3.5	35,095	2–5	4–12
Marion, Hamilton	31.1	68.9	87.3	5.4	4.2	1.6	1.5	35,875	3–5	3–11
Rhea, Roane, Grundy	34.5	65.5	85.7	5.3	6.1	1.6	1.3	35,260	2–4	9–15
TEXAS										
Houston, Milam, Wood	53.3	46.7	72.8	5.3	19.3	1.4	1.2	29,550	29–37	6–13
UTAH										
Carbon, Emery, Grand	45.8	54.2	80.3	5.7	11.7	1.6	0.7	33,420	3–10	4–20
Summit, Uintah, Iron	45.3	54.7	76.2	5.4	13.7	1.2	3.5	31,490	5–17	3–13
VIRGINIA										
Wise, Russell	36.9	63.1	86.3	5.5	5.7	1.6	0.9	35,840	2–5	4–9
Tazewill	17.8	82.2	90.4	4.8	2.9	1.2	0.7	36,960	2–6	2–6
Lee, Scott	37.8	62.2	83.6	5.4	8.3	1.6	1.1	35,085	3–6	3–9
Dickenson, Buchanan, Henico	31.2	68.8	87.3	5.2	4.3	1.8	1.4	35,855	2–4	3–18
Montgomery	13.6	86.4	90.7	4.2	3.3	1.0	0.8	35,715	1–5	16–25
WASHINGTON										
Kittitas, King	43.3	56.7	80.5	6.0	10.8	1.9	0.8	34,005	3–9	10–20
King, Pierce	39.4	60.6	82.5	5.9	8.6	2.0	1.0	34,655	2–6	8–20
Lewis, Thurston	49.3	50.7	71.7	5.8	19.5	1.3	1.7	29,305	16–30	6–23
King	44.8	55.2	76.6	5.7	15.1	1.8	0.8	31,865	7–18	5–16
Pierce	25.4	74.6	87.5	5.4	4.0	2.5	0.6	36,120	2–5	9–15
WEST VIRGINIA										
Logan, Fayette	36.2	63.8	86.3	5.5	5.4	1.7	1.1	35,680	1–3	4–8
McDowell, Fayette, Wyoming	17.7	82.3	90.4	4.8	2.7	1.3	0.8	36,540	2–4	3–6
Raleigh, Mercer, Fayette	18.5	81.5	90.1	4.8	3.0	1.4	0.7	36,560	2–4	3–6
Monongalia, Greenbriar	30.2	69.8	87.2	5.2	5.1	1.6	0.9	35,910	2–4	4–12
Preston, Fayette, Randolph	31.0	69.0	87.5	5.3	4.2	1.5	1.5	36,050	2–4	4–12
Marion, Kanawha, Harrison	40.9	59.1	83.9	5.6	7.4	1.6	1.5	35,075	2–4	4–10
WYOMING										
Sweetwater, Hot Springs	41.8	58.2	77.3	5.3	14.8	1.5	1.1	31,920	8–16	3–8
Sweetwater, Carbon	39.5	60.5	76.2	5.1	16.3	1.6	0.8	30,840	15–25	4–7
Lincoln, Uinta, Sweetwater	43.4	56.6	79.8	5.4	12.2	1.5	1.1	33,075	6–18	4–12
Sheridan, Campbell, Carbon	45.3	54.7	74.1	5.1	18.7	1.3	0.8	29,795	18–30	5–15
Albany, Converse, Freemont	45.1	54.9	73.6	5.2	18.8	1.3	1.1	29,610	17–27	4–15

† 1 kJ/kg = 0.43 Btu/lbm.

APPENDIX F

CONVERTING PROXIMATE TO ULTIMATE ANALYSES

This method gives good results for the great bulk of coals used in steam generation. It is less accurate with anthracite, cannel, and coals with unusual amounts of resins and waxes. The calculational procedure is as follows:

Start with the as-received proximate analysis:

Volatile matter = 38.0%		Sulfur = 2.4%
Fixed carbon = 52.3%		HHV = 13,770 Btu/lbm
Moisture = 1.8%		
Ash = 7.9%		
100.0%		

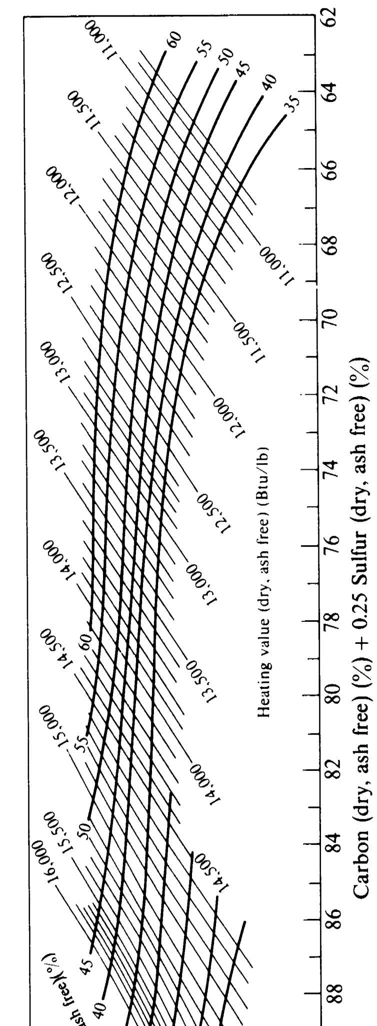
Convert the as-received proximate analysis to a dry, ash-free basis by dividing the above values by $(1-M-A)$ or $(1-0.018-0.079)$ or (0.903):

$$\text{Volatile matter} = \frac{38.0}{0.903} = 42.1\% \qquad \text{Sulfur} = \frac{2.4}{0.903} = 2.7\%$$

$$\text{Fixed carbon} = \frac{52.3}{0.903} = 57.9\% \qquad \text{HHV} = \frac{13{,}770}{0.903} = 15{,}250 \text{ Btu/lbm}$$

$$100.0\%$$

Locate the intersection of the dry, ash-free volatile matter (42.1 percent) and the British thermal unit (15,250) lines on the graph. This corresponds to a hydrogen reading of 5.9% H_2 and a (carbon + sulfur/4) reading of 84.9 percent. Assuming a nitrogen value of 1.5 percent (used for all coals) for the dry, ash-free condition, build up the following ultimate analysis for the dry, ash-free basis.


Carbon (dry, ash free) (%) + 0.25 Sulfur (dry, ash free) (%)
Hydrogen (dry, ash free) (%)
Heating value (dry, ash free) (Btu/lb)
Volatile matter (dry, ash free)(%)

Dry, ash-free ultimate analysis (estimated):

$\%C = [(\%C + \%S/4) \text{ from graph}] - \%S/4 = 84.9 - 2.7/4 = 84.2\%$
$\%H_2 = \%H_2 \text{ (from graph)} = 5.9\%$
$\%N_2 = 1.5\% \text{ (assumed to be the same for all coals)} = 1.5\%$
$\%S = \%S \text{ (from the proximate analysis)} = 2.7\%$
$\%O_2 = 100 - \text{(sum of other values)} = 5.7\%$

100.0%

These dry, ash-free analyses can be converted into an as-received ultimate analysis by multiplying the values by $(1 - M - A)$, or 0.903. This gives:

$C = 76.0\%$
$H_2 = 5.3\%$
$N_2 = 1.4\%$
$S = 2.4\%$
$O_2 = 5.1\%$
$M = 1.8\%$
$A = 7.9\%$

99.9%

or, if the moisture is distributed to H_2 and O_2,

$C = 76.0\%$
$H_2 = 5.5\%$
$N_2 = 1.4\%$
$S = 2.4\%$
$O_2 = 6.7\%$
$A = 7.9\%$

99.9%

This method has been checked against laboratory analyses for many coals and here are some of the results (from E. O. Smith, Asst. Manager, Inspection Dept., Eastern Gas and Fuel Associates):

Producing area	Proximate analysis, as-received					Btu	Ultimate analysis, as-received				
	Moist	VM	FC	Ash	Sulfur			C	H_2	O_2	N_2
Penn. (1)	2.2	16.2	72.1	9.5	2.1	13,710	Actual	79.2	4.4	3.4	1.4
							Calculated	79.4	4.5	3.2	1.3
Penn. (2)	3.3	34.4	54.1	8.2	1.1	13,380	Actual	74.5	5.3	9.4	1.5
							Calculated	75.0	5.3	9.0	1.4
W. Va. (1)	3.3	16.0	76.1	4.6	0.6	14,450	Actual	83.9	4.6	5.2	1.1
							Calculated	83.7	4.7	4.9	1.5
W. Va. (2)	1.8	38.0	52.3	7.9	2.4	13,770	Actual	76.0	5.2	7.1	1.4
							Calculated	76.0	5.4	6.9	1.4
Ky. (1)	3.6	37.2	56.5	2.7	0.7	14,220	Actual	79.6	5.5	9.9	1.6
							Calculated	79.6	5.7	9.8	1.5
Ky. (2)	3.4	37.4	54.8	4.4	1.0	13,800	Actual	77.4	5.5	10.2	1.5
							Calculated	77.6	5.6	9.9	1.5
Ill.	9.2	33.8	48.6	8.4	0.9	11,930	Actual	67.3	5.5	16.3	1.5
							Calculated	67.1	5.6	16.7	1.3
Colo.	14.4	38.4	41.2	6.0	0.8	10,600	Actual	60.6	5.8	25.6	1.2
							Calculated	60.2	6.1	25.6	1.3
Tenn.	5.1	36.3	55.8	2.8	1.0	13,570	Actual	76.5	5.6	12.2	1.9
							Calculated	76.4	5.6	12.7	1.5
Iowa	16.6	36.5	37.4	9.5	4.3	10,480	Actual	57.4	6.0	21.8	1.0
							Calculated	57.6	6.1	21.3	1.2
Alaska	10.7	30.4	44.0	14.9	0.7	9,640	Actual	55.3	5.0	23.6	0.6
							Calculated	55.5	5.2	22.5	1.2

APPENDIX G

LIQUID FUELS

Commercial fuels	Molecular weight	Specific gravity, °API	Flash point, °F	Higher heating value, kJ/kg†	Relative cost, per energy unit
Propane (LPG)‡	44	112.5	···	50,400	122
Butane (LPG)‡	58	103.1	···	49,590	118
Gasolene	113	70.0	0	47,590	167
Gasolene	126	60.0	0	47,120	144
Methanol	32	47.3	60	22,675	
Ethanol (denatured)	46	48.0	170	29,770	
Aviation jet fuel	···	45.0	110	46,050	
Aviation jet fuel	···	50.0	···	46,010	
Kerosene	154	40.0	130	45,940	116
Diesel oil (1-D)	170	30.2	100	44,750	
Diesel oil (2-D)	184	22.2	125	44,450	
Diesel oil (4-D)	198	15.8	130	43,800	
Available fuel oils:					
No. 1 fuel oil	···	42.0	100	46,070	118
No. 2 fuel oil	···	34.0	100	45,260	100
No. 4 fuel oil	···	22.5	130	43,820	76
No. 5 fuel oil	···	18.0	130	43,170	60
No. 6 fuel oil	···	14.5	150	42,330	51

† 1 kJ/kg = 0.43 Btu/lbm.

‡ Stored as liquid under pressure.

Composition of typical American crude oils

Crude Oils	Mass fractions				Specific gravity, °API	HHV, kJ/kg†
	C	H_2	O_2+N_2	S		
Texas No. 1	84.60	10.90	2.87	1.63	21.68	44,140
Texas No. 2	83.26	12.41	3.83	0.50	21.37	45,710
Pennsylvania	84.90	13.70	1.40	0.00	28.20	44,680
California	81.52	11.51	6.42	0.55	14.98	43,420

† 1 kJ/kg = 0.43 Btu/lbm.

APPENDIX H

FUEL-GAS ANALYSES

Fuel gases	Higher heating value,† kJ/m³‡	Composition, in percentage by volume or mole								
		CH_4	C_2H_4	C_2H_6sp	H_2	CO	O_2	N_2	CO_2	H_2O
Natural gases:										
Alabama	36,140	97.6						2.1	0.3	
Arkansas	36,730	99.2						0.6	0.2	
California-A	39,080	77.5		16.0					6.5	
California-B	40,880	83.4		15.4				0.5	0.7	
Illinois	35,400	95.6						3.9	0.5	
Indiana	43,110	75.4		23.4				1.2		
Kansas	36,290	98.0						0.8	1.2	
Kentucky	43,350	75.0		24.0				1.0		
Louisiana-A	34,760	78.8	9.5				0.3	11.3	0.1	
Louisiana-B	36,570	90.0		5.0				5.0		
Missouri	35,490	84.1		6.7				8.4	0.8	
New York	40,840	84.0		15.0				1.0		
Ohio-A	35,000	93.3	0.3		1.8	0.5	0.3	3.4	0.2	0.2
Ohio-B	35,060	93.4	0.4		1.6	0.4	0.4	3.4	0.4	
Oklahoma-A	39,160	73.5		18.4				8.1		
Oklahoma-B	35,490	84.1		6.7				8.4	0.8	
Pennsylvania-A	39,170	90.0		9.0				0.8	0.2	
Pennsylvania-B	41,140	83.4		15.8				0.8		
West Virginia	43,040	76.8		22.5				0.7		

Fuel gases	Higher heating value,† kJ/m³‡	Composition, in percentage by volume or mole								
		CH_4	C_2H_4	C_2H_6	H_2	CO	O_2	N_2	CO_2	C_6H_6
Artificial gases:										
Producer gas										
Anthracite	4,520				15.5	22.7	0.3	56.0	5.5	
Bituminous	5,690	3.7		0.1	11.6	24.4	0.6	54.8	4.8	
Blast-furnace (BF) gas	3,620	0.2			3.6	26.5		57.0	12.7	
B-F gas (lean)	3,170	0.1			2.5	24.1		58.4	14.9	
Coke-oven gas	22,030	33.9	5.2		47.9	6.1	0.6	3.7	2.6	
Illuminating gas	18,560	23.6		10.5	11.7	13.7	0.7	32.6	7.2	
Water gas (carb.)	19,470	15.5	4.7		34.0	32.0	0.7	6.5	4.3	2.3
Landfill gas	22,220	60.0			(Balance is normally CO_2)					

† All gas values are corrected to 1 atm and 20°C (68°F).
‡ 1 kJ/m³ = 0.02684 Btu/ft³.

APPENDIX I

REACTANT PROPERTIES

Substance	Chemical formula	Molecular weight	Density,† kg/m³	Higher heating value kJ/m³‡	Higher heating value kJ/kg‡	Lower heating value kJ/m³‡	Lower heating value kJ/kg‡
Fuels:							
Hydrogen	H_2	2.016	0.0838	11,910	142,097	10,060	120,067
Carbon	C	12.011	...	...	32,778	...	32,778
Sulfur	S	32.064	...	...	9,257	...	9,257
Hydrogen sulfide	H_2S	34,080	1.4168	23,390	16,506	21,540	15,204
Carbon monoxide	CO	28.006	1.1643	11,770	10,110	11,770	10,110
Methane	CH_4	16.043	0.6669	37,030	55,529	33,340	49,994
Methyl alcohol	CH_3OH	32.043	1.3321	31,780	23,858	28,090	21,086
Ethane	C_2H_6	30.071	1.2501	64,910	51,920	59,370	47,489
Ethylene	C_2H_4	28.055	1.1663	58,690	50,322	55,000	47,156
Acetylene	C_2H_2	26.039	1.0825	54,140	50,010	52,290	48,305
Ethyl alcohol	C_2H_5OH	46.071	1.9153	58,630	30,610	53,090	27,717
Propane	C_3H_8	44.099	1.8333	92,390	50,399	85,010	46,370
Propylene	C_3H_6	42.083	1.7495	85,640	48,954	80,110	45,789
n-Butane	C_4H_{10}	58.126	2.4164	119,820	49,589	110,590	45,768
Isobutane	C_4H_{10}	58.126	2.4164	119,540	49,472	110,310	45,652
n-Butene	C_4H_8	56.110	2.3326	113,130	48,503	105,750	45,338
Isobutene	C_4H_8	56.110	2.3326	112,500	48,231	105,110	45,065
n-Pentane	C_5H_{12}	72.153	2.9996	147,170	49,064	136,090	45,370
Isopentane	C_5H_{12}	72.153	2.9996	146,830	48,952	135,750	45,258
Neopentane	C_5H_{12}	72.153	2.9996	146,350	48,791	135,270	45,098
n-Pentene	C_5H_{10}	70.137	2.9157	140,510	48,191	131,280	45,026
n-Hexane	C_6H_{14}	86.181	3.5827	174,710	48,764	161,780	45,156
Benzene	C_6H_6	78.117	3.2475	137,350	42,293	131,810	40,588
Toluene	C_7H_8	92.141	3.8305	164,830	43,030	157,440	41,102
Xylene	C_8H_{10}	106.172	4.4138	191,460	43,377	182,320	41,307
Naphthalene	$C_{10}H_8$	128.179	5.3287	214,450	40,244	207,070	38,860
Ammonia	NH_3	17.031	0.7080	15,920	22,484	13,150	18,572

Substance	Chemical formula	Molecular weight	Density,† kg/m^3	Higher heating value		Lower heating value	
				kJ/m^3‡	kJ/kg‡	kJ/m^3‡	kJ/kg‡
Nonfuels:							
Oxygen	O_2	31.999	1.3303				
Nitrogen	N_2	28.013	1.1646				
Air	···	28.970	1.2043				
Carbon dioxide	CO_2	44.010	1.8296				
Sulfur dioxide	SO_2	64.063	2.6632				

† All gas values corrected to one atmosphere and 20°C (68°F), $\rho = 0.04157$ (M.W.).
‡ 1 kJ/m^3 = 0.02684 Btu/ft^3; 1 kJ/kg = 0.43 Btu/lbm; 1 kg/m^3 = 0.0624 lbm/ft^3.

APPENDIX J

LIST OF CHEMICAL ELEMENTS

Chemical element	Symbol	Atomic number (*Z*)	Chemical element	Symbol	Atomic Number (*Z*)
Actinium	Ac	89	Curium	Cm	96
Aluminum	Al	13	Dysprosium	Dy	66
Americium	Am	95	Einsteinium	Es	99
Antimony	Sb	51	Erbium	Er	68
Argon	A	18	Europium	Eu	63
Arsenic	As	33	Fermium	Fm	100
Astatine	At	85	Fluorine	F	9
Barium	Ba	56	Francium	Fr	87
Berkelium	Bk	97	Gadolinium	Gd	64
Beryllium	Be	4	Gallium	Ga	31
Bismuth	Bi	83	Germanium	Ge	32
Boron	B	5	Gold	Au	79
Bromine	Br	35	Hafnium	Hf	72
Cadmium	Cd	48	Hahnium†	. . .	105
Calcium	Ca	20	Helium	He	2
Californium	Cf	98	Holmium	Ho	67
Carbon	C	6	Hydrogen	H	1
Cerium	Ce	58	Indium	In	49
Cesium	Cs	55	Iodine	I	53
Chlorine	Cl	17	Iridium	Ir	77
Chromium	Cr	24	Iron	Fe	26
Cobalt	Co	27	Krypton	Kr	36
Copper	Cu	29	Lanthanum	La	57

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Chemical element	Symbol	Atomic number (*Z*)	Chemical element	Symbol	Atomic Number (*Z*)
Lawrencium	Lw	103	Rhodium	Rh	45
Lead	Pb	82	Rubidium	Rb	37
Lithium	Li	3	Ruthenium	Ru	44
Lutecium	Lu	71	Rutherfordium†	. . .	104
Magnesium	Mg	12	Samarium	Sm	62
Manganese	Mn	25	Scandium	Sc	21
Mendelevium	Md	101	Selenium	Se	34
Mercury	Hg	80	Silicon	Si	14
Molybdenum	Mo	42	Silver	Ag	47
Neodymium	Nd	60	Sodium	Na	11
Neon	Ne	10	Strontium	Sr	38
Neptunium	Np	93	Sulfur	S	16
Nickel	Ni	28	Tantalum	Ta	73
Niobium	Nb	41	Technetium	Tc	43
Nitrogen	N	7	Tellurium	Te	52
Nobelium	No	102	Terbium	Tb	65
Osmium	Os	76	Thallium	Tl	81
Oxygen	O	8	Thorium	Th	90
Palladium	Pd	46	Thulium	Tm	69
Phosphorus	P	15	Tin	Sn	50
Platinum	Pt	78	Titanium	Ti	22
Plutonium	Pu	94	Tungsten (Wolfram)	W	74
Polonium	Po	84	Uranium	U	92
Potassium	K	19	Vanadium	V	23
Praseodymium	Pr	59	Xenon	Xe	54
Promethium	Pm	61	Ytterbium	Yb	70
Protactinium	Pa	91	Yttrium	Y	39
Radium	Ra	88	Zinc	Zn	30
Radon	Rn	86	Zirconium	Zr	40
Rhenium	Re	75			

† There is currently a disagreement as to who first discovered elements 104 and 105—the Americans or the Russians. The Americans have proposed the name "Rutherfordium" for element 104 and the name "Hahnium" for element 105. The Russians have proposed the Name "Kurchatovium" for element 104 and the name "Neilsbohrium" for element 105. An international body will decide who gets to name these elements.

APPENDIX K

PARTIAL LIST OF ISOTOPES

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
Electron	−1	0	0.000549			
Neutron	0	1	1.008665		11.7 m	β^-
Hydrogen	1	1	1.007825	99.985		
H	1	2	2.01410	0.015		
1.00797	1	3	3.01605		12.26 y	β^-
Helium	2	3	3.01603	0.00013		
He	2	4	4.00260	99.99987		
4.0026	2	5	5.01230		2×10^{-21} s	α
	2	6	6.01888		0.8 s	β^-
	2	8	8.03750		0.122 s	β^-
Lithium	3	5	5.01250		10^{-21} s	α
Li	3	6	6.01512	7.42		
6.939	3	7	7.01600	92.58		
	3	8	8.02247		0.85 s	β^-
Beryllium	4	6	6.01970		4.0×10^{-21} s	β^+
Be	4	7	7.01690		53.6 d	K
9.0122	4	8	8.00530		10^{-16} s	2α
	4	9	9.01218	100.00		
	4	10	10.01350		2.0×10^6 y	β^-
	4	11	11.02160		13.6 s	β^-

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
Boron	5	8	8.02460		0.77 s	β^+
B	5	9	9.01333		8.0×10^{-19} s	p/2α
10.811	5	10	10.01294	19.78		
	5	11	11.00931	80.22		
	5	12	12.01430		0.02 s	β^-
	5	13	13.01780		0.019 s	β^-
Carbon	6	10			19.0 s	β^+
C	6	11	11.01141		20.3 m	β^+
12.011	6	12	12.00000	98.89		
	6	13	13.00335	1.11		
	6	14	14.00323		5730.0 y	β^-
	6	15	15.00939		2.40 s	β^-
Nitrogen	7	12	12.01895		0.011 s	β^+
N	7	13	13.00572		9.96 m	β^+
14.0067	7	14	14.00307	99.63		
	7	15	15.00011	0.37		
	7	16	16.00656		7.20 s	β^-
	7	17	17.00862		4.16 s	β^-
Oxygen	8	14	14.00856		73.0 s	β^+
O	8	15	15.00300		0.122 s	β^+
15.9994	8	16	15.99491	99.759		
	8	17	16.99914	0.037		
	8	18	17.99915	0.204		
	8	19	19.00344		29.0 s	β^-
Fluorine	9	16	16.01148		10^{-19} s	β^+
F	9	17	17.00210		66.0 s	β^+
18.9984	9	18	18.00094		109.7 s	β^+
	9	19	18.99841	100.00		
	9	20	19.99999		11.4 s	β^-
Neon	10	18	18.00546		1.67 s	β^+
Ne	10	19	19.00187		17.5 s	β^+
20.179	10	20	19.99244	90.52		
	10	21	20.99395	0.26		
	10	22	21.99138	9.22		
	10	23	22.99437		37.6 s	β^-
Sodium	11	20	20.00887		0.4 s	β^+
Na	11	21	20.99760		23.0 s	β^+
22.9898	11	22	21.99432		2.62 y	β^+
	11	23	22.98977	100.0		
	11	24	23.99102		15.0 h	β^-
	11	25	24.98984		60.0 s	β^-
Magnesium	12	23	22.99380		11.3 s	β^+
Mg	12	24	23.98504	78.99		
24.305	12	25	24.98584	10.00		
	12	26	25.98259	11.01		

Element Chemical symbol Atomic weight	Atomic number *Z*	Atomic mass number *A*	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
	12	27	26.98436		9.50 m	β^-
	12	28	27.98381		21.3 h	β^-
Aluminum	13	24	24.00006		2.10 s	β^+
Al	13	25	24.99036		7.20 s	β^+
26.98153	13	26	25.98793		7.4×10^5 y	β^+
	13	27	26.98153	100.00		
	13	28	27.98193		2.31 m	β^-
	13	29	28.98053		6.60 s	β^-
Silicon	14	27	26.98667		4.20 s	β^+
Si	14	28	27.97693	92.21		
28.086	14	29	28.97649	4.70		
	14	30	29.97376	3.09		
	14	31	30.97536		2.62 h	β^-
	14	32	31.97396		280 y	β^-
Phosphorus	15	28	27.99168		0.28 s	β^+
P	15	29	28.98178		4.40 s	β^+
30.9738	15	30	29.97863		2.50 m	β^+
	15	31	30.97376	100.00		
	15	32	31.97392		14.3 d	β^-
	15	33	32.97168		25.0 d	β^-
	15	34	33,97331		12.4 s	β^-
Sulfur	16	31	30.97901		2.60 s	β^+
S	16	32	31.97207	95.01		
32.064	16	33	32.97146	0.75		
	16	34	33.96786	4.21		
	16	35	34.96923		86.7 d	β^-
	16	36	35.96709	0.013		
	16	37	36.97029		5.10 m	β^-
Chlorine	17	32	31.98601		0.31 s	β^+
Cl	17	33	32.99725		2.50 s	β^+
35.453	17	34	33.97376		1.56 s	β^+
	17	35	34.96885	75.77		
	17	36	35.96852		3.1×10^5 y	β^-
	17	37	36.96590	24.23		
	17	38	37.96797		37.3 m	β^-
	17	39	38.96742		55.5 m	β^-
Argon	18	35	34.97459		1.83 s	β^+
A	18	36	35.96755	0.337		
39.948	18	37	36.96674		35.0 d	K
	18	38	37.96272	0.063		
	18	39	38.96428		265.0 y	β^-
	18	40	39.96238	99.60		
	18	41	40.96454		1.83 h	β^-
Potassium	19	37	36.97324		1.20 s	β^+
K	19	38	37.96905		7.70 m	β^+
39.0983	19	39	38.96371	93.26		

Element / Chemical symbol / Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
	19	40	39.97400	0.012	1.28×10^9 y	K/β^-
	19	41	40.96184	6.73		
	19	42	41.96352		12.4 h	β^-
	19	43	42.96066		22.4 h	β^-
	19	44	43.96192		22.0 m	β^-
Calcium	20	39	38.97100		0.87 s	β^+
Ca	20	40	39.96259	96.94		
40.080	20	41	40.96228		1.3×10^5 y	K
	20	42	41.95863	0.6445		
	20	43	42.95878	0.135		
	20	44	43.95549	2.09		
	20	45			165 d	β^-
	20	46	45.95367	0.0035		
	20	48	47.95253	0.187		
	20	49	48.95559		8.80 m	β^-
Scandium	21	40	39.97753		0.18 s	β^+
Sc	21	41	40.96860		0.87 s	β^+
44.956	21	43	42.96106		3.89 h	β^+
	21	44	43.95928		3.92 h	β^+
	21	45	44.95592	100.00		
	21	46	45.95487		83.8 d	β^-
	21	47	46.95230		3.40 d	β^-
	21	48	47.95216		44.0 h	β^-
	21	49	48.94997		57.5 m	β^-
Titanium	22	45	44.95797		3.08 h	β^+
Ti	22	46	45.95263	8.25		
47.900	22	47	46.95177	7.45		
	22	48	47.94795	73.70		
	22	49	48.94787	5.40		
	22	50	49.94479	5.20		
	22	51	50.94645		5.80 m	β^-
Vanadium	23	46	45.96028		0.40 s	β^+
V	23	47	46.95469		32.0 m	β^+
50.942	23	48	47.95220		16.1 d	β^+
	23	49	48.94847		330.0 d	K
	23	50	49.94716	0.24	6.0×10^{15} y	K
	23	51	50.94396	99.76		
	23	52	51.94418		3.76 m	β^-
Chromium	24	49	48.95122		42.0 m	β^+
Cr	24	50	49.94605	4.31		
51.996	24	51	50.94418		27.8 d	K
	24	52	51.94050	83.76		
	24	53	52.94065	9.55		
	24	54	53.93890	2.38		
	24	55	54.94095		3.50 m	β^-

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
Manganese	25	50	49.95411		0.29 s	β^+
Mn	25	51	50.94809		45.0 m	β^+
54.938	25	52	51.94618		5.60 d	β^+
	25	53	52.94126		3.8×10^6 y	K
	25	54	53.94040		303.0 d	K
	25	55	54.93805	100.00		
	25	56	55.93904		2.58 h	β^-
Iron	26	52	51.94769		8.00 h	K
Fe	26	53	52.94541		9.00 m	β^+
55.847	26	54	53.93960	5.82		
	26	55	54.93856		2.60 y	K
	26	56	55.93490	91.66		
	26	57	56.93540	2.19		
	26	58	57.93330	0.33		
	26	59	58.93490		45.1 d	β^-
Cobalt	27	54	53.94904		0.18 s	β^+
Co	27	55	54.94188		18.0 h	β^+
68.933	27	56	55.93982		77.3 d	K/β^+
	27	57	56.93587		270.0 d	K
	27	58	57.93520		71.3 d	K
	27	59	58.93320	100.00		
	27	60	59.93344		5.26 y	β^-
	27	61	60.93199		99.0 m	β^-
	27	62	61.93324		13.9 m	β^-
Nickel	28	57	56.9394		36.1 h	K
Ni	28	58	57.9353	68.30		
58.710	28	59	58.9342		8.0×10^4 y	K
	28	60	59.9308	26.13		
	28	61	60.9310	1.09		
	28	62	61.9283	3.56		
	28	63	62.9286		100.0 y	β^-
	28	64	63.9280	0.92		
	28	65	64.9291		2.56 h	β^-
Copper	29	58	57.9456		3.30 s	β^+
Cu	29	60	59.9375		24.0 m	β^+
63.546	29	61	60.9327		3.30 h	β^+
	29	62	61.9316		9.80 m	β^+
	29	63	62.9298	69.20		
	29	64	63.9288		12.9 h	β^+/K/β^-
	29	65	64.9278	30.80		
	29	66	65.9288		5.10 m	β^-
	29	67	66.9278		61.0 h	β^-
Zinc	30	62	61.9339		9.30 h	β^+
Zn	30	63	62.9330		38.8 m	β^+
65.370	30	64	63.9291	48.60		
	30	65	64.9283		243.6 d	K/β^+

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
	30	66	65.9260	27.90		
	30	67	66.9271	4.10		
	30	68	67.9249	18.80		
	30	69	68.9257		58.0 m	β^-
	30	70	69.9253	0.60		
	30	71	70.9273		2.20 m	β^-
Gallium	31	64	63.9368		2.60 m	β^+
Ga	31	65	64.9325		15.0 m	β^+
69.720	31	66	65.9315		9.50 h	β^+
	31	67	66.9283		78.0 h	K
	31	68	67.9270		68.3 m	β^+
	31	69	68.9257	60.10		
	31	70	69.9259		21.0 m	β^-
	31	71	70.9249	39.90		
	31	72	71.9245		14.1 h	β^-
	31	73	72.9248		4.80 h	β^-
Germanium	32	67	66.9330		19.0 m	β^+
Ge	32	69	68.9280		40.0 h	K
72.590	32	70	69.9243	20.52		
	32	71	70.9251		11.0 d	K
	32	72	71.9221	27.43		
	32	73	72.9234	7.76		
	32	74	73.9212	36.53		
	32	75	74.9228		82.8 m	β^-
	32	76	75.9214	7.76		
	32	77	76.9215		11.3 h	β^-
Arsenic	33	71	70.9271		62.0 h	K/β^+
As	33	72	71.9264		26.0 h	β^+
74.9216	33	73	72.9237		80.3 d	K
	33	74	73.9217		17.9 d	K
	33	75	74.9216	100.00		
	33	76	75.9201		26.5 h	β^-
	33	77	76.9206		39.0 h	β^-
	33	78	77.9217		91.0 m	β^-
	33	79	78.9209		9.00 m	β^-
Selenium	34	73	72.9266		7.10 h	β^+
Se	34	74	73.9225	0.87		
78.960	34	75	74.9225		120.4 d	K
	34	76	75.9192	9.02		
	34	77	76.9199	7.58		
	34	78	77.9173	23.52		
	34	79	78.9185		6.5×10^4 y	β^-
	34	80	79.9165	49.82		
	34	81	80.9185		18.6 m	β^-
	34	82	81.9167	9.19		

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
Bromine	35	78	77.9211		6.40 m	β^+
Br	35	79	78.9183	50.69		
79.904	35	80	79.9172		17.6 m	β^-
	35	81	80.9163	49.31		
	35	82	81.9158		35.5 h	β^-
Krypton	36	78	77.9204	0.35		
Kr	36	79	78.9200		34.9 h	K
83.800	36	80	79.9164	2.27		
	36	81	80.9165		2.1×10^5 y	K
	36	82	81.9135	11.56		
	36	83	82.9141	11.55		
	36	84	83.9116	56.90		
	36	85	84.9126		10.76 y	β^-
	36	86	85.9109	17.37		
	36	87	86.9136		76.0 m	β^-
Rubidium	37	84	83.9142		33.0 d	K
Ru	37	85	84.9117	72.15		
85.470	37	86	85.9100		18.66 d	β^-
	37	87	86.9092	27.85	5.0×10^{10} y	β^-
	37	88	87.9113		17.7 m	β^-
Strontium	38	84	83.9142	0.56		
Sr	38	85	84.9095		64.0 d	K
87.620	38	86	85.9094	9.86		
	38	87	86.9089	7.02		
	38	88	87.9056	82.56		
	38	89	88.9057		52.0 d	β^-
	38	90	89.9072		28.1 y	β^-
	38	91	90.9097		9.67 h	β^-
Yttrium	39	88	87.9096		106.6 d	K
Y	39	89	88.9059	100.00		
88.906	39	90	89.9066		64.0 h	β^-
	39	91	90.9069		58.8 d	β^-
	39	92	91.9083		3.54 h	β^-
Zirconium	40	89	88.9086		78.4 h	K
Zr	40	90	89.9047	51.46		
91.220	40	91	90.9056	11.23		
	40	92	91.9050	17.11		
	40	93	92.9063		1.5×10^{-6} y	β^-
	40	94	93.9061	17.40		
	40	95	94.9072		65.0 d	β^-
	40	96	95.9082	2.80	3.6×10^{17}	β^-
	40	97	96.91104		17.0 h	β^-
Niobium	41	92	91.9062		10.13 d	K/β^-
Nb	41	93	92.9064	100.00		
92.906	41	94	93.9063		2.0×10^4 y	β^-
	41	95	94.9060		3.50 d	β^-

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
Molybdenum	42	92	91.9068	14.80		
Mo	42	93	92.9057		3,500 y	K
95.940	42	94	93.9051	9.30		
	42	95	94.9058	15.90		
	42	96	95.9046	16.70		
	42	97	96.9058	9.60		
	42	98	97.9055	24.10		
	42	99	98.9069		66.7 h	β^-
	42	100	99.9076	9.60		
Technetium	43	95	94.9073		20.0 h	K
Tc	43	97	96.9068		2.6×10^6 y	K
———	43	98			4.2×10^6 y	β^-
	43	99	98.9054		2.12×10^5 y	β^-
Ruthenium	44	95	94.9095		1.70 h	K
Ru	44	96	95.9076	5.51		
101.07	44	97			2.90 d	K
	44	98	97.9055	1.87		
	44	99	98.9061	12.72		
	44	100	98.9042	12.62		
	44	101	100.9056	17.07		
	44	102	101.9043	31.63		
	44	103	102.9058		39.6 d	β^-
	44	104	103.9055	18.58		
	44	105	104.9075		4.44 h	β^-
	44	106	105.9073		367.0 d	β^-
Rhodium	45	102	101.9064		206.0 d	$K/\beta^+/\beta^-$
Rh	45	103	102.9055	100.00		
102.905	45	104	103.9064		43.0 s	β^-
Palladium	46	102	101.9056	0.96		
Pd	46	103	102.9058		17.0 d	K
106.400	46	104	103.9040	10.97		
	46	105	104.9051	22.23		
	46	106	105.9032	27.32		
	46	107	106.9049		7.0×10^6 y	β^-
	46	108	107.9039	26.71		
	46	109	108.9059		13.47 h	β^-
	46	110	109.9052	11.81		
	46	111	110.9076		22.0 m	β^-
Silver	47	106	105.9061		8.40 d	K
Ag	47	107	106.9051	51.82		
107.87	47	108	107.9059		2.20 m	β^-
	47	109	108.9047	48.18		
	47	110	109.9072		24.4 s	β^-
Cadmium	48	106	105.9065	1.22		
Cd	48	107	106.9064		6.50 h	K
112.40	48	108	107.9040	0.88		

Element Chemical symbol Atomic weight	Atomic number *Z*	Atomic mass number *A*	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
	48	109	108.9048		450.0 d	K
	48	110	109.9030	12.39		
	48	111	110.9042	12.75		
	48	112	111.9028	24.07		
	48	113	112.9046	12.26		
	48	114	113.9036	28.85		
	48	115	114.9070		53.5 h	β^-
	48	116	115.9050	7.58		
	48	117	116.9076		2.40 h	β^-
Indium	49	113	112.9043	4.28		
In	49	114	113.9070		72.0 s	β^-
114.82	49	115	114.9041	95.72	6.0×10^{14} y	β^-
	49	116	115.9071		14.0 s	β^-
Tin	50	112	111.9048	1.01		
Sn	50	113			115.0 d	K
118.69	50	114	113.9030	0.67		
	50	115	114.9035	0.38		
	50	116	115.9017	14.70		
	50	117	116.9031	7.73		
	50	118	117.9018	24.30		
	50	119	118.9034	8.58		
	50	120	119.9022	32.40		
	50	121	120.9025		27.0 h	β^-
	50	122	121.9034	4.62		
	50	123	122.9037		42.0 m	β^-
	50	124	123.9052	5.61		
Antimony	51	120	119.9040		15.9 m	K
Sb	51	121	120.9038	57.25		
121.75	51	122	121.9035		2.80 d	β^-
	51	123	122.9041	42.75		
Tellurium	52	120	119.9040	0.089		
Te	52	122	121.9030	2.46		
127.60	52	123	122.9042	0.87		
	52	124	123.9028	4.61		
	52	125	124.9044	6.99		
	52	126	125.9032	18.71		
	52	127	126.9053		9.40 h	β^-
	52	128	127.9047	31.79		
	52	129	128.9066		69.0 m	β^-
	52	130	129.9062	34.48		
	52	131	130.9084		25.0 m	β^-
Iodine	53	126	125.9053		13.0 d	$K/\beta^+/\beta^-$
I	53	127	126.9044	100.00		
126.9044	53	128	127.9060		25.08 m	β^-
	53	129	128.9047		1.7×10^7 y	β^-
	53	130	129.9065		12.3 h	β^-
	53	131	130.9060		8.07 d	β^-

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
Xenon	54	124	123.9061	0.096		
Xe	54	125			17.0 h	K
131.30	54	126	125.9042	0.09		
	54	127	126.9055		36.41 d	K
	54	128	127.9035	1.92		
	54	129	128.9048	26.44		
	54	130	129.9035	4.08		
	54	131	130.9051	21.18		
	54	132	132.9042	26.89		
	54	133	132.9054		5.27 d	β^-
	54	134	133.9054	10.44		
	54	135			9.20 h	β^-
	54	136	135.9072	8.87		
Cesium	55	132	131.9060		6.50 d	K
Cs	55	133	132.9051	100.00		
132.905	55	134	133.9064		2.05 y	β^-
	55	137	136.9073		33.0 y	β^-
Barium	56	130	129.9062	0.101		
Ba	56	132	131.9050	0.097		
137.34	56	134	133.9043	2.42		
	56	135	134.9056	6.59		
	56	136	135.9044	7.81		
	56	137	136.9058	11.32		
	56	138	137.9050	71.66		
	56	139	138.9079		82.9 m	β^-
	56	140	139.9099		12.8 d	β^-
Lanthanum	57	138	137.9071	0.089	1.1×10^{11}	$K/\beta^+/\beta^-$
La	57	139	138.9064	99.911		
138.91	57	140	139.9085		40.22 h	β^-
	57	141	140.9095		3.90 h	β^-
Cerium	58	136	135.9071	0.19		
Ce	58	137			9.00 h	K
140.12	58	138	137.9060	0.25		
	58	139	138.9054		140.0 d	K
	58	140	139.9053	88.48		
	58	141	140.9069		33.0 d	β^-
	58	142	141.9093	11.08	5.0×10^{16} y	β^-
	58	143	142.9111		33.0 h	β^-
	58	144	143.9127		285.0 d	β^-
Praseodymium	59	140	139.9079		3.39 m	K
Pr	59	141	140.9077	100.00		
140.907	59	142	141.9087		19.2 h	β^-
	59	143	142.9096		13.7 d	β^-
Neodymium	60	142	141.9075	27.11		
Ne	60	143	142.9096	12.17		
144.24	60	144	143.9099	23.85		

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
	60	145	144.9122	8.30		
	60	146	145.9131	17.22		
	60	147			11.1 d	β^-
	60	148	147.9169	5.73		
	60	149	148.9169		1.73 h	β^-
	60	150	149.9207	5.62		
Promethium	61	146	145.9125		5.52 y	K/β^-
Pm	61	147	146.9152		2.50 y	β^-
———	61	148	147.9171		5.39 d	β^-
	61	149	148.9175		53.1 h	β^-
Samarium	62	144	143.9120	3.09		
Sm	62	145			340.0 d	K
150.35	62	146	145.9129		1.03×10^8 y	α
	62	147	146.9149	14.97	1.06×10^{11} y	α
	62	148	147.9146	11.24	8.0×10^{15} y	α
	62	149	148.9171	13.83	10^{16} y	α
	62	150	149.9173	7.44		
	62	151			93.0 y	β^-
	62	152	151.9195	26.72		
	62	153			46.8 h	β^-
	62	154	153.9220	22.71		
	62	155	154.9242		22.0 m	β^-
Europium	63	148	147.9182		54.5 d	K
Eu	63	151	150.9199	47.82		
151.96	63	153	152.9212	52.18		
	63	154	153.9240		8.20 y	β^-
	63	155	154.9219		4.76 y	β^-
Gadolinium	64	148	147.9181		93.0 y	α
Gd	64	149	148.9193		9.00 d	K
157.24	64	150	149.9185		1.8×10^6 y	α
	64	152	151.9198	0.20	1.1×10^{14} y	α
	64	154	153.9207	2.15		
	64	155	154.9226	14.73		
	64	156	155.9221	20.47		
	64	157	156.9239	15.68		
	64	158	157.9241	24.87		
	64	159			18.0 h	β^-
	64	160	159.9271	21.90		
	64	161			3.70 m	β^-
Terbium	65	158			150.0 y	K
Tb	65	159	158.9253	100.00		
158.925	65	160	159.9269		73.0 d	β^-
Dysprosium	66	156	155.9243	0.052		
Dy	66	157			8.10 h	K
162.50	66	158	157.9243	0.09		
	66	160	159.9252	2.29		

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
	66	161	160.9269	18.88		
	66	162	161.9268	25.53		
	66	163	162.9287	24.97		
	66	164	163.9291	28.18		
	66	165	164.9303		2.30 h	β^-
Holmium	67	164	163.9306		37.0 m	β^-/K
Ho	67	165	164.9303	100.00		
164.93	67	166			26.9 h	β^-
Erbium	68	162	161.9288	0.136		
Er	68	164	163.9293	1.56		
167.26	68	165			10.3 h	K
	68	166	165.9304	33.41		
	68	167	166.9320	22.94		
	68	168	167.9324	27.07		
	68	170	169.9355	14.88		
	68	171			7.50 h	β^-
Thulium	69	168			93.1 d	K
Tm	69	169	168.9344	100.00		
168.93	69	170			128.0 d	β^-
Ytterbium	70	168	167.9339	0.135		
Yb	70	170	169.9349	3.03		
173.04	70	171	170.9365	14.31		
	70	172	171.9366	21.82		
	70	173	172.9383	16.13		
	70	174	173.9390	31.84		
	70	175			101.0 h	β^-
	70	176	175.9427	12.73		
Lutecium	71	173			1.37 y	K
Lu	71	175	174.9409	97.41		
174.97	71	176	175.9427	2.59	3.0×10^{10} y	β^-
	71	177			6.70 d	β^-
Hafnium	72	174	173.9400	0.18	2.0×10^{15} y	α
Hf	72	175			70.0 d	K
178.49	72	176	175.9414	5.20		
	72	177	176.9435	18.50		
	72	178	177.9439	27.14		
	72	179	178.9460	13.75		
	72	180	179.9468	35.23		
	72	181			42.5 d	β^-
Tantalum	73	180	179.9475	0.0123		
Ta	73	181	180.9480	99.9877		
180.948	73	182	181.9475		115.0 d	β^-
Tungsten	74	180	179.9467	0.14		
W	74	181			121.0 d	K
183.85	74	182	181.9483	26.41		

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
	74	183	182.9503	14.40		
	74	184	183.9510	30.64		
	74	185			75.8 d	β^-
	74	186	185.9543	28.41		
	74	187	186.9530		24.0 h	β^-
Rhenium	75	185	184.9530	37.07		
Re	75	186	185.9515		90.0 h	β^-/K
186.207	75	187	186.9560	62.93	5.0×10^{10} y	β^-
	75	188	187.9565		16.7 h	β^-
Osmium	76	184	183.9526	0.018		
Os	76	185			94.0 d	K
190.20	76	186	185.9539	1.59	2.0×10^{15}	α
	76	187	186.9560	1.60		
	76	188	187.9560	13.30		
	76	189	188.9582	16.10		
	76	190	189.9586	26.40		
	76	191	190.8607		15.0 d	β^-
	76	192	191.9615	41.00		
	76	193	192.9650		31.0 h	β^-
Iridium	77	191	190.9606	37.30		
Ir	77	192	191.9636		74.0 d	β^-
192.22	77	193	192.9629	62.70		
	77	194	193.9647		19.2 h	β^-
Platinum	78	190	189.9600	0.0127	6.0×10^{11} y	α
Pt	78	191			3.0 d	K
195.09	78	192	191.9611	0.786	10^{15} y	α
	78	193	192.9640		50.0 y	K
	78	194	193.9628	32.90		
	78	195	194.9648	33.80		
	78	196	195.9650	25.30		
	78	197	196.9666		18.0 h	β^-
	78	198	197.9679	7.21		
Gold	79	196	195.9658		6.18 d	K/β^-
Au	79	197	196.9666	100.00		
196.967	79	198	197.9675		2.693 d	β^-
	79	199	198.9677		3.15 d	β^-
Mercury	80	196	195.9658	0.146		
Hg	80	197			65.0 h	K
200.59	80	198	197.9668	10.01		
	80	199	198.9683	16.84		
	80	200	199.9683	23.13		
	80	201	200.9703	13.22		
	80	202	201.9706	29.80		
	80	203	202.9719		46.57 d	β^-
	80	204	203.9735	6.85		
	80	205	204.9751		5.50 m	β^-

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
Thallium	81	203	202.9723	29.50		
Tl	81	204	203.9721		3.80 y	β^-
204.37	81	205	204.9745	70.50		
	81	206	205.9747		4.19 m	β^-
Lead	82	204	203.9730	1.48		
Pb	82	205	204.9731		1.4×10^7 y	K
207.18	82	206	205.9745	24.10		
	82	207	206.9759	22.10		
	82	208	207.9766	52.30		
	82	209	208.9798		3.30 h	β^-
	82	210	209.9842		21.0 y	β^-
Bismuth	83	208	207.9784		3.7×10^5 y	K
Bi	83	209	208.9804	100.00	2.0×10^{18} y	α
208.98	83	210	209.9841		5.01 d	β^-/α
	83	211	210.9873		2.15 m	α/β^-
Polonium	84	206	205.9805		8.80 d	K/α
Po	84	207	206.9816		5.70 h	K/α
———	84	208	207.9813		2.93 y	α/K
	84	209	208.9825		103.0 y	α/K
	84	210	209.9829		138.4 d	α
	84	211	210.9866		0.52 s	α
	84	212	211.9889		0.304 μs	α
	84	213	212.9928		4.120 μs	α
	84	214	213.9952		0.162 ms	α
	84	215	214.9995		1.780 ms	α
	84	216	216.0019		0.150 s	α
	84	218	218.0089		3.05 m	α
Astatine	85	210	209.9871		8.30 h	K/α
At	85	211	210.9875		7.20 h	K/α
———	85	212	211.9907		0.30 s	α
	85	213	212.9929		0.10 μs	α
	85	214	213.9963		2.00 μs	α
	85	215	214.9987		0.10 ms	α
	85	216	216.0024		0.30 ms	α
	85	217	217.0046		0.032 s	α
	85	218	218.0086		2.00 s	α
	85	219	219.0114		0.90 m	α
Radon	86	219	219.0095		4.00 s	α
Rn	86	220	220.0114		55.0 s	α
———	86	221	221.0154		25.0 m	β^-/α
	86	222	222.0175		3.823 d	α
Francium	87	220	220.0123		27.55 s	α
Fr	87	221	221.0142		4.80 m	α
———	87	222	222.0161		14.8 m	β^-
	87	223	223.0198		22.0 m	β^-

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
Radium	88	220	220.0110		0.023 s	α
Ra	88	221	221.0139		30.0 s	α
——	88	222	222.0154		38.0 s	α
	88	223	223.0186		11.43 s	α
	88	224	224.0202		3.65 d	α
	88	225	225.0219		14.8 d	β^-
	88	226	226.0254		1600.0 y	α
	88	227	227.0276		41.2 m	β^-
	88	228	228.0296		5.75 y	β^-
Actinium	89	225	225.0231		10.0 d	α
Ac	89	226	226.0261		29.0 h	β^-/α
——	89	227	227.0278		21.6 y	β^-
	89	228	228.0295		6.13 h	β^-
	89	229	229.0308		66.0 m	β^-
Thorium	90	227	227.0277		18.7 d	α
Th	90	228	228.0287		1.91 y	α
232.038	90	229	229.0316		7340 y	α
	90	230	230.0331		80,000 y	α
	90	231	231.0347		25.5 h	β^-
	90	232	232.0382	100.00	1.41×10^{10} y	α
	90	233	233.0387		22.2 m	β^-
	90	234			24.2 d	β^-
Protactinium	91	226	226.0278		1.80 m	α
Pa	91	227	227.0289		38.3 m	α/K
——	91	228	228.0310		22.0 h	K
	91	229	229.0321		1.50 d	K
	91	230	230.0345		17.4 d	K/β^-
	91	231	231.0359		33,500 y	α
	91	232	232.0371		1.31 d	β^-
	91	233	233.0384		27.0 d	β^-
	91	234	234.0414		6.75 h	β^-
	91	235	235.0438		23.7 m	β^-
Uranium	92	227	227.0309		1.30 m	α
U	92	228	228.0313		9.30 m	α/K
238.03	92	229	229.0335		58.0 m	K/α
	92	230	230.0339		20.8 d	α
	92	231	231.0363		4.30 d	K
	92	232	232.0372		73.6 y	α
	92	233	233.0395		1.65×10^5 y	α
	92	234	234.0409	0.006	2.4×10^5 y	α
	92	235	235.0439	0.720	7.1×10^8 y	α
	92	236	236.0457		2.39×10^7 y	α
	92	237	237.0469		6.75 d	β^-
	92	238	238.0508	99.274	4.51×10^9	α
	92	239	239.0526		23.5 m	β^-
	92	240	240.0546		14.1 h	β^-

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
Neptunium	93	231	231.0383		50.0 m	α
Np	93	233	233.0406		35.0 m	K
———	93	234	234.0419		4.40 d	K
	93	235	235.0441		410.0 d	K
	93	236	236.0466		22.0 h	β^-/K
	93	237	237.0480		2.14×10^6 y	α
	93	238	238.0494		2.10 d	β^-
	93	239	239.0513		2.35 d	β^-
	93	240	240.0537		63.0 m	β^-
	93	241	241.0558		16.0 m	β^-
Plutonium	94	232	232.0411		36.0 m	K/α
Pu	94	234	234.0433		9.00 h	K
———	94	235	235.0453		26.0 m	K
	94	236	236.0461		2.85 y	α
	94	237	237.0483		45.6 d	K
	94	238	238.0495		86.0 y	α
	94	239	239.0522		24,400 y	α
	94	240	240.0540		6580 y	α
	94	241	241.0568		14.7 y	β^-
	94	242	242.0587		3.79×10^5 y	α
	94	243	243.0601		5.0 h	β^-
	94	244	244,0642		8.0×10^7 y	α
Americium	95	240	240.0552		51.0 h	K
Am	95	241	241.0567		458.0 y	α
———	95	242	242.0574		16.0 h	β^-/K
	95	243	243.0614		7370 y	α
	95	244	244.0625		10.1 h	β^-
	95	245	245.0648		2.10 h	β^-
Curium	96	238	238.0530		2.50 h	K/α
Cm	96	240	240.0555		26.8 d	α
———	96	241	241.0577		32.8 d	K
	96	242	242.0588		163.0 d	α
	96	243	243.0614		28.5 y	α
	96	244	244.0629		17.6 y	α
	96	245	245.0653		8500 y	α
	96	246	246.0674		4730 y	α
Berkelium	97	245	245.0664		4.98 d	K
Bk	97	246	246.0672		1.80 d	K
———	97	247	247.0702		1400 y	α
	97	248	248.0730		9.0 y	β^-/K
	97	249	249.0750		314.0 d	β^-
Californium	98	244	244.0659		20.0 m	α
Cf	98	245	245.0680		44.0 m	K/α
———	98	246	246.0688		36.0 h	α
	98	247	247.0690		3.2 h	K
	98	248	248.0724		350.0 d	α

Element Chemical symbol Atomic weight	Atomic number Z	Atomic mass number A	Isotopic mass, amu	Natural abundance, %	Half-life†	Type of decay†
	98	249	249.0748		360.0 y	α
	98	250	250.0766		13.0 y	α
Einsteinium	99	251	251.0800		1.50 d	K
Es	99	252	252.0829		471.0 y	α
———	99	253	253.0847		20.47 d	α
	99	254	254.0881		276.0 d	α/β^-
	99	255	255.0900		38.4 d	β^-
Fermium	100	250	250.0795		30.0 m	α
Fm	100	252	252.0827		23.0 h	α
———	100	253	253.0852		3.00 d	K/α
	100	254	254.0870		3.20 h	α
	100	255	255.0899		20.1 h	α
Mendelevium	101	255	255.0911		27.0 m	K/α
Mv	101	256	256.0939		76.0 m	K
———	101	257	257.0956		5.20 h	K/α
	101	258	258.0986		55.0 d	α
Nobelium	102	255	255.0933		3.10 m	α
No	102	256	256.0943		3.20 s	α
———	102	257	257.0969		26.0 s	α
Lawrencium	103	255	255.0969		22.0 s	α
Lr	103	256	256.0986		31.0 s	α
———	103	258	258.1018		5.40 s	α
Rutherfordium	104	257	257.1030		4.80 s	α
‡	104	259	259.1057		3.20 s	α
———	104	261	261.1087		65.0 s	α
Hahnium	105	260	260.1213		1.50 s	α/SF
‡	105	261	261.1121		1.80 s	α/SF
———	105	262	262.1138		40.0 s	α

† Abbreviations used in this table. For half-lives; s = seconds, m = minutes; h = hours; d = days; y = years. For types, of radioactive decay: α = alpha decay; β^- = beta decay; β^+ = positron decay; p = proton decay; K = K-capture decay; SF = spontaneous fission.

‡ See footnote at end of App. J.

APPENDIX L

RADIOISOTOPE FUELS

Radioisotope and half-life†	Active material	Mass fraction of radioisotope in material	Melting point, °C‡	Specific power, kW/kg‡	Power density, kW/L‡
$^{90}_{38}Sr$	Metal	55.0% Sr-90	772	0.50	1.28
$t_{1/2} = 28.1$ y	$SrTiO_3$	24.5% Sr-90	1910	0.23	1.17
	SrO	44.0% Sr-90	2457	0.42	1.94
	SrF_2	36.0% Sr-90	1463	0.34	1.44
	$SrTiO_4$	31.5% Sr-90	1860	0.30	1.48
$^{137}_{55}Cs$	CsCl	28.9% Cs-137	645	0.12	0.37
$t_{1/2} = 33.0$ y	$CsSO_4$	26.9% Cs-137	1019	0.11	0.46
$^{144}_{58}Ce$	Ce_2O_3	10.8% Ce-144	2190	2.76	19.0
$t_{1/2} = 285.0$ d	Ce_2O_2S	10.3% Ce-144	1890	2.64	15.8
	Ce_2S_3	9.0% Ce-144	1437	2.31	14.3
$^{147}_{61}Pm$	Metal	95.0% Pm-147	865	0.31	2.30
$t_{1/2} = 2.50$ y	Pm_2O_3	78.0% Pm-147	2130	0.27	1.87
$^{210}_{84}Po$	Metal	95.0% Po-210	254	144.00	1324.0
$t_{1/2} = 138.4$ d	GdPo-Ta (98%)	1.06% Po-210	1675	1.60	16.6
	GdPo-Ta (91%)	4.95% Po-210	1675	7.50	77.2
$^{238}_{94}Pu$	Metal	80.0% Pu-238	600	0.45	6.80
$t_{1/2} = 86.0$ y	PuO_2	71.0% Pu-238	2150	0.40	2.70
	PuC	74.6% Pu-238	1654	0.42	5.70
	PuN	74.6% Pu-238	2570	0.42	6.20
	PuZr	73.0% Pu-238	730	0.41	5.60
	PuZr	77.0% Pu-238	615	0.44	6.50

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Radioisotope and half-life†	Active material	Mass fraction of radioisotope in material	Melting point, °C‡	Specific power, kW/kg‡	Power density, kW/L‡
$^{242}_{96}Cm$ $t_{1/2} = 163.0$ d	Cm_2O_3-AmO_2	35.7% Cm-242	2000	42.80	500.00
$^{244}_{96}Cm$ $t_{1/2} = 17.6$ y	Metal	95.5% Cm-244	1340	2.67	36.00
	Cm_2O_3	86.9% Cm-244	1950	2.42	26.10
	Cm_2O_2S	84.4% Cm-244	2000	2.35	23.30
	CmF_3	77.5% Cm-244	1406	2.15	21.10

† y = years; d = days.

‡ 1 kW/kg = 0.4536 W/lbm; 1 kW/L = 28.31 kW/ft^3; °F = 1.8°C + 32.

Source: From G. L. Tuve and R. E. Bole, *Handbook of Tables for Applied Engineering Science*, The Chemical Rubber Company, Cleveland, Ohio, 1970, p. 348.

APPENDIX M

SOLAR CONSTANTS (FOR NORTHERN LATITUDES)

Date	Angle of declination δ	Equation of time, min	A_S,† kW/m²‡	B_S,† am§	C_S†	Day of year
January						
1	−23.0	−3.6	1231	0.142	0.057	1
11	−21.7	−8.0	1230	0.142	0.058	11
21	−19.6	−11.4	1229	0.142	0.058	21
31	−17.3	−13.5	1224	0.142	0.058	31
February						
1	−17.0	−13.6	1223	0.143	0.059	32
11	−13.9	−14.4	1218	0.143	0.059	42
21	−10.4	−13.8	1213	0.144	0.060	52
28	−7.6	−12.6	1206	0.147	0.063	59
March						
1	−7.4	−12.5	1205	0.148	0.063	60
11	−3.5	−10.2	1195	0.152	0.067	70
21	0.0	−7.4	1185	0.156	0.071	80
31	4.3	−4.3	1169	0.164	0.079	90
April						
1	4.7	−4.0	1167	0.165	0.080	91
11	8.5	−1.1	1151	0.172	0.088	101
21	12.0	1.2	1135	0.180	0.096	111
30	14.9	2.8	1126	0.185	0.104	120

Date	Angle of declination δ	Equation of time, min	A_S,† kW/m²‡	B_S,† am§	C_S†	Day of year
May						
1	15.2	2.9	1125	0.186	0.105	121
11	17.9	3.7	1114	0.191	0.113	131
21	20.3	3.6	1103	0.196	0.121	141
31	22.0	2.5	1098	0.199	0.125	151
June						
1	22.1	2.4	1097	0.199	0.126	152
11	23.1	0.6	1092	0.202	0.130	162
21	23.45	−1.5	1087	0.205	0.134	172
30	23.1	−3.4	1086	0.206	0.135	181
July						
1	23.1	−3.4	1086	0.206	0.135	182
11	22.1	−5.6	1085	0.206	0.135	192
21	20.6	−6.2	1084	0.207	0.136	202
31	18.1	−6.2	1091	0.205	0.132	212
August						
1	17.9	−6.2	1092	0.205	0.132	213
11	15.2	−5.1	1099	0.203	0.126	223
21	12.0	−3.1	1106	0.201	0.122	233
31	8.7	−1.5	1120	0.193	0.113	243
September						
1	8.2	0.0	1122	0.192	0.112	244
11	4.4	3.3	1136	0.185	0.097	254
21	0.0	6.8	1150	0.177	0.092	264
30	−2.9	9.9	1162	0.172	0.086	273
October						
1	−3.3	10.2	1164	0.171	0.086	274
11	−7.2	13.1	1177	0.166	0.079	284
21	−10.8	15.3	1191	0.160	0.073	294
31	−14.3	16.2	1200	0.157	0.070	304
November						
1	−14.6	16.3	1201	0.156	0.069	305
11	−17.5	15.9	1211	0.153	0.066	315
21	−20.0	15.1	1220	0.149	0.063	325
30	−21.7	11.3	1224	0.147	0.061	334
December						
1	−21.9	11.0	1224	0.147	0.061	335
11	−23.0	6.8	1228	0.144	0.059	345
21	−23.45	2.0	1232	0.142	0.057	355
31	−23.1	−3.1	1231	0.142	0.057	365

† A is the apparent solar irradiation at air mass zero (outside the earth's atmosphere).
B is the atmospheric extinction coefficient, in units of (standard atmosphere)$^{-1}$.
C is the ratio of the diffuse to direct normal irradiation on a horizontal surface.
‡ 1 W/m² = 0.3173 Btu/h · ft².
§ am = units of standard air mass.
Source: Reprinted, with permission, from the *Handbook and Product Directory, Applications Volume*, ASHRAE, New York, 1974.

APPENDIX N

SOLAR POSITION AND IRRADIATION VALUES

(For 40° N. Lat.; 1.0 clearness factor; 0 percent ground reflectance)

Date	Solar time a.m.	Solar time p.m.	Solar position angles: Altitude $\|\beta_1\|$	Solar position angles: Azimuth $\|\alpha_1\|$	Total solar insolation, W/m²†: Direct normal	Total solar insolation, W/m²†: Horizontal	Total solar insolation, W/m²†: South-facing vertical
Jan. 21	8	4	8.1	55.3	448	88	265
	9	3	16.9	44.0	753	262	539
	10	2	23.9	30.9	864	400	703
	11	1	28.5	16.1	911	485	797
	12		30.1	0.0	927	517	829
	Surface daily totals, Wh/m²†				6878	2988	5440
Feb. 21	7	5	4.4	72.2	217	32	69
	8	4	15.0	61.8	706	230	337
	9	3	24.5	49.8	863	416	526
	10	2	32.3	35.5	930	561	662
	11	1	37.5	18.7	961	649	744
	12		39.4	0.0	971	681	772
	Surface daily totals, Wh/m²†				8321	4457	5453

Date	Solar time a.m.	Solar time p.m.	Solar position angles: Altitude $\|\beta_1\|$	Solar position angles: Azimuth $\|\alpha_1\|$	Total solar insolation, W/m²†: Direct normal	Horizontal	South-facing vertical
Mar. 21	7	5	11.4	80.2	539	145	110
	8	4	22.5	69.6	788	359	281
	9	3	32.8	57.3	889	545	435
	10	2	41.6	41.9	936	687	555
	11	1	47.7	22.6	961	779	630
	12		50.0	0.0	968	810	656
	Surface daily totals, Wh/m²†				9191	5838	4678
Apr. 21	6	6	7.6	99.2	281	63	13
	7	5	19.1	89.7	649	274	38
	8	4	30.5	79.5	794	479	167
	9	3	41.5	67.5	864	652	293
	10	2	51.4	51.7	901	788	397
	11	1	58.9	29.4	920	873	463
	12		61.9	0.0	924	905	485
	Surface daily totals, Wh/m²†				9746	7168	3221
May 21	5	7	2.1	115.0	3	0	0
	6	5	12.9	105.8	454	154	28
	7	6	24.1	96.9	681	359	41
	8	4	35.6	87.5	788	552	79
	9	3	47.0	76.4	842	716	189
	10	2	57.7	61.3	873	842	280
	11	1	66.5	37.5	892	924	340
	12		70.3	0.0	895	949	359
	Surface daily totals, Wh/m²†				9960	8044	2282
June 21	5	7	4.2	117.3	69	13	3
	6	6	14.8	108.4	489	189	32
	7	5	26.0	99.7	681	388	44
	8	4	37.4	90.7	775	574	50
	9	3	48.8	80.2	829	734	148
	10	2	59.8	65.8	857	857	233
	11	1	69.2	41.9	873	933	290
	12		73.5	0.0	879	958	309
	Surface daily totals, Wh/m²†				10023	8346	1923
July 21	5	7	2.3	115.1	6	0	0
	6	6	13.0	106.0	435	158	28
	7	5	24.3	97.1	656	359	44
	8	4	35.7	87.7	760	548	76
	9	3	47.1	76.6	816	709	183
	10	2	57.8	61.6	848	835	271
	11	1	66.7	37.7	867	914	328
	12		70.5	0.0	870	939	350
	Surface daily totals, Wh/m²†				9651	7987	2213

Date	Solar time a.m.	Solar time p.m.	Solar position angles: Altitude $\|\beta_1\|$	Azimuth $\|\alpha_1\|$	Total solar insolation, W/m²†: Direct normal	Horizontal	South-facing vertical
Aug. 21	6	6	7.7	99.3	255	66	16
	7	5	19.2	90.1	602	274	38
	8	4	30.6	79.7	747	473	158
	9	3	41.6	67.7	820	646	281
	10	2	51.6	51.9	857	775	378
	11	1	59.1	29.5	876	860	441
	12		62.1	0.0	883	889	463
	Surface daily totals, Wh/m²†				9191	7073	3083
Sept. 21	7	5	11.4	80.2	469	136	101
	8	4	22.5	69.5	725	344	265
	9	3	32.8	57.3	829	526	416
	10	2	41.6	41.6	883	665	530
	11	1	47.7	22.6	905	753	605
	12		50.0	0.0	914	785	630
	Surface daily totals, Wh/m²†				8536	5636	4463
Oct. 21	7	5	4.3	72.1	151	22	50
	8	4	14.9	61.7	643	214	315
	9	3	24.4	49.7	810	397	504
	10	2	32.4	35.5	882	536	640
	11	1	37.4	18.7	917	627	722
	12		39.3	0.0	927	656	750
	Surface daily totals, Wh/m²†				7735	4249	5213
Nov. 21	8	4	8.1	55.3	429	88	255
	9	3	16.9	44.0	731	258	526
	10	2	23.9	30.9	845	397	690
	11	1	28.5	16.1	892	482	782
	12		30.1	0.0	908	514	813
	Surface daily totals, Wh/m²†				6707	2969	5314
Dec. 21	8	4	5.5	53.0	281	44	177
	9	3	14.0	41.9	684	205	514
	10	2	20.7	29.4	823	337	697
	11	1	25.0	15.2	883	422	794
	12		26.6	0.0	898	451	829
	Surface daily totals, Wh/m²†				6235	2465	5188

† 1 W/m² = 0.3173 Btu/h · ft²; 1 Wh/m² = 0.09289 Wh/ft² = 0.3173 Btu/ft².

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APPENDIX O

VARIATION OF SOLAR RADIATION WITH LATITUDE

(For northern latitudes)

Date	Latitude, degrees	Direct normal irradiation, Wh/m²†	Total horizontal irradiation, Wh/m²†	Date	Latitude, degrees	Direct normal irradiation, Wh/m²†	Total horizontal irradiation, Wh/m²†
Jan. 21	24	8,718	5,113	Apr. 21	24	9,569	7,735
$\delta = -19.6°$	32	7,748	4,060	$\delta = +12.0°$	32	9,696	7,533
	40	6,878	2,988		40	9,746	7,168
	48	5,390	1,879		48	9,696	6,638
	56	3,549	889		56	9,532	5,954
	64	965	142		64	9,399	5,182
Feb. 21	24	9,569	6,298	May 21	24	9,557	8,057
$\delta = -10.4°$	32	9,053	5,434	$\delta = +20.3°$	32	9,809	8,138
	40	8,321	4,457		40	9,960	8,044
	48	7,344	3,404		48	10,257	7,823
	56	6,260	2,332		56	10,528	7,483
	64	4,514	1,261		64	10,937	7,048
Mar. 21	24	9,702	7,155	June 21	24	9,437	8,113
$\delta = 0.0°$	32	9,494	6,569	$\delta = +23.45°$	32	9,721	8,302
	40	9,191	5,838		40	10,023	8,346
	48	8,763	4,974		48	10,439	8,277
	56	8,151	3,997		56	10,837	8,075
	64	7,237	2,938		64	11,505	7,842

Date	Latitude, degrees	Direct normal irradiation, Wh/m²†	Total horizontal irradiation, Wh/m²†	Date	Latitude, degrees	Direct normal irradiation, Wh/m²†	Total horizontal irradiation, Wh/m²†
July 21	24	9,242	7,962	Oct. 21	24	9,040	6,077
$\delta = +20.6°$	32	9,494	8,063	$\delta = -10.8°$	32	8,498	5,213
	40	9,651	7,987		40	7,735	4,249
	48	9,954	7,798		48	6,789	3,221
	56	10,212	7,477		56	5,686	2,169
	64	10,628	7,086		64	3,902	1,128
Aug. 21	24	9,027	7,590	Nov. 21	24	8,529	5,075
$\delta = +12.0°$	32	9,147	7,414	$\delta = -20.0°$	32	7,584	4,035
	40	9,191	7,073		40	6,707	2,969
	48	9,134	6,575		48	5,257	1,879
	56	8,983	5,938		56	3,448	895
	64	8,851	5,188		64	952	145
Sept. 21	24	9,071	6,915	Dec. 21	24	8,271	4,646
$\delta = 0.0°$	32	8,851	6,348	$\delta = -23.45°$	32	7,401	3,581
	40	8,536	5,636		40	6,235	2,465
	48	8,094	4,797		48	4,551	1,406
	56	7,464	3,845		56	2,357	492
	64	6,537	2,811		64	76	6

† $Wh/m^2 = 0.09289\ Wh/ft^2 = 0.3173\ Btu/ft^2$.

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