

# APPENDIX **A**

## *Thermophysical Properties of Matter*<sup>1</sup>

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| <i>Table</i>                                                                 | <i>Page</i> |
|------------------------------------------------------------------------------|-------------|
| <b>A.1</b> Thermophysical Properties of Selected Metallic Solids             | 983         |
| <b>A.2</b> Thermophysical Properties of Selected Nonmetallic Solids          | 987         |
| <b>A.3</b> Thermophysical Properties of Common Materials                     | 989         |
| Structural Building Materials                                                | 989         |
| Insulating Materials and Systems                                             | 990         |
| Industrial Insulation                                                        | 991         |
| Other Materials                                                              | 993         |
| <b>A.4</b> Thermophysical Properties of Gases at Atmospheric Pressure        | 995         |
| <b>A.5</b> Thermophysical Properties of Saturated Fluids                     | 1000        |
| Saturated Liquids                                                            | 1000        |
| Saturated Liquid–Vapor, 1 atm                                                | 1002        |
| <b>A.6</b> Thermophysical Properties of Saturated Water                      | 1003        |
| <b>A.7</b> Thermophysical Properties of Liquid Metals                        | 1005        |
| <b>A.8</b> Binary Diffusion Coefficients at One Atmosphere                   | 1006        |
| <b>A.9</b> Henry’s Constant for Selected Gases in Water at Moderate Pressure | 1007        |
| <b>A.10</b> The Solubility of Selected Gases and Solids                      | 1007        |

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<sup>1</sup>The convention used to present numerical values of the properties is illustrated by this example:

| $T$<br>(K) | $\nu \cdot 10^7$<br>(m <sup>2</sup> /s) | $k \cdot 10^3$<br>(W/m·K) |
|------------|-----------------------------------------|---------------------------|
| 300        | 0.349                                   | 521                       |

where  $\nu = 0.349 \times 10^{-7}$  m<sup>2</sup>/s and  $k = 521 \times 10^{-3} = 0.521$  W/m·K at 300 K.

|             |                                                                                |      |
|-------------|--------------------------------------------------------------------------------|------|
| <b>A.11</b> | Total, Normal ( $n$ ) or Hemispherical ( $h$ ) Emissivity of Selected Surfaces | 1008 |
|             | Metallic Solids and Their Oxides                                               | 1008 |
|             | Nonmetallic Substances                                                         | 1009 |
| <b>A.12</b> | Solar Radiative Properties for Selected Materials                              | 1010 |
|             | References                                                                     | 1011 |

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TABLE A.1 Thermophysical Properties of Selected Metallic Solids<sup>a</sup>

| Composition                               | Melting Point (K) | Properties at 300 K         |                  |               |                                         | Properties at Various Temperatures (K) |      |      |      |      |      |      |      |      |      |  |  |  |  |
|-------------------------------------------|-------------------|-----------------------------|------------------|---------------|-----------------------------------------|----------------------------------------|------|------|------|------|------|------|------|------|------|--|--|--|--|
|                                           |                   | $\rho$ (kg/m <sup>3</sup> ) | $c_p$ (J/kg · K) | $k$ (W/m · K) | $\alpha \cdot 10^6$ (m <sup>2</sup> /s) | $k$ (W/m · K)/ $c_p$ (J/kg · K)        |      |      |      |      |      |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 100                                    | 200  | 400  | 600  | 800  | 1000 | 1200 | 1500 | 2000 | 2500 |  |  |  |  |
| Aluminum                                  |                   |                             |                  |               |                                         |                                        |      |      |      |      |      |      |      |      |      |  |  |  |  |
| Pure                                      | 933               | 2702                        | 903              | 237           | 97.1                                    | 302                                    | 237  | 240  | 231  | 218  |      |      |      |      |      |  |  |  |  |
| Alloy 2024-T6 (4.5% Cu, 1.5% Mg, 0.6% Mn) | 775               | 2770                        | 875              | 177           | 73.0                                    |                                        |      |      |      |      |      |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 482                                    | 798  | 949  | 1033 | 1146 |      |      |      |      |      |  |  |  |  |
| Alloy 195, Cast (4.5% Cu)                 |                   |                             |                  |               |                                         | 65                                     |      |      |      |      |      |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 473                                    | 787  | 925  | 1042 |      |      |      |      |      |      |  |  |  |  |
| Beryllium                                 | 1550              | 1850                        | 1825             | 200           | 59.2                                    | 990                                    | 301  | 161  | 126  | 106  | 90.8 | 78.7 |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 203                                    | 1114 | 2191 | 2604 | 2823 | 3018 | 3227 | 3519 |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 16.5                                   | 9.69 | 7.04 |      |      |      |      |      |      |      |  |  |  |  |
| Bismuth                                   | 545               | 9780                        | 122              | 7.86          | 6.59                                    | 112                                    | 120  | 127  |      |      |      |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 190                                    | 55.5 | 16.8 | 10.6 | 9.60 | 9.85 |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 128                                    | 600  | 1463 | 1892 | 2160 | 2338 |      |      |      |      |  |  |  |  |
| Boron                                     | 2573              | 2500                        | 1107             | 27.0          | 9.76                                    | 190                                    | 200  | 1463 | 1892 | 2160 | 2338 |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 203                                    | 99.3 | 94.7 |      |      |      |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 198                                    | 222  | 242  |      |      |      |      |      |      |      |  |  |  |  |
| Cadmium                                   | 594               | 8650                        | 231              | 96.8          | 48.4                                    | 203                                    | 222  | 242  |      |      |      |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 159                                    | 111  | 90.9 | 80.7 | 71.3 | 65.4 | 61.9 | 57.2 | 49.4 |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 192                                    | 384  | 484  | 542  | 581  | 616  | 682  | 779  | 937  |      |  |  |  |  |
| Chromium                                  | 2118              | 7160                        | 449              | 93.7          | 29.1                                    | 192                                    | 600  | 1463 | 1892 | 2160 | 2338 |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 203                                    | 99.3 | 94.7 |      |      |      |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 198                                    | 222  | 242  |      |      |      |      |      |      |      |  |  |  |  |
| Cobalt                                    | 1769              | 8862                        | 421              | 99.2          | 26.6                                    | 167                                    | 122  | 85.4 | 67.4 | 58.2 | 52.1 | 49.3 | 42.5 |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 236                                    | 379  | 450  | 503  | 550  | 628  | 733  | 674  |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         |                                        |      |      |      |      |      |      |      |      |      |  |  |  |  |
| Copper                                    | 1358              | 8933                        | 385              | 401           | 117                                     | 482                                    | 413  | 393  | 379  | 366  | 352  | 339  |      |      |      |  |  |  |  |
| Pure                                      |                   |                             |                  |               |                                         | 252                                    | 356  | 397  | 417  | 433  | 451  | 480  |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         |                                        |      |      |      |      |      |      |      |      |      |  |  |  |  |
| Commercial bronze (90% Cu, 10% Al)        | 1293              | 8800                        | 420              | 52            | 14                                      |                                        | 42   | 52   | 59   |      |      |      |      |      |      |  |  |  |  |
| Phosphor gear bronze (89% Cu, 11% Sn)     | 1104              | 8780                        | 355              | 54            | 17                                      |                                        | 785  | 460  | 545  |      |      |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 41                                     | 65   | 74   |      |      |      |      |      |      |      |  |  |  |  |
| Cartridge brass (70% Cu, 30% Zn)          | 1188              | 8530                        | 380              | 110           | 33.9                                    | 75                                     | —    | —    | —    | —    |      |      |      |      |      |  |  |  |  |
| Constantan (55% Cu, 45% Ni)               | 1493              | 8920                        | 384              | 23            | 6.71                                    |                                        | 95   | 137  | 149  |      |      |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 17                                     | 360  | 395  | 425  |      |      |      |      |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 237                                    | 19   | 362  |      |      |      |      |      |      |      |  |  |  |  |
| Germanium                                 | 1211              | 5360                        | 322              | 59.9          | 34.7                                    |                                        | 232  | 96.8 | 43.2 | 27.3 | 19.8 | 17.4 | 17.4 |      |      |  |  |  |  |
|                                           |                   |                             |                  |               |                                         | 190                                    | 290  | 337  | 348  | 357  | 375  | 395  |      |      |      |  |  |  |  |

TABLE A.1 Continued

| Composition                                                                                                 | Melting Point (K)                                                                                         | Properties at 300 K            |                     |                  |                                            | Properties at Various Temperatures (K) |      |      |      |      |      |      |      |      |      |
|-------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|--------------------------------|---------------------|------------------|--------------------------------------------|----------------------------------------|------|------|------|------|------|------|------|------|------|
|                                                                                                             |                                                                                                           | $\rho$<br>(kg/m <sup>3</sup> ) | $c_p$<br>(J/kg · K) | $k$<br>(W/m · K) | $\alpha \cdot 10^6$<br>(m <sup>2</sup> /s) | $k$ (W/m · K)/ $c_p$ (J/kg · K)        |      |      |      |      |      |      |      |      |      |
|                                                                                                             |                                                                                                           |                                |                     |                  |                                            | 100                                    | 200  | 400  | 600  | 800  | 1000 | 1200 | 1500 | 2000 | 2500 |
| Gold                                                                                                        | 1336                                                                                                      | 19300                          | 129                 | 317              | 127                                        | 327                                    | 323  | 311  | 298  | 284  | 270  | 255  |      |      |      |
| Iridium                                                                                                     | 2720                                                                                                      | 22500                          | 130                 | 147              | 50.3                                       | 109                                    | 124  | 131  | 135  | 140  | 145  | 155  |      |      |      |
| Iron                                                                                                        | 1810                                                                                                      | 7870                           | 447                 | 80.2             | 23.1                                       | 172                                    | 153  | 144  | 138  | 132  | 126  | 120  | 111  |      |      |
|                                                                                                             |                                                                                                           |                                |                     |                  |                                            | 90                                     | 122  | 133  | 138  | 144  | 153  | 161  | 172  |      |      |
| Armco<br>(99.75% pure)                                                                                      |                                                                                                           | 7870                           | 447                 | 72.7             | 20.7                                       | 95.6                                   | 80.6 | 65.7 | 53.1 | 42.2 | 32.3 | 28.7 | 31.4 |      |      |
| Carbon steels<br>Plain carbon<br>(Mn $\leq$ 1%,<br>Si $\leq$ 0.1%)                                          | AISI 1010                                                                                                 | 7854                           | 434                 | 60.5             | 17.7                                       | 215                                    | 384  | 490  | 574  | 680  | 975  | 609  | 654  |      |      |
|                                                                                                             |                                                                                                           |                                |                     |                  |                                            |                                        |      |      |      |      |      |      |      |      |      |
| Carbon–silicon<br>(Mn $\leq$ 1%,<br>0.1% < Si $\leq$ 0.6%)                                                  | Carbon–manganese–silicon<br>(1% < Mn $\leq$ 1.65%,<br>0.1% < Si $\leq$ 0.6%)                              | 7832                           | 434                 | 63.9             | 18.8                                       |                                        |      | 56.7 | 48.0 | 39.2 | 30.0 |      |      |      |      |
|                                                                                                             |                                                                                                           |                                |                     |                  |                                            |                                        |      | 487  | 559  | 685  | 1169 |      |      |      |      |
| Carbon–silicon<br>(Mn $\leq$ 1%,<br>0.1% < Si $\leq$ 0.6%)                                                  | Carbon–manganese–silicon<br>(1% < Mn $\leq$ 1.65%,<br>0.1% < Si $\leq$ 0.6%)                              | 7817                           | 446                 | 51.9             | 14.9                                       |                                        |      | 58.7 | 48.8 | 39.2 | 31.3 |      |      |      |      |
|                                                                                                             |                                                                                                           |                                |                     |                  |                                            |                                        |      | 487  | 559  | 685  | 1168 |      |      |      |      |
| Chromium (low) steels<br>$\frac{1}{2}$ Cr– $\frac{1}{4}$ Mo–Si<br>(0.18% C, 0.65% Cr,<br>0.23% Mo, 0.6% Si) | Chromium (low) steels<br>$\frac{1}{2}$ Cr– $\frac{1}{4}$ Mo–Si<br>(0.16% C, 1% Cr,<br>0.54% Mo, 0.39% Si) | 8131                           | 434                 | 41.0             | 11.6                                       |                                        |      | 49.8 | 44.0 | 37.4 | 29.3 |      |      |      |      |
|                                                                                                             |                                                                                                           |                                |                     |                  |                                            |                                        |      | 501  | 582  | 699  | 971  |      |      |      |      |
| Chromium (low) steels<br>$\frac{1}{2}$ Cr– $\frac{1}{4}$ Mo–Si<br>(0.18% C, 0.65% Cr,<br>0.23% Mo, 0.6% Si) | Chromium (low) steels<br>$\frac{1}{2}$ Cr– $\frac{1}{4}$ Mo–Si<br>(0.16% C, 1% Cr,<br>0.54% Mo, 0.39% Si) | 7822                           | 444                 | 37.7             | 10.9                                       |                                        |      | 42.2 | 39.7 | 35.0 | 27.6 |      |      |      |      |
|                                                                                                             |                                                                                                           |                                |                     |                  |                                            |                                        |      | 487  | 559  | 685  | 1090 |      |      |      |      |
| Chromium (low) steels<br>$\frac{1}{2}$ Cr– $\frac{1}{4}$ Mo–Si<br>(0.18% C, 0.65% Cr,<br>0.23% Mo, 0.6% Si) | Chromium (low) steels<br>$\frac{1}{2}$ Cr– $\frac{1}{4}$ Mo–Si<br>(0.16% C, 1% Cr,<br>0.54% Mo, 0.39% Si) | 7858                           | 442                 | 42.3             | 12.2                                       |                                        |      | 38.2 | 36.7 | 33.3 | 26.9 |      |      |      |      |
|                                                                                                             |                                                                                                           |                                |                     |                  |                                            |                                        |      | 492  | 575  | 688  | 969  |      |      |      |      |
| Chromium (low) steels<br>$\frac{1}{2}$ Cr– $\frac{1}{4}$ Mo–Si<br>(0.18% C, 0.65% Cr,<br>0.23% Mo, 0.6% Si) | Chromium (low) steels<br>$\frac{1}{2}$ Cr– $\frac{1}{4}$ Mo–Si<br>(0.16% C, 1% Cr,<br>0.54% Mo, 0.39% Si) | 7836                           | 443                 | 48.9             | 14.1                                       |                                        |      | 42.0 | 39.1 | 34.5 | 27.4 |      |      |      |      |
|                                                                                                             |                                                                                                           |                                |                     |                  |                                            |                                        |      | 492  | 575  | 688  | 969  |      |      |      |      |
| Chromium (low) steels<br>$\frac{1}{2}$ Cr– $\frac{1}{4}$ Mo–Si<br>(0.18% C, 0.65% Cr,<br>0.23% Mo, 0.6% Si) | Chromium (low) steels<br>$\frac{1}{2}$ Cr– $\frac{1}{4}$ Mo–Si<br>(0.16% C, 1% Cr,<br>0.54% Mo, 0.39% Si) | 7836                           | 443                 | 48.9             | 14.1                                       |                                        |      | 46.8 | 42.1 | 36.3 | 28.2 |      |      |      |      |
|                                                                                                             |                                                                                                           |                                |                     |                  |                                            |                                        |      | 492  | 575  | 688  | 969  |      |      |      |      |

|                           |                  |       |       |      |      |      |      |      |      |      |      |      |      |      |      |
|---------------------------|------------------|-------|-------|------|------|------|------|------|------|------|------|------|------|------|------|
| Stainless steels          | AISI 302         | 8055  | 480   | 15.1 | 3.91 |      | 17.3 | 20.0 | 22.8 | 25.4 |      |      |      |      |      |
|                           |                  |       |       |      |      |      | 512  | 559  | 585  | 606  |      |      |      |      |      |
|                           | AISI 304         | 1670  | 477   | 14.9 | 3.95 | 9.2  | 12.6 | 19.8 | 22.6 | 25.4 | 28.0 | 31.7 |      |      |      |
|                           |                  |       |       |      | 272  | 402  | 515  | 557  | 582  | 611  | 640  | 682  |      |      |      |
|                           | AISI 316         | 8238  | 468   | 13.4 | 3.48 |      | 15.2 | 18.3 | 21.3 | 24.2 |      |      |      |      |      |
|                           |                  |       |       |      |      |      | 504  | 550  | 576  | 602  |      |      |      |      |      |
|                           | AISI 347         | 7978  | 480   | 14.2 | 3.71 |      | 15.8 | 18.9 | 21.9 | 24.7 |      |      |      |      |      |
|                           |                  |       |       |      |      |      | 513  | 559  | 585  | 606  |      |      |      |      |      |
|                           | Lead             | 601   | 11340 | 129  | 35.3 | 24.1 | 39.7 | 36.7 | 34.0 | 31.4 |      |      |      |      |      |
|                           |                  |       |       |      |      | 118  | 125  | 132  | 142  |      |      |      |      |      |      |
|                           | Magnesium        | 923   | 1740  | 1024 | 156  | 87.6 | 169  | 159  | 149  | 146  |      |      |      |      |      |
|                           |                  |       |       |      |      | 649  | 934  | 1074 | 1170 | 1267 |      |      |      |      |      |
|                           | Molybdenum       | 2894  | 10240 | 251  | 138  | 53.7 | 179  | 143  | 126  | 118  | 112  | 105  | 98   | 90   | 86   |
|                           |                  |       |       |      |      | 141  | 224  | 261  | 275  | 285  | 295  | 308  | 330  | 380  | 459  |
|                           | Nickel           |       |       |      |      |      |      |      |      |      |      |      |      |      |      |
|                           | Pure             | 1728  | 8900  | 444  | 90.7 | 23.0 | 164  | 107  | 80.2 | 65.6 | 67.6 | 71.8 | 76.2 | 82.6 |      |
|                           |                  |       |       |      |      | 232  | 383  | 485  | 592  | 530  | 562  | 594  | 616  |      |      |
|                           | Nichrome         | 1672  | 8400  | 420  | 12   | 3.4  |      |      | 14   | 16   | 21   |      |      |      |      |
|                           | (80% Ni, 20% Cr) |       |       |      |      |      |      |      | 480  | 525  | 545  |      |      |      |      |
|                           | Inconel X-750    | 1665  | 8510  | 439  | 11.7 | 3.1  | 8.7  | 10.3 | 13.5 | 17.0 | 20.5 | 24.0 | 27.6 | 33.0 |      |
| (73% Ni, 15% Cr, 6.7% Fe) |                  |       |       |      | —    | 372  | 473  | 510  | 546  | 626  | —    | —    | —    |      |      |
| Niobium                   | 2741             | 8570  | 265   | 53.7 | 23.6 | 55.2 | 52.6 | 55.2 | 58.2 | 61.3 | 64.4 | 67.5 | 72.1 | 79.1 |      |
|                           |                  |       |       |      | 188  | 249  | 274  | 283  | 292  | 301  | 310  | 324  | 347  |      |      |
| Palladium                 | 1827             | 12020 | 244   | 71.8 | 24.5 | 76.5 | 71.6 | 73.6 | 79.7 | 86.9 | 94.2 | 102  | 110  |      |      |
|                           |                  |       |       |      | 168  | 227  | 251  | 261  | 271  | 281  | 291  | 307  |      |      |      |
| Platinum                  |                  |       |       |      |      |      |      |      |      |      |      |      |      |      |      |
| Pure                      | 2045             | 21450 | 133   | 71.6 | 25.1 | 77.5 | 72.6 | 71.8 | 73.2 | 75.6 | 78.7 | 82.6 | 89.5 | 99.4 |      |
|                           |                  |       |       |      | 100  | 125  | 136  | 141  | 146  | 152  | 157  | 165  | 179  |      |      |
| Alloy 60Pt–40Rh           | 1800             | 16630 | 162   | 47   | 17.4 |      |      | 52   | 59   | 65   | 69   | 73   | 76   |      |      |
| (60% Pt, 40% Rh)          |                  |       |       |      |      |      |      | —    | —    | —    | —    | —    | —    |      |      |
| Rhenium                   | 3453             | 21100 | 136   | 47.9 | 16.7 | 58.9 | 51.0 | 46.1 | 44.2 | 44.1 | 44.6 | 45.7 | 47.8 | 51.9 |      |
|                           |                  |       |       |      | 97   | 127  | 139  | 145  | 151  | 156  | 162  | 171  | 186  |      |      |
| Rhodium                   | 2236             | 12450 | 243   | 150  | 49.6 | 186  | 154  | 146  | 136  | 127  | 121  | 116  | 110  | 112  |      |
|                           |                  |       |       |      | 147  | 220  | 253  | 274  | 293  | 311  | 327  | 349  | 376  |      |      |
| Silicon                   | 1685             | 2330  | 712   | 148  | 89.2 | 884  | 264  | 98.9 | 61.9 | 42.2 | 31.2 | 25.7 | 22.7 |      |      |
|                           |                  |       |       |      | 259  | 556  | 790  | 867  | 913  | 946  | 967  | 992  |      |      |      |
| Silver                    | 1235             | 10500 | 235   | 429  | 174  | 444  | 430  | 425  | 412  | 396  | 379  | 361  |      |      |      |
|                           |                  |       |       |      | 187  | 225  | 239  | 250  | 262  | 277  | 292  |      |      |      |      |
| Tantalum                  | 3269             | 16600 | 140   | 57.5 | 24.7 | 59.2 | 57.5 | 57.8 | 58.6 | 59.4 | 60.2 | 61.0 | 62.2 | 64.1 | 65.6 |
|                           |                  |       |       |      | 110  | 133  | 144  | 146  | 149  | 152  | 155  | 160  | 172  | 189  |      |
| Thorium                   | 2023             | 11700 | 118   | 54.0 | 39.1 | 59.8 | 54.6 | 54.5 | 55.8 | 56.9 | 56.9 | 58.7 |      |      |      |
|                           |                  |       |       |      | 99   | 112  | 124  | 134  | 145  | 156  | 167  |      |      |      |      |
| Tin                       | 505              | 7310  | 227   | 66.6 | 40.1 | 85.2 | 73.3 | 62.2 |      |      |      |      |      |      |      |
|                           |                  |       |       |      | 188  | 215  | 243  |      |      |      |      |      |      |      |      |

TABLE A.1 Continued

| Composition | Melting Point (K) | Properties at 300 K            |                     |                  |                                            | Properties at Various Temperatures (K) |      |      |      |      |      |      |      |      |      |
|-------------|-------------------|--------------------------------|---------------------|------------------|--------------------------------------------|----------------------------------------|------|------|------|------|------|------|------|------|------|
|             |                   | $\rho$<br>(kg/m <sup>3</sup> ) | $c_p$<br>(J/kg · K) | $k$<br>(W/m · K) | $\alpha \cdot 10^6$<br>(m <sup>2</sup> /s) | $k$ (W/m · K)/ $c_p$ (J/kg · K)        |      |      |      |      |      |      |      |      |      |
|             |                   |                                |                     |                  |                                            | 100                                    | 200  | 400  | 600  | 800  | 1000 | 1200 | 1500 | 2000 | 2500 |
| Titanium    | 1953              | 4500                           | 522                 | 21.9             | 9.32                                       | 30.5                                   | 24.5 | 20.4 | 19.4 | 19.7 | 20.7 | 22.0 | 24.5 |      |      |
| Tungsten    | 3660              | 19300                          | 132                 | 174              | 68.3                                       | 208                                    | 186  | 159  | 137  | 125  | 118  | 113  | 107  | 100  | 95   |
| Uranium     | 1406              | 19070                          | 116                 | 27.6             | 12.5                                       | 21.7                                   | 25.1 | 29.6 | 34.0 | 38.8 | 43.9 | 49.0 | 157  | 167  | 176  |
| Vanadium    | 2192              | 6100                           | 489                 | 30.7             | 10.3                                       | 35.8                                   | 31.3 | 31.3 | 33.3 | 35.7 | 38.2 | 40.8 | 44.6 | 50.9 |      |
| Zinc        | 693               | 7140                           | 389                 | 116              | 41.8                                       | 117                                    | 118  | 111  | 103  | 563  | 597  | 645  | 714  | 867  |      |
| Zirconium   | 2125              | 6570                           | 278                 | 22.7             | 12.4                                       | 33.2                                   | 25.2 | 21.6 | 20.7 | 21.6 | 23.7 | 26.0 | 28.8 | 33.0 |      |
|             |                   |                                |                     |                  |                                            | 205                                    | 264  | 300  | 322  | 342  | 362  | 344  | 344  | 344  |      |

<sup>a</sup>Adapted from References 1–7.

TABLE A.2 Thermophysical Properties of Selected Nonmetallic Solids<sup>a</sup>

| Composition                              | Melting Point (K) | Properties at 300 K            |                     |                  |                                            |  | Properties at Various Temperatures (K) |      |      |      |      |      |      |      |      |      |
|------------------------------------------|-------------------|--------------------------------|---------------------|------------------|--------------------------------------------|--|----------------------------------------|------|------|------|------|------|------|------|------|------|
|                                          |                   | $\rho$<br>(kg/m <sup>3</sup> ) | $c_p$<br>(J/kg · K) | $k$<br>(W/m · K) | $\alpha \cdot 10^6$<br>(m <sup>2</sup> /s) |  | $k$ (W/m · K)/ $c_p$ (J/kg · K)        |      |      |      |      |      |      |      |      |      |
|                                          |                   |                                |                     |                  |                                            |  | 100                                    | 200  | 400  | 600  | 800  | 1000 | 1200 | 1500 | 2000 | 2500 |
| Aluminum oxide, sapphire                 | 2323              | 3970                           | 765                 | 46               | 15.1                                       |  | 450                                    | 82   | 32.4 | 18.9 | 13.0 | 10.5 |      |      |      |      |
|                                          |                   |                                |                     |                  |                                            |  | —                                      | —    | 940  | 1110 | 1180 | 1225 |      |      |      |      |
| Aluminum oxide, polycrystalline          | 2323              | 3970                           | 765                 | 36.0             | 11.9                                       |  | 133                                    | 55   | 26.4 | 15.8 | 10.4 | 7.85 | 6.55 | 5.66 | 6.00 |      |
| Beryllium oxide                          | 2725              | 3000                           | 1030                | 272              | 88.0                                       |  | —                                      | —    | 940  | 1110 | 1180 | 1225 | —    | —    | —    |      |
|                                          |                   |                                |                     |                  |                                            |  |                                        |      | 196  | 111  | 70   | 47   | 33   | 21.5 | 15   |      |
| Boron                                    | 2573              | 2500                           | 1105                | 27.6             | 9.99                                       |  | 190                                    | 52.5 | 1350 | 1690 | 1865 | 1975 | 2055 | 2145 | 2750 |      |
|                                          |                   |                                |                     |                  |                                            |  | —                                      | —    | 18.7 | 11.3 | 8.1  | 6.3  | 5.2  |      |      |      |
|                                          |                   |                                |                     |                  |                                            |  |                                        |      | 1490 | 1880 | 2135 | 2350 | 2555 |      |      |      |
| Boron fiber epoxy (30% vol) composite    | 590               | 2080                           |                     |                  |                                            |  |                                        |      |      |      |      |      |      |      |      |      |
| $k$ ,    to fibers                       |                   |                                |                     | 2.29             |                                            |  | 2.10                                   | 2.23 | 2.28 |      |      |      |      |      |      |      |
| $k$ , ⊥ to fibers                        |                   |                                |                     | 0.59             |                                            |  | 0.37                                   | 0.49 | 0.60 |      |      |      |      |      |      |      |
| $c_p$                                    |                   |                                | 1122                |                  |                                            |  | 364                                    | 757  | 1431 |      |      |      |      |      |      |      |
| Carbon                                   |                   |                                |                     |                  |                                            |  |                                        |      |      |      |      |      |      |      |      |      |
| Amorphous                                | 1500              | 1950                           | —                   | 1.60             | —                                          |  | —                                      | 1.18 | 1.89 | 2.19 | 2.37 | 2.53 | 2.84 | 3.48 | —    |      |
| Diamond, type IIa insulator              | —                 | 3500                           | 509                 | 2300             | —                                          |  | 10,000                                 | 4000 | 1540 |      |      |      |      |      |      |      |
|                                          |                   |                                |                     |                  |                                            |  | 21                                     | 194  | 853  |      |      |      |      |      |      |      |
| Graphite, pyrolytic                      | 2273              | 2210                           |                     | 1950             |                                            |  | 4970                                   | 3230 | 1390 | 892  | 667  | 534  | 448  | 357  | 262  |      |
| $k$ ,    to layers                       |                   |                                |                     |                  |                                            |  | 16.8                                   | 9.23 | 4.09 | 2.68 | 2.01 | 1.60 | 1.34 | 1.08 | 0.81 |      |
| $k$ , ⊥ to layers                        |                   |                                |                     | 5.70             |                                            |  | 136                                    | 411  | 992  | 1406 | 1650 | 1793 | 1890 | 1974 | 2043 |      |
| $c_p$                                    |                   |                                | 709                 |                  |                                            |  |                                        |      |      |      |      |      |      |      |      |      |
| Graphite fiber epoxy (25% vol) composite | 450               | 1400                           |                     |                  |                                            |  |                                        |      |      |      |      |      |      |      |      |      |
| $k$ , heat flow    to fibers             |                   |                                |                     | 11.1             |                                            |  | 5.7                                    | 8.7  | 13.0 |      |      |      |      |      |      |      |
| $k$ , heat flow ⊥ to fibers              |                   |                                |                     | 0.87             |                                            |  | 0.46                                   | 0.68 | 1.1  |      |      |      |      |      |      |      |
| $c_p$                                    |                   |                                | 935                 |                  |                                            |  | 337                                    | 642  | 1216 |      |      |      |      |      |      |      |
| Pyroceram, Corning 9606                  | 1623              | 2600                           | 808                 | 3.98             | 1.89                                       |  | —                                      | 4.78 | 3.64 | 3.28 | 3.08 | 2.96 | 2.87 | 2.79 |      |      |
|                                          |                   |                                |                     |                  |                                            |  |                                        | —    | 908  | 1038 | 1122 | 1197 | 1264 | 1498 |      |      |

TABLE A.2 Continued

| Composition                                                                                                  | Melting Point (K) | Properties at 300 K         |                  |               |                                         | Properties at Various Temperatures (K) |       |      |      |      |      |      |      |      |      |  |
|--------------------------------------------------------------------------------------------------------------|-------------------|-----------------------------|------------------|---------------|-----------------------------------------|----------------------------------------|-------|------|------|------|------|------|------|------|------|--|
|                                                                                                              |                   | $\rho$ (kg/m <sup>3</sup> ) | $c_p$ (J/kg · K) | $k$ (W/m · K) | $\alpha \cdot 10^6$ (m <sup>2</sup> /s) | $k$ (W/m · K)/ $c_p$ (J/kg · K)        |       |      |      |      |      |      |      |      |      |  |
|                                                                                                              |                   |                             |                  |               |                                         | 100                                    | 200   | 400  | 600  | 800  | 1000 | 1200 | 1500 | 2000 | 2500 |  |
| Silicon carbide                                                                                              | 3100              | 3160                        | 675              | 490           | 230                                     |                                        |       | —    | 880  | —    | —    | 87   | 58   | 30   |      |  |
| Silicon dioxide, crystalline (quartz)<br>$k$ , $\parallel$ to $c$ axis<br>$k$ , $\perp$ to $c$ axis<br>$c_p$ | 1883              | 2650                        | 745              | 10.4          |                                         | 39                                     | 16.4  | 7.6  | 5.0  | 4.2  |      |      |      |      |      |  |
|                                                                                                              |                   |                             |                  | 6.21          | 20.8                                    | 9.5                                    | 4.70  | 3.4  | 3.1  |      |      |      |      |      |      |  |
|                                                                                                              |                   |                             |                  |               | —                                       | —                                      | 885   | 1075 | 1250 |      |      |      |      |      |      |  |
| Silicon dioxide, polycrystalline (fused silica)                                                              | 1883              | 2220                        | 745              | 1.38          | 0.834                                   | 0.69                                   | 1.14  | 1.51 | 1.75 | 2.17 | 2.87 | 4.00 |      |      |      |  |
| Silicon nitride                                                                                              | 2173              | 2400                        | 691              | 16.0          | 9.65                                    | —                                      | —     | 13.9 | 11.3 | 9.88 | 8.76 | 8.00 | 7.16 | 6.20 |      |  |
| Sulfur                                                                                                       | 392               | 2070                        | 708              | 0.206         | 0.141                                   | —                                      | 578   | 778  | 937  | 1063 | 1155 | 1226 | 1306 | 1377 |      |  |
| Thorium dioxide                                                                                              | 3573              | 9110                        | 235              | 13            | 6.1                                     | 403                                    | 0.185 | 10.2 | 6.6  | 4.7  | 3.68 | 3.12 | 2.73 | 2.5  |      |  |
| Titanium dioxide, polycrystalline                                                                            | 2133              | 4157                        | 710              | 8.4           | 2.8                                     |                                        |       | 255  | 274  | 285  | 295  | 303  | 315  | 330  |      |  |
|                                                                                                              |                   |                             |                  |               |                                         | 7.01                                   | 5.02  | 3.94 | 3.46 | 3.28 |      |      |      |      |      |  |
|                                                                                                              |                   |                             |                  |               |                                         | 805                                    |       | 805  | 880  | 910  | 930  | 945  |      |      |      |  |

<sup>a</sup>Adapted from References 1, 2, 3 and 6.

**TABLE A.3** Thermophysical Properties of Common Materials<sup>a</sup>**Structural Building Materials**

| Description/Composition               | Typical Properties at 300 K                |                                         |                                   |
|---------------------------------------|--------------------------------------------|-----------------------------------------|-----------------------------------|
|                                       | Density,<br>$\rho$<br>(kg/m <sup>3</sup> ) | Thermal<br>Conductivity, $k$<br>(W/m·K) | Specic<br>Heat, $c_p$<br>(J/kg·K) |
| Building Boards                       |                                            |                                         |                                   |
| Asbestos–cement board                 | 1920                                       | 0.58                                    | —                                 |
| Gypsum or plaster board               | 800                                        | 0.17                                    | —                                 |
| Plywood                               | 545                                        | 0.12                                    | 1215                              |
| Sheathing, regular density            | 290                                        | 0.055                                   | 1300                              |
| Acoustic tile                         | 290                                        | 0.058                                   | 1340                              |
| Hardboard, siding                     | 640                                        | 0.094                                   | 1170                              |
| Hardboard, high density               | 1010                                       | 0.15                                    | 1380                              |
| Particle board, low density           | 590                                        | 0.078                                   | 1300                              |
| Particle board, high density          | 1000                                       | 0.170                                   | 1300                              |
| Woods                                 |                                            |                                         |                                   |
| Hardwoods (oak, maple)                | 720                                        | 0.16                                    | 1255                              |
| Softwoods (fir, pine)                 | 510                                        | 0.12                                    | 1380                              |
| Masonry Materials                     |                                            |                                         |                                   |
| Cement mortar                         | 1860                                       | 0.72                                    | 780                               |
| Brick, common                         | 1920                                       | 0.72                                    | 835                               |
| Brick, face                           | 2083                                       | 1.3                                     | —                                 |
| Clay tile, hollow                     |                                            |                                         |                                   |
| 1 cell deep, 10 cm thick              | —                                          | 0.52                                    | —                                 |
| 3 cells deep, 30 cm thick             | —                                          | 0.69                                    | —                                 |
| Concrete block, 3 oval cores          |                                            |                                         |                                   |
| Sand/gravel, 20 cm thick              | —                                          | 1.0                                     | —                                 |
| Cinder aggregate, 20 cm thick         | —                                          | 0.67                                    | —                                 |
| Concrete block, rectangular core      |                                            |                                         |                                   |
| 2 cores, 20 cm thick, 16 kg           | —                                          | 1.1                                     | —                                 |
| Same with filled cores                | —                                          | 0.60                                    | —                                 |
| Plastering Materials                  |                                            |                                         |                                   |
| Cement plaster, sand aggregate        | 1860                                       | 0.72                                    | —                                 |
| Gypsum plaster, sand aggregate        | 1680                                       | 0.22                                    | 1085                              |
| Gypsum plaster, vermiculite aggregate | 720                                        | 0.25                                    | —                                 |

TABLE A.3 Continued

*Insulating Materials and Systems*

| Description/Composition                                                                                 | Typical Properties at 300 K                |                                           |                                       |
|---------------------------------------------------------------------------------------------------------|--------------------------------------------|-------------------------------------------|---------------------------------------|
|                                                                                                         | Density,<br>$\rho$<br>(kg/m <sup>3</sup> ) | Thermal<br>Conductivity, $k$<br>(W/m · K) | Specific<br>Heat, $c_p$<br>(J/kg · K) |
| Blanket and Batt                                                                                        |                                            |                                           |                                       |
| Glass fiber, paper faced                                                                                | 16                                         | 0.046                                     | —                                     |
|                                                                                                         | 28                                         | 0.038                                     | —                                     |
|                                                                                                         | 40                                         | 0.035                                     | —                                     |
| Glass fiber, coated; duct liner                                                                         | 32                                         | 0.038                                     | 835                                   |
| Board and Slab                                                                                          |                                            |                                           |                                       |
| Cellular glass                                                                                          | 145                                        | 0.058                                     | 1000                                  |
| Glass fiber, organic bonded                                                                             | 105                                        | 0.036                                     | 795                                   |
| Polystyrene, expanded                                                                                   |                                            |                                           |                                       |
| Extruded (R-12)                                                                                         | 55                                         | 0.027                                     | 1210                                  |
| Molded beads                                                                                            | 16                                         | 0.040                                     | 1210                                  |
| Mineral fiberboard; roofing material                                                                    | 265                                        | 0.049                                     | —                                     |
| Wood, shredded/cemented                                                                                 | 350                                        | 0.087                                     | 1590                                  |
| Cork                                                                                                    | 120                                        | 0.039                                     | 1800                                  |
| Loose Fill                                                                                              |                                            |                                           |                                       |
| Cork, granulated                                                                                        | 160                                        | 0.045                                     | —                                     |
| Diatomaceous silica, coarse                                                                             | 350                                        | 0.069                                     | —                                     |
| Powder                                                                                                  | 400                                        | 0.091                                     | —                                     |
| Diatomaceous silica, fine powder                                                                        | 200                                        | 0.052                                     | —                                     |
|                                                                                                         | 275                                        | 0.061                                     | —                                     |
| Glass fiber, poured or blown                                                                            | 16                                         | 0.043                                     | 835                                   |
| Vermiculite, flakes                                                                                     | 80                                         | 0.068                                     | 835                                   |
|                                                                                                         | 160                                        | 0.063                                     | 1000                                  |
| Formed/Foamed-in-Place                                                                                  |                                            |                                           |                                       |
| Mineral wool granules with asbestos/inorganic binders, sprayed                                          | 190                                        | 0.046                                     | —                                     |
| Polyvinyl acetate cork mastic; sprayed or troweled                                                      | —                                          | 0.100                                     | —                                     |
| Urethane, two-part mixture; rigid foam                                                                  | 70                                         | 0.026                                     | 1045                                  |
| Reflective                                                                                              |                                            |                                           |                                       |
| Aluminum foil separating fluffy glass mats; 10–12 layers, evacuated; for cryogenic applications (150 K) | 40                                         | 0.00016                                   | —                                     |
| Aluminum foil and glass paper laminate; 75–150 layers; evacuated; for cryogenic application (150 K)     | 120                                        | 0.000017                                  | —                                     |
| Typical silica powder, evacuated                                                                        | 160                                        | 0.0017                                    | —                                     |

TABLE A.3 Continued

| Industrial Insulation                |                                       |                               |                                                                          |       |       |       |       |       |       |       |       |       |       |       |       |       |
|--------------------------------------|---------------------------------------|-------------------------------|--------------------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Description/<br>Composition          | Maximum<br>Service<br>Temperature (K) | Typical<br>Density<br>(kg/m³) | Typical Thermal Conductivity, $k$ (W/m · K), at Various Temperatures (K) |       |       |       |       |       |       |       |       |       |       |       |       |       |
|                                      |                                       |                               | 200                                                                      | 215   | 230   | 240   | 255   | 270   | 285   | 300   | 310   | 365   | 420   | 530   | 645   | 750   |
| Blankets                             |                                       |                               |                                                                          |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Blanket, mineral fiber,              | 920                                   | 96–192                        |                                                                          |       |       |       |       |       |       |       |       | 0.038 | 0.046 | 0.056 | 0.078 |       |
| metal reinforced                     | 815                                   | 40–96                         |                                                                          |       |       |       |       |       |       |       |       | 0.035 | 0.045 | 0.058 | 0.088 |       |
| Blanket, mineral fiber,              | 450                                   | 10                            |                                                                          |       |       | 0.036 | 0.038 | 0.040 | 0.043 | 0.048 | 0.052 | 0.076 |       |       |       |       |
| glass; fine fiber,                   |                                       |                               |                                                                          |       |       |       |       |       |       |       |       |       |       |       |       |       |
| organic bonded                       |                                       | 12                            |                                                                          |       |       | 0.035 | 0.036 | 0.039 | 0.042 | 0.046 | 0.049 | 0.069 |       |       |       |       |
|                                      |                                       | 16                            |                                                                          |       |       | 0.033 | 0.035 | 0.036 | 0.039 | 0.042 | 0.046 | 0.062 |       |       |       |       |
|                                      |                                       | 24                            |                                                                          |       |       | 0.030 | 0.032 | 0.033 | 0.036 | 0.039 | 0.040 | 0.053 |       |       |       |       |
|                                      |                                       | 32                            |                                                                          |       |       | 0.029 | 0.030 | 0.032 | 0.033 | 0.036 | 0.038 | 0.048 |       |       |       |       |
|                                      |                                       | 48                            |                                                                          |       |       | 0.027 | 0.029 | 0.030 | 0.032 | 0.033 | 0.035 | 0.045 |       |       |       |       |
| Blanket, alumina–silica fiber        |                                       |                               |                                                                          |       |       |       |       |       |       |       |       |       |       |       |       |       |
|                                      | 1530                                  | 48                            |                                                                          |       |       |       |       |       |       |       |       |       |       |       | 0.071 | 0.105 |
|                                      |                                       | 64                            |                                                                          |       |       |       |       |       |       |       |       |       |       |       | 0.059 | 0.087 |
|                                      |                                       | 96                            |                                                                          |       |       |       |       |       |       |       |       |       |       |       | 0.052 | 0.076 |
|                                      |                                       | 128                           |                                                                          |       |       |       |       |       |       |       |       |       |       |       | 0.049 | 0.068 |
| Felt, semirigid;                     | 480                                   | 50–125                        |                                                                          |       |       |       |       |       |       |       |       |       |       |       |       | 0.091 |
| organic bonded                       | 730                                   | 50                            | 0.023                                                                    | 0.025 | 0.026 | 0.027 | 0.029 | 0.030 | 0.032 | 0.033 | 0.035 | 0.051 | 0.063 |       |       |       |
| Felt, laminated;                     |                                       |                               |                                                                          |       |       |       |       |       |       |       |       |       |       |       |       |       |
| no binder                            | 920                                   | 120                           |                                                                          |       |       |       |       |       |       |       |       |       |       | 0.051 | 0.065 | 0.087 |
| Blocks, Boards, and Pipe Insulations |                                       |                               |                                                                          |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Asbestos paper,                      |                                       |                               |                                                                          |       |       |       |       |       |       |       |       |       |       |       |       |       |
| laminated and                        |                                       |                               |                                                                          |       |       |       |       |       |       |       |       |       |       |       |       |       |
| corrugated                           |                                       |                               |                                                                          |       |       |       |       |       |       |       |       |       |       |       |       |       |
| 4-ply                                | 420                                   | 190                           |                                                                          |       |       |       |       |       |       | 0.078 | 0.082 | 0.098 |       |       |       |       |
| 6-ply                                | 420                                   | 255                           |                                                                          |       |       |       |       |       |       | 0.071 | 0.074 | 0.085 |       |       |       |       |
| 8-ply                                | 420                                   | 300                           |                                                                          |       |       |       |       |       |       | 0.068 | 0.071 | 0.082 |       |       |       |       |
| Magnesia, 85%                        | 590                                   | 185                           |                                                                          |       |       |       |       |       |       |       | 0.051 | 0.055 | 0.061 |       |       |       |
| Calcium silicate                     | 920                                   | 190                           |                                                                          |       |       |       |       |       |       |       | 0.055 | 0.059 | 0.063 | 0.075 | 0.089 | 0.104 |

TABLE A.3 Continued

Industrial Insulation (Continued)

| Description/<br>Composition      | Maximum<br>Service<br>Temperature (K) | Typical<br>Density<br>(kg/m <sup>3</sup> ) | Typical Thermal Conductivity, <i>k</i> (W/m · K), at Various Temperatures (K) |       |       |       |       |       |       |       |       |       |       |       |       |       |
|----------------------------------|---------------------------------------|--------------------------------------------|-------------------------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                                  |                                       |                                            | 200                                                                           | 215   | 230   | 240   | 255   | 270   | 285   | 300   | 310   | 365   | 420   | 530   | 645   | 750   |
| Cellular glass                   | 700                                   | 145                                        |                                                                               |       | 0.046 | 0.048 | 0.051 | 0.052 | 0.055 | 0.058 | 0.062 | 0.069 | 0.079 |       |       |       |
| Diatomaceous<br>silica           | 1145                                  | 345                                        |                                                                               |       |       |       |       |       |       |       |       |       |       | 0.092 | 0.098 | 0.104 |
|                                  | 1310                                  | 385                                        |                                                                               |       |       |       |       |       |       |       |       |       |       | 0.101 | 0.100 | 0.115 |
| Polystyrene, rigid               |                                       |                                            |                                                                               |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Extruded (R-12)                  | 350                                   | 56                                         | 0.023                                                                         | 0.023 | 0.022 | 0.023 | 0.023 | 0.025 | 0.026 | 0.027 | 0.029 |       |       |       |       |       |
| Extruded (R-12)                  | 350                                   | 35                                         | 0.023                                                                         | 0.023 | 0.023 | 0.025 | 0.025 | 0.026 | 0.027 | 0.029 |       |       |       |       |       |       |
| Molded beads                     | 350                                   | 16                                         | 0.026                                                                         | 0.029 | 0.030 | 0.033 | 0.035 | 0.036 | 0.038 | 0.040 |       |       |       |       |       |       |
| Rubber, rigid                    |                                       |                                            |                                                                               |       |       |       |       |       |       |       |       |       |       |       |       |       |
| foamed                           | 340                                   | 70                                         |                                                                               |       |       |       |       | 0.029 | 0.030 | 0.032 | 0.033 |       |       |       |       |       |
| Insulating Cement                |                                       |                                            |                                                                               |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Mineral fiber                    |                                       |                                            |                                                                               |       |       |       |       |       |       |       |       |       |       |       |       |       |
| (rock, slag or glass)            |                                       |                                            |                                                                               |       |       |       |       |       |       |       |       |       |       |       |       |       |
| With clay binder                 | 1255                                  | 430                                        |                                                                               |       |       |       |       |       |       |       | 0.071 | 0.079 | 0.088 | 0.105 | 0.123 |       |
| With hydraulic<br>setting binder | 922                                   | 560                                        |                                                                               |       |       |       |       |       |       |       | 0.108 | 0.115 | 0.123 | 0.137 |       |       |
| Loose Fill                       |                                       |                                            |                                                                               |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Cellulose, wood                  |                                       |                                            |                                                                               |       |       |       |       |       |       |       |       |       |       |       |       |       |
| or paper pulp                    | —                                     | 45                                         |                                                                               |       |       |       |       |       | 0.038 | 0.039 | 0.042 |       |       |       |       |       |
| Perlite, expanded                | —                                     | 105                                        | 0.036                                                                         | 0.039 | 0.042 | 0.043 | 0.046 | 0.049 | 0.051 | 0.053 | 0.056 |       |       |       |       |       |
| Vermiculite,                     |                                       |                                            |                                                                               |       |       |       |       |       |       |       |       |       |       |       |       |       |
| expanded                         | —                                     | 122                                        |                                                                               |       | 0.056 | 0.058 | 0.061 | 0.063 | 0.065 | 0.068 | 0.071 |       |       |       |       |       |
|                                  |                                       | 80                                         |                                                                               |       | 0.049 | 0.051 | 0.055 | 0.058 | 0.061 | 0.063 | 0.066 |       |       |       |       |       |

**TABLE A.3** Continued**Other Materials**

| Description/<br>Composition                  | Temperature<br>(K) | Density,<br>$\rho$<br>(kg/m <sup>3</sup> ) | Thermal<br>Conductivity, $k$<br>(W/m·K) | Specic<br>Heat, $c_p$<br>(J/kg·K) |
|----------------------------------------------|--------------------|--------------------------------------------|-----------------------------------------|-----------------------------------|
| Asphalt                                      | 300                | 2115                                       | 0.062                                   | 920                               |
| Bakelite                                     | 300                | 1300                                       | 1.4                                     | 1465                              |
| Brick, refractory                            |                    |                                            |                                         |                                   |
| Carborundum                                  | 872                | —                                          | 18.5                                    | —                                 |
|                                              | 1672               | —                                          | 11.0                                    | —                                 |
| Chrome brick                                 | 473                | 3010                                       | 2.3                                     | 835                               |
|                                              | 823                |                                            | 2.5                                     |                                   |
|                                              | 1173               |                                            | 2.0                                     |                                   |
| Diatomaceous<br>silica, fired                | 478                | —                                          | 0.25                                    | —                                 |
|                                              | 1145               | —                                          | 0.30                                    |                                   |
| Fireclay, burnt 1600 K                       | 773                | 2050                                       | 1.0                                     | 960                               |
|                                              | 1073               | —                                          | 1.1                                     |                                   |
|                                              | 1373               | —                                          | 1.1                                     |                                   |
| Fireclay, burnt 1725 K                       | 773                | 2325                                       | 1.3                                     | 960                               |
|                                              | 1073               |                                            | 1.4                                     |                                   |
|                                              | 1373               |                                            | 1.4                                     |                                   |
| Fireclay brick                               | 478                | 2645                                       | 1.0                                     | 960                               |
|                                              | 922                |                                            | 1.5                                     |                                   |
|                                              | 1478               |                                            | 1.8                                     |                                   |
| Magnesite                                    | 478                | —                                          | 3.8                                     | 1130                              |
|                                              | 922                | —                                          | 2.8                                     |                                   |
|                                              | 1478               |                                            | 1.9                                     |                                   |
| Clay                                         | 300                | 1460                                       | 1.3                                     | 880                               |
| Coal, anthracite                             | 300                | 1350                                       | 0.26                                    | 1260                              |
| Concrete (stone mix)                         | 300                | 2300                                       | 1.4                                     | 880                               |
| Cotton                                       | 300                | 80                                         | 0.06                                    | 1300                              |
| Foodstuffs                                   |                    |                                            |                                         |                                   |
| Banana (75.7%<br>water content)              | 300                | 980                                        | 0.481                                   | 3350                              |
| Apple, red (75%<br>water content)            | 300                | 840                                        | 0.513                                   | 3600                              |
| Cake, batter                                 | 300                | 720                                        | 0.223                                   | —                                 |
| Cake, fully baked                            | 300                | 280                                        | 0.121                                   | —                                 |
| Chicken meat, white<br>(74.4% water content) | 198                | —                                          | 1.60                                    | —                                 |
|                                              | 233                | —                                          | 1.49                                    |                                   |
|                                              | 253                |                                            | 1.35                                    |                                   |
|                                              | 263                |                                            | 1.20                                    |                                   |
|                                              | 273                |                                            | 0.476                                   |                                   |
|                                              | 283                |                                            | 0.480                                   |                                   |
|                                              | 293                |                                            | 0.489                                   |                                   |
| Glass                                        |                    |                                            |                                         |                                   |
| Plate (soda lime)                            | 300                | 2500                                       | 1.4                                     | 750                               |
| Pyrex                                        | 300                | 2225                                       | 1.4                                     | 835                               |

**TABLE A.3** *Continued****Other Materials (Continued)***

| Description/<br>Composition | Temperature<br>(K) | Density,<br>$\rho$<br>(kg/m <sup>3</sup> ) | Thermal<br>Conductivity, $k$<br>(W/m·K) | Specic<br>Heat, $c_p$<br>(J/kg·K) |
|-----------------------------|--------------------|--------------------------------------------|-----------------------------------------|-----------------------------------|
| Ice                         | 273                | 920                                        | 1.88                                    | 2040                              |
|                             | 253                | —                                          | 2.03                                    | 1945                              |
| Leather (sole)              | 300                | 998                                        | 0.159                                   | —                                 |
| Paper                       | 300                | 930                                        | 0.180                                   | 1340                              |
| Paraffin                    | 300                | 900                                        | 0.240                                   | 2890                              |
| Rock                        |                    |                                            |                                         |                                   |
| Granite, Barre              | 300                | 2630                                       | 2.79                                    | 775                               |
| Limestone, Salem            | 300                | 2320                                       | 2.15                                    | 810                               |
| Marble, Halston             | 300                | 2680                                       | 2.80                                    | 830                               |
| Quartzite, Sioux            | 300                | 2640                                       | 5.38                                    | 1105                              |
| Sandstone, Berea            | 300                | 2150                                       | 2.90                                    | 745                               |
| Rubber, vulcanized          |                    |                                            |                                         |                                   |
| Soft                        | 300                | 1100                                       | 0.13                                    | 2010                              |
| Hard                        | 300                | 1190                                       | 0.16                                    | —                                 |
| Sand                        | 300                | 1515                                       | 0.27                                    | 800                               |
| Soil                        | 300                | 2050                                       | 0.52                                    | 1840                              |
| Snow                        | 273                | 110                                        | 0.049                                   | —                                 |
|                             |                    | 500                                        | 0.190                                   | —                                 |
| Teflon                      | 300                | 2200                                       | 0.35                                    | —                                 |
|                             | 400                |                                            | 0.45                                    | —                                 |
| Tissue, human               |                    |                                            |                                         |                                   |
| Skin                        | 300                | —                                          | 0.37                                    | —                                 |
| Fat layer (adipose)         | 300                | —                                          | 0.2                                     | —                                 |
| Muscle                      | 300                | —                                          | 0.5                                     | —                                 |
| Wood, cross grain           |                    |                                            |                                         |                                   |
| Balsa                       | 300                | 140                                        | 0.055                                   | —                                 |
| Cypress                     | 300                | 465                                        | 0.097                                   | —                                 |
| Fir                         | 300                | 415                                        | 0.11                                    | 2720                              |
| Oak                         | 300                | 545                                        | 0.17                                    | 2385                              |
| Yellow pine                 | 300                | 640                                        | 0.15                                    | 2805                              |
| White pine                  | 300                | 435                                        | 0.11                                    | —                                 |
| Wood, radial                |                    |                                            |                                         |                                   |
| Oak                         | 300                | 545                                        | 0.19                                    | 2385                              |
| Fir                         | 300                | 420                                        | 0.14                                    | 2720                              |

<sup>a</sup>Adapted from References 1 and 8–13.

**TABLE A.4** Thermophysical Properties  
of Gases at Atmospheric Pressure<sup>a</sup>

| $T$<br>(K)                                                                | $\rho$<br>(kg/m <sup>3</sup> ) | $c_p$<br>(kJ/kg·K) | $\mu \cdot 10^7$<br>(N·s/m <sup>2</sup> ) | $\nu \cdot 10^6$<br>(m <sup>2</sup> /s) | $k \cdot 10^3$<br>(W/m·K) | $\alpha \cdot 10^6$<br>(m <sup>2</sup> /s) | $Pr$  |
|---------------------------------------------------------------------------|--------------------------------|--------------------|-------------------------------------------|-----------------------------------------|---------------------------|--------------------------------------------|-------|
| <b>Air, <math>\mathcal{M} = 28.97</math> kg/kmol</b>                      |                                |                    |                                           |                                         |                           |                                            |       |
| 100                                                                       | 3.5562                         | 1.032              | 71.1                                      | 2.00                                    | 9.34                      | 2.54                                       | 0.786 |
| 150                                                                       | 2.3364                         | 1.012              | 103.4                                     | 4.426                                   | 13.8                      | 5.84                                       | 0.758 |
| 200                                                                       | 1.7458                         | 1.007              | 132.5                                     | 7.590                                   | 18.1                      | 10.3                                       | 0.737 |
| 250                                                                       | 1.3947                         | 1.006              | 159.6                                     | 11.44                                   | 22.3                      | 15.9                                       | 0.720 |
| 300                                                                       | 1.1614                         | 1.007              | 184.6                                     | 15.89                                   | 26.3                      | 22.5                                       | 0.707 |
| 350                                                                       | 0.9950                         | 1.009              | 208.2                                     | 20.92                                   | 30.0                      | 29.9                                       | 0.700 |
| 400                                                                       | 0.8711                         | 1.014              | 230.1                                     | 26.41                                   | 33.8                      | 38.3                                       | 0.690 |
| 450                                                                       | 0.7740                         | 1.021              | 250.7                                     | 32.39                                   | 37.3                      | 47.2                                       | 0.686 |
| 500                                                                       | 0.6964                         | 1.030              | 270.1                                     | 38.79                                   | 40.7                      | 56.7                                       | 0.684 |
| 550                                                                       | 0.6329                         | 1.040              | 288.4                                     | 45.57                                   | 43.9                      | 66.7                                       | 0.683 |
| 600                                                                       | 0.5804                         | 1.051              | 305.8                                     | 52.69                                   | 46.9                      | 76.9                                       | 0.685 |
| 650                                                                       | 0.5356                         | 1.063              | 322.5                                     | 60.21                                   | 49.7                      | 87.3                                       | 0.690 |
| 700                                                                       | 0.4975                         | 1.075              | 338.8                                     | 68.10                                   | 52.4                      | 98.0                                       | 0.695 |
| 750                                                                       | 0.4643                         | 1.087              | 354.6                                     | 76.37                                   | 54.9                      | 109                                        | 0.702 |
| 800                                                                       | 0.4354                         | 1.099              | 369.8                                     | 84.93                                   | 57.3                      | 120                                        | 0.709 |
| 850                                                                       | 0.4097                         | 1.110              | 384.3                                     | 93.80                                   | 59.6                      | 131                                        | 0.716 |
| 900                                                                       | 0.3868                         | 1.121              | 398.1                                     | 102.9                                   | 62.0                      | 143                                        | 0.720 |
| 950                                                                       | 0.3666                         | 1.131              | 411.3                                     | 112.2                                   | 64.3                      | 155                                        | 0.723 |
| 1000                                                                      | 0.3482                         | 1.141              | 424.4                                     | 121.9                                   | 66.7                      | 168                                        | 0.726 |
| 1100                                                                      | 0.3166                         | 1.159              | 449.0                                     | 141.8                                   | 71.5                      | 195                                        | 0.728 |
| 1200                                                                      | 0.2902                         | 1.175              | 473.0                                     | 162.9                                   | 76.3                      | 224                                        | 0.728 |
| 1300                                                                      | 0.2679                         | 1.189              | 496.0                                     | 185.1                                   | 82                        | 257                                        | 0.719 |
| 1400                                                                      | 0.2488                         | 1.207              | 530                                       | 213                                     | 91                        | 303                                        | 0.703 |
| 1500                                                                      | 0.2322                         | 1.230              | 557                                       | 240                                     | 100                       | 350                                        | 0.685 |
| 1600                                                                      | 0.2177                         | 1.248              | 584                                       | 268                                     | 106                       | 390                                        | 0.688 |
| 1700                                                                      | 0.2049                         | 1.267              | 611                                       | 298                                     | 113                       | 435                                        | 0.685 |
| 1800                                                                      | 0.1935                         | 1.286              | 637                                       | 329                                     | 120                       | 482                                        | 0.683 |
| 1900                                                                      | 0.1833                         | 1.307              | 663                                       | 362                                     | 128                       | 534                                        | 0.677 |
| 2000                                                                      | 0.1741                         | 1.337              | 689                                       | 396                                     | 137                       | 589                                        | 0.672 |
| 2100                                                                      | 0.1658                         | 1.372              | 715                                       | 431                                     | 147                       | 646                                        | 0.667 |
| 2200                                                                      | 0.1582                         | 1.417              | 740                                       | 468                                     | 160                       | 714                                        | 0.655 |
| 2300                                                                      | 0.1513                         | 1.478              | 766                                       | 506                                     | 175                       | 783                                        | 0.647 |
| 2400                                                                      | 0.1448                         | 1.558              | 792                                       | 547                                     | 196                       | 869                                        | 0.630 |
| 2500                                                                      | 0.1389                         | 1.665              | 818                                       | 589                                     | 222                       | 960                                        | 0.613 |
| 3000                                                                      | 0.1135                         | 2.726              | 955                                       | 841                                     | 486                       | 1570                                       | 0.536 |
| <b>Ammonia (NH<sub>3</sub>), <math>\mathcal{M} = 17.03</math> kg/kmol</b> |                                |                    |                                           |                                         |                           |                                            |       |
| 300                                                                       | 0.6894                         | 2.158              | 101.5                                     | 14.7                                    | 24.7                      | 16.6                                       | 0.887 |
| 320                                                                       | 0.6448                         | 2.170              | 109                                       | 16.9                                    | 27.2                      | 19.4                                       | 0.870 |
| 340                                                                       | 0.6059                         | 2.192              | 116.5                                     | 19.2                                    | 29.3                      | 22.1                                       | 0.872 |
| 360                                                                       | 0.5716                         | 2.221              | 124                                       | 21.7                                    | 31.6                      | 24.9                                       | 0.872 |
| 380                                                                       | 0.5410                         | 2.254              | 131                                       | 24.2                                    | 34.0                      | 27.9                                       | 0.869 |

TABLE A.4 Continued

| $T$<br>(K)                                                                       | $\rho$<br>(kg/m <sup>3</sup> ) | $c_p$<br>(kJ/kg · K) | $\mu \cdot 10^7$<br>(N · s/m <sup>2</sup> ) | $\nu \cdot 10^6$<br>(m <sup>2</sup> /s) | $k \cdot 10^3$<br>(W/m · K) | $\alpha \cdot 10^6$<br>(m <sup>2</sup> /s) | $Pr$  |
|----------------------------------------------------------------------------------|--------------------------------|----------------------|---------------------------------------------|-----------------------------------------|-----------------------------|--------------------------------------------|-------|
| <b>Ammonia (NH<sub>3</sub>) (continued)</b>                                      |                                |                      |                                             |                                         |                             |                                            |       |
| 400                                                                              | 0.5136                         | 2.287                | 138                                         | 26.9                                    | 37.0                        | 31.5                                       | 0.853 |
| 420                                                                              | 0.4888                         | 2.322                | 145                                         | 29.7                                    | 40.4                        | 35.6                                       | 0.833 |
| 440                                                                              | 0.4664                         | 2.357                | 152.5                                       | 32.7                                    | 43.5                        | 39.6                                       | 0.826 |
| 460                                                                              | 0.4460                         | 2.393                | 159                                         | 35.7                                    | 46.3                        | 43.4                                       | 0.822 |
| 480                                                                              | 0.4273                         | 2.430                | 166.5                                       | 39.0                                    | 49.2                        | 47.4                                       | 0.822 |
| 500                                                                              | 0.4101                         | 2.467                | 173                                         | 42.2                                    | 52.5                        | 51.9                                       | 0.813 |
| 520                                                                              | 0.3942                         | 2.504                | 180                                         | 45.7                                    | 54.5                        | 55.2                                       | 0.827 |
| 540                                                                              | 0.3795                         | 2.540                | 186.5                                       | 49.1                                    | 57.5                        | 59.7                                       | 0.824 |
| 560                                                                              | 0.3708                         | 2.577                | 193                                         | 52.0                                    | 60.6                        | 63.4                                       | 0.827 |
| 580                                                                              | 0.3533                         | 2.613                | 199.5                                       | 56.5                                    | 63.8                        | 69.1                                       | 0.817 |
| <b>Carbon Dioxide (CO<sub>2</sub>), <math>\mathcal{M} = 44.01</math> kg/kmol</b> |                                |                      |                                             |                                         |                             |                                            |       |
| 280                                                                              | 1.9022                         | 0.830                | 140                                         | 7.36                                    | 15.20                       | 9.63                                       | 0.765 |
| 300                                                                              | 1.7730                         | 0.851                | 149                                         | 8.40                                    | 16.55                       | 11.0                                       | 0.766 |
| 320                                                                              | 1.6609                         | 0.872                | 156                                         | 9.39                                    | 18.05                       | 12.5                                       | 0.754 |
| 340                                                                              | 1.5618                         | 0.891                | 165                                         | 10.6                                    | 19.70                       | 14.2                                       | 0.746 |
| 360                                                                              | 1.4743                         | 0.908                | 173                                         | 11.7                                    | 21.2                        | 15.8                                       | 0.741 |
| 380                                                                              | 1.3961                         | 0.926                | 181                                         | 13.0                                    | 22.75                       | 17.6                                       | 0.737 |
| 400                                                                              | 1.3257                         | 0.942                | 190                                         | 14.3                                    | 24.3                        | 19.5                                       | 0.737 |
| 450                                                                              | 1.1782                         | 0.981                | 210                                         | 17.8                                    | 28.3                        | 24.5                                       | 0.728 |
| 500                                                                              | 1.0594                         | 1.02                 | 231                                         | 21.8                                    | 32.5                        | 30.1                                       | 0.725 |
| 550                                                                              | 0.9625                         | 1.05                 | 251                                         | 26.1                                    | 36.6                        | 36.2                                       | 0.721 |
| 600                                                                              | 0.8826                         | 1.08                 | 270                                         | 30.6                                    | 40.7                        | 42.7                                       | 0.717 |
| 650                                                                              | 0.8143                         | 1.10                 | 288                                         | 35.4                                    | 44.5                        | 49.7                                       | 0.712 |
| 700                                                                              | 0.7564                         | 1.13                 | 305                                         | 40.3                                    | 48.1                        | 56.3                                       | 0.717 |
| 750                                                                              | 0.7057                         | 1.15                 | 321                                         | 45.5                                    | 51.7                        | 63.7                                       | 0.714 |
| 800                                                                              | 0.6614                         | 1.17                 | 337                                         | 51.0                                    | 55.1                        | 71.2                                       | 0.716 |
| <b>Carbon Monoxide (CO), <math>\mathcal{M} = 28.01</math> kg/kmol</b>            |                                |                      |                                             |                                         |                             |                                            |       |
| 200                                                                              | 1.6888                         | 1.045                | 127                                         | 7.52                                    | 17.0                        | 9.63                                       | 0.781 |
| 220                                                                              | 1.5341                         | 1.044                | 137                                         | 8.93                                    | 19.0                        | 11.9                                       | 0.753 |
| 240                                                                              | 1.4055                         | 1.043                | 147                                         | 10.5                                    | 20.6                        | 14.1                                       | 0.744 |
| 260                                                                              | 1.2967                         | 1.043                | 157                                         | 12.1                                    | 22.1                        | 16.3                                       | 0.741 |
| 280                                                                              | 1.2038                         | 1.042                | 166                                         | 13.8                                    | 23.6                        | 18.8                                       | 0.733 |
| 300                                                                              | 1.1233                         | 1.043                | 175                                         | 15.6                                    | 25.0                        | 21.3                                       | 0.730 |
| 320                                                                              | 1.0529                         | 1.043                | 184                                         | 17.5                                    | 26.3                        | 23.9                                       | 0.730 |
| 340                                                                              | 0.9909                         | 1.044                | 193                                         | 19.5                                    | 27.8                        | 26.9                                       | 0.725 |
| 360                                                                              | 0.9357                         | 1.045                | 202                                         | 21.6                                    | 29.1                        | 29.8                                       | 0.725 |
| 380                                                                              | 0.8864                         | 1.047                | 210                                         | 23.7                                    | 30.5                        | 32.9                                       | 0.729 |
| 400                                                                              | 0.8421                         | 1.049                | 218                                         | 25.9                                    | 31.8                        | 36.0                                       | 0.719 |
| 450                                                                              | 0.7483                         | 1.055                | 237                                         | 31.7                                    | 35.0                        | 44.3                                       | 0.714 |
| 500                                                                              | 0.67352                        | 1.065                | 254                                         | 37.7                                    | 38.1                        | 53.1                                       | 0.710 |
| 550                                                                              | 0.61226                        | 1.076                | 271                                         | 44.3                                    | 41.1                        | 62.4                                       | 0.710 |
| 600                                                                              | 0.56126                        | 1.088                | 286                                         | 51.0                                    | 44.0                        | 72.1                                       | 0.707 |

**TABLE A.4** *Continued*

| $T$<br>(K)                                                                | $\rho$<br>(kg/m <sup>3</sup> ) | $c_p$<br>(kJ/kg·K) | $\mu \cdot 10^7$<br>(N·s/m <sup>2</sup> ) | $\nu \cdot 10^6$<br>(m <sup>2</sup> /s) | $k \cdot 10^3$<br>(W/m·K) | $\alpha \cdot 10^6$<br>(m <sup>2</sup> /s) | $Pr$  |
|---------------------------------------------------------------------------|--------------------------------|--------------------|-------------------------------------------|-----------------------------------------|---------------------------|--------------------------------------------|-------|
| <b>Carbon Monoxide (CO) (<i>continued</i>)</b>                            |                                |                    |                                           |                                         |                           |                                            |       |
| 650                                                                       | 0.51806                        | 1.101              | 301                                       | 58.1                                    | 47.0                      | 82.4                                       | 0.705 |
| 700                                                                       | 0.48102                        | 1.114              | 315                                       | 65.5                                    | 50.0                      | 93.3                                       | 0.702 |
| 750                                                                       | 0.44899                        | 1.127              | 329                                       | 73.3                                    | 52.8                      | 104                                        | 0.702 |
| 800                                                                       | 0.42095                        | 1.140              | 343                                       | 81.5                                    | 55.5                      | 116                                        | 0.705 |
| <b>Helium (He), <math>\mathcal{M} = 4.003</math> kg/kmol</b>              |                                |                    |                                           |                                         |                           |                                            |       |
| 100                                                                       | 0.4871                         | 5.193              | 96.3                                      | 19.8                                    | 73.0                      | 28.9                                       | 0.686 |
| 120                                                                       | 0.4060                         | 5.193              | 107                                       | 26.4                                    | 81.9                      | 38.8                                       | 0.679 |
| 140                                                                       | 0.3481                         | 5.193              | 118                                       | 33.9                                    | 90.7                      | 50.2                                       | 0.676 |
| 160                                                                       | —                              | 5.193              | 129                                       | —                                       | 99.2                      | —                                          | —     |
| 180                                                                       | 0.2708                         | 5.193              | 139                                       | 51.3                                    | 107.2                     | 76.2                                       | 0.673 |
| 200                                                                       | —                              | 5.193              | 150                                       | —                                       | 115.1                     | —                                          | —     |
| 220                                                                       | 0.2216                         | 5.193              | 160                                       | 72.2                                    | 123.1                     | 107                                        | 0.675 |
| 240                                                                       | —                              | 5.193              | 170                                       | —                                       | 130                       | —                                          | —     |
| 260                                                                       | 0.1875                         | 5.193              | 180                                       | 96.0                                    | 137                       | 141                                        | 0.682 |
| 280                                                                       | —                              | 5.193              | 190                                       | —                                       | 145                       | —                                          | —     |
| 300                                                                       | 0.1625                         | 5.193              | 199                                       | 122                                     | 152                       | 180                                        | 0.680 |
| 350                                                                       | —                              | 5.193              | 221                                       | —                                       | 170                       | —                                          | —     |
| 400                                                                       | 0.1219                         | 5.193              | 243                                       | 199                                     | 187                       | 295                                        | 0.675 |
| 450                                                                       | —                              | 5.193              | 263                                       | —                                       | 204                       | —                                          | —     |
| 500                                                                       | 0.09754                        | 5.193              | 283                                       | 290                                     | 220                       | 434                                        | 0.668 |
| 550                                                                       | —                              | 5.193              | —                                         | —                                       | —                         | —                                          | —     |
| 600                                                                       | —                              | 5.193              | 320                                       | —                                       | 252                       | —                                          | —     |
| 650                                                                       | —                              | 5.193              | 332                                       | —                                       | 264                       | —                                          | —     |
| 700                                                                       | 0.06969                        | 5.193              | 350                                       | 502                                     | 278                       | 768                                        | 0.654 |
| 750                                                                       | —                              | 5.193              | 364                                       | —                                       | 291                       | —                                          | —     |
| 800                                                                       | —                              | 5.193              | 382                                       | —                                       | 304                       | —                                          | —     |
| 900                                                                       | —                              | 5.193              | 414                                       | —                                       | 330                       | —                                          | —     |
| 1000                                                                      | 0.04879                        | 5.193              | 446                                       | 914                                     | 354                       | 1400                                       | 0.654 |
| <b>Hydrogen (H<sub>2</sub>), <math>\mathcal{M} = 2.016</math> kg/kmol</b> |                                |                    |                                           |                                         |                           |                                            |       |
| 100                                                                       | 0.24255                        | 11.23              | 42.1                                      | 17.4                                    | 67.0                      | 24.6                                       | 0.707 |
| 150                                                                       | 0.16156                        | 12.60              | 56.0                                      | 34.7                                    | 101                       | 49.6                                       | 0.699 |
| 200                                                                       | 0.12115                        | 13.54              | 68.1                                      | 56.2                                    | 131                       | 79.9                                       | 0.704 |
| 250                                                                       | 0.09693                        | 14.06              | 78.9                                      | 81.4                                    | 157                       | 115                                        | 0.707 |
| 300                                                                       | 0.08078                        | 14.31              | 89.6                                      | 111                                     | 183                       | 158                                        | 0.701 |
| 350                                                                       | 0.06924                        | 14.43              | 98.8                                      | 143                                     | 204                       | 204                                        | 0.700 |
| 400                                                                       | 0.06059                        | 14.48              | 108.2                                     | 179                                     | 226                       | 258                                        | 0.695 |
| 450                                                                       | 0.05386                        | 14.50              | 117.2                                     | 218                                     | 247                       | 316                                        | 0.689 |
| 500                                                                       | 0.04848                        | 14.52              | 126.4                                     | 261                                     | 266                       | 378                                        | 0.691 |
| 550                                                                       | 0.04407                        | 14.53              | 134.3                                     | 305                                     | 285                       | 445                                        | 0.685 |

TABLE A.4 Continued

| $T$<br>(K)                                                                | $\rho$<br>(kg/m <sup>3</sup> ) | $c_p$<br>(kJ/kg·K) | $\mu \cdot 10^7$<br>(N·s/m <sup>2</sup> ) | $\nu \cdot 10^6$<br>(m <sup>2</sup> /s) | $k \cdot 10^3$<br>(W/m·K) | $\alpha \cdot 10^6$<br>(m <sup>2</sup> /s) | $Pr$  |
|---------------------------------------------------------------------------|--------------------------------|--------------------|-------------------------------------------|-----------------------------------------|---------------------------|--------------------------------------------|-------|
| <b>Hydrogen (H<sub>2</sub>) (continued)</b>                               |                                |                    |                                           |                                         |                           |                                            |       |
| 600                                                                       | 0.04040                        | 14.55              | 142.4                                     | 352                                     | 305                       | 519                                        | 0.678 |
| 700                                                                       | 0.03463                        | 14.61              | 157.8                                     | 456                                     | 342                       | 676                                        | 0.675 |
| 800                                                                       | 0.03030                        | 14.70              | 172.4                                     | 569                                     | 378                       | 849                                        | 0.670 |
| 900                                                                       | 0.02694                        | 14.83              | 186.5                                     | 692                                     | 412                       | 1030                                       | 0.671 |
| 1000                                                                      | 0.02424                        | 14.99              | 201.3                                     | 830                                     | 448                       | 1230                                       | 0.673 |
| 1100                                                                      | 0.02204                        | 15.17              | 213.0                                     | 966                                     | 488                       | 1460                                       | 0.662 |
| 1200                                                                      | 0.02020                        | 15.37              | 226.2                                     | 1120                                    | 528                       | 1700                                       | 0.659 |
| 1300                                                                      | 0.01865                        | 15.59              | 238.5                                     | 1279                                    | 568                       | 1955                                       | 0.655 |
| 1400                                                                      | 0.01732                        | 15.81              | 250.7                                     | 1447                                    | 610                       | 2230                                       | 0.650 |
| 1500                                                                      | 0.01616                        | 16.02              | 262.7                                     | 1626                                    | 655                       | 2530                                       | 0.643 |
| 1600                                                                      | 0.0152                         | 16.28              | 273.7                                     | 1801                                    | 697                       | 2815                                       | 0.639 |
| 1700                                                                      | 0.0143                         | 16.58              | 284.9                                     | 1992                                    | 742                       | 3130                                       | 0.637 |
| 1800                                                                      | 0.0135                         | 16.96              | 296.1                                     | 2193                                    | 786                       | 3435                                       | 0.639 |
| 1900                                                                      | 0.0128                         | 17.49              | 307.2                                     | 2400                                    | 835                       | 3730                                       | 0.643 |
| 2000                                                                      | 0.0121                         | 18.25              | 318.2                                     | 2630                                    | 878                       | 3975                                       | 0.661 |
| <b>Nitrogen (N<sub>2</sub>), <math>\mathcal{M} = 28.01</math> kg/kmol</b> |                                |                    |                                           |                                         |                           |                                            |       |
| 100                                                                       | 3.4388                         | 1.070              | 68.8                                      | 2.00                                    | 9.58                      | 2.60                                       | 0.768 |
| 150                                                                       | 2.2594                         | 1.050              | 100.6                                     | 4.45                                    | 13.9                      | 5.86                                       | 0.759 |
| 200                                                                       | 1.6883                         | 1.043              | 129.2                                     | 7.65                                    | 18.3                      | 10.4                                       | 0.736 |
| 250                                                                       | 1.3488                         | 1.042              | 154.9                                     | 11.48                                   | 22.2                      | 15.8                                       | 0.727 |
| 300                                                                       | 1.1233                         | 1.041              | 178.2                                     | 15.86                                   | 25.9                      | 22.1                                       | 0.716 |
| 350                                                                       | 0.9625                         | 1.042              | 200.0                                     | 20.78                                   | 29.3                      | 29.2                                       | 0.711 |
| 400                                                                       | 0.8425                         | 1.045              | 220.4                                     | 26.16                                   | 32.7                      | 37.1                                       | 0.704 |
| 450                                                                       | 0.7485                         | 1.050              | 239.6                                     | 32.01                                   | 35.8                      | 45.6                                       | 0.703 |
| 500                                                                       | 0.6739                         | 1.056              | 257.7                                     | 38.24                                   | 38.9                      | 54.7                                       | 0.700 |
| 550                                                                       | 0.6124                         | 1.065              | 274.7                                     | 44.86                                   | 41.7                      | 63.9                                       | 0.702 |
| 600                                                                       | 0.5615                         | 1.075              | 290.8                                     | 51.79                                   | 44.6                      | 73.9                                       | 0.701 |
| 700                                                                       | 0.4812                         | 1.098              | 321.0                                     | 66.71                                   | 49.9                      | 94.4                                       | 0.706 |
| 800                                                                       | 0.4211                         | 1.122              | 349.1                                     | 82.90                                   | 54.8                      | 116                                        | 0.715 |
| 900                                                                       | 0.3743                         | 1.146              | 375.3                                     | 100.3                                   | 59.7                      | 139                                        | 0.721 |
| 1000                                                                      | 0.3368                         | 1.167              | 399.9                                     | 118.7                                   | 64.7                      | 165                                        | 0.721 |
| 1100                                                                      | 0.3062                         | 1.187              | 423.2                                     | 138.2                                   | 70.0                      | 193                                        | 0.718 |
| 1200                                                                      | 0.2807                         | 1.204              | 445.3                                     | 158.6                                   | 75.8                      | 224                                        | 0.707 |
| 1300                                                                      | 0.2591                         | 1.219              | 466.2                                     | 179.9                                   | 81.0                      | 256                                        | 0.701 |
| <b>Oxygen (O<sub>2</sub>), <math>\mathcal{M} = 32.00</math> kg/kmol</b>   |                                |                    |                                           |                                         |                           |                                            |       |
| 100                                                                       | 3.945                          | 0.962              | 76.4                                      | 1.94                                    | 9.25                      | 2.44                                       | 0.796 |
| 150                                                                       | 2.585                          | 0.921              | 114.8                                     | 4.44                                    | 13.8                      | 5.80                                       | 0.766 |
| 200                                                                       | 1.930                          | 0.915              | 147.5                                     | 7.64                                    | 18.3                      | 10.4                                       | 0.737 |
| 250                                                                       | 1.542                          | 0.915              | 178.6                                     | 11.58                                   | 22.6                      | 16.0                                       | 0.723 |
| 300                                                                       | 1.284                          | 0.920              | 207.2                                     | 16.14                                   | 26.8                      | 22.7                                       | 0.711 |

**TABLE A.4** Continued

| $T$<br>(K)                                                           | $\rho$<br>(kg/m <sup>3</sup> ) | $c_p$<br>(kJ/kg·K) | $\mu \cdot 10^7$<br>(N·s/m <sup>2</sup> ) | $\nu \cdot 10^6$<br>(m <sup>2</sup> /s) | $k \cdot 10^3$<br>(W/m·K) | $\alpha \cdot 10^6$<br>(m <sup>2</sup> /s) | $Pr$  |
|----------------------------------------------------------------------|--------------------------------|--------------------|-------------------------------------------|-----------------------------------------|---------------------------|--------------------------------------------|-------|
| <b>Oxygen (O<sub>2</sub>) (continued)</b>                            |                                |                    |                                           |                                         |                           |                                            |       |
| 350                                                                  | 1.100                          | 0.929              | 233.5                                     | 21.23                                   | 29.6                      | 29.0                                       | 0.733 |
| 400                                                                  | 0.9620                         | 0.942              | 258.2                                     | 26.84                                   | 33.0                      | 36.4                                       | 0.737 |
| 450                                                                  | 0.8554                         | 0.956              | 281.4                                     | 32.90                                   | 36.3                      | 44.4                                       | 0.741 |
| 500                                                                  | 0.7698                         | 0.972              | 303.3                                     | 39.40                                   | 41.2                      | 55.1                                       | 0.716 |
| 550                                                                  | 0.6998                         | 0.988              | 324.0                                     | 46.30                                   | 44.1                      | 63.8                                       | 0.726 |
| 600                                                                  | 0.6414                         | 1.003              | 343.7                                     | 53.59                                   | 47.3                      | 73.5                                       | 0.729 |
| 700                                                                  | 0.5498                         | 1.031              | 380.8                                     | 69.26                                   | 52.8                      | 93.1                                       | 0.744 |
| 800                                                                  | 0.4810                         | 1.054              | 415.2                                     | 86.32                                   | 58.9                      | 116                                        | 0.743 |
| 900                                                                  | 0.4275                         | 1.074              | 447.2                                     | 104.6                                   | 64.9                      | 141                                        | 0.740 |
| 1000                                                                 | 0.3848                         | 1.090              | 477.0                                     | 124.0                                   | 71.0                      | 169                                        | 0.733 |
| 1100                                                                 | 0.3498                         | 1.103              | 505.5                                     | 144.5                                   | 75.8                      | 196                                        | 0.736 |
| 1200                                                                 | 0.3206                         | 1.115              | 532.5                                     | 166.1                                   | 81.9                      | 229                                        | 0.725 |
| 1300                                                                 | 0.2960                         | 1.125              | 588.4                                     | 188.6                                   | 87.1                      | 262                                        | 0.721 |
| <b>Water Vapor (Steam), <math>\mathcal{M} = 18.02</math> kg/kmol</b> |                                |                    |                                           |                                         |                           |                                            |       |
| 380                                                                  | 0.5863                         | 2.060              | 127.1                                     | 21.68                                   | 24.6                      | 20.4                                       | 1.06  |
| 400                                                                  | 0.5542                         | 2.014              | 134.4                                     | 24.25                                   | 26.1                      | 23.4                                       | 1.04  |
| 450                                                                  | 0.4902                         | 1.980              | 152.5                                     | 31.11                                   | 29.9                      | 30.8                                       | 1.01  |
| 500                                                                  | 0.4405                         | 1.985              | 170.4                                     | 38.68                                   | 33.9                      | 38.8                                       | 0.998 |
| 550                                                                  | 0.4005                         | 1.997              | 188.4                                     | 47.04                                   | 37.9                      | 47.4                                       | 0.993 |
| 600                                                                  | 0.3652                         | 2.026              | 206.7                                     | 56.60                                   | 42.2                      | 57.0                                       | 0.993 |
| 650                                                                  | 0.3380                         | 2.056              | 224.7                                     | 66.48                                   | 46.4                      | 66.8                                       | 0.996 |
| 700                                                                  | 0.3140                         | 2.085              | 242.6                                     | 77.26                                   | 50.5                      | 77.1                                       | 1.00  |
| 750                                                                  | 0.2931                         | 2.119              | 260.4                                     | 88.84                                   | 54.9                      | 88.4                                       | 1.00  |
| 800                                                                  | 0.2739                         | 2.152              | 278.6                                     | 101.7                                   | 59.2                      | 100                                        | 1.01  |
| 850                                                                  | 0.2579                         | 2.186              | 296.9                                     | 115.1                                   | 63.7                      | 113                                        | 1.02  |

<sup>a</sup>Adapted from References 8, 14, and 15.

**TABLE A.5** Thermophysical Properties of Saturated Fluids<sup>a</sup>

| Saturated Liquids                                                  |                                |                                     |                                             |                                         |                                         |                                            |           |                                          |
|--------------------------------------------------------------------|--------------------------------|-------------------------------------|---------------------------------------------|-----------------------------------------|-----------------------------------------|--------------------------------------------|-----------|------------------------------------------|
| <i>T</i><br>(K)                                                    | $\rho$<br>(kg/m <sup>3</sup> ) | <i>c<sub>p</sub></i><br>(kJ/kg · K) | $\mu \cdot 10^2$<br>(N · s/m <sup>2</sup> ) | $\nu \cdot 10^6$<br>(m <sup>2</sup> /s) | <i>k</i> · 10 <sup>3</sup><br>(W/m · K) | $\alpha \cdot 10^7$<br>(m <sup>2</sup> /s) | <i>Pr</i> | $\beta \cdot 10^3$<br>(K <sup>-1</sup> ) |
| Engine Oil (Unused)                                                |                                |                                     |                                             |                                         |                                         |                                            |           |                                          |
| 273                                                                | 899.1                          | 1.796                               | 385                                         | 4280                                    | 147                                     | 0.910                                      | 47,000    | 0.70                                     |
| 280                                                                | 895.3                          | 1.827                               | 217                                         | 2430                                    | 144                                     | 0.880                                      | 27,500    | 0.70                                     |
| 290                                                                | 890.0                          | 1.868                               | 99.9                                        | 1120                                    | 145                                     | 0.872                                      | 12,900    | 0.70                                     |
| 300                                                                | 884.1                          | 1.909                               | 48.6                                        | 550                                     | 145                                     | 0.859                                      | 6400      | 0.70                                     |
| 310                                                                | 877.9                          | 1.951                               | 25.3                                        | 288                                     | 145                                     | 0.847                                      | 3400      | 0.70                                     |
| 320                                                                | 871.8                          | 1.993                               | 14.1                                        | 161                                     | 143                                     | 0.823                                      | 1965      | 0.70                                     |
| 330                                                                | 865.8                          | 2.035                               | 8.36                                        | 96.6                                    | 141                                     | 0.800                                      | 1205      | 0.70                                     |
| 340                                                                | 859.9                          | 2.076                               | 5.31                                        | 61.7                                    | 139                                     | 0.779                                      | 793       | 0.70                                     |
| 350                                                                | 853.9                          | 2.118                               | 3.56                                        | 41.7                                    | 138                                     | 0.763                                      | 546       | 0.70                                     |
| 360                                                                | 847.8                          | 2.161                               | 2.52                                        | 29.7                                    | 138                                     | 0.753                                      | 395       | 0.70                                     |
| 370                                                                | 841.8                          | 2.206                               | 1.86                                        | 22.0                                    | 137                                     | 0.738                                      | 300       | 0.70                                     |
| 380                                                                | 836.0                          | 2.250                               | 1.41                                        | 16.9                                    | 136                                     | 0.723                                      | 233       | 0.70                                     |
| 390                                                                | 830.6                          | 2.294                               | 1.10                                        | 13.3                                    | 135                                     | 0.709                                      | 187       | 0.70                                     |
| 400                                                                | 825.1                          | 2.337                               | 0.874                                       | 10.6                                    | 134                                     | 0.695                                      | 152       | 0.70                                     |
| 410                                                                | 818.9                          | 2.381                               | 0.698                                       | 8.52                                    | 133                                     | 0.682                                      | 125       | 0.70                                     |
| 420                                                                | 812.1                          | 2.427                               | 0.564                                       | 6.94                                    | 133                                     | 0.675                                      | 103       | 0.70                                     |
| 430                                                                | 806.5                          | 2.471                               | 0.470                                       | 5.83                                    | 132                                     | 0.662                                      | 88        | 0.70                                     |
| Ethylene Glycol [C <sub>2</sub> H <sub>4</sub> (OH) <sub>2</sub> ] |                                |                                     |                                             |                                         |                                         |                                            |           |                                          |
| 273                                                                | 1130.8                         | 2.294                               | 6.51                                        | 57.6                                    | 242                                     | 0.933                                      | 617       | 0.65                                     |
| 280                                                                | 1125.8                         | 2.323                               | 4.20                                        | 37.3                                    | 244                                     | 0.933                                      | 400       | 0.65                                     |
| 290                                                                | 1118.8                         | 2.368                               | 2.47                                        | 22.1                                    | 248                                     | 0.936                                      | 236       | 0.65                                     |
| 300                                                                | 1114.4                         | 2.415                               | 1.57                                        | 14.1                                    | 252                                     | 0.939                                      | 151       | 0.65                                     |
| 310                                                                | 1103.7                         | 2.460                               | 1.07                                        | 9.65                                    | 255                                     | 0.939                                      | 103       | 0.65                                     |
| 320                                                                | 1096.2                         | 2.505                               | 0.757                                       | 6.91                                    | 258                                     | 0.940                                      | 73.5      | 0.65                                     |
| 330                                                                | 1089.5                         | 2.549                               | 0.561                                       | 5.15                                    | 260                                     | 0.936                                      | 55.0      | 0.65                                     |
| 340                                                                | 1083.8                         | 2.592                               | 0.431                                       | 3.98                                    | 261                                     | 0.929                                      | 42.8      | 0.65                                     |
| 350                                                                | 1079.0                         | 2.637                               | 0.342                                       | 3.17                                    | 261                                     | 0.917                                      | 34.6      | 0.65                                     |
| 360                                                                | 1074.0                         | 2.682                               | 0.278                                       | 2.59                                    | 261                                     | 0.906                                      | 28.6      | 0.65                                     |
| 370                                                                | 1066.7                         | 2.728                               | 0.228                                       | 2.14                                    | 262                                     | 0.900                                      | 23.7      | 0.65                                     |
| 373                                                                | 1058.5                         | 2.742                               | 0.215                                       | 2.03                                    | 263                                     | 0.906                                      | 22.4      | 0.65                                     |
| Glycerin [C <sub>3</sub> H <sub>5</sub> (OH) <sub>3</sub> ]        |                                |                                     |                                             |                                         |                                         |                                            |           |                                          |
| 273                                                                | 1276.0                         | 2.261                               | 1060                                        | 8310                                    | 282                                     | 0.977                                      | 85,000    | 0.47                                     |
| 280                                                                | 1271.9                         | 2.298                               | 534                                         | 4200                                    | 284                                     | 0.972                                      | 43,200    | 0.47                                     |
| 290                                                                | 1265.8                         | 2.367                               | 185                                         | 1460                                    | 286                                     | 0.955                                      | 15,300    | 0.48                                     |
| 300                                                                | 1259.9                         | 2.427                               | 79.9                                        | 634                                     | 286                                     | 0.935                                      | 6780      | 0.48                                     |
| 310                                                                | 1253.9                         | 2.490                               | 35.2                                        | 281                                     | 286                                     | 0.916                                      | 3060      | 0.49                                     |
| 320                                                                | 1247.2                         | 2.564                               | 21.0                                        | 168                                     | 287                                     | 0.897                                      | 1870      | 0.50                                     |

TABLE A.5 Continued

*Saturated Liquids (Continued)*

| $T$<br>(K)                                                        | $\rho$<br>(kg/m <sup>3</sup> ) | $c_p$<br>(kJ/kg · K) | $\mu \cdot 10^2$<br>(N · s/m <sup>2</sup> ) | $\nu \cdot 10^6$<br>(m <sup>2</sup> /s) | $k \cdot 10^3$<br>(W/m · K) | $\alpha \cdot 10^7$<br>(m <sup>2</sup> /s) | $Pr$   | $\beta \cdot 10^3$<br>(K <sup>-1</sup> ) |
|-------------------------------------------------------------------|--------------------------------|----------------------|---------------------------------------------|-----------------------------------------|-----------------------------|--------------------------------------------|--------|------------------------------------------|
| <b>Refrigerant-134a (C<sub>2</sub>H<sub>2</sub>F<sub>4</sub>)</b> |                                |                      |                                             |                                         |                             |                                            |        |                                          |
| 230                                                               | 1426.8                         | 1.249                | 0.04912                                     | 0.3443                                  | 112.1                       | 0.629                                      | 5.5    | 2.02                                     |
| 240                                                               | 1397.7                         | 1.267                | 0.04202                                     | 0.3006                                  | 107.3                       | 0.606                                      | 5.0    | 2.11                                     |
| 250                                                               | 1367.9                         | 1.287                | 0.03633                                     | 0.2656                                  | 102.5                       | 0.583                                      | 4.6    | 2.23                                     |
| 260                                                               | 1337.1                         | 1.308                | 0.03166                                     | 0.2368                                  | 97.9                        | 0.560                                      | 4.2    | 2.36                                     |
| 270                                                               | 1305.1                         | 1.333                | 0.02775                                     | 0.2127                                  | 93.4                        | 0.537                                      | 4.0    | 2.53                                     |
| 280                                                               | 1271.8                         | 1.361                | 0.02443                                     | 0.1921                                  | 89.0                        | 0.514                                      | 3.7    | 2.73                                     |
| 290                                                               | 1236.8                         | 1.393                | 0.02156                                     | 0.1744                                  | 84.6                        | 0.491                                      | 3.5    | 2.98                                     |
| 300                                                               | 1199.7                         | 1.432                | 0.01905                                     | 0.1588                                  | 80.3                        | 0.468                                      | 3.4    | 3.30                                     |
| 310                                                               | 1159.9                         | 1.481                | 0.01680                                     | 0.1449                                  | 76.1                        | 0.443                                      | 3.3    | 3.73                                     |
| 320                                                               | 1116.8                         | 1.543                | 0.01478                                     | 0.1323                                  | 71.8                        | 0.417                                      | 3.2    | 4.33                                     |
| 330                                                               | 1069.1                         | 1.627                | 0.01292                                     | 0.1209                                  | 67.5                        | 0.388                                      | 3.1    | 5.19                                     |
| 340                                                               | 1015.0                         | 1.751                | 0.01118                                     | 0.1102                                  | 63.1                        | 0.355                                      | 3.1    | 6.57                                     |
| 350                                                               | 951.3                          | 1.961                | 0.00951                                     | 0.1000                                  | 58.6                        | 0.314                                      | 3.2    | 9.10                                     |
| 360                                                               | 870.1                          | 2.437                | 0.00781                                     | 0.0898                                  | 54.1                        | 0.255                                      | 3.5    | 15.39                                    |
| 370                                                               | 740.3                          | 5.105                | 0.00580                                     | 0.0783                                  | 51.8                        | 0.137                                      | 5.7    | 55.24                                    |
| <b>Refrigerant-22 (CHClF<sub>2</sub>)</b>                         |                                |                      |                                             |                                         |                             |                                            |        |                                          |
| 230                                                               | 1416.0                         | 1.087                | 0.03558                                     | 0.2513                                  | 114.5                       | 0.744                                      | 3.4    | 2.05                                     |
| 240                                                               | 1386.6                         | 1.100                | 0.03145                                     | 0.2268                                  | 109.8                       | 0.720                                      | 3.2    | 2.16                                     |
| 250                                                               | 1356.3                         | 1.117                | 0.02796                                     | 0.2062                                  | 105.2                       | 0.695                                      | 3.0    | 2.29                                     |
| 260                                                               | 1324.9                         | 1.137                | 0.02497                                     | 0.1884                                  | 100.7                       | 0.668                                      | 2.8    | 2.45                                     |
| 270                                                               | 1292.1                         | 1.161                | 0.02235                                     | 0.1730                                  | 96.2                        | 0.641                                      | 2.7    | 2.63                                     |
| 280                                                               | 1257.9                         | 1.189                | 0.02005                                     | 0.1594                                  | 91.7                        | 0.613                                      | 2.6    | 2.86                                     |
| 290                                                               | 1221.7                         | 1.223                | 0.01798                                     | 0.1472                                  | 87.2                        | 0.583                                      | 2.5    | 3.15                                     |
| 300                                                               | 1183.4                         | 1.265                | 0.01610                                     | 0.1361                                  | 82.6                        | 0.552                                      | 2.5    | 3.51                                     |
| 310                                                               | 1142.2                         | 1.319                | 0.01438                                     | 0.1259                                  | 78.1                        | 0.518                                      | 2.4    | 4.00                                     |
| 320                                                               | 1097.4                         | 1.391                | 0.01278                                     | 0.1165                                  | 73.4                        | 0.481                                      | 2.4    | 4.69                                     |
| 330                                                               | 1047.5                         | 1.495                | 0.01127                                     | 0.1075                                  | 68.6                        | 0.438                                      | 2.5    | 5.75                                     |
| 340                                                               | 990.1                          | 1.665                | 0.00980                                     | 0.0989                                  | 63.6                        | 0.386                                      | 2.6    | 7.56                                     |
| 350                                                               | 920.1                          | 1.997                | 0.00831                                     | 0.0904                                  | 58.3                        | 0.317                                      | 2.8    | 11.35                                    |
| 360                                                               | 823.4                          | 3.001                | 0.00668                                     | 0.0811                                  | 53.1                        | 0.215                                      | 3.8    | 23.88                                    |
| <b>Mercury (Hg)</b>                                               |                                |                      |                                             |                                         |                             |                                            |        |                                          |
| 273                                                               | 13,595                         | 0.1404               | 0.1688                                      | 0.1240                                  | 8180                        | 42.85                                      | 0.0290 | 0.181                                    |
| 300                                                               | 13,529                         | 0.1393               | 0.1523                                      | 0.1125                                  | 8540                        | 45.30                                      | 0.0248 | 0.181                                    |
| 350                                                               | 13,407                         | 0.1377               | 0.1309                                      | 0.0976                                  | 9180                        | 49.75                                      | 0.0196 | 0.181                                    |
| 400                                                               | 13,287                         | 0.1365               | 0.1171                                      | 0.0882                                  | 9800                        | 54.05                                      | 0.0163 | 0.181                                    |
| 450                                                               | 13,167                         | 0.1357               | 0.1075                                      | 0.0816                                  | 10,400                      | 58.10                                      | 0.0140 | 0.181                                    |
| 500                                                               | 13,048                         | 0.1353               | 0.1007                                      | 0.0771                                  | 10,950                      | 61.90                                      | 0.0125 | 0.182                                    |
| 550                                                               | 12,929                         | 0.1352               | 0.0953                                      | 0.0737                                  | 11,450                      | 65.55                                      | 0.0112 | 0.184                                    |
| 600                                                               | 12,809                         | 0.1355               | 0.0911                                      | 0.0711                                  | 11,950                      | 68.80                                      | 0.0103 | 0.187                                    |

TABLE A.5 Continued

| Saturated Liquid–Vapor, 1 atm <sup>b</sup> |                         |                  |                                |                                  |                              |
|--------------------------------------------|-------------------------|------------------|--------------------------------|----------------------------------|------------------------------|
| Fluid                                      | $T_{\text{sat}}$<br>(K) | $h_g$<br>(kJ/kg) | $\rho$<br>(kg/m <sup>3</sup> ) | $\rho_g$<br>(kg/m <sup>3</sup> ) | $\sigma \cdot 10^3$<br>(N/m) |
| Ethanol                                    | 351                     | 846              | 757                            | 1.44                             | 17.7                         |
| Ethylene glycol                            | 470                     | 812              | 1111 <sup>c</sup>              | —                                | 32.7                         |
| Glycerin                                   | 563                     | 974              | 1260 <sup>c</sup>              | —                                | 63.0 <sup>c</sup>            |
| Mercury                                    | 630                     | 301              | 12,740                         | 3.90                             | 417                          |
| Refrigerant R-134a                         | 247                     | 217              | 1377                           | 5.26                             | 15.4                         |
| Refrigerant R-22                           | 232                     | 234              | 1409                           | 4.70                             | 18.1                         |

<sup>a</sup>Adapted from References 15–19.  
<sup>b</sup>Adapted from References 8, 20, and 21.  
<sup>c</sup>Property value corresponding to 300 K.

**TABLE A.6** Thermophysical Properties of Saturated Water<sup>a</sup>

| Temperature,<br><i>T</i><br>(K) | Specific<br>Volume<br>(m <sup>3</sup> /kg) |                      | Heat of<br>Vapor-<br>ization,<br><i>h<sub>g</sub></i><br>(kJ/kg) | Specific<br>Heat<br>(kJ/kg · K) |                        | Viscosity<br>(N · s/m <sup>2</sup> ) |                                        | Thermal<br>Conductivity<br>(W/m · K) |                                        | Prandtl<br>Number |                       | Surface<br>Tension,<br><i>σ</i> · 10 <sup>3</sup><br>(N/m) | Expansion<br>Coef-<br>ficient,<br><i>β</i> · 10 <sup>6</sup><br>(K <sup>-1</sup> ) | Temper-<br>ature,<br><i>T</i> (K) |
|---------------------------------|--------------------------------------------|----------------------|------------------------------------------------------------------|---------------------------------|------------------------|--------------------------------------|----------------------------------------|--------------------------------------|----------------------------------------|-------------------|-----------------------|------------------------------------------------------------|------------------------------------------------------------------------------------|-----------------------------------|
|                                 | <i>v</i> · 10 <sup>3</sup>                 | <i>v<sub>g</sub></i> |                                                                  | <i>c<sub>p</sub></i>            | <i>c<sub>p,g</sub></i> | <i>μ</i> · 10 <sup>6</sup>           | <i>μ<sub>g</sub></i> · 10 <sup>6</sup> | <i>k</i> · 10 <sup>3</sup>           | <i>k<sub>g</sub></i> · 10 <sup>3</sup> | <i>Pr</i>         | <i>Pr<sub>g</sub></i> |                                                            |                                                                                    |                                   |
| 273.15                          | 1.000                                      | 206.3                | 2502                                                             | 4.217                           | 1.854                  | 1750                                 | 8.02                                   | 569                                  | 18.2                                   | 12.99             | 0.815                 | 75.5                                                       | -68.05                                                                             | 273.15                            |
| 275                             | 1.000                                      | 181.7                | 2497                                                             | 4.211                           | 1.855                  | 1652                                 | 8.09                                   | 574                                  | 18.3                                   | 12.22             | 0.817                 | 75.3                                                       | -32.74                                                                             | 275                               |
| 280                             | 1.000                                      | 130.4                | 2485                                                             | 4.198                           | 1.858                  | 1422                                 | 8.29                                   | 582                                  | 18.6                                   | 10.26             | 0.825                 | 74.8                                                       | 46.04                                                                              | 280                               |
| 285                             | 1.000                                      | 99.4                 | 2473                                                             | 4.189                           | 1.861                  | 1225                                 | 8.49                                   | 590                                  | 18.9                                   | 8.81              | 0.833                 | 74.3                                                       | 114.1                                                                              | 285                               |
| 290                             | 1.001                                      | 69.7                 | 2461                                                             | 4.184                           | 1.864                  | 1080                                 | 8.69                                   | 598                                  | 19.3                                   | 7.56              | 0.841                 | 73.7                                                       | 174.0                                                                              | 290                               |
| 295                             | 1.002                                      | 51.94                | 2449                                                             | 4.181                           | 1.868                  | 959                                  | 8.89                                   | 606                                  | 19.5                                   | 6.62              | 0.849                 | 72.7                                                       | 227.5                                                                              | 295                               |
| 300                             | 1.003                                      | 39.13                | 2438                                                             | 4.179                           | 1.872                  | 855                                  | 9.09                                   | 613                                  | 19.6                                   | 5.83              | 0.857                 | 71.7                                                       | 276.1                                                                              | 300                               |
| 305                             | 1.005                                      | 29.74                | 2426                                                             | 4.178                           | 1.877                  | 769                                  | 9.29                                   | 620                                  | 20.1                                   | 5.20              | 0.865                 | 70.9                                                       | 320.6                                                                              | 305                               |
| 310                             | 1.007                                      | 22.93                | 2414                                                             | 4.178                           | 1.882                  | 695                                  | 9.49                                   | 628                                  | 20.4                                   | 4.62              | 0.873                 | 70.0                                                       | 361.9                                                                              | 310                               |
| 315                             | 1.009                                      | 17.82                | 2402                                                             | 4.179                           | 1.888                  | 631                                  | 9.69                                   | 634                                  | 20.7                                   | 4.16              | 0.883                 | 69.2                                                       | 400.4                                                                              | 315                               |
| 320                             | 1.011                                      | 13.98                | 2390                                                             | 4.180                           | 1.895                  | 577                                  | 9.89                                   | 640                                  | 21.0                                   | 3.77              | 0.894                 | 68.3                                                       | 436.7                                                                              | 320                               |
| 325                             | 1.013                                      | 11.06                | 2378                                                             | 4.182                           | 1.903                  | 528                                  | 10.09                                  | 645                                  | 21.3                                   | 3.42              | 0.901                 | 67.5                                                       | 471.2                                                                              | 325                               |
| 330                             | 1.016                                      | 8.82                 | 2366                                                             | 4.184                           | 1.911                  | 489                                  | 10.29                                  | 650                                  | 21.7                                   | 3.15              | 0.908                 | 66.6                                                       | 504.0                                                                              | 330                               |
| 335                             | 1.018                                      | 7.09                 | 2354                                                             | 4.186                           | 1.920                  | 453                                  | 10.49                                  | 656                                  | 22.0                                   | 2.88              | 0.916                 | 65.8                                                       | 535.5                                                                              | 335                               |
| 340                             | 1.021                                      | 5.74                 | 2342                                                             | 4.188                           | 1.930                  | 420                                  | 10.69                                  | 660                                  | 22.3                                   | 2.66              | 0.925                 | 64.9                                                       | 566.0                                                                              | 340                               |
| 345                             | 1.024                                      | 4.683                | 2329                                                             | 4.191                           | 1.941                  | 389                                  | 10.89                                  | 664                                  | 22.6                                   | 2.45              | 0.933                 | 64.1                                                       | 595.4                                                                              | 345                               |
| 350                             | 1.027                                      | 3.846                | 2317                                                             | 4.195                           | 1.954                  | 365                                  | 11.09                                  | 668                                  | 23.0                                   | 2.29              | 0.942                 | 63.2                                                       | 624.2                                                                              | 350                               |
| 355                             | 1.030                                      | 3.180                | 2304                                                             | 4.199                           | 1.968                  | 343                                  | 11.29                                  | 671                                  | 23.3                                   | 2.14              | 0.951                 | 62.3                                                       | 652.3                                                                              | 355                               |
| 360                             | 1.034                                      | 2.645                | 2291                                                             | 4.203                           | 1.983                  | 324                                  | 11.49                                  | 674                                  | 23.7                                   | 2.02              | 0.960                 | 61.4                                                       | 697.9                                                                              | 360                               |
| 365                             | 1.038                                      | 2.212                | 2278                                                             | 4.209                           | 1.999                  | 306                                  | 11.69                                  | 677                                  | 24.1                                   | 1.91              | 0.969                 | 60.5                                                       | 707.1                                                                              | 365                               |
| 370                             | 1.041                                      | 1.861                | 2265                                                             | 4.214                           | 2.017                  | 289                                  | 11.89                                  | 679                                  | 24.5                                   | 1.80              | 0.978                 | 59.5                                                       | 728.7                                                                              | 370                               |
| 373.15                          | 1.044                                      | 1.679                | 2257                                                             | 4.217                           | 2.029                  | 279                                  | 12.02                                  | 680                                  | 24.8                                   | 1.76              | 0.984                 | 58.9                                                       | 750.1                                                                              | 373.15                            |
| 375                             | 1.045                                      | 1.574                | 2252                                                             | 4.220                           | 2.036                  | 274                                  | 12.09                                  | 681                                  | 24.9                                   | 1.70              | 0.987                 | 58.6                                                       | 761                                                                                | 375                               |
| 380                             | 1.049                                      | 1.337                | 2239                                                             | 4.226                           | 2.057                  | 260                                  | 12.29                                  | 683                                  | 25.4                                   | 1.61              | 0.999                 | 57.6                                                       | 788                                                                                | 380                               |
| 385                             | 1.053                                      | 1.142                | 2225                                                             | 4.232                           | 2.080                  | 248                                  | 12.49                                  | 685                                  | 25.8                                   | 1.53              | 1.004                 | 56.6                                                       | 814                                                                                | 385                               |
| 390                             | 1.058                                      | 0.980                | 2212                                                             | 4.239                           | 2.104                  | 237                                  | 12.69                                  | 686                                  | 26.3                                   | 1.47              | 1.013                 | 55.6                                                       | 841                                                                                | 390                               |
| 400                             | 1.067                                      | 0.731                | 2183                                                             | 4.256                           | 2.158                  | 217                                  | 13.05                                  | 688                                  | 27.2                                   | 1.34              | 1.033                 | 53.6                                                       | 896                                                                                | 400                               |
| 410                             | 1.077                                      | 0.553                | 2153                                                             | 4.278                           | 2.221                  | 200                                  | 13.42                                  | 688                                  | 28.2                                   | 1.24              | 1.054                 | 51.5                                                       | 952                                                                                | 410                               |
| 420                             | 1.088                                      | 0.425                | 2123                                                             | 4.302                           | 2.291                  | 185                                  | 13.79                                  | 688                                  | 29.8                                   | 1.16              | 1.075                 | 49.4                                                       | 1010                                                                               | 420                               |
| 430                             | 1.099                                      | 0.331                | 2091                                                             | 4.331                           | 2.369                  | 173                                  | 14.14                                  | 685                                  | 30.4                                   | 1.09              | 1.10                  | 47.2                                                       | 1010                                                                               | 430                               |

TABLE A.6 Continued

| Temperature,<br><i>T</i><br>(K) | Pressure,<br><i>p</i> (bars) <sup>b</sup> | Specic Volume<br>(m <sup>3</sup> /kg) |                       | Heat of Vapor-<br>ization,<br><i>h</i> <sub>g</sub><br>(kJ/kg) | Specic Heat<br>(kJ/kg · K) |                         | Viscosity<br>(N · s/m <sup>2</sup> ) |                                         | Thermal Conductivity<br>(W/m · K) |                                         | Prandtl Number |                        | Surface Tension,<br><i>σ</i> · 10 <sup>3</sup><br>(N/m) | Expansion Coef-<br>cient,<br><i>β</i> · 10 <sup>6</sup><br>(K <sup>-1</sup> ) | Temper-<br>ature,<br><i>T</i> (K) |
|---------------------------------|-------------------------------------------|---------------------------------------|-----------------------|----------------------------------------------------------------|----------------------------|-------------------------|--------------------------------------|-----------------------------------------|-----------------------------------|-----------------------------------------|----------------|------------------------|---------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------|
|                                 |                                           | <i>v</i> · 10 <sup>3</sup>            | <i>v</i> <sub>g</sub> |                                                                | <i>c</i> <sub>p</sub>      | <i>c</i> <sub>p,g</sub> | <i>μ</i> · 10 <sup>6</sup>           | <i>μ</i> <sub>g</sub> · 10 <sup>6</sup> | <i>k</i> · 10 <sup>3</sup>        | <i>k</i> <sub>g</sub> · 10 <sup>3</sup> | <i>Pr</i>      | <i>Pr</i> <sub>g</sub> |                                                         |                                                                               |                                   |
| 440                             | 7.333                                     | 1.110                                 | 0.261                 | 2059                                                           | 4.36                       | 2.46                    | 162                                  | 14.50                                   | 682                               | 31.7                                    | 1.04           | 1.12                   | 45.1                                                    | —                                                                             | 440                               |
| 450                             | 9.319                                     | 1.123                                 | 0.208                 | 2024                                                           | 4.40                       | 2.56                    | 152                                  | 14.85                                   | 678                               | 33.1                                    | 0.99           | 1.14                   | 42.9                                                    | —                                                                             | 450                               |
| 460                             | 11.71                                     | 1.137                                 | 0.167                 | 1989                                                           | 4.44                       | 2.68                    | 143                                  | 15.19                                   | 673                               | 34.6                                    | 0.95           | 1.17                   | 40.7                                                    | —                                                                             | 460                               |
| 470                             | 14.55                                     | 1.152                                 | 0.136                 | 1951                                                           | 4.48                       | 2.79                    | 136                                  | 15.54                                   | 667                               | 36.3                                    | 0.92           | 1.20                   | 38.5                                                    | —                                                                             | 470                               |
| 480                             | 17.90                                     | 1.167                                 | 0.111                 | 1912                                                           | 4.53                       | 2.94                    | 129                                  | 15.88                                   | 660                               | 38.1                                    | 0.89           | 1.23                   | 36.2                                                    | —                                                                             | 480                               |
| 490                             | 21.83                                     | 1.184                                 | 0.0922                | 1870                                                           | 4.59                       | 3.10                    | 124                                  | 16.23                                   | 651                               | 40.1                                    | 0.87           | 1.25                   | 33.9                                                    | —                                                                             | 490                               |
| 500                             | 26.40                                     | 1.203                                 | 0.0766                | 1825                                                           | 4.66                       | 3.27                    | 118                                  | 16.59                                   | 642                               | 42.3                                    | 0.86           | 1.28                   | 31.6                                                    | —                                                                             | 500                               |
| 510                             | 31.66                                     | 1.222                                 | 0.0631                | 1779                                                           | 4.74                       | 3.47                    | 113                                  | 16.95                                   | 631                               | 44.7                                    | 0.85           | 1.31                   | 29.3                                                    | —                                                                             | 510                               |
| 520                             | 37.70                                     | 1.244                                 | 0.0525                | 1730                                                           | 4.84                       | 3.70                    | 108                                  | 17.33                                   | 621                               | 47.5                                    | 0.84           | 1.35                   | 26.9                                                    | —                                                                             | 520                               |
| 530                             | 44.58                                     | 1.268                                 | 0.0445                | 1679                                                           | 4.95                       | 3.96                    | 104                                  | 17.72                                   | 608                               | 50.6                                    | 0.85           | 1.39                   | 24.5                                                    | —                                                                             | 530                               |
| 540                             | 52.38                                     | 1.294                                 | 0.0375                | 1622                                                           | 5.08                       | 4.27                    | 101                                  | 18.1                                    | 594                               | 54.0                                    | 0.86           | 1.43                   | 22.1                                                    | —                                                                             | 540                               |
| 550                             | 61.19                                     | 1.323                                 | 0.0317                | 1564                                                           | 5.24                       | 4.64                    | 97                                   | 18.6                                    | 580                               | 58.3                                    | 0.87           | 1.47                   | 19.7                                                    | —                                                                             | 550                               |
| 560                             | 71.08                                     | 1.355                                 | 0.0269                | 1499                                                           | 5.43                       | 5.09                    | 94                                   | 19.1                                    | 563                               | 63.7                                    | 0.90           | 1.52                   | 17.3                                                    | —                                                                             | 560                               |
| 570                             | 82.16                                     | 1.392                                 | 0.0228                | 1429                                                           | 5.68                       | 5.67                    | 91                                   | 19.7                                    | 548                               | 76.7                                    | 0.94           | 1.59                   | 15.0                                                    | —                                                                             | 570                               |
| 580                             | 94.51                                     | 1.433                                 | 0.0193                | 1353                                                           | 6.00                       | 6.40                    | 88                                   | 20.4                                    | 528                               | 76.7                                    | 0.99           | 1.68                   | 12.8                                                    | —                                                                             | 580                               |
| 590                             | 108.3                                     | 1.482                                 | 0.0163                | 1274                                                           | 6.41                       | 7.35                    | 84                                   | 21.5                                    | 513                               | 84.1                                    | 1.05           | 1.84                   | 10.5                                                    | —                                                                             | 590                               |
| 600                             | 123.5                                     | 1.541                                 | 0.0137                | 1176                                                           | 7.00                       | 8.75                    | 81                                   | 22.7                                    | 497                               | 92.9                                    | 1.14           | 2.15                   | 8.4                                                     | —                                                                             | 600                               |
| 610                             | 137.3                                     | 1.612                                 | 0.0115                | 1068                                                           | 7.85                       | 11.1                    | 77                                   | 24.1                                    | 467                               | 103                                     | 1.30           | 2.60                   | 6.3                                                     | —                                                                             | 610                               |
| 620                             | 159.1                                     | 1.705                                 | 0.0094                | 941                                                            | 9.35                       | 15.4                    | 72                                   | 25.9                                    | 444                               | 114                                     | 1.52           | 3.46                   | 4.5                                                     | —                                                                             | 620                               |
| 625                             | 169.1                                     | 1.778                                 | 0.0085                | 858                                                            | 10.6                       | 18.3                    | 70                                   | 27.0                                    | 430                               | 121                                     | 1.65           | 4.20                   | 3.5                                                     | —                                                                             | 625                               |
| 630                             | 179.7                                     | 1.856                                 | 0.0075                | 781                                                            | 12.6                       | 22.1                    | 67                                   | 28.0                                    | 412                               | 130                                     | 2.0            | 4.8                    | 2.6                                                     | —                                                                             | 630                               |
| 635                             | 190.9                                     | 1.935                                 | 0.0066                | 683                                                            | 16.4                       | 27.6                    | 64                                   | 30.0                                    | 392                               | 141                                     | 2.7            | 6.0                    | 1.5                                                     | —                                                                             | 635                               |
| 640                             | 202.7                                     | 2.075                                 | 0.0057                | 560                                                            | 26                         | 42                      | 59                                   | 32.0                                    | 367                               | 155                                     | 4.2            | 9.6                    | 0.8                                                     | —                                                                             | 640                               |
| 645                             | 215.2                                     | 2.351                                 | 0.0045                | 361                                                            | 90                         | —                       | 54                                   | 37.0                                    | 331                               | 178                                     | 12             | 26                     | 0.1                                                     | —                                                                             | 645                               |
| 647.3 <sup>c</sup>              | 221.2                                     | 3.170                                 | 0.0032                | 0                                                              | ∞                          | ∞                       | 45                                   | 45.0                                    | 238                               | 238                                     | ∞              | ∞                      | 0.0                                                     | —                                                                             | 647.3 <sup>c</sup>                |

<sup>a</sup>Adapted from Reference 22.  
<sup>b</sup>1 bar = 10<sup>5</sup> N/m<sup>2</sup>.  
<sup>c</sup>Critical temperature.

**TABLE A.7** Thermophysical Properties of Liquid Metals<sup>a</sup>

| Composition            | Melting Point (K) | <i>T</i> (K)  | $\rho$ (kg/m <sup>3</sup> ) | $c_p$ (kJ/kg · K) | $\nu \cdot 10^7$ (m <sup>2</sup> /s) | <i>k</i> (W/m · K) | $\alpha \cdot 10^5$ (m <sup>2</sup> /s) | <i>Pr</i> |
|------------------------|-------------------|---------------|-----------------------------|-------------------|--------------------------------------|--------------------|-----------------------------------------|-----------|
| Bismuth                | 544               | 589           | 10,011                      | 0.1444            | 1.617                                | 16.4               | 1.138                                   | 0.0142    |
|                        |                   | 811           | 9739                        | 0.1545            | 1.133                                | 15.6               | 1.035                                   | 0.0110    |
|                        |                   | 1033          | 9467                        | 0.1645            | 0.8343                               | 15.6               | 1.001                                   | 0.0083    |
| Lead                   | 600               | 644           | 10,540                      | 0.159             | 2.276                                | 16.1               | 1.084                                   | 0.024     |
|                        |                   | 755           | 10,412                      | 0.155             | 1.849                                | 15.6               | 1.223                                   | 0.017     |
|                        |                   | 977           | 10,140                      | —                 | 1.347                                | 14.9               | —                                       | —         |
| Potassium              | 337               | 422           | 807.3                       | 0.80              | 4.608                                | 45.0               | 6.99                                    | 0.0066    |
|                        |                   | 700           | 741.7                       | 0.75              | 2.397                                | 39.5               | 7.07                                    | 0.0034    |
|                        |                   | 977           | 674.4                       | 0.75              | 1.905                                | 33.1               | 6.55                                    | 0.0029    |
| Sodium                 | 371               | 366           | 929.1                       | 1.38              | 7.516                                | 86.2               | 6.71                                    | 0.011     |
|                        |                   | 644           | 860.2                       | 1.30              | 3.270                                | 72.3               | 6.48                                    | 0.0051    |
|                        |                   | 977           | 778.5                       | 1.26              | 2.285                                | 59.7               | 6.12                                    | 0.0037    |
| NaK,<br>(45%/55%)      | 292               | 366           | 887.4                       | 1.130             | 6.522                                | 25.6               | 2.552                                   | 0.026     |
|                        |                   | 644           | 821.7                       | 1.055             | 2.871                                | 27.5               | 3.17                                    | 0.0091    |
|                        |                   | 977           | 740.1                       | 1.043             | 2.174                                | 28.9               | 3.74                                    | 0.0058    |
| NaK,<br>(22%/78%)      | 262               | 366           | 849.0                       | 0.946             | 5.797                                | 24.4               | 3.05                                    | 0.019     |
|                        |                   | 672           | 775.3                       | 0.879             | 2.666                                | 26.7               | 3.92                                    | 0.0068    |
|                        |                   | 1033          | 690.4                       | 0.883             | 2.118                                | —                  | —                                       | —         |
| PbBi,<br>(44.5%/55.5%) | 398               | 422           | 10,524                      | 0.147             | —                                    | 9.05               | 0.586                                   | —         |
|                        |                   | 644           | 10,236                      | 0.147             | 1.496                                | 11.86              | 0.790                                   | 0.189     |
|                        |                   | 922           | 9835                        | —                 | 1.171                                | —                  | —                                       | —         |
| Mercury                | 234               | See Table A.5 |                             |                   |                                      |                    |                                         |           |

<sup>a</sup>Adapted from Reference 23.

**TABLE A.8** Binary Diffusion Coefficients at One Atmosphere<sup>a,b</sup>

| Substance A             | Substance B      | <i>T</i><br>(K) | <i>D</i> <sub>AB</sub><br>(m <sup>2</sup> /s) |
|-------------------------|------------------|-----------------|-----------------------------------------------|
| <b>Gases</b>            |                  |                 |                                               |
| NH <sub>3</sub>         | Air              | 298             | $0.28 \times 10^{-4}$                         |
| H <sub>2</sub> O        | Air              | 298             | $0.26 \times 10^{-4}$                         |
| CO <sub>2</sub>         | Air              | 298             | $0.16 \times 10^{-4}$                         |
| H <sub>2</sub>          | Air              | 298             | $0.41 \times 10^{-4}$                         |
| O <sub>2</sub>          | Air              | 298             | $0.21 \times 10^{-4}$                         |
| Acetone                 | Air              | 273             | $0.11 \times 10^{-4}$                         |
| Benzene                 | Air              | 298             | $0.88 \times 10^{-5}$                         |
| Naphthalene             | Air              | 300             | $0.62 \times 10^{-5}$                         |
| Ar                      | N <sub>2</sub>   | 293             | $0.19 \times 10^{-4}$                         |
| H <sub>2</sub>          | O <sub>2</sub>   | 273             | $0.70 \times 10^{-4}$                         |
| H <sub>2</sub>          | N <sub>2</sub>   | 273             | $0.68 \times 10^{-4}$                         |
| H <sub>2</sub>          | CO <sub>2</sub>  | 273             | $0.55 \times 10^{-4}$                         |
| CO <sub>2</sub>         | N <sub>2</sub>   | 293             | $0.16 \times 10^{-4}$                         |
| CO <sub>2</sub>         | O <sub>2</sub>   | 273             | $0.14 \times 10^{-4}$                         |
| O <sub>2</sub>          | N <sub>2</sub>   | 273             | $0.18 \times 10^{-4}$                         |
| <b>Dilute Solutions</b> |                  |                 |                                               |
| Caffeine                | H <sub>2</sub> O | 298             | $0.63 \times 10^{-9}$                         |
| Ethanol                 | H <sub>2</sub> O | 298             | $0.12 \times 10^{-8}$                         |
| Glucose                 | H <sub>2</sub> O | 298             | $0.69 \times 10^{-9}$                         |
| Glycerol                | H <sub>2</sub> O | 298             | $0.94 \times 10^{-9}$                         |
| Acetone                 | H <sub>2</sub> O | 298             | $0.13 \times 10^{-8}$                         |
| CO <sub>2</sub>         | H <sub>2</sub> O | 298             | $0.20 \times 10^{-8}$                         |
| O <sub>2</sub>          | H <sub>2</sub> O | 298             | $0.24 \times 10^{-8}$                         |
| H <sub>2</sub>          | H <sub>2</sub> O | 298             | $0.63 \times 10^{-8}$                         |
| N <sub>2</sub>          | H <sub>2</sub> O | 298             | $0.26 \times 10^{-8}$                         |
| <b>Solids</b>           |                  |                 |                                               |
| O <sub>2</sub>          | Rubber           | 298             | $0.21 \times 10^{-9}$                         |
| N <sub>2</sub>          | Rubber           | 298             | $0.15 \times 10^{-9}$                         |
| CO <sub>2</sub>         | Rubber           | 298             | $0.11 \times 10^{-9}$                         |
| He                      | SiO <sub>2</sub> | 293             | $0.4 \times 10^{-13}$                         |
| H <sub>2</sub>          | Fe               | 293             | $0.26 \times 10^{-12}$                        |
| Cd                      | Cu               | 293             | $0.27 \times 10^{-18}$                        |
| Al                      | Cu               | 293             | $0.13 \times 10^{-33}$                        |

<sup>a</sup>Adapted with permission from References 24, 25, and 26.<sup>b</sup>Assuming ideal gas behavior, the pressure and temperature dependence of the diffusion coefficient for a binary mixture of gases may be estimated from the relation

$$D_{AB} \propto p^{-1} T^{3/2}$$

**TABLE A.9** Henry's Constant for Selected Gases in Water at Moderate Pressure<sup>a</sup>

| $H = p_{A,i}/x_{A,i}$ (bars) |                 |                 |                  |                 |                 |                 |                |                |
|------------------------------|-----------------|-----------------|------------------|-----------------|-----------------|-----------------|----------------|----------------|
| $T$<br>(K)                   | NH <sub>3</sub> | Cl <sub>2</sub> | H <sub>2</sub> S | SO <sub>2</sub> | CO <sub>2</sub> | CH <sub>4</sub> | O <sub>2</sub> | H <sub>2</sub> |
| 273                          | 21              | 265             | 260              | 165             | 710             | 22,880          | 25,500         | 58,000         |
| 280                          | 23              | 365             | 335              | 210             | 960             | 27,800          | 30,500         | 61,500         |
| 290                          | 26              | 480             | 450              | 315             | 1300            | 35,200          | 37,600         | 66,500         |
| 300                          | 30              | 615             | 570              | 440             | 1730            | 42,800          | 45,700         | 71,600         |
| 310                          | —               | 755             | 700              | 600             | 2175            | 50,000          | 52,500         | 76,000         |
| 320                          | —               | 860             | 835              | 800             | 2650            | 56,300          | 56,800         | 78,600         |
| 323                          | —               | 890             | 870              | 850             | 2870            | 58,000          | 58,000         | 79,000         |

<sup>a</sup>Adapted with permission from Reference 27.**TABLE A.10** The Solubility of Selected Gases and Solids<sup>a</sup>

| Gas             | Solid            | $T$<br>(K) | $S = C_{A,i}/p_{A,i}$<br>(kmol/m <sup>3</sup> ·bar) |
|-----------------|------------------|------------|-----------------------------------------------------|
| O <sub>2</sub>  | Rubber           | 298        | $3.12 \times 10^{-3}$                               |
| N <sub>2</sub>  | Rubber           | 298        | $1.56 \times 10^{-3}$                               |
| CO <sub>2</sub> | Rubber           | 298        | $40.15 \times 10^{-3}$                              |
| He              | SiO <sub>2</sub> | 293        | $0.45 \times 10^{-3}$                               |
| H <sub>2</sub>  | Ni               | 358        | $9.01 \times 10^{-3}$                               |

<sup>a</sup>Adapted with permission from Reference 26.

TABLE A.11 Total, Normal (*n*) or Hemispherical (*h*) Emissivity of Selected Surfaces

| Metallic Solids and Their Oxides <sup>a</sup> |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
|-----------------------------------------------|--------------|------------------------------------------------------------------------|------|------|------|------|------|------|------|------|------|------|
| Description/Composition                       |              | Emissivity, $\epsilon_n$ or $\epsilon_h$ , at Various Temperatures (K) |      |      |      |      |      |      |      |      |      |      |
|                                               |              | 100                                                                    | 200  | 300  | 400  | 600  | 800  | 1000 | 1200 | 1500 | 2000 | 2500 |
| Aluminum                                      |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Highly polished, film                         | ( <i>h</i> ) | 0.02                                                                   | 0.03 | 0.04 | 0.05 | 0.06 |      |      |      |      |      |      |
| Foil, bright                                  | ( <i>h</i> ) | 0.06                                                                   | 0.06 | 0.07 |      |      |      |      |      |      |      |      |
| Anodized                                      | ( <i>h</i> ) |                                                                        |      | 0.82 | 0.76 |      |      |      |      |      |      |      |
| Chromium                                      |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Polished or plated                            | ( <i>n</i> ) | 0.05                                                                   | 0.07 | 0.10 | 0.12 | 0.14 |      |      |      |      |      |      |
| Copper                                        |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Highly polished                               | ( <i>h</i> ) |                                                                        |      | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 |      |      |      |      |
| Stably oxidized                               | ( <i>h</i> ) |                                                                        |      |      |      | 0.50 | 0.58 | 0.80 |      |      |      |      |
| Gold                                          |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Highly polished or film                       | ( <i>h</i> ) | 0.01                                                                   | 0.02 | 0.03 | 0.03 | 0.04 | 0.05 | 0.06 |      |      |      |      |
| Foil, bright                                  | ( <i>h</i> ) | 0.06                                                                   | 0.07 | 0.07 |      |      |      |      |      |      |      |      |
| Molybdenum                                    |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Polished                                      | ( <i>h</i> ) |                                                                        |      |      |      | 0.06 | 0.08 | 0.10 | 0.12 | 0.15 | 0.21 | 0.26 |
| Shot-blasted, rough                           | ( <i>h</i> ) |                                                                        |      |      |      | 0.25 | 0.28 | 0.31 | 0.35 | 0.42 |      |      |
| Stably oxidized                               | ( <i>h</i> ) |                                                                        |      |      |      | 0.80 | 0.82 |      |      |      |      |      |
| Nickel                                        |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Polished                                      | ( <i>h</i> ) |                                                                        |      |      |      | 0.09 | 0.11 | 0.14 | 0.17 |      |      |      |
| Stably oxidized                               | ( <i>h</i> ) |                                                                        |      |      |      | 0.40 | 0.49 | 0.57 |      |      |      |      |
| Platinum                                      |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Polished                                      | ( <i>h</i> ) |                                                                        |      |      |      |      | 0.10 | 0.13 | 0.15 | 0.18 |      |      |
| Silver                                        |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Polished                                      | ( <i>h</i> ) |                                                                        |      | 0.02 | 0.02 | 0.03 | 0.05 | 0.08 |      |      |      |      |
| Stainless steels                              |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Typical, polished                             | ( <i>n</i> ) |                                                                        |      | 0.17 | 0.17 | 0.19 | 0.23 | 0.30 |      |      |      |      |
| Typical, cleaned                              | ( <i>n</i> ) |                                                                        |      | 0.22 | 0.22 | 0.24 | 0.28 | 0.35 |      |      |      |      |
| Typical, lightly oxidized                     | ( <i>n</i> ) |                                                                        |      |      |      |      | 0.33 | 0.40 |      |      |      |      |
| Typical, highly oxidized                      | ( <i>n</i> ) |                                                                        |      |      |      |      | 0.67 | 0.70 | 0.76 |      |      |      |
| AISI 347, stably oxidized                     | ( <i>n</i> ) |                                                                        |      |      |      | 0.87 | 0.88 | 0.89 | 0.90 |      |      |      |
| Tantalum                                      |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Polished                                      | ( <i>h</i> ) |                                                                        |      |      |      |      |      |      | 0.11 | 0.17 | 0.23 | 0.28 |
| Tungsten                                      |              |                                                                        |      |      |      |      |      |      |      |      |      |      |
| Polished                                      | ( <i>h</i> ) |                                                                        |      |      |      |      |      | 0.10 | 0.13 | 0.18 | 0.25 | 0.29 |

**TABLE A.11** Continued**Nonmetallic Substances<sup>b</sup>**

| Description/Composition       |     | Temperature<br>(K) | Emissivity<br>$\epsilon$ |
|-------------------------------|-----|--------------------|--------------------------|
| Aluminum oxide                | (n) | 600                | 0.69                     |
|                               |     | 1000               | 0.55                     |
|                               |     | 1500               | 0.41                     |
| Asphalt pavement              | (h) | 300                | 0.85–0.93                |
| Building materials            |     |                    |                          |
| Asbestos sheet                | (h) | 300                | 0.93–0.96                |
| Brick, red                    | (h) | 300                | 0.93–0.96                |
| Gypsum or plaster board       | (h) | 300                | 0.90–0.92                |
| Wood                          | (h) | 300                | 0.82–0.92                |
| Cloth                         | (h) | 300                | 0.75–0.90                |
| Concrete                      | (h) | 300                | 0.88–0.93                |
| Glass, window                 | (h) | 300                | 0.90–0.95                |
| Ice                           | (h) | 273                | 0.95–0.98                |
| Paints                        |     |                    |                          |
| Black (Parsons)               | (h) | 300                | 0.98                     |
| White, acrylic                | (h) | 300                | 0.90                     |
| White, zinc oxide             | (h) | 300                | 0.92                     |
| Paper, white                  | (h) | 300                | 0.92–0.97                |
| Pyrex                         | (n) | 300                | 0.82                     |
|                               |     | 600                | 0.80                     |
|                               |     | 1000               | 0.71                     |
|                               |     | 1200               | 0.62                     |
| Pyroceram                     | (n) | 300                | 0.85                     |
|                               |     | 600                | 0.78                     |
|                               |     | 1000               | 0.69                     |
|                               |     | 1500               | 0.57                     |
| Refractories (furnace liners) |     |                    |                          |
| Alumina brick                 | (n) | 800                | 0.40                     |
|                               |     | 1000               | 0.33                     |
|                               |     | 1400               | 0.28                     |
|                               |     | 1600               | 0.33                     |
| Magnesia brick                | (n) | 800                | 0.45                     |
|                               |     | 1000               | 0.36                     |
|                               |     | 1400               | 0.31                     |
|                               |     | 1600               | 0.40                     |
| Kaolin insulating brick       | (n) | 800                | 0.70                     |
|                               |     | 1200               | 0.57                     |
|                               |     | 1400               | 0.47                     |
|                               |     | 1600               | 0.53                     |
| Sand                          | (h) | 300                | 0.90                     |
| Silicon carbide               | (n) | 600                | 0.87                     |
|                               |     | 1000               | 0.87                     |
|                               |     | 1500               | 0.85                     |
| Skin                          | (h) | 300                | 0.95                     |
| Snow                          | (h) | 273                | 0.82–0.90                |

**TABLE A.11** *Continued***Nonmetallic Substances<sup>b</sup>**

| Description/Composition |     | Temperature<br>(K) | Emissivity<br>$\epsilon$ |
|-------------------------|-----|--------------------|--------------------------|
| Soil                    | (h) | 300                | 0.93–0.96                |
| Rocks                   | (h) | 300                | 0.88–0.95                |
| Teflon                  | (h) | 300                | 0.85                     |
|                         |     | 400                | 0.87                     |
|                         |     | 500                | 0.92                     |
| Vegetation              | (h) | 300                | 0.92–0.96                |
| Water                   | (h) | 300                | 0.96                     |

<sup>a</sup>Adapted from Reference 1.<sup>b</sup>Adapted from References 1, 9, 28, and 29.**TABLE A.12** Solar Radiative Properties for Selected Materials<sup>a</sup>

| Description/Composition     | $\alpha_s$ | $\epsilon^b$ | $\alpha_s/\epsilon$ | $\tau_s$ |
|-----------------------------|------------|--------------|---------------------|----------|
| Aluminum                    |            |              |                     |          |
| Polished                    | 0.09       | 0.03         | 3.0                 |          |
| Anodized                    | 0.14       | 0.84         | 0.17                |          |
| Quartz overcoated           | 0.11       | 0.37         | 0.30                |          |
| Foil                        | 0.15       | 0.05         | 3.0                 |          |
| Brick, red (Purdue)         | 0.63       | 0.93         | 0.68                |          |
| Concrete                    | 0.60       | 0.88         | 0.68                |          |
| Galvanized sheet metal      |            |              |                     |          |
| Clean, new                  | 0.65       | 0.13         | 5.0                 |          |
| Oxidized, weathered         | 0.80       | 0.28         | 2.9                 |          |
| Glass, 3.2-mm thickness     |            |              |                     |          |
| Float or tempered           |            |              |                     | 0.79     |
| Low iron oxide type         |            |              |                     | 0.88     |
| Metal, plated               |            |              |                     |          |
| Black sulfide               | 0.92       | 0.10         | 9.2                 |          |
| Black cobalt oxide          | 0.93       | 0.30         | 3.1                 |          |
| Black nickel oxide          | 0.92       | 0.08         | 11                  |          |
| Black chrome                | 0.87       | 0.09         | 9.7                 |          |
| Mylar, 0.13-mm thickness    |            |              |                     | 0.87     |
| Paints                      |            |              |                     |          |
| Black (Parsons)             | 0.98       | 0.98         | 1.0                 |          |
| White, acrylic              | 0.26       | 0.90         | 0.29                |          |
| White, zinc oxide           | 0.16       | 0.93         | 0.17                |          |
| Plexiglas, 3.2-mm thickness |            |              |                     | 0.90     |
| Snow                        |            |              |                     |          |
| Fine particles, fresh       | 0.13       | 0.82         | 0.16                |          |
| Ice granules                | 0.33       | 0.89         | 0.37                |          |
| Tedlar, 0.10-mm thickness   |            |              |                     | 0.92     |
| Teflon, 0.13-mm thickness   |            |              |                     | 0.92     |

<sup>a</sup>Adapted with permission from Reference 29.<sup>b</sup>The emissivity values in this table correspond to a surface temperature of approximately 300 K.