

Table 34. Saturated Liquid Densities for R-41 from 131 to 309 K (-224 to 96°F) Extrapolated from Isochoric (p,p,T) Data.

| Temperature<br>K | Vapor<br>Pressure<br>MPa | Density<br>kg/m <sup>3</sup> | Temperature<br>°F | Vapor<br>Pressure<br>psia | Density<br>lb/ft <sup>3</sup> |
|------------------|--------------------------|------------------------------|-------------------|---------------------------|-------------------------------|
| 130.785          | 0.0004                   | 1007.747                     | -224.275          | 0.058                     | 62.8551                       |
| 140.784          | 0.0014                   | 988.908                      | -206.277          | 0.203                     | 61.6801                       |
| 152.713          | 0.0048                   | 966.101                      | -184.805          | 0.696                     | 60.2576                       |
| 166.519          | 0.0158                   | 939.357                      | -159.954          | 2.292                     | 58.5895                       |
| 181.998          | 0.0472                   | 907.781                      | -132.092          | 6.846                     | 56.6200                       |
| 197.962          | 0.1198                   | 875.030                      | -103.356          | 17.376                    | 54.5773                       |
| 217.537          | 0.3000                   | 831.220                      | -68.121           | 43.511                    | 51.8448                       |
| 236.983          | 0.6603                   | 784.123                      | -33.119           | 95.769                    | 48.9072                       |
| 256.759          | 1.2743                   | 730.022                      | 2.478             | 184.822                   | 45.5329                       |
| 275.799          | 2.1968                   | 669.316                      | 36.750            | 318.620                   | 41.7465                       |
| 285.861          | 2.8503                   | 631.151                      | 54.862            | 413.403                   | 39.3661                       |
| 297.612          | 3.7895                   | 576.839                      | 76.014            | 549.622                   | 35.9786                       |
| 308.959          | 4.9099                   | 501.276                      | 96.438            | 712.123                   | 31.2655                       |

Table 35. Isochoric Heat Capacities ( $C_v$ ) for R-41 from 148 to 343 K (-193 to 157°F).

| Temperature<br>K | Heat Capacity<br>J/(mole·K) | Density<br>kg/m <sup>3</sup> | Pressure<br>MPa | Temperature<br>°F | Heat Capacity<br>BTU/(lb·°F) | Density<br>lb/ft <sup>3</sup> | Pressure<br>psia |
|------------------|-----------------------------|------------------------------|-----------------|-------------------|------------------------------|-------------------------------|------------------|
| 148.371          | 47.40                       | 980.16                       | 10.157          | -192.62           | 0.3327                       | 61.189                        | 1473.2           |
| 152.215          | 46.44                       | 978.95                       | 18.001          | -185.70           | 0.3259                       | 61.114                        | 2610.8           |
| 156.062          | 46.40                       | 977.77                       | 25.835          | -178.78           | 0.3257                       | 61.040                        | 3747.0           |
| 163.611          | 45.63                       | 951.78                       | 9.859           | -165.19           | 0.3203                       | 59.418                        | 1429.9           |
| 167.527          | 44.88                       | 950.65                       | 17.045          | -158.14           | 0.3150                       | 59.347                        | 2472.2           |
| 171.441          | 44.75                       | 949.55                       | 24.197          | -151.10           | 0.3141                       | 59.278                        | 3509.5           |
| 175.337          | 44.75                       | 948.47                       | 31.183          | -144.08           | 0.3141                       | 59.211                        | 4522.8           |
| 184.739          | 44.12                       | 910.91                       | 9.211           | -127.16           | 0.3097                       | 56.866                        | 1336.0           |
| 188.751          | 42.89                       | 909.89                       | 15.479          | -119.94           | 0.3010                       | 56.803                        | 2245.0           |
| 192.773          | 42.73                       | 908.90                       | 21.785          | -112.70           | 0.2999                       | 56.741                        | 3159.7           |
| 196.773          | 42.81                       | 907.93                       | 27.948          | -105.50           | 0.3005                       | 56.680                        | 4053.5           |
| 203.880          | 42.42                       | 873.03                       | 9.122           | -92.70            | 0.2977                       | 54.501                        | 1323.1           |
| 207.990          | 41.75                       | 872.11                       | 14.702          | -85.31            | 0.2930                       | 54.444                        | 2132.4           |
| 212.090          | 41.62                       | 871.22                       | 20.261          | -77.93            | 0.2921                       | 54.388                        | 2938.6           |
| 216.170          | 41.70                       | 870.35                       | 25.725          | -70.58            | 0.2927                       | 54.334                        | 3731.2           |
| 220.240          | 41.78                       | 869.50                       | 31.092          | -63.26            | 0.2932                       | 54.281                        | 4509.6           |
| 222.687          | 41.45                       | 833.49                       | 8.794           | -58.85            | 0.2909                       | 52.033                        | 1275.4           |
| 226.888          | 40.77                       | 832.66                       | 13.692          | -51.29            | 0.2862                       | 51.981                        | 1985.8           |
| 231.072          | 40.76                       | 831.87                       | 18.566          | -43.76            | 0.2861                       | 51.932                        | 2692.8           |
| 235.239          | 40.79                       | 831.10                       | 23.370          | -36.26            | 0.2863                       | 51.884                        | 3389.5           |
| 239.396          | 40.96                       | 830.34                       | 28.110          | -28.77            | 0.2875                       | 51.836                        | 4077.0           |
| 242.409          | 40.83                       | 788.80                       | 8.494           | -23.35            | 0.2866                       | 49.243                        | 1232.0           |
| 246.712          | 40.27                       | 788.08                       | 12.709          | -15.61            | 0.2826                       | 49.198                        | 1843.3           |
| 250.996          | 40.37                       | 787.39                       | 16.904          | -7.89             | 0.2833                       | 49.155                        | 2451.7           |
| 255.277          | 40.38                       | 786.71                       | 21.066          | -0.19             | 0.2834                       | 49.113                        | 3055.3           |
| 259.537          | 40.38                       | 786.05                       | 25.169          | 7.48              | 0.2834                       | 49.072                        | 3650.4           |
| 263.547          | 40.47                       | 785.42                       | 28.999          | 14.70             | 0.2840                       | 49.032                        | 4206.0           |
| 263.247          | 40.58                       | 736.81                       | 8.432           | 14.16             | 0.2848                       | 45.998                        | 1222.9           |
| 267.655          | 40.26                       | 736.20                       | 11.944          | 22.09             | 0.2826                       | 45.959                        | 1732.4           |
| 272.049          | 40.26                       | 735.62                       | 15.444          | 30.00             | 0.2826                       | 45.923                        | 2239.9           |
| 276.430          | 40.26                       | 735.04                       | 18.921          | 37.89             | 0.2826                       | 45.887                        | 2744.3           |

Table 35. Isochoric Heat Capacities ( $C_v$ ) for R-41 from 148 to 343 K (-193 to 157°F) (continued).

| Temperature<br>K | Heat Capacity<br>J/(mole·K) | Density<br>kg/m <sup>3</sup> | Pressure<br>MPa | Temperature<br>°F | Heat Capacity<br>BTU/(lb·°F) | Density<br>lb/ft <sup>3</sup> | Pressure<br>psia |
|------------------|-----------------------------|------------------------------|-----------------|-------------------|------------------------------|-------------------------------|------------------|
| 280.813          | 40.44                       | 734.48                       | 22.380          | 45.78             | 0.2838                       | 45.852                        | 3245.9           |
| 285.180          | 40.48                       | 733.91                       | 25.804          | 53.64             | 0.2841                       | 45.817                        | 3742.6           |
| 289.533          | 40.67                       | 733.36                       | 29.196          | 61.47             | 0.2854                       | 45.782                        | 4234.5           |
| 293.880          | 40.77                       | 732.80                       | 32.559          | 69.30             | 0.2862                       | 45.747                        | 4722.2           |
| 283.493          | 40.90                       | 675.15                       | 7.865           | 50.60             | 0.2871                       | 42.148                        | 1140.7           |
| 288.047          | 40.71                       | 674.64                       | 10.682          | 58.80             | 0.2857                       | 42.116                        | 1549.3           |
| 292.599          | 40.72                       | 674.16                       | 13.505          | 66.99             | 0.2858                       | 42.086                        | 1958.8           |
| 297.149          | 40.75                       | 673.69                       | 16.326          | 75.18             | 0.2860                       | 42.057                        | 2367.9           |
| 301.697          | 40.60                       | 673.22                       | 19.140          | 83.37             | 0.2850                       | 42.028                        | 2776.0           |
| 306.230          | 40.76                       | 672.76                       | 21.937          | 91.53             | 0.2861                       | 41.999                        | 3181.7           |
| 310.776          | 40.91                       | 672.30                       | 24.732          | 99.71             | 0.2871                       | 41.970                        | 3587.1           |
| 315.313          | 40.79                       | 671.83                       | 27.511          | 107.88            | 0.2863                       | 41.941                        | 3990.1           |
| 319.841          | 41.12                       | 671.37                       | 30.274          | 116.03            | 0.2886                       | 41.912                        | 4390.8           |
| 324.356          | 41.58                       | 670.92                       | 33.018          | 124.15            | 0.2918                       | 41.884                        | 4788.8           |
| 293.035          | 41.38                       | 640.69                       | 7.687           | 67.77             | 0.2904                       | 39.997                        | 1114.9           |
| 297.659          | 40.84                       | 640.23                       | 10.159          | 76.10             | 0.2866                       | 39.968                        | 1473.5           |
| 302.286          | 40.97                       | 639.80                       | 12.650          | 84.43             | 0.2876                       | 39.941                        | 1834.8           |
| 306.910          | 41.17                       | 639.39                       | 15.142          | 92.75             | 0.2890                       | 39.916                        | 2196.1           |
| 311.533          | 41.37                       | 638.97                       | 17.629          | 101.07            | 0.2904                       | 39.890                        | 2556.9           |
| 316.156          | 41.39                       | 638.56                       | 20.113          | 109.39            | 0.2905                       | 39.864                        | 2917.1           |
| 320.758          | 41.35                       | 638.15                       | 22.580          | 117.68            | 0.2902                       | 39.838                        | 3274.9           |
| 325.353          | 41.44                       | 637.74                       | 25.039          | 125.95            | 0.2909                       | 39.813                        | 3631.7           |
| 329.979          | 41.60                       | 637.32                       | 27.512          | 134.27            | 0.2920                       | 39.787                        | 3990.3           |
| 334.592          | 41.75                       | 636.91                       | 29.972          | 142.58            | 0.2930                       | 39.761                        | 4347.1           |
| 339.218          | 41.83                       | 636.50                       | 32.428          | 150.90            | 0.2936                       | 39.735                        | 4703.3           |
| 295.409          | 41.16                       | 640.45                       | 8.953           | 72.05             | 0.2889                       | 39.982                        | 1298.6           |
| 300.041          | 41.10                       | 640.01                       | 11.441          | 80.39             | 0.2885                       | 39.955                        | 1659.4           |
| 304.682          | 40.93                       | 639.59                       | 13.941          | 88.74             | 0.2873                       | 39.928                        | 2022.0           |
| 309.317          | 41.01                       | 639.17                       | 16.437          | 97.08             | 0.2878                       | 39.902                        | 2384.0           |
| 313.958          | 41.24                       | 638.75                       | 18.932          | 105.44            | 0.2895                       | 39.876                        | 2745.9           |
| 318.600          | 41.33                       | 638.34                       | 21.423          | 113.79            | 0.2901                       | 39.850                        | 3107.2           |
| 323.245          | 41.32                       | 637.92                       | 23.911          | 122.15            | 0.2900                       | 39.824                        | 3468.1           |
| 327.885          | 41.28                       | 637.51                       | 26.393          | 130.51            | 0.2897                       | 39.798                        | 3828.0           |
| 332.520          | 41.57                       | 637.10                       | 28.868          | 138.85            | 0.2918                       | 39.773                        | 4186.9           |

Table 35. Isochoric Heat Capacities ( $C_v$ ) for R-41 from 148 to 343 K (-193 to 157°F) (continued).

| Temperature<br>K | Heat Capacity<br>J/(mole·K) | Density<br>kg/m <sup>3</sup> | Pressure<br>MPa | Temperature<br>°F | Heat Capacity<br>BTU/(lb·°F) | Density<br>lb/ft <sup>3</sup> | Pressure<br>psia |
|------------------|-----------------------------|------------------------------|-----------------|-------------------|------------------------------|-------------------------------|------------------|
| 337.158          | 41.76                       | 636.68                       | 31.336          | 147.20            | 0.2931                       | 39.747                        | 4545.0           |
| 303.889          | 42.30                       | 594.11                       | 7.584           | 87.31             | 0.2969                       | 37.089                        | 1100.0           |
| 308.581          | 41.87                       | 593.72                       | 9.641           | 95.76             | 0.2939                       | 37.065                        | 1398.4           |
| 313.273          | 41.86                       | 593.35                       | 11.714          | 104.20            | 0.2938                       | 37.042                        | 1699.0           |
| 317.975          | 41.67                       | 593.00                       | 13.800          | 112.67            | 0.2925                       | 37.020                        | 2001.5           |
| 322.667          | 41.73                       | 592.65                       | 15.887          | 121.11            | 0.2929                       | 36.998                        | 2304.2           |
| 327.369          | 41.89                       | 592.30                       | 17.981          | 129.57            | 0.2940                       | 36.976                        | 2607.9           |
| 336.793          | 41.76                       | 591.59                       | 22.177          | 146.54            | 0.2931                       | 36.932                        | 3216.5           |
| 341.521          | 41.64                       | 591.24                       | 24.281          | 155.05            | 0.2923                       | 36.910                        | 3521.7           |
| 306.150          | 41.84                       | 593.91                       | 8.574           | 91.38             | 0.2937                       | 37.077                        | 1243.5           |
| 310.881          | 41.74                       | 593.54                       | 10.656          | 99.90             | 0.2930                       | 37.053                        | 1545.5           |
| 315.625          | 41.69                       | 593.18                       | 12.756          | 108.44            | 0.2926                       | 37.031                        | 1850.2           |
| 320.366          | 41.77                       | 592.82                       | 14.863          | 116.97            | 0.2932                       | 37.009                        | 2155.7           |
| 325.118          | 41.75                       | 592.46                       | 16.978          | 125.52            | 0.2930                       | 36.986                        | 2462.5           |
| 329.870          | 41.94                       | 592.11                       | 19.095          | 134.08            | 0.2944                       | 36.964                        | 2769.5           |
| 334.633          | 41.87                       | 591.75                       | 21.216          | 142.65            | 0.2939                       | 36.942                        | 3077.1           |
| 339.387          | 41.88                       | 591.40                       | 23.331          | 151.21            | 0.2939                       | 36.920                        | 3383.9           |
| 309.790          | 43.06                       | 559.96                       | 7.340           | 97.93             | 0.3022                       | 34.957                        | 1064.6           |
| 314.617          | 42.51                       | 559.61                       | 9.162           | 106.62            | 0.2984                       | 34.935                        | 1328.8           |
| 319.442          | 42.43                       | 559.28                       | 11.001          | 115.31            | 0.2978                       | 34.915                        | 1595.6           |
| 324.290          | 42.12                       | 558.96                       | 12.862          | 124.03            | 0.2956                       | 34.895                        | 1865.5           |
| 329.127          | 42.40                       | 558.64                       | 14.727          | 132.74            | 0.2976                       | 34.875                        | 2135.9           |
| 333.993          | 42.20                       | 558.32                       | 16.608          | 141.50            | 0.2962                       | 34.855                        | 2408.9           |
| 338.842          | 42.27                       | 558.00                       | 18.488          | 150.23            | 0.2967                       | 34.835                        | 2681.5           |
| 312.334          | 42.64                       | 559.77                       | 8.297           | 102.51            | 0.2993                       | 34.945                        | 1203.5           |
| 317.173          | 42.37                       | 559.43                       | 10.134          | 111.22            | 0.2974                       | 34.924                        | 1469.9           |
| 322.028          | 42.19                       | 559.11                       | 11.993          | 119.96            | 0.2961                       | 34.904                        | 1739.4           |
| 326.891          | 41.95                       | 558.79                       | 13.864          | 128.71            | 0.2944                       | 34.884                        | 2010.8           |
| 331.759          | 42.17                       | 558.47                       | 15.744          | 137.48            | 0.2960                       | 34.864                        | 2283.5           |
| 336.630          | 42.21                       | 558.15                       | 17.630          | 146.25            | 0.2963                       | 34.844                        | 2557.0           |
| 341.522          | 42.30                       | 557.83                       | 19.529          | 155.05            | 0.2969                       | 34.824                        | 2832.4           |

Table 35. Isochoric Heat Capacities ( $C_v$ ) for R-41 from 148 to 343 K (-193 to 157°F) (continued).

| Temperature<br>K | Heat Capacity<br>J/(mole·K) | Density<br>kg/m <sup>3</sup> | Pressure<br>MPa | Temperature<br>°F | Heat Capacity<br>BTU/(lb·°F) | Density<br>lb/ft <sup>3</sup> | Pressure<br>psia |
|------------------|-----------------------------|------------------------------|-----------------|-------------------|------------------------------|-------------------------------|------------------|
| 320.500          | 50.98                       | 423.52                       | 6.618           | 117.21            | 0.3578                       | 26.439                        | 959.8            |
| 325.616          | 48.15                       | 423.26                       | 7.654           | 126.42            | 0.3379                       | 26.423                        | 1110.1           |
| 330.826          | 46.68                       | 423.04                       | 8.737           | 135.80            | 0.3276                       | 26.410                        | 1267.2           |
| 336.080          | 45.67                       | 422.84                       | 9.848           | 145.26            | 0.3205                       | 26.397                        | 1428.4           |
| 341.380          | 44.92                       | 422.63                       | 10.985          | 154.80            | 0.3153                       | 26.384                        | 1593.2           |
| 323.108          | 48.86                       | 423.37                       | 7.142           | 121.91            | 0.3429                       | 26.430                        | 1035.9           |
| 328.289          | 47.10                       | 423.15                       | 8.207           | 131.23            | 0.3306                       | 26.416                        | 1190.3           |
| 333.528          | 46.14                       | 422.94                       | 9.306           | 140.66            | 0.3238                       | 26.403                        | 1349.8           |
| 338.817          | 45.54                       | 422.73                       | 10.433          | 150.18            | 0.3196                       | 26.390                        | 1513.2           |
| 320.394          | 56.41                       | 199.30                       | 6.069           | 117.02            | 0.3959                       | 12.442                        | 880.2            |
| 326.669          | 51.63                       | 198.94                       | 6.590           | 128.32            | 0.3624                       | 12.419                        | 955.9            |
| 333.055          | 49.26                       | 198.80                       | 7.111           | 139.81            | 0.3457                       | 12.411                        | 1031.4           |
| 339.500          | 47.94                       | 198.69                       | 7.630           | 151.41            | 0.3365                       | 12.404                        | 1106.6           |
| 323.568          | 53.97                       | 199.06                       | 6.334           | 122.74            | 0.3788                       | 12.427                        | 918.7            |
| 329.857          | 50.33                       | 198.86                       | 6.851           | 134.05            | 0.3533                       | 12.414                        | 993.7            |
| 336.255          | 48.52                       | 198.75                       | 7.369           | 145.57            | 0.3405                       | 12.408                        | 1068.8           |
| 342.711          | 46.86                       | 198.64                       | 7.886           | 157.19            | 0.3289                       | 12.401                        | 1143.8           |
| 311.056          | 43.63                       | 59.86                        | 3.237           | 100.21            | 0.3062                       | 3.737                         | 469.5            |
| 318.622          | 42.18                       | 59.83                        | 3.387           | 113.83            | 0.2960                       | 3.735                         | 491.3            |
| 326.203          | 41.15                       | 59.80                        | 3.535           | 127.48            | 0.2888                       | 3.733                         | 512.7            |
| 333.816          | 41.30                       | 59.77                        | 3.682           | 141.18            | 0.2899                       | 3.731                         | 534.0            |
| 341.451          | 40.61                       | 59.75                        | 3.827           | 154.92            | 0.2850                       | 3.730                         | 555.0            |
| 314.884          | 42.14                       | 59.84                        | 3.314           | 107.10            | 0.2958                       | 3.736                         | 480.6            |
| 322.429          | 41.31                       | 59.81                        | 3.462           | 120.68            | 0.2899                       | 3.734                         | 502.1            |
| 329.997          | 41.97                       | 59.79                        | 3.609           | 134.31            | 0.2946                       | 3.733                         | 523.4            |
| 337.588          | 41.60                       | 59.76                        | 3.754           | 147.97            | 0.2920                       | 3.731                         | 544.4            |

Table 36. Two-Phase Heat Capacities for R-41 from 136 to 314 K (-215 to 106°F).

| Temperature<br>K | $C_p^{(2)}$<br>J/(mole·K) | $C_g$<br>J/(mole·K) | Density<br>kg/m <sup>3</sup> | Pressure<br>MPa | Temperature<br>°F | $C_p^{(2)}$<br>BTU/(lb·°F) | $C_g$<br>BTU/(lb·°F) | Density<br>lb/ft <sup>3</sup> | Pressure<br>psia |
|------------------|---------------------------|---------------------|------------------------------|-----------------|-------------------|----------------------------|----------------------|-------------------------------|------------------|
| 136.023          | 71.859                    | 71.835              | 997.70                       | 0.001           | -214.85           | 0.5044                     | 0.5042               | 62.284                        | 0.1              |
| 140.144          | 71.514                    | 71.478              | 990.09                       | 0.001           | -207.43           | 0.5019                     | 0.5017               | 61.809                        | 0.2              |
| 144.237          | 71.289                    | 71.240              | 982.47                       | 0.002           | -200.06           | 0.5004                     | 0.5000               | 61.334                        | 0.3              |
| 148.312          | 71.075                    | 71.008              | 974.82                       | 0.003           | -192.73           | 0.4989                     | 0.4984               | 60.856                        | 0.4              |
| 152.365          | 70.819                    | 70.730              | 967.14                       | 0.005           | -185.43           | 0.4971                     | 0.4964               | 60.377                        | 0.7              |
| 156.398          | 70.613                    | 70.499              | 959.43                       | 0.007           | -178.17           | 0.4956                     | 0.4948               | 59.895                        | 1.0              |
| 160.407          | 70.659                    | 70.515              | 951.69                       | 0.010           | -170.96           | 0.4959                     | 0.4949               | 59.412                        | 1.4              |
| 164.402          | 70.594                    | 70.416              | 943.91                       | 0.013           | -163.76           | 0.4955                     | 0.4942               | 58.926                        | 1.9              |
| 168.369          | 70.638                    | 70.422              | 936.10                       | 0.018           | -156.62           | 0.4958                     | 0.4943               | 58.439                        | 2.6              |
| 172.320          | 70.388                    | 70.129              | 928.24                       | 0.024           | -149.51           | 0.4940                     | 0.4922               | 57.948                        | 3.5              |
| 176.242          | 70.515                    | 70.211              | 920.37                       | 0.032           | -142.45           | 0.4949                     | 0.4928               | 57.457                        | 4.7              |
| 180.148          | 70.683                    | 70.331              | 912.43                       | 0.042           | -135.42           | 0.4961                     | 0.4936               | 56.961                        | 6.1              |
| 184.031          | 70.500                    | 70.096              | 904.45                       | 0.054           | -128.43           | 0.4948                     | 0.4920               | 56.463                        | 7.8              |
| 187.886          | 70.620                    | 70.165              | 896.44                       | 0.068           | -121.49           | 0.4957                     | 0.4925               | 55.963                        | 9.8              |
| 191.726          | 70.713                    | 70.205              | 888.37                       | 0.085           | -114.58           | 0.4963                     | 0.4927               | 55.459                        | 12.3             |
| 195.542          | 71.121                    | 70.561              | 880.24                       | 0.105           | -107.71           | 0.4992                     | 0.4952               | 54.952                        | 15.2             |
| 199.339          | 71.218                    | 70.609              | 872.05                       | 0.129           | -100.88           | 0.4999                     | 0.4956               | 54.440                        | 18.7             |
| 203.109          | 71.371                    | 70.716              | 863.81                       | 0.156           | -94.09            | 0.5009                     | 0.4963               | 53.926                        | 22.7             |
| 206.860          | 71.658                    | 70.962              | 855.50                       | 0.188           | -87.34            | 0.5029                     | 0.4981               | 53.407                        | 27.3             |
| 210.586          | 71.967                    | 71.237              | 847.14                       | 0.224           | -80.63            | 0.5051                     | 0.5000               | 52.885                        | 32.5             |
| 214.292          | 72.244                    | 71.489              | 838.68                       | 0.265           | -73.96            | 0.5071                     | 0.5018               | 52.357                        | 38.5             |
| 217.979          | 72.501                    | 71.730              | 830.14                       | 0.312           | -67.33            | 0.5089                     | 0.5035               | 51.824                        | 45.3             |
| 221.639          | 72.709                    | 71.935              | 821.54                       | 0.364           | -60.74            | 0.5103                     | 0.5049               | 51.287                        | 52.9             |
| 225.276          | 73.237                    | 72.475              | 812.83                       | 0.423           | -54.19            | 0.5140                     | 0.5087               | 50.744                        | 61.3             |
| 228.890          | 73.810                    | 73.078              | 804.04                       | 0.488           | -47.69            | 0.5180                     | 0.5129               | 50.194                        | 70.7             |
| 232.486          | 74.336                    | 73.653              | 795.13                       | 0.559           | -41.21            | 0.5217                     | 0.5169               | 49.638                        | 81.1             |
| 236.059          | 74.715                    | 74.105              | 786.10                       | 0.639           | -34.78            | 0.5244                     | 0.5201               | 49.075                        | 92.6             |
| 239.606          | 75.230                    | 74.719              | 776.97                       | 0.725           | -28.40            | 0.5280                     | 0.5244               | 48.504                        | 105.2            |
| 243.135          | 75.801                    | 75.420              | 767.69                       | 0.820           | -22.05            | 0.5320                     | 0.5293               | 47.925                        | 118.9            |
| 246.639          | 76.041                    | 75.826              | 758.27                       | 0.923           | -15.74            | 0.5337                     | 0.5322               | 47.337                        | 133.8            |
| 250.119          | 76.885                    | 76.877              | 748.70                       | 1.034           | -9.47             | 0.5396                     | 0.5396               | 46.740                        | 150.0            |
| 253.581          | 77.607                    | 77.852              | 738.95                       | 1.155           | -3.24             | 0.5447                     | 0.5464               | 46.131                        | 167.5            |
| 257.022          | 77.964                    | 78.517              | 729.00                       | 1.285           | 2.95              | 0.5472                     | 0.5511               | 45.510                        | 186.3            |
| 260.436          | 78.725                    | 79.649              | 718.86                       | 1.424           | 9.10              | 0.5525                     | 0.5590               | 44.877                        | 206.6            |
| 263.838          | 79.473                    | 80.842              | 708.46                       | 1.574           | 15.22             | 0.5578                     | 0.5674               | 44.228                        | 228.3            |
| 267.218          | 79.960                    | 81.861              | 697.81                       | 1.735           | 21.30             | 0.5612                     | 0.5746               | 43.563                        | 251.6            |
| 270.576          | 80.615                    | 83.151              | 686.86                       | 1.906           | 27.35             | 0.5658                     | 0.5836               | 42.879                        | 276.4            |

Table 36. Two-Phase Heat Capacities for R-41 from 136 to 314 K (-215 to 106°F) (continued).

| Temperature<br>K | $C_p^{(2)}$<br>J/(mole·K) | $C_g$<br>J/(mole·K) | Density<br>kg/m <sup>3</sup> | Pressure<br>MPa | Temperature<br>°F | $C_p^{(2)}$<br>BTU/(lb·°F) | $C_g$<br>BTU/(lb·°F) | Density<br>lb/ft <sup>3</sup> | Pressure<br>psia |
|------------------|---------------------------|---------------------|------------------------------|-----------------|-------------------|----------------------------|----------------------|-------------------------------|------------------|
| 134.063          | 71.904                    | 71.884              | 1001.30                      | 0.001           | -218.38           | 0.5047                     | 0.5045               | 62.509                        | 0.1              |
| 138.189          | 71.598                    | 71.568              | 993.71                       | 0.001           | -210.95           | 0.5025                     | 0.5023               | 62.035                        | 0.1              |
| 142.294          | 71.306                    | 71.263              | 986.09                       | 0.002           | -203.56           | 0.5005                     | 0.5002               | 61.560                        | 0.2              |
| 146.376          | 71.242                    | 71.184              | 978.46                       | 0.002           | -196.21           | 0.5000                     | 0.4996               | 61.083                        | 0.4              |
| 150.430          | 70.987                    | 70.910              | 970.81                       | 0.004           | -188.91           | 0.4982                     | 0.4977               | 60.606                        | 0.6              |
| 154.472          | 70.844                    | 70.743              | 963.12                       | 0.006           | -181.64           | 0.4972                     | 0.4965               | 60.126                        | 0.8              |
| 158.486          | 70.644                    | 70.515              | 955.41                       | 0.008           | -174.41           | 0.4958                     | 0.4949               | 59.644                        | 1.2              |
| 162.480          | 70.561                    | 70.400              | 947.66                       | 0.011           | -167.22           | 0.4952                     | 0.4941               | 59.161                        | 1.7              |
| 166.453          | 70.341                    | 70.143              | 939.88                       | 0.016           | -160.07           | 0.4937                     | 0.4923               | 58.675                        | 2.3              |
| 170.404          | 70.455                    | 70.217              | 932.06                       | 0.021           | -152.96           | 0.4945                     | 0.4928               | 58.187                        | 3.1              |
| 174.336          | 70.438                    | 70.156              | 924.21                       | 0.028           | -145.88           | 0.4944                     | 0.4924               | 57.696                        | 4.1              |
| 178.248          | 70.531                    | 70.203              | 916.30                       | 0.037           | -138.84           | 0.4950                     | 0.4927               | 57.203                        | 5.4              |
| 182.139          | 70.519                    | 70.141              | 908.35                       | 0.048           | -131.84           | 0.4950                     | 0.4923               | 56.707                        | 6.9              |
| 186.011          | 70.526                    | 70.096              | 900.35                       | 0.061           | -124.87           | 0.4950                     | 0.4920               | 56.207                        | 8.8              |
| 189.859          | 70.661                    | 70.178              | 892.31                       | 0.076           | -117.94           | 0.4959                     | 0.4926               | 55.705                        | 11.1             |
| 193.687          | 70.820                    | 70.285              | 884.20                       | 0.095           | -111.05           | 0.4971                     | 0.4933               | 55.199                        | 13.8             |
| 197.488          | 71.136                    | 70.551              | 876.06                       | 0.117           | -104.21           | 0.4993                     | 0.4952               | 54.691                        | 16.9             |
| 201.278          | 71.138                    | 70.505              | 867.83                       | 0.142           | -97.39            | 0.4993                     | 0.4949               | 54.177                        | 20.7             |
| 205.036          | 71.427                    | 70.750              | 859.56                       | 0.172           | -90.62            | 0.5013                     | 0.4966               | 53.661                        | 24.9             |
| 208.772          | 71.857                    | 71.143              | 851.23                       | 0.206           | -83.90            | 0.5043                     | 0.4993               | 53.140                        | 29.9             |
| 212.489          | 72.005                    | 71.261              | 842.81                       | 0.245           | -77.21            | 0.5054                     | 0.5002               | 52.615                        | 35.5             |
| 216.176          | 72.285                    | 71.520              | 834.34                       | 0.289           | -70.57            | 0.5073                     | 0.5020               | 52.086                        | 41.9             |
| 219.846          | 72.570                    | 71.796              | 825.77                       | 0.338           | -63.97            | 0.5093                     | 0.5039               | 51.551                        | 49.0             |
| 223.485          | 73.065                    | 72.295              | 817.14                       | 0.393           | -57.42            | 0.5128                     | 0.5074               | 51.012                        | 57.0             |
| 227.111          | 73.476                    | 72.726              | 808.39                       | 0.455           | -50.89            | 0.5157                     | 0.5104               | 50.466                        | 66.0             |
| 230.712          | 73.661                    | 72.950              | 799.54                       | 0.523           | -44.41            | 0.5170                     | 0.5120               | 49.914                        | 75.9             |
| 234.282          | 74.211                    | 73.561              | 790.62                       | 0.598           | -37.98            | 0.5209                     | 0.5163               | 49.357                        | 86.8             |
| 237.841          | 74.912                    | 74.348              | 781.54                       | 0.681           | -31.57            | 0.5258                     | 0.5218               | 48.790                        | 98.8             |
| 241.373          | 75.328                    | 74.878              | 772.34                       | 0.771           | -25.22            | 0.5287                     | 0.5255               | 48.216                        | 111.9            |
| 244.886          | 75.919                    | 75.616              | 763.01                       | 0.870           | -18.89            | 0.5329                     | 0.5307               | 47.633                        | 126.2            |
| 248.378          | 76.573                    | 76.457              | 753.52                       | 0.977           | -12.61            | 0.5374                     | 0.5366               | 47.040                        | 141.7            |
| 251.850          | 77.099                    | 77.211              | 743.85                       | 1.093           | -6.36             | 0.5411                     | 0.5419               | 46.437                        | 158.5            |
| 255.299          | 77.597                    | 77.988              | 734.01                       | 1.218           | -0.15             | 0.5446                     | 0.5474               | 45.823                        | 176.7            |
| 258.728          | 78.020                    | 78.750              | 723.97                       | 1.353           | 6.02              | 0.5476                     | 0.5527               | 45.196                        | 196.2            |
| 262.135          | 78.639                    | 79.775              | 713.71                       | 1.498           | 12.16             | 0.5519                     | 0.5599               | 44.555                        | 217.2            |
| 265.520          | 79.458                    | 81.079              | 703.20                       | 1.653           | 18.25             | 0.5577                     | 0.5691               | 43.900                        | 239.7            |
| 268.889          | 80.187                    | 82.389              | 692.41                       | 1.818           | 24.31             | 0.5628                     | 0.5783               | 43.226                        | 263.7            |

Table 36. Two-Phase Heat Capacities for R-41 from 136 to 314 K (-215 to 106°F) (continued).

| Temperature<br>K | $C_p^{(2)}$<br>$J/(mole \cdot K)$ | $C_g$<br>$J/(mole \cdot K)$ | Density<br>$kg/m^3$ | Pressure<br>MPa | Temperature<br>°F | $C_p^{(2)}$<br>$BTU/(lb \cdot ^\circ F)$ | $C_g$<br>$BTU/(lb \cdot ^\circ F)$ | Density<br>$lb/ft^3$ | Pressure<br>psia |
|------------------|-----------------------------------|-----------------------------|---------------------|-----------------|-------------------|------------------------------------------|------------------------------------|----------------------|------------------|
| 272.233          | 80.826                            | 83.721                      | 681.32              | 1.995           | 30.33             | 0.5673                                   | 0.5876                             | 42.533               | 289.3            |
| 275.556          | 81.672                            | 85.396                      | 669.88              | 2.183           | 36.31             | 0.5732                                   | 0.5994                             | 41.819               | 316.6            |
| 278.862          | 82.742                            | 87.463                      | 658.04              | 2.382           | 42.26             | 0.5807                                   | 0.6139                             | 41.080               | 345.5            |
| 282.203          | 78.873                            | 84.818                      | 645.54              | 2.598           | 48.28             | 0.5536                                   | 0.5953                             | 40.300               | 376.8            |
| 266.017          | 81.680                            | 81.191                      | 701.63              | 1.676           | 19.14             | 0.5733                                   | 0.5699                             | 43.801               | 243.1            |
| 269.584          | 82.253                            | 82.254                      | 690.14              | 1.854           | 25.56             | 0.5773                                   | 0.5773                             | 43.084               | 268.9            |
| 273.123          | 83.252                            | 83.867                      | 678.30              | 2.044           | 31.93             | 0.5843                                   | 0.5886                             | 42.345               | 296.4            |
| 276.637          | 84.147                            | 85.529                      | 666.07              | 2.246           | 38.26             | 0.5906                                   | 0.6003                             | 41.581               | 325.8            |
| 280.107          | 85.658                            | 87.991                      | 653.45              | 2.461           | 44.50             | 0.6012                                   | 0.6176                             | 40.794               | 356.9            |
| 283.555          | 86.814                            | 90.338                      | 640.30              | 2.689           | 50.71             | 0.6093                                   | 0.6341                             | 39.973               | 390.0            |
| 286.972          | 87.740                            | 92.759                      | 626.56              | 2.931           | 56.86             | 0.6158                                   | 0.6510                             | 39.115               | 425.1            |
| 290.361          | 89.099                            | 96.017                      | 612.11              | 3.186           | 62.96             | 0.6254                                   | 0.6739                             | 38.213               | 462.1            |
| 293.728          | 90.551                            | 99.925                      | 596.76              | 3.456           | 69.02             | 0.6355                                   | 0.7013                             | 37.255               | 501.3            |
| 297.066          | 91.970                            | 104.586                     | 580.32              | 3.741           | 75.03             | 0.6455                                   | 0.7341                             | 36.228               | 542.6            |
| 269.553          | 88.268                            | 82.604                      | 690.24              | 1.852           | 25.51             | 0.6195                                   | 0.5798                             | 43.090               | 268.7            |
| 273.526          | 89.745                            | 84.364                      | 676.92              | 2.066           | 32.66             | 0.6299                                   | 0.5921                             | 42.259               | 299.7            |
| 277.459          | 91.364                            | 86.439                      | 663.13              | 2.296           | 39.74             | 0.6413                                   | 0.6067                             | 41.398               | 333.0            |
| 281.353          | 93.156                            | 88.909                      | 648.78              | 2.542           | 46.75             | 0.6538                                   | 0.6240                             | 40.502               | 368.7            |
| 285.212          | 94.859                            | 91.588                      | 633.74              | 2.804           | 53.69             | 0.6658                                   | 0.6428                             | 39.563               | 406.7            |
| 289.028          | 96.172                            | 94.278                      | 617.90              | 3.084           | 60.56             | 0.6750                                   | 0.6617                             | 38.574               | 447.3            |
| 292.794          | 98.441                            | 98.484                      | 601.13              | 3.380           | 67.34             | 0.6909                                   | 0.6912                             | 37.527               | 490.2            |
| 296.528          | 101.003                           | 103.816                     | 583.06              | 3.694           | 74.06             | 0.7089                                   | 0.7287                             | 36.399               | 535.8            |
| 300.215          | 103.408                           | 110.276                     | 563.39              | 4.027           | 80.70             | 0.7258                                   | 0.7740                             | 35.172               | 584.0            |
| 303.854          | 106.086                           | 119.181                     | 541.51              | 4.377           | 87.25             | 0.7446                                   | 0.8365                             | 33.806               | 634.9            |
| 307.438          | 109.485                           | 132.956                     | 516.40              | 4.746           | 93.70             | 0.7684                                   | 0.9332                             | 32.237               | 688.4            |
| 310.958          | 113.465                           | 157.099                     | 485.90              | 5.133           | 100.04            | 0.7964                                   | 1.1026                             | 30.334               | 744.4            |
| 314.409          | 117.980                           | 218.689                     | 443.79              | 5.537           | 106.25            | 0.8281                                   | 1.5349                             | 27.705               | 803.1            |
| 271.694          | 89.023                            | 83.493                      | 683.14              | 1.966           | 29.36             | 0.6248                                   | 0.5860                             | 42.647               | 285.1            |
| 275.649          | 90.590                            | 85.430                      | 669.56              | 2.188           | 36.48             | 0.6358                                   | 0.5996                             | 41.799               | 317.4            |
| 279.565          | 92.180                            | 87.589                      | 655.46              | 2.427           | 43.53             | 0.6470                                   | 0.6148                             | 40.919               | 351.9            |
| 283.438          | 94.020                            | 90.257                      | 640.76              | 2.681           | 50.50             | 0.6599                                   | 0.6335                             | 40.001               | 388.9            |
| 287.281          | 95.855                            | 93.271                      | 625.28              | 2.953           | 57.42             | 0.6728                                   | 0.6546                             | 39.035               | 428.3            |
| 291.080          | 97.212                            | 96.287                      | 608.92              | 3.242           | 64.26             | 0.6823                                   | 0.6758                             | 38.014               | 470.3            |
| 294.827          | 99.430                            | 100.851                     | 591.50              | 3.548           | 71.00             | 0.6979                                   | 0.7078                             | 36.926               | 514.6            |
| 298.541          | 102.148                           | 106.966                     | 572.59              | 3.873           | 77.69             | 0.7169                                   | 0.7508                             | 35.746               | 561.7            |
| 302.199          | 104.668                           | 114.563                     | 551.83              | 4.215           | 84.27             | 0.7346                                   | 0.8041                             | 34.450               | 611.3            |
| 305.807          | 107.922                           | 125.921                     | 528.37              | 4.575           | 90.77             | 0.7575                                   | 0.8838                             | 32.985               | 663.6            |

Table 36. Two-Phase Heat Capacities for R-41 from 136 to 314 K (-215 to 106°F) (continued).

| Temperature<br>K | $C_p^{(2)}$<br>J/(mole·K) | $C_g$<br>J/(mole·K) | Density<br>kg/m <sup>3</sup> | Pressure<br>MPa | Temperature<br>°F | $C_p^{(2)}$<br>BTU/(lb·°F) | $C_g$<br>BTU/(lb·°F) | Density<br>lb/ft <sup>3</sup> | Pressure<br>psia |
|------------------|---------------------------|---------------------|------------------------------|-----------------|-------------------|----------------------------|----------------------|-------------------------------|------------------|
| 309.361          | 111.724                   | 144.228             | 500.71                       | 4.954           | 97.16             | 0.7842                     | 1.0123               | 31.258                        | 718.5            |
| 312.838          | 116.880                   | 182.168             | 465.35                       | 5.350           | 103.42            | 0.8203                     | 1.2786               | 29.051                        | 775.9            |
| 138.763          | 75.233                    | 74.270              | 992.64                       | 0.001           | -209.91           | 0.5280                     | 0.5213               | 61.969                        | 0.2              |
| 148.037          | 76.372                    | 74.280              | 975.34                       | 0.003           | -193.22           | 0.5360                     | 0.5213               | 60.888                        | 0.4              |
| 156.991          | 77.949                    | 74.005              | 958.29                       | 0.007           | -177.10           | 0.5471                     | 0.5194               | 59.824                        | 1.0              |
| 165.677          | 80.255                    | 73.576              | 941.41                       | 0.015           | -161.47           | 0.5633                     | 0.5164               | 58.770                        | 2.1              |
| 174.111          | 83.666                    | 73.261              | 924.66                       | 0.028           | -146.29           | 0.5872                     | 0.5142               | 57.724                        | 4.0              |
| 182.312          | 88.959                    | 73.782              | 908.00                       | 0.048           | -131.53           | 0.6244                     | 0.5179               | 56.684                        | 7.0              |
| 190.301          | 94.984                    | 73.980              | 891.38                       | 0.078           | -117.15           | 0.6667                     | 0.5192               | 55.647                        | 11.4             |
| 198.079          | 101.839                   | 73.994              | 874.79                       | 0.121           | -103.15           | 0.7148                     | 0.5193               | 54.611                        | 17.5             |
| 205.655          | 109.735                   | 74.093              | 858.19                       | 0.177           | -89.51            | 0.7702                     | 0.5200               | 53.575                        | 25.7             |
| 213.032          | 118.544                   | 74.232              | 841.57                       | 0.251           | -76.23            | 0.8320                     | 0.5210               | 52.537                        | 36.4             |
| 220.229          | 129.115                   | 75.322              | 824.87                       | 0.344           | -63.28            | 0.9062                     | 0.5287               | 51.495                        | 49.8             |
| 227.244          | 139.503                   | 75.499              | 808.06                       | 0.457           | -50.65            | 0.9791                     | 0.5299               | 50.446                        | 66.3             |
| 234.091          | 150.323                   | 75.427              | 791.10                       | 0.594           | -38.32            | 1.0551                     | 0.5294               | 49.386                        | 86.2             |
| 240.771          | 163.031                   | 76.616              | 773.93                       | 0.755           | -26.30            | 1.1443                     | 0.5377               | 48.315                        | 109.5            |
| 247.295          | 175.671                   | 77.124              | 756.48                       | 0.943           | -14.56            | 1.2330                     | 0.5413               | 47.226                        | 136.7            |
| 253.662          | 189.611                   | 78.343              | 738.72                       | 1.158           | -3.10             | 1.3308                     | 0.5499               | 46.117                        | 167.9            |
| 259.881          | 203.752                   | 79.153              | 720.53                       | 1.401           | 8.10              | 1.4301                     | 0.5556               | 44.981                        | 203.2            |
| 265.970          | 218.536                   | 79.940              | 701.78                       | 1.674           | 19.06             | 1.5338                     | 0.5611               | 43.811                        | 242.8            |
| 271.914          | 234.463                   | 81.197              | 682.40                       | 1.977           | 29.76             | 1.6456                     | 0.5699               | 42.601                        | 286.8            |
| 277.712          | 252.595                   | 83.936              | 662.22                       | 2.311           | 40.19             | 1.7729                     | 0.5891               | 41.341                        | 335.2            |

Table 37. Vapor-Phase Speed of Sound Data for R-41 from 249.5 to 350 K (-11 to 170°F).

| Temperature<br>K | Pressure<br>MPa | Sound Speed<br>m/s | Temperature<br>°F | Pressure<br>psia | Sound Speed<br>ft/s |
|------------------|-----------------|--------------------|-------------------|------------------|---------------------|
| 249.500          | 0.6914          | 262.52             | -10.588           | 100.3            | 861.30              |
| 249.500          | 0.5423          | 267.17             | -10.588           | 78.7             | 876.56              |
| 249.500          | 0.4104          | 271.09             | -10.588           | 59.5             | 889.40              |
| 249.500          | 0.2770          | 274.87             | -10.588           | 40.2             | 901.79              |
| 249.500          | 0.1382          | 278.66             | -10.589           | 20.0             | 914.22              |
| 249.500          | 0.0984          | 279.70             | -10.588           | 14.3             | 917.66              |
| 269.500          | 1.3738          | 259.94             | 25.412            | 199.3            | 852.84              |
| 269.500          | 1.0335          | 268.98             | 25.412            | 149.9            | 882.48              |
| 269.499          | 0.6893          | 277.39             | 25.411            | 100.0            | 910.06              |
| 269.501          | 0.3505          | 284.97             | 25.413            | 50.8             | 934.95              |
| 269.500          | 0.1712          | 288.69             | 25.412            | 24.8             | 947.14              |
| 269.500          | 0.1051          | 290.04             | 25.412            | 15.2             | 951.57              |
| 309.998          | 2.7334          | 269.68             | 98.308            | 396.5            | 884.79              |
| 310.000          | 2.4120          | 275.29             | 98.312            | 349.8            | 903.19              |
| 310.000          | 2.0706          | 280.96             | 98.312            | 300.3            | 921.77              |
| 310.000          | 1.7286          | 286.38             | 98.312            | 250.7            | 939.57              |
| 310.000          | 1.3719          | 291.79             | 98.312            | 199.0            | 957.33              |
| 310.000          | 1.0366          | 296.62             | 98.312            | 150.3            | 973.17              |
| 310.000          | 0.6857          | 301.57             | 98.312            | 99.5             | 989.41              |
| 310.000          | 0.5148          | 303.93             | 98.312            | 74.7             | 997.15              |
| 310.000          | 0.3435          | 306.25             | 98.312            | 49.8             | 1004.77             |
| 330.000          | 3.4382          | 278.00             | 134.312           | 498.7            | 912.09              |
| 330.000          | 2.7587          | 286.97             | 134.312           | 400.1            | 941.51              |
| 330.000          | 1.3797          | 303.88             | 134.312           | 200.1            | 996.98              |
| 330.000          | 0.6914          | 311.73             | 134.312           | 100.3            | 1022.72             |
| 330.000          | 0.5044          | 313.78             | 134.312           | 73.2             | 1029.47             |
| 330.000          | 0.3370          | 315.64             | 134.312           | 48.9             | 1035.57             |
| 330.000          | 0.1707          | 317.49             | 134.312           | 24.8             | 1041.64             |
| 350.000          | 3.4419          | 294.73             | 170.312           | 499.2            | 966.96              |
| 350.000          | 2.7612          | 301.47             | 170.312           | 400.5            | 989.08              |
| 350.000          | 2.0509          | 308.37             | 170.312           | 297.5            | 1011.72             |
| 350.000          | 1.3758          | 314.75             | 170.311           | 199.5            | 1032.64             |
| 350.000          | 1.0242          | 318.03             | 170.312           | 148.6            | 1043.40             |
| 350.000          | 0.6875          | 321.16             | 170.312           | 99.7             | 1053.68             |
| 350.000          | 0.5206          | 322.71             | 170.312           | 75.5             | 1058.75             |
| 350.000          | 0.3410          | 324.35             | 170.312           | 49.5             | 1064.14             |
| 350.000          | 0.1789          | 325.85             | 170.312           | 25.9             | 1069.07             |

Table 38. Vapor-Liquid Equilibrium Data for R-41/744 Mixtures from 218 to 290 K (-68 to 62°F).

| x(R-41)<br>Liquid Mole<br>Fraction | Temperature<br>K | Pressure<br>MPa | y(R-41)<br>Vapor Mole<br>Fraction | x(R-41)<br>Liquid Mass<br>Fraction | Temperature<br>°F | Pressure<br>psia | y(R-41)<br>Vapor Mass<br>Fraction |
|------------------------------------|------------------|-----------------|-----------------------------------|------------------------------------|-------------------|------------------|-----------------------------------|
| 0.000                              | 218.00           | 0.551           | 0.0000                            | 0.000                              | -67.29            | 79.9             | 0.000                             |
| 0.014                              | 217.97           | 0.540           | 0.010                             | 0.011                              | -67.35            | 78.3             | 0.008                             |
| 0.153                              | 217.97           | 0.502           | 0.080                             | 0.123                              | -67.35            | 72.8             | 0.063                             |
| 0.319                              | 217.94           | 0.457           | 0.215                             | 0.266                              | -67.40            | 66.2             | 0.175                             |
| 0.433                              | 217.99           | 0.430           | 0.316                             | 0.371                              | -67.31            | 62.4             | 0.263                             |
| 1.000                              | 217.54           | 0.306           | 1.000                             | 1.000                              | -68.12            | 44.5             | 1.000                             |
| 0.000                              | 230.00           | 0.893           | 0.000                             | 0.000                              | -45.69            | 129.5            | 0.000                             |
| 0.440                              | 229.98           | 0.703           | 0.319                             | 0.378                              | -45.73            | 102.0            | 0.266                             |
| 0.473                              | 229.97           | 0.693           | 0.350                             | 0.410                              | -45.73            | 100.6            | 0.294                             |
| 0.553                              | 229.97           | 0.664           | 0.427                             | 0.489                              | -45.73            | 96.3             | 0.366                             |
| 0.590                              | 229.97           | 0.645           | 0.465                             | 0.527                              | -45.74            | 93.6             | 0.402                             |
| 0.636                              | 229.98           | 0.625           | 0.521                             | 0.575                              | -45.73            | 90.7             | 0.457                             |
| 1.000                              | 230.00           | 0.509           | 1.000                             | 1.000                              | -45.69            | 73.8             | 1.000                             |
| 0.000                              | 245.00           | 1.517           | 0.000                             | 0.000                              | -18.69            | 220.0            | 0.000                             |
| 0.327                              | 244.94           | 1.279           | 0.235                             | 0.273                              | -18.79            | 185.5            | 0.192                             |
| 0.448                              | 244.94           | 1.205           | 0.325                             | 0.386                              | -18.80            | 174.7            | 0.271                             |
| 0.520                              | 244.94           | 1.155           | 0.408                             | 0.456                              | -18.79            | 167.5            | 0.348                             |
| 0.640                              | 244.94           | 1.079           | 0.531                             | 0.579                              | -18.80            | 156.4            | 0.467                             |
| 1.000                              | 245.00           | 0.873           | 1.000                             | 1.000                              | -18.69            | 126.6            | 1.000                             |
| 0.000                              | 260.00           | 2.416           | 0.000                             | 0.000                              | 8.31              | 350.4            | 0.000                             |
| 0.325                              | 259.95           | 2.047           | 0.244                             | 0.271                              | 8.22              | 296.9            | 0.200                             |
| 0.410                              | 259.95           | 1.980           |                                   | 0.350                              | 8.22              | 287.1            |                                   |
| 0.555                              | 259.95           | 1.824           | 0.449                             | 0.491                              | 8.23              | 264.5            | 0.387                             |
| 0.666                              | 259.95           | 1.711           | 0.569                             | 0.607                              | 8.22              | 248.1            | 0.505                             |
| 1.000                              | 260.00           | 1.406           | 1.000                             | 1.000                              | 8.31              | 203.9            | 1.000                             |
| 0.000                              | 275.00           | 3.655           | 0.000                             | 0.000                              | 35.31             | 530.1            | 0.000                             |
| 0.410                              | 274.94           | 3.003           | 0.316                             | 0.350                              | 35.21             | 435.6            | 0.263                             |
| 0.489                              | 274.94           | 2.883           | 0.409                             | 0.425                              | 35.21             | 418.2            | 0.349                             |
| 0.586                              | 274.94           | 2.738           | 0.502                             | 0.523                              | 35.21             | 397.2            | 0.438                             |
| 0.672                              | 274.94           | 2.605           | 0.584                             | 0.613                              | 35.21             | 377.8            | 0.520                             |
| 1.000                              | 275.00           | 2.150           | 1.000                             | 1.000                              | 35.31             | 311.9            | 1.000                             |
| 0.000                              | 290.00           | 5.312           | 0.000                             | 0.000                              | 62.31             | 770.4            | 0.000                             |
| 0.229                              | 289.98           | 4.777           | 0.182                             | 0.187                              | 62.28             | 692.8            | 0.147                             |
| 0.338                              | 289.98           | 4.528           | 0.280                             | 0.283                              | 62.28             | 656.7            | 0.231                             |
| 0.295                              | 289.98           | 4.621           | 0.243                             | 0.244                              | 62.28             | 670.2            | 0.199                             |
| 0.441                              | 289.98           | 4.337           |                                   | 0.379                              | 62.27             | 629.0            |                                   |
| 1.000                              | 289.00           | 3.158           | 1.000                             | 1.000                              | 60.51             | 458.0            | 1.000                             |

Table 39. Isochoric (p,ρ,T) Data from 192 to 400 K (−114 to 260°F) for a Mixture of R-41/744 with x(R-41) = 0.49982 Mole Fraction (0.43591 Mass Fraction).

| Temperature<br>K | Pressure<br>MPa | Density<br>kg/m <sup>3</sup> | Temperature<br>°F | Pressure<br>psia | Density<br>lb/ft <sup>3</sup> |
|------------------|-----------------|------------------------------|-------------------|------------------|-------------------------------|
| 192.000          | 3.437           | 1076.33                      | −114.09           | 498.5            | 67.193                        |
| 193.001          | 5.145           | 1076.07                      | −112.29           | 746.3            | 67.177                        |
| 194.001          | 6.824           | 1075.73                      | −110.49           | 989.8            | 67.156                        |
| 195.000          | 8.419           | 1075.27                      | −108.69           | 1221.1           | 67.127                        |
| 196.001          | 9.851           | 1074.58                      | −106.89           | 1428.8           | 67.084                        |
| 198.000          | 12.922          | 1073.63                      | −103.29           | 1874.2           | 67.025                        |
| 200.001          | 16.361          | 1073.13                      | −99.69            | 2373.0           | 66.993                        |
| 202.000          | 19.892          | 1072.75                      | −96.09            | 2885.1           | 66.970                        |
| 204.001          | 23.450          | 1072.43                      | −92.49            | 3401.2           | 66.950                        |
| 206.000          | 27.011          | 1072.13                      | −88.89            | 3917.6           | 66.931                        |
| 207.999          | 30.571          | 1071.85                      | −85.29            | 4433.9           | 66.914                        |
| 210.001          | 34.127          | 1071.58                      | −81.69            | 4949.7           | 66.897                        |
| 206.002          | 3.417           | 1039.65                      | −88.88            | 495.6            | 64.903                        |
| 206.999          | 4.953           | 1039.41                      | −87.09            | 718.4            | 64.888                        |
| 208.001          | 6.448           | 1039.12                      | −85.29            | 935.3            | 64.870                        |
| 209.001          | 7.914           | 1038.74                      | −83.49            | 1147.8           | 64.847                        |
| 210.002          | 9.273           | 1038.18                      | −81.68            | 1345.0           | 64.811                        |
| 211.999          | 11.934          | 1037.13                      | −78.09            | 1730.9           | 64.746                        |
| 214.000          | 14.930          | 1036.59                      | −74.49            | 2165.5           | 64.712                        |
| 216.000          | 18.024          | 1036.21                      | −70.89            | 2614.2           | 64.689                        |
| 218.000          | 21.152          | 1035.90                      | −67.29            | 3067.8           | 64.669                        |
| 220.001          | 24.288          | 1035.61                      | −63.69            | 3522.8           | 64.651                        |
| 221.999          | 27.420          | 1035.34                      | −60.09            | 3977.0           | 64.634                        |
| 223.999          | 30.551          | 1035.08                      | −56.49            | 4431.0           | 64.618                        |
| 225.998          | 33.676          | 1034.84                      | −52.89            | 4884.3           | 64.603                        |
| 220.001          | 3.352           | 1000.69                      | −63.69            | 486.2            | 62.471                        |
| 221.000          | 4.707           | 1000.47                      | −61.89            | 682.7            | 62.458                        |
| 222.000          | 6.029           | 1000.23                      | −60.09            | 874.5            | 62.442                        |
| 223.000          | 7.340           | 999.93                       | −58.29            | 1064.6           | 62.423                        |
| 224.000          | 8.600           | 999.51                       | −56.49            | 1247.4           | 62.398                        |
| 225.999          | 10.951          | 998.42                       | −52.89            | 1588.3           | 62.329                        |
| 227.999          | 13.522          | 997.81                       | −49.29            | 1961.1           | 62.291                        |
| 229.999          | 16.207          | 997.42                       | −45.69            | 2350.6           | 62.267                        |
| 232.002          | 18.931          | 997.10                       | −42.08            | 2745.7           | 62.240                        |

Table 39. Isochoric (p,ρ,T) Data from 192 to 400 K (-114 to 260°F) for a Mixture of R-41/744 with x(R-41) = 0.49982 Mole Fraction (0.43591 Mass Fraction) (continued).

| Temperature<br>K | Pressure<br>MPa | Density<br>kg/m <sup>3</sup> | Temperature<br>°F | Pressure<br>psia | Density<br>lb/ft <sup>3</sup> |
|------------------|-----------------|------------------------------|-------------------|------------------|-------------------------------|
| 234.001          | 21.667          | 996.82                       | -38.49            | 3142.5           | 62.229                        |
| 236.001          | 24.403          | 996.56                       | -34.89            | 3539.4           | 62.213                        |
| 238.000          | 27.139          | 996.31                       | -31.29            | 3936.1           | 62.198                        |
| 240.001          | 29.876          | 996.08                       | -27.69            | 4333.2           | 62.183                        |
| 242.001          | 32.606          | 995.85                       | -24.09            | 4729.1           | 62.169                        |
| 244.001          | 35.320          | 995.63                       | -20.49            | 5122.8           | 62.155                        |
| 236.002          | 3.454           | 952.92                       | -34.88            | 501.0            | 59.489                        |
| 237.002          | 4.606           | 952.73                       | -33.08            | 668.0            | 59.477                        |
| 238.000          | 5.733           | 952.52                       | -31.29            | 831.5            | 59.464                        |
| 239.001          | 6.870           | 952.27                       | -29.49            | 996.5            | 59.448                        |
| 240.000          | 7.980           | 951.96                       | -27.69            | 1157.4           | 59.429                        |
| 242.001          | 10.066          | 950.99                       | -24.09            | 1459.9           | 59.369                        |
| 243.999          | 12.188          | 950.28                       | -20.49            | 1767.7           | 59.324                        |
| 246.000          | 14.447          | 949.85                       | -16.89            | 2095.4           | 59.297                        |
| 248.001          | 16.744          | 949.53                       | -13.29            | 2428.6           | 59.277                        |
| 250.000          | 19.057          | 949.26                       | -9.69             | 2764.0           | 59.260                        |
| 252.001          | 21.371          | 949.00                       | -6.09             | 3099.6           | 59.244                        |
| 254.001          | 23.690          | 948.77                       | -2.49             | 3436.0           | 59.230                        |
| 256.000          | 26.008          | 948.55                       | 1.11              | 3772.1           | 59.216                        |
| 258.000          | 28.319          | 948.33                       | 4.71              | 4107.3           | 59.202                        |
| 260.001          | 30.631          | 948.12                       | 8.31              | 4442.7           | 59.189                        |
| 261.999          | 32.938          | 947.92                       | 11.91             | 4777.3           | 59.177                        |
| 264.000          | 35.241          | 947.72                       | 15.51             | 5111.4           | 59.164                        |
| 253.999          | 3.425           | 891.98                       | -2.49             | 496.8            | 55.685                        |
| 255.002          | 4.364           | 891.83                       | -0.68             | 633.0            | 55.675                        |
| 256.000          | 5.294           | 891.66                       | 1.11              | 767.8            | 55.664                        |
| 257.001          | 6.216           | 891.47                       | 2.91              | 901.5            | 55.652                        |
| 258.000          | 7.137           | 891.24                       | 4.71              | 1035.1           | 55.638                        |
| 259.998          | 8.921           | 890.61                       | 8.31              | 1294.0           | 55.599                        |
| 262.002          | 10.637          | 889.76                       | 11.92             | 1542.8           | 55.546                        |
| 264.000          | 12.423          | 889.23                       | 15.51             | 1801.8           | 55.513                        |
| 266.000          | 14.262          | 888.87                       | 19.11             | 2068.6           | 55.490                        |
| 268.000          | 16.124          | 888.59                       | 22.71             | 2338.6           | 55.473                        |

Table 39. Isochoric (p,ρ,T) Data from 192 to 400 K (-114 to 260°F) for a Mixture of R-41/744 with x(R-41) = 0.49982 Mole Fraction (0.43591 Mass Fraction) (continued).

| Temperature<br>K | Pressure<br>MPa | Density<br>kg/m <sup>3</sup> | Temperature<br>°F | Pressure<br>psia | Density<br>lb/ft <sup>3</sup> |
|------------------|-----------------|------------------------------|-------------------|------------------|-------------------------------|
| 270.000          | 17.990          | 888.34                       | 26.31             | 2609.3           | 55.457                        |
| 272.000          | 19.861          | 888.11                       | 29.91             | 2880.6           | 55.443                        |
| 273.998          | 21.734          | 887.90                       | 33.51             | 3152.3           | 55.430                        |
| 275.999          | 23.608          | 887.70                       | 37.11             | 3424.0           | 55.417                        |
| 278.001          | 25.479          | 887.50                       | 40.71             | 3695.4           | 55.405                        |
| 280.001          | 27.350          | 887.31                       | 44.31             | 3966.8           | 55.393                        |
| 282.000          | 29.220          | 887.12                       | 47.91             | 4238.0           | 55.381                        |
| 284.002          | 31.088          | 886.94                       | 51.52             | 4509.0           | 55.370                        |
| 286.000          | 32.952          | 886.76                       | 55.11             | 4779.3           | 55.359                        |
| 287.999          | 34.811          | 886.59                       | 58.71             | 5048.9           | 55.348                        |
| 274.000          | 5.219           | 821.73                       | 33.51             | 757.0            | 51.299                        |
| 275.000          | 5.939           | 821.58                       | 35.31             | 861.4            | 51.290                        |
| 276.000          | 6.661           | 821.41                       | 37.11             | 966.1            | 51.279                        |
| 277.999          | 8.087           | 820.99                       | 40.71             | 1172.9           | 51.253                        |
| 280.000          | 9.480           | 820.35                       | 44.31             | 1375.0           | 51.213                        |
| 282.000          | 10.853          | 819.69                       | 47.91             | 1574.0           | 51.171                        |
| 284.002          | 12.259          | 819.26                       | 51.52             | 1778.0           | 51.145                        |
| 288.001          | 15.134          | 818.70                       | 58.71             | 2195.1           | 51.110                        |
| 292.000          | 18.034          | 818.28                       | 65.91             | 2615.7           | 51.083                        |
| 296.001          | 20.945          | 817.90                       | 73.11             | 3037.8           | 51.060                        |
| 299.999          | 23.855          | 817.55                       | 80.31             | 3459.9           | 51.038                        |
| 304.001          | 26.773          | 817.21                       | 87.51             | 3883.1           | 51.017                        |
| 308.001          | 29.679          | 816.89                       | 94.71             | 4304.6           | 50.997                        |
| 312.000          | 32.583          | 816.58                       | 101.91            | 4725.8           | 50.977                        |
| 316.000          | 35.479          | 816.27                       | 109.11            | 5145.9           | 50.958                        |
| 292.000          | 5.946           | 730.54                       | 65.91             | 862.4            | 45.606                        |
| 293.000          | 6.461           | 730.42                       | 67.71             | 937.1            | 45.598                        |
| 294.001          | 6.976           | 730.28                       | 69.51             | 1011.8           | 45.590                        |
| 294.999          | 7.491           | 730.13                       | 71.31             | 1086.5           | 45.580                        |
| 296.000          | 8.002           | 729.96                       | 73.11             | 1160.6           | 45.570                        |
| 297.998          | 9.025           | 729.51                       | 76.71             | 1308.9           | 45.542                        |
| 300.000          | 10.036          | 728.95                       | 80.31             | 1455.6           | 45.507                        |
| 304.001          | 12.082          | 728.18                       | 87.51             | 1752.4           | 45.459                        |

Table 39. Isochoric (p,p,T) Data from 192 to 400 K (-114 to 260°F) for a Mixture of R-41/744 with x(R-41) = 0.49982 Mole Fraction (0.43591 Mass Fraction) (continued).

| Temperature<br>K | Pressure<br>MPa | Density<br>kg/m <sup>3</sup> | Temperature<br>°F | Pressure<br>psia | Density<br>lb/ft <sup>3</sup> |
|------------------|-----------------|------------------------------|-------------------|------------------|-------------------------------|
| 308.002          | 14.158          | 727.76                       | 94.72             | 2053.4           | 45.433                        |
| 312.001          | 16.254          | 727.39                       | 101.91            | 2357.5           | 45.409                        |
| 316.000          | 18.361          | 727.06                       | 109.11            | 2663.0           | 45.389                        |
| 320.000          | 20.476          | 726.75                       | 116.31            | 2969.9           | 45.369                        |
| 324.000          | 22.588          | 726.44                       | 123.51            | 3276.1           | 45.350                        |
| 328.002          | 24.706          | 726.16                       | 130.72            | 3583.3           | 45.333                        |
| 332.001          | 26.825          | 725.88                       | 137.91            | 3890.6           | 45.315                        |
| 336.000          | 28.945          | 725.61                       | 145.11            | 4198.1           | 45.298                        |
| 340.001          | 31.063          | 725.34                       | 152.31            | 4505.4           | 45.282                        |
| 344.000          | 33.180          | 725.08                       | 159.51            | 4812.4           | 45.265                        |
| 302.000          | 7.012           | 670.78                       | 83.91             | 1017.0           | 41.876                        |
| 303.000          | 7.423           | 670.66                       | 85.71             | 1076.7           | 41.868                        |
| 304.000          | 7.835           | 670.51                       | 87.51             | 1136.4           | 41.859                        |
| 306.000          | 8.657           | 670.18                       | 91.11             | 1255.6           | 41.838                        |
| 307.999          | 9.480           | 669.74                       | 94.71             | 1375.0           | 41.810                        |
| 312.000          | 11.120          | 668.98                       | 101.91            | 1612.8           | 41.763                        |
| 316.002          | 12.794          | 668.50                       | 109.12            | 1855.6           | 41.733                        |
| 320.000          | 14.485          | 668.13                       | 116.31            | 2100.8           | 41.710                        |
| 324.000          | 16.186          | 667.82                       | 123.51            | 2347.6           | 41.690                        |
| 328.000          | 17.889          | 667.51                       | 130.71            | 2594.6           | 41.671                        |
| 331.999          | 19.607          | 667.23                       | 137.91            | 2843.7           | 41.654                        |
| 336.002          | 21.325          | 666.97                       | 145.12            | 3093.0           | 41.638                        |
| 340.002          | 23.046          | 666.72                       | 152.32            | 3342.6           | 41.622                        |
| 344.000          | 24.768          | 666.47                       | 159.51            | 3592.3           | 41.606                        |
| 348.001          | 26.491          | 666.22                       | 166.71            | 3842.2           | 41.591                        |
| 352.001          | 28.215          | 665.98                       | 173.91            | 4092.2           | 41.576                        |
| 356.001          | 29.938          | 665.74                       | 181.11            | 4342.2           | 41.561                        |
| 360.000          | 31.663          | 665.50                       | 188.31            | 4592.3           | 41.546                        |
| 364.000          | 33.385          | 665.26                       | 195.51            | 4842.1           | 41.531                        |
| 368.001          | 35.106          | 665.03                       | 202.71            | 5091.7           | 41.516                        |
| 312.000          | 7.002           | 468.43                       | 101.91            | 1015.6           | 29.243                        |
| 313.999          | 7.386           | 468.30                       | 105.51            | 1071.2           | 29.235                        |
| 315.998          | 7.774           | 468.16                       | 109.11            | 1127.6           | 29.226                        |

Table 39. Isochoric (p, $\rho$ ,T) Data from 192 to 400 K (-114 to 260°F) for a Mixture of R-41/744 with x(R-41) = 0.49982 Mole Fraction (0.43591 Mass Fraction) (continued).

| Temperature<br>K | Pressure<br>MPa | Density<br>kg/m <sup>3</sup> | Temperature<br>°F | Pressure<br>psia | Density<br>lb/ft <sup>3</sup> |
|------------------|-----------------|------------------------------|-------------------|------------------|-------------------------------|
| 317.999          | 8.171           | 468.00                       | 112.71            | 1185.2           | 29.216                        |
| 319.998          | 8.571           | 467.81                       | 116.31            | 1243.2           | 29.204                        |
| 324.000          | 9.379           | 467.36                       | 123.51            | 1360.3           | 29.176                        |
| 327.999          | 10.195          | 466.87                       | 130.71            | 1478.7           | 29.146                        |
| 332.000          | 11.017          | 466.48                       | 137.91            | 1597.9           | 29.121                        |
| 336.000          | 11.845          | 466.17                       | 145.11            | 1717.9           | 29.102                        |
| 340.002          | 12.678          | 465.91                       | 152.32            | 1838.8           | 29.086                        |
| 344.002          | 13.514          | 465.68                       | 159.52            | 1960.1           | 29.072                        |
| 348.000          | 14.353          | 465.47                       | 166.71            | 2081.8           | 29.059                        |
| 352.000          | 15.193          | 465.28                       | 173.91            | 2203.6           | 29.046                        |
| 355.999          | 16.038          | 465.09                       | 181.11            | 2326.2           | 29.034                        |
| 360.000          | 16.882          | 464.90                       | 188.31            | 2448.5           | 29.023                        |
| 364.002          | 17.727          | 464.73                       | 195.52            | 2571.1           | 29.012                        |
| 368.001          | 18.574          | 464.55                       | 202.71            | 2693.9           | 29.001                        |
| 372.002          | 19.420          | 464.38                       | 209.92            | 2816.6           | 28.990                        |
| 379.999          | 21.113          | 464.04                       | 224.31            | 3062.2           | 28.969                        |
| 384.000          | 21.959          | 463.88                       | 231.51            | 3184.9           | 28.959                        |
| 388.000          | 22.804          | 463.71                       | 238.71            | 3307.5           | 28.949                        |
| 392.000          | 23.650          | 463.55                       | 245.91            | 3430.2           | 28.939                        |
| 395.999          | 24.497          | 463.39                       | 253.11            | 3553.0           | 28.928                        |
| 400.001          | 25.341          | 463.23                       | 260.31            | 3675.4           | 28.918                        |
|                  |                 |                              |                   |                  |                               |
| 320.000          | 8.116           | 374.46                       | 116.31            | 1177.1           | 23.377                        |
| 324.002          | 8.714           | 374.20                       | 123.52            | 1263.9           | 23.361                        |
| 328.000          | 9.316           | 373.86                       | 130.71            | 1351.1           | 23.339                        |
| 332.001          | 9.916           | 373.49                       | 137.91            | 1438.2           | 23.316                        |
| 336.001          | 10.516          | 373.16                       | 145.11            | 1525.3           | 23.295                        |
| 340.001          | 11.117          | 372.88                       | 152.31            | 1612.4           | 23.278                        |
| 348.001          | 12.317          | 372.45                       | 166.71            | 1786.4           | 23.251                        |
| 352.001          | 12.917          | 372.27                       | 173.91            | 1873.5           | 23.240                        |
| 360.001          | 14.116          | 371.93                       | 188.31            | 2047.3           | 23.219                        |
| 367.999          | 15.313          | 371.63                       | 202.71            | 2221.0           | 23.200                        |
| 372.002          | 15.909          | 371.48                       | 209.92            | 2307.4           | 23.191                        |
| 379.999          | 17.102          | 371.20                       | 224.31            | 2480.4           | 23.173                        |
| 388.000          | 18.293          | 370.93                       | 238.71            | 2653.2           | 23.156                        |

Table 39. Isochoric (p,ρ,T) Data from 192 to 400 K (-114 to 260°F) for a Mixture of R-41/744 with x(R-41) = 0.49982 Mole Fraction (0.43591 Mass Fraction) (continued).

| Temperature<br>K | Pressure<br>MPa | Density<br>kg/m <sup>3</sup> | Temperature<br>°F | Pressure<br>psia | Density<br>lb/ft <sup>3</sup> |
|------------------|-----------------|------------------------------|-------------------|------------------|-------------------------------|
| 392.001          | 18.886          | 370.79                       | 245.91            | 2739.2           | 23.148                        |
| 400.001          | 20.070          | 370.52                       | 260.31            | 2910.9           | 23.131                        |
| 319.999          | 7.575           | 262.49                       | 116.31            | 1098.6           | 16.387                        |
| 324.000          | 7.972           | 262.35                       | 123.51            | 1156.2           | 16.378                        |
| 328.001          | 8.364           | 262.18                       | 130.71            | 1213.1           | 16.367                        |
| 332.000          | 8.753           | 261.99                       | 137.91            | 1269.5           | 16.356                        |
| 336.001          | 9.138           | 261.77                       | 145.11            | 1325.3           | 16.342                        |
| 340.001          | 9.520           | 261.54                       | 152.31            | 1380.7           | 16.327                        |
| 347.999          | 10.274          | 261.07                       | 166.71            | 1490.2           | 16.298                        |
| 352.000          | 10.648          | 260.88                       | 173.91            | 1544.4           | 16.286                        |
| 360.001          | 11.391          | 260.55                       | 188.31            | 1652.1           | 16.265                        |
| 368.000          | 12.127          | 260.26                       | 202.71            | 1758.8           | 16.248                        |
| 372.002          | 12.493          | 260.14                       | 209.92            | 1811.9           | 16.240                        |
| 379.999          | 13.221          | 259.90                       | 224.31            | 1917.6           | 16.225                        |
| 388.002          | 13.945          | 259.68                       | 238.72            | 2022.5           | 16.211                        |
| 392.000          | 14.304          | 259.57                       | 245.91            | 2074.7           | 16.205                        |
| 400.000          | 15.021          | 259.37                       | 260.31            | 2178.6           | 16.192                        |
| 320.000          | 6.242           | 154.33                       | 116.31            | 905.4            | 9.634                         |
| 324.000          | 6.447           | 154.42                       | 123.51            | 935.1            | 9.640                         |
| 328.000          | 6.650           | 154.35                       | 130.71            | 964.5            | 9.636                         |
| 332.000          | 6.850           | 154.28                       | 137.91            | 993.6            | 9.631                         |
| 336.000          | 7.049           | 154.20                       | 145.11            | 1022.4           | 9.627                         |
| 340.000          | 7.246           | 154.13                       | 152.31            | 1050.9           | 9.622                         |
| 348.000          | 7.634           | 153.96                       | 166.71            | 1107.3           | 9.612                         |
| 352.001          | 7.827           | 153.88                       | 173.91            | 1135.2           | 9.606                         |
| 360.001          | 8.206           | 153.70                       | 188.31            | 1190.2           | 9.595                         |
| 368.001          | 8.580           | 153.50                       | 202.71            | 1244.4           | 9.583                         |
| 372.001          | 8.765           | 153.40                       | 209.91            | 1271.3           | 9.576                         |
| 379.999          | 9.132           | 153.16                       | 224.31            | 1324.5           | 9.562                         |
| 388.001          | 9.494           | 152.91                       | 238.71            | 1376.9           | 9.546                         |
| 392.002          | 9.673           | 152.79                       | 245.92            | 1402.9           | 9.538                         |
| 400.001          | 10.028          | 152.55                       | 260.31            | 1454.4           | 9.523                         |

Table 39. Isochoric (p,p,T) Data from 192 to 400 K (-114 to 260°F) for a Mixture of R-41/744 with x(R-41) = 0.49982 Mole Fraction (0.43591 Mass Fraction) (continued).

| Temperature<br>K | Pressure<br>MPa | Density<br>kg/m <sup>3</sup> | Temperature<br>°F | Pressure<br>psia | Density<br>lb/ft <sup>3</sup> |
|------------------|-----------------|------------------------------|-------------------|------------------|-------------------------------|
| 320.001          | 3.637           | 67.16                        | 116.31            | 527.5            | 4.193                         |
| 324.002          | 3.710           | 67.14                        | 123.52            | 538.1            | 4.191                         |
| 328.000          | 3.782           | 67.11                        | 130.71            | 548.6            | 4.190                         |
| 332.000          | 3.854           | 67.09                        | 137.91            | 559.0            | 4.188                         |
| 336.001          | 3.925           | 67.07                        | 145.11            | 569.3            | 4.187                         |
| 340.001          | 3.996           | 67.04                        | 152.31            | 579.6            | 4.185                         |
| 348.002          | 4.137           | 67.00                        | 166.72            | 600.0            | 4.182                         |
| 352.001          | 4.207           | 66.97                        | 173.91            | 610.1            | 4.181                         |
| 360.001          | 4.345           | 66.92                        | 188.31            | 630.2            | 4.178                         |
| 368.001          | 4.482           | 66.88                        | 202.71            | 650.1            | 4.175                         |
| 372.001          | 4.551           | 66.85                        | 209.91            | 660.0            | 4.173                         |
| 379.998          | 4.686           | 66.80                        | 224.31            | 679.7            | 4.170                         |
| 388.000          | 4.821           | 66.75                        | 238.71            | 699.2            | 4.167                         |
| 392.000          | 4.887           | 66.72                        | 245.91            | 708.8            | 4.165                         |
| 400.001          | 5.020           | 66.67                        | 260.31            | 728.2            | 4.162                         |

## **APPENDIX B:**

### **EXPERIMENTAL APPARATUS**

Five apparatus were used to acquire the data for this project. These apparatus will be described in this section.

### **B.1 Vapor-Liquid Equilibrium Apparatus**

A schematic diagram of the vapor-liquid equilibrium apparatus used in this project is presented in Figure B1. The apparatus is designed to allow the liquid and vapor of a fluid to come to equilibrium. Then the equilibrium pressure and temperature are measured. Also, the liquid and vapor phase compositions are measured by flashing a small sample of either the liquid or the vapor into a low pressure helium carrier gas and using a gas chromatograph to analyze the sample. The main part of the apparatus consists of an equilibrium cell, two recirculating pumps, and a platinum resistance thermometer that are contained in a Dewar filled with silicone oil. The platinum resistance thermometer has been calibrated on the ITS-90. The pressure transducer and feed system are contained in an insulated box with an independent temperature control system to maintain it at a temperature above the temperature of the Dewar. The pressure transducer is an oscillating quartz crystal pressure transducer calibrated in our laboratory.

One or more mixture components are introduced into the system using the feed system. The liquid and the vapor are continuously circulated to ensure that the system is well mixed. The liquid and vapor samples are withdrawn through capillary tubing to gas chromatograph sampling valves that are used to inject a small quantity of the sample into a helium stream. The helium stream carries the sample to the gas chromatograph where the mixture components are separated. The procedure for calibrating the gas chromatograph is outlined in Appendix C.

### **B.2 Bubble-Point and Near-Saturation (p, $\rho$ ,T) Apparatus**

The apparatus used to measure the bubble-point pressures and near-saturation (p, $\rho$ ,T) data is similar to the vapor-liquid equilibrium apparatus described above. The main part of the apparatus consists of an equilibrium cell, two pumps, and two vibrating tube densimeters. These components are housed in an oven which is used to control the temperature of the system. Figure B2 shows a schematic diagram of this system. The liquid pump is located outside of the system and is used when the system is above room temperature.

The system can either be filled with a standard mixture of known composition, or the liquid composition can be measured. The liquid and the vapor are continuously circulated to ensure that the system is well mixed. Once the system is equilibrated, the temperatures of the main cell and both densimeters are measured, the pressure of the system is recorded, and both the liquid and vapor densities are recorded. The composition of the vapor phase is calculated from the vapor-liquid equilibrium data from the VLE apparatus described above. It is assumed that the vapor composition is that of the vapor in equilibrium with the liquid which is at the temperature and pressure of the main cell. The reason the vapor composition is not measured directly is because the temperature gradients in this apparatus adversely affect the vapor composition determination.

## B.4 Adiabatic Constant Volume Calorimeter

The principal components of the calorimeter used for these measurements are shown in Figure B4. A spherical bomb contains a sample of well-established mass. The volume of the bomb, approximately 73 cm<sup>3</sup> (4.6 in<sup>3</sup>), is known as a function of temperature and pressure. A platinum resistance thermometer is attached to the bomb for the temperature measurement. Temperatures are reported on the ITS-90, after conversions from the original calibration on the IPTS-68. Pressures are measured with an oscillating quartz crystal pressure transducer with a 0 to 70 MPa (0 to 10000 psia) range. Adiabatic conditions are ensured by a high vacuum ( $3 \times 10^{-3}$  Pa ( $4.4 \times 10^{-4}$  psia)) in the can surrounding the bomb, by a temperature-controlled radiation shield, and by a temperature-controlled guard ring which thermally anchors the filling capillary and the lead wires to the bomb.

For heat capacity measurement, a precisely determined electrical energy ( $Q$ ) is applied and the resulting temperature rise ( $\Delta T = T_2 - T_1$ ) is measured. We obtain the heat capacity from

$$C_v = \left( \frac{\delta U}{\delta T} \right)_v = \frac{Q - Q_0 - W_{pv}}{n\Delta T}, \quad (B1)$$

where  $U$  is the internal energy,  $Q_0$  is the energy required to heat the empty calorimeter,  $W_{pv}$  is the change-of-volume work due to the slight dilation of the bomb, and  $n$  is the number of moles contained in the bomb. In this work, the bomb was charged with sample up to the ( $p, T$ ) conditions of the highest-density isochore. The bomb and its contents were cooled to a starting temperature in the single-phase liquid region. The measurements were performed with increasing temperature until either the upper temperature (345 K (161°F)) or pressure limit (35 MPa (5076 psia)) was attained. At the completion of a run, a small part of the sample was cryopumped into a lightweight cylinder for weighing. The next run was started with a smaller density. A maximum of eight runs was measured with one filling of the bomb. When the runs were completed, the remaining sample was discharged and weighed. A series of such runs from different fillings completes the investigation of the ( $p, T, C_v$ ) surface.

## B.5 Spherical Resonator Speed of Sound Apparatus

Accurate data of the speed of sound of a gas are obtained from measurements of the resonant frequencies produced in a stainless steel spherical cavity containing the gas. Measurements of several radial modes are taken at a very stable temperature and pressure. The speed of sound is computed from the frequency at each of the modes, and an average is taken. The sphere radius used in the computation of the speed of sound is found from similar measurements of the radial modes using argon. Highly accurate properties of argon gas, including the speed of sound, are found in the work of M. R. Moldover, et al. [Moldover, M.R.; Mehl, J.B.; Greenspan, M.J. *Accoust. Soc. Am.* 79: 2;

1986]. Also included in this reference is a detailed description of the theory of operation of the spherical resonator.

The spherical steel cavity is mounted in a pressure vessel which also contains the gas. This vessel is surrounded by a temperature shield and is housed in a cryostat which provides cooling for lower temperatures. The pressure vessel has been designed for operation at pressures up to 7 MPa (1000 psia) and temperatures from 249 K to 350 K (−11.5 to 170.3°F). Figure B5 shows a schematic diagram of this apparatus.

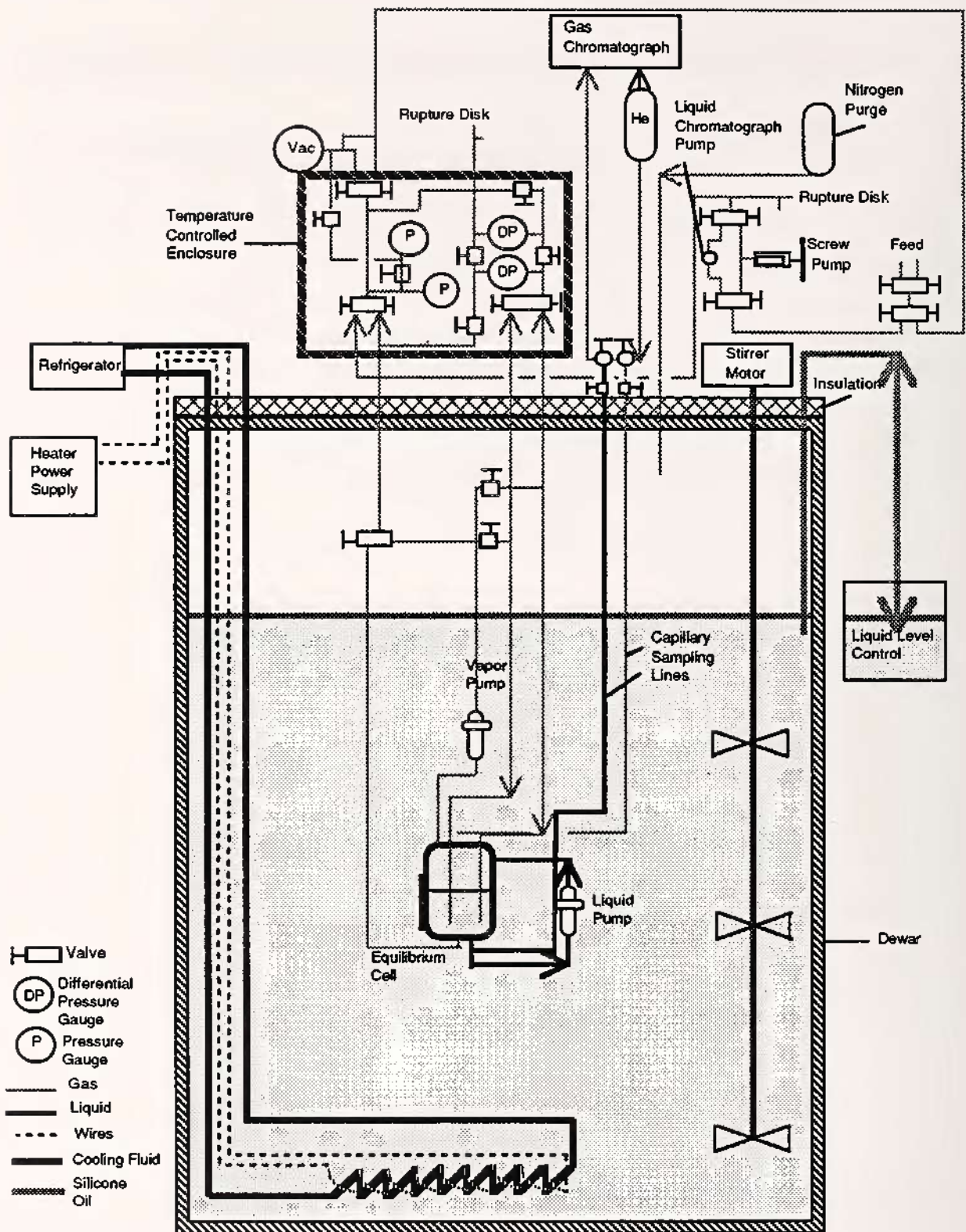


Figure B1. Schematic Diagram of the Dynamic Phase Equilibrium Apparatus.

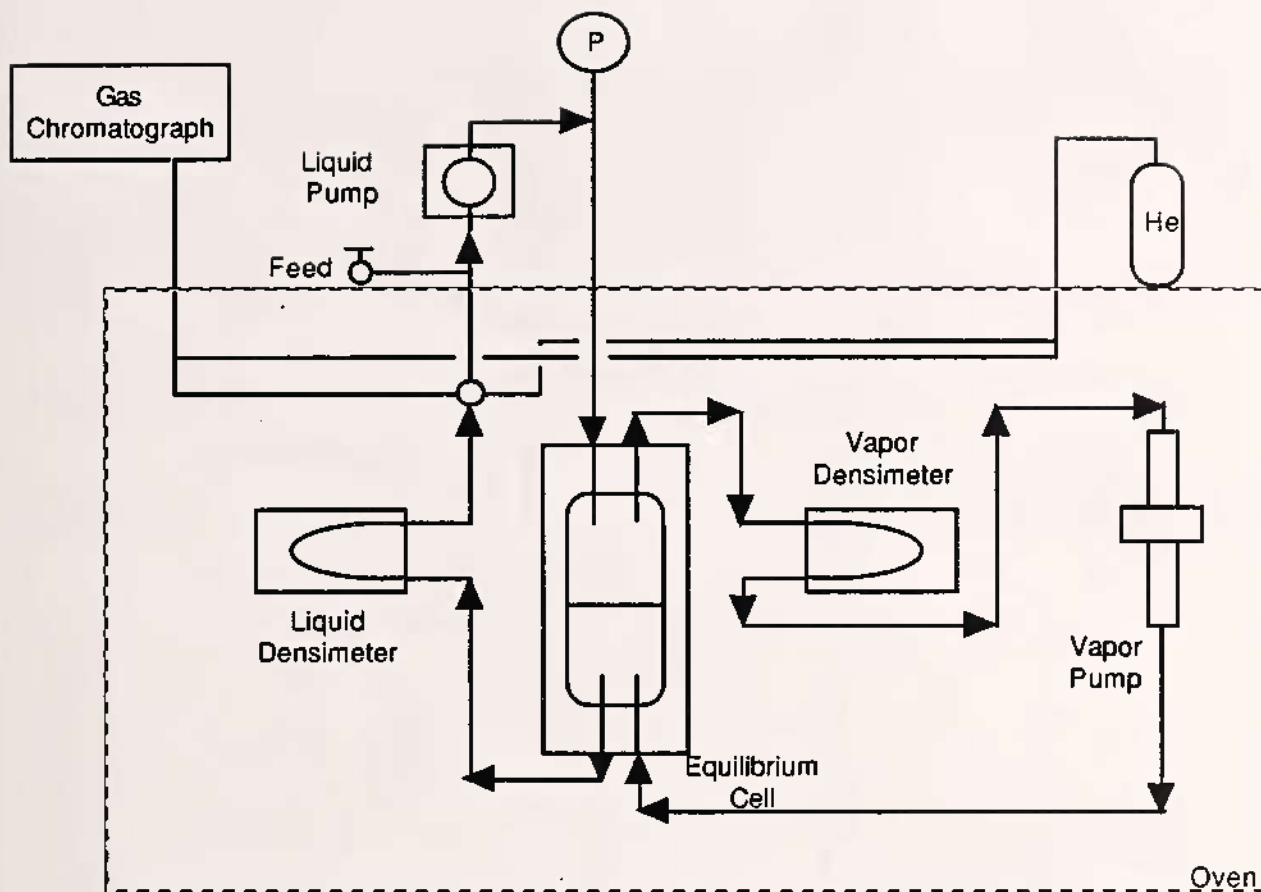


Figure B2. Schematic Diagram of Bubble-Point and Near-Saturation ( $p, \rho, T$ ) Apparatus.

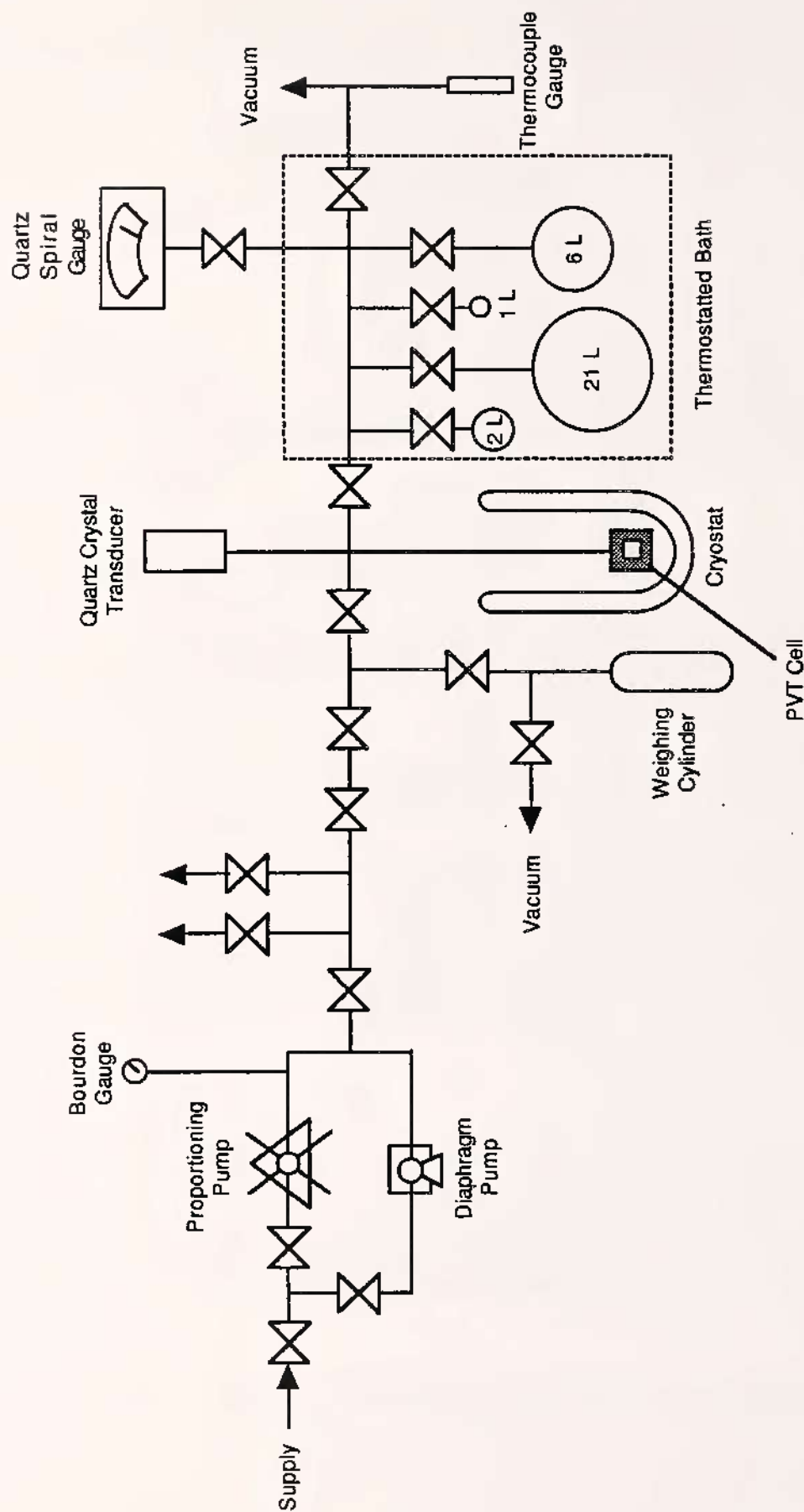


Figure B3. Schematic Diagram of the Isochoric (p,p,T) Apparatus.

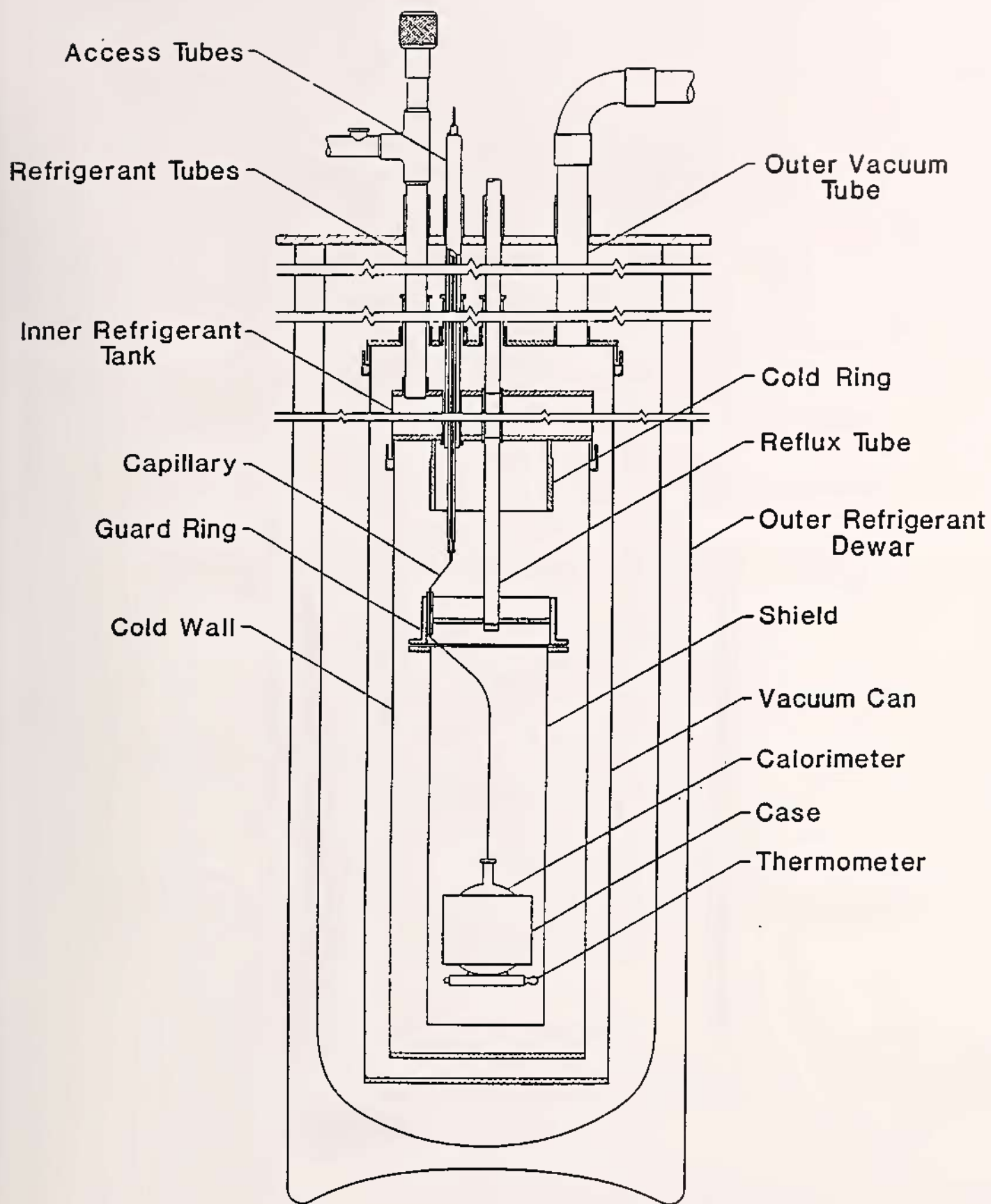


Figure B4. Schematic Diagram of the Calorimeter.

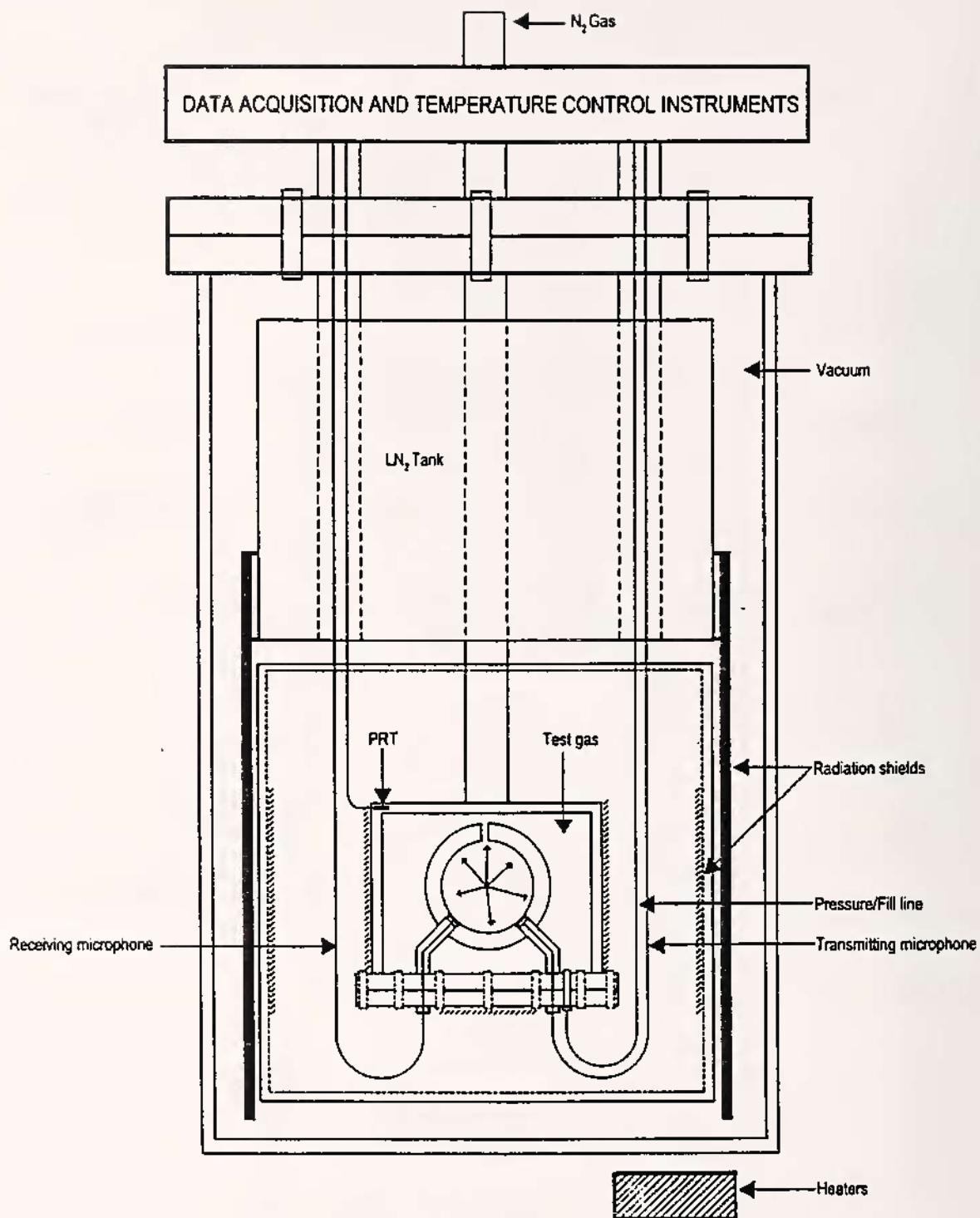


Figure B5. Schematic Diagram of Spherical Resonator Speed of Sound Apparatus.

**APPENDIX C:**  
**ESTIMATES OF STATE-POINT UNCERTAINTIES**

A state point is a group of parameters that uniquely specifies a point in a system such that there are no degrees of freedom. For a binary system, if there are two phases in equilibrium and the temperature and liquid composition (the independent parameters) are known, the state point is specified. The bubble-point pressure, vapor composition, densities, viscosity, surface tension, and many other dependent properties are functions only of the temperature and liquid composition along the two-phase boundary. Therefore, any uncertainties in the temperature and liquid composition directly affect the uncertainty of the dependent properties. Unlike the measurement of an individual parameter where the uncertainty is a function of only the calibration and measurement technique, the state-point uncertainty also depends on the relations among the measured parameters.

The bubble-point pressure state-point uncertainty is defined as the uncertainty of the bubble-point pressure given the uncertainty of the liquid composition measurement, the uncertainty of the temperature measurement, the change of the bubble-point pressure with temperature and composition, and the uncertainty in the pressure measurement. The bubble-point pressure state-point uncertainty can be estimated using eq. (C1).

$$\pm \Delta P_{\sigma} = \pm \left[ \left| \left( \frac{\delta P_{\sigma}}{\delta x} \right)_T \cdot \Delta x \right| + \left| \left( \frac{\delta P_{\sigma}}{\delta T} \right)_x \cdot \Delta T \right| + |\Delta P| \right] \cdot \frac{100}{P}, \quad (C1)$$

where

- $P_{\sigma}$  = bubble-point pressure,
- $\Delta P_{\sigma}$  = bubble-point state-point pressure uncertainty in percent,
- $x$  = measured liquid composition,
- $\Delta x$  = liquid-composition uncertainty,
- $T$  = measured temperature,
- $\Delta T$  = temperature measurement uncertainty,
- $P$  = measured pressure, and
- $\Delta P$  = pressure measurement uncertainty.

The partial derivatives can be calculated using either the experimental data or an equation of state.

The uncertainty of the vapor-composition state point is a function of temperature, liquid composition, and the interdependence of the parameters. It can be determined with a calculation similar to that of the bubble-point pressure state-point uncertainty. The expression for the vapor-composition state-point uncertainty is shown in eq. (C2).

$$\pm \Delta y_{\sigma} = \pm \left[ \left| \left( \frac{\delta y_{\sigma}}{\delta x} \right)_T \cdot \Delta x \right| + \left| \left( \frac{\delta y_{\sigma}}{\delta T} \right)_x \cdot \Delta T \right| + |\Delta y| \right], \quad (C2)$$



**APPENDIX D:**  
**GAS CHROMATOGRAPH CALIBRATION PROCEDURES**

The gas chromatograph calibration procedure involves six steps. The first step is the preparation of two or three standard mixtures for each system. These mixtures are used to determine which GC column to use, to refine the calibration, and to check the sampling system for adsorption or mixing problems. The number of mixtures needed is dependent on the type of GC column used to separate the two components. A short-packed column usually requires two standard mixtures. A capillary column or long-packed column requires three or more mixtures due to the complex behavior of adsorption and desorption along the length of the column.

In the second step, the standard mixtures are used to determine which GC column best separates the two components and what are the appropriate settings on the GC. Table D1 summarizes the GC columns and settings used for each of the systems in this report.

In the third step of the procedure, density-versus-area data are obtained for the pure components from the GC. A specific volume is chosen for injection of the sample into the GC. This volume is filled at different pressures of the pure fluid in a region where the virial equation for the pure fluid can accurately predict the density. The pressure and temperature of the standard volume are recorded before each injection. The density of the injected gas is calculated from the virial equation of state.

The fourth step of the procedure characterizes any peak interaction or sample size dependence by injecting different quantities of the standard mixtures into the GC. The same sample volume used for the pure fluids is filled to different pressures with the standard mixtures. The area-percent-versus-sample-size data are recorded.

The fifth step is determining the correct calibration equation to use with the calibration data. For short-packed columns the area percent of the GC peaks should be independent of the amount of the standard mixture injected. The calibration equation for this type of column is based on combining the area-versus-density data of the two pure components. Usually the area-versus-density relationships for each of the pure components can be represented by a simple quadratic equation. The standard mixture data is used to optimize the fit and to check the accuracy of the equation.

A capillary column or long-packed column shows a dependence of area percent on the sample size injected. The calibration equations for these systems are more complicated than for short-packed columns because they include a size dependence as well as a composition dependence that requires all of the mixture and pure component data to be used in the fit. The procedure is more complicated than the procedure for a short-packed column, but is necessary in order to obtain accurate results.

The final step checks the sampling system for losses due to adsorption or inhomogeneous sampling. The apparatus is filled with one of the standard mixtures, and several samples are analyzed using the sampling system. The composition calculated from the GC should be the same as the composition of the standard mixture. If the composition is not the same as the standard mixture, one of the components may be adsorbing to the walls of the sampling system or the sample is not well mixed before it reaches the GC.

The GC calibration is only accurate within the peak area range of its calibration. If the samples withdrawn from the system are too large or too small, the calculated compositions will be in error.

The size of the sample withdrawn from the apparatus must be adjusted to stay within the limits of the calibration.

Table D1. Summary of the Gas Chromatograph Settings, the Separation Columns, and the Standard Reference Mixtures Used for Each Refrigerant System.

| System        | Column | Column Head Pressure<br>MPa (psi) | Sample Flow<br>cm <sup>3</sup> /min<br>(in <sup>3</sup> /min) | Carrier Flow<br>cm <sup>3</sup> /min<br>(in <sup>3</sup> /min) | Oven Temperature<br>K(°F) | Injector Temperature<br>K(°F) | Detector Temperature<br>K(°F) | Standard Mixtures<br>Mole Fraction(Mass Fraction)                                                  |
|---------------|--------|-----------------------------------|---------------------------------------------------------------|----------------------------------------------------------------|---------------------------|-------------------------------|-------------------------------|----------------------------------------------------------------------------------------------------|
| R-32/134a     | A      | 0.35(50.7)                        | 30(1.8)                                                       | 40(2.4)                                                        | 283.2(50.1)               | 373.2(212)                    | 398.2(257)                    | 0.35/0.65(0.22/0.78)<br>0.65/0.35(0.49/0.51)                                                       |
| R-32/125      | A      | 0.35(50.7)                        | 30(1.8)                                                       | 40(2.4)                                                        | 283.2(50.1)               | 373.2(212)                    | 398.2(257)                    | 0.35/0.65(0.19/0.81)<br>0.65/0.35(0.45/0.55)                                                       |
| R-125/134a    | B      | 0.25(22)                          | -                                                             | -                                                              | 323.2(122)                | 353.2(176)                    | 363.2(194)                    | 0.35/0.65(0.39/0.61)<br>0.50/0.50(0.54/0.46)<br>0.65/0.35(0.69/0.31)                               |
| R-32/125/134a | B      | 0.25(22)                          | -                                                             | -                                                              | 323.2(122)                | 353.2(176)                    | 363.2(194)                    | 0.20/0.20/0.60(0.11/0.25/0.64)<br>0.20/0.60/0.20(0.10/0.70/0.20)<br>0.60/0.20/0.20(0.41/0.32/0.27) |
| R-32/143a     | A      | 0.25(50.7)                        | 30(1.8)                                                       | 40(2.4)                                                        | 303.2(86.0)               | 373.2(212)                    | 398.2(257)                    | 0.35/0.65(0.25/0.75)<br>0.65/0.35(0.53/0.47)                                                       |
| R-125/143a    | C+D    | 0.15(29.2)                        | 25(1.5)                                                       | 15(0.9)                                                        | 323.2(122)                | 353.2(176)                    | 363.2(194)                    | 0.35/0.65(0.43/0.57)<br>0.50/0.50(0.59/0.41)<br>0.65/0.35(0.73/0.27)                               |
| R-143a/134a   | B      | 0.15(36.7)                        | -                                                             | -                                                              | 323.2(122)                | 353.2(176)                    | 363.2(194)                    | 0.35/0.65(0.31/0.69)<br>0.50/0.50(0.45/0.55)<br>0.65/0.35(0.60/0.40)                               |
| R-32/290      | A      | 0.25(50.7)                        | 30(1.8)                                                       | 40(2.4)                                                        | 303.2(86.0)               | 373.2(212)                    | 398.2(257)                    | 0.35/0.65(0.39/0.61)<br>0.65/0.35(0.69/0.31)                                                       |
| R-125/290     | A      | 0.25(50.7)                        | 30(1.8)                                                       | 40(2.4)                                                        | 283.2(50.1)               | 373.2(212)                    | 398.2(257)                    | 0.35/0.65(0.59/0.41)<br>0.65/0.35(0.83/0.17)                                                       |
| R-134a/290    | A      | 0.25(50.7)                        | 30(1.8)                                                       | 40(2.4)                                                        | 283.2(50.1)               | 373.2(212)                    | 398.2(257)                    | 0.35/0.65(0.55/0.45)<br>0.65/0.35(0.81/0.19)                                                       |
| R-41/744      | C      | 0.35(50.7)                        | 30(1.8)                                                       | 40(2.4)                                                        | 293.2(68.0)               | 373.2(212)                    | 398.2(257)                    | 0.50/0.50(0.44/0.56)                                                                               |

Separation Columns (The commercial separation columns are identified in this report in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material or equipment identified are necessarily the best available for the purpose.)

A - 10 ft x 1/8 in SPAL 5% Fluorcol 60/80 Carbopak B

B - 30 m x 0.32 mm GS(Q)

C - 6 ft x 1/8 in Porapak Q 80/100

D - 2 ft x 1/8 in Carbograph1 60/80

**APPENDIX E:**  
**REPRINTS OF PAPERS RELATED TO THE LEMMON-JACOBSEN**  
**MODEL [1] AND REFPROP 6.0 [2]**

Thermodynamic Properties of Mixtures of  
Refrigerants R-32, R-125, R-134a, and R-152a<sup>1</sup>

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## ABSTRACT

A mixture model explicit in Helmholtz energy has been developed which is capable of predicting thermodynamic properties of refrigerant mixtures containing R-32, R-125, R-134a, or R-152a. The Helmholtz energy of the mixture is the sum of the ideal gas contribution, the compressibility (or real gas) contribution, and the contribution from mixing. The contribution from mixing is given by a single equation which is applied to all mixtures used in this work. The independent variables are the reduced density and reduced temperature. The model may be used to calculate thermodynamic properties of mixtures at various compositions including dew- and bubble- point properties and critical points. It incorporates the most accurate published equation of state for each pure fluid. The model may be used to calculate the properties of mixtures generally within the experimental accuracies of the available measured properties. The estimated accuracy of calculated properties is  $\pm 0.1\%$  in density,  $\pm 0.5\%$  in the speed of sound, and  $\pm 1\%$  in heat capacities. Calculated bubble-point pressures are generally accurate to within 1%.

**KEY WORDS:** equation of state; mixtures; R-32; R-125; R-134a; R-152a; thermodynamic properties.

## 1. INTRODUCTION

Applications requiring the use of equations of state capable of accurate prediction of thermodynamic properties of environmentally-safe refrigerant mixtures are increasing. New refrigerants and mixtures of refrigerants are used as environmentally acceptable replacements for chlorofluorocarbons and hydrochlorofluorocarbons in refrigeration, heat pumps, foam-blowing, and other applications. Mixture equations are required to evaluate the performance of possible alternatives to the fully halogenated chlorofluorocarbons as working fluids. Many of the refrigerant mixtures form azeotropes. This is often desirable in vapor compression cycles because the mixture behaves as a pure fluid during phase changes.

The model presented here for mixtures of refrigerants is part of a more generalized model reported by Lemmon and Jacobsen [1] for mixtures of cryogenics, hydrocarbons, and refrigerants. This model was initially reported by Lemmon [2] in a slightly different format. The model is based on corresponding states theory. Reducing parameters which are dependent on the mole fraction are used to modify absolute values of density and temperature. The Helmholtz energy for an ideal solution is determined at the reduced density and temperature of the mixture using accurate pure fluid equations of state for the mixture components.

The portion of the model describing the Helmholtz energy contribution from mixing is nearly the same for all binary mixtures, and relatively simple scaling factors are used to determine its magnitude for a particular application. Experimental data from many different mixtures were used to determine the function. The model is capable of predicting mixture properties for fluids with limited experimental databases. In addition, all vapor and liquid thermodynamic properties, including density, energy, entropy, heat capacity, sound speed, vapor-liquid equilibrium, and the mixture critical temperature, pressure, and density, can be calculated accurately using this approach.

The mixtures studied in this work are:

- R-32/R-125
- R-32/R-134a

- R-125/R-134a
- R-32/R-125/R-134a
- R-134a/R-152a

Data for these mixtures were used to evaluate the behavior of the model, to calculate the coefficients of the generalized refrigerant mixture equation and to calculate the individual parameters for each binary mixture. Table I lists the pure fluid equations of state used in this work. All equations were converted for convenience from the published format to a fundamental form widely used in system analysis and design.

## 2. THE MIXTURE EQUATION FOR ENVIRONMENTALLY-SAFE REFRIGERANTS

The Helmholtz energy for mixtures of refrigerants can be calculated using

$$\alpha_m(\delta, \tau, x) = \alpha_m^i(\delta, \tau, x) + \alpha^E(\delta, \tau, x). \quad (1)$$

The Helmholtz energy for the ideal solution is

$$\alpha_m^i(\delta, \tau, x) = \sum_{i=1}^r x_i \left[ \alpha_i^0(\delta, \tau) + \alpha_i^r(\delta, \tau) + \ln x_i \right], \quad (2)$$

where  $r$  is the number of fluids in the mixture,  $\alpha_i^0$  is the ideal gas Helmholtz energy of component  $i$ , and  $\alpha_i^r$  is the residual Helmholtz energy of component  $i$ . Equations for the ideal gas Helmholtz energy and residual Helmholtz energy for the pure fluids are given in the references shown in Table I.

The contribution to the Helmholtz energy from mixing used in this work is

$$\alpha^E = \sum_{p=1}^r \sum_{q=p+1}^r x_p x_q F_{pq} \sum_{k=1}^{10} N_k \delta^{i_k} \tau^{j_k} + x_{R-32} x_{R-125} (N_{11} \delta \tau + N_{12} \delta) + x_{R-32} x_{R-125} N_{13} \delta, \quad (3)$$

where the  $N_k$ ,  $i_k$ , and  $j_k$  are coefficients and exponents obtained from linear regression of experimental mixture data. The coefficients,  $N_k$ , of the equation are determined using a stepwise least-squares technique with a search and selection procedure which selects an optimum group of terms from a large comprehensive function based on statistical evaluation of the significance of

individual terms. All thermodynamic properties can be calculated from the Helmholtz energy using differentiation with respect to density or temperature as described by Lemmon et al. [3].

The independent parameters of the equation for the contribution to the Helmholtz energy from mixing given in this work are reduced density and temperature and mixture composition. In addition, one other parameter,  $F_{pq}$ , is required which relates the excess-like properties of one binary mixture to those of another. This value is determined with a nonlinear fitting procedure that minimizes the sum of squares of the deviations between the equation and the data for a small select set of measurements.

The reduced density and temperature of the mixture are

$$\delta = \rho / \rho_j \text{ and} \quad (4)$$

$$\tau = T_j / T, \quad (5)$$

where  $T_j$  and  $\rho_j$  are the reducing values,

$$T_j = \sum_{p=1}^r x_p T_{c,p} + \sum_{p=1}^r \sum_{q=p+1}^r x_p x_q \zeta_{pq} \quad (6)$$

$$\rho_j = \left[ \sum_{p=1}^r \frac{x_p}{\rho_{c,p}} + \sum_{p=1}^r \sum_{q=p+1}^r x_p x_q \xi_{pq} \right]^{-1}, \quad (7)$$

and where  $\zeta_{pq}$  and  $\xi_{pq}$  are used to define the shapes of the reducing parameter lines. The units for temperature and density are kelvins and mol-dm<sup>-3</sup>. These reducing parameters are not the same as the critical parameters of the mixture and the use of these parameters allows the calculation of VLE properties above the reducing temperature. These parameters define the relationship between the critical lines of different binary mixtures and are determined simultaneously in the nonlinear fit with the generalized factor. Details of the fitting procedures to determine the generalized factors and mixture parameters are given by Lemmon [2] and are not repeated here. The values of the coefficients and exponents in Eq. (3) are given in Table II. The generalized factors and mixture parameters are given in Table III.

### 3. COMPARISONS OF CALCULATED REFRIGERANT MIXTURE PROPERTIES TO EXPERIMENTAL DATA

Summary comparisons of values calculated using the mixture equation to  $P$ - $\rho$ - $T$  data, isochoric heat capacity data, sound speed data and VLE data for refrigerant mixtures are given in Table IV, as well as the temperature and composition range for the first component listed. Details of the property calculation methods including those for VLE states are given by Lemmon [2].

The accuracies of calculated values of various properties are determined by comparing them to measured values. Statistical analyses are used to determine the overall estimated accuracy of the model in representing the data sets used in determining the coefficients of equations of state, and to define the ranges of estimated accuracies for various properties calculated with the formulation.

The statistics used to evaluate the equation are based on the percent deviation for any property,  $X$ ,

$$\% \Delta X = 100 \left( \frac{X_{\text{data}} - X_{\text{calc}}}{X_{\text{data}}} \right). \quad (8)$$

Using this definition, the statistics in Table IV are defined as:

$$\text{AAD} = \frac{1}{n} \sum_{i=1}^n |\% \Delta X_i|, \quad (9)$$

$$\text{Bias} = \frac{1}{n} \sum_{i=1}^n (\% \Delta X_i). \quad (10)$$

Two of the terms listed in Eq. (3) are specific to the R-32/R-125 binary mixture and another is specific to the R-32/R-134a binary mixture. The mixture model behavior is sensitive to the accuracy of the pure fluid equations of state. The equation of Outcalt and McLinden [5] for R-32 was used in place of the equation from Tillner-Roth and Yokozeki [4] to determine the sensitivity of the deviations of calculated properties to the selection of the R-32 equation. Replacing the equation increased the AAD for the data of Magee [11] by 20%. The deviations for other data in the supercritical region increased as well. The database for mixtures containing R-32 may be more reliable than that for the pure fluid. Additional details of this analysis are given by Lemmon [2]. This issue may be resolved by additional measurements and a revised correlation for R-32.

Likewise, there are similar deficiencies in the R-125 database in the critical region.

#### 4. ACCURACY ASSESSMENT

An assessment has been made to determine the accuracy of the mixture model reported here. Generally, the equation is accurate to  $\pm 0.1\%$  in density,  $\pm 1\%$  in heat capacity, and  $\pm 0.5\%$  for the speed of sound. For binary mixtures, calculated bubble point pressures are generally within  $\pm 1\%$ . The model is valid between from 200 to 450 K up to 60 MPa as verified by experimental data. In regions where there are no binary mixture data, the accuracy is estimated to be of the same magnitude. However, this cannot be verified by the authors until experimental data are available to support these conclusions. Although the equation was developed using mostly binary data, it is accurate in calculating the properties of mixtures with three or more constituents. This conclusion is based upon comparisons of calculated values to the limited data available for multicomponent systems.

Future measurements will confirm whether the equation is valid for other mixtures and in regions not covered by the experimental data used in the development of this model. These data will enable continued evaluation and development of the model.

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Table I. Pure Fluid Equations of State for Refrigerants Used in the Mixture Model.

| Fluid  | Author                        | Temperature Range (K) | Maximum Pressure (MPa) |
|--------|-------------------------------|-----------------------|------------------------|
| R-32   | Tillner-Roth and Yokozeki [4] | 160 - 500             | 60                     |
| R-125  | Outcalt and McLinden [5]      | 174 - 500             | 68                     |
| R-134a | Tillner-Roth and Baehr [6]    | 169.85 - 500          | 70                     |
| R-152a | Tillner-Roth [7]              | 154.65 - 435          | 30                     |

Table II. Coefficients and Exponents of the Mixture Equation

| $k$ | $N_k$                            | $i_k$ | $j_k$ |
|-----|----------------------------------|-------|-------|
| 1   | $-0.245476271425 \times 10^{-1}$ | 1     | 2     |
| 2   | $-0.241206117483$                | 1     | 4     |
| 3   | $-0.513801950309 \times 10^{-2}$ | 1     | -2    |
| 4   | $-0.239824834123 \times 10^{-1}$ | 2     | 1     |
| 5   | $0.259772344008$                 | 3     | 4     |
| 6   | $-0.172014123104$                | 4     | 4     |
| 7   | $0.429490028551 \times 10^{-1}$  | 5     | 4     |
| 8   | $-0.202108593862 \times 10^{-3}$ | 6     | 0     |
| 9   | $-0.382984234857 \times 10^{-2}$ | 6     | 4     |
| 10  | $0.262992331354 \times 10^{-5}$  | 8     | -2    |
| 11  | $-0.198606229861 \times 10^{-1}$ | 1     | 1     |
| 12  | $0.143226453485$                 | 1     | 0     |
| 13  | $0.369107330061 \times 10^{-1}$  | 1     | 0     |

Table III. Parameters of the Mixture Equation

| Binary Mixture | $F_{pq}$  | $\xi_{pq}$  | $\zeta_{pq}$ |
|----------------|-----------|-------------|--------------|
| R-32/R-125     | -0.789585 | -0.00530177 | 14.663390    |
| R-32/R-134a    | -0.314574 | -0.00392017 | 5.737916     |
| R-125/R-134a   | 0.104729  | 0.0         | -2.736948    |
| R-134a/R-152a  | 0.125997  | 0.00487924  | -2.041245    |

Table IV. Comparisons of Mixture Properties Calculated from the Model to Refrigerant Mixture Data

| Author                                                                  | No. Points | Temp. Range | Comp. Range | AAD   | Bias   |
|-------------------------------------------------------------------------|------------|-------------|-------------|-------|--------|
| <b>R-32/R-125 - <math>P</math> - <math>\rho</math> - <math>T</math></b> |            |             |             |       |        |
| Holcomb [8]                                                             | 45         | 279-341     | 0.24-0.96   | 0.940 | 0.361  |
| Kiyoura et al. [9]                                                      | 94         | 330-440     | 0.37-0.61   | 0.487 | -0.486 |
| Kleemiss [10]                                                           | 415        | 243-413     | 0.50-0.51   | 0.187 | -0.035 |
| Magee [11]                                                              | 228        | 200-400     | 0.50        | 0.145 | 0.039  |
| Oguchi et al. [12]                                                      | 6          | 355-430     | 0.87        | 0.275 | -0.138 |
| Piao et al. [13]                                                        | 533        | 263-393     | 0.37-0.90   | 0.245 | -0.098 |
| Sato et al. [14]                                                        | 156        | 320-440     | 0.70-0.90   | 0.333 | -0.328 |
| Weber and Defibaugh [15]                                                | 17         | 338-373     | 0.55        | 0.497 | -0.497 |
| Zhang et al. [16]                                                       | 124        | 300-380     | 0.50-0.70   | 0.279 | -0.273 |
| Overall                                                                 | 1618       | 200-440     | 0.24-0.96   | 0.263 | -0.112 |
| <b>R-32/R-125 - VLE</b>                                                 |            |             |             |       |        |
| Defibaugh and Morrison [17]                                             | 10         | 249-338     | 0.76        | 0.151 | -0.060 |
| Fujiwara et al. [18]                                                    | 8          | 273         | 0.06-0.90   | 2.060 | 2.060  |
| Higashi [19]                                                            | 45         | 283-346     | 0.23-0.90   | 0.329 | 0.322  |
| Holcomb [8]                                                             | 30         | 280-340     | 0.34-0.95   | 0.311 | 0.172  |
| Kleemiss [10]                                                           | 23         | 224-333     | 0.48-0.52   | 0.364 | -0.227 |
| Nagel and Bier [20]                                                     | 34         | 205-345     | 0.24-0.95   | 0.504 | 0.019  |
| Oguchi et al. [12]                                                      | 11         | 250-350     | 0.87        | 0.432 | 0.432  |
| Piao et al. [13]                                                        | 10         | 263-283     | 0.37-0.90*  | 0.665 | -0.648 |
| Widiatmo et al. [21]                                                    | 24         | 280-310     | 0.20-0.90   | 0.530 | 0.383  |
| Overall                                                                 | 195        | 205-350     | 0.06-0.95   | 0.476 | 0.192  |

Table IV. (Continued)

| Author                                                                   | No. Points | Temp. Range | Comp. Range | AAD   | Bias   |
|--------------------------------------------------------------------------|------------|-------------|-------------|-------|--------|
| <b>R-32/R-134a - <math>P</math> - <math>\rho</math> - <math>T</math></b> |            |             |             |       |        |
| Holcomb [8]                                                              | 44         | 279-340     | 0.13-0.97   | 1.123 | 0.535  |
| Kleemiss [10]                                                            | 390        | 243-413     | 0.50-0.56   | 0.090 | 0.001  |
| Magee [11]                                                               | 219        | 200-400     | 0.50        | 0.121 | -0.079 |
| Oguchi et al. [12]                                                       | 19         | 363-473     | 0.39        | 0.426 | 0.407  |
| Piao et al. [13]                                                         | 633        | 263-393     | 0.33-0.89   | 0.405 | -0.225 |
| Sato et al. [22]                                                         | 220        | 320-440     | 0.33-0.89   | 0.147 | -0.011 |
| Weber and Defibaugh [15]                                                 | 17         | 338-373     | 0.51        | 1.048 | -1.048 |
| Widiatmo et al. [23]                                                     | 22         | 280-330     | 0.40        | 0.105 | -0.003 |
| Overall                                                                  | 1564       | 200-473     | 0.13-0.97   | 0.274 | -0.095 |
| <b>R-32/R-134a - <math>c_p</math></b>                                    |            |             |             |       |        |
| Magee [11]                                                               | 131        | 205-343     | 0.50        | 0.373 | 0.294  |
| <b>R-32/R-134a - <math>\omega</math></b>                                 |            |             |             |       |        |
| Hozumi et al. [26]                                                       | 144        | 303-343     | 0.16-0.90   | 0.030 | 0.030  |
| <b>R-32/R-134a - VLE</b>                                                 |            |             |             |       |        |
| Defibaugh and Morrison [17]                                              | 25         | 253-358     | 0.50-0.55   | 0.398 | 0.260  |
| Fujiwara et al. [18]                                                     | 6          | 273-273     | 0.20-0.92   | 3.262 | -3.262 |
| Higashi [24]                                                             | 39         | 283-365     | 0.12-0.67   | 1.171 | 1.104  |
| Holcomb [8]                                                              | 48         | 280-340     | 0.16-0.78   | 0.400 | 0.127  |
| Kleemiss [10]                                                            | 16         | 223-343     | 0.42-0.52   | 0.229 | 0.118  |
| Nagel and Bier [20]                                                      | 50         | 203-369     | 0.21-0.77   | 0.480 | 0.136  |
| Oguchi et al. [12]                                                       | 34         | 238-301     | 0.27-0.71   | 0.868 | 0.776  |
| Piao et al. [13]                                                         | 10         | 261-283     | 0.33-0.89*  | 0.565 | -0.565 |
| Widiatmo et al. [25]                                                     | 30         | 280-340     | 0.33-0.89   | 1.646 | 1.646  |
| Overall                                                                  | 258        | 203-369     | 0.12-0.92   | 0.801 | 0.445  |

Table IV. (Continued)

| Author                                                                         | No.<br>Points | Temp.<br>Range | Comp.<br>Range | AAD   | Bias   |
|--------------------------------------------------------------------------------|---------------|----------------|----------------|-------|--------|
| <b>R-125/R-134a – <math>P</math> - <math>\rho</math> - <math>T</math></b>      |               |                |                |       |        |
| Holcomb [8]                                                                    | 17            | 280-342        | 0.35-0.72      | 0.297 | -0.166 |
| Kleerniss [10]                                                                 | 407           | 243-413        | 0.50-0.51      | 0.125 | -0.103 |
| Magee [11]                                                                     | 268           | 200-400        | 0.50           | 0.110 | -0.076 |
| Weber and Defibaugh [15]                                                       | 18            | 303-373        | 0.50           | 0.378 | -0.353 |
| Widiatmo et al. [23]                                                           | 110           | 280-350        | 0.09-0.92      | 0.112 | -0.093 |
| Overall                                                                        | 820           | 200-413        | 0.09-0.92      | 0.128 | -0.100 |
| <b>R-125/R-134a – VLE</b>                                                      |               |                |                |       |        |
| Higuchi and Higashi [27]                                                       | 55            | 283-365        | 0.18-0.78      | 0.373 | 0.030  |
| Holcomb [8]                                                                    | 40            | 280-340        | 0.26-0.65      | 0.521 | -0.032 |
| Kleerniss [10]                                                                 | 24            | 224-343        | 0.46-0.51      | 0.432 | -0.326 |
| Nagel and Bier [20]                                                            | 31            | 206-365        | 0.25-0.75      | 0.541 | 0.219  |
| Widiatmo et al. [23]                                                           | 75            | 280-350        | 0.09-0.92      | 0.712 | 0.711  |
| Overall                                                                        | 225           | 206-365        | 0.09-0.92      | 0.542 | 0.235  |
| <b>R-32/R-125/R-134a – <math>P</math> - <math>\rho</math> - <math>T</math></b> |               |                |                |       |        |
| Holcomb [8]                                                                    | 42            | 244-346        | 0.20-0.68      | 0.984 | 0.490  |
| Kiyoura et al. [9]                                                             | 105           | 315-440        | 0.38-0.52      | 0.481 | 0.254  |
| Kleerniss [10]                                                                 | 369           | 243-413        | 0.33-0.35      | 0.093 | -0.019 |
| Oguchi et al. [12]                                                             | 12            | 365-430        | 0.38-0.47      | 0.090 | -0.023 |
| Piao et al. [13]                                                               | 994           | 263-393        | 0.19-0.47      | 0.307 | -0.115 |
| Widiatmo et al. [23]                                                           | 53            | 280-340        | 0.38-0.46      | 0.185 | -0.181 |
| Overall                                                                        | 1575          | 243-440        | 0.19-0.68      | 0.278 | -0.056 |

Table IV. (Continued)

| Author                                                                 | No. Points | Temp. Range | Comp. Range | AAD   | Bias   |
|------------------------------------------------------------------------|------------|-------------|-------------|-------|--------|
| <b>R-32/R-125/R-134a - VLE</b>                                         |            |             |             |       |        |
| Higashi [28]                                                           | 52         | 273-359     | 0.17-0.54   | 0.624 | -0.235 |
| Holcomb [8]                                                            | 58         | 221-345     | 0.05-0.60   | 0.901 | 0.030  |
| Kleemiss [10]                                                          | 44         | 222-353     | 0.14-0.66   | 0.372 | -0.306 |
| Nagel and Bier [20]                                                    | 29         | 205-362     | 0.19-0.43   | 0.601 | -0.160 |
| Piao et al. [13]                                                       | 31         | 270-326     | 0.32-0.38   | 0.664 | 0.165  |
| Widiatmo et al. [23]                                                   | 43         | 280-340     | 0.35-0.46   | 0.504 | 0.500  |
| Overall                                                                | 257        | 205-362     | 0.05-0.66   | 0.625 | -0.007 |
| <b>R-134a/R-152a - <math>P</math>-<math>\rho</math>-<math>T</math></b> |            |             |             |       |        |
| Dressner and Bier [29]                                                 | 139        | 333-423     | 0.49-0.54   | 0.225 | -0.076 |
| Tillner-Roth [30]                                                      | 1679       | 243-433     | 0.25-0.75   | 0.073 | 0.034  |
| Weber and Defibaugh [15]                                               | 11         | 353-373     | 0.50        | 0.042 | 0.017  |
| Overall                                                                | 1829       | 243-433     | 0.25-0.75   | 0.085 | 0.025  |
| <b>R-134a/R-152a - <math>\omega</math></b>                             |            |             |             |       |        |
| Grebenkov et al. [31]                                                  | 120        | 230-336     | 0.69        | 0.466 | -0.446 |
| <b>R-134a/R-152a - VLE</b>                                             |            |             |             |       |        |
| Defibaugh and Morrison [17]                                            | 13         | 248-368     | 0.78        | 0.284 | 0.009  |
| Kleiber [32]                                                           | 25         | 255-298     | 0.31-0.98   | 0.146 | -0.134 |
| Tillner-Roth [30]                                                      | 65         | 243-378     | 0.23-0.75   | 0.071 | -0.035 |
| Overall                                                                | 103        | 243-378     | 0.12-0.98   | 0.116 | -0.054 |

\*Dew point compositions

## A NEXT GENERATION REFRIGERANT PROPERTIES DATABASE<sup>1</sup>

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### ABSTRACT

A completely revised version of the REFPROP refrigerant properties database is described. This program is based on the most accurate pure fluid and mixture models currently available. It implements three models for the thermodynamic properties of pure fluids: the modified Benedict-Webb-Rubin (MBWR) and Helmholtz equations of state, and an extended corresponding states (ECS) model. Mixture calculations employ a new model which applies mixing rules to the pure-fluid Helmholtz energies. Viscosity and thermal conductivity are modeled with either fluid-specific correlations or a new variation on the ECS method. These models are implemented in a suite of subroutines written in standard FORTRAN. A separate graphical user interface provides a convenient means of accessing the models. It will generate tables and/or plots for any user-specified mixture. Numerous options to customize the output are available as well as copy and paste capabilities to and from other applications.

### INTRODUCTION

Knowledge of the thermophysical properties is essential for the evaluation of alternative refrigerants and the design of equipment using them. The REFPROP computer database from the National Institute of Standards and Technology (NIST) (Huber *et al.* 1995) has been one of the more widely used tools designed to provide these data. In the initial versions of REFPROP (Gallagher *et al.* 1993), the intent was to provide data on a wide variety of fluids to allow screening studies of possible replacements for the CFC or HCFC refrigerants. For many of these fluids, only sparse data were available, and, consequently, the database relied primarily on a simple model with few adjustable parameters—the Carnahan-Starling-DeSantis (CSD) equation of state. As the alternative refrigerants move from the laboratory to use in commercial equipment, highly accurate properties are required for a more limited set of fluids. We describe a completely revised REFPROP program (designated as Version 6) based on the most accurate pure fluid and mixture models currently available.

### THERMODYNAMIC MODELS

REFPROP 6 calculates the thermodynamic properties using comprehensive equations of state. This approach ensures thermodynamic consistency and allows calculations at all conditions. Other approaches, such as the combination of a vapor-phase model with vapor pressure and liquid density equations may not be applicable in the compressed liquid and supercritical regions and do not always give reliable results for derived properties such as heat capacity and speed of sound.

#### Pure Fluid Models

Three models are used for the thermodynamic properties of pure components, depending on the availability of data. The first is the modified Benedict-Webb-Rubin (MBWR) equation of state. This model was first proposed by Jacobsen and Stewart (1973) and has been applied to a wide variety of fluids, including hydrocarbons, cryogenic fluids, and refrigerants. It is capable of accurately representing the properties of a fluid over wide ranges of temperature, pressure, and density. The MBWR equation is the basis for the current international standard for the properties of R123 (Younglove and McLinden, 1994).

The MBWR equation expresses pressure as an explicit function of temperature and molar density and is of the form,

$$P = \sum_{n=1}^9 \alpha_n \rho^n + \exp\left[\left(\rho/\rho^{crit}\right)^2\right] \sum_{n=10}^{15} \alpha_n \rho^{2n-17}, \quad (1)$$

where the  $\alpha_i$  are simple functions of temperature resulting in a total of 32 adjustable parameters. For a complete description of the energy quantities (enthalpy, entropy, etc.), the MBWR equation is combined with an expression for the molar heat capacity of the ideal-gas state, that is, vapor in the limit of zero pressure. A form combining polynomial and theoretical terms is used:

$$C_p^{id} = \sum_i c_i T^i + \sum_k \frac{u_k^2 \exp(u_k)}{[\exp(u_k) - 1]^2}, \quad \text{with} \quad u_k = \frac{c_k}{T}. \quad (2, 3)$$

All of the thermodynamic properties can be computed from Eqs. (1–3), as detailed by Younglove and McLinden (1994).

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The second high-accuracy pure-fluid equation of state is in terms of reduced molar Helmholtz free energy:

$$a = \frac{A}{RT} = a^{id} + a^r = \ln \delta + \sum_i \alpha_i \tau^{t_i} + \sum_k \alpha_k \tau^{t_k} \delta^{d_k} \exp(-\gamma \delta^{l_k}) \quad (4)$$

where the first two terms on the right side of Eq. (4) constitute the ideal-gas contribution  $a^{id}$ ; they are analogous to the combination of the  $\alpha_1$  term in the MBWR equation of state ( $\alpha_1 = RT$ ) and the ideal-gas heat capacity (Eqs. 2 and 3). The second summation is the residual, or real-fluid, contribution  $a^r$ . The temperature and density are expressed in the dimensionless variables  $\tau = T^*/T$  and  $\delta = \rho/\rho^*$ , where  $T^*$  and  $\rho^*$  are reducing parameters which are often, but not always, equal to the critical parameters. The  $\alpha_i$  and  $\alpha_k$  are numerical coefficients fitted to experimental data and the exponents  $t_i$ ,  $t_k$ ,  $d_i$ , and  $d_k$  are typically determined by a selection algorithm starting with a large bank of terms. The parameter  $\gamma$  is equal to 0 for terms with  $l_k = 0$ ; it is equal to 1 for terms with  $l_k \neq 0$ . This "Helmholtz model" is the basis for the international standard formulation for R134a (Tillner-Roth and Baehr, 1994).

This model is sometimes termed the "fundamental equation" because it gives a complete description of the thermodynamic properties, as discussed by Tillner-Roth and Baehr (1994), but the MBWR equation of state combined with a  $C_p^{id}$  equation is entirely equivalent. The sources for the high-accuracy formulations implemented in the database are summarized in Table 1. The accuracy of these formulations vary, but those for R123 are typical: experimental data are reproduced with average absolute deviations of 0.04 % for densities, 0.05 % for vapor pressures, and 0.75 % for heat capacities.

The third pure-fluid model is the extended corresponding states (ECS) model of Huber and Ely (1994). It is used for fluids with limited experimental data. Simple corresponding states is based on the assumption that different fluids obey, in reduced coordinates, the same intermolecular force law. This assumption leads to the conclusion that, with the appropriate scaling of temperature and density, the reduced residual Helmholtz energies and compressibilities ( $Z = p/RT\rho$ ) of the unknown fluid "j" and a reference fluid "0" (for which an accurate, wide-ranging equation of state is available) are equal:

$$a_j^r(T_j, \rho_j) = a_0^r(T_0, \rho_0) \quad , \quad Z_j(T_j, \rho_j) = Z_0(T_0, \rho_0) \quad (5, 6)$$

When combined with an expression for the ideal gas heat capacity (such as Eqs. 2 and 3), all other thermodynamic properties can be calculated. The reference fluid is evaluated at a "conformal" temperature and density:

$$T_0 = \frac{T_j}{f_j} = T_j \frac{T_0^{crit}}{T_j^{crit} \theta(T)} \quad , \quad \text{and} \quad \rho_0 = \rho_j h_j = \rho_j \frac{\rho_0^{crit}}{\rho_j^{crit}} \phi(T) \quad (7, 8)$$

where the multipliers  $1/f_j$  and  $h_j$  are termed reducing ratios; they are composed of ratios of the critical parameters. Simple corresponding states was developed for spherically symmetric molecules. The ECS model extends the method to other types of molecules by the introduction of the "shape factors"  $\theta$  and  $\phi$ . These shape factors are taken here to be functions only of temperature. (If data sufficient to fit the density dependence were available, it would be preferable to develop a full equation of state.) The shape factors are fitted to experimental data, typically vapor pressures and saturated liquid densities. The reference fluid is chosen to be chemically similar to the fluid of interest. The fluids represented with the ECS model are listed in Table 2.

Table 1—High-accuracy pure-fluid equations of state currently implemented in REFPROP 6

| Fluid                   | Model     | Source                            | Limits of Application           |                |                              |
|-------------------------|-----------|-----------------------------------|---------------------------------|----------------|------------------------------|
|                         |           |                                   | Temperature (K)                 | Pressure (MPa) | Density (kg/m <sup>3</sup> ) |
| R11                     | Helmholtz | Jacobsen <i>et al.</i> (1992)     | 162.68 (T <sub>tp</sub> ) – 625 | 0 – 30         | 0 – 1768                     |
| R12                     | Helmholtz | Marx <i>et al.</i> (1992)         | 116.10 (T <sub>tp</sub> ) – 525 | 0 – 200        | 0 – 1830                     |
| R22                     | Helmholtz | Kamei <i>et al.</i> (1995)        | 115.73 (T <sub>tp</sub> ) – 550 | 0 – 60         | 0 – 1721                     |
| R32                     | MBWR      | Outcalt and McLinden (1995)       | 136.34 (T <sub>tp</sub> ) – 500 | 0 – 60         | 0 – 1429                     |
| R113                    | Helmholtz | Marx <i>et al.</i> (1992)         | 236.93 (T <sub>tp</sub> ) – 525 | 0 – 200        | 0 – 1705                     |
| R123                    | MBWR      | Younglove and McLinden (1994)     | 166 (T <sub>tp</sub> ) – 500    | 0 – 40         | 0 – 1774                     |
| R124                    | Helmholtz | de Vries <i>et al.</i> (1995)     | 100 – 400                       | 0 – 40         | 0 – 1903                     |
| R125                    | MBWR      | Outcalt and McLinden (1995)       | 172.52 (T <sub>tp</sub> ) – 500 | 0 – 60         | 0 – 1691                     |
| R134a                   | Helmholtz | Tillner-Roth and Baehr (1994)     | 169.85 (T <sub>tp</sub> ) – 460 | 0 – 70         | 0 – 1591                     |
| R143a                   | MBWR      | Outcalt and McLinden (1994)       | 161.34 (T <sub>tp</sub> ) – 500 | 0 – 40         | 0 – 1329                     |
| R152a                   | MBWR      | Outcalt and McLinden (1996)       | 154.56 (T <sub>tp</sub> ) – 500 | 0 – 60         | 0 – 1193                     |
| R170 (ethane)           | MBWR      | Younglove and Ely (1987)          | 90.35 (T <sub>tp</sub> ) – 600  | 0 – 70         | 0 – 664                      |
| R290 (propane)          | MBWR      | Younglove and Ely (1987)          | 85.87 (T <sub>tp</sub> ) – 600  | 0 – 100        | 0 – 752                      |
| R600 (butane)           | MBWR      | Younglove and Ely (1987)          | 134.86 (T <sub>tp</sub> ) – 500 | 0 – 70         | 0 – 754                      |
| R600a (isobutane)       | MBWR      | Younglove and Ely (1987)          | 113.55 (T <sub>tp</sub> ) – 600 | 0 – 35         | 0 – 745                      |
| R717 (ammonia)          | Helmholtz | Tillner-Roth <i>et al.</i> (1993) | 195.49 (T <sub>tp</sub> ) – 700 | 0 – 1000       | 0 – 900                      |
| R744 (CO <sub>2</sub> ) | MBWR      | Ely <i>et al.</i> (1987)          | 216.58 (T <sub>tp</sub> ) – 500 | 0 – 40         | 0 – 1178                     |

Table 2—Fluids currently represented with the extended corresponding states (ECS) model in REFPROP 6

| Fluid | Reference Fluid | Fluid | Reference Fluid | Fluid  | Reference Fluid | Fluid | Reference Fluid |
|-------|-----------------|-------|-----------------|--------|-----------------|-------|-----------------|
| R13   | R12             | R115  | R12             | R142b  | R22             | RC270 | propane         |
| R14   | R12             | R116  | R12             | R227ea | R134a           | RC318 | propane         |
| R23   | R134a           | R134  | R134a           | R236fa | R134a           | R1270 | propane         |
| R114  | R12             | R141b | R22             | R245ca | R134a           | RE170 | propane         |

### Mixture Model

The thermodynamic properties of mixtures are calculated with a new model which was developed, in slightly different forms, independently by Tillner-Roth (1993) and Lemmon (1996). It applies mixing rules to the Helmholtz energy of the mixture components:

$$a_{mix} = \frac{A_{mix}}{RT} = \sum_{j=1}^n x_j (a_j^{id} + a_j^r) + x_j \ln x_j + \sum_{p=1}^{n-1} \sum_{q=p+1}^n x_p x_q F_{pq} a_{pq}^{excess} \quad (9)$$

This mixing formula may be applied directly to the Helmholtz equation of state. Application to the MBWR equation of state and the ideal gas heat capacity expression used with the MBWR and ECS models requires transformations:

$$a^r = \frac{1}{RT} \int_V^\infty (P - RT\rho) dV, \text{ and} \quad (10)$$

$$a^{id} = \frac{h_{ref}}{RT} - \frac{s_{ref}}{R} - 1 + \ln \left( \frac{T\rho}{T_{ref}\rho_{ref}} \right) + \frac{1}{RT} \int_{T_{ref}}^T C_p^{id} dT - \frac{1}{R} \int_{T_{ref}}^T \frac{C_p^{id}}{T} dT, \quad (11)$$

where  $h_{ref}$  and  $s_{ref}$  are an arbitrary reference enthalpy and entropy at the reference state specified by  $T_{ref}$  and  $\rho_{ref}$ .

The first summation in Eq. (9) represents the ideal solution; it consists of ideal gas (superscript *id*) and residual or real fluid (superscript *r*) terms for each of the pure fluids in the  $n$  component mixture. The  $x_j \ln x_j$  terms arise from the entropy of mixing of ideal gases where  $x_j$  is the mole fraction of component  $j$ . The double summation accounts for the “excess” free energy or “departure” from ideal solution. The  $F_{pq}$  are generalizing parameters which relate the behavior of one binary pair with another;  $F_{pq}$  multiplies the  $a_{pq}^{excess}$  term(s), which are empirical functions fitted to experimental binary mixture data. The  $a^r$  and  $a_{pq}^{excess}$  functions in Eqs (9 and 10) are not evaluated at the temperature and density of the mixture  $T_{mix}$  and  $\rho_{mix}$  but, rather, at a reduced temperature and density  $\tau$  and  $\delta$ . These  $\tau$  and  $\delta$  are very much in the spirit of the conformal temperature and density of the ECS method and are a key innovation in this model. Several mixing rules for the reducing parameters are used, including

$$\tau = \frac{T^*}{T_{mix}}, \quad \text{with} \quad T^* = \sum_{p=1}^n \sum_{q=1}^n k_{T,pq} x_p x_q (T_p^{crit} T_q^{crit})^{1/2}, \text{ and} \quad (12)$$

$$\delta = \frac{\rho_{mix}}{\rho^*}, \quad \text{with} \quad \frac{1}{\rho^*} = \sum_{p=1}^n \sum_{q=1}^n k_{V,pq} x_p x_q \frac{1}{8} \left[ (V_p^{crit})^{1/3} + (V_q^{crit})^{1/3} \right]^3. \quad (13)$$

If only limited vapor-liquid equilibrium (VLE) data are available the  $a_{pq}^{excess}$  term is taken to be zero, and only the  $k_{T,pq}$  and/or  $k_{V,pq}$  parameters are fitted. The  $k_{T,pq}$  parameter is most closely associated with bubble point pressures, and it is necessary to reproduce azeotropic behavior. The  $k_{V,pq}$  parameter is associated with volume changes on mixing. (Ternary and higher order mixtures are modeled in terms of their constituent binary pairs:  $k_{T,pq} = 1$  and  $k_{V,pq} = 1$  for  $p = q$ .) If extensive data, including single-phase pressure-volume-temperature (PVT) and heat capacity data, are available, the  $a_{pq}^{excess}$  function can be determined. The  $F_{pq}$  parameter is used (either alone or in combination with  $k_{T,pq}$  and  $k_{V,pq}$ ) to generalize the detailed mixture behavior described by the  $a_{pq}^{excess}$  function to other, similar, binary pairs. Lemmon (1996) has determined an  $a_{pq}^{excess}$  function based on data for 28 binary pairs of hydrocarbons, inorganics, and HFC's (but using different mixing rules than Eqs. 12 and 13).

This “mixture Helmholtz model” provides a number of advantages. By applying mixing rules to the Helmholtz energy of the mixture components, it allows the use of high-accuracy equations of state for the components, and the properties of the mixture will reduce exactly to the pure components as the composition approaches a mole fraction of 1. Different components in a mixture may be modeled with different forms; for example, a MBWR equation may be mixed with a Helmholtz equation of state. If the components are modeled with the ECS method, this mixture model allows the use of a different reference fluid for each component. The mixture is modeled in a fundamental way, and thus the departure function is a relatively small contribution to the total Helmholtz energy for most refrigerant mixtures. The great flexibility of the adjustable parameters in this model allows an accurate representation of a wide variety of mixtures, provided sufficient experimental data are available.

## TRANSPORT PROPERTY MODELS

### Pure Fluid Models

The transport properties of viscosity and thermal conductivity are modeled with the residual concept. In this representation, the property  $\chi$  (representing either viscosity  $\eta$  or thermal conductivity  $\lambda$ ) is composed of three contributions:

$$\chi = \chi^{id}(T) + \Delta\chi^r(T, \rho) + \Delta\chi^c(T, \rho) . \quad (14)$$

$\chi^{id}$  is a dilute gas term which is a function only of temperature, and  $\Delta\chi^r$  is a residual term accounting for the behavior at higher densities, including liquid densities.  $\Delta\chi^r$  is primarily a function of density, but it may also be a function of temperature and density. The thermal conductivity approaches infinity at the critical point, and this critical enhancement is expressed by  $\Delta\chi^c$ . This term is significant for thermal conductivity even quite far from the critical point. For viscosity the enhancement is small except extremely close to the critical point and may be safely ignored in all practical applications. A variety of fluid-specific correlations for viscosity and thermal conductivity, based on the residual concept, have been implemented in the database.

Where fluid-specific correlations are not available, the transport properties are modeled with the extended corresponding states method of Klein *et al.* (1996). This method is a modification of the ECS model of Huber *et al.* (1992a, 1992b) and shares many of the concepts of the ECS model for the thermodynamic properties described above. The dilute gas term is modeled using kinetic theory (Hirschfelder *et al.* 1954). The residual term is scaled to the properties of a reference fluid:

$$\Delta\chi_j^r(T, \rho) = \Delta\chi_0^r(T_0, \rho_0) f_j^{1/2} h_j^{-2/3} \left[ \frac{M_j}{M_0} \right]^{1/2} , \quad (15)$$

where  $M$  is molar mass. The determination of the reducing ratios involves an iterative procedure. Eqs. (5) and (6) are iterated to find the  $f_j$  and  $h_j$  satisfying those two conformal relations. The conformal temperature  $T_0$  is defined in Eq. (7). The conformal density  $\rho_0$  in the residual term (but not the critical enhancement) is further modified from that in the thermodynamic ECS method (Eq. 8) by the introduction of a third shape factor  $\Psi$ :

$$\rho_0 = \rho_j \frac{\rho_0^{crit}}{\rho_j^{crit}} \Phi(T) \Psi(\rho) . \quad (16)$$

The shape factor  $\Psi$  is a linear function of density and is determined by a least-squares fit to experimental data. Separate  $\Psi$  functions are determined for viscosity and thermal conductivity.

### Mixture Model

The viscosity of a mixture is calculated with the extended corresponding states method of Klein *et al.* (1996):

$$\eta(T, \rho, x) = \eta^{id}(T, x) + \Delta\eta_0(T/f_x, \rho h_x) F_\eta + \Delta\eta^*(\rho, x) , \quad \text{with} \quad F_\eta = f_x^{1/2} h_x^{-2/3} g_x^{1/2} . \quad (17, 18)$$

The low-density contribution  $\eta^{id}$  is calculated with kinetic theory (Hirschfelder *et al.* 1954) and  $\Delta\eta^*$  is an Enskog-theory hard-sphere correction for size and mass differences given by Ely (1981). The reducing ratios  $f_x$  and  $h_x$  are determined by applying Eqs. (5) and (6) to the mixture. The "mass shape factor" for the mixture,  $g_x$ , is determined by mixing rules applied to the component mass shape factors, defined as

$$g_j^{1/2} = \frac{\Delta\eta_j(T_j, \rho_j)}{\Delta\eta_0(T/f_j, \rho h_j)} f_j^{-1/2} h_j^{2/3} . \quad (19)$$

The residual viscosity of component  $j$  in Eq. (19) is evaluated, using either a fluid-specific correlation or the pure-fluid ECS model described above, at the conformal conditions

$$T_j = \frac{T_{mix} f_j}{f_x} \quad \text{and} \quad \rho_j = \frac{\rho_{mix} h_x}{h_j} . \quad (20, 21)$$

This formulation yields the pure-fluid values exactly as the composition approaches a mole fraction of 1. A analogous method is used for thermal conductivity. For the transport properties, R134a is used as the reference fluid for all mixture components.

## PROPERTY SUBROUTINES

The property models described above are implemented as a suite of FORTRAN subroutines. These routines have been completely rewritten from earlier versions of REFPROP. Source code is provided with the database so that users may link the property routines with their own application. ("Translation" routines will allow applications written using the subroutine calls

of earlier versions of REFPROP to use the new subroutines.) The routines are written in ANSI-standard FORTRAN 77 and are compatible with FORTRAN 90. They are written in a structured format, are internally documented with extensive comments, and have been tested on a variety of compilers.

The fluid or mixture of interest is specified with a (required) call to the subroutine "SETUP." This routine reads the coefficients to the NIST-recommended models for that fluid. Alternative property models and/or nonstandard reference states may be specified by calls to additional (optional) setup routines. Routines are provided to calculate thermodynamic and transport properties and surface tension at a given  $(T, \rho, x)$  state. Iterative routines provide saturation properties at a specified  $(T, x)$  or  $(P, x)$  state. Flash calculations calculate single- or two-phase states at specified  $(P, h, x)$ ,  $(P, T, x)$ , etc.

The routines mentioned above are independent of the model. Underlying these routines are sets of "core" routines for each of the models implemented in the database. Each such set is highly modular and is contained in a separate file. Coefficients needed for a particular model are stored in common blocks, but these commons are referenced only by routines in the same file. These sets of subroutines, thus, resemble "units" in the Pascal language with clearly demarcated "interface" and "local" declarations. This structure is intended to simplify the addition of future models to the database and will make such additions almost totally transparent to the user.

Numerical coefficients to the property models are stored in text files. There is one file per fluid and one file containing coefficients for the mixture departure functions. These files are read (once) upon the call to SETUP. Fluids can be added to or deleted from the database without recompilation.

## USER INTERFACE

A graphical user interface has been developed for REFPROP 6 independent of the code implementing the algorithms. The interface provides a convenient means to calculate and display thermodynamic and transport properties. It is written for the Windows™ operating system. (Mention of commercial products is to fully specify the database and does not constitute endorsement by NIST or imply that they are necessarily the best suited for the purpose.) The interface is written in Pascal; it accesses the FORTRAN property subroutines via a dynamic link library. Screen shots of the interface program are shown in Figures 1 and 2. The program is controlled through the use of the following pull-down menus (visible at the top of Figure 1):

The **File** provides commands to save and print generated tables and plots. Individual items or entire sessions with multiple windows may be saved or recalled. The standard "print setup" and "quit" commands are also present.

The **Edit** menu provides copy and paste commands which allow selected data to be exchanged with other applications.

The **Options** menu provides commands for selecting the unit system, properties of interest, and the reference state. These options may be stored for recall at a later time. A user-defined set of preferences is loaded upon program startup.

The pure fluid or mixture of interest is specified with commands in the **Substance** menu. Most of the refrigerant mixtures of current commercial interest (those having an ASHRAE R400 or R500-series designation) are predefined. In addition, new mixtures can be specified and saved by combining up to five of the pure components listed in Tables 1 and 2.

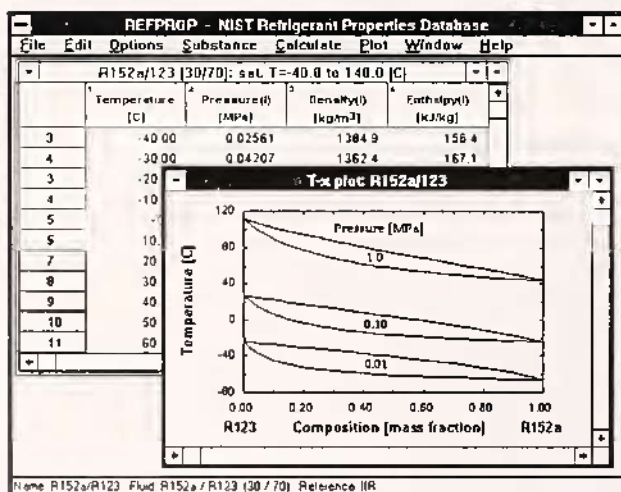


Figure 1. Screen shot of interface showing a typical data table and temperature-composition diagram.

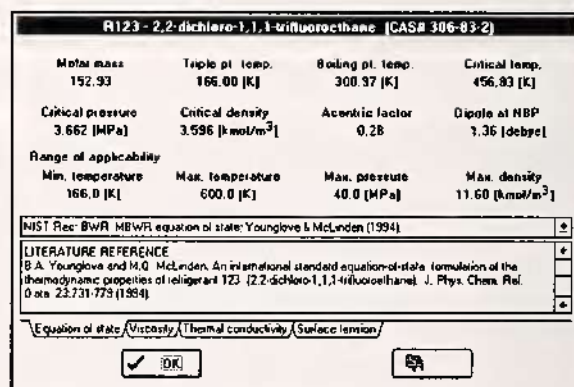


Figure 2. Pure-component information screen available from the interface.

The Calculate menu initiates the calculations that generate a property table. Each property selected for display is shown in a separate column of the table. Two types of tables are provided. The first type, such as that shown in Figure 1, provides properties at saturation or with a property (such as temperature or pressure) held constant with another selected property varying over a specified range. The second type allows the user to select the independent variables. Values of the independent variables may then be entered with the keyboard, read from a file, or pasted from another application.

The Plot menu provides publication-quality x-y plots of any variables appearing in a table. In addition, temperature-entropy, pressure-enthalpy, temperature-composition and pressure-composition diagrams may be generated automatically. Controls are provided to modify the plot size, axis scaling, plot symbols, line type, legend, and other plot features.

Each table or plot appears in a separate window and can be accessed, resized, or retitled with commands in the Window menu. The number of windows is limited only by available memory.

A complete online-help system can be accessed through the Help menu.

A status line at the bottom of the screen displays the currently specified mixture, composition, and reference state. Clicking on the status line will call up a screen for each of the components providing documentation for fluid constants, the source of the models, and their range of applicability, as shown in Figure 2.

## CONCLUSIONS

The new REFPROP 6 database implements a variety of high-accuracy models for the thermodynamic and transport properties of refrigerants and their mixtures. These models are implemented as a suite of FORTRAN 77 subroutines written in a modular fashion; this structure will facilitate the incorporation of additional fluids and future models. A graphical user interface provides a convenient means of accessing the models and producing tables and plots of any specified mixture.

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