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Table 2.1 Partial Electrochemical Reduction Potential Series at 298°C

Half Reaction	Voltage E° (V)
$Ag^+_{aq} + e^- \rightarrow Ag_s$	+0.799
$AgBr_s + e^- \rightarrow Ag_s + Br^-_{aq}$	+0.095
$AgCl_s + e^- \rightarrow Ag_s + Cl^-_{aq}$	+0.222
$HClO_{aq} + H^+ + e^- \rightarrow \frac{1}{2} Cl_{2,g} + H_2O_l$	+1.63
$Cu^{2+}_{aq} + 2e^- \rightarrow Cu_s$	+0.337
$Fe^{2+}_{aq} + 2e^- \rightarrow Fe_s$	−0.440
$Fe^{3+}_{aq} + 3e^- \rightarrow Fe_s$	+0.771
$2H^+_{aq} + 2e^- \rightarrow H_{2,g}$	0.000
$2H_2O_l + 2e^- \rightarrow H_{2,g} + 2OH^-_{aq}$	−0.830
$HO^-_{2aq} + H_2O_l + 2e^- \rightarrow 3OH^-_{aq}$	+0.880
$H_2O_{2,aq} + 2H^+_{aq} + 2e^- \rightarrow 2H_2O_l$	+1.776
$K^+_{aq} + e^- \rightarrow K_s$	−2.925
$Li^+_{aq} + e^- \rightarrow Li_s$	−3.05
$Mg^{2+}_{aq} + 2e^- \rightarrow Mg_s$	−2.37
$N_{2,g} + 4H_2O_l + 4e^- \rightarrow 4OH^-_{aq} + N_2H_{4,aq}$	−1.16
$N_{2,g} + 5H^+_{aq} + 4e^- \rightarrow N_2H^-_{5,aq}$	−0.23
$NO^-_{3aq} + 4H^+_{aq} + 3e^- \rightarrow NO_g + 2H_2O_l$	+0.96
$Na^+_{aq} + e^- \rightarrow Na_s$	−2.71
$Na^{2+}_{aq} + 2e^- \rightarrow Ni_s$	−0.28
$Zn^{2+}_{aq} + 2e^- \rightarrow Zn$	−0.76
$O_{2,g} + 4H^+_{aq} + 4e^- \rightarrow 2H_2O_l$	+1.23
$O_{2,g} + 2H^+_{aq} + 2e^- \rightarrow H_2O_{2,aq}$	+0.68
$O_{2,g} + 2H_2O_l + 4e^- \rightarrow 4OH^-_{aq}$	+0.40
$O_{3,g} + 2H^+_{aq} + 2e^- \rightarrow O_{2,g} + H_2O_l$	+2.07
$S_s + 2H^+_{aq} + 2e^- \rightarrow H_2S_g$	+0.141
$H_2SO_{3,aq} + 4H^+_{aq} + 4e^- \rightarrow S(s) + 3H_2O_l$	+0.450
$HSO^-_{4,aq} + 4H^+_{aq} + 2e^- \rightarrow H2SO_{3,aq} + H_2O_l$	+0.170

Source: From [5].

Table 2.2 Electrical and Ionic Resistivities of Selected Materials

Electron conductors	Electron Resistivity at 293 K (Ωm)
Gold	2.44×10^{-8}
Aluminum	2.28×10^{-8}
Copper	1.7×10^{-8}
Silver	1.6×10^{-8}
Stainless steel	7.2×10^{-7}
Platinum	1.1×10^{-7}
Ruthenium	7.1×10^{-8}
Palladium	10×10^{-8}
Carbon	3.5×10^{-5a}
Water (deionized)	2.5×10^{5}
Polytetrafluoroethylene (Teflon)	10^{16}–10^{17}
Ionic Conductors	**Ionic Resistivity (Ωm)**
Nafion PEFC electrolyte by DuPont, fully humidified	~10 at 353 K
SOFC electrolyte	0.1–1 at 600–1000 K
Liquid electrolytes	Highly concentration, temperature, and ion dependent

[a] Dependent on direction and molecular structure.

Table 3.3 Enthalpy of Formation, Gibbs Energy of Formation, and Entropy Values at 298 K, 1 atm

Species	Molecular Formula	$\bar{h}^\circ_f$ (kJ/kmol)	$\bar{g}^\circ_f$ (kJ/kmol)	$\bar{s}^\circ$ (kJ/kmol · K)
Carbon	C_s	0	0	5.74
Hydrogen	$H_{2,g}$	0	0	130.57
Nitrogen	$N_{2,g}$	0	0	191.50
Oxygen	$O_{2,g}$	0	0	205.03
Carbon monoxide	CO_g	−110,530	−137,150	197.54
Carbon dioxide	$CO_{2,g}$	−393,520	−394,380	213.69
Water vapor	H_2O_g	−241,820	−228,590	188.72
Liquid water	H_2O_l	−285,830	−237,180	69.95
Hydrogen peroxide	$H_2O_{2,g}$	−136,310	−105,600	232.63
Ammonia	$NH_{3,g}$	−46,190	−16,590	192.33
Hydroxyl	OH_g	39,460	34,280	183.75
Methane	$CH_{4,g}$	−74,850	−50,790	186.16
Ethane	$C_2H_{6,g}$	−84,680	−32,890	229.49
Propane	$C_3H_{8,g}$	−103,850	−23,490	269.91
Octane vapor	$C_8H_{18,g}$	−208,450	17,320	463.67
Octane liquid	$C_8H_{18,l}$	−249,910	6,610	360.79
Benzene	$C_6H_{6,g}$	82,930	129,660	269.20
Methanol vapor	CH_3OH_g	−200,890	−162,140	239.70
Methanol liquid	CH_3OH_l	−238,810	−166,290	126.80
Ethanol vapor	$C_2H_5OH_g$	−235,310	−168,570	282.59
Ethanol liquid	$C_2H_5OH_l$	−277,690	−174,890	160.70

Source: From [1].

$$H = U + \frac{P}{\rho} = U + Pv \qquad G \equiv H - TS$$

Table A.1 Critical Properties of Selected Fuel Cell Gases

Specie	Critical Pressure (kPa)	Critical Temperature (K)
Air	37,700	133
Carbon Dioxide, CO_2	73,900	304
Carbon Monoxide, CO	35,000	133
Ethanol, C_2H_5OH	63,800	516
Hydrogen, H_2	13,000	33.2
Methanol, CH_3OH	79,600	513
Nitrogen, N_2	33,900	126
Oxygen, O_2	50,500	154
Water, H_2O	220,900	647.3

Source: Adapted from M. J. Moran and H. N. Shapiro, *Fundamentals of Engineering Thermodynamics*, 3rd Edition, Wiley, New York, 1995.

Constants	Value	Unit
F	96485	C/eq.
R_u	8.314	J/mol.K

$$P = \frac{R_u T}{v - b} - \frac{a}{v^2} \qquad PV = nR_u T$$

$$a = \frac{27}{64}\frac{R_u^2 T_c^2}{P_c} \qquad b = \frac{R_u}{8}\frac{T_c}{P_c}$$

$$\dot{n}_x = \frac{iA}{nF} = \frac{I}{nF} \qquad \rho = \frac{RA}{l} = \frac{1}{\sigma}$$

$$\frac{-\Delta G}{nF} = E^\circ \qquad \frac{-\Delta H}{nF} = E_{th} = E^{\circ\circ}$$

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

$$\bar{u}_2 - \bar{u}_1 = \int_{T_1}^{T_2} \bar{c}_v(T)\,dT \qquad \bar{h}_2 - \bar{h}_1 = \int_{T_1}^{T_2} \bar{c}_p(T)\,dT$$

$$\bar{s}_2 - \bar{s}_{ref} = \int_{T_{ref_1}}^{T_2} \frac{\bar{c}_p(T)\,dT}{T} - R_u \ln \frac{P_2}{P_{ref}}$$

$$\nu_A A + \nu_B B \leftrightarrow \nu_C C + \nu_D D$$

$$\Delta G = \Delta G^\circ(T) - R_u T \ln\left[\frac{a_A^{\nu_A} a_B^{\nu_B}}{a_C^{\nu_C} a_D^{\nu_D}}\right]$$

$$\frac{\bar{c}_p(T)_{H_2}}{R_u} = 3.057 + 2.677 \times 10^{-3}T - 5.810 \times 10^{-6}T^2 + 5.521 \times 10^{-9}T^3 - 1.812 \times 10^{-12}T^4$$

$$\frac{\bar{c}_p(T)_{O_2}}{R_u} = 3.626 - 1.878 \times 10^{-3}T + 7.055 \times 10^{-6}T^2 - 6.764 \times 10^{-9}T^3 + 2.156 \times 10^{-12}T^4$$

$$\frac{\bar{c}_p(T)_{N_2}}{R_u} = 3.675 - 1.208 \times 10^{-3}T + 2.324 \times 10^{-6}T^2 - 0.632 \times 10^{-9}T^3 - 0.226 \times 10^{-12}T^4$$

$$\frac{\bar{c}_p(T)_{Air}}{R_u} = 3.653 - 1.337 \times 10^{-3}T + 3.294 \times 10^{-6}T^2 - 1.913 \times 10^{-9}T^3 + 0.2763 \times 10^{-12}T^4$$

$$\frac{\bar{c}_p(T)_{H_2O}}{R_u} = 4.070 - 1.108 \times 10^{-3}T + 4.152 \times 10^{-6}T^2 - 2.964 \times 10^{-9}T^3 + 0.807 \times 10^{-12}T^4$$

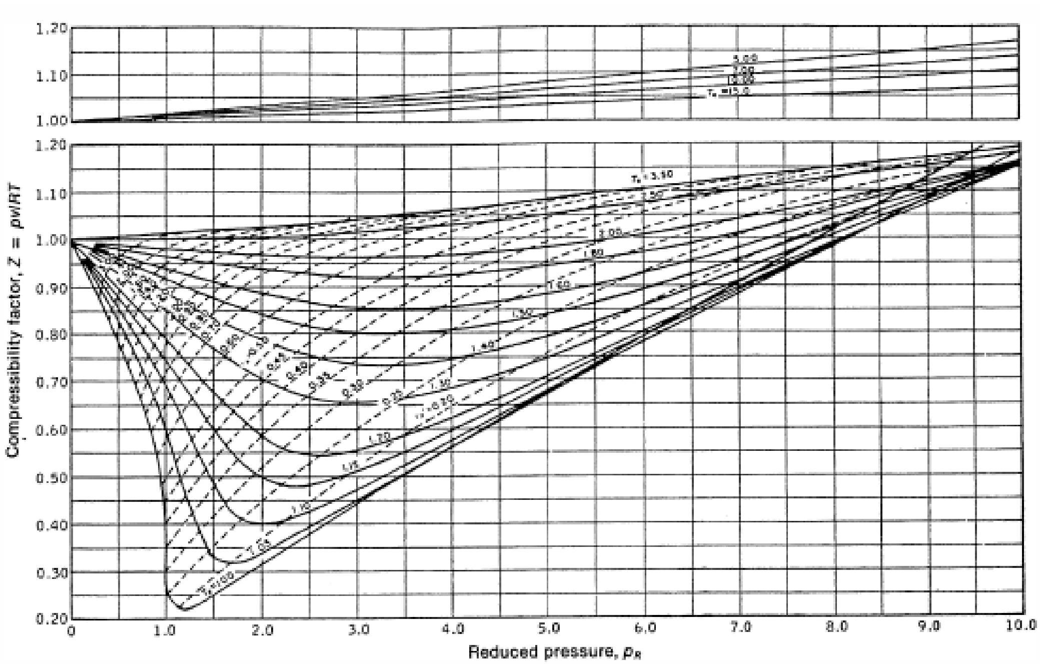

Figure 3.3 Generalized compressibility chart. (Reproduced from E. F. Obert, *Concepts of Thermodynamics*, McGraw-Hill, New York, 1960.)

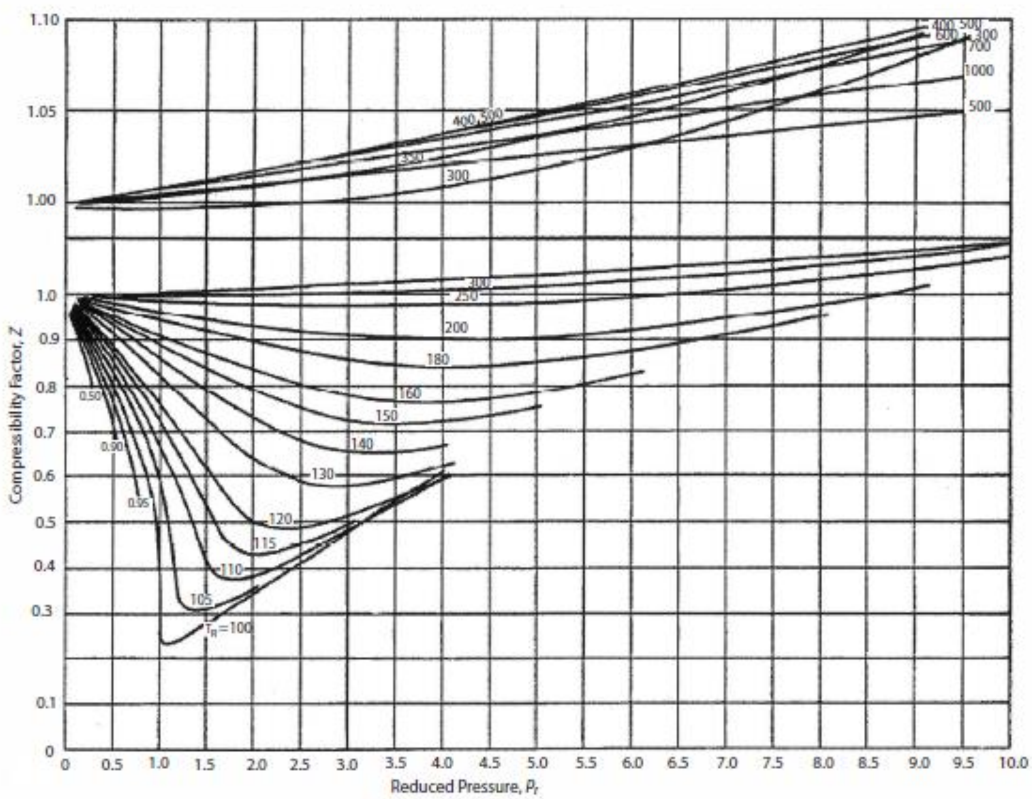

Figure 3.4 Experimentally measured hydrogen compressibility chart. (Reproduced with permission from [3]. Copyright American Chemical Society.)

$$E(T,P) = -\frac{\Delta G}{nF} + \frac{RT}{nF}\ ln\left[\frac{\left(\frac{P_{H_2}}{P^0}\right)\left(\frac{P_{O_2}}{P^0}\right)^{\frac{1}{2}}}{\left(\frac{P_{H_2O}}{P^0}\right)}\right]$$

A

MM5481 Fuel Cells

Appendix

Some selected journals which publish fuel cell articles:

Applied Catalysis A- General
Catalysis Today
Chemical Reviews
Electrochimica Acta
Electrochemical and Solid State Letters
Electrochemistry
Electrochemistry Communications
Fuel Cells
International Journal of Heat and Mass Transfer
International Journal of Hydrogen Energy
Journal of Applied Electrochemistry
Journal of Catalysts
Journal of Electroanalytical Chemistry
Journal of Fuel Cell Science and Technology
Journal of New Materials for Electrochemical Systems
Journal of Physical Chemistry B
Journal of Power Sources
Journal of the American Ceramic Society
Journal of the Electrochemical Society
Journal of Materials Science
Journal of Membrane Science
Solid State Ionics

Some selected general interest Websites:

http://www.fuelcells.org/ Regularly updated fuel cell information site
http://www.cafcp.org/ California fuel cell vehicle partnership site
http://www.sae.org/fuelcells/fuelcells.htm American Society of Automotive Engineers Fuel Cell site
http://www.hfcletter.com/ Hydrogen and fuel cell letter
http://www.fuelcelltoday.com/ Regularly updated fuel cell information site

http://www.fuelcellsworks.com/ Regularly updated fuel cell information site

http://www.fuelcelleurope.org/ European fuel cell information site

http://www.eere.energy.gov/hydrogenandfuelcells/ U.S. Department of Energy, Energy Efficiency and Renewables program information site

http://www.fossil.energy.gov/programs/powersystems/fuelcells/ U.S. Department of Energy, fuel cells program information site

http://www.hydrogenassociation.org/general/fuelingSearch.asp National Hydrogen association site

http://webbook.nist.gov/chemistry/ National Institute of Standards and Technology site for thermofluidic property data.

http://www.convertit.com/ Units conversion calculator

Table A.1 Critical Properties of Selected Fuel Cell Gases

Specie	Critical Pressure (kPa)	Critical Temperature (K)
Air	37,700	133
Carbon Dioxide, CO_2	73,900	304
Carbon Monoxide, CO	35,000	133
Ethanol, C_2H_5OH	63,800	516
Hydrogen, H_2	13,000	33.2
Methanol, CH_3OH	79,600	513
Nitrogen, N_2	33,900	126
Oxygen, O_2	50,500	154
Water, H_2O	220,900	647.3

Source: Adapted from M. J. Moran and H. N. Shapiro, *Fundamentals of Engineering Thermodynamics*, 3rd Edition, Wiley, New York, 1995.

Table A.2 Heats of Formation, Gibbs Heat of Formation, and Absolute Entropy of Selected Species at STP Conditions (298 K and 1 atm)

Specie	$\bar{h}_f^o$ (kJ/kmol)	$\bar{g}_f^o$ (kJ/kmol)	$\bar{s}^o$ (kJ/kmol K)
Carbon Dioxide, CO_2	−393,520	−394,380	213.69
Carbon Monoxide, CO	−110,530	−137,150	197.54
Ethanol, $C_2H_5OH_g$	−235,310	−168,570	282.59
Ethanol, $C_2H_5OH_l$	−277,690	174,890	160.70
Hydrogen, H_2	0	0	130.57
Methane, $CH4_g$	−74,850	−50,790	186.16
Methanol, CH_3OH_g	−200,890	−162,140	239.70
Methanol, CH_3OH_l	−238,810	−166,290	126.80
Nitrogen, N_2	0	0	191.50
Oxygen, O_2	0	0	205.03
Water, H_2O_g	−241,820	−228,590	188.72
Water, H_2O_l	−285,830	−237,180	69.95

Source: Adapted from M. J. Moran and H. N. Shapiro, *Fundamentals of Engineering Thermodynamics*, 3rd Edition, Wiley, New York, 1995.

Table A.3 Ideal Gas Properties of Air[a]

T	h	p_r	u	v_r	s^o
200	199.97	0.3363	142.56	1707.	1.29559
210	209.97	0.3987	149.69	1512.	1.34444
220	219.97	0.4690	156.82	1346.	1.39105
230	230.02	0.5477	164.00	1205.	1.43557
240	240.02	0.6355	171.13	1084.	1.47824
250	250.05	0.7329	178.28	979.	1.51917
260	260.09	0.8405	185.45	887.8	1.55848
270	270.11	0.9590	192.60	808.0	1.59634
280	280.13	1.0889	199.75	738.0	1.63279
285	285.14	1.1584	203.33	706.1	1.65055
290	290.16	1.2311	206.91	676.1	1.66802
295	295.17	1.3068	210.49	647.9	1.68515
300	300.19	1.3860	214.07	621.2	1.70203
305	305.22	1.4686	217.67	596.0	1.71865
310	310.24	1.5546	221.25	572.3	1.73498
315	315.27	1.6442	224.85	549.8	1.75106
320	320.29	1.7375	228.42	528.6	1.76690
325	325.31	1.8345	232.02	508.4	1.78249
330	330.34	1.9352	235.61	489.4	1.79783
340	340.42	2.149	242.82	454.1	1.82790
350	350.49	2.379	250.02	422.2	1.85708
360	360.58	2.626	257.24	393.4	1.88543
370	370.67	2.892	264.46	367.2	1.91313
380	380.77	3.176	271.69	343.4	1.94001
390	390.88	3.481	278.93	321.5	1.96633
400	400.98	3.806	286.16	301.6	1.99194
410	411.12	4.153	293.43	283.3	2.01699
420	421.26	4.522	300.69	266.6	2.04142
430	431.43	4.915	307.99	251.1	2.06533
440	441.61	5.332	315.30	236.8	2.08870
450	451.80	5.775	322.62	223.6	2.11161
460	462.02	6.245	329.97	211.4	2.13407
470	472.24	6.742	337.32	200.1	2.15604
480	482.49	7.268	344.70	189.5	2.17760
490	492.74	7.824	352.08	179.7	2.19876
500	503.02	8.411	359.49	170.6	2.21952
510	513.32	9.031	366.92	162.1	2.23993
520	523.63	9.684	374.36	154.1	2.25997
530	533.98	10.37	381.84	146.7	2.27967
540	544.35	11.10	389.34	139.7	2.29906

(*Continued*)

Table A.3 (*Continued*)

T	h	p_r	u	v_r	s^o
550	554.74	11.86	396.86	133.1	2.31809
560	565.17	12.66	404.42	127.0	2.33685
570	575.59	13.50	411.97	121.2	2.35531
580	586.04	14.38	419.55	115.7	2.37348
590	596.52	15.31	427.15	110.6	2.39140
600	607.02	16.28	434.78	105.8	2.40902
610	617.53	17.30	442.42	101.2	2.42644
620	628.07	18.36	450.09	96.92	2.44356
630	638.63	19.84	457.78	92.84	2.46048
640	649.22	20.64	465.50	88.99	2.47716
650	659.84	21.86	473.25	85.34	2.49364
660	670.47	23.13	481.01	81.89	2.50985
670	681.14	24.46	488.81	78.61	2.52589
680	691.82	25.85	496.62	75.50	2.54175
690	702.52	27.29	504.45	72.56	2.55731
700	713.27	28.80	512.33	69.76	2.57277
710	724.04	30.38	520.23	67.07	2.58810
720	734.82	32.02	528.14	64.53	2.60319
730	745.62	33.72	536.07	62.13	2.61803
740	756.44	35.50	544.02	59.82	2.63280
750	767.29	37.35	551.99	57.63	2.64737
760	778.18	39.27	560.01	55.54	2.66176
770	789.11	41.31	568.07	53.39	2.67595
780	800.03	43.35	576.12	51.64	2.69013
790	810.99	45.55	584.21	49.86	2.70400
800	821.95	47.75	592.30	48.08	2.71787
820	843.98	52.59	608.59	44.84	2.74504
840	866.08	57.60	624.95	41.85	2.77170
860	888.27	63.09	641.40	39.12	2.79783
880	910.56	68.98	657.95	36.61	2.82344
900	932.93	75.29	674.58	34.31	2.84856
920	955.38	82.05	691.28	32.18	2.87324
940	977.92	89.28	708.08	30.22	2.89748
960	1000.55	97.00	725.02	28.40	2.92128
980	1023.25	105.2	741.98	26.73	2.94468
1000	1046.04	114.0	758.94	25.17	2.96770

[a] T (K), h and u (kJ/kg), s^o (kJ/kg·K).

Source: Adapted from K. Wark, *Thermodynamics*, 4th ed., McGraw-Hill, New York, 1983, as based on J. H. Keenan and J. Kaye, *Gas Tables*, Wiley, New York, 1945.

Table A.4 Ideal Gas Properties of Carbon Dioxide (CO_2)[a]

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
0	0	0	0
220	6,601	4,772	202.966
230	6,938	5,026	204.464
240	7,280	5,285	205.920
250	7,627	5,548	207.337
260	7,979	5,817	208.717
270	8,335	6,091	210.062
280	8,697	6,369	211.376
290	9,063	6,651	212.660
298	9,364	6,885	213.685
300	9,431	6,939	213.915
310	9,807	7,230	215.146
320	10,186	7,526	216.351
330	10,570	7,826	217.534
340	10,959	8,131	218.694
350	11,351	8,439	219.831
360	11,748	8,752	220.948
370	12,148	9,068	222.044
380	12,552	9,392	223.122
390	12,960	9,718	224.182
400	13,372	10,046	225.225
410	13,787	10,378	226.250
420	14,206	10,714	227.258
430	14,628	11,053	228.252
440	15,054	11,393	229.230
450	15,483	11,742	230.194
460	15,916	12,091	231.144
470	16,351	12,444	232.080
480	16,791	12,800	233.004
490	17,232	13,158	233.916
500	17,678	13,521	234.814
510	18,126	13,885	235.700
520	18,576	14,253	236.575
530	19,029	14,622	237.439
540	19,485	14,996	238.292
550	19,945	15,372	239.135
560	20,407	15,751	239.962
570	20,870	16,131	240.789
580	21,337	16,515	241.602
590	21,807	16,902	242.405

(*Continued*)

Table A.4 (*Continued*)

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
600	22,280	17,291	243.199
610	22,754	17,683	243.983
620	23,231	18,076	244.758
630	23,709	18,471	245.524
640	24,190	18,869	246.282
650	24,674	19,270	247.032
660	25,160	19,672	247.773
670	25,648	20,078	248.507
680	26,138	20,484	249.233
690	26,631	20,894	249.952
700	27,125	21,305	250.663
710	27,622	21,719	251.368
720	28,121	22,134	252.065
730	28,622	22,552	252.755
740	29,124	22,972	253.439
750	29,629	23,393	254.117
760	30,135	23,817	254.787
770	30,644	24,242	255.452
780	31,154	24,669	256.110
790	31,665	25,097	256.762
800	32,179	25,527	257.408
810	32,694	25,959	258.048
820	33,212	26,394	258.682
830	33,730	26,829	259.311
840	34,251	27,267	259.934
850	34,773	27,706	260.551
860	35,296	28,125	261.164
870	35,821	28,588	261.770
880	36,347	29,031	262.371
890	36,876	29,476	262.968
900	37,405	29,922	263.559
910	37,935	30,369	264.146
920	38,467	30,818	264.728
930	39,000	31,268	265.304
940	39,535	31,719	265.877
950	40,070	32,171	266.444
960	40,607	32,625	267.007
970	41,145	33,081	267.566
980	41,685	33,537	268.119
990	42,226	33,995	268.670
1000	42,769	34,455	269.015

[a] T (K), $\bar{h}$ and $\bar{u}$ (kJ/kmol), $\bar{s}^o$(kJ/kmol·K), $\bar{h}_f^\circ = -393{,}520$ kJ/kmol

Source: Adapted from K. Wark, *Thermodynamics*, 4th Edition, McGraw-Hill, New York, 1983, as based on the JANAF Thermochemical Tables, NSRDS-NBS-37, 1971.

Table A.5 Ideal Gas Properties of Carbon Monoxide (CO)[a]

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
0	0	0	0
220	6,391	4,562	188.683
230	6,683	4,771	189.980
240	6,975	4,979	191.221
250	7,266	5,188	192.411
260	7,558	5,396	193.554
270	7,849	5,604	194.654
280	8,140	5,812	195.173
290	8,432	6,020	196.735
298	8,669	6,190	197.543
300	8,723	6,229	197.723
310	9,014	6,437	198.678
320	9,306	6,645	199.603
330	9,597	6,854	200.500
340	9,889	7,062	201.371
350	10,181	7,271	202.217
360	10,473	7,480	203.040
370	10,765	7,689	203.842
380	11,058	7,899	204.622
390	11,351	8,108	205.383
400	11,644	8,319	206.125
410	11,938	8,529	206.850
420	12,232	8,740	207.549
430	12,526	8,951	208.252
440	12,821	9,163	208.929
450	13,116	9,375	209.593
460	13,412	9,587	210.243
470	13,708	9,800	210.880
480	14,005	10,014	211.504
490	14,302	10,228	212.117
500	14,600	10,443	212.719
510	14,898	10,658	213.310
520	15,197	10,874	213.890
530	15,497	11,090	214.460
540	15,797	11,307	215.020
550	16,097	11,524	215.572
560	16,399	11,743	216.115
570	16,701	11,961	216.649
580	17,003	12,181	217.175
590	17,307	12,401	217.693

(*Continued*)

Table A.5 (*Continued*)

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
600	17,611	12,622	218.204
610	17,915	12,843	218.708
620	18,221	13,066	219.205
630	18,527	13,289	219.695
640	18,833	13,512	220.179
650	19,141	13,736	220.656
660	19,449	13,962	221.127
670	19,758	14,187	221.592
680	20,068	14,414	222.052
690	20,378	14,641	222.505
700	20,690	14,870	222.953
710	21,002	15,099	223.396
720	21,315	15,328	223.833
730	21,628	15,558	224.265
740	21,943	15,789	224.692
750	22,258	16,022	225.115
760	22,573	16,255	225.533
770	22,890	16,488	225.947
780	23,208	16,723	226.357
790	23,526	16,957	226.762
800	23,844	17,193	227.162
810	24,164	17,429	227.559
820	24,483	17,665	227.952
830	24,803	17,902	228.339
840	25,124	18,140	228.724
850	25,446	18,379	229.106
860	25,768	18,617	229.482
870	26,091	18,858	229.856
880	26,415	19,099	230.227
890	26,740	19,341	230.593
900	27,066	19,583	230.957
910	27,392	19,826	231.317
920	27,719	20,070	231.674
930	28,046	20,314	232.028
940	28,375	20,559	232.379
950	28,703	20,805	232.727
960	29,033	21,051	233.072
970	29,362	21,298	233.413
980	29,693	21,545	233.752
990	30,024	21,793	234.088
1000	30,355	22,041	234.421

[a] T (K), $\bar{h}$ and $\bar{u}$ (kJ/kmol), $\bar{s}^o$(kJ/kmol·K), $\bar{h}_f^\circ = -110{,}530$ kJ/kmol

Source: Adapted from K. Wark, *Thermodynamics*, 4th Edition, McGraw-Hill, New York, 1983, as based on the JANAF Thermochemical Tables, NSRDS-NBS-37, 1971.

Table A.6 Ideal Gas Properties of Hydrogen (H_2)[a]

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
0	0	0	0
260	7,370	5,209	126.636
270	7,657	5,412	127.719
280	7,945	5,617	128.765
290	8,233	5,822	129.775
298	8,468	5,989	130.574
300	8,522	6,027	130.754
320	9,100	6,440	132.621
340	9,680	6,853	134.378
360	10,262	7,268	136.039
380	10,843	7,684	137.612
400	11,426	8,100	139.106
420	12,010	8,518	140.529
440	12,594	8,936	141.888
460	13,179	9,355	143.187
480	13,764	9,773	144.432
500	14,350	10,193	145.628
520	14,935	10,611	146.775
560	16,107	11,451	148.945
600	17,280	12,291	150.968
640	18,453	13,133	152.863
680	19,630	13,976	154.645
720	20,807	14,821	156.328
760	21,988	15,669	157.923
800	23,171	16,520	159.440
840	24,359	17,375	160.891
880	25,551	18,235	162.277
920	26,747	19,098	163.607
960	27,948	19,966	164.884
1000	29,154	20,839	166.114

[a] T (K), $\bar{h}$ and $\bar{u}$ (kJ/kmol), $\bar{s}^o$ (kJ/kmol·K), $\bar{h}_f^\circ = 0$ kJ/kmol

Source: Adapted from K. Wark, *Thermodynamics*, 4th Edition, McGraw-Hill, New York, 1983, as based on the JANAF Thermochemical Tables, NSRDS-NBS-37, 1971.

Table A.7 Ideal Gas Properties of Oxygen (O_2)[a]

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
0	0	0	0
220	6,404	4,575	196.171
230	6,694	4,782	197.461
240	6,984	4,989	198.696
250	7,275	5,197	199.885
260	7,566	5,405	201.027
270	7,858	5,613	202.128
280	8,150	5,822	203.191
290	8,443	6,032	204.218
298	8,682	6,203	205.033
300	8,736	6,242	205.213
310	9,030	6,453	206.177
320	9,325	6,664	207.122
330	9,620	6,877	208.020
340	9,916	7,090	208.904
350	10,213	7,303	209.765
360	10,511	7,518	210,604
370	10,809	7,733	211.423
380	11,109	7,949	212.222
390	11,409	8,166	213.002
400	11,711	8,384	213.765
410	12,012	8,603	214.510
420	12,314	8,822	215.241
430	12,618	9,043	215.955
440	12,923	9,264	216.656
450	13,228	9,487	217.342
460	13,535	9,710	218.016
470	13,842	9,935	218.676
480	14,151	10,160	219.326
490	14,460	10,386	219.963
500	14,770	10,614	220.589
510	15,082	10,842	221.206
520	15,395	11,071	221.812
530	15,708	11,301	222.409
540	16,022	11,533	222.997
550	16,338	11,765	223.576
560	16,654	11,998	224.146
570	16,971	12,232	224.708
580	17,290	12,467	225.262
590	17,609	12,703	2250.808

Table A.7 (*Continued*)

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
600	17,929	12,940	226.346
610	18,250	13,178	226.877
620	18,572	13,417	227.400
630	18,895	13,657	227.918
640	19,219	13,898	228.429
650	19,544	14,140	228.932
660	19,870	14,383	229.430
670	20,197	14,626	229.920
680	20,524	14,871	230.405
690	20,854	15,116	230.885
700	21,184	15,364	231.358
710	21,514	15,611	231.827
720	21,845	15,859	232.291
730	22,177	16,107	232.748
740	22,510	16,357	233.201
750	22,844	16,607	233.649
760	23,178	16,859	234.091
770	23,513	17,111	234.528
780	23,850	17,364	234.960
790	24,186	17,618	235.387
800	24,523	17,872	235.810
810	24,861	18,126	236.230
820	25,199	18,382	236.644
830	25,537	18,637	237.055
840	25,877	18,893	237.462
850	26,218	19,150	237.864
860	26,559	19,408	238.264
870	26,899	19,666	238.660
880	27,242	19,925	239.051
890	27,584	20,185	239.439
900	27,928	20,445	239.823
910	28,272	20,706	240.203
920	28,616	20,967	240.580
930	28,960	21,228	240.953
940	29,306	21,491	241.323
950	29,652	21,754	241.689
960	29,999	22,017	242.052
970	30,345	22,280	242.411
980	30,692	22,544	242.768
990	31,041	22,809	243.120
1000	31,339	23,075	243.471

[a] T (K), $\bar{h}$ and $\bar{u}$ (kJ/kmol), $\bar{s}^\circ$(kJ/kmol·K), $\bar{h}_f^\circ = 0$ kJ/kmol

Source: Adapted from K. Wark, *Thermodynamics*, 4th Edition, McGraw-Hill, New York, 1983, as based on the JANAF Thermochemical Tables, NSRDS-NBS-37, 1971.

Table A.8 Ideal Gas Properties of Water Vapor (H_2O)[a]

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
0	0	0	0
220	7,295	5,466	178.576
230	7,628	5,715	180.054
240	7,961	5,965	181.471
250	8,294	6,215	182.831
260	8,627	6,466	184.139
270	8,961	6,716	185.399
280	9,296	6,968	186.616
290	9,631	7,219	187.791
298	9,904	7,425	188.720
300	9,966	7,472	188.928
310	10,302	7,725	190.030
320	10,639	7,978	191.098
330	10,976	8,232	192.136
340	11,314	8,487	193.144
350	11,652	8,742	194.125
360	11,992	8,998	195.081
370	12,331	9,255	196.012
380	12,672	9,513	196.920
390	13,014	9,771	197.807
400	13,356	10,030	198.673
410	13,699	10,290	199.521
420	14,043	10,551	200.350
430	14,388	10,813	201.160
440	14,734	11,075	201.955
450	15,080	11,339	202.734
460	15,428	11,603	203.497
470	15,777	11,869	204.247
480	16,126	12,135	204.982
490	16,477	12,403	205.705
500	16,828	12,671	206.413
510	17,181	12,940	207.112
520	17,534	13,211	207.799
530	17,889	13,482	208.475
540	18,245	13,755	209.139
550	18,601	14,028	209.795
560	18,959	14,303	210.440
570	19,318	14,579	211.075
580	19,678	14,856	211.702
590	20,039	15,134	212.320

Table A.8 (*Continued*)

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
600	20,402	15,413	212.920
610	20,765	15,693	213.529
620	21,130	15,975	214.122
630	21,495	16,257	214.707
640	21,862	16,541	215.285
650	22,230	16,826	215.856
660	22,600	17,112	216.419
670	22,970	17,399	216.976
680	23,342	17,688	217.527
690	23,714	17,978	218.071
700	24,088	18,268	218.610
710	24,464	18,561	219.142
720	24,840	18,854	219.668
730	25,218	19,148	220.189
740	25,597	19,444	220.707
750	25,977	19,741	221.215
760	26,358	20,039	221.720
770	26,741	20,339	222.221
780	27,125	20,639	222.717
790	27,510	20,941	223.207
800	27,896	21,245	223.693
810	28,284	21,549	224.174
820	28,672	21,855	224.651
830	29,062	22,162	225.123
840	29,454	22,470	225.592
850	29,846	22,779	226.057
860	30,240	23,090	226.517
870	30,635	23,402	226.973
880	31,032	23,715	227.426
890	31,429	24,029	227.875
900	31,828	24,345	228.321
910	32,228	24,662	228.763
920	32,629	24,980	229.202
930	33,032	25,300	229.637
940	33,436	25,621	230.070
950	33,841	25,943	230.499
960	34,247	26,265	230.924
970	34,653	26,588	231.347
980	35,061	26,913	231.767
990	35,472	27,240	232.184

[a] T (K), $\bar{h}$ and $\bar{u}$ (kJ/kmol), $\bar{s}^o$(kJ/kmol·K), $\bar{h}_f^\circ = -241{,}820$ kJ/kmol

Source: Adapted from K. Wark, *Thermodynamics*, 4th Edition, McGraw-Hill, New York, 1983, as based on the JANAF Thermochemical Tables, NSRDS-NBS-37, 1971.

Table A.9 Ideal Gas Properties of Nitrogen (N_2)[a]

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
0	0	0	0
220	6,391	4,562	182.639
230	6,683	4,770	183.938
240	6,975	4,979	185.180
250	7,266	5,188	186.370
260	7,558	5,396	187.514
270	7,849	5,604	188.614
280	8,141	5,813	189.673
290	8,432	6,021	190.695
298	8,669	6,190	191.502
300	8,723	6,229	191.682
310	9,014	6,437	192.638
320	9,306	6,645	193.562
330	9,597	6,853	194.459
340	9,888	7,061	195.328
350	10,180	7,270	196.173
360	10,471	7,478	196.995
370	10,763	7,687	197.794
380	11,055	7,895	198.572
390	11,347	8,104	199.331
400	11,640	8,314	200.071
410	11,932	8,523	200.794
420	12,225	8,733	201.499
430	12,518	8,943	202.189
440	12,811	9,153	202.863
450	13,105	9,363	203.523
460	13,399	9,574	204.170
470	13,693	9,786	204.803
480	13,988	9,997	205.424
490	14,285	10,210	206.033
500	14,581	10,423	206.630
510	14,876	10,635	207.216
520	15,172	10,848	207.792
530	15,469	11,062	208.358
540	15,766	11,277	208.914
550	16,064	11,492	209.461
560	16,363	11,707	209.999
570	16,662	11,923	210.528
580	16,962	12,139	211.049
590	17,262	12,356	211.562

Table A.9 (*Continued*)

T	$\bar{h}$	$\bar{u}$	$\bar{s}^o$
600	17,563	12,574	212.066
610	17,864	12,792	212.564
620	18,166	13,011	213.055
630	18,468	13,230	213.541
640	18,772	13,450	214.018
650	19,075	13,671	214.489
660	19,380	13,892	214.954
670	19,685	14,114	215.413
680	19,991	14,337	215.866
690	20,297	14,560	216.314
700	20,604	14,784	216.756
710	20,912	15,008	217.192
720	21,220	15,234	217.624
730	21,529	15,460	218.059
740	21,839	15,686	218.472
750	22,149	15,913	218.889
760	22,460	16,141	219.301
770	22,772	16,370	219.709
780	23,085	16,599	220.113
790	23,398	16,830	220.512
800	23,714	17,061	220.907
810	24,027	17,292	221.298
820	24,342	17,524	221.684
830	24,658	17,757	222.067
840	24,974	17,990	222.447
850	25,292	18,224	222.822
860	25,610	18,459	223.194
870	25,928	18,695	223.562
880	26,248	18,931	223.927
890	26,568	19,168	224.288
900	26,890	19,407	224.647
910	27,210	19,644	225.002
920	27,532	19,883	225.353
930	27,854	20,122	225.701
940	28,178	20,362	226.047
950	28,501	20,603	226.389
960	28,826	20,844	226.728
970	29,151	21,086	227,064
980	29,476	21,328	227.398
990	29,803	21,571	227.728
1000	30,129	21,815	228.057

[a] T (K), $\bar{h}$ and $\bar{u}$ (kJ/kmol), $\bar{s}^\circ$(kJ/kmol·K), $\bar{h}_f = 0$ kJ/kmol

Source: Adapted from K. Wark, *Thermodynamics*, 4th Edition, McGraw-Hill, New York, 1983, as based on the JANAF Thermochemical Tables, NSRDS-NBS-37, 1971.

Table A.10 Saturated Water Vapor Temperature Table[a]

Temperature (°C)	Saturation Pressure (kPa)
−40	0.0128
−35	0.0223
−30	0.0379
−25	0.0632
−20	0.1031
−15	0.1650
−10	0.2595
−5	0.4011
0	0.6102
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
35	5.63
40	7.39
45	9.60
50	12.36
55	15.77
60	19.96
65	25.05
70	31.21
75	38.61
80	47.43
85	57.89
90	70.21
95	84.64
100	101.45
105	120.94
110	143.43
115	169.24
120	198.74
125	232.31
130	270.36
135	313.32
140	361.64
145	415.80
150	476.29

[a] Data below 0°C are based on the Goff–Gratch equation to correlate for saturation vapor pressure over ice [1, 2]:

$$\log_{10}(10 \cdot P_{\text{sat}}) = -9.09718(273.16/T - 1) - 3.56654\log_{10}(273.16/T) + 0.876793(1 - T/273.16) + \log_{10}(6.1071)$$

where T is in Kelvin and P_{sat} is in kPa, and the equation is valid from −100 to 0°C.

Source: Data at 0–150°C from E.W. Lemmon, M.O. McLinden and D.G. Friend, "Thermophysical Properties of Fluid Systems" in NIST Chemistry WebBook, NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and W.G. Mallard, June 2005, National Institute of Standards and Technology, Gaithersburg MD, 20899 (http://webbook.nist. gov).

Table A.11 Surface Tension of Water in Contact with Air

Temperature (°C)	Surface Tension (N/m)
0	7.56×10^{-2}
5	7.49×10^{-2}
10	7.42×10^{-2}
20	7.28×10^{-2}
30	7.12×10^{-2}
40	6.96×10^{-2}
50	6.79×10^{-2}
60	6.62×10^{-2}
70	6.44×10^{-2}

Source: International Association for the Properties of Water Steam, Viscosity of Thermal Conductivity of Heavy Water Substance in Physical Chemistry of Aqueous Systems: Proceedings of the 12th International Conference on the Properties of Water and Steam, Orlando, FL, 1994, al07–al38.

Other Useful Relations:

Saturation pressure of vapor over liquid water [3]:

$$\ln P_{\text{sat}} = -34.625 + 0.258T - 4.8419 \times 10^{-4}T^2 + 3.3282 \times 10^{-7}T^3$$

where T is in Kelvin, and P_{sat} is in Pa.

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3. J. M. Prausnitz, R. C. Reid, and T. K. Sherwood, *The Properties of Gases and Liquids, – 3*, McGraw-Hill, New York, 1997.