



PROGRAM : NATIONAL DIPLOMA
CHEMICAL ENGINEERING

SUBJECT : THERMODYNAMICS III

CODE : CIT3111

DATE : WINTER SSA EXAMINATION 2016
27 JULY 2016

DURATION : (SESSION 3) 15:00 - 18:00

WEIGHT : 40 : 60

TOTAL MARKS : 100

EXAMINER : DR K MOOTHI

MODERATOR : DR H RUTTO

NUMBER OF PAGES : 09 PAGES

INSTRUCTIONS : QUESTION PAPERS MUST BE HANDED IN.

REQUIREMENTS : Use of scientific (non-programmable) calculator is permitted
(only one per candidate).

INSTRUCTIONS TO CANDIDATES:

- PLEASE ANSWER ALL THE QUESTIONS.
 - Number each question clearly; the order of answer/s does not matter.
 - Show all units in calculations.
 - Write clearly and legibly
-

Question One**[Total: 20 Marks]**

1.1 A power plant generates 750 MW; the reactor temperature is 315°C and a river with water temperature of 20°C is available.

- (a) Calculate the maximum possible thermal efficiency of the plant, and what is the minimum rate at which heat must be discarded to the river? **[6]**
- (b) If the actual thermal efficiency of the plant is 60% of the maximum, at what rate must heat be discarded to the river, and what is the temperature rise of the river if it has a flowrate of 165 m³ s⁻¹? **[6]**

Use following information for the river water: $\rho = 1 \frac{\text{g}}{\text{cm}^3}$ and $C_p = 1 \frac{\text{cal}}{\text{gK}}$

1.2 Using the following fundamental property relations for a homogeneous fluid of constant composition:

$$dU = TdS - PdV$$

$$dH = TdS + VdP$$

$$dA = -PdV - SdT$$

$$dG = VdP - SdT$$

and the Maxwell's equations:

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$$

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$$

$$\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T$$

$$\left(\frac{\partial V}{\partial T}\right)_P = -\left(\frac{\partial S}{\partial P}\right)_T$$

Show that:

$$dU = C_V dT + \left[T \left(\frac{\partial P}{\partial T} \right)_V - P \right] dV$$

$$dS = C_V \frac{dT}{T} + \left(\frac{\partial P}{\partial T} \right)_V dV$$

[6]

Write these expressions for the ideal gas.

[2]

Question Two**[Total: 30 Marks]**

- 2.1 State the three alternative statements of the Second Law of Thermodynamics. [9]
- 2.2 Fill in the blanks for the following statements:
- (a) A reservoir that supplies energy in the form of heat is called a _____ [2]
 - (b) A reservoir that absorbs energy in the form of heat is called a _____ [2]
 - (c) Heat engine operating in a completely reversible manner is called a _____ [2]
- 2.3 What is the final temperature when 1-butene gas initially at 1033.15 K (760°C) and 4 bar undergoes reversible adiabatic expansion to 1 bar? [15]
Assume 1-butene gas to be an ideal gas at these conditions.
For the iterations, assume starting $T = 700^\circ\text{C}$

Question Three**[Total: 20 Marks]**

- 3.1 A refrigeration system cools a brine from 298.15K to 258.15K (25°C to -15°C) at the rate of 20 kgs⁻¹. Heat is discarded to the atmosphere at a temperature of 303.15 K (30°C). What is the power requirement if the thermodynamic efficiency of the system is 0.2? The specific heat of the brine is 3.5 kJ kg⁻¹K⁻¹. [10]
- 3.2 A Carnot engine receives 250 kW of heat from a heat-source reservoir at 798.15 K (525°C) and rejects heat to a heat-sink reservoir at 323.15 K (50°C). Calculate:
- (a) the power developed and [5]
 - (b) the heat rejected [5]

Question Four**[Total: 10 Marks]**

Using the Virial equation of state, estimate the residual enthalpy and entropy for benzene at 400 °C and 55.5 bar.
Given: $T_c = 562.2 \text{ K}$ $P_c = 48.98 \text{ bar}$ $\omega = 0.210$

Question Five**[Total: 20 Marks]**

- Assuming the validity of Raoult's law, do the following calculations for the benzene (1)/toluene (2) system:
- (a) Given $x_1 = 0.33$ and $T = 373.15 \text{ K}$, find y_1 and P ; [12]
 - (b) Given $y_1 = 0.33$ and $T = 373.15 \text{ K}$, find x_1 and P [8]

END**[Total: 100 Marks]**

USEFUL EQUATIONS AND FORMULAE

$$PV = nRT; \quad \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}; \quad v = \frac{V^t}{m}; \quad v = \frac{V^t}{n}; \quad \rho = v^{-1}; \quad P = \frac{F}{A}$$

$$P_{abs} = P_g(\text{or } \rho gh) + P_{atm}; \quad dW = Fdl; \quad W = -\int_{V_1}^{V_2} P dV;$$

$$\Delta E_{system} + \Delta E_{surroundings} = 0; \quad \eta = \frac{W_{irreversible}}{W_{reversible}}; \quad \frac{dm_{cv}}{dt} = \Delta \dot{m} = \dot{m}_{out} - \dot{m}_{in}$$

$$\text{Energy balance for open systems: } \frac{d(mU)_{cv}}{dt} = -\dot{m}\Delta\left[U + \frac{1}{2}u^2 + gh\right] + \dot{Q} + \dot{W}$$

$$\text{Energy balance for steady-state flow processes: } \Delta \dot{m}\left(H + \frac{1}{2}u^2 + gh\right) = \dot{Q} + \dot{W}_s$$

$$\text{Interpolation: } M = \left(\frac{X_2 - X}{X_2 - X_1}\right)M_1 + \left(\frac{X - X_1}{X_2 - X_1}\right)M_2$$

Mechanically reversible closed processes:

$$Q = n\Delta U = n \int_{T_1}^{T_2} C_v dT$$

$$Q = n\Delta H = n \int_{T_1}^{T_2} C_p dT$$

$$Q = -W$$

$$W = \Delta U = C_v \Delta T = \frac{R\Delta T}{\gamma - 1} = \frac{R(T_2 - T_1)}{\gamma - 1} = \frac{P_2 V_2 - P_1 V_1}{\gamma - 1} = \frac{P_1 V_1}{\gamma - 1} \left[\left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} - 1 \right] = \frac{RT_1}{\gamma - 1} \left[\left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} - 1 \right];$$

$$\gamma = \frac{C_p}{C_v};$$

Virial equation:

$$\frac{PV}{RT} = 1 + \frac{B}{V} + \frac{C}{V^2};$$

Lee/ Kesler correlation:

$$Z = Z^0 + \omega Z^1;$$

Generalized Pitzer correlation:

$$Z = 1 + (B^0 + \omega B^1) \frac{P_r}{T_r} \left(B^0 = 0.083 - \frac{0.422}{T_r^{1.6}}; B^1 = 0.139 - \frac{0.172}{T_r^{4.2}} \right)$$

Ideal gas:

$$Q = n\Delta H = n\langle C_p \rangle_H (T_1 - T_0); \quad \langle C_p \rangle_H = R \left[A + \frac{B}{2} T_o(\tau + 1) + \frac{C}{3} T_o^2(\tau^2 + \tau + 1) + \frac{D}{\tau T_o^2} \right] \langle C_p \rangle_H$$

Clapeyron equation:

$$\Delta H = T\Delta V \frac{dP^{sat}}{dT};$$

General entropy change:

$$\Delta S = C_p \ln \frac{T_2}{T_1} - \ln \frac{P_2}{P_1}$$

Entropy change for an ideal gas:

$$\frac{\Delta S}{R} = \frac{\langle c_p^{ig} \rangle_s}{R} \ln \frac{T}{T_o} - \ln \frac{P}{P_o} ;$$

$$\frac{\langle c_p^{ig} \rangle_s}{R} = A + \left[BT_o + \left(CT_o^2 + \frac{D}{\tau^2 T_o^2} \right) \left(\frac{\tau+1}{\tau} \right) \right] \left(\frac{\tau-1}{\ln \tau} \right)$$

For residual properties:

$$\begin{aligned} \frac{H^R}{RT_c} &= \left(\frac{H^R}{RT_c} \right)^0 + \omega \left(\frac{H^R}{RT_c} \right)^1 & ; & \quad \frac{S^R}{R} = \left(\frac{S^R}{R} \right)^0 + \omega \left(\frac{S^R}{R} \right)^1 \\ \frac{H^R}{RT_c} &= P_r \left[\left(0.083 - \frac{1.097}{T_r^{1.6}} \right) + \omega \left(0.139 - \frac{0.894}{T_r^{4.2}} \right) \right] & ; & \quad \frac{S^R}{R} = -P_r \left[\frac{0.675}{T_r^{2.6}} + \omega \left(\frac{0.722}{T_r^{5.2}} \right) \right] \end{aligned}$$

Raoult's law:

$$y_i P = x_i P_i^{sat} \text{ where } P = \sum_i x_i P_i^{sat} \text{ or } P = \frac{1}{\sum_i y_i / P_i^{sat}}$$

Modified Raoult's law:

$$y_i P = x_i \gamma_i P_i^{sat} \text{ where } P = \sum_i x_i \gamma_i P_i^{sat} \text{ or } P = \frac{1}{\sum_i y_i / \gamma_i P_i^{sat}}$$

Fugacity and fugacity coefficient:

$$\phi = (\phi^0)(\phi^1)^\omega \quad ; \quad \ln \phi = (B^0 + \omega B^1) \frac{P_r}{T_r}$$

ANTOINE PARAMETERS TABLE

$\ln P^{sat}/\text{kPa} = A - \frac{B}{T + C}$			
Table 10.2 Parameters for the Antoine Equation			
	A	B	C
Acetone	14.3916	2795.82	-43.15
Acetonitrile	14.7258	3271.24	-31.30
Benzene	13.8594	2773.78	-53.08
Chlorobenzene	13.9926	3295.12	-55.60
1-Chlorobutane	13.9600	2826.26	-49.05
1,4-Dioxane	14.1177	2966.88	-63.15
Ethanol	16.6758	3674.49	-46.70
Ethylbenzene	14.0045	3279.47	-59.95
n-Heptane	13.8587	2991.32	-56.51
Methanol	16.5938	3644.30	-33.39
Methyl acetate	14.4015	2739.17	-50.03
n-Pentane	13.8183	2477.07	-39.94
1-Propanol	16.0692	3448.66	-69.06
Toluene	14.0098	3103.01	-53.36
Water	16.2620	3799.89	-46.80

Table A.1: Conversion Factors

Quantity	Conversion
Length	$1 \text{ m} = 100 \text{ cm}$ $= 3.28084(\text{ft}) = 39.3701(\text{in})$
Mass	$1 \text{ kg} = 10^3 \text{ g}$ $= 2.20462(\text{lb}_m)$
Force	$1 \text{ N} = 1 \text{ kg m s}^{-2}$ $= 10^5(\text{dyne})$ $= 0.224809(\text{lb}_f)$
Pressure	$1 \text{ bar} = 10^5 \text{ kg m}^{-1} \text{ s}^{-2} = 10^5 \text{ N m}^{-2}$ $= 10^5 \text{ Pa} = 10^2 \text{ kPa}$ $= 10^6(\text{dyne}) \text{ cm}^{-2}$ $= 0.986923(\text{atm})$ $= 14.5038(\text{psia})$ $= 750.061(\text{torr})$
Volume	$1 \text{ m}^3 = 10^6 \text{ cm}^3 = 10^3 \text{ liters}$ $= 35.3147(\text{ft})^3$ $= 264.172(\text{gal})$
Density	$1 \text{ g cm}^{-3} = 10^3 \text{ kg m}^{-3}$ $= 62.4278(\text{lb}_m)(\text{ft})^{-3}$
Energy	$1 \text{ J} = 1 \text{ kg m}^2 \text{ s}^{-2} = 1 \text{ N m}$ $= 1 \text{ m}^3 \text{ Pa} = 10^{-5} \text{ m}^3 \text{ bar} = 10 \text{ cm}^3 \text{ bar}$ $= 9.86923 \text{ cm}^3(\text{atm})$ $= 10^7(\text{dyne}) \text{ cm} = 10^7(\text{erg})$ $= 0.239006(\text{cal})$ $= 5.12197 \times 10^{-3}(\text{ft})^3(\text{psia}) = 0.737562(\text{ft})(\text{lb}_f)$ $= 9.47831 \times 10^{-4}(\text{Btu}) = 2.77778 \times 10^{-7} \text{ kWhr}$
Power	$1 \text{ kW} = 10^3 \text{ W} = 10^3 \text{ kg m}^2 \text{ s}^{-3} = 10^3 \text{ J s}^{-1}$ $= 239.006(\text{cal}) \text{ s}^{-1}$ $= 737.562(\text{ft})(\text{lb}_f) \text{ s}^{-1}$ $= 0.947831(\text{Btu}) \text{ s}^{-1}$ $= 1.34102(\text{hp})$

Table A.2: Values of the Universal Gas Constant

$$\begin{aligned}
 R &= 8.314 \text{ J mol}^{-1} \text{ K}^{-1} = 8.314 \text{ m}^3 \text{ Pa mol}^{-1} \text{ K}^{-1} \\
 &= 83.14 \text{ cm}^3 \text{ bar mol}^{-1} \text{ K}^{-1} = 8,314 \text{ cm}^3 \text{ kPa mol}^{-1} \text{ K}^{-1} \\
 &= 82.06 \text{ cm}^3(\text{atm}) \text{ mol}^{-1} \text{ K}^{-1} = 62,356 \text{ cm}^3(\text{torr}) \text{ mol}^{-1} \text{ K}^{-1} \\
 &= 1.987(\text{cal}) \text{ mol}^{-1} \text{ K}^{-1} = 1.986(\text{Btu})(\text{lb mole})^{-1}(\text{R})^{-1} \\
 &= 0.7302(\text{ft})^3(\text{atm})(\text{lb mol})^{-1}(\text{R})^{-1} = 10.73(\text{ft})^3(\text{psia})(\text{lb mol})^{-1}(\text{R})^{-1} \\
 &= 1,545(\text{ft})(\text{lb}_f)(\text{lb mol})^{-1}(\text{R})^{-1}
 \end{aligned}$$

HEAT CAPACITIES**Table C.1 Heat Capacities of Gases in the Ideal-Gas State[†]**Constants in equation $C_p^{ig}/R = A + BT + CT^2 + DT^{-3}$ T (kelvins) from 298.15 to T_{max}

Chemical species		T_{max}	C_p^{ig}/R	A	$10^3 B$	$10^6 C$	$10^{-5} D$
Paraffins:							
Methane	CH ₄	1500	4.217	1.702	9.081	-2.164	
Ethane	C ₂ H ₆	1500	6.369	1.131	19.225	-5.561	
Propane	C ₃ H ₈	1500	9.001	1.213	28.785	-8.824	
n-Butane	C ₄ H ₁₀	1500	11.928	1.935	36.915	-11.402	
iso-Butane	C ₄ H ₁₀	1500	11.901	1.677	37.853	-11.945	
n-Pentane	C ₅ H ₁₂	1500	14.731	2.464	45.351	-14.111	
n-Hexane	C ₆ H ₁₄	1500	17.550	3.025	53.722	-16.791	
n-Heptane	C ₇ H ₁₆	1500	20.361	3.570	62.127	-19.486	
n-Octane	C ₈ H ₁₈	1500	23.174	4.108	70.567	-22.208	
1-Alkenes:							
Ethylene	C ₂ H ₄	1500	5.325	1.424	14.394	-4.392	
Propylene	C ₃ H ₆	1500	7.792	1.637	22.706	-6.915	
1-Butene	C ₄ H ₈	1500	10.520	1.967	31.630	-9.873	
1-Pentene	C ₅ H ₁₀	1500	13.437	2.691	39.753	-12.447	
1-Hexene	C ₆ H ₁₂	1500	16.240	3.220	48.189	-15.157	
1-Heptene	C ₇ H ₁₄	1500	19.053	3.768	56.588	-17.847	
1-Octene	C ₈ H ₁₆	1500	21.868	4.324	64.960	-20.521	
Miscellaneous organics:							
Acetaldehyde	C ₂ H ₄ O	1000	6.506	1.693	17.978	-6.158	
Acetylene	C ₂ H ₂	1500	5.253	6.132	1.952	.....	-1.299
Benzene	C ₆ H ₆	1500	10.259	-0.206	39.064	-13.301	
1,3-Butadiene	C ₄ H ₆	1500	10.720	2.734	26.786	-8.882	
Cyclohexane	C ₆ H ₁₂	1500	13.121	-3.876	63.249	-20.928	
Ethanol	C ₂ H ₅ O	1500	8.948	3.518	20.001	-6.002	
Ethylbenzene	C ₈ H ₁₀	1500	15.993	1.124	55.380	-18.476	
Ethylene oxide	C ₂ H ₄ O	1000	5.784	-0.385	23.463	-9.296	
Formaldehyde	CH ₂ O	1500	4.191	2.264	7.022	-1.877	
Methanol	CH ₄ O	1500	5.547	2.211	12.216	-3.450	
Styrene	C ₈ H ₈	1500	15.534	2.050	50.192	-16.662	
Toluene	C ₇ H ₈	1500	12.922	0.290	47.052	-15.716	
Miscellaneous inorganics:							
Air		2000	3.509	3.355	0.575	.....	-0.016
Ammonia	NH ₃	1800	4.269	3.578	3.020	.....	-0.186
Bromine	Br ₂	3000	4.337	4.493	0.056	.....	-0.154
Carbon monoxide	CO	2500	3.507	3.376	0.557	.....	-0.031
Carbon dioxide	CO ₂	2000	4.467	5.457	1.045	.....	-1.157
Carbon disulfide	CS ₂	1800	5.532	6.311	0.805	.....	-0.906
Chlorine	Cl ₂	3000	4.082	4.442	0.089	.....	-0.344
Hydrogen	H ₂	3000	3.468	3.249	0.422	.....	0.083
Hydrogen sulfide	H ₂ S	2300	4.114	3.931	1.490	.....	-0.232
Hydrogen chloride	HCl	2000	3.512	3.156	0.623	.....	0.151
Hydrogen cyanide	HCN	2500	4.326	4.736	1.359	.....	-0.725
Nitrogen	N ₂	2000	3.502	3.280	0.593	.....	0.040
Nitrous oxide	N ₂ O	2000	4.646	5.328	1.214	.....	-0.928
Nitric oxide	NO	2000	3.590	3.387	0.629	.....	0.014
Nitrogen dioxide	NO ₂	2000	4.447	4.982	1.195	.....	-0.792
Dinitrogen tetroxide	N ₂ O ₄	2000	9.198	11.660	2.257	.....	-2.787
Oxygen	O ₂	2000	3.535	3.639	0.506	.....	-0.227
Sulfur dioxide	SO ₂	2000	4.796	5.699	0.801	.....	-1.015
Sulfur trioxide	SO ₃	2000	6.094	8.060	1.056	.....	-2.028
Water	H ₂ O	2000	4.038	3.470	1.450	.....	0.121

[†] Selected from H. M. Spencer, *Ind. Eng. Chem.*, vol. 40, pp. 2152-2154, 1948; K. K. Kelley, *U.S. Bur. Mines Bull.* 584, 1960; L. B. Pankratz, *U.S. Bur. Mines Bull.* 672, 1982.

STANDARD ENTHALPIES OF FORMATION**Table C.4** Standard Enthalpies and Gibbs Energies of Formation at 298.15 K (25°C)[†]

Joules per mole of the substance formed

Chemical species		State (Note 2)	$\Delta H_{f,298}^\circ$ (Note 1)	$\Delta G_{f,298}^\circ$ (Note 1)
Paraffins				
Methane	CH ₄	(g)	-74 520	-50 460
Ethane	C ₂ H ₆	(g)	-83 820	-31 855
Propane	C ₃ H ₈	(g)	-104 680	-24 290
n-Butane	C ₄ H ₁₀	(g)	-125 790	-16 570
n-Pentane	C ₅ H ₁₂	(g)	-146 760	-8 650
n-Hexane	C ₆ H ₁₄	(g)	-166 920	150
n-Heptane	C ₇ H ₁₆	(g)	-187 780	8 260
n-Octane	C ₈ H ₁₈	(g)	-208 750	16 260
1-Alkenes:				
Ethylene	C ₂ H ₄	(g)	52 510	68 460
Propylene	C ₃ H ₆	(g)	19 710	62 205
1-Butene	C ₄ H ₈	(g)	-540	70 340
1-Pentene	C ₅ H ₁₀	(g)	-21 280	78 410
1-Hexene	C ₆ H ₁₂	(g)	-41 950	86 830
1-Heptene	C ₇ H ₁₄	(g)	-62 760	
Miscellaneous organics:				
Acetaldehyde	C ₂ H ₄ O	(g)	-166 190	-128 860
Acetic acid	C ₂ H ₄ O ₂	(l)	-484 500	-389 900
Acetylene	C ₂ H ₂	(g)	227 480	209 970
Benzene	C ₆ H ₆	(g)	82 930	129 665
Benzene	C ₆ H ₆	(l)	49 080	124 520
1,3-Butadiene	C ₄ H ₆	(g)	109 240	149 795
Cyclohexane	C ₆ H ₁₂	(g)	-123 140	31 920
Cyclohexane	C ₆ H ₁₂	(l)	-156 230	26 850
1,2-Ethanediol	C ₂ H ₆ O ₂	(l)	-454 800	-323 080
Ethanol	C ₂ H ₆ O	(g)	-235 100	-168 490
Ethanol	C ₂ H ₆ O	(l)	-277 690	-174 780
Ethylbenzene	C ₈ H ₁₀	(g)	29 920	130 890
Ethylene oxide	C ₂ H ₄ O	(g)	-52 630	-13 010
Formaldehyde	CH ₂ O	(g)	-108 570	-102 530
Methanol	CH ₄ O	(g)	-200 660	-161 960
Methanol	CH ₄ O	(l)	-238 660	-166 270
Methyleyclohexane	C ₇ H ₁₄	(g)	-154 770	27 480
Methyleyclohexane	C ₇ H ₁₄	(l)	-190 160	20 560
Styrene	C ₈ H ₈	(g)	147 360	213 900
Toluene	C ₇ H ₈	(g)	50 170	122 050
Toluene	C ₇ H ₈	(l)	12 180	113 630

Table C.4 (Continued)

Chemical species		State (Note 2)	$\Delta H_{f,298}^\circ$ (Note 1)	$\Delta G_{f,298}^\circ$ (Note 1)
Miscellaneous inorganics:				
Ammonia	NH ₃	(g)	-46 110	-16 450
Ammonia	NH ₃	(aq)		-26 500
Calcium carbide	CaC ₂	(s)	-59 800	-64 900
Calcium carbonate	CaCO ₃	(s)	-1206 920	-1128 790
Calcium chloride	CaCl ₂	(s)	-795 800	-748 100
Calcium chloride	CaCl ₂	(aq)		-8101900
Calcium chloride	CaCl ₂ ·6H ₂ O	(s)	-2607 900	
Calcium hydroxide	Ca(OH) ₂	(s)	-986 090	-898 490
Calcium hydroxide	Ca(OH) ₂	(aq)		-868 070
Calcium oxide	CaO	(s)	-635 090	-604 030
Carbon dioxide	CO ₂	(g)	-393 509	-394 359
Carbon monoxide	CO	(g)	-110 525	-137 169
Hydrochloric acid	HCl	(g)	-92 307	-95 299
Hydrogen cyanide	HCN	(g)	135 100	124 700
Hydrogen sulfide	H ₂ S	(g)	-20 630	-33 560
Iron oxide	FeO	(s)	-272 000	
Iron oxide (hematite)	Fe ₂ O ₃	(s)	-824 200	-742 200
Iron oxide (magnetite)	Fe ₃ O ₄	(s)	-1118 400	-1015 400
Iron sulfide (pyrite)	FeS ₂	(s)	-178 200	-166 900
Lithium chloride	LiCl	(s)	-408 610	
Lithium chloride	LiCl·H ₂ O	(s)	-712 580	
Lithium chloride	LiCl·2H ₂ O	(s)	-1012 650	
Lithium chloride	LiCl·3H ₂ O	(s)	-1311 300	
Nitric acid	HNO ₃	(l)	-174 100	-80 710
Nitric acid	HNO ₃	(aq)		-111 250
Nitrogen oxides	NO	(g)	90 250	86 550
	NO ₂	(g)	33 180	51 310
	N ₂ O	(g)	82 050	104 200
	N ₂ O ₄	(g)	9 160	97 540
	N ₂ O ₄	(l)		
Sodium carbonate	Na ₂ CO ₃	(s)	-1130 680	-1044 440
Sodium carbonate	Na ₂ CO ₃ ·10H ₂ O	(s)	-4081 320	
Sodium chloride	NaCl	(s)	-411 153	-384 138
Sodium chloride	NaCl	(aq)		-393 133
Sodium hydroxide	NaOH	(s)	-425 609	-379 494
Sodium hydroxide	NaOH	(aq)		-419 150
Sulfur dioxide	SO ₂	(g)	-296 830	-300 194
Sulfur trioxide	SO ₃	(g)	-395 720	-371 060
Sulfur trioxide	SO ₃	(l)	-441 040	
Sulfuric acid	H ₂ SO ₄	(l)	-813 989	-690 003
Sulfuric acid	H ₂ SO ₄	(aq)		-744 530
Water	H ₂ O	(g)	-241 818	-228 572
Water	H ₂ O	(l)	-285 830	-237 129

[†]From TRC Thermodynamic Tables—Hydrocarbons, Thermodynamics Research Center, Texas A. & M. Univ. System, College Station, TX; "The NBS Tables of Chemical Thermodynamic Properties," J. Phys. and Chem. Reference Data, vol. 11, supp. 2, 1982.

Notes

1. The standard property changes of formation $\Delta H_{f,298}^\circ$ and $\Delta G_{f,298}^\circ$ are the changes occurring when 1 mol of the listed compound is formed from its elements with each substance in its standard state at 298.15 K (25°C).
2. Standard states: (a) Gases (g): pure ideal gas at 1 bar and 298.15 K (25°C). (b) Liquids (l) and solids (s): pure substance at 1 bar and 298.15 K (25°C). (c) Solutes in aqueous solution (aq): Hypothetical ideal 1-molal solution of solute in water at 1 bar and 298.15 K (25°C).