

NAME: _____ Section: _____ Student Number: _____

Spring 2020

Chemistry 2000 Midterm #2A

_____/ 65 marks

- INSTRUCTIONS:
- 1) Please read over the test carefully before beginning. You should have 8 pages of questions, a blank “overflow” page and two pages of data sheets with periodic table.
 - 2) If your work is not legible, it will be given a mark of zero.
 - 3) Marks will be deducted for incorrect information added to an otherwise correct answer.
 - 4) Marks will be deducted for improper use of significant figures and for missing or incorrect units.
 - 5) Show your work for all calculations. Numerical answers without supporting calculations will not be given full credit.
 - 6) You may use a calculator but only for the purposes of calculation. No text-capable calculators are allowed.
 - 7) You have 90 minutes to complete this test.
-

Confidentiality Agreement:

I agree not to discuss (or in any other way divulge) the contents of this exam until after 8:30 pm Mountain Time on Tuesday, March 17th, 2020. I understand that breaking this agreement would constitute academic misconduct, a serious offense with serious consequences. The minimum punishment would be a mark of 0/65 on this exam and removal of the “overwrite midterm mark with final exam mark” option for my grade in this course; the maximum punishment would include expulsion from this university.

Signature: _____

Date: _____

Course: CHEM 2000 (General Chemistry II)

Semester: Spring 2020

The University of Lethbridge

Question Breakdown

Q1	/ 7
Q2	/ 6
Q3	/ 13
Q4	/ 10
Q5	/ 3
Q6	/ 8
Q7	/ 18

Total	/ 65
--------------	------

1. [7 marks]
 (a) Complete each statement with one of the following symbols: >, < or = [4 marks]

For an allowed process at constant temperature and pressure,

i. $\Delta S_{universe} > 0$

ii. $\Delta G < 0$

iii. $E > 0$

iv. $K > Q$

(b) One of the statements in part (a) is true under any conditions (not just at constant temperature and pressure). Which one? [1 mark]

$\Delta S_{universe} > 0$

(c) In statement (a) i., why do we have to write $\Delta S_{universe}$? Why can't we just write ΔS ? [1 mark]

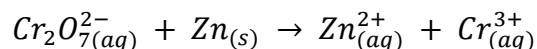
ΔS refers to the entropy change for the system only. $\Delta S_{universe}$ also includes the entropy change for the surroundings, and the second law of thermodynamics states that the entropy of the universe must increase in any thermodynamically allowed process.

(d) In statement ii. in part (a), can ΔG be replaced by ΔG° ? Why or why not? [1 mark]

No.

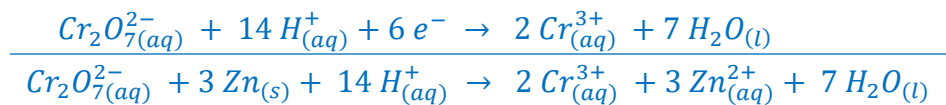
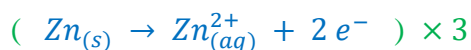
ΔG° refers specifically to the free energy change of a reaction under standard conditions. ΔG refers to the free energy change of a reaction under whatever conditions it is actually being run.

2. Consider the following reaction that takes place in aqueous acid. [6 marks]



(a) Balance this equation under acidic conditions. [3 marks]

For full marks, your answer must include balanced half reactions.



(b) Identify the oxidizing agent. [1 mark]



(c) Identify the reducing agent. [1 mark]

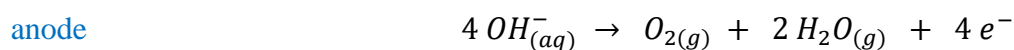
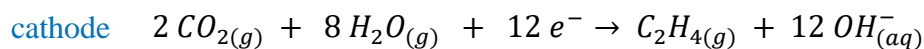


(d) What is ν_e for this reaction? [1 mark]

6

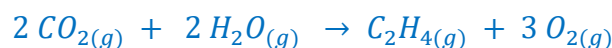
NAME: _____ Section: _____ Student Number: _____

3. Ethene, essential in making plastics, can be produced electrolytically from carbon dioxide and water using surplus electricity. The two half-reactions involved are shown below. **[13 marks]**
Water is written in the gas phase for consistency with later parts of the question which will deal with this process at high temperature.



- (a) Clearly label which half-reaction occurs at the anode and which occurs at the cathode. *[1 mark]*
see above

- (b) Write the overall balanced reaction for this process. *[1 mark]*



- (c) What is ν_e for this process? *[1 mark]*

12

- (d) Calculate the standard Gibbs free energy change for this process. *[2 marks]*

For consistency with later parts of the question, please use data for water in the gas phase.

$$\Delta_r G^\circ = \Delta_f G^\circ(\text{C}_2\text{H}_{4(g)}) + 3 \Delta_f G^\circ(\text{O}_{2(g)}) - [2 \Delta_f G^\circ(\text{CO}_{2(g)}) + 2 \Delta_f G^\circ(\text{H}_2\text{O}_{(g)})]$$

$$\Delta_r G^\circ = \left(68.36 \frac{\text{kJ}}{\text{mol}}\right) + 3 \left(0 \frac{\text{kJ}}{\text{mol}}\right) - \left[2 \left(-394.37 \frac{\text{kJ}}{\text{mol}}\right) + 2 \left(-228.6 \frac{\text{kJ}}{\text{mol}}\right)\right]$$

$$\Delta_r G^\circ = 1314.3 \frac{\text{kJ}}{\text{mol}}$$

- (e) Calculate the standard cell potential (or standard emf) for this process. *[2 marks]*

$$\Delta_r G^\circ = -\nu_e F E^\circ$$

$$E^\circ = -\frac{\Delta_r G^\circ}{\nu_e F}$$

$$E^\circ = -\frac{\left(1314.3 \frac{\text{kJ}}{\text{mol}}\right)\left(\frac{1000 \text{ J}}{1 \text{ kJ}}\right)}{(12)\left(96485 \frac{\text{C}}{\text{mol}}\right)}$$

$$E^\circ = -1.1352 \frac{\text{J}}{\text{C}} = -1.1352 \text{ V}$$

NAME: _____ Section: _____ Student Number: _____

3. ...continued

- (f) Calculate Q for this process when it is performed at $800\text{ }^\circ\text{C}$ and the partial pressures of carbon dioxide and water vapour are both 1.00 kbar while the partial pressures of ethene and oxygen are both 1.00 mbar . [3 marks]

$$a_{\text{CO}_2} = \frac{1.00\text{ kbar}}{1\text{ bar}} \times \frac{1000\text{ bar}}{1\text{ kbar}} = 1.00 \times 10^3$$

$$a_{\text{C}_2\text{H}_4} = \frac{1.00\text{ mbar}}{1\text{ bar}} \times \frac{1\text{ bar}}{1000\text{ mbar}} = 1.00 \times 10^{-3}$$

$$a_{\text{H}_2\text{O}} = \frac{1.00\text{ kbar}}{1\text{ bar}} \times \frac{1000\text{ bar}}{1\text{ kbar}} = 1.00 \times 10^3$$

$$a_{\text{O}_2} = \frac{1.00\text{ mbar}}{1\text{ bar}} \times \frac{1\text{ bar}}{1000\text{ mbar}} = 1.00 \times 10^{-3}$$

$$Q = \frac{(a_{\text{C}_2\text{H}_4})(a_{\text{O}_2})^3}{(a_{\text{CO}_2})^2(a_{\text{H}_2\text{O}})^2}$$

$$Q = \frac{(1.00 \times 10^{-3})(1.00 \times 10^{-3})^3}{(1.00 \times 10^3)^2(1.00 \times 10^3)^2}$$

$$Q = 1.00 \times 10^{-24}$$

- (g) Calculate the cell potential (or emf) for this process under the conditions described in part (f). The standard cell potential for this process at $800\text{ }^\circ\text{C}$ is -1.120 V . [3 marks]

$$E = E^\circ - \frac{RT}{\nu_e F} \ln Q$$

$$E = (-1.120\text{ V}) - \frac{(8.314462 \frac{\text{J}}{\text{mol}\cdot\text{K}})(1073.15\text{ K})}{(12)(96485 \frac{\text{C}}{\text{mol}})} \ln(1.00 \times 10^{-24}) \left(\frac{1\text{ V}}{1 \frac{\text{J}}{\text{C}}} \right)$$

$$E = (-1.120\text{ V}) - (-0.42587\text{ V})$$

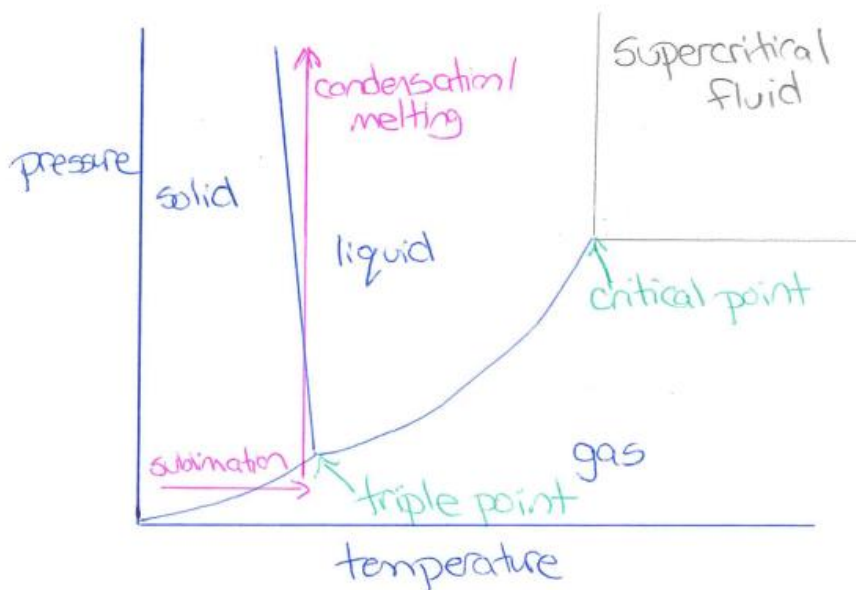
$$E = -0.694\text{ V}$$

4. [10 marks]

(a) Draw a phase diagram for water. Your diagram must include: [8 marks]

- Labeled axes
- Labeled phases
- Labeled triple point
- Labeled critical point

You do not need to include numerical values on your diagram.

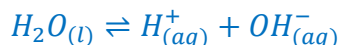


(b) On your phase diagram, draw a line of constant pressure where only sublimation occurs. Label your line “sublimation”. [1 mark]

(c) On your phase diagram, draw a line of constant temp. where condensation is followed by melting. Label your line “condensation/melting”. [1 mark]

5. The dissociation of water into $H_{(aq)}^+$ and $OH_{(aq)}^-$ is an endothermic process. Would you expect the pH of water to increase or decrease as the temperature of water increases at constant pressure? Justify your answer. [3 marks]

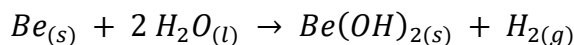
Hint: remember that $pH = -\log(a_{H_{(aq)}^+})$



This process is endothermic, so heating the system will push the equilibrium more toward the products side (Le Châtelier’s principle). Therefore, as temperature increases, concentration of H^+ increases and the pH decreases.

NAME: _____ Section: _____ Student Number: _____

6. In CHEM 1000, you would have learned that the following reaction does NOT occur (unlike the analogous reaction of water with any of the other Group 2 metals): **[8 marks]**



- (a) Is this reaction thermodynamically allowed at 25 °C if the pressure of $\text{H}_{2(g)}$ is 0.05 bar?

[6 marks]

$$\Delta_r G^\circ = [\Delta_f G^\circ(\text{Be}(\text{OH})_{2(s)}) + \Delta_f G^\circ(\text{H}_{2(g)})] - [\Delta_f G^\circ(\text{Be}_{(s)}) + 2\Delta_f G^\circ(\text{H}_2\text{O}_{(l)})]$$

$$\Delta_r G^\circ = \left[\left(-818 \frac{\text{kJ}}{\text{mol}} \right) + \left(0 \frac{\text{kJ}}{\text{mol}} \right) \right] - \left[\left(0 \frac{\text{kJ}}{\text{mol}} \right) + 2 \left(-237.140 \frac{\text{kJ}}{\text{mol}} \right) \right]$$

$$\Delta_r G^\circ = -344 \frac{\text{kJ}}{\text{mol}}$$

$$Q = \frac{(a_{\text{Be}(\text{OH})_2})(a_{\text{H}_2})}{(a_{\text{Be}})(a_{\text{H}_2\text{O}})^2}$$

$$Q = \frac{(1)(0.05)}{(1)(1)^2}$$

$$Q = 0.05$$

$$T = 298.15 \text{ K}$$

$$\Delta_r G = \Delta_r G^\circ + RT \ln Q$$

$$\Delta_r G = \left(-344 \frac{\text{kJ}}{\text{mol}} \right) + \left(8.314462 \frac{\text{J}}{\text{mol}\cdot\text{K}} \right) (298.15 \text{ K}) \ln(0.05)$$

$$\Delta_r G = -351 \frac{\text{kJ}}{\text{mol}}$$

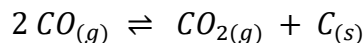
$\Delta_r G$ is negative, so the reaction is thermodynamically allowed.

- (b) Discuss briefly the agreement or disagreement between the result of your calculation and the observation that beryllium does not react with water. **[2 marks]**

The fact that the reaction is thermodynamically allowed means that it *may* happen not that it must happen. In order for a reaction to occur, it must be both thermodynamically and kinetically favourable, so it's possible that the activation energy for this reaction may be too high. It's also possible that a passivation layer of BeO means that the beryllium wouldn't actually be in contact with water if a sample of beryllium were placed in water.

NAME: _____ Section: _____ Student Number: _____

7. The Boudouard reaction is the following: [18 marks]



This reaction is a serious nuisance in industrial processes involving carbon monoxide since it results in the deposition of graphite, which leads to fouling of the lines transporting this gas.

- (a) Is this a redox reaction? Justify your answer. [1 mark]

Yes. The oxidation state of carbon is different in the products than in the reactant.

In CO , it is +2. In CO_2 , it is +4. In C , it is 0.

- (b) Calculate the equilibrium constant for this reaction at 25 °C. Is the reaction reactant-favoured or product-favoured under standard conditions? [5 marks]

$$\Delta_r G^\circ = [\Delta_f G^\circ(\text{CO}_{2(g)}) + \Delta_f G^\circ(\text{C}_{(s)})] - 2\Delta_f G^\circ(\text{CO}_{(g)})$$

$$\Delta_r G^\circ = \left[\left(-394.37 \frac{\text{kJ}}{\text{mol}} \right) + \left(0 \frac{\text{kJ}}{\text{mol}} \right) \right] - 2 \left(-137.17 \frac{\text{kJ}}{\text{mol}} \right)$$

$$\Delta_r G^\circ = -120.03 \frac{\text{kJ}}{\text{mol}}$$

$$\Delta_r G^\circ = -1.2003 \times 10^5 \frac{\text{J}}{\text{mol}}$$

$$T = 298.15 \text{ K}$$

$$\Delta_r G^\circ = -RT \ln K$$

$$K = e^{\frac{-\Delta_r G^\circ}{RT}}$$

$$K = e^{\frac{-(-1.2003 \times 10^5 \frac{\text{J}}{\text{mol}})}{(8.314462 \frac{\text{J}}{\text{mol} \cdot \text{K}})(298.15 \text{ K})}}$$

$$K = e^{48.420}$$

$$K = 1.07 \times 10^{21}$$

K is very large, so this is a strongly product-favoured reaction under standard conditions.

NAME: _____ Section: _____ Student Number: _____

7. ...continued

(c) Estimate the equilibrium constant for this reaction at 250 °C.

[6 marks]

$$T_1 = 25\text{ °C} = 298.15\text{ K}$$

$$T_2 = 250\text{ °C} = 523.15\text{ K}$$

$$K_1 = 1.07 \times 10^{21}$$

$$K_2 = ???$$

$$\Delta_r H^\circ = [\Delta_f H^\circ(\text{CO}_{2(g)}) + \Delta_f H^\circ(\text{C}_{(s)})] - 2\Delta_f H^\circ(\text{CO}_{(g)})$$

$$\Delta_r H^\circ = \left[\left(-393.51 \frac{\text{kJ}}{\text{mol}} \right) + \left(0 \frac{\text{kJ}}{\text{mol}} \right) \right] - 2 \left(-110.53 \frac{\text{kJ}}{\text{mol}} \right)$$

$$\Delta_r H^\circ = -172.45 \frac{\text{kJ}}{\text{mol}}$$

$$\Delta_r H^\circ = -1.7245 \times 10^5 \frac{\text{J}}{\text{mol}}$$

$$\ln \left(\frac{K_2}{K_1} \right) = \frac{\Delta_r H^\circ}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)$$

$$\ln \left(\frac{K_2}{1.07 \times 10^{21}} \right) = \left(\frac{-1.7245 \times 10^5 \frac{\text{J}}{\text{mol}}}{8.314\,462 \frac{\text{J}}{\text{mol}\cdot\text{K}}} \right) \left(\frac{1}{298.15\text{ K}} - \frac{1}{523.15\text{ K}} \right)$$

$$\ln \left(\frac{K_2}{1.07 \times 10^{21}} \right) = -29.919$$

$$\frac{K_2}{1.07 \times 10^{21}} = e^{-29.919}$$

$$\frac{K_2}{1.07 \times 10^{21}} = 1.01 \times 10^{-13}$$

$$K_2 = (1.07 \times 10^{21})(1.01 \times 10^{-13})$$

$$K_2 = 1.08 \times 10^8$$

NAME: _____ Section: _____ Student Number: _____

7. ...continued

- (d) At 975 K, the equilibrium constant for the Boudouard reaction is 1. Suppose that a container holds 58 bar of CO at 975 K. What will the partial pressures of CO and CO₂ be when the system reaches equilibrium in this container? [6 marks]

	$2 \text{CO}_{(g)}$	\rightleftharpoons	$\text{CO}_{2(g)}$	+	$\text{C}_{(s)}$
I bar)	58		0		0
C (bar)	$-2x$		$+x$		$+x$
E (bar)	$58 - 2x$		x		x

$$K = \frac{(a_{\text{CO}_2(g)})(a_{\text{C}(s)})}{(a_{\text{CO}(g)})^2}$$

$$a_{\text{CO}(g)} = \frac{(58-2x) \text{ bar}}{1 \text{ bar}} = 58 - 2x$$

$$a_{\text{CO}_2(g)} = \frac{x \text{ bar}}{1 \text{ bar}} = x$$

$$a_{\text{C}(s)} = 1$$

$$K = \frac{(x)(1)}{(58-2x)^2}$$

$$1 = \frac{x}{(58-2x)^2}$$

$$(58 - 2x)^2 = x$$

$$3364 - 232x + 4x^2 = x$$

$$4x^2 - 233x + 3364 = 0$$

$$x = \frac{-(-233) \pm \sqrt{(-233)^2 - 4(4)(3364)}}{2(4)}$$

$$x = \frac{233 \pm \sqrt{465}}{8}$$

$$x = 31.8 \text{ or } 26.4$$

But x cannot be 31.8 because that would give a negative value for the pressure of CO. Therefore, $x = 26.4$.

$$p_{\text{CO}_2(g)} = (x)(1 \text{ bar}) = (26.4)(1 \text{ bar}) = 26.4 \text{ bar}$$

$$p_{\text{CO}(g)} = (58 - 2x)(1 \text{ bar}) = (58 - 2(26.4))(1 \text{ bar}) = (58 - 52.8) \text{ bar} = 5 \text{ bar}$$

Some Useful Constants and Formulae

Fundamental Constants and Conversion Factors

Atomic mass unit (u)	$1.660\,539 \times 10^{-27} \text{ kg}$	Kelvin temperature scale	$0 \text{ K} = -273.15 \text{ }^\circ\text{C}$
Avogadro's number (N_A)	$6.022\,141 \times 10^{23} \text{ mol}^{-1}$	K_w (at $25 \text{ }^\circ\text{C}$)	10^{-14}
Boltzmann constant (k_B)	$1.380\,649 \times 10^{-23} \text{ J}\cdot\text{K}^{-1}$	Planck's constant (h)	$6.626\,070 \times 10^{-34} \text{ J}\cdot\text{Hz}^{-1}$
Charge of electron	$-1.602\,176 \times 10^{-19} \text{ C}$	Speed of light in vacuum (c)	$2.997\,925 \times 10^8 \text{ m}\cdot\text{s}^{-1}$
Faraday's constant (F)	$96\,485 \text{ C}\cdot\text{mol}^{-1}$	Volume conversion	$1000 \text{ L} = 1 \text{ m}^3$
Ideal gas constant (R)	$8.314\,462 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$	Pressure conversions	$1 \text{ bar} = 100 \text{ kPa}$
	$8.314\,462 \text{ m}^3\cdot\text{Pa}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$		$1 \text{ atm} = 1.01325 \text{ bar}$

Formulae

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$PV = nRT$$

$$S = k_B \ln \Omega$$

$$\Delta S = \frac{q_{rev}}{T}$$

$$\Delta_r G = \Delta_r H - T \Delta_r S$$

$$\Delta_r G = \Delta_r G^\circ + RT \ln Q$$

$$\Delta_r G^\circ = -RT \ln K$$

$$\ln \left(\frac{K_2}{K_1} \right) = \frac{\Delta_r H^\circ}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)$$

$$P_A = X_A P_A^*$$

$$[A] = k_H P_A$$

$$X = \frac{n}{\sum n}$$

$$\Delta_r G = -\nu_e F E$$

$$E = E^\circ - \frac{RT}{\nu_e F} \ln Q$$

$$pH = -\log a_{H^+}$$

$$pK_a = -\log K_a$$

$$pK_b = -\log K_b$$

$$K_w = K_a \cdot K_b$$

$$pH = pK_a + \log \left(\frac{a_{A^-}}{a_{HA}} \right)$$

$$\Delta H_{rxn}^0 = \sum (\Delta H_f^0(\text{products})) - \sum (\Delta H_f^0(\text{reactants}))$$

$$\Delta S_{rxn}^0 = \sum (S^0(\text{products})) - \sum (S^0(\text{reactants}))$$

$$\Delta G_{rxn}^0 = \sum (\Delta G_f^0(\text{products})) - \sum (\Delta G_f^0(\text{reactants}))$$

Activities

Solid	$a = 1$
Pure liquid	$a = 1$
Ideal Solvent	$a = X$
Ideal Solute	$a = \frac{c}{c^\circ}$
Ideal Gas	$a = \frac{P}{P^\circ}$

CHEM 2000 Standard Periodic Table

1																	18	
1.0079 H 1												13	14	15	16	17	4.0026 He 2	
6.941 Li 3	9.0122 Be 4												10.811 B 5	12.011 C 6	14.0067 N 7	15.9994 O 8	18.9984 F 9	20.1797 Ne 10
22.9898 Na 11	24.3050 Mg 12	3	4	5	6	7	8	9	10	11	12	26.9815 Al 13	28.0855 Si 14	30.9738 P 15	32.066 S 16	35.4527 Cl 17	39.948 Ar 18	
39.0983 K 19	40.078 Ca 20	44.9559 Sc 21	47.88 Ti 22	50.9415 V 23	51.9961 Cr 24	54.9380 Mn 25	55.847 Fe 26	58.9332 Co 27	58.693 Ni 28	63.546 Cu 29	65.39 Zn 30	69.723 Ga 31	72.61 Ge 32	74.9216 As 33	78.96 Se 34	79.904 Br 35	83.80 Kr 36	
85.4678 Rb 37	87.62 Sr 38	88.9059 Y 39	91.224 Zr 40	92.9064 Nb 41	95.94 Mo 42	(98) Tc 43	101.07 Ru 44	102.906 Rh 45	106.42 Pd 46	107.868 Ag 47	112.411 Cd 48	114.82 In 49	118.710 Sn 50	121.757 Sb 51	127.60 Te 52	126.905 I 53	131.29 Xe 54	
132.905 Cs 55	137.327 Ba 56	La-Lu	178.49 Hf 72	180.948 Ta 73	183.85 W 74	186.207 Re 75	190.2 Os 76	192.22 Ir 77	195.08 Pt 78	196.967 Au 79	200.59 Hg 80	204.383 Tl 81	207.19 Pb 82	208.980 Bi 83	(210) Po 84	(210) At 85	(222) Rn 86	
(223) Fr 87	226.025 Ra 88	Ac-Lr	(265) Rf 104	(268) Db 105	(271) Sg 106	(270) Bh 107	(277) Hs 108	(276) Mt 109	(281) Ds 110	(280) Rg 111	(285) Cn 112	(284) Nh 113	(289) Fl 114	(288) Mc 115	(293) Lv 116	(294) Ts 117	(294) Og 118	
		138.906 La 57	140.115 Ce 58	140.908 Pr 59	144.24 Nd 60	(145) Pm 61	150.36 Sm 62	151.965 Eu 63	157.25 Gd 64	158.925 Tb 65	162.50 Dy 66	164.930 Ho 67	167.26 Er 68	168.934 Tm 69	173.04 Yb 70	174.967 Lu 71		
		227.028 Ac 89	232.038 Th 90	231.036 Pa 91	238.029 U 92	237.048 Np 93	(240) Pu 94	(243) Am 95	(247) Cm 96	(247) Bk 97	(251) Cf 98	(252) Es 99	(257) Fm 100	(258) Md 101	(259) No 102	(262) Lr 103		

Developed by Prof. R. T. Boéré (updated 2016)

Some Useful Thermodynamic Properties

Substance	$\Delta_f H^\circ \left(\frac{kJ}{mol} \right)$	$\Delta_f G^\circ \left(\frac{kJ}{mol} \right)$
$Be(OH)_{2(s)}$	-904	-818
$C_2H_{4(g)}$	52.47	68.36
$CO_{(g)}$	-110.53	-137.17
$CO_{2(g)}$	-393.51	-394.37
$H_2O_{(g)}$	-241.8	-228.6
$H_2O_{(l)}$	-285.830	-237.140