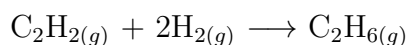


Chemistry 431  
 Problem Set 5  
 Fall 2023  
 Solutions

1. Use Tables 4.1 and 4.2 to calculate the enthalpy of the reaction



at 25.°C.

**Answer:**

$$\begin{aligned}\Delta_{r,m}H^\ominus &= \Delta_{f,m}H^\ominus(\text{C}_2\text{H}_6) - 2\Delta_{f,m}H^\ominus(\text{H}_2) - \Delta_{f,m}H^\ominus(\text{C}_2\text{H}_2) \\ &= [-84. - 2(0) - 227.4] \text{ kJ mol}^{-1} = -311.4 \text{ kJ mol}^{-1}\end{aligned}$$

2. Use Tables 4.1 and 4.2 to determine the enthalpy of the reaction of problem 1 at 35.°C. You may assume the heat capacities given in the table are independent of temperature.

**Answer:**

$$\begin{aligned}\Delta_{r,m}H^\ominus(T_2) &= \Delta_{r,m}H^\ominus(T_1) + \Delta C_p \Delta T \\ &= -311400 \text{ J mol}^{-1} + [C_p(\text{C}_2\text{H}_6) - 2C_p(\text{H}_2) - C_p(\text{C}_2\text{H}_2)]10\text{K} \\ &= -311400 \text{ J mol}^{-1} + [52.5 - 2(28.8) - 44.] \text{ J mol}^{-1}\text{K}^{-1}(10 \text{ K}) = -311.891 \text{ kJ mol}^{-1}\end{aligned}$$

3. The enthalpy of combustion of liquid d-citrene ( $\text{C}_{10}\text{H}_{16}$ ) is  $\Delta H = -420.79 \text{ kJ mol}^{-1}$  at 298. K. Use Tables 4.1 and 4.2 to determine the enthalpy of formation of liquid d-citrene.

**Answer:**

$$\begin{aligned}\text{C}_{10}\text{H}_{16(l)} + 14\text{O}_2(g) &\longrightarrow 10\text{CO}_2(g) + 8\text{H}_2\text{O}(l) \\ \Delta_{r,m}H^\ominus &= 8\Delta_{f,m}H^\ominus(\text{H}_2\text{O}(l)) + 10\Delta_{f,m}H^\ominus(\text{CO}_2(g)) - \Delta_{f,m}H^\ominus(\text{C}_{10}\text{H}_{16(l)}) - 14\Delta_{f,m}H^\ominus(\text{O}_2(g)) \\ -420.79 \text{ kJ mol}^{-1} &= 8(-285.8 \text{ kJ mol}^{-1}) + 10(-393.5 \text{ kJ mol}^{-1}) - \Delta_{f,m}H^\ominus(\text{C}_{10}\text{H}_{16(l)}) \\ \Delta_{f,m}H^\ominus(\text{C}_{10}\text{H}_{16(l)}) &= -5801 \text{ kJ mol}^{-1}\end{aligned}$$

4. Use the data from problem 3 to determine the heat liberated if 10.0 g of liquid d-citrene are burned in a bomb calorimeter thermostated to 298. K.

**Answer:**

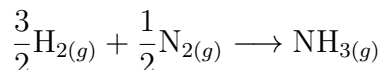
$$\begin{aligned}\Delta_{r,m}U &= \Delta_{r,m}H - RT\Delta n_{gas} \\ &= -420790 \text{ J mol}^{-1} - (8.3144 \text{ J mol}^{-1}\text{K}^{-1})(298 \text{ K})(-4)\end{aligned}$$

$$= -410990 \text{ J mol}^{-1}$$

$$q = (10 \text{ g}) \left( \frac{\text{mol}}{136 \text{ g}} \right) (-410990 \text{ J mol}^{-1}) = -30.2 \text{ kJ}$$

5. When exactly 0.015 moles of  $\text{H}_2$  gas and 0.005 moles of  $\text{N}_2$  gas at  $25.^\circ\text{C}$  react adiabatically and completely to form pure  $\text{NH}_3$  gas in a container of fixed volume, the final temperature of the product is found to be  $1860.\text{K}$ . Assuming only the temperature of the product gas changes and the temperature of the insulating chamber does not change, calculate the molar enthalpy of formation of  $\text{NH}_{3(g)}$  at  $298\text{K}$ . You should assume the molar constant volume heat capacity of  $\text{NH}_{3(g)}$  to be a constant and equal to  $27.8 \text{ J mol}^{-1}\text{K}^{-1}$ , and that all gases are ideal.

**Answer:**



Then 0.01 moles of ammonia gas are formed.

$$\Delta U = -(0.01 \text{ mol})(27.8 \text{ J mol}^{-1}\text{K}^{-1})(1860 \text{ K} - 298 \text{ K}) = -434.2 \text{ J}$$

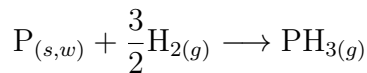
$$\Delta_m U = \frac{-434.2 \text{ J}}{0.01 \text{ mol}} = -43424. \text{ J mol}^{-1}$$

$$\Delta_m H = \Delta U_m + RT\Delta n_{gas}$$

$$= -43424. \text{ J mol}^{-1} + (8.3144 \text{ J mol}^{-1}\text{K}^{-1})(298 \text{ K})(-1) = -45900 \text{ J mol}^{-1}$$

6. The standard enthalpy of formation of  $\text{PH}_{3(g)}$  is  $5.400 \text{ kJ}$  per mole of  $\text{PH}_{3(g)}$  at  $298\text{K}$  and  $3.158 \text{ kJ}$  per mole of  $\text{PH}_{3(g)}$  at  $373\text{K}$ . Given the constant pressure heat capacities of solid white phosphorous (the most stable form of elemental phosphorous at 1 bar pressure the both conditions of temperature) and  $\text{PH}_{3(g)}$  are respectively  $23.8 \text{ J mol}^{-1}\text{K}^{-1}$  and  $37.1 \text{ J mol}^{-1}\text{K}^{-1}$ , calculate the constant pressure heat capacity of hydrogen gas. Assume all heat capacities are temperature independent. Compare the determined constant pressure heat capacity of  $\text{H}_2$  with that expected for an ideal diatomic gas.

**Answer:**



$$\Delta_{f,m}H^\ominus(373 \text{ K}) = \Delta_{f,m}H^\ominus(298 \text{ K}) + \left[ C_{P,m}(\text{PH}_{3(g)}) - C_{P,m}(\text{P}_{s,w}) - \frac{3}{2}C_{P,m}(\text{H}_{2(g)}) \right] \Delta T$$

$$3158 \text{ J mol}^{-1} = 5400 \text{ J mol}^{-1} + (75. \text{ K}) \left[ 37.1 \text{ J mol}^{-1}\text{K}^{-1} - 23.8 \text{ J mol}^{-1}\text{K}^{-1} - \frac{3}{2}C_{P,m}(\text{H}_{2(g)}) \right]$$

$$C_{P,m}(\text{H}_{2(g)}) = 28.8 \text{ J mol}^{-1}\text{K}^{-1}$$

$$\frac{7}{2}R = \frac{7}{2}(8.3144 \text{ J mol}^{-1}\text{K}^{-1}) = 29.1 \text{ J mol}^{-1}\text{K}^{-1}$$

7. Calculate the heat liberated to the surroundings when 10.0 grams of liquid ethanol ( $\text{C}_2\text{H}_5\text{OH}$ ) are burned in pure oxygen gas to produce  $\text{CO}_2$  gas and  $\text{H}_2\text{O}$  liquid in a bomb calorimeter of fixed volume with the thermostat set to  $100.^\circ\text{C}$ . The required data are found in Tables 4.1 and 4.2 of the textbook.

**Answer:**



$$\Delta_{r,m}H^\ominus(298\text{K}) = [2(-393.5) + 3(-285.8) - (-277.6)] \text{ kJ mol}^{-1} = -1366.8 \text{ kJ mol}^{-1}$$

$$\Delta_{r,m}H^\ominus(373 \text{ K}) = \Delta_{r,m}H^\ominus(298 \text{ K}) + \Delta C_P \Delta T$$

$$= -1366800 \text{ J mol}^{-1} + [3(75.3) + 2(37.1) - 3(29.4) - 112.2] \text{ J mol}^{-1}\text{K}^{-1}(75 \text{ K}) = -1359322 \text{ J mol}^{-1}$$

$$\Delta_{r,m}U(373 \text{ K}) = \Delta_{r,m}H^\ominus(373 \text{ K}) - RT\Delta n_{gas} = -1359322 \text{ J mol}^{-1} - (8.3144 \text{ J mol}^{-1}\text{K}^{-1})(373 \text{ K})(-1)$$

$$= -1356221 \text{ J mol}^{-1}$$

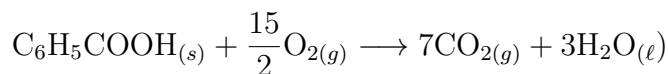
$$n = \frac{10 \text{ g}}{46 \text{ g mol}^{-1}} = 0.217 \text{ mol}$$

$$q_{sys} = \Delta U = (0.217 \text{ mol})(-1356221 \text{ J mol}^{-1}) = -294830 \text{ J}$$

$$q_{surr} = -q_{sys} = 294830 \text{ J}$$

8. A large metal bomb calorimeter of constant volume is known to have a heat capacity of  $28749 \text{ J K}^{-1}$ . When exactly 5.0 grams of solid benzoic acid ( $\text{C}_6\text{H}_5\text{COOH}$ ) are placed in the bomb with excess oxygen gas at  $25.0^\circ\text{C}$ , and combusted adiabatically to produce gas phase carbon dioxide and liquid phase water, the temperature rise of the calorimeter is found to be  $4.60\text{K}$ . Assuming the reactants and products contribute negligibly to the overall heat capacity of the system, calculate the molar enthalpy change of combustion reaction for the benzoic acid at  $25.0^\circ\text{C}$ .

**Answer:**



$$q = \Delta_r U = -C\Delta T = -(28749 \text{ J K}^{-1})(4.6 \text{ K}) = -132245.4 \text{ J}$$

$$n = \frac{5.0 \text{ g}}{122. \text{ g mol}^{-1}} = 0.0410 \text{ mol}$$

$$\Delta_{r,m}U = \frac{-132245.4 \text{ J}}{0.0410 \text{ mol}} = -3226787.8 \text{ J mol}^{-1}$$

$$\Delta_{r,m}H = \Delta U_{r,m} + RT\Delta n_{gas}$$

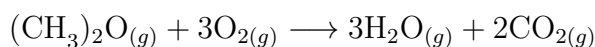
$$= -3226787.8 \text{ J mol}^{-1} + (8.3144 \text{ J mol}^{-1}\text{K}^{-1})(298 \text{ K}) \left(-\frac{1}{2}\right) = -3228027 \text{ J mol}^{-1}$$

$$= -3228.0 \text{ kJ mol}^{-1}$$

9. When 1.00 grams of gas-phase dimethyl ether  $[(\text{CH}_3)_2\text{O}]$  at 298. K are burned isothermally in excess pure oxygen to produce gas-phase water and gas-phase carbon dioxide under standard conditions of pressure, the heat liberated to the surroundings is measured to be 2882. Joules. Calculate the heat liberated to the surroundings if the same mixture of dimethyl ether and excess oxygen at 373. K are burned isothermally in a container of fixed volume. You can use the following table of thermodynamic data and assume the constant pressure heat capacities are temperature independent.

Substance	$C_P$ ( $\text{J mol}^{-1}\text{K}^{-1}$ )
$(\text{CH}_3)_2\text{O}_{(g)}$	64.4
$\text{H}_2\text{O}_{(g)}$	33.6
$\text{CO}_{2(g)}$	37.1
$\text{O}_{2(g)}$	29.4

**Answer:**



$$n = \frac{1.00 \text{ g}}{46.0 \text{ g mol}^{-1}} = 2.17 \times 10^{-2} \text{ mol}$$

$$\Delta_{r,m}H^\ominus = \frac{-2882. \text{ J}}{2.17 \times 10^{-2} \text{ mol}} = -132800 \text{ J mol}^{-1}$$

$$\Delta_{r,m}H^\ominus(373) = \Delta_{r,m}H^\ominus(298) + \Delta C_P \Delta T = -132800 \text{ J mol}^{-1}$$

$$+ [3(33.6) + 2(37.1) - 3(29.4) - 64.4] \text{ J mol}^{-1}\text{K}^{-1}(75. \text{ K}) = -131120 \text{ J mol}^{-1}$$

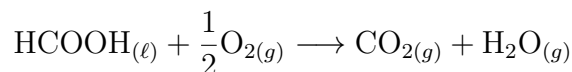
$$\Delta_{r,m}U = \Delta_{r,m}H^\ominus - RT\Delta n_{gas}$$

$$= -131120 \text{ J mol}^{-1} - (8.3144 \text{ J mol}^{-1}\text{K}^{-1})(373. \text{ K})(1) = -134221 \text{ J mol}^{-1}$$

$$q_{surr} = -\Delta U = (134221 \text{ J mol}^{-1})(2.17 \times 10^{-2} \text{ mol}) = 2913 \text{ J}$$

10. When 10.00 grams of liquid formic acid ( $\text{HCOOH}$ ) are burned in pure oxygen producing gas-phase water and carbon dioxide in a container of fixed volume at a constant temperature of 25.0°C, the reaction is exothermic with  $q = -55440$ . Joules. Calculate the heat associated with burning the 10.0 grams of liquid formic acid to produce the same products if the temperature is fixed at 35.0°C, and the reaction is carried out at a constant pressure of 1.00 bar. The constant pressure heat capacities are 99.0  $\text{J mol}^{-1}\text{K}^{-1}$  for liquid formic acid, 37.1  $\text{J mol}^{-1}\text{K}^{-1}$  for gas-phase carbon dioxide, 33.6  $\text{J mol}^{-1}\text{K}^{-1}$  for gas-phase water and 29.4  $\text{J mol}^{-1}\text{K}^{-1}$  for gas-phase oxygen. You can assume all values of  $C_P$  are temperature independent.

**Answer:**



$$n = \frac{10.00 \text{ g}}{46.00 \text{ g mol}^{-1}} = 0.2174 \text{ mol}$$

$$\begin{aligned} \Delta_{r,m}U &= \frac{-55440 \text{ J}}{0.2174 \text{ mol}} = -255014 \text{ J mol}^{-1} \\ \Delta_{r,m}H^{\ominus}(298 \text{ K}) &= \Delta_{r,m}U + RT\Delta n_{gas} \\ &= -255014 \text{ J mol}^{-1} + (8.3144 \text{ J mol}^{-1}\text{K}^{-1})(298. \text{ K})(3/2) = -251297 \text{ J mol}^{-1} \\ \Delta_{r,m}H^{\ominus}(308 \text{ K}) &= \Delta_{r,m}H^{\ominus}(298 \text{ K}) + \Delta C_P\Delta T \\ &= -251297 \text{ J mol}^{-1} \\ &+ (33.6 \text{ J mol}^{-1}\text{K}^{-1} + 37.1 \text{ J mol}^{-1}\text{K}^{-1} - 99.0 \text{ J mol}^{-1}\text{K}^{-1} - 0.5 \times 29.4 \text{ J mol}^{-1}\text{K}^{-1})(10. \text{ K}) \\ &= -251108 \text{ J mol}^{-1} \\ q &= n\Delta_{r,m}H^{\ominus} = (-251108 \text{ J mol}^{-1})(0.2174 \text{ mol}) = -54591 \text{ J} \end{aligned}$$

11. At 298K the standard enthalpy of combustion of solid phenol ( $\text{C}_6\text{H}_5\text{OH}$ ) in pure oxygen gas to produce gas phase  $\text{CO}_2$  and liquid water is  $\Delta_{\text{combustion},m}H^{\ominus} = -3054. \text{ kJ mol}^{-1}$ . Use the table of constant pressure heat capacities given below to calculate the heat for the system for the combustion of 2.00 grams of phenol when the reaction takes place in a container of fixed volume at 323K.

Substance	$C_P$ ( $\text{J mol}^{-1}\text{K}^{-1}$ )
$\text{C}_6\text{H}_5\text{OH}_{(s)}$	127.4
$\text{O}_{2(g)}$	29.4
$\text{CO}_{2(g)}$	37.1
$\text{H}_2\text{O}_{(\ell)}$	75.3

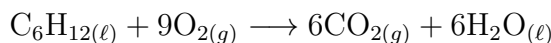
**Answer:**

$$\begin{aligned} \text{C}_6\text{H}_5\text{OH}_{(s)} + 7\text{O}_{2(g)} &\longrightarrow 6\text{CO}_{2(g)} + 3\text{H}_2\text{O}_{(\ell)} \\ n &= \frac{2.00 \text{ g}}{94.1 \text{ g mol}^{-1}} = 2.125 \times 10^{-2} \text{ mol} \\ \Delta_{r,m}H^{\ominus}(323\text{K}) &= \Delta_{r,m}H^{\ominus}(298\text{K}) + \Delta C_P\Delta T \\ &= -3054 \times 10^3 \text{ J mol}^{-1} + [3(75.3) + 6(37.1) - 127.4 - 7(29.4)] \text{ J mol}^{-1}\text{K}^{-1}(25 \text{ K}) = -3051000 \text{ J mol}^{-1} \\ \Delta_{r,m}U &= \Delta_{r,m}H^{\ominus} - RT\Delta n_{gas} = -3051000 \text{ J mol}^{-1} - (8.3144 \text{ J mol}^{-1}\text{K}^{-1})(323 \text{ K})(-1) = -3048432 \text{ J} \\ q &= n\Delta_{r,m}U = -64.8 \text{ kJ} \end{aligned}$$

12. When 10.0 g of liquid-phase cyclohexane ( $\text{C}_6\text{H}_{12}$ ) are burned in pure oxygen gas to produce gas-phase carbon dioxide and liquid water in a bomb calorimeter of fixed volume at a constant temperature of 350K, 463 kJ of heat are liberated to the surroundings. Use the table of thermodynamic data valid at 298K given below to calculate the standard enthalpy of formation of liquid-phase cyclohexane at 298K assuming the heat capacities of all species are temperature independent.

Substance	$\Delta_{f,m}H^\ominus$ kJ mol <sup>-1</sup>	$C_P$ (J mol <sup>-1</sup> K <sup>-1</sup> )
C <sub>6</sub> H <sub>12</sub> ( $\ell$ )		154.9
O <sub>2</sub> ( $g$ )		29.4
H <sub>2</sub> O( $\ell$ )	-285.8	75.3
CO <sub>2</sub> ( $g$ )	-393.5	37.1

**Answer:**



$$n = \frac{10.0 \text{ g}}{84.0 \text{ g mol}^{-1}} = 0.119 \text{ mol}$$

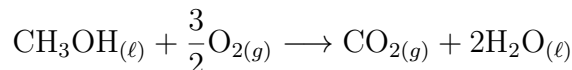
$$q_m = \Delta_{r,m}U(350) = \frac{-463. \text{ kJ}}{0.119 \text{ mol}} = -3891 \text{ kJ mol}^{-1}$$

$$\begin{aligned} \Delta_{r,m}H^\ominus(350) &= \Delta_{r,m}U(350) + RT\Delta n_g \\ &= -3891 \times 10^3 \text{ J mol}^{-1} + (8.3144 \text{ J mol}^{-1}\text{K}^{-1})(350 \text{ K})(-3) = -3899 \text{ kJ mol}^{-1} \end{aligned}$$

$$\begin{aligned} \Delta_{r,m}H^\ominus(298) &= \Delta_{r,m}H^\ominus(350) + \Delta C_P\Delta T \\ &= -3899 \times 10^3 \text{ J mol}^{-1} + [6(75.3 \text{ J mol}^{-1}\text{K}^{-1}) + 6(37.1 \text{ J mol}^{-1}\text{K}^{-1}) \\ &\quad - 9(29.4 \text{ J mol}^{-1}\text{K}^{-1}) - 154.9 \text{ J mol}^{-1}\text{K}^{-1}] = -3912 \text{ kJ mol}^{-1} \\ &= 6\Delta_{f,m}H^\ominus(\text{H}_2\text{O}(\ell)) + 6\Delta_{f,m}H^\ominus(\text{CO}_2(g)) - 9\Delta_{f,m}H^\ominus(\text{O}_2(g)) - \Delta_{f,m}H^\ominus(\text{C}_6\text{H}_{12}(\ell)) \\ \Delta_{f,m}H^\ominus(\text{C}_6\text{H}_{12}(\ell)) &= 3912 \text{ kJ mol}^{-1} + 6(-285.8 \text{ kJ mol}^{-1}) + 6(-393.5 \text{ kJ mol}^{-1}) - 9(0) \\ &= -163.8 \text{ kJ mol}^{-1} \end{aligned}$$

13. When 1.00 grams of liquid methanol (CH<sub>3</sub>OH) are burned in a container of fixed volume at 50.0°C in pure oxygen gas to produce gas-phase carbon dioxide and liquid water, the exothermic reaction releases 22650 Joules of heat to the surroundings. Given the constant pressure heat capacities of CO<sub>2</sub>( $g$ ), H<sub>2</sub>O( $\ell$ ), CH<sub>3</sub>OH( $\ell$ ) and O<sub>2</sub>( $g$ ) are respectively 37.1 J mol<sup>-1</sup>K<sup>-1</sup>, 75.3 J mol<sup>-1</sup>K<sup>-1</sup>, 44.1 J mol<sup>-1</sup>K<sup>-1</sup>, and 29.4 J mol<sup>-1</sup>K<sup>-1</sup>, calculate the molar enthalpy change for the reaction at 25.0°C. You can assume the constant pressure heat capacities of all species are independent of temperature.

**Answer:**



$$n = \frac{1.00 \text{ g}}{32.0 \text{ g mol}^{-1}} = 0.0312 \text{ mol}$$

At 50.0°C

$$q_m = \Delta_{r,m}U = \frac{-22650 \text{ J}}{0.0312 \text{ mol}} = -724800 \text{ J mol}^{-1}$$

$$\begin{aligned} \Delta_{r,m}H^\ominus &= \Delta U_{r,m} + RT\Delta n_{gas} = -724800 \text{ J mol}^{-1} + (8.3144 \text{ J mol}^{-1}\text{K}^{-1})(323. \text{ K})(-1/2) \\ &= -726143 \text{ J mol}^{-1} \end{aligned}$$

At 25.0°C

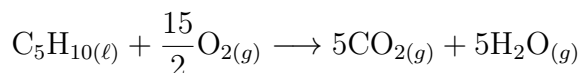
$$\Delta_{r,m}H^{\ominus}(T_2) = \Delta_{r,m}H(T_1)^{\ominus} + \Delta C_P \Delta T$$

$$\begin{aligned} \Delta_{r,m}H^{\ominus}(298. \text{ K}) &= -726143 \text{ J mol}^{-1} + [37.1 \text{ J mol}^{-1}\text{K}^{-1} + 2(75.3) \text{ J mol}^{-1}\text{K}^{-1} - 44.1 \text{ J mol}^{-1}\text{K}^{-1} \\ &\quad - (3/2)(29.4) \text{ J mol}^{-1}\text{K}^{-1}](-25.0 \text{ K}) = -728630 \text{ J mol}^{-1} \end{aligned}$$

14. Use the table of thermodynamic data below valid at 298 K to calculate the heat of the system associated with the combustion of 50.053 grams liquid cyclopentane ( $\text{C}_5\text{H}_{10}$ ) in pure oxygen to produce carbon dioxide gas and gas-phase water in a bomb of fixed volume in a heat bath with the thermostat set to 298 K.

Substance	$\Delta_{f,m}H^{\ominus}$ (kJ mol) <sup>-1</sup>
$\text{CO}_{2(g)}$	-393.5
$\text{O}_{2(g)}$	0
$\text{H}_2\text{O}_{(g)}$	-241.8
$\text{C}_5\text{H}_{10(\ell)}$	-105.1

**Answer:**



$$\begin{aligned} \Delta_{r,m}H^{\ominus} &= 5\Delta_{f,m}H^{\ominus}(\text{CO}_{2(g)}) + 5\Delta_{f,m}H^{\ominus}(\text{H}_2\text{O}_{(g)}) - \frac{15}{2}(0) - \Delta_{f,m}H^{\ominus}(\text{C}_5\text{H}_{10(\ell)}) \\ &= 5(-393.5 \text{ kJ mol}^{-1}) + 5(-241.8 \text{ kJ mol}^{-1}) - (-105.1 \text{ kJ mol}^{-1}) = -3071.4 \text{ kJ mol}^{-1} \end{aligned}$$

$$\begin{aligned} \Delta U_{r,m} &= \Delta_{r,m}H^{\ominus} - RT\Delta n_{gas} \\ &= -3071.4 \times 10^3 \text{ J mol}^{-1} - (8.3144 \text{ J mol}^{-1}\text{K}^{-1})(298 \text{ K})(2.5) = -3077.6 \text{ kJ mol}^{-1} \end{aligned}$$

$$n = \frac{50.053 \text{ g}}{70.134 \text{ g mol}^{-1}} = 0.7137 \text{ mol}$$

$$q = n\Delta_{r,m}U = (0.7137 \text{ mol})(-3077.6 \text{ kJ mol}^{-1}) = -2196.5 \text{ kJ}$$