Chapter 9: Phenomena

Phenomena: Below is data from three different reactions carried out with three different amounts of reactants. All reactants were carried out in expandable/contractable containers at 25°C. What patterns do you see in the data. You do not need to know what work, heat, eternal energy, or enthalpy are to find the patterns in the data.

\[
\text{C(s) + O}_2(g) \rightarrow \text{CO}_2(g)
\]

<table>
<thead>
<tr>
<th>Starting Amount of C</th>
<th>Starting Amount of O(_2)</th>
<th>Observations of Container</th>
<th>Work</th>
<th>Heat</th>
<th>Enteral Energy</th>
<th>Enthalpy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00 mol</td>
<td>1.00 mol</td>
<td>Hot Same Size</td>
<td>0.0 kJ</td>
<td>-394 kJ</td>
<td>-394 kJ</td>
<td>-394 kJ</td>
</tr>
<tr>
<td>1.00 mol</td>
<td>2.00 mol</td>
<td>Hot Same Size</td>
<td>0.0 kJ</td>
<td>-394 kJ</td>
<td>-394 kJ</td>
<td>-394 kJ</td>
</tr>
<tr>
<td>2.00 mol</td>
<td>1.00 mol</td>
<td>Hot Same Size</td>
<td>0.0 kJ</td>
<td>-788 kJ</td>
<td>-788 kJ</td>
<td>-788 kJ</td>
</tr>
</tbody>
</table>

\[
\text{CO}_2(s) + 2\text{H}_2\text{O}(l) \rightarrow \text{CH}_4(g) + 2\text{O}_2(g)
\]

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00 mol</td>
<td>1.00 mol</td>
<td>Cold Expanded</td>
<td>-5.0 kJ</td>
<td>890 kJ</td>
<td>885 kJ</td>
<td>890 kJ</td>
</tr>
<tr>
<td>1.00 mol</td>
<td>2.00 mol</td>
<td>Cold Expanded</td>
<td>-9.9 kJ</td>
<td>1780 kJ</td>
<td>1770 kJ</td>
<td>1780 kJ</td>
</tr>
<tr>
<td>2.00 mol</td>
<td>2.00 mol</td>
<td>Cold Expanded</td>
<td>-7.4 kJ</td>
<td>1335 kJ</td>
<td>1328 kJ</td>
<td>1335 kJ</td>
</tr>
</tbody>
</table>

\[
\text{N}_2(g) + 2\text{O}_2(g) \rightarrow 2\text{NO}_2(g)
\]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00 mol</td>
<td>1.00 mol</td>
<td>Cold Contract</td>
<td>1.3 kJ</td>
<td>27 kJ</td>
<td>28 kJ</td>
<td>27 kJ</td>
</tr>
<tr>
<td>1.00 mol</td>
<td>2.00 mol</td>
<td>Cold Contract</td>
<td>2.5 kJ</td>
<td>53 kJ</td>
<td>56 kJ</td>
<td>53 kJ</td>
</tr>
<tr>
<td>2.00 mol</td>
<td>2.00 mol</td>
<td>Cold Contract</td>
<td>2.5 kJ</td>
<td>53 kJ</td>
<td>56 kJ</td>
<td>53 kJ</td>
</tr>
</tbody>
</table>
Big Idea: Heat and work are equivalent ways of changing the energy of a system. The total energy of an isolated system is constant. The change in enthalpy of a reaction indicates whether a reaction is endothermic or exothermic.
Energy Facts

Global Sources of Energy 2013

<table>
<thead>
<tr>
<th>Source of Energy</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum</td>
<td>31.1%</td>
</tr>
<tr>
<td>Coal</td>
<td>28.9%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>21.4%</td>
</tr>
<tr>
<td>Renewable</td>
<td>13.8%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>4.8%</td>
</tr>
</tbody>
</table>
### Energy Facts

#### 2012

<table>
<thead>
<tr>
<th>Country</th>
<th>Energy Consumption (Quadrillion Btu)</th>
<th>Country</th>
<th>Energy Consumption/person (MBtu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>105.9</td>
<td>Canada</td>
<td>382.6</td>
</tr>
<tr>
<td>United States</td>
<td>95.1</td>
<td>Saudi Arabia</td>
<td>324.6</td>
</tr>
<tr>
<td>Russia</td>
<td>31.5</td>
<td>United States</td>
<td>302.8</td>
</tr>
<tr>
<td>India</td>
<td>23.9</td>
<td>Korea, South</td>
<td>235.6</td>
</tr>
<tr>
<td>Japan</td>
<td>20.3</td>
<td>Russia</td>
<td>220.1</td>
</tr>
<tr>
<td>Germany</td>
<td>13.5</td>
<td>France</td>
<td>168.1</td>
</tr>
<tr>
<td>Canada</td>
<td>13.4</td>
<td>Germany</td>
<td>164.6</td>
</tr>
<tr>
<td>Brazil</td>
<td>12.1</td>
<td>Japan</td>
<td>159.1</td>
</tr>
<tr>
<td>Korea, South</td>
<td>11.5</td>
<td>Iran</td>
<td>122.2</td>
</tr>
<tr>
<td>France</td>
<td>10.7</td>
<td>Italy</td>
<td>117.8</td>
</tr>
<tr>
<td>Iran</td>
<td>9.6</td>
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</tr>
<tr>
<td>Saudi Arabia</td>
<td>9.3</td>
<td>Mexico</td>
<td>66.8</td>
</tr>
<tr>
<td>Mexico</td>
<td>7.8</td>
<td>Brazil</td>
<td>62.3</td>
</tr>
<tr>
<td>Italy</td>
<td>7.2</td>
<td>Indonesia</td>
<td>26.6</td>
</tr>
<tr>
<td>Indonesia</td>
<td>6.4</td>
<td>India</td>
<td>19.0</td>
</tr>
</tbody>
</table>

http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=44&pid=44&aid=2

Chapter 9: Energy, Enthalpy, and Thermochemistry
### US Sources of Energy 2014 (Quadrillion Btu)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum</td>
<td>31%</td>
<td>35%</td>
<td>37%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>21%</td>
<td>28%</td>
<td>25%</td>
</tr>
<tr>
<td>Coal</td>
<td>29%</td>
<td>18%</td>
<td>21%</td>
</tr>
<tr>
<td>Renewable</td>
<td>14%</td>
<td>10%</td>
<td>8%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>5%</td>
<td>8%</td>
<td>9%</td>
</tr>
</tbody>
</table>

[http://www.eia.doe.gov/aer/pecss_diagram.html](http://www.eia.doe.gov/aer/pecss_diagram.html)
Energy Facts

How do we generate electricity?
Internal Energy

- **System**: The object of study.
- **Surrounding**: The region outside the system.
- **Internal Energy** \((E)\): The capacity to do work or to produce heat.
- **Temperature** \((T)\): How hot or cold an object is.
- **Heat** \((q)\): The energy that is transferred as a result of a temperature difference between a system and its surroundings.

**Note**: If heat enters the system \(q\) is positive (endothermic reaction). If heat leaves the system \(q\) is negative (exothermic reaction).

- **Work** \((w)\): The energy expended during the act of moving an object against an opposing force.

**Note**: If the system expands, \(w\) is negative. If the system contracts, \(w\) is positive.
Student Question

Which of these changes results in an increase in the internal energy of the system?

a) The system **absorbs** heat and **does** work on the surroundings.

b) The system **releases** heat and **does** work on the surroundings.

c) The system **absorbs** heat and **has** work done on it by the surroundings.

d) The system **releases** heat and **has** work done on it by the surroundings.
Internal Energy

Student Question

Helium gas, at a pressure of 2 Pa, is placed in a container with a movable piston. On the other side of the piston is a vacuum. The He gas is allowed to expand such that the volume of the helium goes from 2 m$^3$ to 4 m$^3$. How much work does the helium gas do?

a) 8 J  
b) 4 J  
c) 0 J  
d) -4 J  
e) None of the above
Internal Energy

- **Heat Capacity (C):** The ratio of heat supplied to the temperature rise produced (units $\frac{J}{^\circ C}$)

- **Molar Heat Capacity:** The heat capacity per mole of substance (units $\frac{J}{mol\cdot ^\circ C}$)
  
  **Note:** Many books use $C_m$ for molar heat capacity.

- **Specific Heat Capacity:** The heat capacity per gram of substance (units $\frac{J}{g\cdot ^\circ C}$)
  
  **Note:** Many books use $C_s$ for specific heat capacity.

  **Note:** If the subscript $V$ is added to any of the heat capacities it is the heat capacity at constant volume. If the subscript $P$ is added to any of the heat capacities it is the heat capacity at constant pressure.
### Internal Energy

#### Molar Heat Capacities at 298 K

<table>
<thead>
<tr>
<th>Gas</th>
<th>$C_V (\text{J/mol·K})$</th>
<th>$C_P (\text{J/mol·K})$</th>
<th>$C_P - C_V (\text{J/mol·K})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>He, Ne, Ar</td>
<td>12.47</td>
<td>20.80</td>
<td>8.33</td>
</tr>
<tr>
<td>$\text{H}_2$</td>
<td>20.54</td>
<td>28.86</td>
<td>8.32</td>
</tr>
<tr>
<td>$\text{N}_2$</td>
<td>20.71</td>
<td>29.03</td>
<td>8.32</td>
</tr>
<tr>
<td>$\text{N}_2\text{O}$</td>
<td>30.38</td>
<td>38.70</td>
<td>8.32</td>
</tr>
<tr>
<td>$\text{CO}_2$</td>
<td>28.95</td>
<td>37.27</td>
<td>8.32</td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_6$</td>
<td>44.60</td>
<td>52.92</td>
<td>8.32</td>
</tr>
</tbody>
</table>

#### Specific Heat Capacities

<table>
<thead>
<tr>
<th>Substances</th>
<th>$C (\text{J/g·K})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2\text{O}(l)$</td>
<td>4.18</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}(s)$</td>
<td>2.03</td>
</tr>
<tr>
<td>$\text{Al}(s)$</td>
<td>0.89</td>
</tr>
<tr>
<td>$\text{Fe}(s)$</td>
<td>0.45</td>
</tr>
<tr>
<td>$\text{Hg}(l)$</td>
<td>0.14</td>
</tr>
<tr>
<td>$\text{C}(s)$</td>
<td>0.71</td>
</tr>
</tbody>
</table>

$$ q = nC\Delta T $$

$$ q = mC\Delta T $$

**Note:** The smaller the heat capacity, the faster the transfer of heat.
Chapter 9: Energy, Enthalpy, and Thermochemistry

Internal Energy

$C_V$ (Monatomic Ideal Gas)

Know

$\Delta E = q + w = \Delta PE + \Delta KE$

Potential Energy

Kinetic Energy

Work

Heat

Putting it together

Only true for ideal monatomic gases
Internal Energy

$C_P$ (Monatomic Ideal Gas)

Know

$\Delta E = q + w = \Delta PE + \Delta KE$

Potential Energy

Kinetic Energy

Work

Heat

Putting it together

Only true for ideal monatomic gases
Internal Energy

- **State Function**: A property of a substance that is independent of how a substance was prepared.

- Are $\Delta E$, $q$, and $w$ state functions?

1 mol of monatomic ideal gas

- Path A
  - 1.0 atm, 1.0 L $\rightarrow$ 1.0 atm, 2.0 L $\rightarrow$ 2.0 atm, 2.0 L

- Path B
  - 1.0 atm, 1.0 L $\rightarrow$ 2.0 atm, 1.0 L $\rightarrow$ 2.0 atm, 2.0 L
**Internal Energy**

Path B (Monatomic Ideal Gas)

1.0 atm, 1.0 L $\rightarrow$ 2.0 atm, 1.0 L $\rightarrow$ 2.0 atm, 2.0 L

- Step 1 (Constant Volume)

**Heat**

- $q = nC_V\Delta T$
- $C_V = \frac{3}{2} R$
  (For monatomic ideal gas)
- $q = n\frac{3}{2} R\Delta T$

Problem: We do not know $T$

- $(\Delta P)V = nR\Delta T$

- $q = \frac{3}{2}(\Delta P)V = \frac{3}{2}(P_f - P_i)V$
- $q = \frac{3}{2}(2.0 \text{ atm} - 1.0 \text{ atm})(1.0 \text{ L})$
- $q = 1.5 \text{ L} \cdot \text{ atm} = 150 J$

**Work**

- $w = -P_{ex}\Delta V = 0.0 J$
  ($\Delta V=0$)

**Internal Energy**

- $\Delta E = q + w$
- $\Delta E = 150 J + 0.0 J$
- $\Delta E = 150 J$
**Internal Energy**

**Path B (Monatomic Ideal Gas)**

1.0 atm, 1.0 L $\rightarrow$ 2.0 atm, 1.0 L $\rightarrow$ 2.0 atm, 2.0 L

- Step 2 (Constant Pressure)

**Heat**

- $q = nC_P \Delta T$
- $C_P = \frac{5}{2}R$
  (For monatomic ideal gas)
- $q = n\frac{5}{2}R\Delta T$

Problem: We do not know $T$

- $P\Delta V = nR\Delta T$
- $q = \frac{5}{2}P\Delta V = \frac{5}{2}P(V_f - V_i)$
- $q = \frac{5}{2}(2.0 \text{ atm})(2.0L - 1.0L)$
- $q = 5.0L \cdot \text{ atm}$
- $q = 5.0 \times 10^2 J$

**Work**

- $w = -P_{ex} \Delta V$
- $w = -P_{ex}(V_f - V_i)$
- $w = -(2.0 \text{ atm})(2.0L - 1.0L)$
- $w = -2.0L \cdot \text{ atm} = -2.0 \times 10^2 J$

**Internal Energy**

- $\Delta E = q + w$
- $\Delta E = 5.0 \times 10^2 J + -2.0 \times 10^2 J$
- $\Delta E = 3.0 \times 10^2 J$
Internal Energy

- **Path A**
  1.0 atm, 1.0 L → 1.0 atm, 2.0 L → 2.0 atm, 2.0 L

- **Path B**
  1.0 atm, 1.0 L → 2.0 atm, 1.0 L → 2.0 atm, 2.0 L

<table>
<thead>
<tr>
<th>Path B (totals)</th>
<th>Path A (totals)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q = 150 J + 5.0 \times 10^2 J )</td>
<td>( q = 550 J )</td>
</tr>
<tr>
<td>( q = 650 J )</td>
<td></td>
</tr>
<tr>
<td>( w = 0.0 J - 2.0 \times 10^2 J )</td>
<td>( w = -1.0 \times 10^2 J )</td>
</tr>
<tr>
<td>( w = -2.0 \times 10^2 J )</td>
<td></td>
</tr>
<tr>
<td>( \Delta E = 150 J + 3.0 \times 10^2 J )</td>
<td>( \Delta E = 450 J )</td>
</tr>
</tbody>
</table>
Path A (Monatomic ideal gas)
1.0 atm, 1.0 L → 1.0 atm, 2.0 L → 2.0 atm, 2.0 L

- **Step 1:** $q = 250 \text{ J}$  
  $w = -1.0 \times 10^2 \text{ J}$  
  $\Delta E = 150 \text{ J}$
- **Step 2:** $q = 3.0 \times 10^2 \text{ J}$  
  $w = 0.0 \text{ J}$  
  $\Delta E = 3.0 \times 10^2 \text{ J}$

Path B (Monatomic ideal gas)
1.0 atm, 1.0 L → 2.0 atm, 1.0 L → 2.0 atm, 2.0 L

- **Step 1:** $q = 150 \text{ J}$  
  $w = 0.0 \text{ J}$  
  $\Delta E = 150 \text{ J}$
- **Step 2:** $q = 5.0 \times 10^2 \text{ J}$  
  $w = -2.0 \times 10^2 \text{ J}$  
  $\Delta E = 3.0 \times 10^2 \text{ J}$

These values were calculated in class.
Enthalpy

Path B (Monatomic Ideal Gas)
1.0 atm, 1.0 L $\rightarrow$ 2.0 atm, 1.0 L $\rightarrow$ 2.0 atm, 2.0 L

- **Step 1 (Constant Volume)**
  - $\Delta H = \Delta E + \Delta(PV) = \Delta E + V\Delta P$
  - $V\Delta P = (1.0L)(2.0\text{atm} - 1.0\text{atm}) = 1.0L \cdot \text{atm}$
  - $V\Delta P = 1.0L \cdot \text{atm}(\frac{101.325J}{1L \cdot \text{atm}}) = 1.0 \times 10^2 J$
  - $\Delta H = 150J + 1.0 \times 10^2 J = 250J$

- **Step 2 (Constant Pressure)**
  - $\Delta H = q = 5.0 \times 10^2 J$

- **Total $\Delta H$**
  - $\Delta H_{tot} = 250J + 5.0 \times 10^2 J = 750J$
Heat of Fusion ($\Delta H_{\text{fus}}$): The amount of heat that needs to be supplied to turn a solid into a liquid.

Heat of Vaporization ($\Delta H_{\text{vap}}$): The amount of heat that needs to be supplied to turn a liquid into a gas.
Calculate the quantity of heat released when 4.00 g of CH\(_4\) (g) are burned in excess oxygen according to the reaction:

\[
\text{CH}_4(\text{g}) + 2\text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g}) + 2\text{H}_2\text{O}(\text{g}) \quad \Delta H^\circ_{\text{rxn}} = -802.2 \text{ kJ}
\]

Helpful information: \(M_{\text{CH}_4} = 16.05 \frac{\text{g}}{\text{mol}}\)

\[
\begin{align*}
a) & \quad 802 \text{ kJ} \\
b) & \quad 401 \text{ kJ} \\
c) & \quad 200. \text{ kJ} \\
d) & \quad 100. \text{ kJ} \\
e) & \quad \text{None of the above}
\end{align*}
\]
Standard State (°)

- For a gas, the standard state is exactly 1 atm.
- For a substance in solution, the standard state is exactly 1 M.
- For a pure substance in a condensed state (liquid or solid), the standard state is the pure liquid or solid.
- For an element, the standard state is the form in which the element exists (is most stable) under conditions of 1 atm and the temperature of interest.

Note: The temperature of the system is usually noted as a subscript. If no temperature is stated, assume 25°C.

Note: Only the change in enthalpy is important, therefore, the standard state of elements are set to 0.
Standard Enthalpy of formation ($\Delta H_f^\circ$):

- The standard reaction enthalpy per mole of compound for the compound’s synthesis from its elements in their most stable form at 1 atm and the specified temperature.

**Note:** The reaction must be written such that only 1 mole of product forms.
**Student Question**

For which reaction is $\Delta H_{rxn}^{\circ} = \Delta H_f^{\circ}$?

a) $2\text{H}_2(\text{g}) + \text{O}_2(\text{g}) \rightarrow 2\text{H}_2\text{O}(\text{l})$

b) $2\text{C( graphite)} + \text{H}_2(\text{g}) \rightarrow \text{C}_2\text{H}_2(\text{g})$

c) $\text{C(diamond)} + \text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g})$

d) $\text{NO}(\text{g}) + \frac{1}{2}\text{O}_2(\text{g}) \rightarrow \text{NO}_2(\text{g})$

e) None of the above
Standard Enthalpy of Combustion \((\Delta H^\circ_c)\):

- The change of enthalpy per mole of substance when it burns (reacts with oxygen) completely under standard conditions.

**Note:** The reaction is written such that 1 mole of substance combusts.

**Note:** When carbon is in the reactants, \(\text{CO}_2\) forms, and when H is in the reactants, \(\text{H}_2\text{O}\) forms. For standard enthalpies of combustion water is always assumed to be in the liquid phase.

**Example:**
\[
\text{C}_3\text{H}_8(\text{g}) + 5\text{O}_2(\text{g}) \rightarrow 3\text{CO}_2(\text{g}) + 4\text{H}_2\text{O}(\text{l})
\]
Hess’s Law:

- A reaction’s enthalpy is the sum of the enthalpies of any sequence of reactions (at the same temperature and pressure) into which the overall reaction can be divided.

Things to remember

- If you add reactions together, add ΔH’s.
- If you flip a reaction, flip the sign of ΔH.
- If you multiply a reaction by a constant, multiply ΔH by the same constant.
Hess’s Law

1. $\text{CCl}_4(g) + 4\text{HCl}(g) \rightarrow \text{CH}_4(g) + 4\text{Cl}_2(g)$
   \[\Delta H_1 = 397.0 \text{ kJ}\]

2. $\frac{1}{2}\text{H}_2(g) + \frac{1}{2}\text{Cl}_2(g) \rightarrow \text{HCl}(g)$
   \[\Delta H_2 = -92.3 \text{ kJ}\]

3. $\text{C(graphite)} + 2\text{H}_2(g) \rightarrow \text{CH}_4(g)$
   \[\Delta H_3 = -74.81 \text{ kJ}\]

Calculate the standard enthalpy of formation of $\text{CCl}_4(g)$ using the thermochemical equations.
Hess’s Law

- **Given**

\[ \text{Na}(s) + \frac{1}{2} \text{H}_2(g) + \text{C(graphtite)} + \frac{3}{2} \text{O}_2(g) \rightarrow \text{NaHCO}_3(s) \quad \Delta H^\circ_f(\text{NaHCO}_3) \]
\[ 2\text{Na}(s) + \text{C(graphtite)} + \frac{3}{2} \text{O}_2(g) \rightarrow \text{Na}_2\text{CO}_3(s) \quad \Delta H^\circ_f(\text{Na}_2\text{CO}_3) \]
\[ \text{C(graphtite)} + \text{O}_2(g) \rightarrow \text{CO}_2(g) \]
\[ \text{H}_2(g) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{H}_2\text{O}(l) \]

- **What is \( \Delta H^\circ_{\text{rxn}} \) of**

\[ 2\text{NaHCO}_3(s) \rightarrow \text{Na}_2\text{CO}_3(s) + \text{CO}_2(g) + \text{H}_2\text{O}(l) \]

\[ 2\text{NaHCO}_3(s) \rightarrow 2\text{Na}(s) + \text{H}_2(g) + 2\text{C(graphtite)} + \frac{3}{2} \text{O}_2(g) \quad - 2\Delta H^\circ_f(\text{NaHCO}_3) \]
\[ 2\text{Na}(s) + \text{C(graphtite)} + \frac{3}{2} \text{O}_2(g) \rightarrow \text{Na}_2\text{CO}_3(s) \]
\[ \text{C(graphtite)} + \text{O}_2(g) \rightarrow \text{CO}_2(g) \]
\[ \text{H}_2(g) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{H}_2\text{O}(l) \]

\[ 2\text{NaHCO}_3(s) \rightarrow \text{Na}_2\text{CO}_3(s) + \text{CO}_2(g) + \text{H}_2\text{O}(l) \]

\[ \Delta H^\circ_{\text{rxn}} = \Delta H^\circ_f(\text{Na}_2\text{CO}_3) + \Delta H^\circ_f(\text{CO}_2) + \Delta H^\circ_f(\text{H}_2\text{O}) - 2\Delta H^\circ_f(\text{NaHCO}_3) \]
Hess’s Law

\[ \Delta H_{rxn}^\circ = \sum \Delta H_f^\circ (\text{products}) - \sum \Delta H_f^\circ (\text{reactants}) \]

<table>
<thead>
<tr>
<th>Substance</th>
<th>( \Delta H_f^\circ ) (kJ/mol)</th>
<th>( \Delta G_f^\circ ) (kJ/mol)</th>
<th>( \Delta S^\circ ) (J/mol·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{C}_2\text{H}_4(\text{g}) )</td>
<td>52</td>
<td>68</td>
<td>219</td>
</tr>
<tr>
<td>( \text{CH}_4(\text{g}) )</td>
<td>-75</td>
<td>-51</td>
<td>186</td>
</tr>
<tr>
<td>( \text{CO}_2(\text{g}) )</td>
<td>-393.5</td>
<td>-394</td>
<td>214</td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_6(\text{g}) )</td>
<td>-84.7</td>
<td>-32.9</td>
<td>229.5</td>
</tr>
<tr>
<td>( \text{O}(\text{g}) )</td>
<td>-110.5</td>
<td>-137</td>
<td>198</td>
</tr>
<tr>
<td>( \text{CH}_3\text{CO}_2\text{H}(\text{l}) )</td>
<td>-484</td>
<td>-389</td>
<td>160.</td>
</tr>
<tr>
<td>( \text{CH}_3\text{OH}(\text{g}) )</td>
<td>-201</td>
<td>-163</td>
<td>240.</td>
</tr>
<tr>
<td>( \text{CH}_3\text{CH}_2\text{OH}(\text{l}) )</td>
<td>-278</td>
<td>-175</td>
<td>161</td>
</tr>
<tr>
<td>( \text{C}<em>6\text{H}</em>{12}\text{O}_6(\text{s}) )</td>
<td>-1275</td>
<td>-911</td>
<td>212</td>
</tr>
<tr>
<td>( \text{HCl}(\text{g}) )</td>
<td>-92</td>
<td>-95</td>
<td>187</td>
</tr>
<tr>
<td>( \text{H}_2(\text{g}) )</td>
<td>0</td>
<td>0</td>
<td>131</td>
</tr>
<tr>
<td>( \text{H}_2\text{O}(\text{l}) )</td>
<td>-286</td>
<td>-237</td>
<td>70</td>
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<tr>
<td>( \text{H}_2\text{O}(\text{g}) )</td>
<td>-242</td>
<td>-229</td>
<td>189</td>
</tr>
<tr>
<td>( \text{Fe}(\text{s}) )</td>
<td>0</td>
<td>0</td>
<td>27</td>
</tr>
<tr>
<td>( \text{Fe}_2\text{O}_3(\text{s}) )</td>
<td>-826</td>
<td>-740</td>
<td>90.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substance</th>
<th>( \Delta H_f^\circ ) (kJ/mol)</th>
<th>( \Delta G_f^\circ ) (kJ/mol)</th>
<th>( \Delta S^\circ ) (J/mol·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{N}_2(\text{g}) )</td>
<td>0</td>
<td>0</td>
<td>192</td>
</tr>
<tr>
<td>( \text{NO}_2(\text{g}) )</td>
<td>34</td>
<td>52</td>
<td>240.</td>
</tr>
<tr>
<td>( \text{NO}(\text{g}) )</td>
<td>90.</td>
<td>87</td>
<td>211</td>
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<tr>
<td>( \text{N}_2\text{O}_4(\text{g}) )</td>
<td>10.</td>
<td>98</td>
<td>304</td>
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<tr>
<td>( \text{NH}_3(\text{g}) )</td>
<td>-46</td>
<td>-17</td>
<td>193</td>
</tr>
<tr>
<td>( \text{HNO}_3(\text{l}) )</td>
<td>-174</td>
<td>-81</td>
<td>156</td>
</tr>
<tr>
<td>( \text{NH}_4\text{Cl}(\text{s}) )</td>
<td>-314</td>
<td>-203</td>
<td>96</td>
</tr>
<tr>
<td>( \text{O}_2(\text{g}) )</td>
<td>0</td>
<td>0</td>
<td>205</td>
</tr>
<tr>
<td>( \text{P}<em>4\text{O}</em>{10}(\text{s}) )</td>
<td>-2984</td>
<td>-2698</td>
<td>229</td>
</tr>
<tr>
<td>( \text{H}_3\text{PO}_4(\text{s}) )</td>
<td>-1279</td>
<td>-1119</td>
<td>110</td>
</tr>
<tr>
<td>( \text{S}_{\text{rhombic}}(\text{s}) )</td>
<td>0</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>( \text{H}_2\text{S}(\text{g}) )</td>
<td>-21</td>
<td>-34</td>
<td>206</td>
</tr>
<tr>
<td>( \text{SO}_2(\text{g}) )</td>
<td>-297</td>
<td>-300</td>
<td>248</td>
</tr>
<tr>
<td>( \text{SO}_3(\text{g}) )</td>
<td>-396</td>
<td>-371</td>
<td>257</td>
</tr>
</tbody>
</table>

* Other \( \Delta H_f^\circ \) can be found in appendix 4 in the back of your book.
Student Question

Calculate $\Delta H_{rxn}^\circ$ (kJ) for the following reaction from the listed standard enthalpies of formation:

$$4\text{NH}_3(g) + 5\text{O}_2(g) \rightarrow 4\text{NO}(g) + 6\text{H}_2\text{O}(g)$$

- a) -862 kJ
- b) -908 kJ
- c) -1276 kJ
- d) Not enough information
- e) None of the above
Chapter 9: Energy, Enthalpy, and Thermochemistry

Calorimetry

Constant Volume Calorimetry (Bomb)

- No matter is exchanged
- No heat is exchanged

Used to find $\Delta E_{\text{com}}$

Constant Pressure Calorimetry (Coffee Cup)

- No heat is exchanged

Used to find $\Delta H$ ($\Delta H_{\text{fus}}$ and $\Delta H_{\text{rxn}}$) and $C$

No matter is exchanged
A 0.0116 mol sample of hexane, C\textsubscript{6}H\textsubscript{14}, undergoes complete combustion with excess O\textsubscript{2} in a bomb calorimeter. The change in temperature of the water (1500. g) surrounding the bomb is 6.66\degree C. The heat capacity of the bomb is 4.04 \( \frac{kJ}{\circ C} \). What is energy of combustion for the reaction of C\textsubscript{6}H\textsubscript{14} in \( \frac{kJ}{mol} \).

**Helpful Information:** \( C_{H_2O} = 4.184 \frac{J}{g\circ C} \)

\[
\begin{align*}
a) & \ -68.7 \ \frac{kJ}{mol} \\
b) & \ -2.32 \times 10^{3} \ \frac{kJ}{mol} \\
c) & \ -4.72 \times 10^{3} \ \frac{kJ}{mol} \\
d) & \ -3.61 \times 10^{6} \ \frac{kJ}{mol} \\
e) & \ None \ of \ the \ above
\end{align*}
\]
100. mL of 0.500 M HCl (0.0500 mol HCl) was mixed with 75.0 mL of 0.500 M NaOH (0.0375 mol NaOH) in a constant-pressure calorimeter of negligible heat capacity. The initial temperature of the HCl and NaOH solution was the same, 22.50°C, and the final temperature of the mixed solution was 25.86°C. Calculate the heat change for the neutralization reaction on a molar basis.

Assume that the densities and specific heats of the solutions are the same as for water (1.00 g/mL and 4.184 J/g°C, respectively)
Energy Released from Different Fuel Sources

- **Natural Gas**
  \[ \text{CH}_4(\text{l}) + 2\text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g}) + 2\text{H}_2\text{O}(\text{g}) \]
  \[51 \frac{\text{kJ}}{\text{g}}\]

- **Coal**
  \[ \text{C}(\text{s}) + \text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g}) \]
  \[17 - 33 \frac{\text{kJ}}{\text{g}}\] Depending on impurities

- **Gasoline**
  \[ \text{C}_x\text{H}_y(\text{l}) + \text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g}) + \text{H}_2\text{O}(\text{g}) \text{unbalanced} \]
  \[48 \frac{\text{kJ}}{\text{g}}\]

- **Hydrogen**
  \[ \text{H}_2(\text{g}) + \text{O}_2(\text{g}) \rightarrow \text{H}_2\text{O}(\text{l}) \]
  \[141 \frac{\text{kJ}}{\text{g}}\]
Although there is an abundance of hydrogen containing compounds on earth, very little is free hydrogen.

**Where do we get H\textsubscript{2} from?**

- **Natural Gas:**
  \[
  \text{CH}_4(g) + \text{H}_2\text{O}(g) \xrightarrow{1000^\circ C} 3\text{H}_2(g) + \text{CO}(g)
  \]

  **Problem:** Uses fossil fuels, need heat (energy), more economical to burn the CH\textsubscript{4}.

- **Electrolysis of Water:**
  If a current is passed through H\textsubscript{2}O the water breaks down into its elements.

  **Problem:** The price of electricity is too high to make this competitive as a fuel. Most electricity is generated from fossil fuels.
**H₂ Fuel**

**Thermal Decomposition:**
- \( \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2 \) (T=3000°C ~ \( \frac{1}{2}\text{H}_2\text{O} \) dissociates)
- \( 2\text{HI} \rightarrow \text{I}_2 + \text{H}_2 \) (435°C)
- \( 2\text{H}_2\text{O} + \text{SO}_2 + \text{I}_2 \rightarrow \text{H}_2\text{SO}_4 \) (90°C)
- \( \text{H}_2\text{SO}_4 \rightarrow \text{SO}_2 + \text{H}_2\text{O} + \frac{1}{2}\text{O}_2 \) (825°C)
- \( \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2 \)

**Problem:** Still needs very high temperatures

**Biological Hydrogen Production:**
- If certain algae are deprived of sulfur they will switch from producing \( \text{O}_2 \) during photosynthesis to \( \text{H}_2 \).

**Problem:** Currently the yields are too small to be a viable commercial option.
H₂ Fuel

Other Problems:
- How to transport H₂?
  - H₂ decomposes on metal surfaces
  - H atoms are so small they can migrate into metal weakening it.
- How to store H₂ in cars?
  - At STP, to produce the same amount of energy in a 20 gallon (76 liters) tank of gasoline you would need to have a 240,000L tank of H₂
  - H₂(ℓ)
  - Insulated
  - Metal hydrides
**Big Idea:** Heat and work are equivalent ways of changing the energy of a system. The total energy of an isolated system is constant. The change in enthalpy of a reaction indicates whether a reaction is endothermic or exothermic.

**Energy Facts**

**Internal Energy**
- Know the 1st law of thermodynamics and its implications (1&16)
  - *The energy of the universe is constant*
  - Be able to calculate internal energy (E) (20&21)
    - \( \Delta E = q + w \)
  - Be able to calculate work (w) (10,18&93)
    - \( w = -P_{ex}\Delta V \)
  - Be able to calculate heat (q) (11&38)
    - \( q = C\Delta T \)

Numbers correspond to end of chapter questions.
Take Away from Chapter 9

- **Enthalpy**
  - Be able to calculate change in enthalpy (\(\Delta H\)) (31, 32, 33, 35, 36, & 51)
    - \(\Delta H = \Delta E + \Delta (PV)\)
    - \(\Delta H = q\) (At constant pressure)
  - Know implications of sign of \(\Delta H\) (26)
    - \(\Delta H\) is -, exothermic reaction
    - \(\Delta H\) is +, endothermic reaction
  - Be able to draw heating curves
    - Know the implications/meaning of \(\Delta H_{vap}\) and \(\Delta H_{fus}\)
  - Know how to use change in enthalpy as a conversion factor (29 & 30)

- **Hess’s Law**
  - Know how to get \(\Delta H_{rxn}^\circ\) from other known \(\Delta H_{rxn}^\circ\) (60, 62, 63, & 64)
  - Know how to get \(\Delta H_{rxn}^\circ\) from \(\Delta H_f^\circ\) (70, 71, & 75)
    - \(\Delta H_{rxn}^\circ = \sum \Delta H_f^\circ (prod) - \sum \Delta H_f^\circ (reac)\)

Numbers correspond to end of chapter questions.
Take Away from Chapter 9

- **Calorimetry**
  - Understand the differences/limitations between constant volume and constant pressure calorimetry (37)
  - Be able to solve bomb calorimeter (constant volume) problems (51)
    - \[ \Delta E_{com} = -C_{cal} \Delta T \]
  - Be able to solve coffee cup calorimeter (constant pressure) problems

- Solve for \( C \) of non soluble substance (40&42)
  - \( q_{H_2O} = -q_{substance} \) (if needed add heat \( q_{cal} \) to \( q_{H_2O} \))
  - \( m_{H_2O}C_{H_2O}\Delta T_{H_2O} = -m_{sub}C_{sub}\Delta T_{sub} \)

- Solve for \( \Delta H_{fus} \)
  - \( q_{solid} = -q_{liquid} \) (if needed add heat \( q_{cal} \) to \( q_{liquid} \))
  - \( q_s(T_{is}\rightarrow T_{ms}) + q_{fus} + q_{l\ (that\ was\ s)}(T_{ms}\rightarrow T_f) = -q_l \)
  - \( m_sC_s(T_{ms} - T_{is}) + n_s\Delta H_{fus} + m_sC_l(T_f - T_{ms}) = -m_lC_l(T_f - T_{il}) \)
Calorimetry (Continued)

- Be able to solve coffee cup calorimeter problems
  
  Solve for $\Delta H_{rxn}$ (45, 48, 49, 50)
  
  $\Delta H_{rxn} = -q_{solution}$ (if needed add heat $q_{cal}$ to $q_{solution}$)
  
  $\Delta H_{rxn} = -m_{solution} C_{H_2O} \Delta T_{solution}$ (Most times need to divide by number of moles. Be careful many of these are limiting reagent problems.)

H$_2$ Fuel

Numbers correspond to end of chapter questions.