Topic 5: Energetics

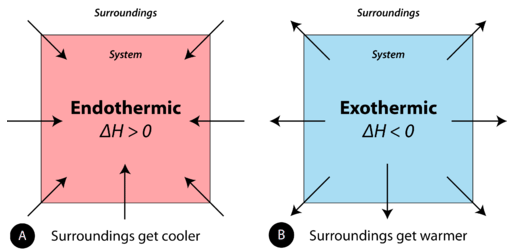
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| **5.1** | **Measuring energy changes** |
| 5.1.1 | Heat is a form of energy |
| 5.1.2 | Temperature is a measure of the average kinetic energy of the particles |
| 5.1.3 | Total energy is conserved in chemical reactions |
| 5.1.4 | Chemical reactions that involve transfer of heat between the system and the surroundings are described as endothermic or exothermic |
| 5.1.5 | The enthalpy change (ΔH) for chemical reactions is indicated in kJ mol-1 |
| 5.1.6 | ΔH values are usually expressed under standard conditions, given by ΔH° including standard states |
| 5.1.7 | Calculations of the heat change when the temperature of a pure substance is changed using |
| 5.1.8 | A calorimetry experiment for an enthalpy of reaction should be covered and the results evaluated |

# Heat and Temperature

* Energetics is the study of heat changes in chemical reactions
  + Heat is a form of energy
* Energy can neither be created nor destroyed. Total energy is always conserved and can only be transferred
* **Heat energy always flows from a higher temperature object to a lower temperature object**
* The Kelvin scale is based on kinetic energy, so 0K means that there is no kinetic movement at all

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| Definitions |
| **Heat** – A measure of the total kinetic energy of particles in a substance  **Temperature** –A measure of the average kinetic energy of particles in a substance |

# Enthalpy (H)

* **Enthalpy (H): The amount of heat energy contained in a substance**
* Enthalpy is stored in the chemical bonds as potential energy
* When substances react, the total enthalpy of a system cannot be measured (due to loss of heat), but it is possible to measure the difference in the enthalpy between the reactants and products
* Enthalpy is denoted as **H**, however heat change is denoted as **ΔH**
* The enthalpy change for chemical reactions is denoted kJ mol-1
* The reaction mixture is called the system (the chemical reaction), which **gives heat** **to** or **takes** **heat from** the surroundings (anything around the system)
* Chemical reactions that involve transfer of heat between system and the surroundings are described as exothermic and endothermic

# *Exothermic: Heat is Released*

* In exothermic reactions **heat is released** to the surroundings
  + This is because more heat energy is released than what is added
  + So, the overall heat energy is released from the system, causing the surroundings to become hotter
* Exothermic reactions have **negative ΔH values**, because heat is released (thus enthalpy decreases, -ΔH)
* In an exothermic reaction, the **products are more stable than the reactants** as they have a lower enthalpy
  + Less heat means more stable
* This means the reaction is downhill in terms of heat energy
* Exothermic reactions release energy (as heat)
* Examples include:
  + **Bond forming**: Removing heat brings atoms closer together, forming bonds
  + When chemical bonds are formed, heat is released *(See 5.3)*
  + Gas -> Liquid -> Solid: Heat is removed, thus these are exothermic reactions
  + Rain: The condensation of water vapor into rain releases energy in the form of heat
  + Combustion: The burning of carbon compounds uses oxygen from air, and produces CO2, H2O and lots of heat

# *Endothermic: Heat is Absorbed*

* In endothermic reactions **heat is absorbed from the surroundings**
  + This is because more heat energy is added than what is released
  + So, the overall heat energy is absorbed by the system, causing the surroundings to become cooler.
* Endothermic reactions have **positive ΔH values**, because heat is absorbed (thus, enthalpy increases +ΔH)
* In an endothermic reaction, the **produces are less stable than the reactants** as they have a higher enthalpy
  + More heat means less stable
* This means the reaction is uphill in terms of heat energy
* Exothermic reactions require energy (through heat)
* Examples include:
  + **Bond breaking**: Adding heat separates atoms, breaks bonds *(See 5.3)*
  + Photosynthesis: Plants absorb heat energy from sunlight to convert CO2 and water into glucose and oxygen
  + Solid -> Liquid -> Gas: Heat is added, so the reactions are endothermic

# *Energy Diagrams: Endothermic and Exothermic Reaction*

Enthalpy

Enthalpy

Reaction Pathway

Reaction Pathway

# Standard Enthalpy change:

* Standard enthalpy change of reaction: The enthalpy change of a reaction carried out under standard with everything in its standard state
* Only can be measured, not
* Standard enthalpy change is measured in **kJ mol-1**

1. : Refers to Enthalpy change

A positive value indicates an endothermic reaction while a negative value indicates an exothermic reaction

b) : Refers to standard conditions where **289K, 101.3 kPa, 1 mol dm-3**

Standard conditions are necessary as enthalpy changes will have different values depending on the conditions under which they are measured. Therefore, all enthalpy changes are performed under standard conditions

c) : Refers to the type of enthalpy change

Sometimes, bond enthalpies are average values/differ (slightly) from one compound to another so the standard enthalpy will not be the same value in the data booklet

# *Standard Enthalpy of Formation:*

* The standard enthalpy change of formation (): The energy change when one mole of a compound is formed from its elements in their standard states under standard conditions
* To calculate enthalpy change from formation:
* values are found in the data booklet (remember to include coefficients) (Elements have a value of zero)

# *Standard Enthalpy of Combustion:*

* The standard enthalpy change of combustion (∆Hc°): The energy released when one mole of a compound is completely **burned in excess oxygen** under standard conditions with no change in pressure
* Combustion reactions always produce CO2 and H2O
* **All combustion reactions are exothermic** (always negative) as heat is released during combustion process
* To calculate enthalpy change from combustion:

# Thermochemical equations

* Thermochemical equations give the balanced equation with an enthalpy charge
* State symbols must be shown, as depends on the state of the reactants or products
* In order to calculate energy changes for a specific amount of a substance using the thermochemical equation:

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| Question |
| Calculate the energy released, in kJ, when 0.500kJ SO3 reacts with water  *Step 1: Calculate how many moles of SO3 there are:*  *Step 2: Compare to thermochemical equation:*  1 mol of SO3 releases 129.6 kJ, therefore 12.5 mol of SO3 releases kJ  *Step 3: Use ratios:* |

# Heat changes calculations

* Heat changes (enthalpy) can be calculated from the temperature changes:
* : heat change
* : mass (Use the mass of water unless specified)
* : specific heat capacity
  + Specific heat capacity (c): The energy required to raise the temperature of 1g of substance by 1K
* : Temperature change
  + If the temperature of the compound increased, then the reaction is endothermic and must be positive
  + If the temperature of the compound decreased, then the reaction is exothermic and must be negative

For calorimetry experiments take the absolute value of then:

* + *If the temperature of the water INCREASED, then the reaction is exothermic and must be negative*
  + *If the temperature of the water DECREASED, then the reaction is endothermic and must be positive*

# Enthalpy Change

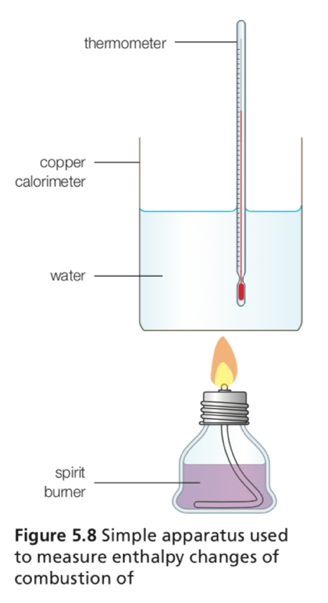
* To calculate enthalpy change (), the equation below can be used:
* However, can be either positive or negative. Simply add a positive or negative sign to when:
  + The temperature of the substance INCREASED, then the reaction was endothermic and is positive
  + The temperature of the substance DECREASED, then the reaction was exothermic and is negative

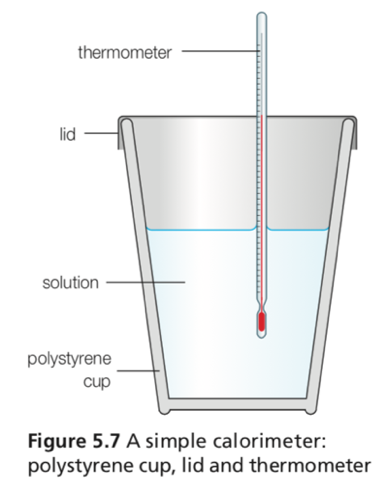
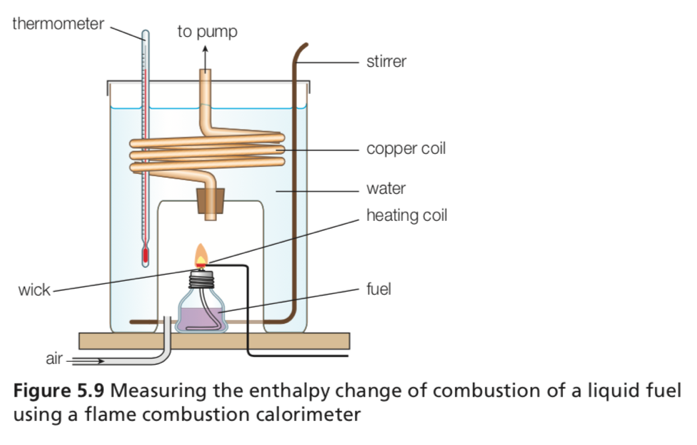
# *Standard Enthalpy of Neutralization:*

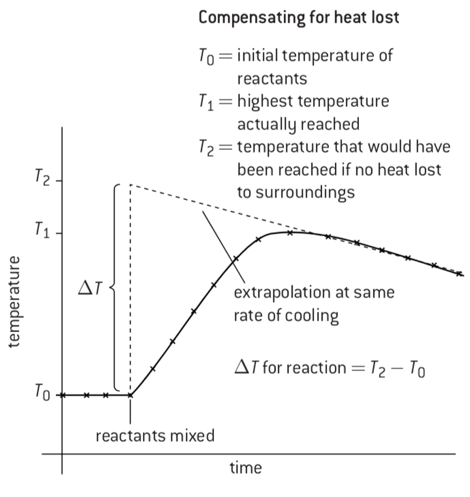
* The standard enthalpy change of neutralization (∆Hneut°): The enthalpy change when a strong acid and base react together to form one mole of water under standard conditions
* **Neutralization reactions are exothermic** (always negative) as heat is released
* To calculate enthalpy change from combustion:

1. Calculate the number of moles of acid and base using
2. Determine the limiting reactant. This will tell you how many moles of water can be produced
3. Add the volumes of acid and base together (where 1cm3=1g) to get the mass
4. Use to calculate enthalpy change
5. Use where is number of moles of water produced

# Calorimetry

* Calorimetry is the process of measuring the amount of heat released or absorbed during a chemical reaction
* When the reaction occurs, it is either going to give off or take in heat
* The change in heat can be measured by observing the temperature of water, as water can serve as the surroundings
* There are many ways to perform calorimetry, the most common is to use a bomb shell
* Calorimetry is performed many different ways:



* However, when using calorimetry several assumptions are made
* This is because heat loss and incomplete combustion can lead to systematic errors in experimental results
* These assumptions are:

1. That all the heat is transferred to the water

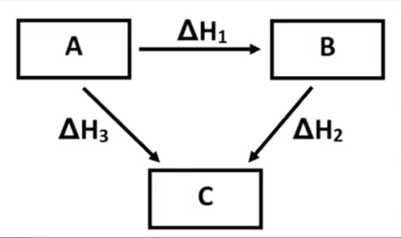
*(Some might be transferred to the metal or is still inside the system)*

1. That all the solution has dissolved
2. The mass of the water remained constant
3. There was an unlimited oxygen source
4. The experiment was under standard conditions

* **To compensate for heat lost by the water we can extrapolate the graph recorded**
* By extrapolating the graph, the temperature rise that would have taken place had the reaction been instantaneous can be calculated by taking

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| **5.2** | **Hess’s Law** |
| 5.2.1 | The enthalpy change for a reaction that is accrued out in a series of steps is equal to the sum of the enthalpy changes for the individual steps |
| 5.2.2 | Application of Hess’s Law to calculate enthalpy changes |
| 5.2.3 | Calculation of reactions using data |
| 5.2.4 | Determination of the enthalpy change of a reaction that is the sum of multiple reactions with known enthalpy changes |

# Hess’s Law

* Hess’s Law states that regardless of the multiple stages or steps of a reaction, the total enthalpy change for the reaction is the sum of all changes
* This means the enthalpy change going from A to B **is the same** whether the reaction proceeds directly to A or whether it goes via A to C then B
* This is known as an energy diagram and can be written as two reactions that when combined produce the overall equation: ∆H3 = ∆H1 + ∆H2

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| Question |
| Using the equation below:  Which is the enthalpy change for the following reaction?  As you can see, if we reverse the second reaction (and change the sign of the enthalpy), it cancels to give the above reaction, therefore the enthalpy change is -390 + 520 = 130 kJ mol-1 |

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| **5.3** | **Bond enthalpies** |
| 5.3.1 | Bond-forming releases energy and bond-breaking requires energy |
| 5.3.2 | Average bond enthalpy is the energy needed to break one mol of a bond in a gaseous molecule averaged over similar compounds |
| 5.3.3 | Calculations of the enthalpy changes from known bond enthalpy values and comparison of these to experimentally measured values |
| 5.3.4 | Sketching and evaluation of potential energy profiles in determining whether reactants or products are more stable and if the reaction is exothermic or endothermic |
| 5.3.5 | Discussion of the bond strength in ozone relative to oxygen in its importance to the atmosphere |

# Bond enthalpy

* Average bond enthalpy: The energy required to break one mole of the same type of bond in the gaseous state averaged over a variety of similar compounds
* Energy is released through the **formation** of chemical bonds
  + **Bond forming**: Removing heat brings atoms closer together, forming bonds
  + Releases energy, negative therefore exothermic
* Energy is required when **breaking** chemical bonds
  + **Bond breaking**: Adding heat separates atoms, breaks bonds *(See 5.3)*
  + Requires energy, positive therefore endothermic
* The enthalpy of reaction () can be calculated using bond enthalpies
* Since there are average bond enthalpies, the calculation gives only an approximate result. To calculate:
* represents the bond energy per mol of bonds (see data booklet)
* When the reaction is endothermic
* When the reaction is exothermic

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| Question |
| Calculate the enthalpy of reaction of methane: |

* However, bond enthalpies can only be used by themselves if all the reactants and products are in the gaseous state

# Ozone depletion

* Oxygen is present in the atmosphere in two forms:
  + Normal oxygen: O2
  + Ozone: O3
* Much of the harmful UV radiation is absorbed by the ozone layer
* The ozone layer forms a protective screen which absorbed the UV light to ensure that the radiation that reaches the surface of the Earth is different from the emitted by the Sun
  + Without the ozone layer the UV radiation would have caused damage to living tissue
* The bond in oxygen and ozone are both broken when they absorb UV radiation of sufficient energy
* However, both oxygen and ozone are **broken by UV light of different wavelengths**
* This is because the bonds in oxygen, O2, are stronger than those in ozone, O3
* The stronger double bond in O2 requires higher energy UV radiation (Shorter wavelength) to break
* The wavelengths of light needed to break the bonds in ozone are calculated using a modified Planck’s equation:

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| Ozone depletion question: |
| The bond energy in ozone is . Calculate the wavelength of UV radiation needed to break the bond  One mole of photons are needed to break one mole of bonds. The energy of a mole of photos is the energy of one photon multiplied by Avogadro’s number ()  We want to find wavelength, , so by rearranging Planck’s equation:  Any radiation in the UV region with a wavelength smaller than 330nm breaks the bond in ozone |

* The bonds in O3 are broken by UV radiation with a wavelength of <330nm
* The bond in O2 is broken by UV radiation with a wavelength of <242nm

# The Ozone-Oxygen Cycle

* The ozone–oxygen cycle is the process by which ozone is continually regenerated in Earth's stratosphere
* It describes how ozone is both formed and depleted by natural processes in the atmosphere *(diagram on right)*
* **In the atmosphere, high-energy UV breaks the strong bonds in O2 so that O3 can be formed. Lower-energy UV breaks the weaker bonds in O3**
* This cycle of reactions is significant because dangerous ultraviolet light has been absorbed and the stratosphere has become warmer

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| **15.1** | **Enthalpy cycles** |
| 15.1.1 | Representative equations can be used for enthalpy/energy of hydration, ionization, atomization, electron affinity, lattice, covalent bond and solution |
| 15.1.2 | Enthalpy of solution, hydration enthalpy and lattice enthalpy are related in an energy cycle |
| 15.1.3 | Construction of Born-Haber cycles for group 1 and 2 oxides and chlorides |
| 15.1.4 | Construction of energy cycles from Born-Haber or dissolution energy cycles |
| 15.1.5 | Relate size and charge of ions to lattice and hydration enthalpies |
| 15.1.6 | Perform lab experiments which could include single replacement reactions in aqueous solutions |

# Born-Haber Cycle

* Born-Haber cycles are energy cycles describing the formation of ionic compounds
* Lattice enthalpy cannot be measured because gaseous ions do not combine directly to form a compound
* The Born-Haber cycle allows the experimental lattice enthalpy to be calculated from other enthalpy changes
  + Hess’s law can be used to find any missing value from a Born Haber cycle, not just a lattice enthalpy
* Remember the following:

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| Energy cycle | Definition | Equation |
| Ionization enthalpy  *First ionization energy* | The energy required to remove 1 mole of an electron from 1 mole of an atom in gaseous state\*  Since ionization always requires energy, it is always endothermic |  |
| *Second ionization energy* | *The energy required to remove 1 mole of an electron from 1 mole of an ion in its gaseous state\** |  |
| Electron affinity enthalpy  *First electron affinity* | The energy change when 1 mole of an electron is added to 1 mole of an atom in its gaseous state\* |  |
| Lattice Enthalpy | The energy required when 1 mole of an ionic compound is formed from its gaseous ions\* |  |
| Atomization Enthalpy | The energy change to make 1 mole of gaseous atoms from its elements\* |  |

\* “under standard conditions” with regarding enthalpy

* The Born-Haber cycle will contain all enthalpy cycles listed above
* By rearranging this formula, we can solve for lattice energy (Hess’s Law)

# Energy Cycle: Enthalpy of solution, hydration and lattice enthalpy

* Other energy cycles include the one between enthalpy of solution, hydrate and lattice enthalpy
  + Enthalpy of solution (): The enthalpy change when one mole of an ionic compound is dissolved in water to infinite dilution
  + Enthalpy of Hydration (): The enthalpy change when one mole of gaseous ions dissolve to give an infinitely dilute solution
* The enthalpy of solution is found by (Hess’s Law):
* First the solid ionic compound is broken down into its gaseous ions ()
* Then the gaseous ions are then hydrated by water molecules ()

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| **15.2** | **Entropy and spontaneity** |
| 15.2.1 | Entropy (S) refers to the distribution of available energy among the particles. The more ways the energy can be distributed the higher the entropy |
| 15.2.2 | Gibbs free energy (G) relates the energy that can be obtained from a chemical reaction to the change in enthalpy (), change in entropy (), and absolute temperature (T) |
| 15.2.3 | Entropy of gas > liquid > solid under same conditions |
| 15.2.4 | Prediction of weather a change will result in an increase or decrease in entropy by considering the states of the reactants and products |
| 15.2.5 | Calculations of entropy changes () from given standard entropy values ( |
| 15.2.6 | Application of in predicting spontaneity and calculation of various conditions of enthalpy and temperature that will affect this |
| 16.2.7 | Relation of to position of equilibrium |

# Entropy

* Entropy (S) refers to the distribution of available energy among the particles in a system
  + The more ways the energy can be distributed the higher the energy
* Entropy is sometimes referred to as a measure of disorder of a system
* The change in the disorder of a system is known as the entropy change,
* The more disordered a system becomes the more positive the value of becomes
* Systems which become more ordered will have decreasing values
* Standard entropy: The entropy content of one mole of substance under a standard state
* Factors that increase the entropy of a system include:

1. Changes of state, gas has the most entropy, solids have the least (account for coefficients)
   * Solids have low entropy values
   * Gas molecules have a high entropy value
2. Increased number of particles (Example, increasing concentration)
3. Increased temperature (which increases movement of particles)
4. More complicated structure (or more atoms attached)
5. Dissolution (dissolving) of an ionic compound

* Unlike enthalpy, absolute values of entropy can be measured
* The standard entropy change for a reaction can be determined by (account for coefficients):

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| Entropy question: |
| Calculate the standard entropy for the formation of ammonia:  Step 1: Calculate the standard entropies of each molecule/compound (account for coefficients)  The standard entropies of hydrogen, nitrogen and ammonia are 131, 192 and 192 kJ mol-1 respectively |

* can also be calculated in a **reversible** process by:
* The second law of thermodynamics states that the entropy of a spontaneous reaction (when not in equilibrium) will increase over time. When the system is at equilibrium will have 0 entropy

# Spontaneity

* A reaction is said to be spontaneous if the system moves from a less stable to a more stable state
* Spontaneity depends both upon the enthalpy change and the entropy change
* These two factors are combined and expressed as the Gibbs energy change , often called “free energy change”
* The standard free energy change is defined as:
* A spontaneous reaction is one that releases free energy, so must be negative if the reaction is spontaneous
  1. If the reaction is spontaneous
  2. If the reaction is at equilibrium
  3. If the reaction is not spontaneous
* Some reactions will always be spontaneous depending on , and
* and can be either positive or negative, while can either be a low or high value. The spontaneity can then be:

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| --- | --- | --- | --- | --- |
|  |  |  |  | Spontaneity |
| + | + | Low | + | Not Spontaneous |
| High | - | Spontaneous |
| + | - | Low/High | + | Not spontaneous |
| - | + | Low/high | - | Spontaneous |
| - | - | Low | - | Spontaneous |
| High | + | Non spontaneous |

* Spontaneity can also be found by substituting values into:

1. Substitute 100 for and
2. Substitute 0.1 for a low temperature, and 10 for a high temperature
3. If is negative the reaction is spontaneous. If is positive, the reaction is not spontaneous