

# How can chemical processes be designed to optimise efficiency?

## AREA OF STUDY 1

### What are the options for energy production?

#### Outcome 1

Compare fuels quantitatively with reference to combustion products and energy outputs, apply knowledge of the electrochemical series to design, construct and test galvanic cells, and evaluate energy resources based on energy efficiency, renewability and environmental impact.

#### Key knowledge

##### Obtaining energy from fuels

- the definition of a fuel, including the distinction between fossil fuels and biofuels with reference to origin and renewability (ability of a resource to be replaced by natural processes within a relatively short period of time)
- combustion of fuels as exothermic reactions with reference to the use of the joule (SI unit), energy transformations, their efficiencies and measurement of enthalpy change including symbol ( $\Delta H$ ) and common units ( $\text{kJ mol}^{-1}$ ,  $\text{kJ g}^{-1}$ ,  $\text{MJ/tonne}$ )
- the writing of balanced thermochemical equations, including states, for the complete and incomplete combustion of hydrocarbons, methanol and ethanol, using experimental data and data tables
- the definition of gas pressure including units, universal gas equation and standard laboratory conditions (SLC) at  $25^\circ\text{C}$  and  $100\text{ kPa}$
- calculations related to combustion of fuels; use of mass–mass, mass–volume and volume–volume stoichiometry in calculations of enthalpy change (excluding solution stoichiometry) to determine heat energy released, moles of reactants and products and net volume of greenhouse gases at a given  $T$  and  $P$  (or net mass) released per MJ of energy obtained
- the use of specific heat capacity of water to determine approximate amount of heat energy released in combustion of a fuel.

##### Fuel choices

- the comparison of fossil fuels (coal, crude oil, petroleum gas, coal seam gas) and biofuels (biogas, bioethanol, biodiesel) with reference to energy content, renewability and environmental impacts related to sourcing and combustion
- the comparison of the suitability of petrodiesel and biodiesel as transport fuels with reference to sources, chemical structures, combustion products, flow along fuel lines (implications of hygroscopic properties and impact of outside temperature on viscosity) and the environmental impacts associated with their extraction and production.

##### Galvanic cells as a source of energy

- redox reactions with reference to electron transfer, reduction and oxidation reactions, reducing and oxidising agents, and use of oxidation numbers to identify conjugate reducing and oxidising agents
- the writing of balanced redox half-equations; balanced ionic equations, including states, for overall redox reactions
- galvanic cells as primary cells and as portable or fixed chemical energy storage devices that can produce electricity (details of specific cells not required) including common design features (anode, cathode, electrolytes, salt bridge and separation of half-cells) and chemical processes (electron and ion flows, half-equations and overall equations)

- the comparison of the energy transformations occurring in spontaneous exothermic redox reactions involving direct contact between reactants (transformation of chemical energy to heat energy) compared with those occurring when the reactants are separated in galvanic cells (transformation of chemical energy to electrical energy)
- the use of the electrochemical series in designing and constructing galvanic cells and as a tool for predicting products of redox reactions, deducing overall equations from redox half-equations; determining maximum cell voltage under standard conditions.

#### Rechargeable batteries

- the operation of rechargeable batteries (secondary cells) with reference to discharging as a galvanic cell and recharging as an electrolytic cell, including the redox principles (redox

reactions and polarity of electrodes) and the factors affecting battery life with reference to components and temperature (no specific battery is required).

#### Fuel cells as a source of energy

- the common design features of fuel cells including use of porous electrodes for gaseous reactants to increase cell efficiency (details of specific cells not required)
- the comparison of the use of fuel cells and combustion of fuels to supply energy with reference to their energy efficiencies (qualitative), safety, fuel supply (including the storage of hydrogen), production of greenhouse gases and applications
- the comparison of fuel cells and galvanic cells with reference to their definitions, functions, design features, energy transformations, energy efficiencies (qualitative) and applications.

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## Energy from fuels

### FUELS

Fuels contain chemical energy that is relatively easily released as a useful source of energy. Energy sources can be classified in terms of their renewability.

- Non-renewable** resources are those used at a rate faster than they can be replaced. Examples are fossil fuels, which include coal, crude oil, petroleum gas and coal seam gas.
- Renewable resources** are continually being replaced naturally. Examples are wind, water, tides, biomass and solar energy. Biofuels, such as biogas, bioethanol and biodiesel, are fuels obtained from living systems. Biofuels are renewable but not necessarily **sustainable**. Sustainable sources of energy are those that are not expected to be depleted within the lifetime of the human race. The use of these sources causes no long-term damage to the environment.

### Non-renewable fuels

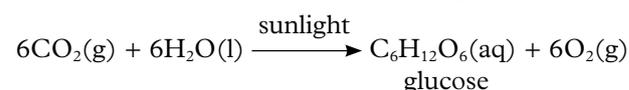
These fuels have been formed over millions of years from plant and animal matter (Table 3.1.1). The chemical energy contained in fossil fuels has come from solar energy. Using fossil fuels has significant environment disadvantages such as:

- enhancing the greenhouse effect, as greenhouse gases, CO<sub>2</sub> and H<sub>2</sub>O, are emitted when the fuels are burnt

- producing SO<sub>2</sub> gas, which forms acid rain
- producing nitrogen oxides, which increase air pollution.

### Renewable fuels

Either directly or indirectly, living organisms obtain energy from the sun by the process of **photosynthesis**. The equation for this process can be represented as:



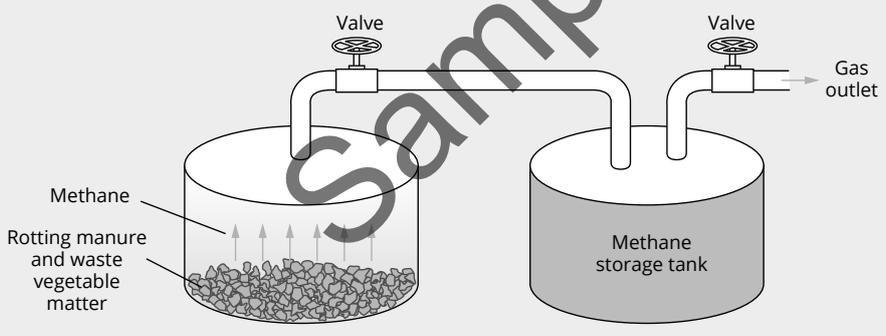
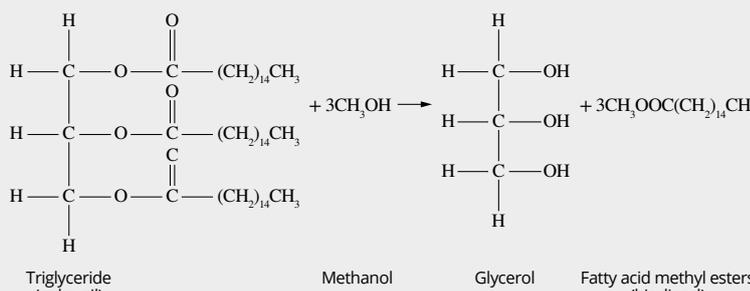
Plants convert solar energy to chemical energy in glucose, which then undergoes polymerisation to form starch and cellulose. Starch is stored in plants and then hydrolysed to glucose, for the subsequent controlled release of energy in the process of respiration. Starch, cellulose and other plant material may be converted to biofuels such as biogas, bioethanol and biodiesel for transport and other industrial and domestic uses (Table 3.1.2).

**Biofuels** are renewable fuels made from plants such as sugar cane, grains, vegetable waste or oils. Whilst carbon dioxide is produced when biofuels burn, the plants also absorb it as they grow. The use of biofuels should therefore lead to an overall reduction in the levels of carbon dioxide emitted. However, when sourcing plants to be used as fuels, energy is needed in growing and harvesting them. This energy production produces greenhouse gases so the production of biofuels is not **carbon neutral**.

An issue arises with respect to biofuel production: to produce biofuels, is it appropriate to use farm land that could be used for growing food crops?

# KEY KNOWLEDGE

Fossil fuel	Description	Reasons for use	Energy content and use
<b>Coal</b>	<ul style="list-style-type: none"> <li>Mixture of organic molecules with molar masses as high as 3000</li> <li>Found as black coal, brown coal and peat, with decreasing percentage carbon content</li> </ul>	<ul style="list-style-type: none"> <li>Cheap to mine</li> <li>Large deposits worldwide</li> </ul>	<ul style="list-style-type: none"> <li>The higher the percentage carbon, the higher the energy content, the greater the efficiency of energy production and the less the environmental impact</li> <li>Produces more pollutants than other fossil fuels</li> <li>Used in electricity production</li> <li>High energy content</li> </ul>
<b>Crude oil</b>	<ul style="list-style-type: none"> <li>Mixture of alkanes</li> <li>Needs to be fractionally distilled and then cracked to obtain useful fuels such as petrol</li> </ul>	<ul style="list-style-type: none"> <li>Relatively cheap and easy to mine, but known deposits may only last decades</li> </ul>	<ul style="list-style-type: none"> <li>Transport fuel</li> <li>High energy content</li> </ul>
<b>Petroleum gas</b>	<ul style="list-style-type: none"> <li>May be found trapped between rock layers; called shale gas</li> <li>A component of crude oil</li> </ul>	<ul style="list-style-type: none"> <li>Relatively cheap</li> <li>Widely available</li> <li>Readily transported</li> </ul>	<ul style="list-style-type: none"> <li>Transport fuel</li> <li>High energy content</li> </ul>
<b>Natural gas including coal seam gas</b>	<ul style="list-style-type: none"> <li>Natural gas adsorbed onto coal surface is called coal seam gas; it usually contains water</li> </ul>	<ul style="list-style-type: none"> <li>More efficient in energy production compared to coal</li> <li>Moderate cost</li> <li>When burnt, produces less particulate matter in emissions than coal</li> </ul>	<ul style="list-style-type: none"> <li>Electricity production; heating; cooking; transport fuel</li> <li>High energy content</li> </ul>

Biofuel and how it is produced	Energy content and use
<p><b>Biogas</b></p> <ul style="list-style-type: none"> <li>Mainly a gaseous mixture of CO<sub>2</sub> and CH<sub>4</sub></li> <li>Generated when organic wastematter is digested anaerobically by the action of microorganisms (Figure 3.1.1)</li> </ul>  <p><b>Figure 3.1.1</b> A biogas digester.</p>	<ul style="list-style-type: none"> <li>Low energy content</li> <li>For heating and to power homes and farms</li> </ul>
<p><b>Bioethanol</b></p> <ul style="list-style-type: none"> <li>Produced by fermentation of glucose—an anaerobic process involving yeast:</li> </ul> $C_6H_{12}O_6(aq) \rightarrow 2CH_3CH_2OH(aq) + 2CO_2(g)$	<ul style="list-style-type: none"> <li>Less energy available per litre than petrol</li> <li>Transport fuel, but causes greater engine wear than petrol</li> </ul>
<p><b>Biodiesel</b></p> <ul style="list-style-type: none"> <li>Composed of a mixture of esters</li> <li>Produced by reaction between vegetable oils (esters) and an alcohol, commonly methanol (Figure 3.1.2)</li> </ul>  <p><b>Figure 3.1.2</b> Chemical equation showing the production of a biodiesel.</p>	<ul style="list-style-type: none"> <li>More energy available per litre than petrol</li> <li>Transport fuel</li> </ul>

# KEY KNOWLEDGE

## ENERGY TRANSFORMATIONS

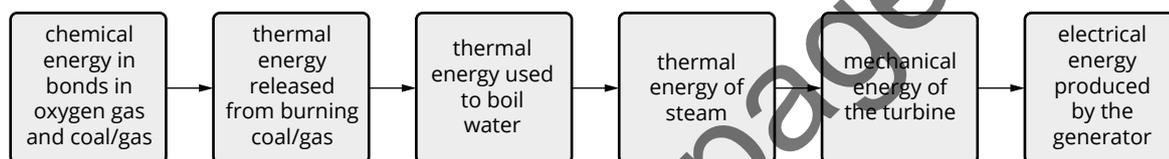
Combustion of fuels releases the chemical energy in the fuel as heat energy. This heat energy can be transformed into kinetic or electrical energy for use in vehicles and power stations.

**Energy efficiency** is the percentage of energy from a source that is converted into useful energy. Power stations are approximately 30–40% efficient (Figure 3.1.3). When natural gas, petrol or biofuels are used in the combustion engines of vehicles, the efficiency of energy transformations is about 25%. As a general rule, the more energy transformations that are involved, the lower the efficiency.

A **joule** is the unit of energy. Other related units are:

- kilojoules:  $1 \text{ kJ} = 10^3 \text{ J}$
- megajoules:  $1 \text{ MJ} = 10^6 \text{ J}$ .

The energy available from fuels (energy content) can be measured using units such as  $\text{kJ mol}^{-1}$ ,  $\text{kJ g}^{-1}$  and  $\text{MJ tonne}^{-1}$ .



**Figure 3.1.3** Energy transformations in coal and gas-burning power stations.

## PETRODIESEL AND BIODIESEL

Petrodiesel and biodiesel are used as transport fuels. The suitability of the two fuels for this purpose is compared in Table 3.1.3.

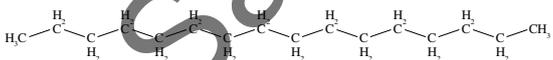
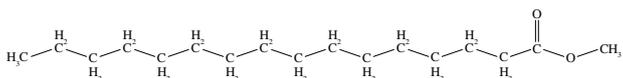
## ENERGY AND CHEMICAL REACTIONS

Chemical energy is stored in the bonds between atoms and between molecules. It results from attractions and repulsions between electrons and protons, and vibrations and rotations of nuclei.

The **chemical energy** of a substance is called its **heat content** or **enthalpy** and is given the symbol  $H$ . We can measure the change in enthalpy,  $\Delta H$ , for a chemical reaction:

$$\Delta H = H_{\text{products}} - H_{\text{reactants}}$$

**Table 3.1.3** Comparison of petrodiesel and biodiesel

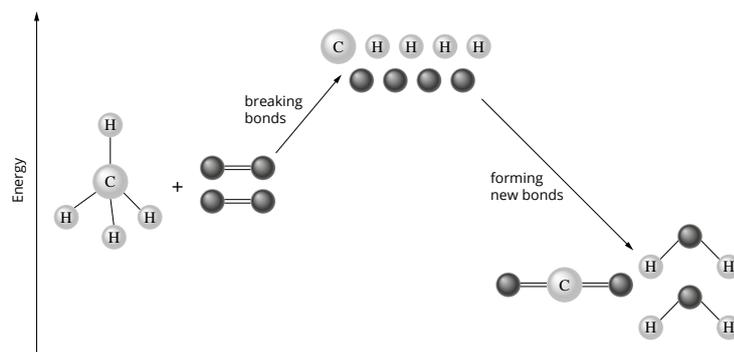
Property or characteristic	Petrodiesel	Biodiesel
Sources	Produced from crude oil	Produced by reaction of vegetable oils, from plant matter, with alcohols
Chemical structures, intermolecular forces; melting points and viscosity	 <p>Non-polar molecules with only dispersion forces between them, hence lower melting point and viscosity than biodiesel</p>	 <p>Polar ester link causes stronger intermolecular forces to exist (dipole-dipole attractions), resulting in higher melting point and viscosity than petrodiesel</p>
Flow along fuel lines	Flows better at low temperatures than biodiesel as less viscous, because the molecules are smaller and non-polar with weaker dispersion forces between them	Does not flow as well in cold climates and at low temperatures, due to higher viscosity resulting from the stronger dipole-dipole forces between the polar ends of the molecules
Hygroscopic properties	Non-polar molecules do not attract water	Hygroscopic so absorbs water in storage due to polar ends of biodiesel molecules. This reduces the efficiency with which it burns
Combustion products	$\text{CO}_2$ and $\text{H}_2\text{O}$	$\text{CO}_2$ and $\text{H}_2\text{O}$
Energy content	$40 \text{ MJ L}^{-1}$ (10% more than biodiesel)	$36 \text{ MJ L}^{-1}$ (burns more efficiently and cleanly than petrodiesel)
Environmental impacts	<ul style="list-style-type: none"> <li>• extraction</li> <li>• production</li> </ul> Energy is used when extracting and producing these fuels. The greenhouse gases, $\text{CO}_2$ and $\text{H}_2\text{O}$ , are released in this process. Greenhouse gases are also emitted when the fuels are combusted, so use of petrodiesel has significant environmental effects	Although the production process may result in the generation of greenhouse gases, biodiesel is closer to being carbon neutral because $\text{CO}_2$ and $\text{H}_2\text{O}$ , released on combustion, are converted by photosynthesis into more plant matter

# KEY KNOWLEDGE

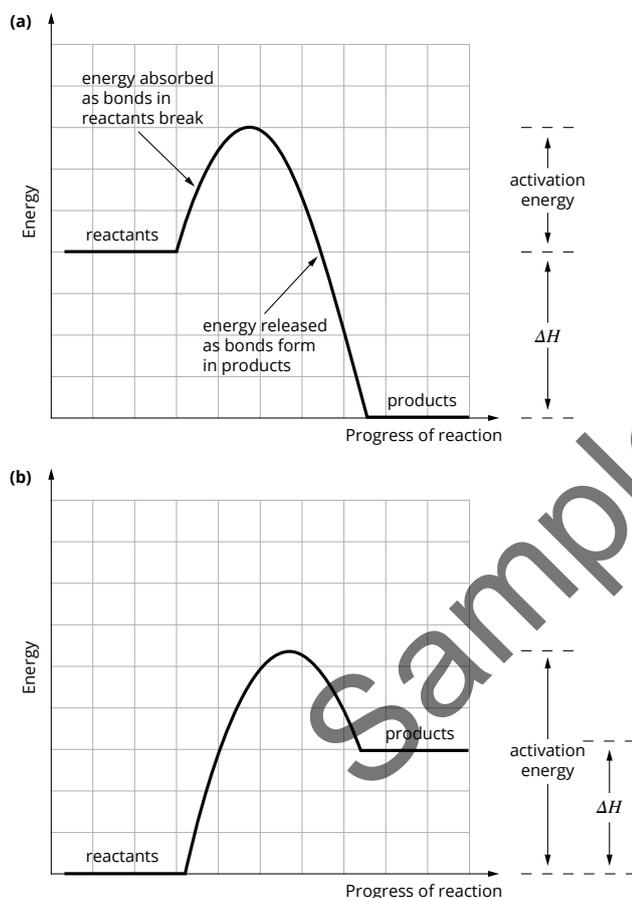
## Exothermic and endothermic reactions

Depending on the enthalpy change that occurs, a reaction is described as **exothermic** or **endothermic** (Table 3.1.4).

Table 3.1.4 Comparison of exothermic and endothermic reactions	
Exothermic reaction	Endothermic reaction
More energy is released than absorbed (Figure 3.1.5a)	More energy is absorbed than released (Figure 3.1.5b)
$\Delta H$ is negative	$\Delta H$ is positive



**Figure 3.1.4** Energy changes in the breaking and forming of bonds in the reaction between methane and oxygen.



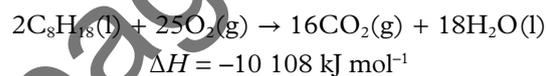
**Figure 3.1.5** Energy profiles of (a) exothermic and (b) endothermic reactions.

During a chemical reaction the bonds of the reactant particles absorb energy and break (Figure 3.1.4). The new bonds of the product particles are then formed, releasing energy. The energy needed for a reaction to occur is called the **activation energy** (Figure 3.1.5).

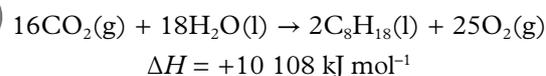
The combustion of fuels is an exothermic reaction, releasing a substantial quantity of energy.

## Thermochemical equations

**Thermochemical equations** are chemical equations that include a  $\Delta H$  value, showing the energy released or absorbed if the moles of reactants shown in the equation react completely. For example, when two moles of octane ( $C_8H_{18}$ ) are burnt, 10 108 kJ of energy is released.



If one mole of octane is burnt, only 5054 kJ of energy is released. When the equation is reversed, the sign of the  $\Delta H$  is also reversed:



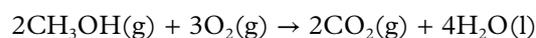
For thermochemical equations, it is important to understand that:

- when an equation is reversed, the  $\Delta H$  for the reversed reaction has the same magnitude but opposite sign from the original equation
- when the coefficients in an equation are doubled, the  $\Delta H$  for the new equation will be doubled; similarly, if the coefficients in an equation are halved, the  $\Delta H$  for the new equation will be halved
- because a change of state involves a change in enthalpy, the states of the reactants and products are important.

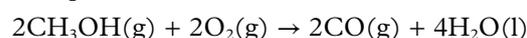
## Complete and incomplete combustion

When a hydrocarbon fuel undergoes complete combustion in excess oxygen,  $CO_2$  and  $H_2O$  are produced. If the oxygen supply is limited, CO or C can be produced instead of  $CO_2$ . Carbon monoxide is also produced when methanol and ethanol burn in limited oxygen.

Complete combustion of methanol:



Incomplete combustion of methanol:



# KEY KNOWLEDGE

## SPECIFIC HEAT CAPACITY

The **specific heat capacity** of a substance is the amount of energy needed to raise the temperature of one gram of the substance by 1°C.

The specific heat capacity of water is 4.18 J g<sup>-1</sup> °C<sup>-1</sup>. Different substances have different heat capacities; heat capacity is a measure of how effectively a substance stores energy. To calculate the energy change that occurs when a mass of a compound undergoes a change in temperature, use the following formula:

$$\text{energy (J)} = \text{specific heat capacity (J g}^{-1} \text{ °C}^{-1}) \times m \text{ (g)} \times \Delta T \text{ (°C)}$$

## Gases

A property of gases that can be measured is **pressure**, symbol  $P$ . Pressure is defined as the force exerted on a unit area. A number of different units are used to measure pressure (Table 3.1.5).

atm	mmHg	kPa	bar
1.00	760	101.3	1.013

Alternatively, this can be expressed as:

$$1 \text{ bar} = 100 \text{ kPa} = 0.987 \text{ atm} = 750 \text{ mmHg}$$

A number of units are commonly used to measure gas **volume**, symbol  $V$  (Table 3.1.6).

mL	cm <sup>3</sup>	L	dm <sup>3</sup>	m <sup>3</sup>
1.0 × 10 <sup>3</sup>	1.0 × 10 <sup>3</sup>	1.0	1.0	1 × 10 <sup>-3</sup>

When used in calculations, temperatures need to be measured using the **kelvin** scale, rather than the Celsius scale. A temperature in degrees Celsius ( $t$ ) can be converted to kelvin ( $T$ ) using the formula  $T = t + 273$  (Table 3.1.7).

$t$ (°C)	$T$ (K)
-273	0
0	273
100	373

## UNIVERSAL GAS EQUATION

The **universal gas equation** is the relationship between the pressure, volume, amount and temperature of a gas:

$$PV = nRT$$

The value of  $R$ , the **universal gas constant**, depends on the units used for pressure, volume and temperature:

$$R = 8.31 \text{ J K}^{-1} \text{ mol}^{-1} \text{ when}$$

- $P$  is the pressure in kPa and  $V$  is the volume in L or dm<sup>3</sup> or
- $P$  is the pressure in Pa and  $V$  is the volume in m<sup>3</sup>.

The temperature,  $T$ , is always measured in kelvin.

The amount, in mol, of a gas at any conditions of volume, pressure and temperature can be calculated by rearranging the equation as:

$$n = \frac{PV}{RT}$$

## Molar volume

The **molar volume** ( $V_m$ ) of a gas is the volume occupied by one mole of the gas. This is almost the same for different gases at the same temperature and pressure. Commonly, two sets of conditions are used to give a standard value for molar volume (Table 3.1.8). Note that standard pressure is defined as 100 kPa, which is called a bar.

Standard condition	$V_m$ (L)	$T$ (°C)	$P$ (kPa)
SLC (standard laboratory conditions)	24.8	25	100
STP (standard temperature and pressure)	22.7	0	100

## Stoichiometry involving reactions of fuels

Formulas	Description and unit
$n = \frac{m}{M}$	$n$ Amount in moles (mol) $m$ Mass in grams (g) $M$ Molar mass in grams per mole (g mol <sup>-1</sup> )
$n = cV$ (for solutions)	$N_A$ Avogadro's number = 6.023 × 10 <sup>23</sup> particles mol <sup>-1</sup>
$n = \frac{PV}{RT}$ (for gases)	$N$ Number of particles
$n = \frac{V}{V_m}$ (for gases)	$c$ Concentration in moles per litre (mol L <sup>-1</sup> ) or molar (M)
$n = \frac{N}{N_A}$	$V$ Volume of gas in litres (L) $P$ Pressure in kilopascals (kPa) $T$ Temperature in kelvin (K) $R$ General gas constant = 8.31 J K <sup>-1</sup> mol <sup>-1</sup> $V_m$ Molar volume of gas in litres (L mol <sup>-1</sup> )

# KEY KNOWLEDGE

## USING STOICHIOMETRY

Example: Determine the volume of CO<sub>2</sub> gas produced at SLC when 4.60 g of CH<sub>3</sub>CH<sub>2</sub>OH reacts with excess oxygen gas.

Thinking	Working
1. Write a balanced equation.	$\text{CH}_3\text{CH}_2\text{OH}(\text{g}) + 3\text{O}_2(\text{g}) \rightarrow 2\text{CO}_2(\text{g}) + 3\text{H}_2\text{O}(\text{l})$
2. Determine the number of moles of the 'known substance' using $n = \frac{m}{M}$ .	$n(\text{CH}_3\text{CH}_2\text{OH}) = \frac{4.60}{46.0}$ $= 0.100 \text{ mol}$
3. Use the mole ratio from the balanced chemical equation to calculate the amount, in mol, of the unknown substance: $\frac{n(\text{unknown substance})}{n(\text{known substance})} = \frac{\text{coefficient (unknown substance)}}{\text{coefficient (known substance)}}$	$\frac{n(\text{CO}_2)}{n(\text{CH}_3\text{CH}_2\text{OH})} = \frac{2}{1}$ $n(\text{CO}_2) = \frac{2}{1} \times n(\text{CH}_3\text{CH}_2\text{OH})$ $= \frac{2}{1} \times 0.100$ $= 0.200 \text{ mol}$
4. Calculate the quantity required for the 'unknown substance'.	$n(\text{CO}_2) = \frac{V(\text{CO}_2)}{V_m}$ $V(\text{CO}_2) = n(\text{CO}_2) \times V_m$ $= 0.2000 \times 24.8$ $= 4.96 \text{ L}$

If the reactants and products are in the gaseous state, stoichiometric calculations do not always require the calculation of the number of moles. The same number of moles of different gases occupies the same volume at constant temperature and pressure, so the **mole ratio** in a balanced chemical equation can also be used as a volume ratio.

- Each O atom has gained these electrons and has been reduced. The half-equation is:



Magnesium is called the **reducing agent** (reductant) and oxygen is called the **oxidising agent** (oxidant). During the reaction some of the chemical energy in the reactants, magnesium solid and oxygen gas, is converted into heat energy and light energy, as the solid magnesium oxide product forms.

Some of the concepts involved in redox reactions are shown in Figure 3.1.6.

## Galvanic cells as a source of energy

### REDOX REACTIONS

Redox (reduction-oxidation) reactions involve a transfer of electrons. The term OIL RIG is one way to remember the movement of electrons in the processes of oxidation and reduction:

- in **oxidation** electrons are lost: Oxidation is Loss (OIL)
- in **reduction** electrons are gained: Reduction is Gain (RIG).

Consider the burning of magnesium in oxygen:  $2\text{Mg}(\text{s}) + \text{O}_2(\text{g}) \rightarrow 2\text{MgO}(\text{s})$ . The electronic configuration of each Mg atom is 2,8,2, which becomes 2,8 as the Mg<sup>2+</sup> ion is formed. The configuration of each O atom changes from 2,6 to 2,8 as the O<sup>2-</sup> ion is formed.

- Each Mg atom has lost electrons and been oxidised.

This can be represented as a half-equation:

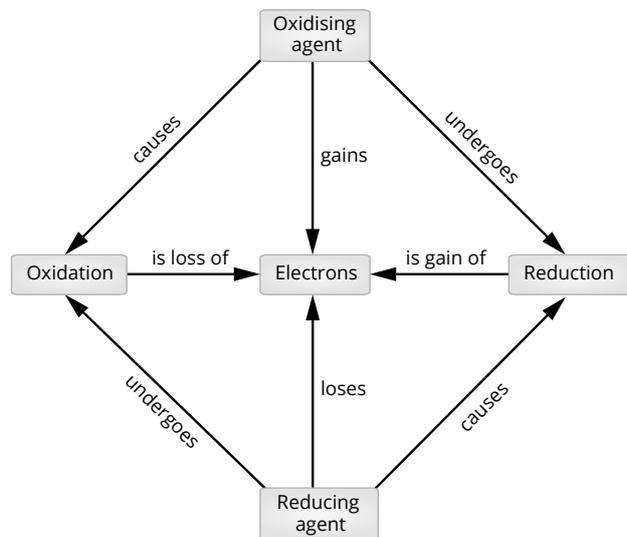


Figure 3.1.6 Concepts associated with redox reactions.

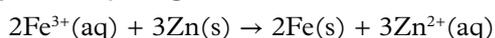
# KEY KNOWLEDGE

## Balancing redox equations

Half-equations can be written for oxidation and reduction reactions. The number of atoms of each element and the charge on both sides of the equation must be balanced.

For example, consider the reaction between  $\text{Fe}^{3+}(\text{aq})$  and  $\text{Zn}(\text{s})$ . Zn is the reducing agent (reductant) and  $\text{Fe}^{3+}$  is the oxidising agent (oxidant).

- Reduction:  $\text{Fe}^{3+}(\text{aq}) + 3\text{e}^- \rightarrow \text{Fe}(\text{s})$
- Oxidation:  $\text{Zn}(\text{s}) \rightarrow \text{Zn}^{2+}(\text{aq}) + 2\text{e}^-$
- Overall equation (if necessary, multiply half-equations by integers and add so electrons cancel):



The  $\text{Zn}^{2+}/\text{Zn}$  and  $\text{Fe}^{3+}/\text{Fe}$  pairs in the reaction above are called **conjugate redox pairs**. A conjugate redox pair is made up of an oxidising agent and the reducing agent that is formed when it gains electrons.

Half-equations are balanced by following the rules in Table 3.1.10.

## Oxidation numbers

Oxidation is defined as occurring when there is an increase in **oxidation number** and reduction occurs when there is a decrease in oxidation number.

Oxidation numbers:

- are used to decide if a reaction is a redox reaction
- have no physical meaning; they are defined to enable reactions involving molecules as well as those involving ions to be described as redox reactions
- are determined using the rules in Table 3.1.11.

## GALVANIC CELLS

**Galvanic cells** are electrochemical cells that convert chemical energy to electrical energy. They involve **spontaneous** exothermic redox reactions. The two half-reactions occur in two separate **half-cells**. This prevents direct contact between the oxidising agent and reducing agent, so electrons can only be transferred by travelling through an external circuit, between the negative and positive electrodes. The flow of electrons provides electrical energy.

Table 3.1.10 Rules for balancing redox half-equations in acidic solutions

Rule	Example: reduction of $\text{Cr}_2\text{O}_7^{2-}(\text{aq})$ to $\text{Cr}^{3+}(\text{aq})$
1. Balance all elements except hydrogen and oxygen.	$\text{Cr}_2\text{O}_7^{2-} \rightarrow 2\text{Cr}^{3+}$
2. Balance oxygen atoms using $\text{H}_2\text{O}$ molecules.	$\text{Cr}_2\text{O}_7^{2-} \rightarrow 2\text{Cr}^{3+} + 7\text{H}_2\text{O}$
3. Balance hydrogen atoms using $\text{H}^+$ ions.	$\text{Cr}_2\text{O}_7^{2-} + 14\text{H}^+ \rightarrow 2\text{Cr}^{3+}(\text{aq}) + 7\text{H}_2\text{O}$
4. Balance charge using electrons, and add states.	$\text{Cr}_2\text{O}_7^{2-}(\text{aq}) + 14\text{H}^+(\text{aq}) + 6\text{e}^- \rightarrow 2\text{Cr}^{3+}(\text{aq}) + 7\text{H}_2\text{O}(\text{l})$

Table 3.1.11 Rules for determining oxidation numbers

Species	Oxidation number	Examples
Elements	0	$\text{Cl}_2$ , Mg, C, $\text{O}_2$ , $\text{H}_2$
Ions	Charge on the ion.	$\text{Na}^+ = +1$ ; $\text{Cl}^- = -1$
Oxygen in compounds	Defined as $-2$ in its compounds. $\text{H}_2\text{O}_2$ is an exception, where it is $-1$ .	$\text{O} = -2$ in $\text{H}_2\text{O}$ , $\text{CO}_2$ , $\text{Na}_2\text{O}$
Hydrogen in compounds	Defined as $+1$ in compounds with non-metals; exception is $-1$ in compounds with metals.	$\text{H} = +1$ in $\text{HCl}$ , $\text{H}_2\text{S}$ , $\text{CH}_4$ $\text{H} = -1$ in $\text{NaH}$
Molecular ions and molecules	The sum of the oxidation numbers equals the charge on the molecular ion (zero in the case of neutral molecules). The most electronegative element has the negative oxidation number.	For $\text{MnO}_4^-$ oxygen is defined as $-2$ . Because there are 4 oxygen atoms, in order to have an overall charge on the $\text{MnO}_4^-$ ion of $-1$ , Mn must have an oxidation number of $+7$ . Let oxidation number of Mn be $x$ : $x + 4(-2) = -1$ So $x = +7$

# KEY KNOWLEDGE

## The Daniell cell

The general features of galvanic cells are illustrated by the Daniell cell shown below (Figure 3.1.7).

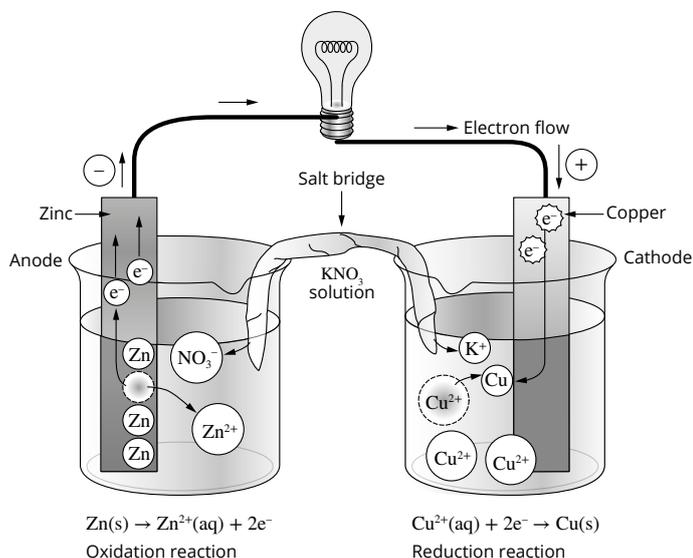
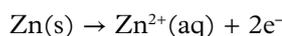
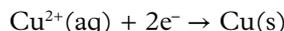


Figure 3.1.7 General features of a galvanic cell.

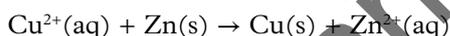
The zinc metal electrode is oxidised to zinc ions:



The electrons produced move through the wire (the external circuit) toward the positive electrode, where they reduce copper ions:



The number of electrons produced is equal to the number consumed at the other half-cell. The overall equation is the sum of the two half-equations:



Zn is oxidised and acts as the reducing agent.  $\text{Cu}^{2+}$  is reduced and acts as the oxidising agent.

The **salt bridge** (often a piece of filter paper soaked in a solution of a soluble ionic compound) balances the charges formed and consumed in each half-cell. At the negative electrode, the positive  $\text{Zn}^{2+}$  ions being formed are balanced by negative ions moving from the salt bridge. At the positive electrode, the  $\text{Cu}^{2+}$  ions being consumed are balanced by positive ions from the salt bridge.

By definition, the electrode where oxidation occurs is the **anode** and the electrode where reduction occurs is the **cathode**. In galvanic cells, the anode is negative and the cathode is positive. (You can remember oxidation occurs at the anode because oxidation and anode start with vowels; both reduction and cathode start with consonants.)

Each half-cell contains a conjugate redox pair. In the cell in Figure 3.1.7 the pairs can be written as  $\text{Zn}^{2+}(\text{aq})/\text{Zn(s)}$  and  $\text{Cu}^{2+}(\text{aq})/\text{Cu(s)}$ . In the salt bridge, cations move towards the cathode and anions move towards the anode.

## THE ELECTROCHEMICAL SERIES

The **electrochemical series** (Appendix 1) shows the relative strengths of oxidising agents and reducing agents. Half-reactions are written as reduction reactions, with the strongest oxidising agent at the top of the table on the left-hand side and the strongest reducing agent at the bottom of the table on the right-hand side.

The **standard hydrogen half-cell** is used as a reference (Figure 3.1.8) and given an  $E^{\circ}$  value of 0 V. This half-cell operates at the standard conditions of 1 bar, 1 M and  $25^{\circ}\text{C}$ . The half-equation for the cell is:

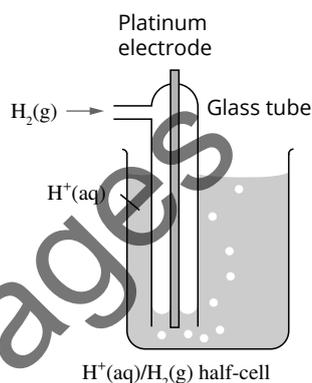
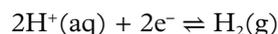


Figure 3.1.8 The standard hydrogen half-cell.

The electrochemical series is constructed by measuring the voltages of different half-cells when they are connected to the standard hydrogen electrode. Equations for half-reactions that occur in half-cells that are positive with respect to the standard hydrogen electrode are above the  $\text{H}^{+}(\text{aq})/\text{H}_2(\text{g})$  equation in the series and those that are negative are below it.

The cell voltage for any combination of two half-cells can be calculated using the  $E^{\circ}$  values from the electrochemical series.

$$E_{\text{cell}}^{\circ} = E^{\circ}(\text{of half-equation containing oxidising agent}) - E^{\circ}(\text{of half-equation containing reducing agent})$$

## Using the electrochemical series

A spontaneous reaction occurs when the strongest oxidising agent and strongest reducing agent react, which means the  $E^{\circ}$  of the oxidising agent is more positive (higher in the table) than the  $E^{\circ}$  of the reducing agent. If there are several possible oxidising agents and reducing agents present, the pair that is most likely to react will be furthest apart in the series.

## KEY KNOWLEDGE

**Example:** A cell is made from  $\text{Ag}^+(\text{aq})/\text{Ag}(\text{s})$  and  $\text{Zn}^{2+}(\text{aq})/\text{Zn}(\text{s})$  half-cells. Use the electrochemical series to predict the electrode reactions, write the overall cell equation and determine the maximum cell voltage under standard conditions.

Thinking	Working
Write the relevant half-equations.	$\text{Ag}^+ + \text{e}^- \rightarrow \text{Ag}$ $\text{Zn}^{2+} + 2\text{e}^- \rightarrow \text{Zn}$
Of the chemicals in the cell, the chemical highest on the left of the electrochemical series (the strongest oxidising agent) will react with the chemical lowest on the right of the electrochemical series (the strongest reducing agent). Write the anode reaction and the cathode reaction.	$\text{Ag}^+$ is the strongest oxidising agent. $\text{Zn}$ is the strongest reducing agent. So $\text{Ag}^+$ and $\text{Zn}$ will react. Anode reaction: $\text{Zn} \rightarrow \text{Zn}^{2+} + 2\text{e}^-$ Cathode reaction: $\text{Ag}^+ + \text{e}^- \rightarrow \text{Ag}$
Write the overall cell equation, including states.	$2\text{Ag}^+(\text{aq}) + \text{Zn}(\text{s}) \rightarrow 2\text{Ag}(\text{s}) + \text{Zn}^{2+}(\text{aq})$
Calculate the cell voltage.	$E^\circ_{\text{cell}} = E^\circ \text{ at cathode} - E^\circ \text{ at anode}$ $= +0.80 - (-0.76)$ $= 1.56 \text{ V}$

### Limitations of predictions using the electrochemical series

There are two significant limitations with the use of the electrochemical series.

- The electrochemical series applies to reactions under standard conditions. For non-standard conditions, the series cannot be used reliably to predict reactions.
- It predicts the likelihood of a reaction, but not the rate of reaction. A reaction may not be observed when chemicals are directly mixed together if the reaction occurs slowly.

### Primary and secondary cells

Galvanic cells can be classified as:

- primary cells**, which cannot be recharged because the products of the cell reaction during electricity production do not all remain in contact with the electrodes
- secondary cells**, which can be recharged.

### Rechargeable batteries (secondary cells)

In secondary cells, the products of the cell reaction remain in contact with the electrodes, so that recharging is possible. When a cell is recharged, electrical energy from a battery charger is converted to chemical energy

by reversing the normal discharge reaction of the cell. The products in the cell become reactants again.

The polarity of the electrodes does not change for the discharge or recharge reactions, but the process at each electrode is reversed. The behaviour of a secondary cell is summarised in Table 3.1.12.

**Battery life** is a measure of the number of charge/discharge cycles before a battery has to be discarded. Battery life decreases over time. Factors affecting battery life include:

- side reactions that reduce the amount of active material in a battery
- not all the discharge products remain in contact with the electrodes
- some of the discharge products become coarse and resist current flow
- impurities may be present in electrodes or half-cell chemicals
- contact of the electrolyte with the electrodes can decrease.

The rate of deterioration of a battery increases as temperature increases. During the cell reaction, energy is released and some is converted into heat energy, raising the temperature. This increases the rate of side reactions and reduces battery life.

Table 3.1.12 Operation of secondary cells while discharging and recharging

	During discharge	During recharge
Type of cell	Acts as a galvanic cell	Acts as an electrolytic cell (see electrolytic cells later)
Nature of reaction	Spontaneous reaction	Non-spontaneous reaction
Energy transformation	Chemical to electrical	Electrical to chemical
At negative electrode	Electrons spontaneously flow from this electrode Anode—oxidation occurs	Electrons are pumped onto this electrode Cathode—reduction occurs
At positive electrode	Electrons spontaneously flow to this electrode Cathode—reduction occurs	Electrons are withdrawn from this electrode Anode—oxidation occurs

# KEY KNOWLEDGE

## FUEL CELLS

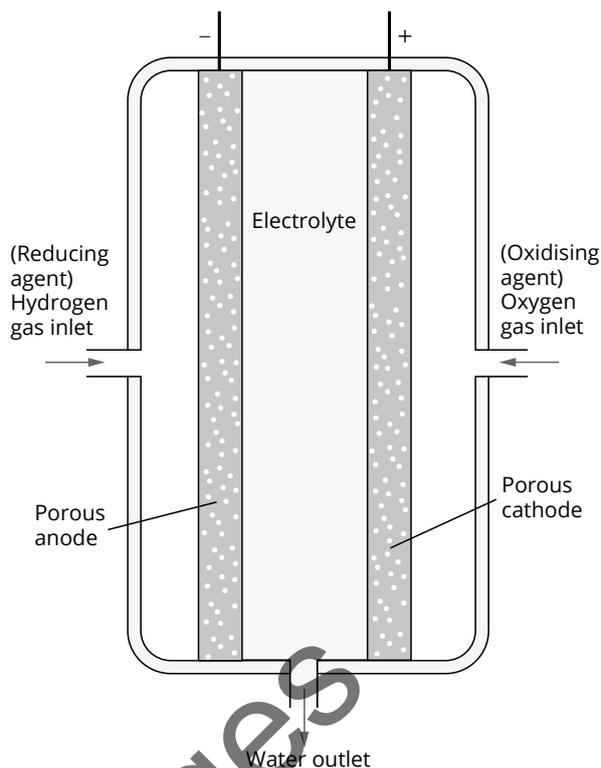
In **fuel cells** (Figure 3.1.9), a spontaneous reaction occurs that converts chemical energy to electrical energy for as long as reactants are continuously provided. Unlike the cells described above, chemical energy is not stored within the cell. Fuel cells using hydrogen gas as a fuel can use either an alkaline or acid electrolyte, and produce about 1 V. Water is the only chemical product and heat energy as well as electrical energy is released.

The nature of the electrodes is crucial to the operation of the fuel cell. They must:

- be conductors
- have catalytic properties to speed up the rate of the electrode reactions
- be porous so that they keep the gaseous fuel and oxidising agent apart, but allow each to be in contact with the electrolyte.

### Comparison of use of fuel cells and combustion of fuels to supply energy

Energy generation from fuel cells, gas-fired power stations and petrol-driven vehicles are compared in Table 3.1.13.



For a cell using an acidic electrolyte:  
 Anode reaction:  $\text{H}_2(\text{g}) \rightarrow 2\text{H}^+(\text{aq}) + 2\text{e}^-$   
 Cathode reaction:  $\text{O}_2(\text{g}) + 4\text{H}^+(\text{aq}) + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}(\text{l})$   
 Overall reaction:  $2\text{H}_2(\text{g}) + \text{O}_2(\text{g}) \rightarrow 2\text{H}_2\text{O}(\text{l})$

Figure 3.1.9 A simple hydrogen–oxygen fuel cell.

Property	Fuel cells	Gas-fired power stations	Petrol-driven vehicles
Efficiency	Up to 80% efficient	30–40% efficient	25% efficient
Energy transformations	Chemical energy is converted directly to electrical energy	Large energy losses due to the multiple energy transformations involved: chemical → thermal → mechanical → electrical	Chemical energy is first converted to thermal energy which is then transformed to mechanical energy: chemical → thermal → mechanical
Cost	Slow rate of reaction, requiring expensive catalytic electrode materials so that adequate currents can be produced	Gas is cheap to mine and currently produces electricity relatively inexpensively; available in limited amounts	The cost and supply of petrol is dependent on world politics; available in limited supplies
Fuel supply and production of greenhouse gases	Need a constant fuel supply. Water and heat are the by-products. At present, hydrogen is produced using hydrocarbon fuels, with the release of $\text{CO}_2$ and water vapour. A cleaner process would be to use solar or wind power to generate electricity to electrolyse water and produce hydrogen. Storage of hydrogen is difficult (Table 3.1.15)	Need a constant fuel supply. The greenhouse gases, $\text{CO}_2$ and water vapour, are released into the atmosphere when natural gas is burnt to produce electricity	Need a constant fuel supply. Greenhouse gases, $\text{CO}_2$ and water vapour, are released into the atmosphere when petrol is burnt to produce energy
Applications	Able to be used near population centres as a power station or in vehicles; modular nature makes it easy to increase energy production as demand requires; this technology is currently being developed and costs are falling	Large scale electricity generation; best located away from population centres, necessitating the use of long power lines to carry electricity	Used to power vehicles

# KEY KNOWLEDGE

## Hydrogen as a fuel

H<sub>2</sub>/O<sub>2</sub> fuel cells offer the prospect of a clean, efficient energy resource. There are difficulties associated with the production (Table 3.1.14), storage (Table 3.1.15) and safety (Table 3.1.16) of hydrogen fuel.

Alternative storage methods under development include:

- adsorption onto the surface of materials, including metal hydrides
- adsorption into the lattice structure of some materials

- reversible reactions which consume hydrogen under some conditions and release it when conditions are changed.

Strict codes and standards are required, but it is expected that in the future hydrogen will be able to be used with similar safety to petrol.

## Comparison of fuel cells with other galvanic cells

Similarities and differences between fuel cells and other galvanic cells (primary and secondary) are shown in Table 3.1.17.

Renewable energy sources	Non-renewable energy sources
<ul style="list-style-type: none"> <li>• Collection of methane gas from landfill sites for use in steam reforming to produce H<sub>2</sub> gas</li> <li>• Splitting water using electricity from solar cells and wind turbines</li> </ul>	<ul style="list-style-type: none"> <li>• Fossil fuels are used in a steam reforming process to produce H<sub>2</sub> gas:  <math display="block">\text{CH}_4(\text{g}) + \text{H}_2\text{O}(\text{g}) \rightleftharpoons \text{CO}(\text{g}) + 3\text{H}_2(\text{g})</math> </li> <li>• The carbon monoxide generated can be used to generate further hydrogen:  <math display="block">\text{CO}(\text{g}) + \text{H}_2\text{O}(\text{g}) \rightleftharpoons \text{CO}_2(\text{g}) + \text{H}_2(\text{g})</math> </li> </ul>

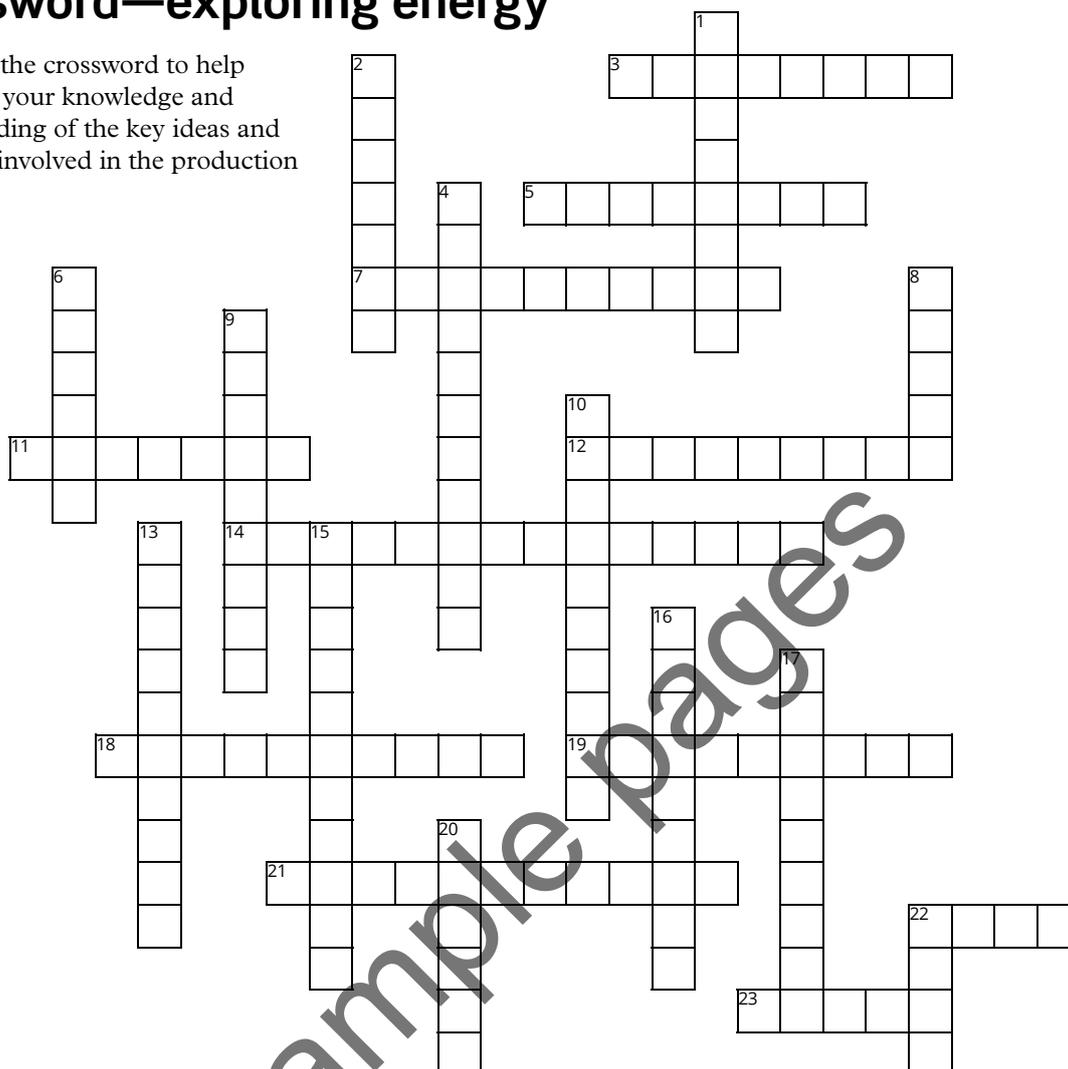
Method of storage	Associated disadvantages
Liquid hydrogen	Tanks must be well insulated and very large, taking up significant space in the car boot
Compressed hydrogen	Very large high pressure tanks are required

Property	Comment
Highly combustible	Burns readily and forms highly explosive gas mixtures with air
Low density	Rises rapidly and quickly disperses, often without ignition
Odourless and colourless	Gas leaks are hard to detect

	Fuel cells	Other galvanic cells
Function	<ul style="list-style-type: none"> <li>• Can be used as a portable energy source or for large scale electricity generation</li> </ul>	<ul style="list-style-type: none"> <li>• Used as a portable energy source</li> </ul>
Energy transformations and efficiencies	<ul style="list-style-type: none"> <li>• Constantly converts chemical energy to electrical energy as reactants are pumped into the cell</li> <li>• High efficiencies</li> </ul>	<ul style="list-style-type: none"> <li>• Stores chemical energy for conversion to electrical energy</li> <li>• High efficiencies</li> </ul>
Design features	<ul style="list-style-type: none"> <li>• Separate anode and cathode compartments; contact between the fuel and oxidising agent is prevented</li> <li>• Electrodes enable contact between fuel (reducing agent) and electrolyte and between oxidising agent and electrolyte</li> <li>• Electrolyte enables movement of ions to balance charge and complete the circuit; cations move towards the cathode and anions towards the anode</li> <li>• Oxidation occurs at the anode</li> <li>• Reduction occurs at the cathode</li> <li>• Anode is negative and cathode is positive</li> </ul>	<ul style="list-style-type: none"> <li>• Separate anode and cathode compartments; contact between the reactants is prevented</li> <li>• Electrolyte (may include salt bridge) enables movement of ions to balance charge and complete the circuit; cations move towards the cathode and anions towards the anode</li> <li>• Oxidation occurs at the anode</li> <li>• Reduction occurs at the cathode</li> <li>• Anode is negative and cathode is positive when producing electricity</li> </ul>
Applications	<ul style="list-style-type: none"> <li>• Power stations, rockets, cars, computers, cameras</li> </ul>	<ul style="list-style-type: none"> <li>• Cars, phones, computers, cameras</li> </ul>

## Crossword—exploring energy

Complete the crossword to help you check your knowledge and understanding of the key ideas and processes involved in the production of energy.



### Across

- 3 A type of natural gas trapped by pressure on the surface of coal. (4, 4)
- 5 Another name for chemical energy or heat content of a substance. (8)
- 7 A reaction that releases energy to the surroundings. (10)
- 11 The electrode where reduction occurs. (7)
- 12 An energy source that can be replaced at an equal or faster rate than it can be consumed. (9)
- 14 Name for a chemical equation that includes the enthalpy change of the reaction. (14)
- 18 A device used to complete a circuit by balancing the ions in each half-cell. (4, 6)
- 19 A type of cell that is rechargeable. (9)
- 21 The property of absorbing moisture from the air. (11)
- 22 Chemical that produces useful amounts of energy when burnt. (4)
- 23 The electrode where oxidation occurs. (5)

### Down

- 1 Electrochemical cells that spontaneously convert chemical to electrical energy. (8)
- 2 A fuel that can be produced from crops or other organic material. (7)
- 4 Chemical reaction that occurs of its own accord. (11)
- 6 A mixture of gases produced by the breakdown of organic matter in the absence of oxygen. (6)
- 8 SI unit for energy. (5)
- 9 A process that involves a loss of electrons. (9)
- 10 A type of gas that is able to absorb and re-radiate heat radiation. (10)
- 13 The name for the energy needed to break the bonds between atoms in the reactants. (10)
- 15 A solution that conducts electricity. (11)
- 16 A measure of a fluid's resistance to flow. (9)
- 17 A process that involves a decrease in oxidation number. (9)
- 20 A type of fuel that that has been produced over a long time by the breakdown of organic material. (6)
- 22 A type of cell that continually converts chemical energy to electrical energy as reactants are supplied to it. (4)

## Combustion of fuels—thermochemical equations and specific heat capacity

Use the terms in the boxes to help you complete this worksheet. Some terms may be used more than once and others not at all.

chemical energy	enthalpy	activation energy	energy source	exothermic
endothermic	$H$	$\Delta H$	$H_{\text{products}} - H_{\text{reactants}}$	negative
positive	heat capacity	joules	$\Delta T$	

- 1 The combustion of fuels releases a significant quantity of heat that can be used as an \_\_\_\_\_  
 \_\_\_\_\_. \_\_\_\_\_ is the energy stored in the  
 bonds between atoms and between molecules arising from attractions and repulsions between subatomic  
 particles. It is called \_\_\_\_\_ and is represented by the symbol, \_\_\_\_\_. All combustion  
 reactions are \_\_\_\_\_ reactions. In such reactions, the enthalpy change, symbol \_\_\_\_\_, has  
 a \_\_\_\_\_ sign.  $\Delta H =$  \_\_\_\_\_
- 2 Energy profile diagrams can be used to represent the energy changes in chemical reactions. Draw and label,  
 using the terms and symbols in the box below, an energy profile diagram for the reaction:

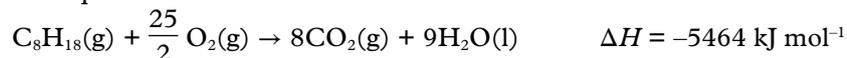


activation energy	energy	$\text{CH}_4(\text{g}) + 2\text{O}_2(\text{g})$	$\text{CO}_2(\text{g}) + 2\text{H}_2\text{O}(\text{l})$
$\Delta H = -890 \text{ kJ mol}^{-1}$	energy absorbed as bonds break	energy released as bonds form	progress of reaction

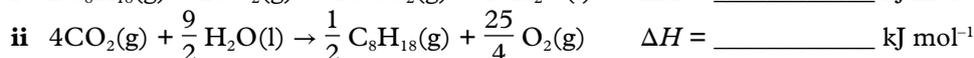
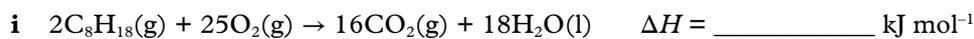
Sample pages

## WORKSHEET 2

- 3 Thermochemical equations are balanced chemical equations that include the  $\Delta H$  for the reaction. Consider the thermochemical equation for octane:



- a Determine the value and sign of the  $\Delta H$  for the following equations:



- b Select the correct alternatives to complete this sentence. The reaction represented by equation **i** is an exothermic/endothermic reaction whereas the reaction represented by equation **ii** is an exothermic/endothermic reaction.

- 4 Butane gas,  $\text{C}_4\text{H}_{10}$ , can be used as a fuel to heat water. If exactly 1.00 L of water is heated from  $20.0^\circ\text{C}$  to  $100.0^\circ\text{C}$ , calculate:

- a the energy absorbed by the water from the combustion of butane  
b the mass of butane consumed to supply the energy in part a.

Use the information provided below.

Specific heat capacity of water	$4.18 \text{ J } ^\circ\text{C}^{-1} \text{ mol}^{-1}$
Heat of combustion of butane	$-2874 \text{ kJ mol}^{-1}$
Molar mass of butane	$58.48 \text{ g mol}^{-1}$
Density of water	$1.00 \text{ g mL}^{-1}$

Thinking	Working
Determine the $\Delta T$ for the experiment.	$\Delta T =$
a The formula to determine the energy released by the fuel is: Energy = specific heat capacity $\times$ mass $\times$ $\Delta T$	Energy =
b Use the heat of combustion of the fuel to calculate the mass of fuel consumed to produce the energy calculated in part a.	

## Gases—the universal gas equation

When fossil fuels and biofuels are burnt completely, the products are carbon dioxide and water vapour. Both products are greenhouse gases. One factor to consider when comparing fuels is the volume of greenhouse gases produced per MJ of energy. This worksheet revises concepts involving gases and greenhouse gas emissions.

### GAS PRESSURE

- 1 The following measurements of pressures are equivalent.

$$1.00 \text{ atm} = 760 \text{ mmHg} = 101.3 \text{ kPa} = 1.013 \text{ bar}$$

$$100 \text{ kPa} = 1.00 \text{ bar}$$

Convert the pressures below to the alternative units in each case. An example is shown.

1.30 atm to mmHg $1.00 \text{ atm} = 760 \text{ mmHg}$ so $1.30 \text{ atm} = 1.30 \times 760$ $= 988 \text{ mmHg}$	145 kPa to bar	3.50 bar to atm
480 mmHg to kPa	1.5 atm to kPa	150 mmHg to bar

### VOLUME

- 2 The following measurements of volume are equivalent.

$$1.0 \times 10^3 \text{ mL} = 1.0 \times 10^3 \text{ cm}^3 = 1.0 \text{ L} = 1.0 \text{ dm}^3 = 1.0 \times 10^{-3} \text{ m}^3$$

Convert the volumes given below to the alternative units in each case. An example is shown.

1.3 dm <sup>3</sup> to mL $1 \text{ dm}^3 = 1000 \text{ mL}$ So $1.3 \text{ dm}^3 = 1.3 \times 1000$ $= 1.3 \times 10^3 \text{ mL}$	300 mL to L	4.3 L to m <sup>3</sup>
2.8 L to mL	0.85 m <sup>3</sup> to L	480 cm <sup>3</sup> to dm <sup>3</sup>

# WORKSHEET 3

## UNIVERSAL GAS EQUATION

- 3 The universal gas equation,  $PV = nRT$ , combines different scientists' experiments on gases into a single equation. The value of the universal gas constant,  $R$ , in the equation depends on the units used for pressure, temperature and volume.

If the value of  $R = 8.31 \text{ J K}^{-1} \text{ mol}^{-1}$  in the universal gas equation, state the units used for pressure, volume and temperature below:

Pressure in \_\_\_\_\_

Volume in \_\_\_\_\_

Temperature in \_\_\_\_\_

- 4 Methane is the major component of natural gas. It is used for heating and cooking in homes. At  $25^\circ\text{C}$  and  $101.3 \text{ kPa}$  the molar enthalpy of combustion of methane is  $-889 \text{ kJ mol}^{-1}$ .

a Write a balanced thermochemical equation for the reaction.

\_\_\_\_\_

- b Use the universal gas equation to calculate the volume of the greenhouse gas,  $\text{CO}_2$  (measured at  $25^\circ\text{C}$  and  $101.3 \text{ kPa}$ ), that would be produced to supply  $1.00 \text{ MJ}$  of energy to a household from the combustion of methane.

\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

Sample pages

# PRACTICAL ACTIVITY 1

## The molar volume of hydrogen

### MATERIALS

- 20 mL 2 M HCl
- 8 cm length of magnesium ribbon that has a mass of no more than 0.08 g
- 100 mL gas syringe
- set of apparatus to clamp the syringe to a retort stand
- 18 mm test-tube
- one-hole stopper to fit test-tube
- retort stand, bosshead and clamp to support test-tube
- 4 cm length of glass tubing to fit the one-hole stopper
- approx. 50 cm length of rubber tubing to connect the gas syringe to the glass tubing through the one-hole stopper
- 100 mL measuring cylinder
- electronic balance
- emery paper or steel wool for cleaning the magnesium ribbon
- safety glasses

As directed by your teacher, complete the risk assessment and management table by referring to the hazard labels on the reagent bottles or material safety data sheets (MSDS) or your teacher's risk assessment for the activity.



### DURATION

40 minutes

### INTRODUCTION

Gases are produced when fuels burn. An understanding of the behaviour of gases and gas laws allows us to calculate the volume of gaseous products and compare volumes of greenhouse gases released by different fuels.

In this experiment, you will determine the number of mole of hydrogen gas produced in a reaction. From measurements of the gas volume and pressure, the molar volume of hydrogen at standard laboratory conditions (SLC) can be calculated.

### PURPOSE

To determine the molar volume of hydrogen gas at SLC, 25°C and 100 kPa.

### PRE-LAB SAFETY INFORMATION

Material used	Hazard	Control
2 M HCl	Toxic by all routes of exposure; lung irritation	Wear eye and skin protection

Please indicate that you have understood the information in the safety table.

Name (print): \_\_\_\_\_

I understand the safety information (signature): \_\_\_\_\_

### PROCEDURE

- 1 Clamp the stoppered test-tube and gas syringe to their respective retort stands and connect the test-tube and syringe using the rubber tubing. Check that the equipment is secure.
- 2 Remove the stopper from the test-tube and carefully pour about 15 mL of 2 M hydrochloric acid into the test-tube down one side, keeping the other side dry.
- 3 Clean and accurately weigh the magnesium ribbon, making sure that it weighs no more than 0.08 g.
- 4 Tilt the test-tube and carefully place the magnesium ribbon on the dry side of the test-tube making sure that the magnesium does not contact the acid. Replace the stopper tightly.
- 5 Carefully withdraw the plunger of the syringe and then release it. If the system has no leaks, the plunger will return to its original position. Once any leaks have been fixed, record in the Results table the initial volume shown on the syringe.
- 6 Tilt or shake the test-tube so that the magnesium contacts the acid. As gas fills the syringe, rotate the plunger gently to prevent it from sticking.
- 7 Once the magnesium has been used up, allow the test-tube to cool. Record the final volume of gas in the syringe when the plunger has completely stopped moving. Calculate and record the increase in the volume of gas in the syringe.
- 8 Record the room temperature and atmospheric pressure.
- 9 From data supplied by your teacher, record the water vapour pressure at room temperature. To allow for the pressure of water vapour in the syringe, subtract the water vapour pressure from atmospheric pressure.

# PRACTICAL ACTIVITY 1

## RESULTS

Record your results in the following table.

Results table	
Mass of magnesium	
Initial volume of syringe	
Final volume of syringe	
Volume of gas	
Temperature	
Atmospheric pressure $P_{\text{atm}}$	
Water vapour pressure at measured temperature $P(\text{H}_2\text{O})$	
Pressure of $\text{H}_2$ gas = $P_{\text{atm}} - P_{\text{vapour}}$	

## DISCUSSION

1 Write a balanced equation for the reaction between magnesium and hydrochloric acid.

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2 Calculate the amount, in mole, of magnesium reacted.

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3 Using the amount of magnesium reacted, calculate the amount, in mole, of  $\text{H}_2$  gas produced.

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4 This amount of  $\text{H}_2$  gas occupied the measured volume at the experimental pressure and temperature. Calculate the volume occupied by one mole (molar volume) at these experimental conditions.

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## PRACTICAL ACTIVITY 1 continued

- 5 Convert your answer to question 4 to molar volume at standard laboratory conditions (SLC), 25°C and 100 kPa.

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- 6 How close is your result for the molar volume of hydrogen to the accepted molar volume of an ideal gas? Suggest two sources of error for the molar volume you have calculated.

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- 7 Explain why the molar volume of any gas at specified conditions, such as SLC, is the same.

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- 8 Using your measurements for the volume, temperature and pressure of the hydrogen gas sample and the universal gas equation, calculate the mole of H<sub>2</sub> gas produced. Compare your answer with your answer to question 3; how well do the two answers agree?

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### CONCLUSION

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# PRACTICAL ACTIVITY 2

## Energy from different fuels

### INTRODUCTION

Alcohols are useful fuels. Both methanol and ethanol have been used as substitutes for petrol. In this experiment, the energy released by burning alcohol is used to heat water. Knowing that 4.18 J of energy is required to heat 1 g (1 mL) of water by 1°C, the quantity of energy released by combustion of the alcohol can be calculated.

4.18 J g<sup>-1</sup> °C<sup>-1</sup> is the specific heat capacity of water.

### PURPOSE

To measure and compare the thermal energy released during the combustion of various alcohols.

### USE OF ELECTRONIC DATA EQUIPMENT

- 1 A temperature probe can be used instead of a thermometer. Collect data for 10 minutes.
- 2 Data collection should begin about 45 seconds before the burner is lit.
- 3 Extinguish the burner once the temperature rises by about 20°C or after 7 minutes of data collection, whichever occurs first.
- 4 Display each set of data as a graph of temperature versus time.

### PRE-LAB SAFETY INFORMATION

Material used	Hazard	Control
Ethanol	Toxic and highly flammable	Avoid skin contact. Do not breathe vapour
Propan-1-ol	Toxic and highly flammable	Avoid skin contact. Do not breathe vapour
Butan-1-ol	Toxic and highly flammable	Avoid skin contact. Do not breathe vapour
Filling spirit burners	Flammable liquids	Do not fill near open flame

Please indicate that you have understood the information in the safety table.

Name (print): \_\_\_\_\_

I understand the safety information (signature): \_\_\_\_\_

### PROCEDURE

- 1 Using a retort stand and clamp, set up the steel can 3–4 cm above the wick of the spirit burner.
- 2 Pour 200 mL of water into the can and record its temperature.
- 3 Weigh the spirit burner and alcohol. Record the mass and the name of the alcohol.
- 4 Light the burner and heat the water. Stir continuously.
- 5 Once the water temperature has increased by about 20°C, extinguish the burner and record the highest temperature reached by the water.
- 6 Record the mass of the burner and hence deduce the mass of alcohol consumed. Record this mass.
- 7 Repeat the experiment using another alcohol.

### NOTE TO TEACHERS

This practical activity could be used either as a class practical activity or as an assessment task for:

- Unit 3 Area of Study 1, Outcome 1: a report of a laboratory investigation, or
- Unit 4 Area of Study 3, Outcome 3: one of the experiments for collecting primary data for the Practical Investigation, if *Energy* is chosen as the area to investigate.

If used as an assessment task, teachers should produce their own questions, in addition to those given, to assess this outcome according to the VCAA guidelines.

### MATERIALS

- spirit burner containing an alcohol, ethanol (CH<sub>3</sub>CH<sub>2</sub>OH), propan-1-ol (CH<sub>3</sub>CH<sub>2</sub>CH<sub>2</sub>OH) or butan-1-ol, CH<sub>3</sub>CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>OH
- 250 mL measuring cylinder
- steel can
- thermometer, –10 to 110°C
- retort stand and clamp
- bench mat
- electronic balance
- safety glasses

As directed by your teacher, complete the risk assessment and management table by referring to the hazard labels on the reagent bottles or material safety data sheets (MSDS) or your teacher's risk assessment for the activity.



### DURATION

30 minutes

## PRACTICAL ACTIVITY 2 continued

### RESULTS

Record your results in the following table.

Results table	
<b>Methanol</b>	
Mass of spirit burner and alcohol initially	
Mass of spirit burner and alcohol finally	
Mass of ethanol	
Initial temperature	
Final temperature	
$\Delta T$	
<b>Ethanol</b>	
Mass of spirit burner and alcohol initially	
Mass of spirit burner and alcohol finally	
Mass of propan-1-ol	
Initial temperature	
Final temperature	
$\Delta T$	
<b>Propanol</b>	
Mass of spirit burner and alcohol initially	
Mass of spirit burner and alcohol finally	
Mass of butan-1-ol	
Initial temperature	
Final temperature	
$\Delta T$	

Sample pages



## PRACTICAL ACTIVITY 2 continued

- 4 Calculate the heat of combustion for each alcohol in units of  $\text{kJ mol}^{-1}$ .

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- 5 Compare the values obtained for heats of combustion of each alcohol in units of  $\text{kJ g}^{-1}$ .

a On the basis of its heat of combustion, which alcohol would be the most suitable alternative fuel to petrol? Petrol has a heat of combustion of approximately  $48 \text{ kJ g}^{-1}$ .

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b Why is a high energy release per unit mass an important consideration in selecting a fuel for vehicles, particularly for air transport?

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- 6 The heats of combustion of ethanol, propan-1-ol and butan-1-ol are  $-1364$ ,  $-2021$  and  $-2670 \text{ kJ mol}^{-1}$ .

a How well do your results agree with these values?

b Comment on the main sources of error in this experiment and suggest how the experiment could be improved.

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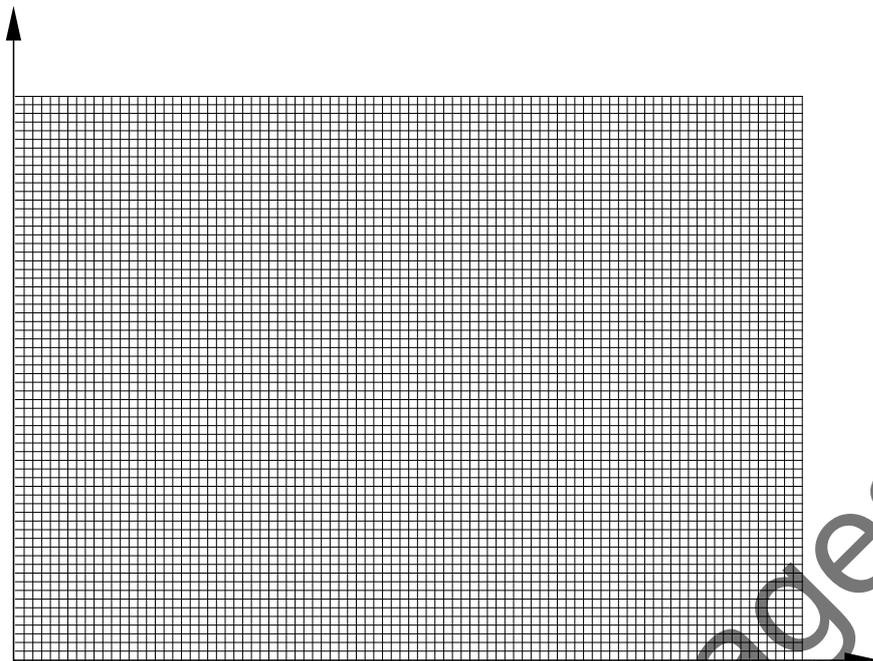
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## PRACTICAL ACTIVITY 2

- 7 a Graph the theoretical heats of combustion for each alcohol as stated in question 6 against the number of carbon atoms in each alcohol.



- b Estimate the value of the heat of combustion for pentan-1-ol.  
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- c Check reference tables of chemical data to see how close your estimate for pentan-1-ol is to the established value.  
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### CONCLUSION

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# PRACTICAL ACTIVITY 3

## NOTE TO TEACHERS

This practical activity could be used either as a class practical activity or as an assessment task for:

- Unit 3 Area of Study 1, Outcome 1: a report of a laboratory investigation, or
- Unit 4 Area of Study 3, Outcome 3: one of the experiments for collecting primary data for the Practical Investigation, if *Energy* is chosen as the area to investigate.

If used as an assessment task, teachers should produce their own questions, in addition to those given, to assess this outcome according to the VCAA guidelines.

## MATERIALS

- 50 mL 0.1 M copper(II) nitrate solution
- 50 mL 0.1 M zinc nitrate solution
- 50 mL of an equal mixture of 0.05 M iodine and 0.1 M potassium iodide solution
- 50 mL of an equal mixture of 0.1 M iron(III) nitrate and 0.1 M iron(II) sulfate solution
- 50 mL 0.1 M potassium nitrate solution
- copper electrode
- zinc electrode
- 2 × carbon rods
- 5 × 100 mL beakers
- voltmeter
- 2 × wire leads with alligator clips
- 6 × strips of 2 cm × 15 cm chromatography paper or cartridge paper
- safety glasses

As directed by your teacher, complete the risk assessment and management table by referring to the hazard labels on the reagent bottles or material safety data sheets (MSDS) or your teacher's risk assessment for the activity.

## Half-cells and the electrochemical series

### INTRODUCTION

During the operation of a galvanic cell, the relative abilities of the chemical species in the half-cells to donate and accept electrons determine which electrode is positive and which is negative. The half-cell containing the stronger reducing agent will undergo an oxidation reaction; the electrode in this half-cell will be negative. The other half-cell will contain the stronger oxidising agent and undergo a reduction reaction.

### PURPOSE

To construct a number of different electrochemical cells and use them to determine the relative positions of various pairs of oxidising agents and reducing agents in the electrochemical series.

### PRE-LAB SAFETY INFORMATION

Material used	Hazard	Control
0.1 M copper(II) sulfate solution		
0.1 M zinc nitrate solution		
0.1 M iron(III) nitrate solution		
0.1 M iron(II) sulfate solution		

Complete and indicate that you have understood the information in the safety table.

Name (print): \_\_\_\_\_

I understand the safety information (signature): \_\_\_\_\_

### RESULTS

Record your results in the following table.

Voltage and electrode polarity		
Cell	Voltage (V)	Positive electrode
$\text{Cu}^{2+}/\text{Cu}$ and $\text{Zn}^{2+}/\text{Zn}$		
$\text{Fe}^{3+}/\text{Fe}^{2+}$ and $\text{Zn}^{2+}/\text{Zn}$		
$\text{Fe}^{3+}/\text{Fe}^{2+}$ and $\text{I}_2/\text{I}^-$		
$\text{Cu}^{2+}/\text{Cu}$ and $\text{I}_2/\text{I}^-$		
$\text{Cu}^{2+}/\text{Cu}$ and $\text{Fe}^{3+}/\text{Fe}^{2+}$		
$\text{I}_2/\text{I}^-$ and $\text{Zn}^{2+}/\text{Zn}$		



### DURATION

40 minutes

# PRACTICAL ACTIVITY 3

## DISCUSSION

- 1 Draw a diagram of the cell constructed from  $\text{Cu}^{2+}/\text{Cu}$  and  $\text{I}_2/\text{I}^-$  half-cells and the cell constructed from  $\text{Fe}^{3+}/\text{Fe}^{2+}$  and  $\text{Zn}^{2+}/\text{Zn}$  half-cells. Label the contents of the half-cells, the positive and negative electrodes, the anode and cathode, the direction of electron flow through the external circuit and the direction the ions move in the salt bridge.

$\text{Cu}^{2+}/\text{Cu}$  and  $\text{I}_2/\text{I}^-$  cell

$\text{Fe}^{3+}/\text{Fe}^{2+}$  and  $\text{Zn}^{2+}/\text{Zn}$  cell

- 2 Write half-equations for the reactions occurring in each half-cell and hence write an overall equation for the reaction in each cell.

a  $\text{Cu}^{2+}/\text{Cu}$  and  $\text{Zn}^{2+}/\text{Zn}$

Anode reaction: \_\_\_\_\_

Cathode reaction: \_\_\_\_\_

Overall reaction: \_\_\_\_\_

b  $\text{Cu}^{2+}/\text{Cu}$  and  $\text{I}_2/\text{I}^-$

Anode reaction: \_\_\_\_\_

Cathode reaction: \_\_\_\_\_

Overall reaction: \_\_\_\_\_

c  $\text{Fe}^{3+}/\text{Fe}^{2+}$  and  $\text{Zn}^{2+}/\text{Zn}$

Anode reaction: \_\_\_\_\_

Cathode reaction: \_\_\_\_\_

Overall reaction: \_\_\_\_\_

d  $\text{Cu}^{2+}/\text{Cu}$  and  $\text{Fe}^{3+}/\text{Fe}^{2+}$

Anode reaction: \_\_\_\_\_

Cathode reaction: \_\_\_\_\_

Overall reaction: \_\_\_\_\_

e  $\text{Fe}^{3+}/\text{Fe}^{2+}$  and  $\text{I}_2/\text{I}^-$

Anode reaction: \_\_\_\_\_

Cathode reaction: \_\_\_\_\_

Overall reaction: \_\_\_\_\_

f  $\text{I}_2/\text{I}^-$  and  $\text{Zn}^{2+}/\text{Zn}$

Anode reaction: \_\_\_\_\_

Cathode reaction: \_\_\_\_\_

Overall reaction: \_\_\_\_\_

## PRACTICAL ACTIVITY 3 continued

- 3 Examine the results you have obtained and write the four half-cell reactions as reduction reactions, listing them in order of increasing reducing agent strength. (Your list should show the strongest oxidising agent in the upper left corner and the strongest reducing agent in the lower right corner.) This is an electrochemical series.

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- 4 Compare the order of your equations in question 3 with that of the equations listed in the electrochemical series in the Appendix. Are they the same? Why might differences arise?

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- 5 What is the function of the salt bridge in an electrochemical cell?

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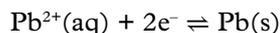
- 6 Why was it necessary to use a new salt bridge for each electrochemical cell?

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- 7 Consider the  $\text{Pb}^{2+}/\text{Pb}$  half-cell. If lead is a stronger reducing agent than copper, but  $\text{Pb}^{2+}(\text{aq})$  is a stronger oxidising agent than  $\text{Zn}^{2+}(\text{aq})$ , where in your electrochemical series would you place the following equation?



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### CONCLUSION

- 1 List the electrochemical series determined in this experiment.

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- 2 Briefly discuss any problems you have encountered and possible modifications.

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- 3 Briefly evaluate the procedure and the reliability of the data, including a discussion of errors.

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# ASSESSMENT TASKS

## Sample assessment tasks

The choice of assessment tasks for Outcome 1 of Area of Study 1 is provided in the *VCE Chemistry Study Design*. These tasks should be assessed according to the performance descriptors in the *VCAA Assessment Guide*.

### OUTCOME 1

Compare fuels quantitatively with reference to combustion products and energy outputs, apply knowledge of the electrochemical cells, construct and test galvanic cells and evaluate energy resources based on energy efficiency, renewability and environmental impact.

### ASSESSMENT TASKS

The *VCE Chemistry Study Design* lists four alternative ways of testing this outcome. Teachers may require students to do one task or they may ask them to complete two tasks. There are 50 marks allocated. Two possible ways of testing this outcome using this student workbook are described below.

#### A report on a laboratory investigation

One of the following three practical activities in this workbook could be selected to provide activities suitable for this assessment task:

- Practical activity 3: *Half-cells and the electrochemical series*
- Practical activity 4: *Order of half-equations in the electrochemical series*
- Practical activity 5: *Fuel cells*

#### A comparison of two electricity-generating cells

Practical activities in this student workbook could be used in different ways as the basis for this task:

- a Two fuel cells could be compared using Practical activity 5 *Fuel cells*
- b One of the fuel cells in Practical activity 5 *Fuel cells* could be compared with the cell in Practical activity 6 *The dry cell*
- c One of the fuel cells in Practical activity 5 *Fuel cells* and one of the cells in Practical activity 3 *Half-cells and the electrochemical series*, or from Practical activity 4 *Order of half-equations in the electrochemical series—Student designed practical activity*, could be compared.

To complete this assessment task, a report could be set for the students in which they:

- compare the design and use of materials in the two energy-producing cells
- evaluate the energy resources based on energy efficiency, renewability and environmental impact.

Assistance for teachers: Answers to Worksheets and Hints and lab support for practical activities in this book are found online on the *Heinemann Chemistry 2 5th Edition ProductLink* at [www.pearsonplaces.com.au](http://www.pearsonplaces.com.au)