Core topics

Essential idea: Materials science involves understanding the properties of a material, and then applying those properties to desired structures.

<table>
<tr><th colspan="2">A.1 Materials science introduction</th></tr>
<tr><td colspan="2">Nature of science:
Improvements in technology—different materials were used for different purposes before the development of a scientific understanding of their properties. (1.8)
Patterns in science—history has characterized civilizations by the materials they used: Stone Age, Bronze Age and Iron Age. There are various ways of classifying materials according to desired patterns. (3.1)</td></tr>
<tr><td>Understandings:
• Materials are classified based on their uses, properties, or bonding and structure.
• The properties of a material based on the degree of covalent, ionic or metallic character in a compound can be deduced from its position on a bonding triangle.
• Composites are mixtures in which materials are composed of two distinct phases, a reinforcing phase that is embedded in a matrix phase.
Applications and skills:
• Use of bond triangle diagrams for binary compounds from electronegativity data.
• Evaluation of various ways of classifying materials.
• Relating physical characteristics (melting point, permeability, conductivity, elasticity, brittleness) of a material to its bonding and structures (packing arrangements, electron mobility, ability of atoms to slide relative to one another).</td><td>International-mindedness:
• What materials were used by ancient civilizations, such as the Aztecs, Romans, and Chinese? Even though these ancient civilizations were located in geographically diverse locations, the materials they used were similar.
Theory of knowledge:
• Although it is convenient to classify materials into categories no single classification is “perfect”. How do we evaluate the different classification systems we use in the different areas of knowledge? How does our need to categorize the world help and hinder the pursuit of knowledge?
Utilization:
Syllabus and cross-curricular links:
Topic 4.2—the role of electronegativity in bonding types</td></tr>
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A.1 Materials science introduction	
Guidance: • Permeability to moisture should be considered with respect to bonding and simple packing arrangements. • Consider properties of metals, polymers and ceramics in terms of metallic, covalent, and ionic bonding. • See section 29 of the data booklet for a triangular bonding diagram.	**Aims:** • **Aims 1** and **3**: Investigation of tetrahedra of structure and bonding types and where covalent networks and polymers fit on these diagrams. • **Aim 6**: Experiments could include investigating the stretching of rubber bands under different chemical environments, or properties of metals, polymers, ceramics, or composites, making thin concrete slabs from various ratios of cement, gravel, and sand and investigating the breaking strength upon drying.

Essential idea: Metals can be extracted from their ores and alloyed for desired characteristics. ICP-MS/OES Spectroscopy ionizes metals and uses mass and emission spectra for analysis.

A.2 Metals and inductively coupled plasma (ICP) spectroscopy

Nature of science:

Development of new instruments and techniques—ICP spectroscopy, developed from an understanding of scientific principles, can be used to identify and quantify trace amounts of metals. (1.8)

Details of data—with the discovery that trace amounts of certain materials can greatly enhance a metal's performance, alloying was initially more of an art than a science. (3.1)

Understandings:

- Reduction by coke (carbon), a more reactive metal, or electrolysis are means of obtaining some metals from their ores.
- The relationship between charge and the number of moles of electrons is given by Faraday's constant, *F*.
- Alloys are homogeneous mixtures of metals with other metals or non-metals.
- Diamagnetic and paramagnetic compounds differ in electron spin pairing and their behaviour in magnetic fields.
- Trace amounts of metals can be identified and quantified by ionizing them with argon gas plasma in Inductively Coupled Plasma (ICP) Spectroscopy using Mass Spectroscopy ICP-MS and Optical Emission Spectroscopy ICP-OES.

Applications and skills:

- Deduction of redox equations for the reduction of metals.
- Relating the method of extraction to the position of a metal on the activity series.
- Explanation of the production of aluminium by the electrolysis of alumina in molten cryolite
- Explanation of how alloying alters properties of metals.

International-mindedness:

- The use of rare earth metals, or exotic minerals, has grown dramatically. They are used in green technology, medicines, lasers, weapons technology and elsewhere. They are expensive to obtain but growing in demand. What happens if rare earth reserves are controlled only by a few countries but are used by many countries?

Theory of knowledge:

- What factors/outcomes should be used to determine how time, money, and effort is spent on scientific research? Who decides which knowledge is to be pursued?

Utilization:

Syllabus and cross-curricular links:
Topics 2.1 and 12.1—mass spectrometry
Topic 2.2—emission spectra
Topic 9.1—oxidation and reduction

Aims:

- **Aim 6**: Experiments could include calculating the Faraday constant via electrolysis of aqueous copper sulfate, solving for the concentration of a nickel or copper solution using Beer's law and spectrophotometry. Analysis of alloy composition labs could also be conducted such as colorimetric determination of manganese in a paper clip or gravimetric analysis of silver or copper in a coin.

A.2 Metals and inductively coupled plasma (ICP) spectroscopy	
• Solving stoichiometric problems using Faraday’s constant based on mass deposits in electrolysis. • Discussion of paramagnetism and diamagnetism in relation to electron structure of metals. • Explanation of the plasma state and its production in ICP- MS/OES. • Identify metals and abundances from simple data and calibration curves provided from ICP-MS and ICP-OES. • Explanation of the separation and quantification of metallic ions by MS and OES. • Uses of ICP-MS and ICP-OES. **Guidance:** • Faraday’s constant is given in the data booklet in section 2. • Details of operating parts of ICP-MS and ICP-OES instruments will not be assessed. • Only analysis of metals should be covered. • The importance of calibration should be covered.	• **Aim 7**: Animations involving ICP could be used. • **Aim 7**: Simulations and virtual experiments could be used to investigate semiconductors.

Essential idea: Catalysts work by providing an alternate reaction pathway for the reaction. Catalysts always increase the rate of the reaction and are left unchanged at the end of the reaction.

A.3 Catalysts	
Nature of science: Use of models—catalysts were used to increase reaction rates before the development of an understanding of how they work. This led to models that are constantly being tested and improved. (1.10)	
Understandings: • Reactants adsorb onto heterogeneous catalysts at active sites and the products desorb. • Homogeneous catalysts chemically combine with the reactants to form a temporary activated complex or a reaction intermediate. • Transition metal catalytic properties depend on the adsorption/absorption properties of the metal and the variable oxidation states. • Zeolites act as selective catalysts because of their cage structure. • Catalytic particles are nearly always nanoparticles that have large surface areas per unit mass. **Applications and skills:** • Explanation of factors involved in choosing a catalyst for a process. • Description of how metals work as heterogeneous catalysts. • Description of the benefits of nanocatalysts in industry. **Guidance:** • Consider catalytic properties such as selectivity for only the desired product, efficiency, ability to work in mild/severe conditions, environmental impact and impurities. • The use of carbon nanocatalysts should be covered.	**International-mindedness:** • Palladium, platinum and rhodium are common catalysts that are used in catalytic converters. Because of the value of these metals, catalytic converter thefts are on the rise. **Theory of knowledge:** • Some materials used as effective catalysts are toxic and harmful to the environment. Is environmental degradation justified in the pursuit of knowledge? **Utilization:** Syllabus and cross-curricular links: Topics 6.1 and 16.1—reaction mechanisms Topic 10.2—esterification and hydrogenation reactions Topic 16.2—activation energy Option B.10—hydrogenation of fats **Aims:** • **Aims 1** and **3**: Investigate various catalysts for both the benefits and risks. • **Aim 6**: Experiments could include investigating the decomposition of potassium sodium tartrate with cobalt chloride and the decomposition of hydrogen peroxide with manganese (IV) oxide. • **Aim 6**: An ion exchange using zeolite could be explored. • **Aim 7**: Virtual experiments and simulations involving nanoparticles as catalysts could be done here.

Essential idea: Liquid crystals are fluids that have physical properties which are dependent on molecular orientation relative to some fixed axis in the material.

A.4 Liquid crystals

Nature of science

Serendipity and scientific discoveries—Friedrich Reinitzer accidently discovered flowing liquid crystals in 1888 while experimenting on cholesterol. (1.4)

Understandings:

- Liquid crystals are fluids that have physical properties (electrical, optical and elasticity) that are dependent on molecular orientation to some fixed axis in the material.
- Thermotropic liquid-crystal materials are pure substances that show liquid-crystal behaviour over a temperature range.
- Lyotropic liquid crystals are solutions that show the liquid-crystal state over a (certain) range of concentrations.
- Nematic liquid crystal phase is characterized by rod shaped molecules which are randomly distributed but on average align in the same direction.

Applications and skills:

- Discussion of the properties needed for a substance to be used in liquid-crystal displays (LCD).
- Explanation of liquid-crystal behaviour on a molecular level.

Guidance:

- Properties needed for liquid crystals include: chemically stable, a phase which is stable over a suitable temperature range, polar so they can change orientation when an electric field is applied, and rapid switching speed.
- Soap and water is an example of lyotropic liquid crystals and the biphenyl nitriles are examples of thermotropic liquid crystals.
- Liquid crystal behaviour should be limited to the biphenyl nitriles.
- Smectics and other liquid crystals types need not be discussed.

International-mindedness:

- The production of many electronic goods is concentrated in areas of the world where the working conditions may not be ideal. Should there be internationally set labour standards for all workers? What implications would this have on the cost of consumer goods?

Theory of knowledge:

- Developments in technology mean that we can store more and more information available on an increasingly smaller scale. Does this mean that we can access more knowledge?

Utilization:

Syllabus and cross-curricular links:
Topic 20.3—chirality and stereoisomers

Aims:

- **Aim 6**: Experiments could include investigating a thermotropic liquid crystal and the temperature range which affects these crystals.
- **Aim 7**: Computer animations could be used to investigate thermotropic liquid crystals.

Essential idea: Polymers are made up of repeating monomer units which can be manipulated in various ways to give structures with desired properties.

A.5 Polymers

Nature of science:

Advances in technology—as a result of advances in technology (X-ray diffraction, scanning tunnelling electron microscopes, etc), scientists have been able to understand what occurs on the molecular level and manipulate matter in new ways. This allows new polymers to be developed. (3.7)

Theories can be superseded—Staudinger's proposal of macromolecules made of many repeating units was integral in the development of polymer science. (1.9)

Ethics and risk assessment—polymer development and use has grown quicker than an understanding of the risks involved, such as recycling or possible carcinogenic properties. (4.5)

Understandings:

- Thermoplastics soften when heated and harden when cooled.
- A thermosetting polymer is a prepolymer in a soft solid or viscous state that changes irreversibly into a hardened thermoset by curing.
- Elastomers are flexible and can be deformed under force but will return to nearly their original shape once the stress is released.
- High density polyethene (HDPE) has no branching allowing chains to be packed together.
- Low density polyethene (LDPE) has some branching and is more flexible.
- Plasticizers added to a polymer increase the flexibility by weakening the intermolecular forces between the polymer chains.
- Atom economy is a measure of efficiency applied in green chemistry.
- Isotactic addition polymers have substituents on the same side.
- Atactic addition polymers have the substituents randomly placed.

Applications and skills:

- Description of the use of plasticizers in polyvinyl chloride and volatile hydrocarbons in the formation of expanded polystyrene.

International-mindedness:

- Plastics were virtually unheard of prior to the second world war. How has the introduction of plastics affected the world economically, socially and environmentally?

Utilization:

Syllabus and cross-curricular links:
Topics 10.2 and 20.1—addition and condensation reactions

Aims:

- **Aim 6**: Physical properties of high and low density polyethene could be investigated or synthesis of a polyester, polyamide or other polymer could be quantitatively performed to measure atom efficiency.

A.5 Polymers	
• Solving problems and evaluating atom economy in synthesis reactions. • Description of how the properties of polymers depend on their structural features. • Description of ways of modifying the properties of polymers, including LDPE and HDPE. • Deduction of structures of polymers formed from polymerizing 2-methylpropene. **Guidance:** • The equation for percent atom economy is provided in the data booklet in section 1. • Consider only polystyrene foams as examples of polymer property manipulation.	

Essential idea: Chemical techniques position atoms in molecules using chemical reactions whilst physical techniques allow atoms/molecules to be manipulated and positioned to specific requirements.

A.6 Nanotechnology	
Nature of science: Improvements in apparatus—high power electron microscopes have allowed for the study of positioning of atoms. (1.8) The need to regard theories as uncertain—the role of trial and error in the development of nanotubes and their associated theories. (2.2) *"The principles of physics, as far as I can see, do not speak against the possibility of manoeuvring things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big."* — Richard Feynman, Nobel Prize winner in Physics	
Understandings: • Molecular self-assembly is the bottom-up assembly of nanoparticles and can occur by selectively attaching molecules to specific surfaces. Self-assembly can also occur spontaneously in solution. • Possible methods of producing nanotubes are arc discharge, chemical vapour deposition (CVD) and high pressure carbon monoxide (HIPCO). • Arc discharge involves either vaporizing the surface of one of the carbon electrodes, or discharging an arc through metal electrodes submersed in a hydrocarbon solvent, which forms a small rod-shaped deposit on the anode. **Applications and skills:** • Distinguishing between physical and chemical techniques in manipulating atoms to form molecules. • Description of the structure and properties of carbon nanotubes. • Explanation of why an inert gas, and not oxygen, is necessary for CVD preparation of carbon nanotubes. • Explanation of the production of carbon from hydrocarbon solvents in arc discharge by oxidation at the anode. • Deduction of equations for the production of carbon atoms from HIPCO.	**International-mindedness:** • Some studies have shown that inhaling nanoparticle dust can be as harmful as asbestos. Should nanotechnology be regulated or will this hinder research? • International collaboration in space exploration is growing. Would a carbon nanotube space elevator be feasible, or wanted? What are the implications? **Theory of knowledge:** • The use of the scanning tunnelling microscope has allowed us to "see" individual atoms, which was previously thought to be unattainable. How do these advances in technology change our view of what knowledge is attainable? • Some people are concerned about the possible implication of nanotechnology. How do we evaluate the possible consequences of future developments in this area? Is the knowledge we need publicly available or do we rely on the authority of experts? **Utilization:** • Protein synthesis in cells is a form of nanotechnology with ribosomes acting as molecular assemblers. Syllabus and cross-curricular links: Topics 4.3—molecular polarity

A.6 Nanotechnology	
• Discussion of some implications and applications of nanotechnology. • Explanation of why nanotubes are strong and good conductors of electricity. **Guidance:** • Possible implications of nanotechnology include uncertainty as to toxicity levels on a nanoscale, unknown health risks with new materials, concern that human defence systems are not effective against particles on the nanoscale, responsibilities of the industries and governments involved in this research. • Conductivity of graphene and fullerenes can be explained in terms of delocalization of electrons. An explanation based on hybridization is not required.	**Aims:** • **Aims 1**, **8** and **9**: Investigate the theoretical and large scale manufacturing of nanotechnology products and their implications. Examples could include sporting equipment, medicinal products, construction, environmental cleaning, robotics, weaponry or other theoretical commercial uses. • **Aims 7**, **8** and **9**: Animations, simulations, and videos of nanotube manufacture and uses should be used.

Essential idea: Although materials science generates many useful new products there are challenges associated with recycling of and high levels of toxicity of some of these materials.

A.7 Environmental impact—plastics

Nature of science:

Risks and problems—scientific research often proceeds with perceived benefits in mind, but the risks and implications also need to be considered. (4.8)

Understandings:

- Plastics do not degrade easily because of their strong covalent bonds.
- Burning of polyvinyl chloride releases dioxins, HCl gas and incomplete hydrocarbon combustion products.
- Dioxins contain unsaturated six-member heterocyclic rings with two oxygen atoms, usually in positions 1 and 4.
- Chlorinated dioxins are hormone disrupting, leading to cellular and genetic damage.
- Plastics require more processing to be recycled than other materials.
- Plastics are recycled based on different resin types.

Applications and skills:

- Deduction of the equation for any given combustion reaction.
- Discussion of why the recycling of polymers is an energy intensive process.
- Discussion of the environmental impact of the use of plastics.
- Comparison of the structures of polychlorinated biphenyls (PCBs) and dioxins.
- Discussion of the health concerns of using volatile plasticizers in polymer production.
- Distinguish possible Resin Identification Codes (RICs) of plastics from an IR spectrum.

International-mindedness:

- The international symbol for recycle, reuse and reduce is a Mobius strip designed in the late 1960s. However, global recognition of this symbol ranks well below other symbols. What factors influence the recognition of symbols?
- How can nations address the problem of the plastic gyre in the Pacific Ocean?

Theory of knowledge:

- The products of science and technology can have a negative impact on the environment. Are scientists ethically responsible for the impact of their products?

Utilization:

Syllabus and cross-curricular links:
Topic 9.1—redox reactions
Topic 10.1—organic compounds
Topic 11.3—infrared spectroscopy
Biology option C.3—impact of humans on ecosystems

Aims:

- **Aim 7**: Database of RIC codes and IR spectra can be used.
- **Aim 8**: The development of green chemistry has raised the awareness of the environmental and the ethical implications of using science and technology.

A.7 Environmental impact—plastics	
Guidance: • Dioxins do not decompose in the environment and can be passed on in the food chain. • Consider polychlorinated dibenzodioxins (PCDD) and PCBs as examples of carcinogenic chlorinated dioxins or dioxin-like substances. • Consider phthalate esters as examples of plasticizers. • House fires can release many toxins due to plastics (shower curtains, etc). Low smoke zero halogen cabling is often used in wiring to prevent these hazards. • Resin Identification Codes (RICs) are in the data booklet in section 30. • Structures of various materials molecules are in the data booklet in section 31.	