Cambridge IGCSE · Chemistry 0620 · Notes

Extraction of metals

Read online at **pastopic.com/cambridge/chemistry-0620/notes/extraction-of-metals**

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Read first: **Reactivity series and corrosion**, **Redox**, **Electrochemistry**

What you need to know

By the end of this topic you should be able to:

1. **Link how easy a metal is to get from its ore to its place in the reactivity series.** The more reactive the metal, the harder it is to extract: metals above carbon need electrolysis; metals below carbon can be got by heating their oxide with carbon.
2. **Describe how iron is extracted from hematite in the blast furnace**, step by step:
   - carbon (coke) burns to give out heat and make carbon dioxide;
   - carbon dioxide is reduced to carbon monoxide;
   - carbon monoxide reduces iron(III) oxide to iron;
   - limestone (calcium carbonate) breaks down on heating (thermal decomposition) to calcium oxide;
   - calcium oxide removes the sandy impurity as slag.

   At Core you describe these in words; symbol equations are not needed.
3. **State that the main ore of aluminium is bauxite** and that aluminium is extracted by **electrolysis**.
4. **Extended only:** write the five symbol equations for the blast furnace.
5. **Extended only:** describe the extraction of aluminium from purified bauxite (aluminium oxide): what **cryolite** does, why the **carbon anodes** must be replaced regularly, and the **ionic half-equations** at the electrodes.

How bauxite is purified is not needed. The reactivity series itself is in the topic Reactivity series and corrosion, and electrolysis in general is in Electrochemistry.

Understand it

Ores and why extraction is needed

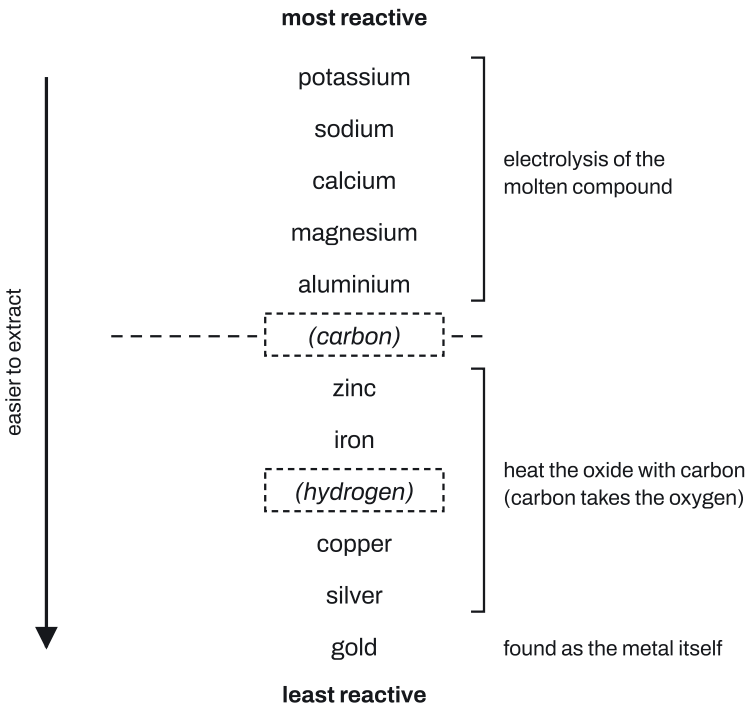
Most metals are found in the Earth's crust joined to other elements, as compounds in rocks called **ores**. The two you must know:

Ore	Metal	Main compound in it
hematite	iron	iron(III) oxide, $\mathrm{Fe_2O_3}$
bauxite	aluminium	aluminium oxide, $\mathrm{Al_2O_3}$

In an oxide the metal is present as positive ions. **Extracting** the metal means taking the oxygen away (a **reduction**), so that the ions become metal atoms again.

How the reactivity series decides the method

A reactive metal holds on to oxygen tightly, so it is hard to pull the oxygen off. An unreactive metal lets go easily. So **the lower a metal is in the reactivity series, the easier it is to extract**.

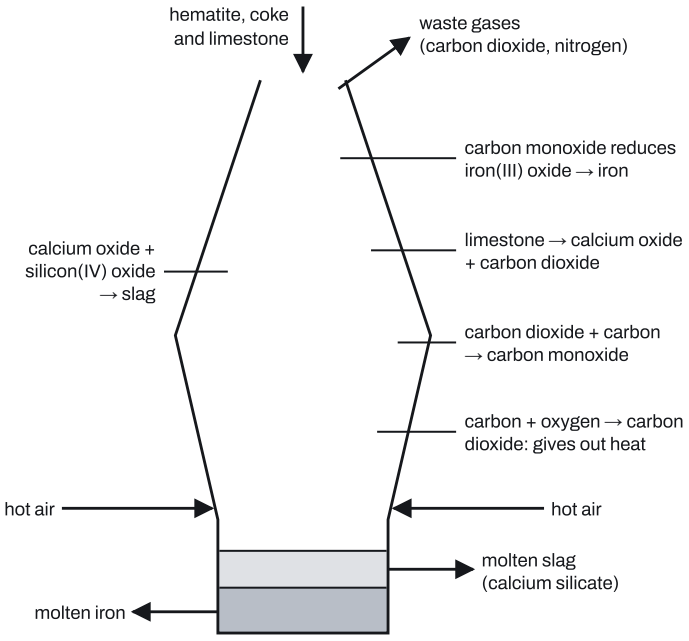


Carbon is the key marker:

- **Below carbon** (zinc, iron, copper ...): carbon is more reactive than the metal, so heated carbon (or carbon monoxide) takes the oxygen from the metal oxide. This is cheap, so it is used whenever it works. For example, zinc oxide heated with carbon gives zinc: $\mathrm{2ZnO + C \rightarrow 2Zn + CO_2}$.
- **Above carbon** (potassium, sodium, calcium, magnesium, aluminium): the metal is more reactive than carbon, so carbon cannot take its oxygen. These metals are extracted by **electrolysis** of a molten compound, which uses a lot of electricity and costs more.
- **At the very bottom**, gold is so unreactive that it is found as the metal itself, not as a compound.

The blast furnace

Iron is extracted from hematite in a **blast furnace**, a tall tower that runs day and night.



hottest at the bottom, where the coke burns in the hot air

What goes in: hematite (the iron ore), **coke** (almost pure carbon) and **limestone** (calcium carbonate) at the top; **hot air** blown in near the bottom.

What comes out: molten iron and **molten slag** from taps at the bottom; **waste gases** (mainly nitrogen from the air, and carbon dioxide) from the top.

The reactions, from the bottom up:

1. **Coke burns in the hot air.** This is the reaction that heats the furnace (it is very exothermic) and it makes carbon dioxide: $\mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2}$
2. **Carbon dioxide is reduced to carbon monoxide** as it rises through more hot coke: $\mathrm{C} + \mathrm{CO_2} \rightarrow 2\mathrm{CO}$ Here the carbon dioxide loses oxygen (it is reduced) and the carbon gains oxygen (it is oxidised).
3. **Carbon monoxide reduces iron(III) oxide to iron.** Carbon monoxide is the **reducing agent**: it takes the oxygen and becomes carbon dioxide. $\mathrm{Fe_2O_3} + 3\mathrm{CO} \rightarrow 2\mathrm{Fe} + 3\mathrm{CO_2}$ The furnace is hotter than iron's melting point, so the iron forms as a liquid and runs to the bottom.
4. **Limestone decomposes in the heat** (thermal decomposition) into calcium oxide and carbon dioxide: $\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2}$
5. **Calcium oxide removes the main impurity**, silicon(IV) oxide (sand), as **slag** (calcium silicate): $\mathrm{CaO} + \mathrm{SiO_2} \rightarrow \mathrm{CaSiO_3}$ Calcium oxide is a **basic** oxide and silicon(IV) oxide is an **acidic** oxide, so this is an **acid–base (neutralisation) reaction**.

Molten slag is **less dense** than molten iron, so it floats on top, and the two are let out through separate taps.

So coke has **two jobs**: it is the fuel that **heats** the furnace, and it makes the **carbon monoxide** that reduces the ore. Limestone has one job: to get rid of the silicon(IV) oxide. The hot air supplies the **oxygen** for the coke to burn.

Three of the substances are made in one reaction and used up in another: **carbon dioxide** (made in step 1, used in step 2), **carbon monoxide** (made in step 2, used in step 3), and **calcium oxide** (made in step 4, used in step 5).

Thermal decomposition of limestone

Thermal decomposition means **breaking a substance down into two or more simpler substances by heating it**. Limestone, calcium carbonate, is the classic example: it gives **calcium oxide** (a white solid, also called lime or quicklime) and **carbon dioxide** (the gas that turns limewater milky). Do not mix up the names: **limestone** is calcium carbonate; **lime** is calcium oxide; **slaked lime** is calcium hydroxide; **limewater** is a solution of calcium hydroxide. Only limestone gives off carbon dioxide when heated.

Oxidation and reduction in extraction

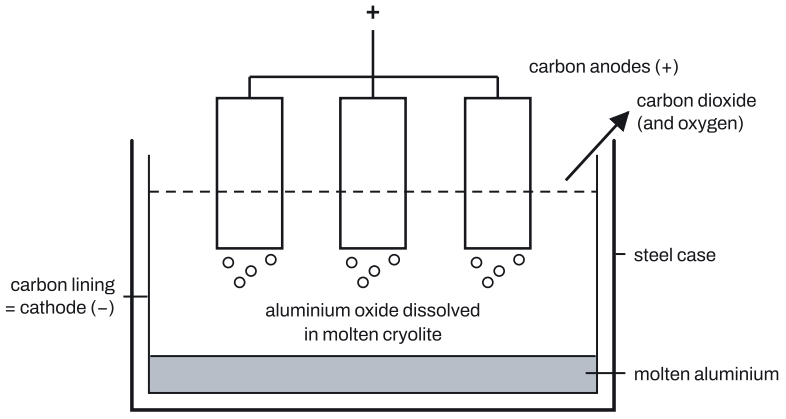
At IGCSE there are two ways to spot them:

- **Oxygen:** a substance that **loses oxygen** is **reduced**; one that **gains oxygen** is **oxidised**. In $\mathrm{Fe_2O_3} + 3\mathrm{CO} \rightarrow 2\mathrm{Fe} + 3\mathrm{CO_2}$, iron(III) oxide loses oxygen (reduced) and carbon monoxide gains oxygen (oxidised). A reaction in which both happen is a **redox** reaction.
- **Extended only: oxidation numbers and electrons.** Iron goes from $+3$ in $\mathrm{Fe_2O_3}$ to 0 in Fe: a decrease in oxidation number, so iron is reduced. At an aluminium cathode, $\mathrm{Al^{3+}}$ gains electrons (reduction); at the anode, $\mathrm{O^{2-}}$ loses electrons (oxidation).

Burning coke is a redox reaction (carbon gains oxygen); heating limestone is not (nothing gains or loses oxygen, the compound just splits).

Extended only: extracting aluminium

Aluminium is above carbon, so it is extracted by **electrolysis** of purified bauxite, which is **aluminium oxide**.



cathode (–): $Al^{3+} + 3e^- \rightarrow Al$

anode (+): $2O^{2-} \rightarrow O_2 + 4e^-$, then $C + O_2 \rightarrow CO_2$

The electrolyte. Aluminium oxide is an ionic compound; its ions can move only when it is melted or dissolved. Pure aluminium oxide melts at over 2000 °C, which would take enormous amounts of energy. So it is **dissolved in molten cryolite**, another aluminium compound. Cryolite is the **solvent**. The mixture is liquid at a much **lower temperature** (just under 1000 °C), which **saves energy** (and money), and it **conducts electricity better** than molten aluminium oxide alone. Cryolite is **not** a catalyst and is not an ore; it does not change the melting point of aluminium oxide itself, it lowers the temperature at which the electrolyte is liquid.

The electrodes. Both electrodes are **carbon (graphite)**. The carbon lining of the tank is the **cathode** (negative) and large carbon blocks dipping in from above are the **anodes** (positive).

At the cathode (−): aluminium ions gain electrons and become aluminium, which sinks to the bottom as a liquid and is tapped off.

$$\mathrm{Al^{3+} + 3e^- \rightarrow Al}$$

At the anode (+): oxide ions lose electrons and become oxygen gas.

$$\mathrm{2O^{2-} \rightarrow O_2 + 4e^-}$$

Two oxide ions make one $\mathrm{O_2}$ molecule, and each oxide ion loses two electrons, so **four** electrons are released.

Why the anodes must be replaced. The anodes are very hot, and the oxygen made on them **reacts with the carbon** to form **carbon dioxide**: $\mathrm{C + O_2 \rightarrow CO_2}$. The anodes slowly **burn away**, so they get smaller and must be replaced regularly. This is also why the gas leaving the cell is mainly carbon dioxide rather than oxygen. The cathode is not replaced: aluminium forms on it, and nothing attacks it.

Overall, the aluminium oxide is split into its elements: $\mathrm{2Al_2O_3 \rightarrow 4Al + 3O_2}$.

Key facts and formulas

"Given" means the exam paper prints it. "Learn it" means you must remember it. Chemistry 0620 has no formula sheet, so everything here must be learned (the Periodic Table in the paper gives relative atomic masses).

Formula	Status
Hematite = main iron ore, mainly iron(III) oxide $\mathrm{Fe_2O_3}$; bauxite = main aluminium ore, mainly aluminium oxide $\mathrm{Al_2O_3}$	Learn it
Above carbon → electrolysis of the molten compound; below carbon → heat the oxide with carbon; lower = easier to extract	Learn it
Raw materials: hematite, coke, limestone (top), hot air (bottom); products: molten iron, slag, waste gases ($\mathrm{CO_2}$, $\mathrm{N_2}$)	Learn it
Heating: $\mathrm{C + O_2 \rightarrow CO_2}$ (exothermic)	Learn it

Formula	Status
Making the reducing agent: $\mathrm{C} + \mathrm{CO_2} \rightarrow 2\mathrm{CO}$	Learn it
Reduction of the ore: $\mathrm{Fe_2O_3} + 3\mathrm{CO} \rightarrow 2\mathrm{Fe} + 3\mathrm{CO_2}$	Learn it
Thermal decomposition: $\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2}$	Learn it
Slag: $\mathrm{CaO} + \mathrm{SiO_2} \rightarrow \mathrm{CaSiO_3}$ (acid–base)	Learn it
Extended only: cryolite = solvent for aluminium oxide; lowers the operating temperature and improves conductivity	Learn it
Extended only: cathode $\mathrm{Al^{3+}} + 3\mathrm{e^-} \rightarrow \mathrm{Al}$; anode $2\mathrm{O^{2-}} \rightarrow \mathrm{O_2} + 4\mathrm{e^-}$	Learn it
Extended only: anodes burn away: $\mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2}$	Learn it
Reduced = loses oxygen; oxidised = gains oxygen	Learn it
Extended only: reduced = gains electrons or oxidation number decreases; oxidised = loses electrons or oxidation number increases	Learn it

Core candidates learn these reactions as word equations; Extended candidates learn the symbol equations too.

How to do it

In the questions we have tagged for this topic (121 questions, 2021–2025, from all four papers), the types came up this often. 50 of the 121 questions mix types, so the counts add up to 203.

Question type	Questions
Describe the blast furnace: jobs of coke, air, carbon monoxide and limestone; slag; what goes in and out	39
Name an ore, or the metal compound in it	35
Thermal decomposition of limestone: products, meaning, reaction type	34
Describe aluminium electrolysis: cryolite, electrodes, products, anodes (Extended only)	22
Explain or identify oxidation and reduction in an extraction reaction	18
Write, complete or choose a blast-furnace (or carbon-reduction) equation	17
Choose the extraction method from the reactivity series, or explain why electrolysis	17

Question type	Questions
Write or choose the electrode half-equations for aluminium (Extended only)	13
Converting blast-furnace iron into steel (older syllabus)	4
Calculations with extraction equations	2
Unfamiliar extraction: zinc	2

1. Describe the blast furnace (39 questions)

1. **Read which step the question is about**: heating, making the reducing agent, reducing the ore, or removing impurities. Examiners report many answers that describe slag when the question asked about heating, or the other way round.
2. **Give the job and the chemistry together**:
   - **coke**: burns in air to **heat** the furnace, and makes **carbon monoxide** (via carbon dioxide). "Two reasons for coke" = these two.
   - **hot air**: supplies **oxygen** for the coke to burn, which heats the furnace.
   - **carbon monoxide**: the **reducing agent**; it reduces iron(III) oxide to iron.
   - **limestone**: decomposes to calcium oxide, which reacts with **silicon(IV) oxide** (the impurity) to form **slag**.
3. **Name exact substances.** "Carbon monoxide", not "carbon" or "carbon dioxide", reduces the ore; "calcium oxide", not "limestone", reacts with the impurity; the waste gases are "carbon dioxide and nitrogen".

Variants you will meet:

- **Labelled diagram**: where does air enter (near the bottom), what leaves at each tap (slag above, iron below), what goes in at the top (hematite, coke, limestone).
- **Which reaction heats the furnace?** Only the burning of carbon, $\mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2}$.
- **Order of steps**: coke burns → carbon dioxide reduced to carbon monoxide → iron(III) oxide reduced.
- **Which substances are both made and used up?** Carbon dioxide and carbon monoxide (and calcium oxide).
- **Choose from a list** (Paper 4 starter questions): "the reducing agent" = carbon monoxide; "reacts with impurities to form slag" = calcium oxide; "the main impurity" = silicon(IV) oxide.
- **Statements to reject**: "carbon monoxide removes the silicon(IV) oxide", "limestone reduces the ore", "iron(III) oxide is oxidised", "slag is denser than iron", "air oxidises the molten iron", "carbon dioxide reduces the ore".
- **"Two reasons why air is blown in"**: to **burn the coke** (which **heats** the furnace), and to **form carbon monoxide** (the carbon dioxide made by burning reacts with more coke to give carbon monoxide).
- **Why is the iron molten?** The furnace is hotter than the melting point of iron.
- **How do you know slag is less dense?** On the diagram it is above the iron (its tap is higher).

- **Why is the reaction of calcium oxide with silicon(IV) oxide acid–base?** Calcium oxide is basic and silicon(IV) oxide is acidic.
- **Fill-in sentences** (Core Paper 3): choose "air", "reduced", "dioxide", "slag" and so on from a word list.

2. Name an ore, or the metal compound in it (35 questions)

1. **Iron**: **hematite**, mainly **iron(III) oxide**.
2. **Aluminium**: **bauxite**, mainly **aluminium oxide**.
3. **Spell them so they are recognisable.** Near-misses are accepted, but not a different word.

Variants you will meet:

- **Choose from a list** in a starter question ("is an ore of iron", "contains aluminium oxide").
- **Traps**: cryolite is not an ore; hematite is not an aluminium ore; limestone is not an iron ore; "iron oxide" or "alumina" is not the name of an ore.
- **Four-statement multiple choice**, for example about aluminium: check each statement against its ore (bauxite), its method (electrolysis, not carbon) and its place in the series (below calcium, above carbon).
- **An older-syllabus paper** (0620/41/O/N/21) also asked for the ore of zinc (zinc blende, zinc sulfide); that ore is not in the current syllabus.

3. Thermal decomposition of limestone (34 questions)

1. **Products**: calcium carbonate → **calcium oxide** + **carbon dioxide**.
2. **Name the reaction type**: write the whole term, **thermal decomposition**. "Decomposition" alone may lose the mark.
3. **Define it**: a substance **breaks down** into simpler substances **when heated**. Both ideas are needed.

Variants you will meet:

- **Word equation to complete**: calcium carbonate → calcium oxide + carbon dioxide.
- **Identify the products from a description**: a white solid (calcium oxide) and a colourless gas that turns limewater milky (carbon dioxide).
- **Distractors**: calcium hydroxide, carbon monoxide, calcium, calcium silicate, oxygen.
- **Lime, limestone, limewater, slaked lime**: only limestone gives off carbon dioxide when heated.
- **Reaction types side by side**: coke (burning) is **redox**; limestone is **thermal decomposition**; hematite is **reduced**; calcium oxide + silicon(IV) oxide is **acid–base**.
- **Which equation makes the substance that removes silicon(IV) oxide?** $\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2}$.

4. Describe aluminium electrolysis (22 questions)

Extended only, except that Core Paper 3 may ask you to label the cathode or name the products (aluminium at the negative electrode, oxygen at the positive electrode).

1. **Electrolyte**: aluminium oxide (purified bauxite) **dissolved in molten cryolite**.
2. **Why cryolite (two reasons)**: it **lowers the operating temperature** (the mixture melts at a lower temperature than aluminium oxide alone), saving energy; and it **improves the conductivity** of the electrolyte.
3. **Electrodes**: both **carbon (graphite)**. Aluminium forms at the **cathode** (negative); oxygen forms at the **anode** (positive).
4. **Why the anodes are replaced**: the **oxygen reacts with the carbon** anodes to form **carbon dioxide**, so they **burn away** (two marks: the reaction, and the product).

Variants you will meet:

- **Why does the molten mixture conduct?** Its **ions can move**.
- **Why is the main gas at the anode carbon dioxide, not oxygen?** The oxygen reacts with the hot carbon anode.
- **Which statement is correct?** Reject "cryolite is a catalyst", "cryolite raises the melting point", "aluminium forms at the anode", "the cathode is replaced", "aluminium ions are oxidised", "oxygen gains electrons at the anode", "cryolite removes impurities".
- **Mass of the anode**: it **decreases**, because carbon reacts to form carbon dioxide.

5. Explain or identify oxidation and reduction in an extraction reaction (18 questions)

1. **Find the named substance** on both sides of the equation.
2. **Say what happens to its oxygen**: "iron(III) oxide **loses oxygen**, so it is reduced"; "carbon monoxide **gains oxygen**, so it is oxidised". Name the substance; "oxygen is lost" alone is not enough.
3. **Extended only:** you may instead use oxidation numbers (iron $+3 \rightarrow 0$, a decrease, so reduction) or electrons (gain = reduction, loss = oxidation).

Variants you will meet:

- **Unfamiliar reducing agents** work the same way: aluminium, sodium hydride or carbon taking oxygen from a metal oxide. The metal oxide loses oxygen, so it is reduced.
- $\mathrm{C} + \mathrm{CO_2} \rightarrow 2\mathrm{CO}$: carbon dioxide is reduced (loses oxygen); carbon is oxidised (gains oxygen).
- **Name the type of reaction** in which oxidation and reduction happen together: **redox**.
- **Define reduction** (Core): loss of oxygen.
- **Extended only:** define reduction as gain of electrons, or a decrease in oxidation number.
- **Why is the anode process oxidation?** Oxide ions **lose electrons**.
- **Extended only: state the change in oxidation number** of iron: from $+3$ to 0.

6. Write, complete or choose a blast-furnace equation (17 questions)

Extended candidates write the five equations in "Key facts and formulas". Core candidates complete equations whose start is given.

1. **Write the formulae** of every reactant and product (iron(III) oxide is $\mathrm{Fe_2O_3}$; slag is $\mathrm{CaSiO_3}$).
2. **Balance** by counting atoms of each element on both sides. Mark schemes often give one mark for the right formulae and one for balancing.

Variants you will meet:

- **Two equations for removing silicon(IV) oxide**: $\mathrm{CaCO_3 \rightarrow CaO + CO_2}$ then $\mathrm{CaO + SiO_2 \rightarrow CaSiO_3}$, sometimes with the type of each (thermal decomposition; acid–base or neutralisation).
- **Other iron oxides or reducing agents**: balance by counting, for example $\mathrm{Fe_3O_4 + 4CO \rightarrow 3Fe + 4CO_2}$, or $\mathrm{Fe_2O_3 + 3C \rightarrow 2Fe + 3CO}$.
- **An unfamiliar ore reduced by carbon**: the oxygen ends up in carbon monoxide or carbon dioxide; balance the oxygen atoms. If the ore contains two metals, both come out together and must then be separated.
- **Which reaction does (or does not) happen in the furnace?** Reject FeO in place of $\mathrm{Fe_2O_3}$, calcium as a reducing agent, iron reacting with oxygen, and carbon monoxide reducing silicon(IV) oxide.

7. Choose the extraction method from the reactivity series (17 questions)

1. **Place the metal** relative to carbon.
2. **Above carbon** (K, Na, Ca, Mg, Al): **electrolysis** of the molten compound. **Below carbon** (Zn, Fe, Cu ...): **reduction** by heating the oxide with carbon.
3. **For "explain why electrolysis, not carbon"**: the metal is **more reactive than carbon** (above carbon in the series), so carbon cannot remove its oxygen.

Variants you will meet:

- **Unknown metals placed around carbon**: each metal above carbon → electrolysis; each below → heating with carbon.
- **Which metal is easiest to obtain?** The one lowest in the series.
- **Which metal is obtained by heating its oxide with carbon?** One below carbon, such as zinc.
- **Order metals from how easily carbon reduces their oxides**: an oxide reduced at a lower temperature belongs to a less reactive metal; an oxide not reduced at all belongs to the most reactive.
- **Name the process** used to extract aluminium (electrolysis) or iron (reduction with carbon).

8. Write or choose the electrode half-equations for aluminium (13 questions)

Extended only.

1. **Cathode (negative)**: positive ions gain electrons: $\mathrm{Al^{3+} + 3e^- \rightarrow Al}$. One mark is often for $\mathrm{Al^{3+} + 3e^-}$ on the left, one for the whole equation.
2. **Anode (positive)**: negative ions lose electrons: $\mathrm{2O^{2-} \rightarrow O_2 + 4e^-}$.
3. **Check both atoms and charge**: the total charge must be equal on each side.

Variants you will meet: find the missing numbers ($x\mathrm{O}^{2-} \rightarrow \mathrm{O}_2 + y\mathrm{e}^-$ gives $x = 2, y = 4$); choose the row with each equation at the right electrode. Traps: electrons on the wrong side, "$3\mathrm{Al}$" as the product, O^{2-} gaining electrons, or the two electrodes swapped. The anode may have a second reaction, $\mathrm{C} + \mathrm{O}_2 \rightarrow \mathrm{CO}_2$.

9. Converting blast-furnace iron into steel (4 questions)

These are all from 2021–2022 papers, under an older syllabus. The 2026–2028 syllabus does not include how steel is made, so you will not be asked this. (What alloys such as steel are, and why they are used, is in Properties, uses and alloys.)

10. Calculations with extraction equations (2 questions)

Use the mole methods from Relative masses and the mole.

1. **Percentage by mass of a metal in its oxide**: $\dfrac{\text{mass of metal atoms in the formula}}{M_r} \times 100$. For $\mathrm{Fe_3O_4}$: $\dfrac{3 \times 56}{232} \times 100 = 72.4\%$.
2. **Reacting masses**: find the moles of what you know, use the ratio in the equation, then convert to mass. Or scale a given mass ratio: if a mass of ore gives a known mass of iron, the same ratio applies to any other mass.

11. Unfamiliar extraction: zinc (2 questions)

A "suggest" question about a metal you have not studied. Use what you know:

1. Zinc is **below carbon**, so zinc oxide is reduced by heating it with carbon in a furnace.
2. **Why is the zinc a gas?** The furnace is **hotter than the boiling point of zinc**.
3. **Gaseous zinc turning into molten zinc** is **condensation**.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.

Example 1

Cobalt is a metal that lies below iron but above hydrogen in the reactivity series. Metal Q reacts vigorously with cold water.

(a) Suggest how cobalt could be extracted from cobalt(II) oxide, CoO. Explain your answer using the reactivity series. **[2]**

(b) Explain why metal Q is **not** extracted by heating its oxide with carbon, and name the method that is used. **[2]**

(c) Put copper, cobalt and Q in order of how easily each is extracted from its ore, easiest first. **[1]**

(d) In the reaction in (a), state which substance is reduced and explain how you know. **[2]**

(a) Heat cobalt(II) oxide with carbon (reduction with carbon) **(B1)**, because cobalt is **below carbon** in the series, so carbon can remove the oxygen **(B1)**. The equation would be $2\mathrm{CoO} + \mathrm{C} \rightarrow 2\mathrm{Co} + \mathrm{CO_2}$.

(b) Only potassium, sodium and calcium react vigorously with cold water, so Q is **above carbon** (more reactive than carbon) and carbon cannot take its oxygen **(B1)**. It is extracted by **electrolysis** of its molten compound **(B1)**.

(c) copper, cobalt, Q **(B1)**. The lower a metal is in the series, the easier it is to extract.

(d) Cobalt(II) oxide is reduced **(B1)** because it **loses oxygen (B1)**.

Example 2

Extended only: a blast furnace is fed with coke, limestone, hot air and an ore containing iron(III) oxide and silicon(IV) oxide. Use A_r: C = 12, O = 16, Si = 28, Ca = 40, Fe = 56.

(a) Explain, with a symbol equation for each, the **two** reactions of coke in the furnace and the purpose of each. **[4]**

(b) In one batch, 400 kg of iron(III) oxide is reduced by carbon monoxide. Calculate the mass of carbon monoxide used and the mass of iron formed. **[4]**

(c) The same batch contains 90 kg of silicon(IV) oxide. Calculate the minimum mass of limestone needed to remove it, and the mass of slag formed. **[3]**

(d) State the change in oxidation number of iron in (b), and explain what it shows. **[2]**

(a) Coke burns in the air: $\mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2}$ **(B1)**. This is exothermic and **heats the furnace (B1)**. The carbon dioxide reacts with more coke: $\mathrm{C} + \mathrm{CO_2} \rightarrow 2\mathrm{CO}$ **(B1)**, making **carbon monoxide, the reducing agent** that reduces the ore **(B1)**.

(b) $\mathrm{Fe_2O_3} + 3\mathrm{CO} \rightarrow 2\mathrm{Fe} + 3\mathrm{CO_2}$. $M_r(\mathrm{Fe_2O_3}) = 2(56) + 3(16) = 160$.

Moles of $\mathrm{Fe_2O_3} = \dfrac{400\,000}{160} = 2500$ mol. **M1**

Moles of CO $= 3 \times 2500 = 7500$ mol; mass $= 7500 \times 28 = 210\,000$ g $= 210$ kg. **M1 A1**

Moles of Fe $= 2 \times 2500 = 5000$ mol; mass $= 5000 \times 56 = 280\,000$ g $= 280$ kg. **A1**

(c) $\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2}$ and $\mathrm{CaO} + \mathrm{SiO_2} \rightarrow \mathrm{CaSiO_3}$: one mole of limestone removes one mole of silicon(IV) oxide.

Moles of $\mathrm{SiO_2} = \dfrac{90\,000}{60} = 1500$ mol. **M1**

Mass of $\mathrm{CaCO_3} = 1500 \times 100 = 150\,000\ \mathrm{g} = 150$ kg. **A1**

Mass of slag, $\mathrm{CaSiO_3}$ ($M_r = 116$) $= 1500 \times 116 = 174\,000\ \mathrm{g} = 174$ kg. **A1**

(d) From $+3$ (in $\mathrm{Fe_2O_3}$) to 0 (in Fe) **(B1)**. The oxidation number decreases, so iron is **reduced (B1)**.

Example 3

Extended only: aluminium is made by electrolysis of aluminium oxide dissolved in molten cryolite, using carbon electrodes.

(a) Give **two** reasons why the aluminium oxide is dissolved in molten cryolite rather than electrolysed on its own. **[2]**

(b) Write the ionic half-equation for the reaction at each electrode, and state which one is an oxidation. **[3]**

(c) Explain why the anodes must be replaced regularly but the cathode does not. **[2]**

(d) One cell makes 540 kg of aluminium. The overall reaction is $2\mathrm{Al_2O_3} \rightarrow 4\mathrm{Al} + 3\mathrm{O_2}$. Assuming all the oxygen reacts with the anodes to form carbon dioxide, calculate the mass of carbon anode used up. A_r: C = 12, Al = 27. **[3]**

(a) The mixture is liquid at a **much lower temperature**, so **less energy** is needed **(B1)**; the solution **conducts electricity better** than molten aluminium oxide alone **(B1)**.

(b) Cathode: $\mathrm{Al^{3+}} + 3\mathrm{e^-} \rightarrow \mathrm{Al}$ **(B1)**. Anode: $2\mathrm{O^{2-}} \rightarrow \mathrm{O_2} + 4\mathrm{e^-}$ **(B1)**. The anode reaction is the oxidation, because the oxide ions **lose electrons (B1)**.

(c) Oxygen forms at the hot carbon anodes and **reacts with the carbon to form carbon dioxide**, so the anodes burn away **(B1)**. Aluminium forms at the cathode and does not react with it, so the cathode is not used up **(B1)**.

(d) Moles of Al $= \dfrac{540\,000}{27} = 20\,000$ mol. **M1**

From the equation, 4 mol Al come with 3 mol $\mathrm{O_2}$: moles of $\mathrm{O_2} = 20\,000 \times \dfrac{3}{4} = 15\,000$ mol. **M1**

$\mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2}$, so 15 000 mol of carbon react: mass $= 15\,000 \times 12 = 180\,000\ \mathrm{g} = 180$ kg. **A1**

Common mistakes

- **Saying carbon (or carbon dioxide) reduces iron(III) oxide.** In the blast furnace the reducing agent is **carbon monoxide**. Examiners also see "reduction" written when the question asks for the "reducing agent", a substance.
- **Mixing up the stages.** When asked why coke is burned, write about **heat** and making carbon monoxide, not slag. When asked about limestone, write about slag, not heat.
- **Forgetting that burning carbon is what heats the furnace.** Many candidates think the reduction of the ore provides the heat; it is the combustion of coke.
- **Saying limestone (or carbon monoxide) reacts with the impurity.** It is **calcium oxide**, made from limestone, that reacts with **silicon(IV) oxide**.
- **Writing "decomposition"** without "thermal", or defining thermal decomposition without both "breaks down" and "by heat".
- **Mixing up lime, limestone and limewater**, or calling limestone "lime rock". Limestone is calcium carbonate.
- **Spelling that changes the word**, such as "slug" for slag. A spelling that sounds right (for hematite or bauxite) is usually accepted, but one that reads as a different word is not.
- **Calling cryolite a catalyst or an ore**, or saying it "raises" a melting point, or that it lowers the melting point **of aluminium oxide** (that is fixed). It is a **solvent** that lets the electrolyte be liquid at a lower temperature.
- **Saying the anodes "corrode" or "dissolve"** without saying why. Say: the **oxygen reacts with the carbon** to make **carbon dioxide**.
- **Putting aluminium at the anode**, or writing $\mathrm{Al^{3+}} + 3\mathrm{e^-} \rightarrow 3\mathrm{Al}$.
- **Unbalanced anode equation**: $\mathrm{O^{2-}} \rightarrow \mathrm{O_2} + 2\mathrm{e^-}$ has the wrong number of oxygen atoms; the right one needs $2\mathrm{O^{2-}}$ and $4\mathrm{e^-}$.
- **Explaining reduction without naming the substance.** Write "iron(III) oxide loses oxygen", not just "oxygen is removed". When asked which substance is oxidised, remember the reducing agent is the one oxidised.
- **Explaining "why electrolysis" with "aluminium is very reactive"** only. Compare it with **carbon**: aluminium is more reactive than carbon.

How to get the marks

- **"Name"** and **"State"**: one word or phrase, exactly right: hematite, bauxite, cryolite, carbon monoxide, slag, calcium silicate, thermal decomposition. No explanation needed.
- **"Give two reasons"** for coke: heat (it burns exothermically) **and** making carbon monoxide. For cryolite: lower operating temperature (saves energy) **and** better conductivity. Two different ideas, one mark each.
- **"Describe" the blast furnace** in a longer answer: cover each bullet the question lists, with a named substance for each step (how carbon monoxide is made, what it does, what limestone does). An equation, where you know it, makes each step clear.

- **"Explain how this equation shows X is reduced"**: name X and say it **loses oxygen**. **Extended only:** you may say its oxidation number decreases instead.
- **"Explain" why electrolysis**: position relative to **carbon** in the reactivity series.
- **"Explain" why the anodes are replaced**: two marks, one for **carbon reacts with oxygen**, one for **forms carbon dioxide**.
- **Symbol equations**: correct formulae first (often **M1**), then balancing (**A1**). State symbols only if asked.
- **Half-equations**: electrons on the correct side, correct numbers, and the charges balance. A wrong number of electrons loses the mark.
- **Calculations**: show the M_r and moles; give the unit (g, kg or tonnes) the question uses. Method marks follow through from an earlier slip.
- **"Suggest"** means apply what you know to something new, such as an unfamiliar ore or reducing agent: carbon takes oxygen from the oxide of a metal below it.

Quick check

1. Name the main ore of aluminium and the main compound in it, and the main ore of iron and the main compound in it.
2. Which of these metals must be extracted by electrolysis: magnesium, copper, calcium, zinc? Explain your choice.
3. Limestone is heated strongly in the blast furnace. Name the type of reaction, name both products, and state what one of the products then does.
4. **Extended only:** write the half-equation for the formation of oxygen at the anode in the extraction of aluminium, and explain why the gas leaving the anode is mainly carbon dioxide.
5. **Extended only:** an iron ore is 60% iron(III) oxide by mass. Calculate the maximum mass of iron that can be extracted from 800 tonnes of the ore. A_r: O = 16, Fe = 56.

Answers

1. Aluminium: **bauxite**, mainly **aluminium oxide**. Iron: **hematite**, mainly **iron(III) oxide**.
2. **Magnesium and calcium.** They are above carbon in the reactivity series (more reactive than carbon), so carbon cannot remove the oxygen from their oxides. Copper and zinc are below carbon, so their oxides can be reduced by heating with carbon.
3. **Thermal decomposition.** Products: **calcium oxide** and **carbon dioxide**. The calcium oxide reacts with silicon(IV) oxide (the impurity in the ore) to form **slag** (calcium silicate).
4. $2\mathrm{O}^{2-} \rightarrow \mathrm{O}_2 + 4\mathrm{e}^-$. The oxygen reacts with the hot **carbon** anodes to form **carbon dioxide** ($\mathrm{C} + \mathrm{O}_2 \rightarrow \mathrm{CO}_2$).
5. Mass of $\mathrm{Fe_2O_3} = 0.60 \times 800 = 480$ tonnes. Percentage of iron in $\mathrm{Fe_2O_3} = \dfrac{2 \times 56}{160} \times 100 = 70\%$. Mass of iron $= 0.70 \times 480 = 336$ tonnes.

Past questions to try

- **0620/42/F/M/24 Q1**: every stage of the blast furnace, with a percentage by mass (Extended only).
- **0620/42/O/N/24 Q2**: cryolite, the electrode half-equations and why the gas at the anode is carbon dioxide (Extended only).
- **0620/11/M/J/23 Q28**: choosing extraction methods for metals placed around carbon.
- **0620/33/O/N/23 Q5**: which substance is oxidised when carbon monoxide is made, and the decomposition of limestone.