Unit 3 Chemistry SAC 1 – Assessment Guide

An analysis and evaluation of a chemical innovation, research study, case study, socio-scientific issue, or media communication.

Case Study

Both methanol and hydrogen can be used as fuel sources to produce electricity through fuel cells. These fuel cells can then provide electricity to run cars or buses.

Methanol and hydrogen production processes are presented in Figure 1. Hydrogen can be produced through the electrolysis of water, where the electricity is sourced from renewable energy; the hydrogen gas is then liquefied at high pressure and transported for the end use. The methanol production involves capturing CO_2 from the air (or from heavy industry) and synthesising it with added hydrogen to obtain methanol through green chemistry processes.

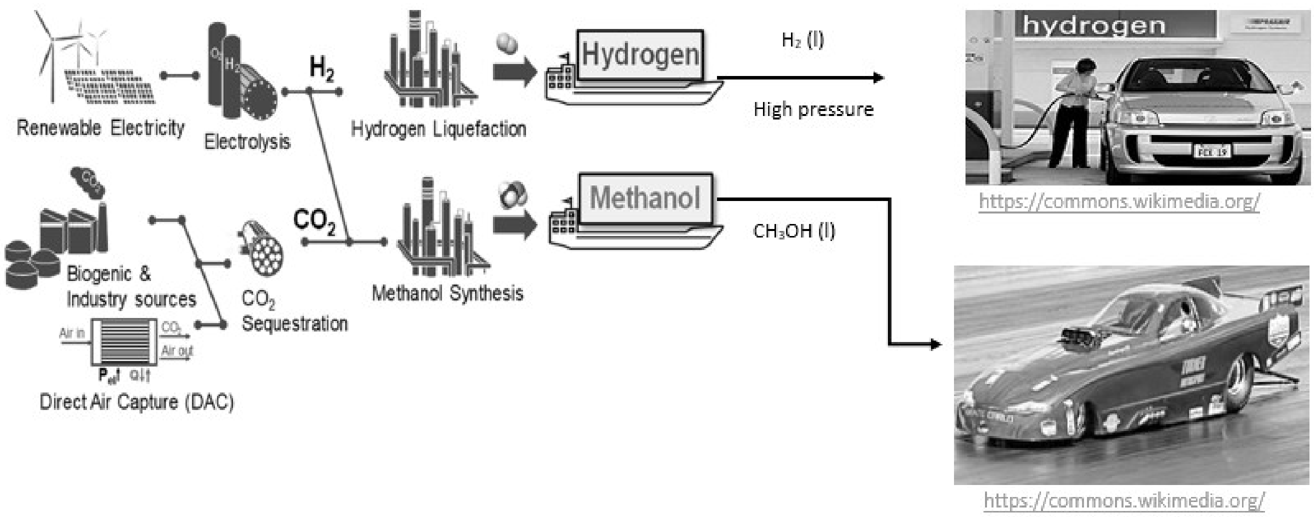


Figure 1. A diagram of hydrogen and methanol production using green chemistry approaches.

After production, each of these fuels can be used to power cars or buses by using either a Methanol Fuel Cell (MFC) or a Hydrogen Fuel Cell (HFC) respectively (see Figure 2).

Source: Adapted from Schorn et al 2021. Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations, *Advances in Applied Energy 3 2021*, Published by Elsevier, accessed on the 15th July 2023 from https://www.sciencedirect.com/science/article/pii/S2666792421000421?via%3Dihub

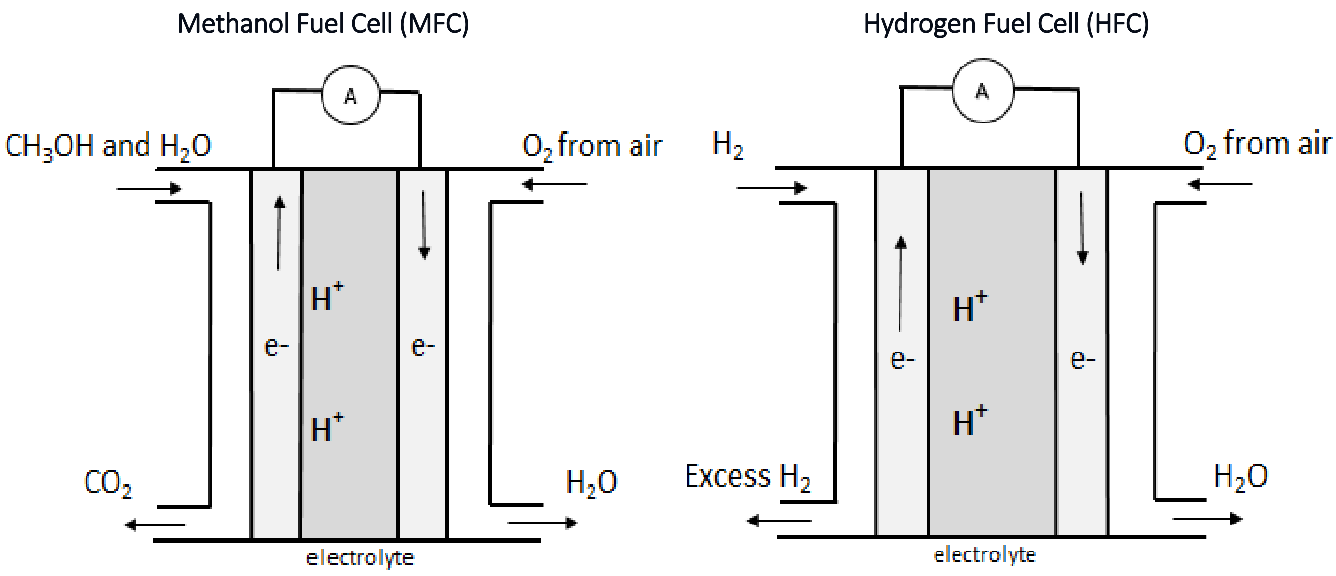


Figure 2. Diagrams of a methanol fuel cell (MFC) and a hydrogen fuel cell (HFC).

A selection of fuel properties is shown in Table 1.

Table 1. Selected Fuel Properties

Property	CH_3OH	H_2
Density (kg/m^3)	792 as liq.	0.08375 (as gas) 70.8 (as liq.)
Flashpoint (°C)	11	-253
Heat of Combustion (kJ/g)	22.7	141
Heat of Combustion (kJ/mol)	726	282
Volume expansion ratio from Liquid to Gas	-	1 to 848

Sources: Adapted from:
Barbir F., n.d.. Safety issues of hydrogen in vehicles, accessed on the 15th July 2023 from https://courses.engr.illinois.edu/npre470/sp2019/web/readings/Hydrogen%20safety%20issues.pdf
Lanz, A., et al., 2001. Hydrogen Fuel Cell Engines and Related Technologies College of the Desert, Palm Desert, CA, USA, accessed on the 15th July from https://www.energy.gov/hydrogen-fuel-cells
Advanced motor fuels, 2023. Methanol, accessed on the 15th July from https://www.iea-amf.org/content/fuel_information/methanol#:~:text=Low%20lean%20flammability%20limit,to%20the%20lower%20heating%20value

Media Communication

[1] - "Hydrogen and methanol both qualify as substitutes for current energy carriers." The method proposes an option for, "…a methanol production plant with power stations and other manufacturing plants, such as cement and pulp-and-paper mills, to reduce carbon dioxide emissions and store excess energy generated from power plants."

[2] - "Methanol, a liquid fuel with controlled flammability, easy transportation, storage, versatility, retrofitting capabilities and the ability to serve as a fuel additive, offers advantages over hydrogen, despite hydrogen having the highest energy density."

[3] - "Acute exposure of humans to methanol by inhalation or ingestion may result in visual disturbances, such as

blurred or dimness of vision, leading to blindness…”.

[4] - “…Hydrogen has a very low ignition energy, about one order of magnitude lower than other fuels. […] [It also] has a flame velocity seven times faster than that of natural gas or gasoline”.

Sources: Adapted from:

[1] – Schorn et al 2021. Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations, *Advances in Applied Energy 3 2021*, Published by Elsevier, accessed on the 15th July 2023 from https://www.sciencedirect.com/science/article/pii/S2666792421000421?via%3Dihub

[2] – Samuel Emebu [a e], Clara Mendoza Martinez [b], Osaze Omoregbe [c e], Aleksi Mankonen [b], Ebuka A. Ogbuoji [f], Ibrahim Shaikh [a], Even Pettersen [d], Marek Kubalčík [a], Charity Okieimen [e] Chemical Engineering Science, Volume 278, 15 August 2023, 118888

[3] – USEPA, 2000. Methanol, accessed on the 15th July 2023 from https://www.epa.gov/sites/default/files/2016-09/documents/methanol.pdf

[4] – Barbir F., n.d.. Safety issues of hydrogen in vehicles, accessed on the 15th July 2023 from https://courses.engr.illinois.edu/npre470/sp2019/web/readings/Hydrogen%20safety%20issues.pdf

contemporary responses to challenges and the role of innovation in the design of fuel cells to meet society’s energy needs, with reference to green chemistry principles: design for energy efficiency, and use of renewable feedstocks

discuss relevant chemical information, ideas, concepts, theories and models and the connections between them

Question 1a (1 mark)

After production (see Figure 1), methanol and hydrogen are transported to fuel stations.

Outline a safety issue with either the transport, storage or usage of hydrogen compared to methanol.

Answer:

- *Leaks – any leak can cause a fire and, hence, they are a safety concern. Hydrogen is transported and stored in liquid form under high pressure; it has a low ignition energy and can ignite faster than methanol. Methanol is a liquid at working pressure, thus requiring a higher ignition energy, and, hence, presents fewer risks.*
- *Flash point – hydrogen has a lower flash point than methanol; both are flammable, but, in the presence of oxygen and an ignition source, hydrogen ignites much more easily than methanol.*
- *Flame expansion – a hydrogen flame expands faster than a methanol flame due to hydrogen’s lower density, thus presenting a higher risk.*
- *Fumes inhalation – methanol fumes inhalation can lead to visual disturbances, therefore impacting safe driving, while hydrogen is unlikely to have a major effect.*

Marking Protocol:

One mark for any of the above points.

the common design features and general operating principles of fuel cells, including the use of porous electrodes for gaseous reactants to increase cell efficiency

Question 1b (1 mark)

Identify a similarity between MFCs and HFCs that explains why they are considered fuel cells.

Answer:

- *Fuel/reactants is/are continuously supplied to the cell.*
- *Products are continuously removed from the cell.*
- *Reactants are separated so that the potential chemical energy is transformed into electrical energy.*
- *They both produce only DC power.*

Marking Protocol:

One mark for any one of the above points.

the writing of balanced half-equations (including states) for oxidation and reduction reactions, and the overall redox cell reaction in both acidic and basic conditions

Question 1c (3 marks)

Write half equations for the reactions occurring at the anode and cathode of the MFC. Write the overall equation (including states) for the MFC as it operates.

Answer:

- Anode: $CH_3OH_{(l)} + H_2O_{(l)} \rightarrow CO_{2(g)} + 6H^+_{(aq)} + 6e^-$
- Cathode: $O_{2(g)} + 4H^+_{(aq)} + 4e^- \rightarrow 2H_2O_{(l)}$
- Overall equation: $2CH_3OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 4H_2O_{(l)}$

Marking Protocol:

One mark for each of the above points.

the writing of balanced half-equations (including states) for oxidation and reduction reactions, and the overall redox cell reaction in both acidic and basic conditions	**Question 1d** (3 marks) Write half equations for the reactions occurring at the anode and cathode of the HFC. Write the overall equation (including states) for the HFC as it operates.	**Answer:** • Anode: $H_{2(g)} \text{-->} 2H^{+}_{(aq)} + 2e^{-}$ • Cathode: $O_{2(g)} + 4H^{+}_{(aq)} + 4e^{-} \text{-->} 2H_2O_{(l)}$ • Overall equation: $2H_{2(g)} + O_{2(g)} \text{-->} 2H_2O_{(l)}$ **Marking Protocol:** One mark for each of the above points.

calculation of energy transformation efficiency during combustion as a percentage of chemical energy converted to useful energy	**Question 1e** (3 marks) The theoretical voltage produced by a MFC is +1.6 V and the actual efficiency is 40%. The actual efficiency of the HFC is 60%. Which cell provides the highest actual voltage? Show your working.	**Answer:** • *The hydrogen fuel cell.* • *E(MFC) = +1.6 V x 40% = +0.64 V* • *E(HFC) = +1.23 V x 60% = +0.74 V* **Marking Protocol:** One mark for each of the above points. N.B. The potential energy value for a HFC is derived from the electrochemical series.

the definition of a fuel, including the distinction between fossil fuels (coal, natural gas, petrol) and biofuels (biogas, bioethanol, biodiesel) with reference to their renewability (ability of a resource to be replaced by natural processes within a relatively short period of time) point/s *apply sustainability concepts (green chemistry principles, development goals and the transition from a linear towards a circular economy) to analyse and evaluate responses to chemistry-based scenarios, case studies, issues and challenges* *critically evaluate and interpret a range of scientific and media texts (including journal articles, mass media communications and opinions in the public domain), processes, claims and conclusions related to*	**Question 1f** (2 marks) Compare and discuss the environmental impact of using MFCs and HFCs when their reactants are sourced via renewable processes.	**Answer:** • *Production of CO_2 – MFCs produce CO_2 while HFCs only produce water. At SLC, H_2O is a liquid and not a greenhouse gas. HFC use is therefore more environmentally friendly than MFC use.* • *C- Zero Emissions – In this initiative, CO_2 is captured from the atmosphere and transformed into methanol. More research is needed to determine whether the CO_2 that is captured can negate the CO_2 that is produced during MFC use; if so, this process could have net carbon neutrality. Hydrogen production involves only renewable electricity; the electrolysis produces only hydrogen and oxygen and no other greenhouse gases. Hence, HFCs are a 'clean' technology with zero carbon emissions.* **Marking Protocol:** Two marks for any of the above points.

chemistry by considering the quality of available evidence

calculations related to the application of stoichiometry to reactions involving the combustion of fuels, including mass-mass, mass-volume and volume-volume stoichiometry, to determine heat energy released, reactant and product amounts and net volume or mass of major greenhouse gases (CO2, CH4 and H2O), limited to standard laboratory conditions (SLC)	**Question 1g** (3 marks) Assuming SLC, what is the amount of greenhouse gas, in kg, that is produced from the reaction of 1.0 kg of fuel in a methanol fuel cell? Show your working.	**Answer:** $2CH_3OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 4H_2O_{(l)}$ • *$n(CH_3OH) = m/M = (1000\ g)/(12+3+16+1)\ g/mol) = 31.25\ mol$* • *$n(CH_3OH) : n(CO_2) = 2 : 2$* *$n(CO_2) = 31.25\ mol$* • *$m(CO_2) = n \times M = 31.25 \times (12+2 \times 16) = 1375\ g = 1.4\ kg$* **Marking Protocol:** One mark for each of the above points. N.B. Only calculations for the methanol reaction are relevant.

combustion (complete and incomplete) reactions of fuels as exothermic reactions: the writing of balanced thermochemical equations, including states, for the complete and incomplete combustion of organic molecules using experimental data and data tables	**Question 1h** (1 mark) Write the thermochemical equation for the complete combustion of methanol at SLC.	**Answer:** • *$2CH_3OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 4H_2O_{(l)}$ $\Delta H = -1452\ kJ/mol$* • *$CH_3OH_{(l)} + 3/2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(l)}$ $\Delta H = -726\ kJ/mol$* **Marking Protocol:** One mark for either of the above points.

A student researched whether a small battery can be replaced with a galvanic cell that can be assembled in the school laboratory.

<u>The Primary Cell – Battery</u>

Zinc-silver oxide cells are frequently used to power small electronics and photographic equipment. The cell configuration below (Figure 3) includes: an amalgamated zinc anode; silver oxide as the cathode material; and a potassium hydroxide electrolyte. During discharge, zinc will form zinc oxide whilst silver (I) oxide will form silver.

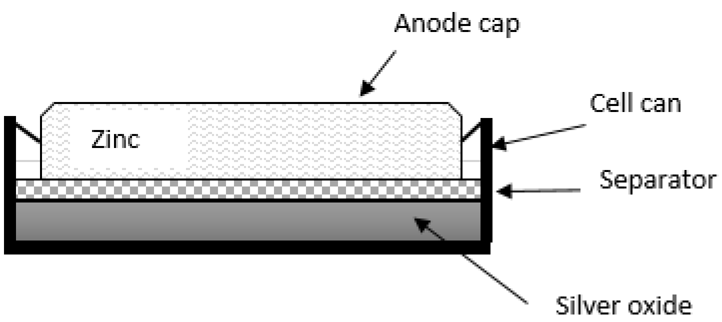


Figure 3. A schematic representation of a zinc-silver oxide cell.

Through the research, the student identified the battery discharge curve as well as other properties:

- a long service life;
- a lack of mercury, lead and cadmium, making the silver oxide batteries environmentally friendly; and
- a silver oxide system that is best suited for operation between -20°C and 54°C (with the starting cell potential being 1.55 V).

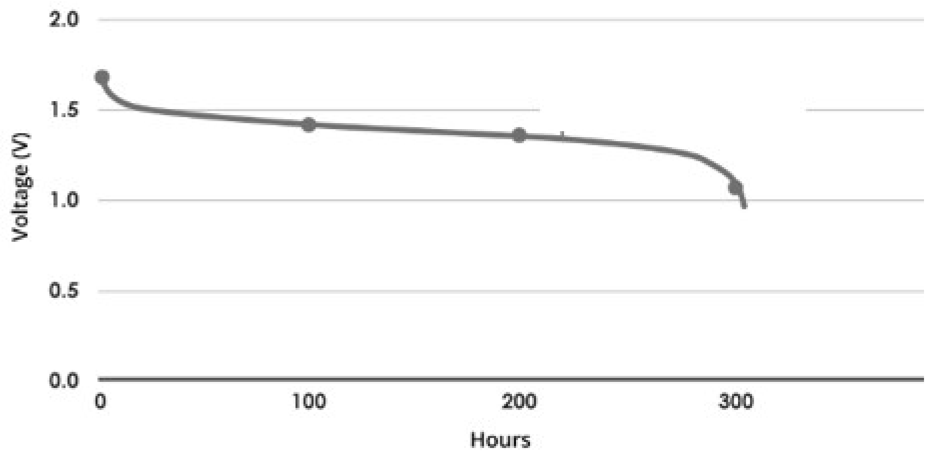


Figure 4. A silver oxide battery discharge curve.

Source: GP Industrial, 2023. Silver oxide button batteries, accessed on the 15th July 2023 from https://ind.gpbatteries.com/products/primary-batteries/silver-oxide-batteries/silver-oxide-button-batteries.html

the common design features and general operating principles of non-rechargeable (primary) galvanic cells converting chemical energy into electrical energy, including electrode polarities and the role of the electrodes (inert and reactive) and electrolyte solutions	**Question 2a** (1 mark) State the polarity of the zinc electrode.	**Answer:** • *Negative.* **Marking Protocol:** One mark for the above point.

The writing of balanced half-equations (including states) for oxidation and reduction reactions, and the overall redox cell reaction in both acidic and basic conditions	**Question 2b** (3 marks) Write the equations for the reactions that are occurring at the anode and the cathode as well as the overall equation.	**Answer:** • Anode: $Zn_{(s)} + 2OH^{-}_{(aq)}$ --> $ZnO_{(s)} + H_2O_{(l)} + 2e^{-}$ • Cathode: $Ag_2O_{(s)} + H_2O_{(l)} + 2e^{-}$ --> $2Ag_{(s)} + 2OH^{-}_{(aq)}$ • Overall equation: $Zn_{(s)} + Ag_2O_{(s)}$ --> $ZnO_{(s)} + Ag_{(s)}$ **Marking Protocol:** One mark for each of the above points.

redox reactions as simultaneous oxidation and reduction processes, and the use of oxidation numbers to identify the reducing agent, oxidising agent and conjugate redox pairs	**Question 2c** (2 marks) Identify the oxidising agent (oxidant) in the battery. Justify your answer using oxidation numbers.	**Answer:** • *The oxidising agent is $Ag_2O_{(s)}$ (or Ag in $Ag_2O_{(s)}$).* • *Ag from $Ag_2O_{(s)}$ changes ON rom +1 to ON of 0 in Ag.* **Marking Protocol:** One mark for each of the above points.

The Galvanic Cell

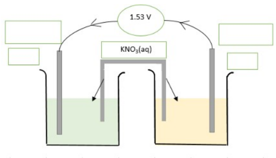
Using the electrochemical series, the student constructs a galvanic cell with a similar potential difference to the zinc-silver oxide cell. The electrodes are made of reactive metals and the electrolytes consist of ions of the same metal as the electrode. The metals available in the lab are Al, Zn, Fe, Pb and Cu. The student chooses a combination of oxidising and reducing agents that give a potential difference of +1.53 V. The galvanic cell is tested at SLC.

the common design features and general operating principles of non-rechargeable (primary) galvanic cells converting chemical energy into electrical energy, including electrode polarities and the role of the electrodes (inert and reactive) and electrolyte solutions dot point/s

Question 2d (4 marks)

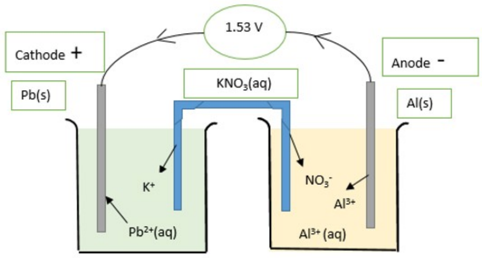
Annotate the diagram below identifying:

- The anode and its polarity
- The cathode and its polarity
- The electrode material (metal species) in each half cell
- The movement of ions from the internal circuit.



Answer:

- *Right Box: Anode -*
- *Left Box: Cathode +*
- *Anode: $Al_{(s)}$*
  Cathode: $Pb_{(s)}$
- *NO_3^- to the Al^{3+}/Al cell and K^+ to the Pb^{2+}/Pb cell.*
  OR



Marking Protocol:

One mark for each of the above points.

the writing of balanced half-equations (including states) for oxidation and reduction reactions, and the overall redox cell reaction in both acidic and basic conditions

the use and limitations of the electrochemical series in designing galvanic cells and as a tool for predicting the products of redox reactions, for deducing overall equations from redox half-equations and for determining maximum cell voltage under standard conditions

redox reactions as simultaneous oxidation and reduction processes, and the use of oxidation numbers to identify the reducing agent, oxidising agent and conjugate redox

Question 2e (3 marks)

Write the equations for the reactions that are occurring at the anode and the cathode as well as the overall equation.

Answer:

- Anode: $Al_{(s)}$ --> $Al^{3+}_{(aq)} + 3e^-$
- Cathode: $Pb^{2+}_{(aq)} + 2e^-$ --> $Pb_{(s)}$
- Overall equation: $2Al_{(s)} + 3Pb^{2+}_{(aq)}$ --> $2Al^{3+}_{(aq)} + 3Pb_{(s)}$

Marking Protocol:

One mark for each of the above points.

the application of Faraday's Laws and stoichiometry to determine the quantity of galvanic or fuel cell reactant and product, and the current or time required to either use a particular quantity of reactant or produce a particular quantity of product	**Question 2f** (4 marks) Assume that the mass of each of the electrodes is 3.00g and that they are 70.0% immersed in the electrolyte. If the operating current is 0.500 A, how many hours can this galvanic cell generate electricity for? Show your working.	**Answer:** $Al(s) \rightarrow Al^{3+}(aq) + 3e^-$ • *m(Al in contact with the electrolyte) = 70% x 3.0 g = 2.10 g* n*(Al) = m/M= 2.10/27 = 0.0778 mol* • *n(e⁻)= 3 x n(Al) = 3 x 0.0778 = 0.233 mol* • *Q= n(e⁻)x F = 0.233 x 96500 = 22485 C (or 22517 without rounding)* • *t = Q/I = 22485/0.500 = 44969 s = 12.49 h = 12.5 h* **Marking Protocol:** One mark for each of the above points.
the common design features and general operating principles of non-rechargeable (primary) galvanic cells converting chemical energy into electrical energy, including electrode polarities and the role of the electrodes (inert and reactive) and electrolyte solutions *critically evaluate and interpret a range of scientific and media texts (including journal articles, mass media communications and opinions in the public domain), processes, claims and conclusions related to chemistry by considering the quality of available evidence*	**Question 2g** (6 marks) Using the data from the student's research, compare the small battery and the galvanic cell. Analyse their durability, operational reliability and the materials that are used, including their structures and how they operate.	**Answer:** • <u>Durability</u>: *The battery has a robust structure that is resistant to shock and vibration. The galvanic cell is made in the lab with liquids contained in beakers; therefore, it is not robust or resistant to shocks or vibration.* • <u>Operational reliability</u>: *The battery can operate continuously for 300 hours (see Figure 4), having a long service life. The galvanic cell can operate only for around 12.5 hours. After 12.5 hours, the anode will disintegrate, the external circuit will be destroyed, the reactions will cease and the system will no longer produce electricity.* • <u>Materials used</u>: *The battery does not contain toxic metals of concern, such as mercury, lead or cadmium, making it environmentally friendly. The galvanic cell contains lead, a toxic metal; therefore, it is not a good environmental choice.* **Marking Protocol:** Two marks for each of the above points. N.B. Each point must include a comparison between the battery and the galvanic cell.