

- (b) Anode: $\text{Ag(s)} \rightarrow \text{Ag}^+(\text{aq}) + \text{e}^-$
Cathode: $\text{Ag}^+(\text{aq}) + \text{e}^- \rightarrow \text{Ag(s)}$
- (c) $\text{Ag}^+(\text{aq}) + \text{Ag(s)} \rightarrow \text{Ag}^+(\text{aq}) + \text{Ag(s)}$ $E^\ominus = 0 \text{ V}$
Working voltage must be above minimum voltage
- (d) Increase concentration of AgNO_3 in solution.
Increase voltage.

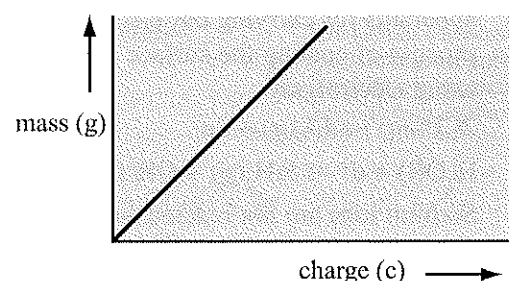
7. Need to ensure that only Cu is deposited on the cathode; other cations could interfere.
8. (a) Different half cell reactions are possible when the electrolyte is varied.
(b) Some electrodes are inert, others can be oxidised, leading to different products at the anode.
9. inert anode: $2\text{H}_2\text{O(l)} \rightarrow \text{O}_2(\text{g}) + 4\text{H}^+(\text{aq}) + 4\text{e}^-$
inert cathode: $2\text{H}_2\text{O(l)} + 2\text{e}^- \rightarrow \text{H}_2(\text{g}) + 2\text{OH}^-(\text{aq})$
10. E^\ominus for oxidation of Cu is -0.34 V . This is a lower numerical value than oxidation of Cl^- (-1.36 V) and H_2O (-1.23 V). $\text{Cu(s)} \rightarrow \text{Cu}^{2+}(\text{aq})$ requires less input of electricity.
11. $\text{Zn}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Zn(s)}$
 Zn^{2+} has a lower numerical E^\ominus value (-0.76 V) than reduction of H_2O (-0.83 V).
12. (a) $2\text{H}_2\text{O(l)} \rightarrow 4\text{H}^+(\text{aq}) + \text{O}_2(\text{g}) + 4\text{e}^-$
(b) $2\text{H}^+(\text{aq}) + 2\text{e}^- \rightarrow \text{H}_2(\text{g})$
(c) $2\text{H}_2\text{O(l)} \rightarrow 2\text{H}_2(\text{g}) + \text{O}_2(\text{g})$
(d) -1.23 V
13. H_2O is reduced in preference because reduction of water has a lower numerical E^\ominus value.
14. Br^- , I^- , OH^-
15. (a)

Electrodes used	Anode half equation	Cathode half equation	Minimum net cell voltage required
Cu	$\text{Cu(s)} \rightarrow \text{Cu}^{2+}(\text{aq}) + 2\text{e}^-$	$\text{H}_2\text{O(l)} + \text{e}^- \rightarrow \frac{1}{2}\text{H}_2(\text{g}) + \text{OH}^-(\text{aq})$	-1.17
Pt	$\text{I}^-(\text{aq}) \rightarrow \frac{1}{2}\text{I}_2(\text{s}) + \text{e}^-$	$\text{H}_2\text{O(l)} + \text{e}^- \rightarrow \frac{1}{2}\text{H}_2(\text{g}) + \text{OH}^-(\text{aq})$	-1.37

- (b) copper :
 $\text{Cu} + 2\text{H}_2\text{O(l)} \rightarrow \text{Cu}^{2+}(\text{aq}) + 2\text{OH}^-(\text{aq}) + \text{H}_2(\text{g})$
platinum:
 $2\text{I}^-(\text{aq}) + 2\text{H}_2\text{O(l)} \rightarrow \text{I}_2(\text{s}) + 2\text{OH}^-(\text{aq}) + \text{H}_2(\text{g})$
16. (a) oxygen
(b) hydrogen
(c) high chloride ion concentration
(d) concentration of electrolyte, temperature, voltage applied
(e) -1.08 V
(f) -0.84 V

13 Faraday's First Law

1. D
2. B
3. (a) $20 \text{ g Ag} = 0.1854 \text{ mol}$, so 0.1854 moles of electrons required
Charge (Q) = $96\,500 \times 0.1854 = 17\,887 \text{ C}$
(b)



4. Weigh electrodes before and after and determine difference.
5. (a) Mass of the product formed in an electrolytic cell is directly proportional to the amount of charge applied.
(b) Enables calculations to be made of the amount of electricity to be applied and its cost.
6. (a) Faraday
(b) electric charge applied
(c) use ammeter to measure the flow of current in a measured time
(d) 1 faraday or $96\,500 \text{ C}$
(e) $19\,300 \text{ C}$

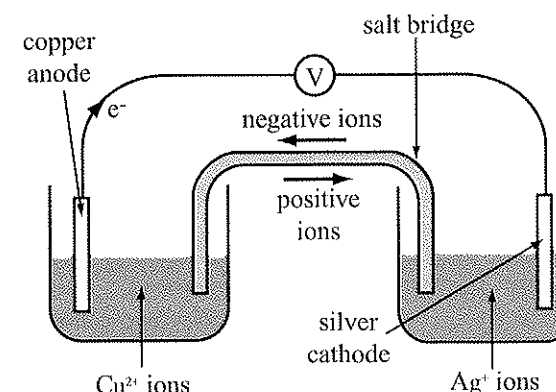
14 Revision of Galvanic Cells

1. Two half cells, each containing electrolyte and an electrode. Electrodes connected by an external wire. Electrolytes connected by a salt bridge. (This could also be answered as a labelled diagram.)
2. (a)

Reactants	Observations	Results
(i) Fe in Cu^{2+}	brown deposit, Fe dissolves	$\text{Cu}^{2+} \rightarrow \text{Cu(s)}$ $\text{Fe} \rightarrow \text{Fe}^{2+}(\text{aq})$
(ii) Zn in Cu^{2+}	brown deposit, Zn dissolves	$\text{Zn(s)} \rightarrow \text{Zn}^{2+}(\text{aq})$ $\text{Cu}^{2+}(\text{aq}) \rightarrow \text{Cu(s)}$
(iii) Cu in Zn^{2+}	no change	no reaction
(iv) Mg in Cu^{2+}	brown deposit, Mg dissolves	$\text{Mg} \rightarrow \text{Mg}^{2+}(\text{aq})$ $\text{Cu}^{2+}(\text{aq}) \rightarrow \text{Cu(s)}$
(v) Pb in Zn^{2+}	no change	no reaction
(vi) Fe in Zn^{2+}	no change	no reaction
(vii) Mg in Zn(s)	silver-grey deposit, Mg dissolves	$\text{Mg} \rightarrow \text{Mg}^{2+}(\text{aq})$ $\text{Zn}^{2+}(\text{aq}) \rightarrow \text{Zn(s)}$
(viii) Pb in Fe^{2+}	no change	no reaction

- (b) (i) $\text{Cu}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Cu(s)}$
 $\text{Fe(s)} \rightarrow \text{Fe}^{2+}(\text{aq})$
(ii) $\text{Zn(s)} \rightarrow \text{Zn}^{2+}(\text{aq}) + 2\text{e}^-$
 $\text{Cu}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Cu(s)}$
(iv) $\text{Mg(s)} \rightarrow \text{Mg}^{2+}(\text{aq}) + 2\text{e}^-$
 $\text{Cu}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Cu(s)}$
(vii) $\text{Mg(s)} \rightarrow \text{Mg}^{2+}(\text{aq}) + 2\text{e}^-$
 $\text{Zn}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Zn(s)}$

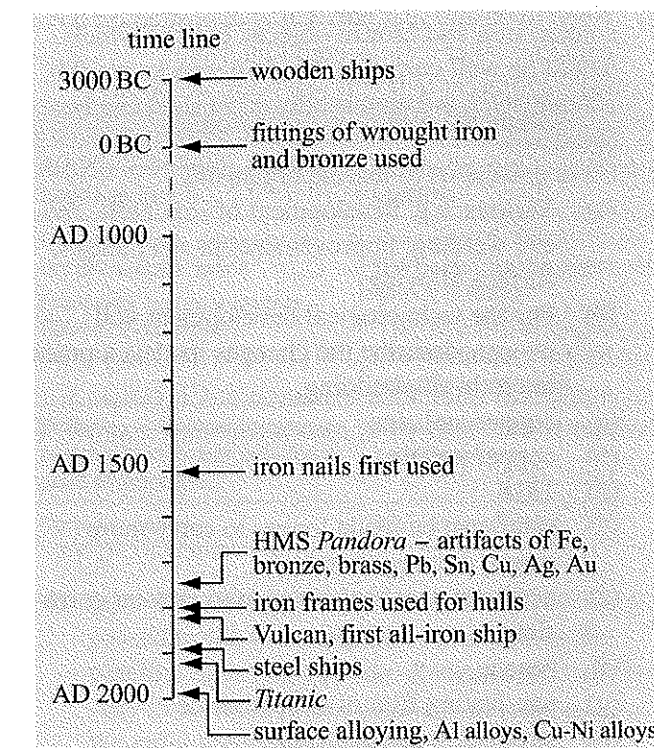
3. Order in activity series is the same as order in the standard potential table; most active metal is strongest reductant. Both depend on electron affinity.
4. 25°C , 1 M electrolyte solutions, against hydrogen half cell of $\text{Pt, H}_2/\text{H}^+$.
5. (a) Mg, Zn, Cu, Ag. Mg displaces other three, so it is the strongest reductant. Zn displaces Cu and Cu displaces Ag.
(b) (i) 0.46 V
(ii) 1.10 V
(iii) 2.70 V
(iv) 3.16 V
(v) 1.60 V
(c) Non-standard conditions. Concentration of electrolyte less than 1 M , temperature less than 25°C .
(d) The further apart the metal pairs, the greater the cell potential.



6. Electrode that does not oxidise, it just acts as a conductor. Carbon/platinum.
7. (a) zinc
(b) calcium
(c) magnesium
8. (a) anode
(b) voltmeter (in external circuit)
(c) reductant
(d) Fe

15 Ships of Iron and Steel

1. (a) Alloy of copper and zinc.
(b) Object recovered from a wreck or other archaeological site.
(c) Copper sheets used to cover wood in ships.
(d) Ships made of both wood and iron or steel.
- 2.



3. Iron ships were longer, stronger, safer, easier to shape and more economical than wood.
4. Iron is relatively unreactive, being less reactive than zinc. It is harder and holds its shape better than Cu, Pb, Ag, Sn and Au. Iron supplies were more abundant.
5. (a) A mixture of two or more metals.
(b) Alloying metals can change the physical properties and make it more suitable for a specific use.
6. (a) aluminium and copper
(b) Al — light — used in dinghies and to lighten ships and thus improve economy and speed
Cu — toxic to marine organisms — used to prevent growth of organisms on hulls
7. Not suitable for the North Atlantic Ocean, which is very cold, as the steel used was brittle at low temperatures due to the relatively high content of sulfur and phosphorus.
8. (a) light, inexpensive
(b) improved appearance, corrosion resistant
(c) improved strength, corrosion resistant
9. More economical than using an expensive alloy throughout.

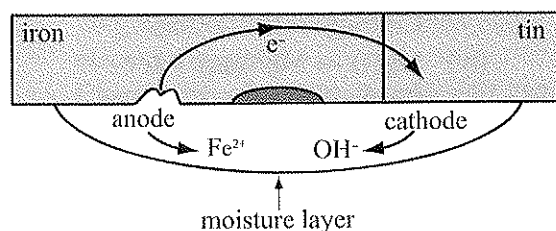
10. Silver and gold objects would be well preserved as they are relatively unreactive metals. Bronze and copper would show pitting and discolouration as signs of corrosion; however, they are harder than silver and gold so they would hold their shape better than silver and gold.
11. Types of metals present and degree of corrosion indicate age. For example, ancient wrecks would contain iron and bronze objects, both of which would be well corroded. Modern wrecks would contain steel and metals alloyed in steel can be identified.
12. Cu is poisonous to marine organisms.
13. (a) Various, e.g. development of iron nails, rivets, welding, improvements in steel alloys, surface alloying.
(b) For the technological development you choose, describe the changes its development led to in shipbuilding.
14. (a) copper and zinc
(b) copper and tin
(c) 1818
(d) safer, can be made longer to carry more cargo, more economical
(e) need constant maintenance to prevent corrosion
(f) bronze
(g) passivating film of copper oxide
(h) stronger, more malleable

16 Protection from Corrosion in the Marine Environment

- oxygen, water, an electrolyte
- $\text{Fe(s)} \rightarrow \text{Fe}^{2+}(\text{aq}) + 2\text{e}^-$
 $2\text{H}_2\text{O(l)} + 2\text{e}^- \rightarrow \text{H}_2(\text{g}) + 2\text{OH}^-(\text{aq})$
- (a) To gain strength, malleability and corrosion resistance.
(b) Steel with high nickel content or a surface alloy of chromium.
- D
- B
- C
- A
- A
- Paints and lacquers pollute the sea water as the coating deteriorates. To protect steel, coating must remain intact, so regular maintenance is required. This would require dry-docking of vessel.
- Metals are closely bound into the surface layers of the steel using a laser. Binding is very strong, so there is less environmental pollution than with coatings and the surface does not deteriorate. Process is cost effective and can be carried out

inside relatively inaccessible places such as inside pipes.

11. (a)



- (b) Iron is the stronger reductant so is oxidised.
(c) Tin is less chemically reactive than iron and so is less likely to react with food. If tin is damaged, galvanic cell forms and steel rusts.
12. (a) (i) layers of paints P and Q, both damaged and intact
(ii) amount of rusting
(iii) same steels used, same size and shape pieces, same thickness of layers of paints, shaken in same way, left in same environment, in sea water, same temperature and for the same period of time
(b) As controls, for comparison, to check validity of experiment.
(c) To see how easily the paint layer is damaged and whether the protection is lost with abrasion.

13. (a)

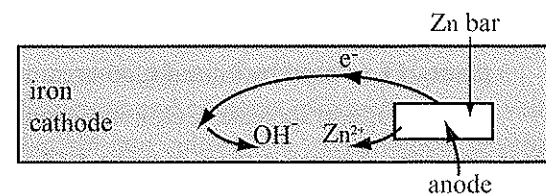
Steel sample	Observations	
	Unshaken	Shaken
Untreated	Rusted ++	Rusted +++
Tin-plated	No rust	Rusted ++++
Zinc-plated	No rust	No rust Zinc layer corroded

- (b) Intact layers of metals kept moisture and oxygen away from steel, so steel did not rust as did the untreated samples. Mechanical damage increased the amount of rust in untreated samples. Tin promoted rusting of steel as a galvanic cell was set up with steel as the anode. Zinc protected steel due to being the stronger reductant.
(c) Metal plating protects steel from rusting. A more active metal provides protection even when the layer is damaged. However, a less active metal promotes rusting once the layer is damaged.
(d) A copper coating would protect while intact, but would speed up rusting once damaged.

14. (a) nickel, manganese, chromium
(b) Rustmaster
(c) prevents ion movement
(d) polluting, maintenance required
(e) chloride ions
(f) lead
(g) keeps air and moisture away from steel
(h) anode

17 Cathodic Protection

- (a) A layer of zinc is used to coat the iron, either by dipping iron in hot zinc or by electroplating. As long as the zinc layer remains unbroken, it provides a physical barrier, keeping air and water away from the iron. If the coating is scratched or cracked, a galvanic cell is set up in which Zn is oxidised in preference to iron.
(b) When the Zn coating is scratched or cracked.
- (a)



- (b) anode: $\text{Zn(s)} \rightarrow \text{Zn}^{2+}(\text{aq}) + 2\text{e}^-$
cathode: $\text{O}_2(\text{aq}) + 2\text{H}_2\text{O(l)} + 4\text{e}^- \rightarrow 4\text{OH}^-(\text{aq})$
- (c) 1.16 V
(d) cathodic protection
(e) The anode material must be a stronger reductant than iron so that the iron becomes the cathode and the attached metal becomes the anode. The more negative the reduction potential, the stronger the reductant.
(f) Not suitable. Cannot act as anode in a galvanic cell with iron as it is a weaker reductant than iron.
(g) Mg and Al. Both have a more negative reduction potential than iron so will be more readily oxidised.
 $\text{Mg}^{2+} + 2\text{e}^- \rightarrow \text{Mg(s)} \quad -2.36 \text{ V}$
 $\text{Al}^{3+} + 3\text{e}^- \rightarrow \text{Al(s)} \quad -1.68 \text{ V}$
compared with:
 $\text{Fe}^{2+} + 2\text{e}^- \rightarrow \text{Fe(s)} \quad -0.44 \text{ V}$

(h)

Advantages	Disadvantages
Very effective protection. Long term — as long as anodes are maintained. Easy to replace anode. Low cost compared to paints and lacquers.	Anodes need to be regularly replaced. Pollutes environment. Not suitable for inaccessible structures such as underground pipes and tanks.

3.

Paint	Sacrificial anode
Regular maintenance of paint layer required.	Regular replacement of anode required.
Covers all hull, ship must be dry-docked for repair. Corrosion occurs if layer is flawed or damaged.	Only needs to be attached at a few points, can be done while ship is in water. Very effective as long as some anode remains. Damage does not affect protection.
Polluting — solvents evaporate as paint dries, water polluted as paint deteriorates.	Metal ions released to water as anode oxidises.
More expensive.	More cost-effective.

- (a) The voltage is applied so that electrons are passed to the metal pipeline. This causes the pipeline to be the cathode. Reduction occurs there. Any iron which does corrode is quickly restored to the solid metal by the potential.
(b) anode: $2\text{H}_2\text{O(l)} \rightarrow 4\text{H}^+(\text{aq}) + \text{O}_2(\text{g}) + 4\text{e}^-$
cathode: $\text{O}_2(\text{g}) + 2\text{H}_2\text{O(l)} + 4\text{e}^- \rightarrow 4\text{OH}^-(\text{aq})$
(c) Impressed current system can be maintained from the surface by ensuring a constant voltage supply. Sacrificial anode must be attached to the tank so regular access to the tank is required.
(d)

Sacrificial anode	Impressed current
No voltage supplied.	Constant voltage needed.
Anode needs regular replacement.	No parts need regular replacement.
Polluting (anode oxidises).	Non-polluting.
Very effective protection.	Very effective protection.
Cheap to set up and maintain.	Cheap to maintain, more expensive to set up.

- In both systems, the steel structure behaves as a cathode and this protects the structure from corrosion.

6. (a) In your answer you should:
 - explain the necessity for protection from corrosion in ships;
 - describe the methods of cathodic protection and the chemistry involved in these methods (with equations); and
 - compare the advantages of these methods over those previously used.
 (b) These methods allow steel structures, including ships, to be more durable (last longer) and to be safer, which reduces the overall cost and makes the use of shipping transport more affordable to people. It also reduces the likelihood of environmental damage, e.g. by oil spills.
7. In your answer you should discuss the demands of people for cheaper, faster, more versatile and more economical boats and how this drives scientists to develop better technology, including lighter, stronger and more corrosion-resistant alloys for ships. You could describe the change from predominantly wooden to mainly steel ships and the advantages of this change. Include the increase in safety required by society in ship transportation.
8. (a) Sacrificial anodes — bars of anode material need regular replacement.
Impressed currents — voltage must be constantly supplied.
(b) Corrosion will begin immediately.
9. Appearance of object, environment of structure, accessibility for regular maintenance, cost of installation and maintenance, possible environmental pollution.
10. (a) Mg, Zn
(b) zinc
(c) iron structure
(d) Mg reacts with water forming magnesium hydroxide and hydrogen. Zn is less reactive.
(e) Anode oxidises.
(f) $\text{Mg(s)} \rightarrow \text{Mg}^{2+}(\text{aq}) + 2\text{e}^-$
(g) buried structures, underground pipes and tanks

18 Ocean Depths

1. B
2. C
3. A
4. (a) Solubility decreases with increasing temperature.
(b) Solubility increases with increasing temperature, although with NaCl the increase is only slight.

5. Temperature of surface water varies from poles to equator, but NaCl solubility changes little with temperature.
6. N_2 and O_2 only form weak intermolecular bonds with solvent molecules whereas CO_2 reacts with water readily to form carbonic acid.
7. N_2 is the most abundant gas in the atmosphere (79%) but is present in very small quantities in the ocean whereas CO_2 is only 0.04% of the atmosphere, but it is the greatest concentration in the ocean. O_2 is 21% of the atmosphere, but only slightly soluble in water, giving about 1.2 mg/100 mL in surface layers.
8. (a) (i) Plants take in CO_2 for photosynthesis and release O_2 from this process. They use some of this O_2 for respiration.
(ii) Animals use O_2 in respiration and produce CO_2 as a waste product.
(b) Plants contribute a net amount of O_2 to surface layers whereas animals take in O_2 and release CO_2 . In dark depths, there are no plants. O_2 is used by animals, so organisms deplete O_2 and increase CO_2 concentrations.
9. Heat capacity of water is high. It takes $4.18 \times 10^3 \text{ J}$ of heat to raise the temperature of 1 kg of water by 1 K.
10. (a) Little difference between surface and deep layers. Depths of ocean very slightly less salty due to low temperatures.
(b) Temperature decreases with depth to near freezing below about 1000 m.
(c) Pressure increases with depth at about 1 atmosphere/100 m.
11. Complete blackness, freezing temperatures, little or no oxygen and extremely high pressure make conditions impossible for humans to survive without a purpose-built submersible.
12. (a) Increases with increase in temperature.
(b) O_2 concentration decreases with increasing temperature.
(c) As temperature increases, the rate of corrosion increases until the level of O_2 in water becomes limiting. Then the rate drops off due to insufficient O_2 for reaction.
13. (a) Prepare three samples of sea water with different O_2 concentrations as follows:
 - (i) aerate for several hours with a fish tank aerator
 - (ii) boil for several minutes and cool in a sealed container at room temperature

- (iii) leave open to the air at room temperature (control).
Take care to maintain volume and hence salt concentration of all samples during treatment. Measure O_2 levels with a data logger and O_2 probe. Record measurements.
Immerse identical steel samples in each sample for several days, at same temperature, with containers sealed.
Observe corrosion and formation of rust (or use $\text{K}_3\text{Fe}(\text{CN})_6$ indicator to test for Fe^{2+} ions in the solution).

(b)

Sample	Observations
sea water	some rust and evidence of some corrosion on steel surface
boiled sea water	no corrosion or rust evident
aerated sea water	pitted surface and a lot of rust present

- (c) Higher temperature and increased salt concentration would show greater corrosion. However, depletion of O_2 above about 40°C would limit the effect of temperature.
14. Structure and contents of wreck provide valuable insight into culture and technological development of different societies throughout history. Provide scientific knowledge related to chemistry and biology of the materials found and the environment of the ocean.
15. (a) light needed and only penetrates surface layers
(b) CO_2
(c) near freezing
(d) dissolve from atmosphere
(e) 10 atmospheres
(f) NaCl concentration varies little with temperature
(g) carbonic acid
(h) increase
(i) diffusion

19 Are Ocean Depths Conducive to Corrosion?

1.

Case for corrosion (corrosion occurs)	Case against ship corroding
<ul style="list-style-type: none"> • water has dissolved salts — good electrolyte • mainly steel ship, other metals present so galvanic cells can occur 	<ul style="list-style-type: none"> • freezing temperature • alkaline pH • no oxygen • few or no damaging organisms

2. Our group decided that the *Titanic* wouldn't corrode because it's too deep for oxygen to penetrate and corrosion needs oxygen. We also thought that the freezing temperature and alkaline pH would really slow corrosion down. So, even though there is salty water, the ship wouldn't corrode.
3. The discovery of the *Titanic* showed that the ship was badly corroded, with large outcrops of rust extending from all metal parts of the ship. The conditions were as expected, no light, freezing temperatures, high pressure, very little oxygen. However, many forms of life were found around the wreck and the pH of the surrounding sediment was acid. Scientists had thought, like our group, that there would be little corrosion.

20 Rethinking Corrosion at Depth

1. (a) Aim: To compare the rate of corrosion of iron in solutions of different pH.
Hypothesis: pH affects the rate of corrosion of iron.
(b) The product of corrosion was soluble in the acids, no rust was seen in N and O, but corrosion was greatest in the solution of lowest pH, solution N. As the pH increased, the amount of corrosion decreased.
(c) Keep all conditions standard except for pH, e.g. same salt concentration (hence same conductivity of solutions), same amount of exposure to air, same temperature. Repeat the experiment many times. Repeat using iron samples of varying composition. Improve accuracy of weighing. Make sure all corrosion products removed before weighing.
2. (a) Freezing temperature, high pressure, no light, no oxygen, pH about 8.
(b) Life was present, especially bacteria, and pH about 4.2.
(c) Bacteria are able to oxidise the iron to Fe^{2+} as a source of electrons for the reduction of sulfate to sulfide.
 $\text{SO}_4^{2-}(\text{aq}) \rightarrow \text{S(s)} \rightarrow \text{S}^{2-}(\text{aq})$
The acidic environment accelerates corrosion with the cathodic reaction $2\text{H}^+(\text{aq}) + 2\text{e}^- \rightarrow \text{H}_2(\text{g})$.
3. The many different kinds of bacteria can produce acids as wastes and the chemical reactions occurring cause acids to build up in the sediments around the wreck. Iron is a non-passivating metal and is relatively active, so it reacts with the acid to form iron(II) ions and hydrogen.
 $\text{Fe(s)} + 2\text{H}^+(\text{aq}) \rightarrow \text{Fe}^{2+}(\text{aq}) + \text{H}_2(\text{g})$