

A Short Course of Rust

Setting the Scene

You will be working as a member of the Short Courses Team at North Western University preparing to run a 4 day training course for engineers working for a Middle Eastern oil company. You will need to work through the new activities to be included in the course, checking the experiments and questions, providing written answers and specimen results and suggesting any necessary changes to the activities.

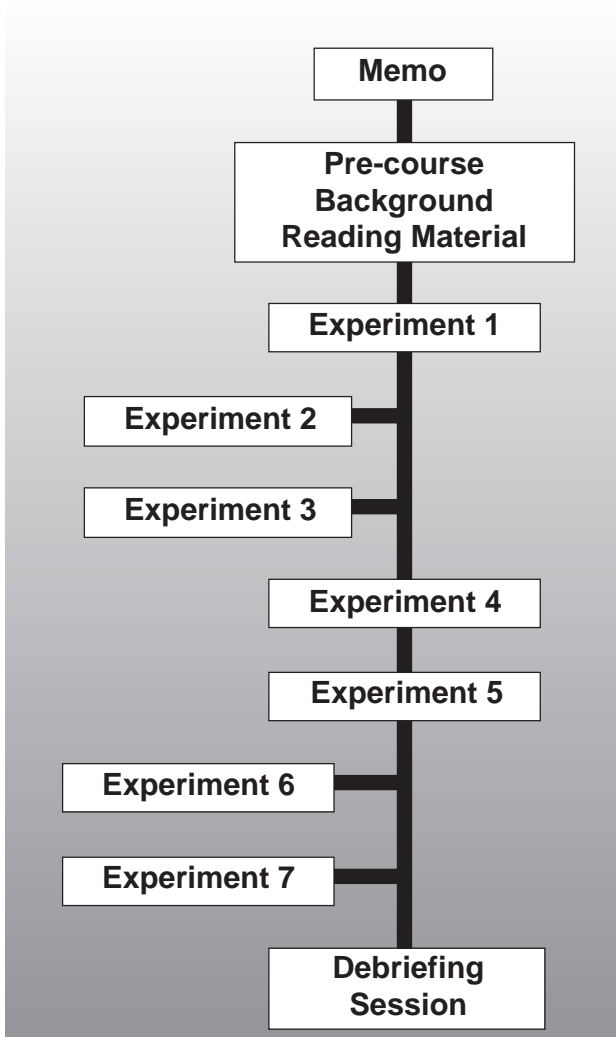
Pupil Research Brief

Study Guide

Syllabus Targets *Science you will learn about in this Brief*

- some compounds are made of ions. The ions are formed when atoms of one element gain electrons from, or lose electrons to, the atoms of another element
- the atoms which lose electrons become positively charged ions and the atoms which gain electrons become negatively charged ions
- some metals are more reactive than others
- by observing how various metals react, a reactivity series can be produced, this is a list with the most reactive metal at the top
- a more reactive metal can replace a less reactive metal from its compounds
- when they are dissolved in water, ionic compounds conduct electricity because the ions are free to move
- the current is due to negatively charged ions moving to the positive terminal (electrode) and positively charged ions moving to the negative electrode
- at the negative electrode positively charged ions gain electrons (reduction), and at the positive electrode negatively charged ions lose electrons (oxidation)

Route through the Brief



Outcome Checklist

You will produce notes on your work for the Short Courses Organiser. A memo and experimental notes guide you through the Brief. You should make sure you produce the following items as you work through the Brief.

Pre-course Background Reading Material

- a list of key learning points
- a list of questions for the course participants

Experiment sheets 1 to 7

- notes on clarity of instructions
- notes on how well experiments worked and any problems to look out for
- specimen results for each experiment carried out
- key learning points or outcomes for each experiment carried out
- worked answers for the questions set
- suggestions for any changes to the activities

Debriefing session

- summary of notes from the above items suitable for feedback to class or teacher

Corrosion and Protection Centre North Western University

Memo

From Short Courses Organiser

To Short Courses Team

Date

4-day training course for Middle Eastern oil company engineers in Dubai on the corrosion and protection of buried pipelines

Many thanks for agreeing to run the course in Dubai. As you know other colleagues have run similar courses before, but I felt we needed to make a few changes to our previous programme and so I have enclosed suggestions for some new activities. I hope you feel that these are appropriate, but since you have not run the activities before it will be a good idea if you work through the experiments yourselves, checking procedures, questions and providing written answers. It is our experience that course participants expect a set of written answers to take away after they have tackled the tasks themselves.

The course is based on practical work with follow-up questions for each practical activity. Since you will be running these practicals, please check them carefully so that you are confident they work well and also to familiarise yourself with the procedures, results and any of the potential problem areas. Where appropriate, it will be very useful to have a set of 'specimen results' from the experiments. Therefore, for each practical activity please check and report on the following points.

1. How clear are the instructions and how easy are they to follow?
2. Do the experiments generally work well, and are there any problems to look out for?
3. Obtain a set of 'specimen results' for each experiment, where appropriate.
4. Identify the key learning points or outcomes for each experiment.
5. Provide 'worked answers' for each of the questions set.
6. Make suggestions for changes, if any, to the activities.

In addition, please look through the Pre-Course Background Reading Material and (a) make a list of the key learning points, and (b) suggest some suitable questions for participants, based on the reading content.

I look forward to a debriefing before you go off to Dubai. Please file all your experimental results, answers to questions, suggestions for changes, and any notes relating to the requests above. We can go over these at the debriefing session.

S.L.

Corrosion and Protection Centre North Western University

DRAFT MATERIALS

Four-day training course on corrosion and protection.

Contents

1. Pre-Course Background Reading Material.
2. Practical Activities.
 - Experiment 1. Conditions needed for steel to corrode.
 - Experiment 2. Corrosion of steel under a droplet of salt solution.
 - Experiment 3. Corrosion protection by painting steel.
 - Experiment 4. The reactivity series of metals.
 - Experiment 5. Comparison of zinc and magnesium as sacrificial anodes.

Note: I have two further draft experiments, 6 and 7. These deal with: (i) corrosion prevention by cathodic protection and (ii) corrosion monitoring of buried structures. They would make good extension activities if time is available. See me for further details.

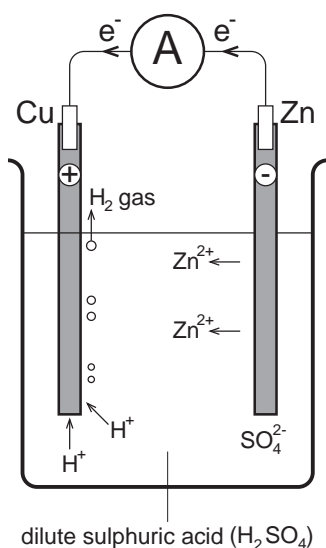
Training programme on the corrosion and protection of buried pipelines

Pre-Course Background Reading Material for Participants

The following notes have been compiled from a range of publications including research papers from journals, conference presentations, reports and text-books. The purpose of these notes is to provide you with useful and interesting background material on corrosion and corrosion protection methods in order to help you prepare for the training course you will be attending.

The Corrosion Process

When a metal corrodes an electrochemical cell is set up between different regions in the metal and its environment. In order to understand the corrosion process it is helpful to understand how a simple electrochemical cell works. For example, if zinc and copper electrodes are dipped into an electrolyte (e.g. sulphuric acid) a simple cell is set up. If the metals are in direct contact or linked by a conducting wire, an electric current will flow.



Zinc is more reactive than copper and so will dissolve in the acid more easily than copper. As the zinc slowly dissolves, zinc ions (Zn^{2+}) go into solution. They are positively charged and so they leave electrons (e^-) behind at the zinc electrode. The zinc is said to be oxidised in an anodic reaction by releasing electrons:



The electrons move through the connecting wire to the copper electrode. Here they are picked up by hydrogen ions (H^+) in the acid solution forming hydrogen gas which collects on the copper electrode. The H^+ ions are reduced in a cathodic reaction, by accepting electrons:

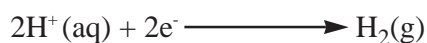


Figure 1. A simple electrochemical cell

As the reaction continues the zinc electrode will dissolve (or corrode).

Rusting of iron is an **electrochemical process** which requires both air and water. Anodic (electron releasing) and cathodic (electron accepting) areas are set up in the iron (see Figure 2 on next page).

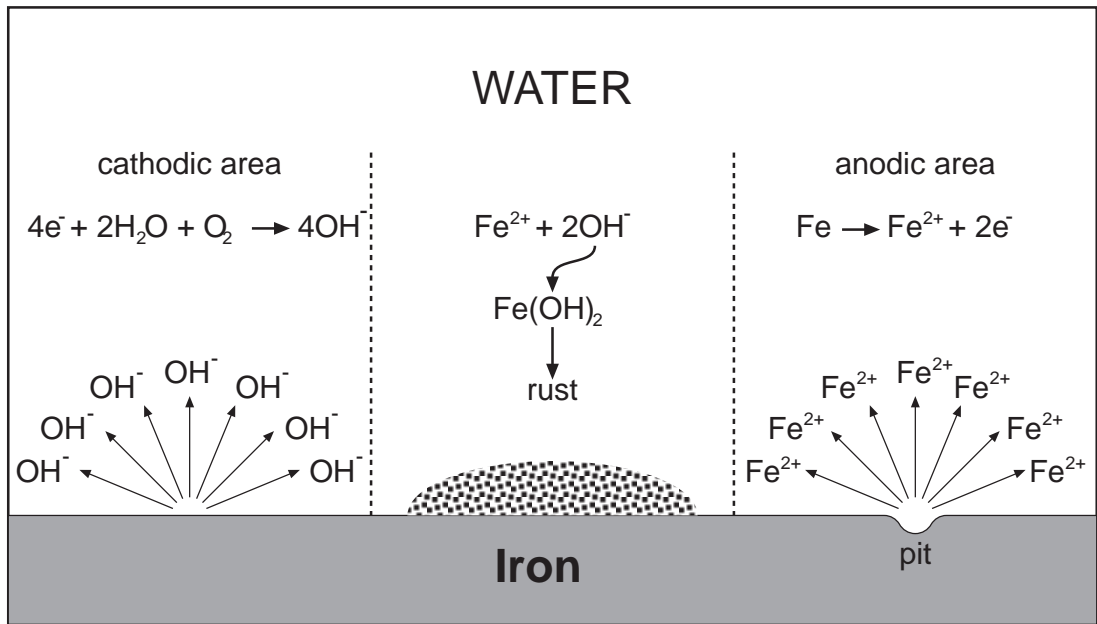
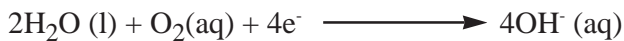


Fig. 2. Corrosion of iron in the presence of air and water

At the anodic areas, iron is oxidised and dissolves:



The electrons released flow through the iron to a cathodic area where they are accepted in a reaction with oxygen dissolved in water:



The Fe^{2+} and OH^- ions produced at the anodic and cathodic areas respectively, migrate outwards and where they meet, iron(II) hydroxide is formed:



The iron (II) hydroxide later becomes further oxidised by oxygen in the air to rust, hydrated iron (III) oxide. The iron dissolves or corrodes only in the anodic areas where 'pits' are formed in the iron.

Cathodic areas tend to be set up in the iron where the oxygen supply is good or where the iron contains alloying additions or impurities, causing other parts of the iron to become anodic and therefore corrode.

Corrosion and Corrosion Protection

1. Counting the cost of corrosion - a summary of key findings from the Hoar Report.

The last major survey of corrosion and its prevention in the U.K. was undertaken by the Committee on Corrosion and Protection under the chairmanship of Dr. T. P. Hoar. It was set up in March 1969 by the then Minister of Technology, Anthony Wedgwood Benn. This was a very large scale survey to investigate all key aspects of corrosion and its prevention including the costs to major industries, possible savings expected from improved technology, education needs, and research and development requirements.

The results, reported in 1971, conservatively estimated the costs of corrosion at £1365 million per year which represented at that time 3.5 per cent of the gross national product. These costs were made up of direct costs arising in the industries and to the users of the products, because of the need for protection, maintenance and replacement of the materials of construction. The Committee believed that a saving of approximately £310 million per year could be achieved with better use of improved technology.

It is estimated that the 1997 costs would be ten times those given for 1971!

2. Extracts from P. W. Shantery's paper: 'Underground Corrosion Control Using Pipeline Coatings and Cathodic Protection'.

Published in the Proceedings of the Conference: 'Underground Corrosion of Pipes and Structures' Oct. 1990, Gatlinburg, TN, USA.

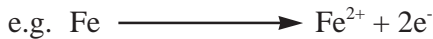
To control corrosion, the most obvious method is the isolation of the pipe by use of coatings, as practised by ancient civilisations. For example, near the pyramid of King Sahu-Re in Egypt, a 47 mm diameter copper pipe, estimated at about 4500 years old, was set into a hewn rock channel and covered with lime mortar for protection. Many different protective coatings have been used over the years including coal-tar and asphalt, asbestos, jute, glass wool, and felt wrappings in conjunction with asphalt and coal tar coating materials. Nowadays, as well as modern, high performance paints, plastic materials such as polyvinyl chloride (PVC) and polyethylene with adhesive backings and primers, are applied to pipelines during construction using machines which move along, applying the coatings during burial. Coatings reduce corrosion by providing a high electrical resistance between the metal and the corrosive external environment.

Pipe coatings alone will not protect a pipe from corrosion due to the fact that:

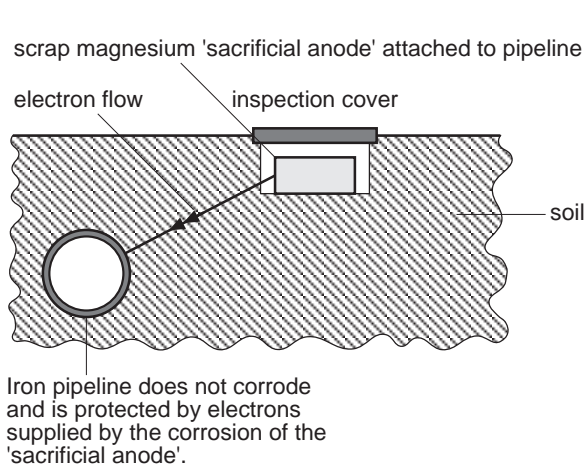
- the coating materials absorb and transmit air and water at rates dependent on their physical properties, on the environmental conditions, and on time;
- the electrical resistance of coatings decreases with service time;
- perfect pipe coatings are never achieved in practice, and in many cases may be locally damaged during burial.

To supplement the protection supplied by the coating, particularly at any holes in the coating, the application of cathodic protection is common. Steel can be protected electrically underground; either by an active anode (e.g. zinc), or by another anode and an external voltage supply (e.g. steel anode and 1.5V battery). The method is known as ‘cathodic protection’ (CP) because the protected structure is made the cathode during operation. CP can be applied using two approaches: ‘sacrificial protection’, commonly using zinc, aluminium or magnesium alloy anodes, or ‘impressed current protection’. In the latter, although steel could be used, it is preferable to use special alloy anodes with very very low corrosion rates (e.g. silicon iron, platinised titanium) and an external voltage supply.

These methods of corrosion protection work because the rusting of iron is an oxidation process which involves the loss of electrons from the iron:



If we supply electrons to the iron therefore, as happens with cathodic protection, the iron will not rust (Figure 3).



The two metals are connected electrically and the more reactive magnesium becomes the anode and the less reactive iron pipe the cathode:



The magnesium corrodes in preference to the iron. This corrosion or oxidation process releases electrons which flow to the iron cathode, thus preventing it from corroding.

Figure 3. Iron pipeline protected by electron supply in cathodic protection

Back in 1824, the Man-of-War ‘Sammarang’ was fitted with zinc bars to protect the copper cladding of the hull from corrosion. In 1906, direct current generation was used in Germany to protect 300m of buried gas and water pipelines. Kuhn reported in 1933 that cathodic protection of buried steel pipes could be monitored using a copper/copper sulphate reference electrode (1).

Cathodic protection efficiency of coated pipelines is affected by the number of defects (areas of bare metal) on the coating, and the electrical resistance of the coating material.

References

- (1) Kuhn, R.J. *Proceedings*, American Petroleum Institute, Vol.14, Section IV, 1933, p153.

3. Extracts from S.D. Heaver's paper 'Bacterial Corrosion of Underground Pipelines in the Absence of Air (Anaerobic Corrosion)'

Published in the Proceedings of the Conference 'Underground Corrosion of Pipes and Structures', Oct. 1990, Gatlinburg, TN, USA.

It has been known for some time that the corrosion of iron requires the presence of oxygen. It was quite startling therefore when corrosion of underground pipes was found to occur in soils with practically no oxygen present. The process was subsequently called anaerobic corrosion (meaning 'in the absence of air'). In anaerobic environments, steel can suffer from severe corrosion. The surface of the iron is generally covered with a black corrosion product, iron sulphide, which may be detected by adding a little acid and noting the smell of hydrogen sulphide (rotting eggs smell and very poisonous!).

Anaerobic corrosion occurs throughout the world. For example, in 1964 more than 50% of leakages from buried steel pipes were due to this type of corrosion.

Sulphate-Reducing Bacteria

Animals breathe oxygen from the air, breathing out carbon dioxide in the process known as respiration. In 1934, von Wolzogen Kühr proposed that anaerobic corrosion was caused by bacteria which use sulphur not oxygen during respiration (1). Thus, in order to grow they require sulphur as sulphate ions SO_4^{2-} and the almost complete absence of oxygen. In turn, they breath out hydrogen sulphide gas (2). Unfortunately, hydrogen sulphide is very corrosive to steel, forming iron sulphide, which can give rise to extremely fast corrosion rates underground.

Rates of Anaerobic Corrosion

Normal corrosion rates of unprotected iron underground are about 0.1 to 0.5 mm per year. However, anaerobic corrosion rates can be over 10 times these values. As pipe walls typically have less than 6 mm thickness of steel, in the worst cases they can perforate and leak in less than 2 years!

References

1. von Wolzogen Kühr, C.A.H. and van der Vlugt, L.W., *Water*, Vol.18, 1934, p147.
2. Postgate, J.R., *The Sulphate Reducing Bacteria*, Cambridge University Press, New York, 1979.

4. Current Research in Cathodic Protection

Pipeline corrosion and protection is a field where there is a great diversity of current research taking place. This includes, for example: research into the barrier properties and adhesive properties of organic tar epoxy and polythene tape coatings used to protect gas and oil pipelines, the use of voltage mapping techniques over the surface of buried pipelines under cathodic protection, to determine defects in pipe coatings, comparisons of the performance of zinc and aluminium sacrificial anodes used in buried land and offshore pipelines and structures, and the causes and effects of stray current corrosion arising from the stray currents produced, for example, by the Manchester Metrolink which interfere with the cathodic protection systems of nearby buried gas and water pipelines.

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Short Course in Corrosion and Protection of Buried Pipelines

Practical Activities

Fundamentals of Corrosion

Experiment 1: Conditions needed for steel to corrode

Introduction

When steel corrodes, rust is produced which is an hydrated form of iron oxide - FeO(OH).

Using the apparatus list below, design an investigation which would demonstrate that both oxygen (from the air) and water are necessary for steel to rust.

Apparatus : 4 mild steel nails
4 test-tubes, 2 with stoppers
anhydrous calcium chloride - **Hazard: wear eye protection and avoid skin contact**
freshly boiled water
unboiled water
oil
medium abrasive paper
labels

Investigation Report: Your report should address the points and questions outlined below.

- (1) Provide a summary outlining clearly the investigation procedure.
- (2) Give a labelled diagram of the apparatus and experimental conditions.
- (3) Give brief answers to the following:
 - (i) which nail or nails would you expect to show signs of rusting and give explanations?
 - (ii) what do your predicted results tell you about the necessary conditions for rusting to take place?
 - (iii) why was one sample of water boiled and the other not?
 - (iv) why was oil used?
 - (v) what are the reasons for using:
 - (a) anhydrous calcium chloride and (b) abrasive paper?
 - (vi) can you suggest a simple way of preventing steel from rusting?

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Practical Activities

Experiment 2: Corrosion of steel under a droplet of salt solution

Introduction

This experiment shows how corrosion occurs on a single piece of metal with two separate reactions happening at the same time. Use the apparatus and procedure below.

Apparatus: mild steel strip (approx. 4 x 4 cm)
medium abrasive paper
salt solution with indicators: (3g NaCl, 1g $K_3Fe(CN)_6$ + 10 drops of phenolphthalein solution in 100 cm³ of de-ionised water) **Hazard:**
do not swallow or allow to get in the eyes
magnifying glass
dropper pipette

Procedure and Questions

1. Clean a mild steel strip with the abrasive paper to remove all surface dirt, rust etc. After this do not touch the steel surfaces - handle only at the edges.
2. Place several drops of salt solution indicator on the cleaned surface of the metal strip. Do not let the solution spread over the surface - if it does then you have added too much solution or the surface is dirty and you will have to start again.
3. Observe the process of corrosion on the steel surface by eye, or with the magnifying glass - things should start to happen after a few minutes, particularly if you keep it very still. Write down or draw what you see:
 - at the edge of the droplet
 - at the centre of the droplet
 - in a ring between the centre and the edge.

N.B. Phenolphthalein is a pH indicator. It changes colour to pink at pH greater than 8.5; i.e. alkaline. $K_3Fe(CN)_6$ - potassium ferricyanide - is an indicator for iron ions. It changes colour to deep blue when Fe^{2+} ions are produced during the corrosion reaction of iron. Rust ($FeO(OH)$) has a brown colour.

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Practical Activities

Experiment 2: continued

- Two processes appear to be happening here on the same bit of metal. Where are they happening and what might they be?
- Where does corrosion happen? Does there appear to be any corrosion at the edge of the droplet? Can you explain your observations?
- Study Figure 1 below and use it to help explain what is happening in the corrosion process. The figure is not complete, so you can complete it by identifying letters a to g. You may find the introduction to the pre-course background reading material helpful for this.

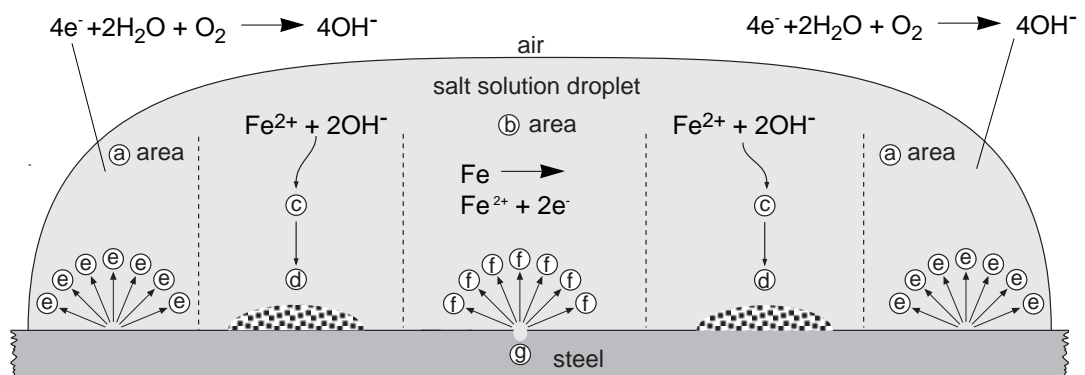


Figure 1. Salt solution droplet in contact with steel surface

- | | | | |
|---|-------|---|-------|
| a | _____ | e | _____ |
| b | _____ | f | _____ |
| c | _____ | g | _____ |
| d | _____ | | |

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Practical Activities

Experiment 3: Corrosion protection by painting steel

Introduction

Painting is the most common method of corrosion control. Generally paints function not by keeping water or oxygen from the metal surface (most paints are, in fact, very permeable), but by offering a high electrical resistance between the metal and its environment. We have seen earlier that corrosion depends on the movement of ions and if there is a high resistance to their flow, then corrosion cannot continue.

In this experiment you will investigate how painting steel might protect it from corrosion and how corrosion is affected when painted steel is damaged.

Apparatus :

- 'L'-shaped bent strips of thin, pre-painted steel (~ 4 x 20 cm)
- adhesive plastic tape
- abrasive paper
- shallow plastic tray
- 1ohm resistor, connecting wires and clips
- zinc anode
- millivoltmeter
- sodium chloride solution (1M)

Procedure

1. For each strip of steel make different size areas of bare metal 'defect' in the paint on the upper side of the longer length of steel by rubbing areas of the paint away with abrasive paper. You may also like to include either a bare steel sample (abrade all the paint away) or a completely painted sample.
2. Remove enough paint from the shorter length of steel to make an electrical connection to it with a clip.
3. If the steel strips are not painted at the cut edges, you must now protect them by covering the edges with some adhesive plastic tape. Also, tape over at the bend as the paint may have been damaged there.
4. Put one of your prepared steel strips and the zinc anode into the tray and cover them with the sodium chloride solution. Connect the strip and zinc anode across a 1 ohm resistor, (see Figure 1).
5. Now connect the millivoltmeter across the resistor and record the results in Table 1 (or a copy).

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Practical Activities

Experiment 3: Continued

- Repeat using your prepared strips with different sized defects.

Approximate size (in cm^3) of exposed bare steel	Voltage (mV) measured across resistor	Current flowing (mA) through resistor

Table 1

Questions

- Measure the voltage across the resistor and calculate the current flowing through it. Use this to complete the above table.
- Describe the relationship between the current flowing through the resistor and the area of the bare metal defect in the painted steel surface.
- How do you think paint protects metals from corrosion?
- Why must care be taken when burying a steel pipe?

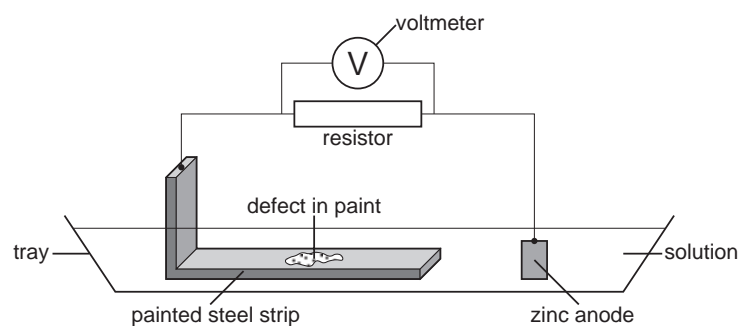


Figure 1. Set-up of apparatus to observe effect of painting and damaged paint on corrosion of steel

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Practical Activities

Experiment 4: The Reactivity Series of Metals

Introduction

This experiment demonstrates that different metals have different reactivities in solutions and that they can be placed within a 'reactivity' series in order of their reactivity. A knowledge of a metal's position in this series can help decide its ability to protect another metal from corrosion.

Apparatus: pieces of steel, copper, zinc and magnesium
beaker
abrasive paper
connecting wires and clips
voltmeter
dilute sulphuric acid (1M) - Hazard: wear goggles when handling
sodium chloride solution (1M) - optional

Part one

1. Use the abrasive paper to clean each piece of metal.
2. Place the copper in the beaker, and **wearing goggles** add a small amount of sulphuric acid. Note what happens.
3. Pour out the acid and wash the metal and beaker thoroughly.
4. Repeat steps 2 and 3 for steel, and then again for zinc and magnesium and note what happens.

Part two

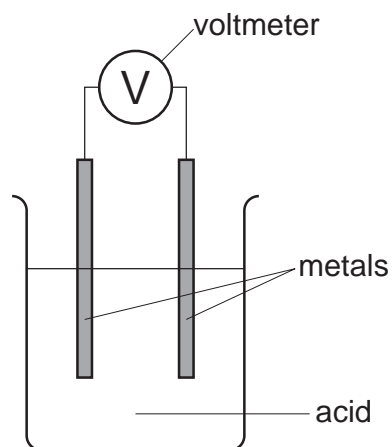
1. Clean each piece of metal with abrasive paper.
2. Connect the pieces of copper and zinc to the voltmeter, as shown in Figure 3 and record the voltmeter reading after leaving for a few minutes.
3. Observe and record what is happening to the metals.
4. Repeat this experiment with the following combinations:
 - copper and steel
 - steel and zinc
 - steel and magnesium
 - zinc and magnesium.

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Practical Activities

Experiment 4: continued



Note: if the voltmeter shows a negative reading, swap the connecting wires around.

Figure 1. Set-up of apparatus for part two investigation

5. Repeat the whole experiment, but now use sodium chloride solution, if time allows.
6. Record all your observations and results in a table.

Questions

1. Which pairs of metals have the largest voltage differences? Why is this?
2. Which is the most reactive metal?
3. Which metal is the least reactive?
4. Can you put these metals in order of reactivity?
5. How could this experiment show us how it would be possible to protect steel from corrosion with the help of another metal?

This type of protection, where one metal is 'sacrificed' or corroded in order to protect another from corrosion is called cathodic protection. The metal being protected is made the cathode and the metal which is being 'used up' is made the 'sacrificial' anode.

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Short Course in Corrosion and Protection of Buried Pipelines

Practical Activities

Experiment 5: Comparing zinc and magnesium as sacrificial anodes

Note from Short Courses Organiser to Short Courses Planning Team

I thought it might be a good idea at this point to have the course participants carry out a simple investigation to compare the use of zinc and magnesium as sacrificial anodes in the cathodic protection of steel underground pipes in different types of soil.

Different soils have different mineral content and therefore different electrical resistance to the flow of current. This is likely to affect the choice of sacrificial anode to be used in the protection of steel underground pipes.

Decisions about choices of sacrificial anode will involve consideration of rate of corrosion of anode, cost of anode, type of soil.

I suggest you keep it fairly basic using small thin strips of zinc and magnesium (to protect a piece of steel), connecting wires, beakers and the standard solutions* to represent soils of high and low resistance. Since the investigation is to compare zinc and magnesium it will of course need to be designed as a fair test.

Could you also come up with some appropriate questions to follow on from the experiment in order to test the course participants' understanding of the cathodic protection process? You will of course need to try out the investigation and make a note of the answers as usual.

* Note: standard soil solutions are available.

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Extension Practical Activities

Experiment 6: Corrosion prevention by cathodic protection

Introduction

From the reactivity series, we can predict which metals might protect iron or steel from corrosion. In this experiment we test this prediction using zinc and solutions with electrical conductivities similar to soils (it is difficult to use real soils as you cannot see easily what is happening!). The experiment also tests whether supplying an electric current to the steel bar or strip (using a steel anode and a 1.5V battery - 'impressed current') might protect the steel from corroding.

Apparatus:

- rods, bars or strips of iron or steel about 30 cm in length
- zinc rod or sheet about (2 x 2 cm)
- medium abrasive paper
- copper/copper sulphate or other reference electrode (see Figure 2) **Hazard: do not swallow or allow to get into the eyes**
- 'soil solution A' (300 mg L⁻¹ MgSO₄·7H₂O, 200 mg L⁻¹ CaSO₄·2H₂O, 350 mg L⁻¹ CaCl₂·2H₂O, 100 mg L⁻¹ NaHCO₃)
- 'soil solution B' (as solution A but diluted 10 times)
- millivoltmeter or multimeter
- 1 ohm resistor
- connecting wires and clips
- steel anode and 1.5V 'C' or 'D' battery
- laboratory stand to hold the reference electrode
- shallow tray to hold the steel rod and solution

Procedure

1. Clean your steel bar or strip and the piece of zinc with abrasive paper. Place them both into the shallow tray; make sure to keep the zinc at one end of the steel bar (see Figure 1 on the next page). Connect each of them to a length of insulated wire.
2. 'Soil solutions A and B' represent high and low electrical conductivity soils. Your course tutor will probably want some groups to investigate one solution, whilst the other groups use the other solution, although you may have time to do both. Fill the tray with your soil solution. Make sure it is sufficiently deep to cover both the steel and the zinc.

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Extension Practical Activities

Experiment 6: continued

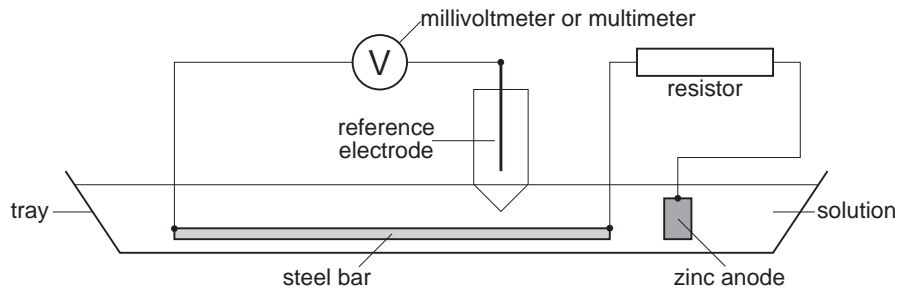


Figure 1. Cathodic protection

3. Connect the millivoltmeter or multimeter directly between the steel and the zinc and record the voltage. Make sure to connect the steel to the positive (red) terminal and the zinc to the negative (black) terminal - giving a negative voltage reading.
4. Now connect the steel and zinc together through the 1 ohm resistor and the millivoltmeter or multimeter between the steel and the reference electrode, as shown in Figure 1.
5. Record the values of voltage as a function of distance from the zinc anode end as you move the reference electrode along the length of the steel bar. Allow 1 minute for the reference electrode to stabilise at each position along the steel strip before making a voltage measurement.
6. Repeat (5), but this time using the 1.5V battery and the separate steel anode (in place of the resistor and zinc anode respectively). Make sure to connect the negative terminal of the battery to the protected steel rod.
7. Complete your table by sharing data from a team who used the other soil solution. Plot the data out on graph paper.

Note: instead of using a battery and steel anode in Step 6, you could use a magnesium anode in place of the zinc anode. You could then compare and comment on your results for the zinc and magnesium anodes.

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Extension Practical Activities

Experiment 6: continued

Questions

1. This method, using a sacrificial anode of a more reactive metal, is called 'cathodic protection'. Can cathodic protection be used to protect iron and steel structures from corrosion in other environments? Name some other environments where this method should work.
2. When will the method definitely not work?
3. The experiment above uses a sacrificial anode (zinc metal) to supply electrons to the steel to prevent it from corroding. Electrons can also be supplied to the steel using a battery or power source. Write down any advantages or disadvantages of each method that you can think of.
4. What do you think 'sacrificial' means when applied to the anode? Does the amount of zinc metal present change with time? How could you measure this?
5. What other methods can you think of which might protect steel from corrosion? (Think of everyday uses for steel objects).
6. Is there a current flowing between the zinc and the steel? How could you measure it? Measure it now; what is its value? Could you use this to calculate the corrosion rate of the zinc anode?
7. Look carefully at your results in your tables and graphs. How does the voltage (or current) change as you move the reference electrode along the steel bar, and so further away from the zinc anode and/or the steel anode and battery? What does this tell you about the effectiveness of the sacrificial anode and/or the steel anode and battery in protecting a long steel structure over its entire length. Also comment on your results for the different soil solutions A and B.
8. Imagine a long buried pipeline. How would you make sure that cathodic protection is effective for the entire length of the pipeline?

Making the reference electrode

You need a 'reference' electrode for this study. This provides a half-cell potential which is unaffected by the concentration or composition of the electrolyte. A reference electrode may be available already. However, it is quite easy to make your own (see Figure 2 on the next page).

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Extension Practical Activities

Experiment 6: continued

Apparatus:

- length of copper rod
- medium abrasive paper
- copper sulphate solution (saturated) **Hazard: do not swallow or allow to get into the eyes**
- a glass or plastic tube
- a rubber bung to fit the tube with a hole in it of the same diameter as the copper rod
- a wooden or porous plug to fit the tube, pre-soaked for a week in 0.1M sodium chloride solution
- silicone sealant (rapid cure)

Procedure

1. Push fit the wooden plug into the bottom end of the tube. **Hazard: use a screwing action and be careful so that the glass does not break.** You should seal around the plug with silicone sealant in case of leaks. You may have to let this dry for a short time.
2. Fill the tube full with saturated copper sulphate solution. Add a few crystals of solid copper sulphate to make sure it really is saturated.
3. Push fit the rubber bung into the top of the tube using a screwing action. Try to make sure that there is as little air as possible in the tube.
4. Clean the copper rod with abrasive paper then straight away push it through the bung into the solution. Leave a short length of rod out of the top of the bung. This will become your electrical connection.

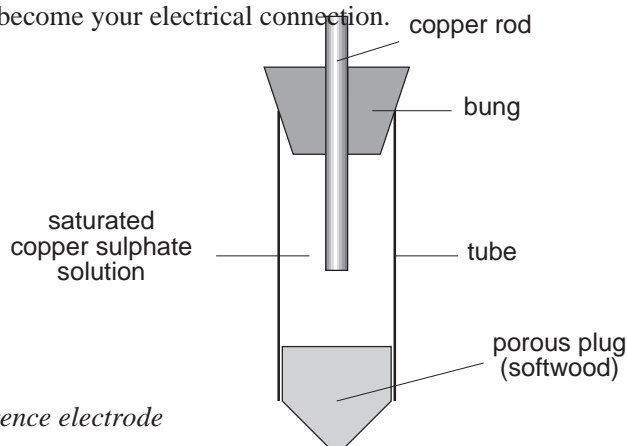


Figure 2. Reference electrode

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Extension Practical Activities

Experiment 7: Corrosion monitoring of buried structures

Introduction

We often need to know whether the paint on a buried pipe, or the cathodic protection system, is still working. Of course, we could do this by digging the pipe up but it would be very expensive! In this experiment we will investigate whether it is possible to monitor the condition of a buried structure at ground level.

Apparatus:

- strips of thin pre-painted steel (approx. 4 x 10 cm)
- adhesive plastic tape
- abrasive paper
- deep tank (eg. a fish tank)
- reference electrode (eg copper/copper sulphate) **Hazard: do not swallow or allow to get into the eyes**
- 1 ohm resistor, connecting wires and clips
- zinc anode, or steel anode and 1.5V battery
- millivoltmeter or multimeter
- washed, damp builder's sand
- backfill mixture

Procedure (see also Experiment 3)

1. Prepare a steel strip by making a 'defect' in the paint on one side of the strip. The bare metal should be approximately 1 cm² in area.
2. Remove enough paint from one end of the strip to make an electrical connection to it with a clip. Insulate this connection with plastic tape. As with Experiment 3, protect the cut edges by covering them with adhesive tape.
3. Make a wire connection to the anode material and insulate this also.
4. Put a layer of sand about 1 cm in thickness on the bottom of the container. Place the steel strip on top of the sand.
5. Fill the container completely with sand, and dig out a hole in which to place the zinc anode. Fill the hole with the backfill mixture and then push the zinc into it.
6. Connect the zinc anode and steel strip together via the 1 ohm resistor.
7. Connect the millivoltmeter or multimeter between the reference electrode and the steel strip. Map the surface of the sand with the reference electrode, noting the voltages at each point. Write down the voltages on a piece of graph paper with the X and Y axes representing the surface of the sand.

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Extension Practical Activities

Experiment 7: continued

Activities

1. Can you locate the positions of the anode and the steel strip by looking at the voltages measured on the top of the sand?
2. Can you locate the defect on the steel strip?

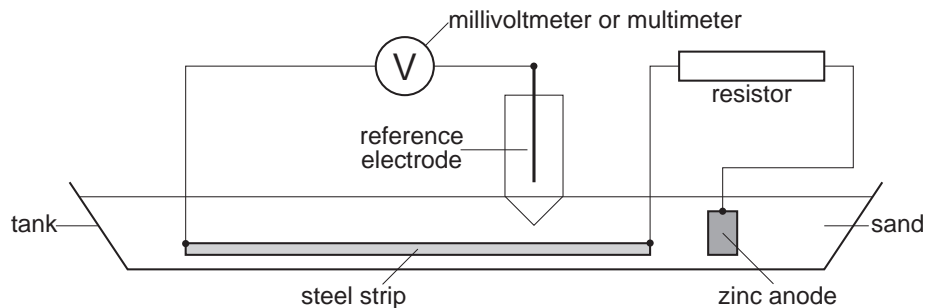
Variations

1. Repeat the experiment using strips with larger and smaller defects and/or strips with the same size defects but at different depths in the sand.
2. Repeat using a steel anode with different numbers of batteries in place of the steel anode.

Long-term test

1. Leave a steel strip connected to a pre-weighed zinc anode buried in the sand for one or two weeks. Map the surface at intervals (between measurements cover the sand in the container with a plastic sheet to stop it drying out). Does the pattern of measured voltages change with time?
2. Remove both the strip and the anode from the sand. Clean the zinc anode and reweigh it. Has it changed mass?
3. Look closely at the paint on the surface of the steel strip, especially close to the edge of the defect (use a magnifying glass). Do you see any changes in the paint? Try pulling the paint off with sticky tape. Does it come off easily? How does its adhesion compare to the paint on a new strip?

Figure 1. Corrosion monitoring of buried structures



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Extension Practical Activities

Distance along steel rod from anode end (cm)	Voltage readings			
	Zinc anode in soln. 'A'	Zinc anode in soln. 'B'	Steel anode plus battery in soln. 'A'	Steel anode plus battery in soln. 'B'
2				
4				
6				
8				
10				
12				
14				
16				
18				
20				
22				
24				
26				

Results table for Experiment 6