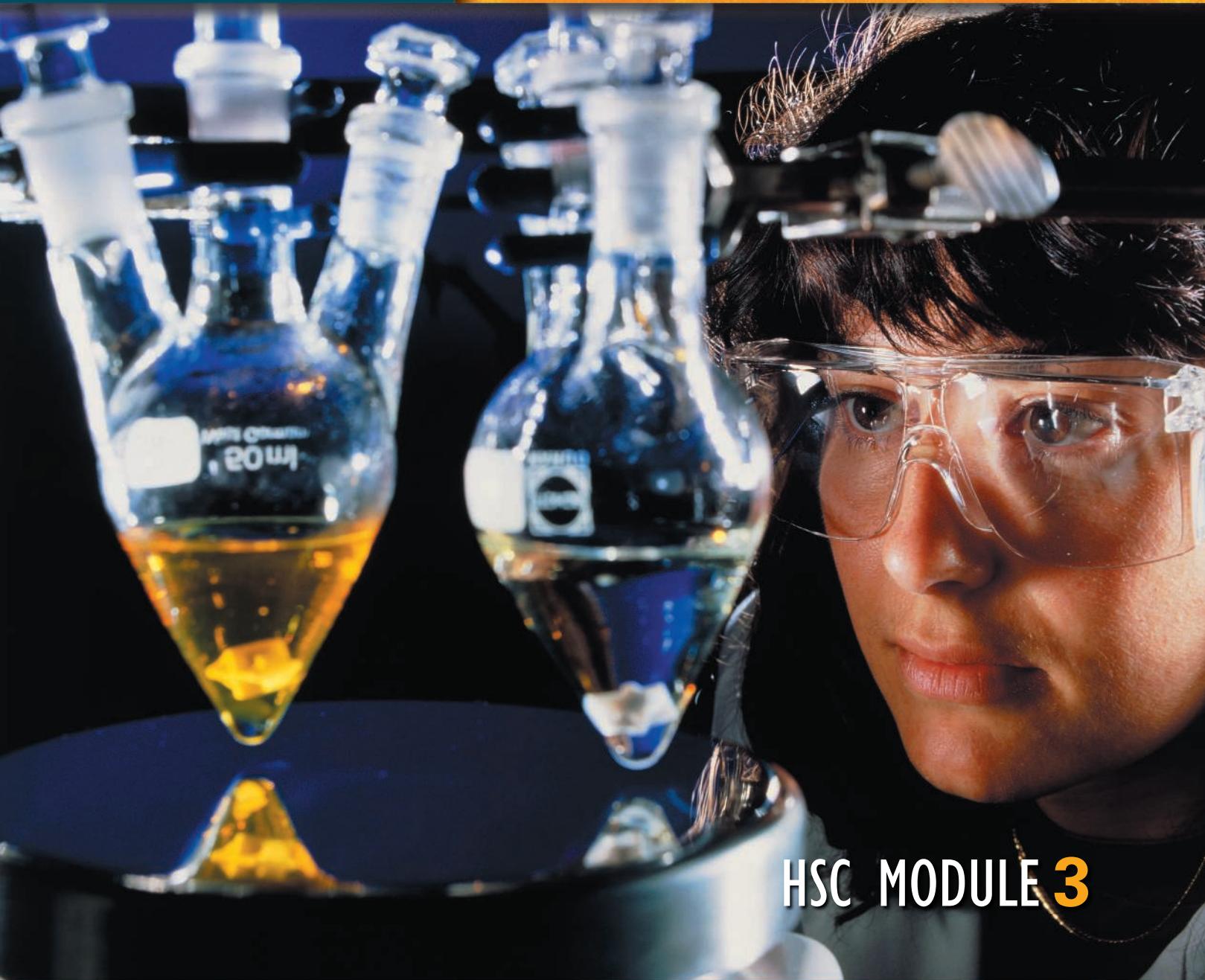


- Chapter 11  
The industrial chemist
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# CHEMICAL MONITORING AND MANAGEMENT



HSC MODULE 3

# Chapter

# 11

# THE INDUSTRIAL CHEMIST



**Figure 11.1**

An analytical chemist uses a wide variety of instruments to analyse different materials including soils, food, alloys and drugs.

## Introduction

As a senior chemistry student at high school you may have already had some experience in applying for a part-time job. Should you continue your chemistry studies at university or TAFE you will certainly be reading advertisements for employment in chemical industries. Chemistry graduates are employed in a diverse range of industries including mining, pharmaceuticals and plastics, as well as in government agencies and universities.

## In this chapter

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| 11.1 The work of an industrial chemist | page 235 |
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## 11.1 THE WORK OF AN INDUSTRIAL CHEMIST

### Remember

Before beginning this section, you should be able to:

- gather information from secondary sources by accessing information from a range of resources including popular scientific journals, digital technologies and the Internet
- evaluate the relevance of first-hand and secondary information and data in relation to the area of investigation
- identify the sources of pollution that accompany the combustion of organic compounds, and explain how these can be avoided.

### Key content

By the end of this section, you should be able to:

- outline the role of a chemist employed in a named industry or enterprise, identifying the branch of chemistry undertaken by the chemist and explaining a chemical principle that the chemist uses
- identify the need for collaboration between chemists as they collect and analyse data
- describe an example of a chemical reaction such as combustion, where reactants form different products under different conditions and thus would need monitoring
- gather, process and present information from secondary sources about the work of practising scientists identifying (a) the variety of chemical occupations and (b) a specific chemical occupation for a more detailed study.

**monitoring:** observing and undertaking chemical checks to ensure compliance with standards

**Figure 11.2**

Forensic scientists often major in chemistry during their university studies. As part of their work, they analyse materials such as paint, fibres, plastics, glass, soil and bones. They use a wide variety of instruments to assist in their analysis.

### The role of a working chemist

Chemists employed in the industrial sector have many roles including the following.

- Designing chemical processes for the manufacture of a chemical product to ensure the rate of the reaction and yield of product are optimised.* The *development chemist* works with and supervises skilled laboratory technicians. Collaboration and teamwork are essential as data is collected and analysed. The chemist's role is to determine the appropriate conditions to perform the reactions on an industrial rather than a laboratory scale. They develop safe procedures that will be used later for quality control.
- Working with chemical engineers to design the equipment to carry out the industrial process.* These *production chemists* supervise the production process and ensure quality control of the final product. Various instrumental techniques involving the use of equipment such as chromatographs and spectrometers are commonly employed by the analytical chemists to monitor the quality of the products. Production chemists also ensure that Environment Protection Authority (EPA) guidelines related to emissions and effluents are followed so that the environment is not polluted.
- Undertaking ongoing research to improve the product or process or to develop new products.* The *product development chemist* is a research position. A *research chemist* often works in a team headed by the chief chemist. The team has regular meetings to plan their research and to develop new ideas for the production of new or improved products. The team then undertakes experiments to test their ideas. They publish technical reports on their investigations. These papers may form the focus of conferences. Following successful consumer testing, a marketable product eventually emerges.



- Monitoring work practices to ensure the safety of all chemical employees.* A thorough knowledge of the safety issues described in the material safety data sheets (MSDS) is mandatory for all personnel. One of the chemists will act as a safety officer to ensure compliance.

Teamwork, collaboration and communication skills are important for all those working as chemists. Any one company may employ many different types of chemists. Some members of the team may be skilled in analytical work while others have skills in preparative or theoretical chemistry. Increasingly, chemists are trained in a variety of disciplines and may graduate as physical chemists, agricultural chemists or forensic chemists.

There is a great variety of chemical occupations. Some of these are listed below.

### Environmental chemists

Environmental chemists are employed by a wide variety of organisations, including mining companies, the Environmental Protection Authority and local government. Environmental chemists have developed expertise in analytical chemistry during their training. They collect, analyse and assess environmental data from the air, water and soil. Water resource authorities and air quality management authorities employ environmental chemists who monitor water and air samples for pollutants. Environmental chemists have strengths in analytical procedures and instrumental analysis. Following their analyses, environmental chemists write concise reports about their investigations.

### Metallurgical chemists

**metallurgy:** science of the properties of metals

**Metallurgical** chemists have high-level knowledge of metals, alloys and ores and their reactions. Metallurgical chemists specialise in all aspects of the use and development of metals and alloys in our technological society. In mining companies they design and monitor methods of extracting metals from ores. They investigate ways that metals could be combined with other materials such as polymers or ceramics. Metallurgical chemists are also employed in industries such as metal manufacturing and chemical engineering. In production-based industries the metallurgical chemist will be involved in optimising plant performance and developing new procedures.



**Figure 11.3**

A metallurgical chemist monitors the quality of the aluminium at each stage of a production process.

### Biochemists

Determining the chemical structure and functions of molecules (such as carbohydrates, fats, proteins and nucleic acids) in living things is the

major role of a biochemist. In their university training, biochemists have studied organic chemistry and biochemistry. New medical, industrial and agricultural products are developed as a result of their research. Biochemists may be employed in a wide variety of areas including pharmaceutical laboratories, hospitals and in the food and agricultural industries.

## Monitoring combustion reactions

Chemists and chemical engineers are actively researching new combustion technologies. Discovering new ways to improve the efficiency of fuel combustion and minimise pollution is an important area of research. New combustion technologies will significantly reduce energy costs, boost productivity and help to clean up greenhouse gas emissions. For example, NGPC (new generation pulse combustion) is a developing technology that allows unburnt exhaust gases to be recirculated; the flame that results is much hotter and cleaner. The recirculation is achieved by combining the pulsing effect of the sound waves produced in the combustion process with a new geometry of the burner and combustion chamber. The pulsing combustion process draws in new air, and the flame consists of a series of 'flamelets', which are ignited by the hot products of the previous flamelets.

Developmental studies carried out at CSIRO laboratories have shown the technique to be promising in that zero levels of unburnt hydrocarbons and carbon monoxide have been achieved. Until this breakthrough by the CSIRO, it had been impossible to keep a pulsing flame burning at low burning rates.

## SYLLABUS FOCUS

### 22. USING INSTRUCTION TERMS CORRECTLY

When answering questions, it is important to know what the instruction terms ('verbs') require you to do. Here is an example:

**'Contrast'**

This instruction word requires you to say how things are different or opposite.

***Example:***

Contrast the work of development and production chemists in industry.

***Answer:***

The development chemist works with and supervises skilled laboratory technicians to collect and analyse data. The development chemist's role is to determine the appropriate conditions to perform the reactions on an industrial rather than a laboratory scale. In contrast, the production chemist supervises the production process and ensures quality control of the final product. Production chemists use various instrumental techniques to monitor the quality of the products. Production chemists also ensure that EPA guidelines related to emissions and effluents are followed so that the environment is not polluted.

Using current technologies, chemists and technicians must monitor the emissions from combustion reactions in order to ensure that the minimum amounts of toxic materials are released into the environment. Toxic emissions result from incomplete combustion reactions as well as other reactions that occur in association with the main combustion process. Thus, sulfur dioxide is released by the combustion of sulfur compounds in coal and fuels derived from crude oil. The high temperatures in internal combustion engines lead to the reaction of nitrogen and oxygen in the air to form nitrogen oxides.

## Monitoring and managing combustion in the internal combustion engine

Let us examine the combustion of petrol in an internal combustion engine. In a plentiful supply of oxygen the octane, C<sub>8</sub>H<sub>18</sub>, can burn completely to form carbon dioxide and water.

### Complete combustion



In most engines there is normally insufficient oxygen to achieve complete combustion. The incomplete combustion normally occurs with the release of carbon monoxide and/or soot. Unburnt fuel vapours are also emitted in the exhaust gases. The following equations suggest some possible stoichiometries during incomplete combustion of octane.



**Figure 11.4**

The exhaust gases emitted from internal combustion engines are composed of many vapours and particulates, including carbon monoxide, unburnt fuel and soot.

### Incomplete combustion

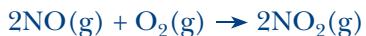
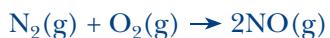
#### (a) Formation of carbon monoxide



#### (b) Formation of carbon monoxide and soot



At the high temperatures in the engine, nitrogen and oxygen combine to form nitrogen oxides (NO<sub>x</sub>).



**gas-liquid chromatography (GLC):** separation and analysis of mixtures of gases based on their differential absorption while passing through (in a carrier gas stream) tubes containing granulated particles coated with a thin liquid film

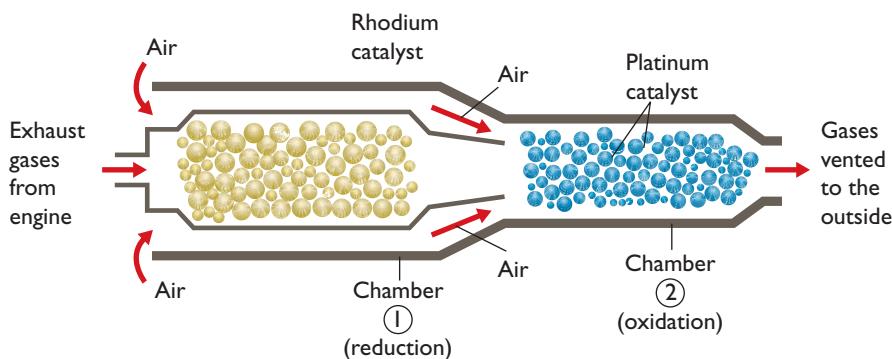
**Gas-liquid chromatography (GLC)** analysis of exhaust gases from internal combustion engines using liquid hydrocarbon fuels shows that the concentration of carbon monoxide is low when the engine is operating at high speed with maximum oxygen intake, but high when the engine is operating at low speed. The reverse is true of the nitrogen oxide content of the exhaust gases. The high temperatures in the engine produced by near complete combustion promote the formation of NO<sub>x</sub> whereas when the engine is operating at low speed, the concentration of these pollutants is low.

The engine must be tuned to reduce emissions and achieve optimum power performance.

## Catalytic converters and emission control

Industrial chemists have developed catalysts that help to reduce carbon monoxide, nitrogen oxide and unburnt hydrocarbon emissions from vehicle exhausts. Catalytic converters are made from alloys of rhodium and platinum that operate at temperatures as low as 150°C. They speed up reactions that convert pollutant gases to materials which are present in the air naturally. Unburnt fuel vapours are also oxidised on the catalyst's surface.

In order for the catalyst system to work, oxygen sensors must be fitted to monitor the exhaust gases. Electronic feedback controls the fuel injection system so that the correct amounts of fuel and oxygen are mixed prior to combustion. This process ensures that there is sufficient oxygen for the oxidation of both CO and hydrocarbons on the catalyst, as well as providing conditions for the reduction of NO<sub>x</sub> to nitrogen. This system is also known as a 'three-way' system. The reactions involved are:



**Figure 11.5**

The three-way system of catalytic converters turns NO into nitrogen and CO into CO<sub>2</sub>. Unburnt fuel is converted to carbon dioxide and water.

### Step 1: Rhodium catalyst in first chamber



### Step 2: Platinum catalyst in second chamber

Additional air is added to the exhaust gases for this step.



Table 11.1 compares emissions from a normal car engine to one fitted with a computer controlled three-way catalytic converter.

**Table 11.1** Effect of the use of a three-way catalyst on emissions

Pollutant	Exhaust pollutant concentration (ppm)	
	Normal engine	Engine with three-way catalyst
carbon monoxide	8300	<100
nitrogen oxides	2500	500
hydrocarbons	1800	<100

In most modern engines, a lean fuel mixture is used. A lean mixture has more than the required stoichiometric amount of air (oxygen) to burn the fuel. Typically in lean engines, this is a 1:18 ratio of fuel to air (by mass) compared with a 1:14 ratio in a normal engine. The benefits are that less CO and unburnt fuel vapours are produced and the additional NO<sub>x</sub> that

is formed due to the higher combustion temperatures are removed by the catalytic converters. Lean-burn engines will work efficiently only when the fuel-air mixture is computer controlled. This is called *electronic fuel injection*.

### Monitoring combustion in various industries

Let us investigate the role of an industrial chemist in the steel industry or in a coal-fired power station. An important part of their role would be to monitor and manage the level of combustion products released to the environment. The exhausts that will be released to the environment would be continuously monitored to determine the concentrations of carbon monoxide, unburnt hydrocarbons, nitrogen oxides and sulfur dioxide using gas probes and gas chromatographs linked to computer control systems. Levels of particulate matter (such as soot and aerosols of metal oxides) as well as sulfuric acid aerosols would also be monitored by collecting and analysing samples removed from the waste gas stream.



**Figure 11.6**

Various sensors can be used to monitor the levels of gases in an exhaust stream.

In smaller industries where flue gases emitted from boilers and combustion turbines must be monitored by EPA regulations, mobile laboratories can be contracted to make regular visits to monitor emission levels on-site. Such mobile emission testing labs consist of a truck outfitted with modern instrumentation (e.g. high-performance gas-liquid chromatographs and mass spectrometers) that can be linked to sampling ducts in the combustion chamber. Mass emission rates of pollutant gases are measured under a variety of load conditions and the results compared to EPA

regulations. Adjustments have to be made to the combustion chamber wherever the levels of emissions fail to meet EPA standards.

Coal usually contains variable amounts of sulfur compounds. On combustion, sulfur dioxide and sulfur trioxide will form. Sulfur trioxide levels in the vapour state, as well as the amount deposited on the fly ash, is monitored by industrial chemists to ensure the environment is not contaminated by sulfur trioxide levels above the EPA standards. Where sulfur trioxide is present in the gas stream it dissolves in water vapour to form sulfuric acid aerosols. The concentration of the sulfuric acid can be determined by measuring the acid's dew-point temperature (ADT). The temperature at which droplets of sulfuric acid will just condense from the saturated vapour state onto a cooled surface is the technique used to measure ADT. This temperature is directly related to the sulfuric acid concentration in the vapour state.

## 11.1 DATA ANALYSIS

Chemical careers  
– polymer chemist

## 11.1 Questions

1. Chemists work in a wide variety of industries. Identify the type of chemist who would be involved in each of the following activities.
  - (a) Investigating the chemical reactions involved in starch production in a rice crop
  - (b) Monitoring the gaseous emissions from a steel manufacturing company
  - (c) Developing and testing new alloys of copper
  - (d) Studying the properties of adhesives and paints
2. (a) Define the following terms.
  - (i) complete combustion
  - (ii) incomplete combustion

(b) Write a balanced equation for the combustion of methane in which the combustion process is:

  - (i) complete
  - (ii) incomplete, and CO and CO<sub>2</sub> are formed in a ratio of 4 : 1.

(c) The combustion of natural gas may be used to provide heat energy to a water boiler in a hospital. Identify the monitoring procedures and the instruments used by an industrial chemist to ensure that the combustion process was working efficiently.
3. Ethyne, C<sub>2</sub>H<sub>2</sub>, is a member of the hydrocarbon homologous series called *alkynes*. Ethyne burns in air to produce copious quantities of soot as well as some carbon monoxide, carbon dioxide and water vapour.
  - (a) Write a balanced equation for the combustion of ethyne in which soot and carbon monoxide are produced in a 5 : 1 mole ratio.
  - (b) Explain, in terms of the oxygen : fuel ratio, how more complete combustion of ethyne could be achieved.
  - (c) (i) Explain how the complete combustion of ethyne could be achieved.  
(ii) Write a balanced equation for the complete combustion of ethyne.
  - (d) The enthalpy change for the complete combustion of ethyne is -1301 kJ/mol  
(i) Classify this reaction as exothermic or endothermic.
4. All modern cars that burn unleaded petrol use catalytic converters in their exhaust systems.
  - (a) Explain the purpose of these catalytic converters.
  - (b) Identify the metals present in these catalysts.
  - (c) Write an equation to show the oxidation reaction that reduces carbon monoxide levels in vehicular exhausts.
  - (d) Explain how the catalytic converter removes unburnt fuel vapours from the combustion product mixture.
  - (e) A catalytic converter is fitted to a normal engine that is producing 7500 ppm of carbon monoxide. The level of carbon monoxide in the exhaust is reduced to 75 ppm with the converter. By what factor has the level of carbon monoxide been reduced in the exhaust?
5. In a petrol engine the fuel vapour is burning explosively. As a consequence the temperature in the combustion cylinders is very high (~2800°C).
  - (a) Under these high-temperature conditions, the major gases in the air combine to form nitric oxide. Write a balanced equation for this reaction.
  - (b) Explain, with the aid of an equation, how the three-way catalytic converter removes the nitric oxide from the exhaust gas.
  - (c) Engine technology has improved by redesigning engines to have hemispherical tops so that there are no cool spots in the cylinder.
    - (i) Explain why cool zones are undesirable in the combustion cylinders.
    - (ii) Temperature sensors allow the temperature of the engine to be monitored. If the temperature sensor detects that the engine is cold, predict whether the air-fuel metering system will activate to let in more air, or to reduce the air supply.

## 11.2 THE HABER PROCESS

### Remember

Before beginning this section, you should be able to:

- define Le Chatelier's principle
- identify factors that can affect the equilibrium in a reversible reaction
- describe the role of catalysts in chemical reactions,
- explain the role of catalysts in changing the activation energy and hence the rate of chemical reaction.

**feedstock:** materials required for an industrial process; feedstocks may be natural raw materials or processed raw materials

### Key content

By the end of this section, you should be able to:

- identify and describe the industrial uses of ammonia
- identify that ammonia can be synthesised from its component gases, nitrogen and hydrogen
- describe how the synthesis of ammonia occurs as a reversible reaction that will reach equilibrium
- identify the reaction of hydrogen with nitrogen as exothermic
- explain why the rate of reaction is increased by higher temperatures
- explain why the yield of product in the Haber process is reduced at higher temperatures using Le Chatelier's principle
- explain why the Haber process is based on a delicate balancing act involving reaction energy, reaction rate and equilibrium
- explain how the use of a catalyst will lower the reaction temperature required and identify the catalyst(s) used in the Haber process
- analyse the impact of increased pressure on the system involved in the Haber process
- explain why monitoring of the reaction vessel used in the Haber process is crucial, and discuss the monitoring required
- gather and process information from secondary sources to describe the conditions under which Haber developed the industrial synthesis of ammonia, and evaluate its significance at that time in world history.

### The uses and importance of ammonia

Ammonia is a choking gas which produces an alkaline solution when dissolved in water. Solutions of ammonia in water are used domestically as cleaning agents to dissolve and remove grease and dirt from floors and windows. Ammonia can also be used as a refrigerant gas.

Ammonia is the **feedstock** for a large variety of industrial chemicals. The production of various types of fertilisers accounts for over 80% of the worldwide use of ammonia. Some of these uses of ammonia are listed in Table 11.2.

**Table 11.2** Uses of products derived from ammonia

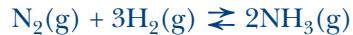
Industrial product derived from ammonia	Use of product
urea ammonium sulfate ammonium nitrate ammonium hydrogen phosphate	fertilisers
nitric acid	production of explosives such as TNT, nitrocellulose and nitroglycerine; production of nitrate salts; strong laboratory acid
acrylonitrile	acrylic plastics
diaminoalkanes	nylon plastics
cyanides	extraction of gold from gold veins
hydrazine	rocket propellant
sulfonamides	antibiotic drugs
aniline derivatives	dyes
alkylammonium hydrocarbons	cationic detergents

### Industrial manufacture of ammonia

The production of industrial chemicals often involves balancing the conditions of the reaction so that the products are produced at a fast rate and the quantity of product (the **yield**) is maximised. Industrial chemists are employed by companies to undertake research to find faster and more efficient ways of producing their product. In industry, time is money!

Ammonia is manufactured by a process first developed by Fritz Haber in the early twentieth century (see Data Analysis 11.2). Haber manufactured ammonia from its component gaseous elements. The reaction is an example of an exothermic equilibrium.

The standard enthalpy change ( $\Delta H^\circ$ ) for the reaction is  $-92\text{ kJ/mol}$ .



At standard conditions of temperature and pressure this equilibrium lies well to the left, and very little ammonia is present in the equilibrium mixture. The conditions used in the Haber process, however, make the process viable as a means of manufacturing ammonia on a commercial scale.

**yield:** the quantity of product formed in a process; usually expressed as a percentage of the expected amount of product

Ammonia was used in the nineteenth century to revive ladies who fainted at high society functions.

Ammonia can be generated in small amounts by burning feathers.



**Figure 11.8**

The Burrup Fertiliser plant uses desalinated water from the Indian Ocean for the ammonia process.

## Feedstocks for the Haber process

The ammonia industry requires supplies of nitrogen and hydrogen. These are derived from such common feedstocks as air, water and natural gas. The company *Incitec Fertilisers* has ammonia plants in Newcastle and Brisbane. The ammonia produced is not only used to make solid fertiliser, but is also applied directly to the soil in anhydrous gaseous form from tanks containing liquefied ammonia. The world's largest ammonia plant, built by *Burrup Fertilisers*, has come into operation on the Burrup Peninsula in Western Australia. A desalination plant converts sea water to fresh water, which is required for the ammonia process. The liquid ammonia produced (760 kilotonnes per annum) will be shipped directly from this coastal facility to India for the manufacture of ammonium phosphate fertiliser.

The source of hydrogen varies from one plant to another.

### Nitrogen

Filtered air is the source of nitrogen for the Haber process. Air contains ~78% nitrogen by volume. An expensive method of extracting nitrogen from the air is to fractionally distill liquefied air. Nitrogen has a lower boiling point than oxygen and so distils off before the oxygen.

More commonly, the nitrogen required for the Haber process is extracted from the air using chemical reactions involving natural gas or methane. This process also yields the hydrogen required for the Haber process as described in the next section.



**Figure 11.7**

Nitrogen is essential for plant growth, and nitrogen is a major component of fertilisers. Urea and ammonium nitrate are important fertilisers. They can be made from ammonia.

### Hydrogen

Hydrogen can be obtained by the electrolysis of salt water. The electrolysis of salt water is used in the chlor-alkali industry to produce sodium hydroxide and chlorine. The hydrogen that is a by-product can be sold to the ammonia industry as a feedstock for the Haber process.

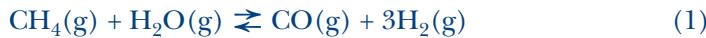


Hydrogen is also obtained electrolytically in regions such as Tasmania where extensive hydroelectricity is generated.

More commonly, the hydrogen is derived from the steam reforming of natural gas, which is composed mainly of methane, CH<sub>4</sub>. Regions such as coastal Western Australia utilise some of their plentiful supply of natural gas for the production of hydrogen.

The following steps are used in extracting the hydrogen from the natural gas and introducing the required nitrogen gas into the mixture.

1. Natural gas is purified to remove sulfur compounds that will ultimately ‘poison’ the Haber catalyst. The impure natural gas is mixed with hydrogen over a cobalt/nickel/alumina catalyst. Hydrogen sulfide is formed and this is removed by reaction with zinc oxide to produce zinc sulfide solid and water vapour.
2. The hydrogen is extracted from the pressurised natural gas by reacting the natural gas with steam over a nickel catalyst at 750°C in a furnace. Carbon monoxide and some carbon dioxide are also formed. This process is called *primary steam reforming*. About 90% of the methane is consumed. The reaction is endothermic ( $\Delta H = +210 \text{ kJ/mol}$ ).



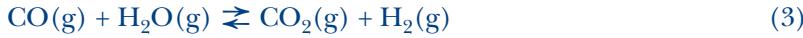
3. Air (oxygen + nitrogen) is then introduced and some of the hydrogen burns in the added oxygen to produce steam. The nitrogen remains unreacted. The higher temperatures (~1000°C) produced by the combustion of some of the hydrogen ensures that almost all of the remaining methane combusts to form carbon dioxide, or reacts with the steam to produce carbon monoxide and more hydrogen (via reaction 1). These reactions are exothermic.



4. Carbon monoxide is removed from the gaseous mixture by passing the cooled gas mixture in turn over two different catalysts. The carbon monoxide combines with steam to generate carbon dioxide and hydrogen. It is important to remove the carbon monoxide as it would poison the Haber catalyst. The CO level is reduced to 0.2%. The reaction is exothermic, and the heat released is recovered for further use.

Catalyst 1: iron oxide (~400°C)

Catalyst 2: copper (~200°C)

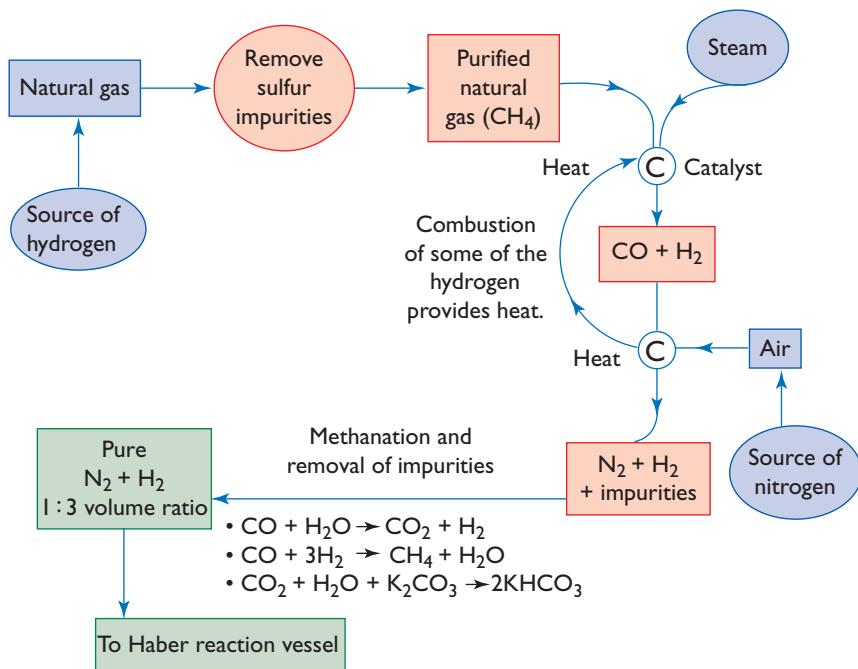


5. The acidic carbon dioxide in the gas mixture is removed by neutralisation with a hot solution of potassium carbonate under high pressure. Thermal decomposition of the potassium hydrogen carbonate regenerates the potassium carbonate for further use. The carbon dioxide evolved in the thermal decomposition is often reacted with ammonia to manufacture urea fertiliser.



6. The gaseous mixture from the previous step is methanated. This involves catalytic hydrogenation of the traces of CO or CO<sub>2</sub> to form methane and water vapour. This is the reverse of reaction (1) and is essential to remove all traces of CO and CO<sub>2</sub>.

7. The final gaseous mixture contains nitrogen and hydrogen in the approximate mole or volume ratio of 1 : 3 as required for the reaction stoichiometry of the Haber process. Very small amounts of methane and argon are present as impurities. The mixture is compressed to 20–25 MPa before being sent to the Haber chamber.



## SYLLABUS FOCUS

### 23. LE CHATELIER'S PRINCIPLE IN INDUSTRY

Le Chatelier's principle states:

*If a system is in equilibrium and a change is made that upsets the equilibrium, then the system alters in such a way as to counteract the change and a new equilibrium is established.*

In industry, it is vital to maximise the yield of the desired products and minimise the amounts of leftover reactants. The following rules can be used to predict the most suitable reaction conditions to achieve the highest possible yield of product.

#### Rule 1: Temperature

If the forward reaction is endothermic, *increasing* the temperature favours the formation of the product. The yield of product will be increased.

If the forward reaction is exothermic, *reducing* the temperature favours the formation of the product. The yield of the product will be increased.

These rules apply to all reactions.

#### Rule 2. Pressure

This rule applies only to reactions with one or more gaseous reactants or products. Reference should be made to the balanced equilibrium equation to ascertain the number of moles of gaseous products and reactants.

Increasing the system pressure (by reducing the volume) causes the equilibrium to shift to the side of the equation with the least number of gaseous molecules.

Decreasing the system pressure (by increasing the volume) causes the equilibrium to shift to the side of the equation with the most number of gaseous molecules.

Where there are equal numbers of molecules on the reactant and product sides, pressure has no effect on the position of the equilibrium.

### Rule 3. Concentration

Increasing the reactant concentration shifts the equilibrium to the right to make more products and to reduce the concentration of the added reactant.

Decreasing the concentration of a reactant shifts the equilibrium to the left to make more of that reactant. Consequently the concentration of products decreases.

### Rule 4. Catalysts

Catalysts make reactions go faster. They do not affect the position of equilibrium. Catalysts cause the forward and reverse reactions to speed up by equal amounts.

Catalysts are useful because they lower the activation energy, and equilibrium is achieved faster. This is important in industry as there are considerable savings to be made in time and energy as reactions can be conducted (where appropriate) at lower temperatures.

## The Haber process

The conditions employed in the Haber process vary from one manufacturing plant to another. The selected set of conditions represents a compromise between equilibrium, kinetic and economic factors. Let us examine these key factors.

### Equilibrium factors

Le Chatelier's principle can be used to analyse the effect of temperature and pressure on the ammonia equilibrium. In the following discussion we shall use this principle to predict the conditions that will maximise the yield of ammonia at equilibrium:

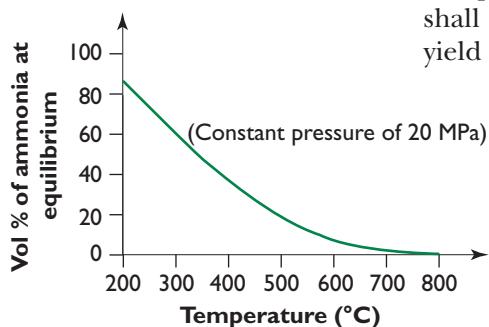


Figure 11.10  
The yield of ammonia decreases as temperature increases.



#### Temperature

Because the ammonia equilibrium is exothermic, an increase in temperature will cause the equilibrium to shift to the left to use up the added heat. Thus a high temperature will reduce the yield of ammonia. Le Chatelier's principle predicts that low temperatures favour higher yields of ammonia.

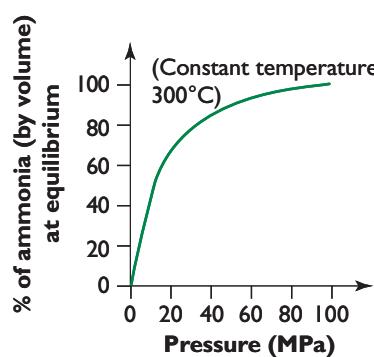


Figure 11.11  
The yield of ammonia increases as pressure increases.

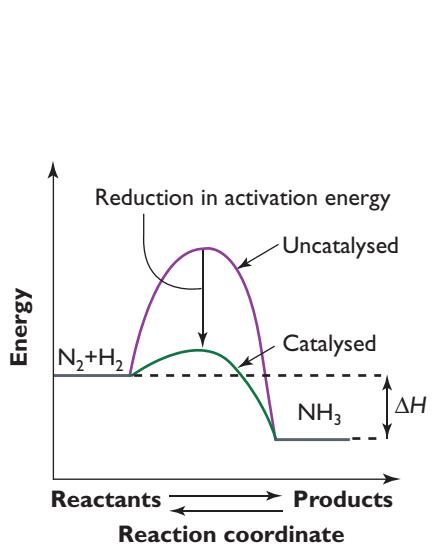
#### Pressure

The stoichiometric equation for the Haber process shows that 4 moles (1 + 3) of reactants are converted to 2 moles of products. Le Chatelier's principle predicts that an increase in pressure in the system will favour the reaction direction that leads to a lowering of gas pressure due to the formation of fewer molecules. This is the forward reaction; consequently, the higher the system pressure the greater the yield of ammonia.

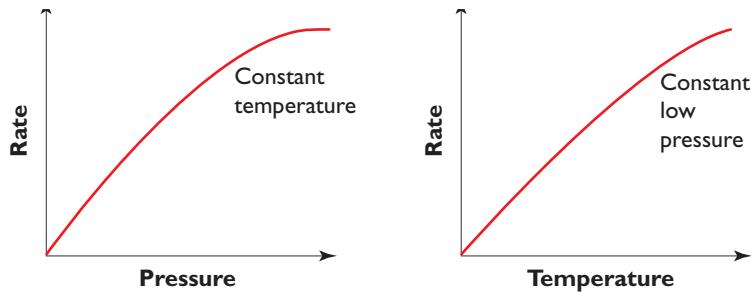
### Kinetic factors

Kinetic factors relate to the speed at which reactions occur and how rapidly the ammonia is formed. It is important in industry to have a high rate of production due to economic considerations.

The kinetic theory of gases predicts that the rate of a reaction increases when more successful collisions occur in the shortest time. High temperatures favour an increase in reaction rate as the molecules have higher kinetic energies, and more molecules have sufficient energy to overcome the activation energy barrier. High gas pressure also favours the frequency of successful molecular collisions. The presence of a suitable catalyst further increases the reaction rate as the activation energy for the reaction is lowered. The catalyst does not alter the position of the final equilibrium, but it does result in that equilibrium being reached faster.



**Figure 11.13**  
Catalysts lower the activation energy and increase the reaction rate.

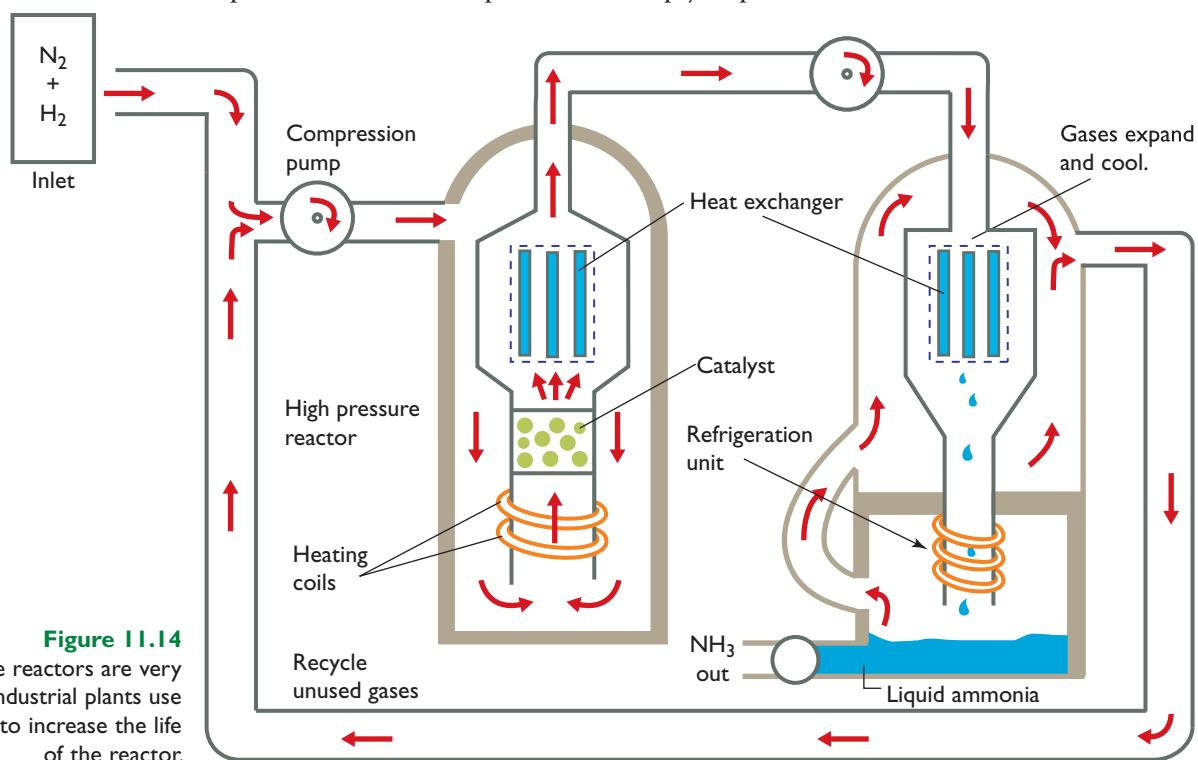


**Figure 11.12**  
High pressure and high temperature result in a rate increase.

### Economic factors

Constructing strong pipes and maintaining a high-pressure reactor vessel is very expensive; consequentially, the selected pressure should not be too high.

The ammonia plant should be located near supplies of natural gas, which is required for the production of hydrogen. Ammonia plants may be located near chlor-alkali factories as they also produce hydrogen gas. The plant should also be located near haulage centres so that the final product can be transported as cheaply as possible.



**Figure 11.14**

High-pressure reactors are very expensive. Many industrial plants use a lower pressure to increase the life of the reactor.

The heat released by the exothermic reaction is not wasted. Heat exchangers allow the heat to be recycled for use elsewhere in the factory complex. For example, recycled heat is used to create steam for the conversion of methane to carbon monoxide and hydrogen.

The carbon dioxide evolved in the thermal decomposition of potassium hydrogen carbonate is not wasted. As well as using it to manufacture urea, it is sold on to brewers and soft drink manufacturers.

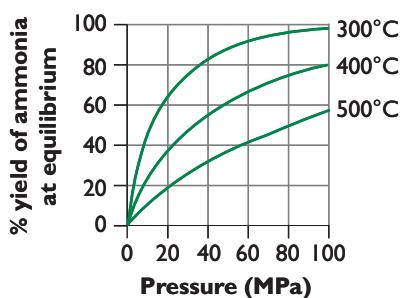
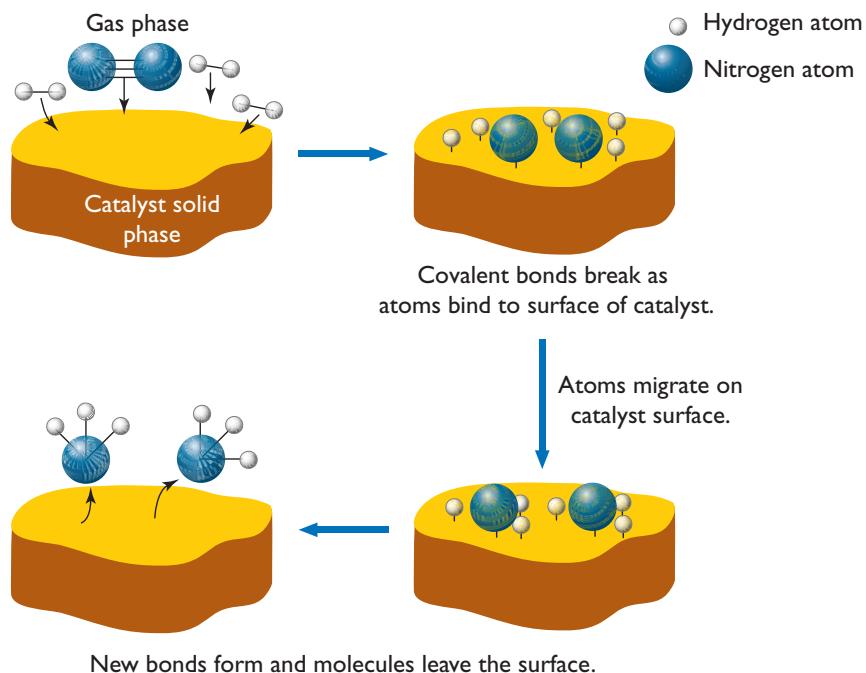
### Compromise conditions

The set of conditions that are commonly employed vary. Here are some typical ranges.

- *Reactants:* N<sub>2</sub> and H<sub>2</sub> (mole ratio 1 : 3). Although Le Chatelier's principle predicts that the equilibrium can be shifted to the product side by increasing reactant concentration, it is important that the 1 : 3 mole stoichiometry is maintained.
- *Pressure:* 15–35 MPa (typically ~20–25 MPa). Although equilibrium and kinetic considerations suggest that the pressure should be as high as possible, economic and safety considerations require a lower pressure so that the reaction vessel has as long a lifetime as possible.
- *Temperature:* 400°C–550°C. Equilibrium and kinetic factors are in conflict here. This compromise temperature allows the reactants to have sufficient kinetic energy to overcome the activation energy barrier as well as achieve a reasonable yield per cycle through the reaction vessel.
- *Catalyst:* magnetite (Fe<sub>3</sub>O<sub>4</sub>) fused with K<sub>2</sub>O, Al<sub>2</sub>O<sub>3</sub> and CaO (the magnetite is then reduced to porous iron). It is essential that the iron catalyst be ground to a fine powder to expose a high surface area for the gases to adsorb onto its surface. Figure 11.15 models the reaction on the catalyst surface. The use of the catalyst allows lower temperatures and pressures to be used to achieve acceptable reaction rates without too great a loss in yield of product per cycle.

**Figure 11.15**

This model shows how the reactant bonds are broken and how atoms migrate on the surface of the catalyst before recombining to form ammonia molecules.



**Figure 11.16**

This graph summarises the effect of pressure and temperature on the yield of ammonia.

- *Yield of ammonia:* ~15–20% per cycle. After 5–6 cycles about 98% of the reactants are converted to ammonia.



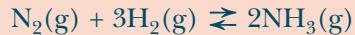
## THE HABER PROCESS

### SAMPLE PROBLEM 11.1 ➤

The constant removal of ammonia by liquefaction (under pressure) is another means of shifting the reaction equilibrium in favour of ammonia formation. Le Chatelier's principle predicts this. The constant removal of the ammonia product causes the equilibrium to shift to the right.

These conditions represent a compromise based on the equilibrium, kinetic and economic factors already discussed. Figure 11.16 shows a graph of the combined effects of temperature and pressure on the yield of ammonia.

The following table provides information about the effect of pressure on the yield of ammonia in the Haber process. The data refers to a constant temperature of 400°C. Use this information and Le Chatelier's principle to discuss the effect of pressure on the yield of ammonia, and explain why ammonia manufacturers typically maintain pressures around 200–300 atm.



Pressure (atm*)	100	300	600	1000
Yield of ammonia (% by volume)	25	47	66	80

(\*1 atm = 101.3 kPa)

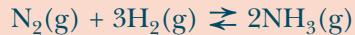
### SOLUTION ➤➤➤➤

The data shows that the yield of ammonia increases as pressure increases. This is in agreement with Le Chatelier's principle, which predicts that an increase in pressure will favour the side of the equilibrium with lower number of molecules (i.e. the product side: 2 moles versus 4 moles). The equilibrium shifts to the ammonia side to counteract the imposed pressure change.

Although high pressures favour increased yields of ammonia, more moderate pressures are used for safety and economic reasons. Very high pressures require the construction and maintenance of strongly reinforced reactor vessels. Such vessels are expensive and do not have as long a production life as vessels designed to operate at lower pressures. Although the yield is reduced at these lower pressures, the recycling of unreacted gases ultimately leads to a high production yield.

### SAMPLE PROBLEM 11.2 ➤

The following table provides equilibrium data on the effect of temperature on the concentration of gases in the ammonia equilibrium at 300 atm pressure.



T (°C)	P (atm)	[NH <sub>3</sub> ] mol/L	[H <sub>2</sub> ] mol/L	[N <sub>2</sub> ] mol/L
400	300	2.580	2.139	0.713
500	300	1.239	2.618	0.873
600	300	0.557	2.723	0.908

- Use this data to identify whether this reaction equilibrium is endothermic or exothermic. Justify your response.
- Explain why moderate temperatures (~400°C) are used in the industrial manufacture of ammonia.

**SOLUTION**

- (a) The reaction equilibrium is exothermic. The data shows that as the temperature increases, the concentration of ammonia decreases and the concentration of reactants increases. This is consistent with an exothermic equilibrium in which heat is a product. Le Chatelier's principle predicts that the addition of more heat will force the equilibrium towards the reactant side of the equilibrium to use up some of the added heat.
- (b) The data shows that lower temperatures favour higher yields of ammonia. If the temperature is too low, however, the rate of reaction will be too low and insufficient reactant molecules will have the energy needed to overcome the activation energy barrier. Thus a moderate temperature is used as a compromise between these opposing factors.

Ammonia does not support combustion. However, ammonia will undergo combustion in oxygen to produce nitrogen and water vapour.

### Monitoring and management

Industrial chemists and chemical engineers employed in the manufacturing of ammonia need to perform a range of monitoring activities to ensure quality control. These include:

1. Continuous monitoring of the high-pressure reaction vessel. This ensures that the production of ammonia occurs under safe conditions. If the pressure is too low then the yield of ammonia will drop. Pressure data from various sensors is monitored centrally.
2. Temperature monitoring. This is critical to ensure that the temperature remains in the optimum range. If the temperature is too high then the yield of ammonia is reduced. Temperature data from various temperature sensors is monitored centrally.
3. Monitoring the furnaces that produce the hydrogen and nitrogen feedstocks. These feedstocks must be produced in the correct mole ratios and kept free from contamination with sulfur compounds or carbon monoxide. Carbon monoxide and carbon dioxide sensors send information about the gas stream to a central monitoring computer.
4. Monitoring the activity of the catalyst, which has a lifetime of 5–10 years. The particle size of the catalyst must be monitored to ensure it has a high surface area.
5. Monitoring the ammonia liquefaction process during each cycle to ensure optimal yield of ammonia.

Research chemists in the ammonia industry continue to identify new catalysts and production line efficiencies. As most ammonia is used in the fertilizer industry and in the manufacture of explosives, there is an ever-increasing demand for this important product.

## 11.2 DATA ANALYSIS

The history of the Haber process

### 11.2 Questions

1. The following table records the world nitrogen fertiliser use in the period 1905–1939.
  - (a) Explain the trend in nitrogenous fertiliser use during this period.
  - (b) Identify a major chemical process that was developed in the early twentieth century, and which enabled the increased usage of fertilisers.
  - (c) Ammonium nitrate was an important synthetic fertiliser developed at this time.

Explain with the aid of equations how this fertiliser can be made.

**Table 11.3** World nitrogenous fertiliser use (megatonnes of nitrogen)

Period	N (Mt)
1905–06	0.4
1909–10	0.6
1919–20	0.7
1929–30	1.8
1932–33	1.2
1938–39	2.7

2. The following table provides data for the equilibrium concentrations of nitrogen, hydrogen and ammonia. The reaction vessel has a volume of 1 litre.

Temperature (°C)	[N <sub>2</sub> ] (mol/L)	[H <sub>2</sub> ] (mol/L)	[NH <sub>3</sub> ] (mol/L)
227	0.34	0.83	3.40
427	0.88	1.46	1.01

- (a) Write the equilibrium equation for the formation of ammonia from its gaseous elements.
  - (b) Use the tabulated data to explain whether this ammonia formation equilibrium is endothermic or exothermic.
  - (c) The equilibrium system at 227°C is changed by injecting 0.1 moles of nitrogen gas into the reaction vessel. Use Le Chatelier's principle to describe how the concentration of nitrogen will change over time following this injection.
3. (a) Explain why the Haber process uses an iron catalyst.
- (b) Identify substances that can poison the catalyst and which must be removed from the feedstocks before reaction begins.
- (c) Nitrogen and hydrogen are mixed in a very strong vessel at 400°C and very high pressure (~1000 atm). No catalyst is added. Explain whether any ammonia will form.
4. In most ammonia plants, the yield of ammonia is about 20% per run. Explain how manufacturers are able to boost this yield to near 100%.
5. A laboratory experiment was conducted to investigate the reaction of nitrogen and hydrogen over an iron catalyst at 600°C and 400 atm pressure. The reaction vessel is constructed with a movable piston to change the volume of the apparatus. Figure 11.17 shows a graph of the concentration of ammonia in the reaction vessel over time.

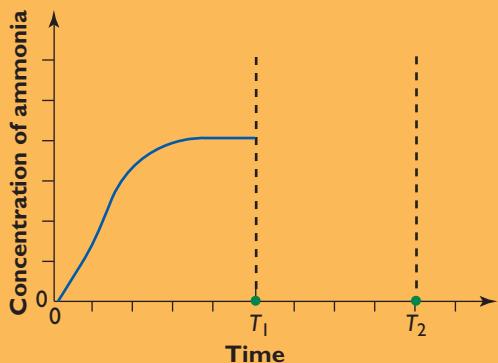


Figure 11.17 Use the ammonia graph to answer question 5.

Once equilibrium is established, the piston is moved rapidly (at time =  $T_1$ ) until the volume of the vessel is double its previous value. Temperature is held constant throughout. At some later time ( $T_2$ ) the system has reached a new equilibrium. Copy Figure 11.17 and show on your graph the change in the concentration of ammonia following the change in vessel volume. Justify your answer.

6. Figure 11.18 shows a graph of the change in concentration of hydrogen gas with time in a Haber reaction vessel. The system reaches equilibrium. At time  $X$ , as shown, some additional hydrogen is injected so as to instantly double the equilibrium hydrogen concentration. The temperature is held constant. Equilibrium is reached at time =  $2X$ .

Copy Figure 11.18 and show on your graph the subsequent changes in hydrogen concentration after time  $X$ .

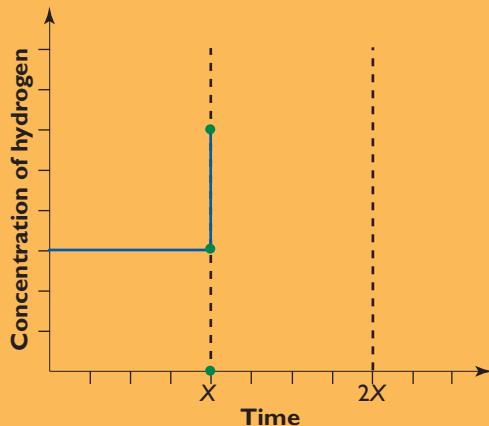


Figure 11.18 Use the graph to answer question 6.

7. The modern ammonia industry is largely automated. The world's largest ammonia plant has come into operation on the Burrup Peninsula in Western Australia. If you were an industrial chemist employed at this facility, explain briefly what monitoring activities you would be required to perform.
8. The heat released in the Haber process is not lost. Identify one use for this heat.
9. In the Haber process, carbon monoxide is produced during the preparation of the hydrogen feedstock from methane. This gas is removed by reacting it with steam over iron oxide and copper catalysts. Write a whole formula equation for this reaction.



## SUMMARY

- There is a wide variety of careers in chemistry. Developmental chemists ‘scale up’ reactions and processes so they can be conducted on an industrial scale. Production chemists supervise the production process and ensure quality control. Research chemists develop new products or procedures and may undertake original research.
- Industrial chemists work in a variety of chemical industries. They manage and monitor chemical processes such as those involving combustion reactions.
- Chemists monitor conditions in combustion reactions in order to minimise pollution and maximise energy output. Incomplete combustion is associated with the production of pollutant gases such as carbon monoxide.
- The Haber process is an important industrial process for the manufacture of ammonia from nitrogen and hydrogen.
- The production of ammonia and other important products illustrates the laws of chemical equilibrium and kinetics.
- Chemists monitor the furnaces that produce the hydrogen and nitrogen feedstocks so that the feedstocks are produced in the correct mole ratios and are free from contamination with sulfur compounds or carbon monoxide.
- The Haber process occurs at high pressures, moderate temperatures and in the presence of an iron catalyst. Chemists monitor the production line to ensure production efficiencies and quality control.
- Ammonia is used to make fertilisers, explosives, detergents and dyes.

# DATA ANALYSIS

## 11.1 DATA ANALYSIS

### CHEMICAL CAREERS – POLYMER CHEMIST

#### The polymer industry

Polymer chemistry is a diverse field of employment for chemists. About 50% of chemists work with polymers at some time during their careers. The majority of polymer chemists work in industry, although some are employed by chemistry faculties at universities and by government agencies. The industries that employ polymer chemists include those that manufacture synthetic fibres, packaging materials, adhesives, coatings, synthetic rubber, agricultural chemicals, aerospace materials, biodegradable natural polymers (e.g. starch) and biomedical materials such as artificial skin.

Polymer chemistry is oriented towards producing new products and materials. Polymer chemists synthesise and study the physical and chemical properties of polymeric molecules. They aim to produce new characteristics in polymers by manipulating functional groups and structures of molecules. Polymer chemists work in association with marketing personnel to ensure that the product meets the customers' requirements. The direction of polymer chemistry research has changed over recent years to develop biodegradable 'green' polymers that do not pollute the environment.

#### Examples of polymer development

The following are some examples of research and development that polymer chemists carry out.

##### Polymeric clothing fibres

Altering the structure or incorporating chemical additives can change the properties of fibres used in clothing. Elastic fibres such as natural rubber have been replaced by synthetic polymeric fibres to create fabrics such as *Lycra*, which is used in swimming costumes and sports wear. By testing new chemical additives, polymer chemists develop ways of making fabrics that withstand higher temperatures and exposure to ultraviolet light, or have improved permeability to water vapour.

##### *Liquid-crystal polymers*

These are special materials that align and flow readily when heated above a certain temperature. They produce high tensile strength polymer fibres with temperature resistance. These high performance polymers can be spun into strong fibres, or be injection moulded to produce components for the electronics industry.

##### *Detergent polymers*

Polymer chemists are employed by detergent manufacturers to develop polymeric materials that, when added to automatic dishwashing detergents, reduce the attack of the alkalis in the detergent on glass containers, which forms chalky films.

##### Analytical methods

Polymer chemists use a wide range of instrumental analyses to characterise polymers and to measure their properties. Some of these analytical methods and tests are summarised below:

Property	Analytical methods and tests
Chemical and structural characterisation	(a) Average molar weight determination using a variety of techniques including viscometry, gel permeation chromatography and mass spectroscopy (mass spectroscopy is used only for low molecular weight polymers) (b) Crystallinity using X-ray diffraction
Mechanical and physical properties	(a) Tensile strength and hardness tests (b) Adhesion tests; surface tension (c) Wear and friction characteristics
Chemical reactivity	(a) Reactivity towards acids, bases and oxygen (b) Degradation responses to varying environmental conditions (e.g. UV exposure) (c) Biocompatibility using tissue culture techniques
Thermal properties	(a) Melting point and thermal conductivity (b) Glass transition temperature analysis (c) Calorimetry
Solubility and solution properties	(a) Viscoelastic and flow properties (b) Dissolution in solvents and phase separation

# DATA ANALYSIS

## Case studies

The following case studies relate to the plastics manufacturing industry. They examine:

- (a) the use of gas–liquid chromatography (GLC) to test for volatile material in the polymer
- (b) the determination of molecular weight using
  - (i) melt flow index (MFI)
  - (ii) gel permeation chromatography (GPC).

### Using GLC to test for volatile material in the polymer

Petrochemicals such as ethylene and its derivatives are used to manufacture plastics. If plastics contain significant amounts of volatile un-polymerised monomers or other impurities, the material becomes subject to discolouration and cracking. Gases may also be released when the polymer comes into contact with other chemicals, including food. The production chemist in the polymer industry maintains quality control by testing samples of the polymer for the presence of the volatile materials, including monomers.

*Chemical principle used:* Each volatile compound in the plastic has a unique retention time in the GLC column due to differing solubilities in the stationary liquid phase that coats the granules of the GLC column.

*Analytical procedure:* The volatile components that are released from a heated sample of the plastic are combined with a helium carrier gas and passed through a GLC column. The least soluble components in the liquid phase are the

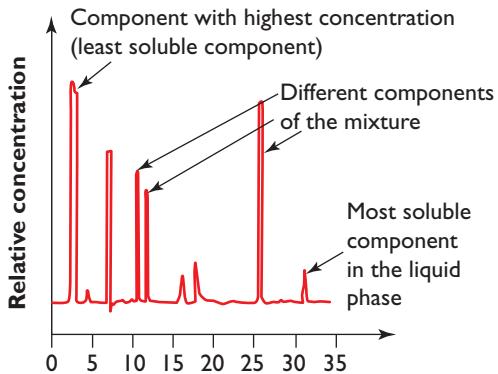
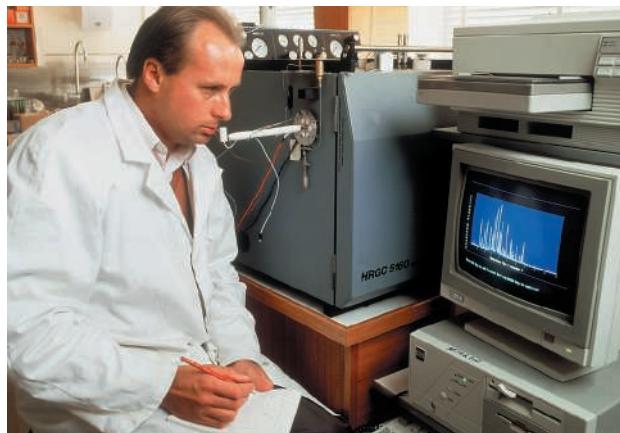
first to pass through the column and be registered by the sensors. The more soluble the components the longer is their time on the column. The GLC is connected to a detector, computer interface and computer which produces a graph or *chromatogram*. Each component of the mixture produces a peak. The height and area under the peak provide a measure of the relative proportion of each component in the mixture.

### Determining molecular weight using melt flow index (MFI) and gel permeation chromatography (GPC)

The molecular weight distribution strongly influences the properties of the polymer produced by a given technique. For example, molecular weight influences melt viscosity and toughness of the polymer. The production chemist working in the plastics industry needs to measure the molecular weight distribution of selected samples of the plastics that are produced. A rapid (but less accurate) method that is used is the measurement of the melt flow index (MFI) of the polymer. A more exact (but more time consuming) measurement uses the technique called *gel permeation chromatography* (GPC).

### Using melt flow index (MFI)

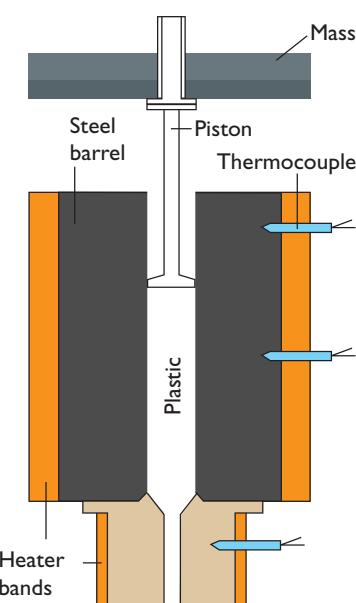
*Chemical principle used:* Polymers with different molecular weight distributions vary in their viscosity when melted. Branching and the presence of functional groups along the chain also affect viscosity. The higher the relative molecular weight the higher the viscosity and the lower the melt flow index.



**Figure 11.19** The relative proportion of each component of the mixture is a function of the height and area under each peak.

# DATA ANALYSIS

**Analytical procedure:** The MFI is the output mass (in grams) of melted polymer (at 190°C) in 10 minutes through a fixed aperture (2.1 mm wide × 8 mm long) by application of a standard pressure via a piston with a load of mass 10 kg. The lower the melt viscosity the greater the rate of extrusion. The MFI for HDPE is typically 0.40.

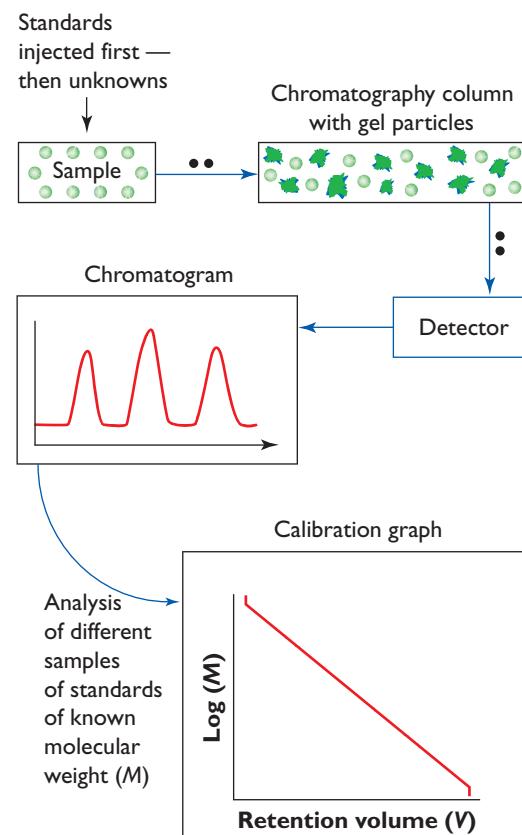


**Figure 11.20** The melt flow index is related to the molecular weight of the polymer sample.

**Using gel permeation chromatography (GPC)**  
**Chemical principle used:** Polymer molecules are separated on the basis of their size (related to molecular weight). Small polymer molecules can enter the pores of the gel and are retained longer on the chromatography column. Large polymer molecules are excluded from the pores and pass through the column rapidly. This technique is used mainly for linear rather than branched polymers.

**Analytical procedure:** The chromatography column is packed with a polystyrene gel cross-linked with divinyl benzene. An organic solvent is used to run a series of at least five calibration standards (polystyrene standards of known narrow range molecular weight ( $M$ ) and concentration). The eluted samples of each standard are analysed by light refraction

techniques to determine the retention time (and retention volume) on the column. The calibration graph is a plot of  $\log M$  versus retention volume,  $V$ . Unknowns are then run and their retention times measured. The average molecular weight and molecular weight distribution of each unknown can then be read from the calibration graph. This technique is useful in determining the distribution of molecular weights in a polymer sample.



**Figure 11.21** There is a relationship between molecular weight and retention volume.

## Questions

1. Explain why the polymer industry is researching the development of 'green' plastics.
2. Explain why elastomeric synthetic polymers have replaced natural rubber fibres in some clothing fabrics.

# DATA ANALYSIS

3. Identify the property of a polymer that is determined by each of the following tests.
  - (a) hardness tests
  - (b) testing phase separation in various liquids
  - (c) X-ray diffraction tests
  - (d) effect of UV exposure
  - (e) testing thermal conductivity.
4. Explain why a polymer chemist is also an analytical chemist.
5. Petrochemicals such as ethylene are produced from crude oil. Ethylene is the feedstock for the production of polyethylene. It is important that the ethylene feedstock is pure.
  - (a) Identify a method that a polymer chemist could use to ensure that the ethylene monomer is not contaminated with impurities.
  - (b) Identify the chemical principle that the polymer chemist uses in the technique selected in (a).
  - (c) The ethylene is polymerised and the polymer chemist uses a quick method to determine the molecular weight distribution of the sample. Identify the technique used and the principle behind its use.

# DATA ANALYSIS

## 11.2 DATA ANALYSIS

### THE HISTORY OF THE HABER PROCESS

Read the following information and answer the questions that follow.

Fritz Haber was a German chemist who developed the method of producing ammonia from hydrogen and nitrogen. His 1905 experiments produced small yields of ammonia when nitrogen and hydrogen gases were combined at 1000°C over an iron catalyst.

Other catalysts were then tested. Osmium was found to be the best, but was very expensive. Further investigations showed that the gas pressure needed to be raised and the temperature lowered to achieve better yields. By 1909, Haber had been able to synthesise about 100 g of ammonia using his modified procedures. Some of this original batch of ammonia is now on display in the Science Museum in London.

Carl Bosch, a chemical engineer who was employed by BASF in Mannheim, then scaled the process up to industrial levels. Bosch showed that the best yields (~15%) were achieved at pressures around 15–20 MPa and temperatures around 500°C using an iron-based catalyst. By continuously recycling the unreacted gases, the yield of ammonia could be raised to 98%. In 1913, the process was producing 30 tonnes of ammonia a day. By the end of 1914 the production had been raised to 200 tonnes per day.

In the years prior to World War I, Haber realised that the manufacture of nitric acid from the oxidation of ammonia would be vital for the production of nitrogenous fertilisers that were needed for agriculture. This synthetic method of fertiliser production was important in producing greater crop yields for the ever-growing human population. At the start of World War I, Britain and its allies blockaded the Atlantic sea routes from Chile and this prevented Germany from importing nitrates (e.g. Chile saltpetre) for use

in agriculture as well as in the manufacture of gunpowder and explosives. Consequently, Haber's synthetic ammonia process allowed Germany to supply the explosives for its war effort, and to produce fertilisers to grow the crops needed to feed the large German population and its troops. Haber was a patriotic German and served in the German army during the war. He helped to direct the use of poison gas warfare against the allied troops in the trenches. This use of toxic chlorine and phosgene gas almost won the war for Germany.

After the war, Haber was considered by many on the Allied side to be a war criminal for his development of gas warfare. However, others believed him to be a German patriot who used his scientific skills for the good of his country. Haber was devastated by Germany's loss, and his physical and mental health suffered.

In 1918, Haber was awarded the Nobel Prize in Chemistry for his ammonia process and the contribution it made to the improved nutrition of humanity through the production of synthetic fertilisers. The prize was not announced until November 1919. It was finally presented in June 1920. In 1931 Bosch was awarded the Nobel Prize for inventing and developing the high-pressure technology to enable commercial production.

In the 1920s, Haber worked to rebuild German science. He investigated the pyrolysis of hydrocarbons and the electrochemical reduction of aromatic hydrocarbons. He also developed new understandings in thermodynamics and the role of catalysts in chemical change.

In 1933, Haber — along with Albert Einstein — was forced out of Germany by the Nuremberg racial purity laws that the Nazis imposed on Jews and other non-Aryan races. He fled to the USA and was forced into retirement. His expulsion from his beloved Germany led to a despondency that ultimately caused his early death in 1934.

Today the Haber process is an important industrial process. About 85% of the ammonia produced around the world is used to manufacture fertilisers for farming. Without synthetic fertilisers the world could not produce sufficient food to sustain the growing population.

# DATA ANALYSIS

## Questions

1. Identify the gases that Haber used to manufacture ammonia.
2. Name two catalysts that Haber investigated for the synthesis of ammonia.
3. Identify Carl Bosch's contributions to the development of the ammonia industry.
4. Explain how high yields of ammonia were eventually obtained.
5. Explain the importance of the Haber process during World War I.
6. Explain how the development of the Haber process was important to the improvement of human nutrition.