INDUSTRIAL CHEMISTRY
THE PRODUCTION OF AMMONIA

Many reactions proceed too slowly under normal conditions of temperature and pressure. Some reactions proceed at very fast rates but produce very small quantities of product.

In order to maximise profits and to reduce costs to consumers, industries aim to minimise the costs of industrial processes. This involves a consideration of yields and rates.

The reactions that cause greatest concerns to industries include:

- Reactions with low equilibrium constants. Low equilibrium constants result in low yields of product.
  
  *For example:* The production of ammonia, nitric acid and sulfuric acid.

- Reactions with slow reaction rates.

- Exothermic processes.

  Lower temperatures are required to increase yields, however, this results in slower reaction rates. Industries will generally employ lower temperatures and use catalysts to compromise on the decreased reaction rates.

  *For example:* The production of sulfuric acid, nitric acid and ammonia.

THE GREATEST COSTS ASSOCIATED WITH INDUSTRIAL PROCESSES INCLUDE:

- The costs of raw materials.

  To maximise profits, yields are maximised.

- Generating high pressures.

  Industries avoid using extremes of pressure to maximise the yield of product as high pressures require very powerful and expensive pumping equipment together with vessels that can withstand the high pressures. These added costs may not justify the use of higher pressures, and in many cases, it is more profitable to lower the pressure and obtain a lower yield of product.

- Generating high temperatures.

  Industries decrease these costs by using heat evolved in exothermic processes to fuel other reactions in the plant.

- The time required to produce the product.

  Rates are increased by using appropriate catalysts.
Note:

Industries use processes that use less energy to decrease costs and preserve finite sources. For example:

- The heat produced in one stage of a chemical process is frequently recycled and used to heat other stages of the process.

- The heat exchangers which remove and recycle heat operate 24 hours per day so that the enormous costs associated with warming up equipment are avoided.

- Industries often exist as integrated complexes i.e. A collection of related industries are located within a close proximity of one another. The by-products of one industry (eg. heat) can then be used as a raw material for another industry, reducing wastage, environmental pollution and costs.

- If sufficient thermal energy is produced, it may be possible to convert it to electrical energy for use in the plant. In some cases, excess supplies are sold to an electricity supply grid.

MAXIMISING YIELDS

Industries will attempt to maximise yields by manipulating Le Chatelier’s Principle.

Yields may be cost effectively increased by changing the following reaction conditions:

- Adding an excess amount of the cheaper reactant.
- Periodically removing products.
- Changing the temperature and pressure of the reaction system.

MAXIMISING RATES

As time has a significant impact on the cost of products and staff, industries will also attempt to maximise the speed or time taken to produce a product.

Conditions that favour fast reaction rates include:

- High reactant concentrations.
- High pressures.
- High temperatures.
- High surface areas.
- Use of catalysts.
FACTORS INFLUENCING THE METHOD IN WHICH A CHEMICAL IS PRODUCED

The operating conditions and any compromises that are required are determined by running small scale experiments, and choosing the set of conditions that will maximise profits i.e. those conditions that result in the highest possible yield of product in the shortest possible time.

Other considerations include:

- Raw materials – cost, availability, purity, safety.
- Environmental impact – pollution, storage/hazards of waste products, use of water bodies to cool equipment.
- Transporting of raw materials and product.
- Location of plant.
- Availability of necessary technology.
- Availability of appropriately qualified staff.

TYPES OF CHEMICAL PROCESSES

Batch Processing

In this process, fixed amounts of reactants are mixed to produce fixed amounts products. This method is usually reserved for the production of small amounts of product and/or reactions that display high equilibrium constants.

Continuous Flow Processing

In this process, reactants are continuously supplied at one end, to produce a continual supply of products, which are then removed at the other end of the processing line. This process is only cost effective if sufficient demand exists for the large amounts of products derived via the process. Continuous flow processing also allows for greater control over reaction conditions, making it the preferred technique for many large scale operations. Reactants may be added or products removed at any stage of a process to increase product yields.
PLANT LOCATION AND STRUCTURE

Factors to Consider:

- Accessibility to raw materials.
- Transportation costs.
- Availability of energy/power sources.
- The price of land.
- Availability of water supplies.
- Storage of raw materials and waste products.
- Disposal of waste products.
- Pollution and its effects on the environment.
- Recycling energy, water and waste products.

GREEN CHEMISTRY

Green chemistry involves the design of chemical processes and products that reduce or eliminate the use and generation of hazardous substances in the manufacture and application of the products. By eliminating and reducing waste from chemical processes, green chemistry aims to develop a sustainable approach to a cleaner environment that is beneficial to both our society and the economy.

The hazards that green chemistry aims to avoid completely include:

- Toxicity.
- Physical hazards like explosions.
- Impact on global climate change.
- Depletion of resources.

The major difference between green and environmental chemistry is that environmental chemistry focuses on pollution control once the pollutants have been produced whereas green chemistry aims to avoid pollution in the first place.
THE 12 PRINCIPLES OF GREEN CHEMISTRY

Taken From Heinemann Chemistry 2

1. **Prevent waste**
   It is better to design chemical processes to prevent waste than to treat waste or clean it up after it is formed.

2. **Design safer chemicals and products**
   Design chemical products to be fully effective, yet have little or no toxicity.

3. **Design less hazardous chemical syntheses**
   Methods should be designed that use and generate substances with little or no toxicity to humans and the environment.

4. **Use renewable raw materials**
   Use starting materials that are derived from renewable resources such as plant material rather than those such as from fossil fuels that will eventually run out.

5. **Use catalysts, not stoichiometric reagents**
   Minimise waste by using catalysts in small amounts that can carry out a single reaction many times. They are preferable to stoichiometric reagents, which are used in excess and work only once.

6. **Avoid chemical derivatives**
   Avoid using blocking or protecting groups or any temporary modifications if possible. Derivatives use additional reagents and generate waste.

7. **Maximise atom economy**
   Design syntheses so that the final product contains the maximum proportion of the starting materials. There should be few, if any, wasted atoms.

8. **Use safer solvents and reaction conditions**
   Avoid using toxic solvents to dissolve reactants or extract products.

9. **Increase energy efficiency**
   Energy requirements should be minimised. Run chemical reactions at room temperature and pressure whenever possible.

10. **Design for degradation**
    Chemical products should be designed to break down to harmless substances after use so that they do not accumulate in the environment.
11. **Analyse in real time to prevent pollution**

Include continuous monitoring and control during process to minimise or eliminate the formation of by-products.

12. **Minimise the potential for accidents**

Design chemicals and their forms (solid, liquid or gas) to minimise the potential for chemical accidents including explosions, fires and releases to the environment.

**BENEFITS OF GREEN CHEMISTRY**

Some of the many benefits of a green chemistry approach include:

- Higher atom economy.
- Advocating energy efficient processes.
- Lowers cost of production and regulation.
- Less wastes.
- Safer products.
- Healthier workplaces and communities.
- Protects human health (end-users) and the environment.
- Offers businesses a competitive advantage in the market place.
- Economical stimulus.
YIELD VERSUS ATOM ECONOMY

The yield of a reaction tells us how efficient a reaction is in terms of the amount of product we obtain, relative to the maximum we could get from the amount of reactants we used. It is calculated using the formula:

\[
\% \text{ Yield} = \frac{\text{mass of product obtained (g)}}{\text{theoretical yield (g)}} \times 100
\]

However, it does not take into account the waste products.

Efficient chemical processes have high atom economy, and are important for sustainable development. Atom economy is determined by measuring the amount of starting materials that are incorporated into the desired products, and distinguishing them from those that are wasted (incorporated into undesirable products). Atom economy can be calculated by:

\[
\% \text{ Atom economy} = \frac{\text{Relative Molar Mass of Desired Product}}{\text{Sum of Relative Molar Masses of all Products}} \times 100
\]

A given chemical reaction might have high yield but low atom economy, hence not be seen as a adhering to green chemistry guidelines.

WORKED EXAMPLE 1

(a) Calculate the percentage atom economy of \(22\text{CHCl}_2\), which is formed according to the following chemical equation:

\[
4\text{CH}_4(g) + 2\text{Cl}_2(g) \rightarrow 2\text{CH}_2\text{Cl}_2(aq) + 2\text{HCl}(aq)
\]

\[
\% \text{ Atom economy} = \frac{85}{85 + 36.6} \times 100 = 53.8\%
\]

(b) Would this method of \(\text{CH}_2\text{Cl}_2\) production be considered as a “Green” process? Give a reason for your answer.

An atom economy of 53.8% is particularly poor, and this is a very wasteful process. This would not be considered a green process, as one the key principles of green chemistry is that it is better to develop reactions with fewer waste products than to have to clean up the waste (eg. achieve high atom economy).

(c) How could a chemical company maximise their profits from this chemical process?

Use waste products in other chemical reactions. The by-product is hydrogen chloride, which can be sold as a gas or made into hydrochloric acid. These useful substances can then be sold, reducing the potential wastage from the initial process. Alternatively, waste products that are non-toxic and biodegradable are favourable.
WASTE MANAGEMENT AND POLLUTION
IN THE CHEMICAL INDUSTRY

A waste product is an unusable or unwanted substance produced during or as a result of a chemical process.

Chemical waste is generated in many chemical processes and if not managed correctly, can impose adverse effects on human health and the environment.

Responsible industries therefore practise sound waste management by implementing the following actions:

1. Prevention
2. Elimination
3. Reduction
4. Recycling
5. Treatment
6. Disposal

WASTE TREATMENT

There are many different forms of waste treatment including:

- Landfill
- Dumping at sea
- Dispersion in controlled amounts in water or air
- Vitrification (sealing in molten slag)
- High-temperature incineration (1100°C)
- Removal of pollutants from waste gases and liquids
- Storage in sealed drums in secure locations
- High-temperature steam and water treatments

Which treatment process is used by industries depends upon:

- The physical form of the waste
- The hazardness of the waste
- Threats to animals, people and the environment
- The cost of the process
AMMONIA (NH₃)
USES OF AMMONIA

Ammonia is one of the most widely produced chemicals in the world. It is widely used in the production of fertilisers, cleaning products, synthetic fibres, explosives, pharmaceuticals, nitric acid and in the treatment of effluent.

Around 85% of the ammonia is used in fertiliser manufacture:

<table>
<thead>
<tr>
<th>Fertiliser</th>
<th>Chemicals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium sulfate, (NH₄)₂SO₄</td>
<td>Synthesis of:</td>
</tr>
<tr>
<td>2NH₃(g) + H₂SO₄(l) ⇌ (NH₄)₂SO₄(s)</td>
<td>- Nitric acid, HNO₃, which is used in making explosives such as TNT (2,4,6-trinitrotoluene), nitroglycerine which is also used as a vasodilator (a substance that dilates blood vessels) and PETN (pentaerythritol nitrate).</td>
</tr>
<tr>
<td>Ammonium nitrate, NH₄NO₃</td>
<td>- Sodium hydrogen carbonate (sodium bicarbonate), NaHCO₃</td>
</tr>
<tr>
<td>2NH₃(g) + HNO₃(l) ⇌ NH₄NO₃(s)</td>
<td>- Sodium carbonate, Na₂CO₃</td>
</tr>
<tr>
<td>Urea, (NH₂)₂CO, also used in the production of barbiturates (sedatives), is made by the reaction of ammonia with carbon dioxide</td>
<td>- Hydrogen cyanide (hydrocyanic acid), HCN</td>
</tr>
<tr>
<td>2NH₃(g) + CO₂(g) ⇌ (NH₂)₂CO(s) + H₂O(l)</td>
<td>- Hydrazine, N₂H₄ (used in rocket propulsion systems)</td>
</tr>
<tr>
<td>Ammonium phosphate, (NH₄)₃PO₄</td>
<td>Explosives</td>
</tr>
<tr>
<td></td>
<td>Ammonium nitrate, NH₄NO₃</td>
</tr>
<tr>
<td>Fibres and Plastics</td>
<td></td>
</tr>
<tr>
<td>Nylon, -[CH₂]₄-CO-NH-[CH₂]₆-NH-CO]-, and other polyamides</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Used for making ice, large scale refrigeration plants, air-conditioning units in buildings and plants</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td></td>
</tr>
<tr>
<td>Used in the manufacture of drugs such as sulfonamide which inhibit the growth and multiplication of bacteria that require p-aminobenzoic acid (PABA) for the biosynthesis of folic acids, anti-malarials and vitamins such as the B vitamins nicotinamide (niacinamide) and thiamine.</td>
<td></td>
</tr>
</tbody>
</table>
Pulp and Paper  
Ammonium hydrogen sulfite, NH₄HSO₃, enables some hardwoods to be used

Mining and Metallurgy  
Used in nitriding (bright annealing) steel, used in zinc and nickel extraction

Cleaning  
Ammonia in solution is used as a cleaning agent such as in 'cloudy ammonia'

**PROPERTIES OF AMMONIA**

**Ammonia**

- A colourless liquefied gas
- Has a pungent smell and is irritating to eyes and lungs
- Is a gas at room temperature (m.p. -77.7°C, b.p. -33.4°C)
- Is non flammable
- Is toxic
- Is corrosive
- Is considered dangerous for the environment

**Ammonia is a polar molecule:**

Due to the large difference in electronegativity between nitrogen and hydrogen, the hydrogen atoms in the molecule are slightly positive and the nitrogen atom is slightly negative.

**Ammonia is soluble in aqueous solutions:**

Ammonia molecules form hydrogen bonds with water molecules causing ammonia to be soluble in water.

**Ammonia is a gas at room temperature and pressure:**

The intermolecular forces between ammonia molecules are not strong enough for it to exist as a liquid or solid at these conditions.
REATIONS OF AMMONIA

Acid/Base Nature:

Ammonia is generally considered to be a weak base and reacts with water by accepting a proton.

\[ \text{NH}_3(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{NH}_4^+(aq) + \text{OH}^-(aq) \]

Very rarely it can act as an acid as shown below.

\[ 2\text{Li}_3(aq) + 2\text{NH}_3(aq) \rightarrow 2\text{LiNH}_2(aq) + \text{H}_2(g) \]

Combustion:

\[ 4\text{NH}_3(g) + 3\text{O}_2(g) \rightarrow 2\text{N}_2(g) + 6\text{H}_2\text{O}(g) \]

THE PRODUCTION OF AMMONIA

Ammonia is manufactured from nitrogen and hydrogen gas using the Haber process.

\[ \text{N}_2(g) + 3\text{H}_2(g) \rightleftharpoons \text{NH}_3(g) \quad \Delta H = -91 \text{ kJ mol}^{-1} \]

Raw Materials:

Nitrogen is extracted from air at $-190^\circ C$, at which point $\text{N}_2$ is a gas and $\text{O}_2$ is a liquid.

Hydrogen is produced from a variety of sources, depending upon the location of the ammonia plant. Fossil fuels are usually used, with natural gas being the simplest, least expensive and most efficient source.

The production of hydrogen from natural gas involves mixing the natural gas with steam (between $700^\circ C$ and $1100^\circ C$) at high pressure (between 25 to 35 atm) in the presence of nickel catalyst. The process, which is known as steam reforming, results in the production of carbon monoxide and hydrogen.

\[ 4\text{CH}_4(g) + 2\text{H}_2\text{O}(g) \rightleftharpoons \text{CO}_2(g) + 3\text{H}_2(g) \quad \Delta H = 206 \text{ kJ mol}^{-1} \]

The carbon monoxide gas acts as a catalytic poison in ammonia synthesis and is therefore converted to carbon dioxide.

\[ \text{CO}(g) + \text{H}_2\text{O}(g) \rightleftharpoons \text{CO}_2(g) + \text{H}_2(g) \quad \Delta H = -41 \text{ kJ mol}^{-1} \]

As carbon dioxide also acts as a catalytic poison in ammonia synthesis it is removed by passing the gaseous mixture through a suitable base, leaving a mixture of hydrogen and nitrogen (from the air) in the mole ratio 1 : 3. This is exactly the ratio required to form ammonia in the Haber process.
THE HABER PROCESS

\[ N_2(g) + 3H_2(g) \rightleftharpoons NH_3(g) \quad \Delta H = -91 \text{ kJ mol}^{-1} \]

Nitrogen and hydrogen gas enter the converter of the ammonia plant in a 1:3 ratio.

As the gaseous mixture passes over the catalyst, approximately 20% is converted to ammonia.

The gas mixture leaving the converter is cooled to about \(-50^\circ C\) to liquefy the ammonia so it can be removed.

The gas mixture is then passed across the catalyst several more times until a yield of around 98% is achieved.

**Note:** Removing the ammonia shifts the equilibrium to the right to partly compensate for the loss, hence maximising yields.
CONDITIONS NEEDED FOR MAXIMUM YIELD:

In order to obtain the highest possible yield of ammonia at the minimum cost, reaction conditions must be carefully controlled.

A RATE VS YIELD CONFLICT EXISTS AS THE FORWARD REACTION IS EXOTHERMIC.

As the reaction rate increases with increasing temperature – high temperatures are favoured in order to produce as much product as possible over the shortest amount of time.

However, higher temperatures favour a net back reaction decreasing the yield of product.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$K_{eq}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>$6.4 \times 10^2$</td>
</tr>
<tr>
<td>200</td>
<td>$4.4 \times 10^{-1}$</td>
</tr>
<tr>
<td>300</td>
<td>$4.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>400</td>
<td>$1.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>500</td>
<td>$1.5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

As the temperature increases, the equilibrium constant decreases as the yield of ammonia decreases.

Resolution: Use lower temperatures (between 400° C and 500° C) and compensate for the slower reaction rates by using a catalyst (porous iron/iron oxide - $Fe_{3}O_{4}$).

A Pressure vs Cost conflict exists.

Greater pressures would lead to higher yields of ammonia.

If the pressure within the equilibrium mixture is increased, the system moves to decrease the pressure by favouring the reaction that will produce the fewer mole of gaseous particles. In this case, a forward reaction would be favoured.

Although yields would be improved by using higher pressures, reactions are performed between 100 and 350 atmosphere of pressure, as the added costs involved in using high pressures does not justify the improvement in the observed yields.
Note:

- Rates and yields can be further maximised by adding an excess of the cheaper reactant.
- Heat released by the exothermic reaction between nitrogen and hydrogen must be removed or the temperature would rise above the optimum value. This waste heat is used to heat up the incoming gas mixture, providing an important cost saving.

**SUMMARY**

<table>
<thead>
<tr>
<th>Conditions Needed For</th>
<th>↑ Rate</th>
<th>↑ Temp</th>
<th>↑ Concentrations of reactants (↑ Pressure)</th>
<th>↑ Surface area, ↑ Efficiency catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>↑ Yield</td>
<td>↓ Yield</td>
<td>↓ Temp</td>
<td>↑ Reactant concentration (↑ Pressure)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>↓ Product concentration (remove product)</td>
<td></td>
</tr>
<tr>
<td>Minimal cost</td>
<td></td>
<td>↓ Temp</td>
<td>↓ Pressure</td>
<td>Cheap catalyst</td>
</tr>
</tbody>
</table>

Actual conditions used:

- 400-450˚C
- 200 atm
- Porous iron pellets with Al₂O₃ and KOH
Sulfur-containing compounds need to be removed from the hydrocarbon feedstock so as to minimise the emissions of damaging sulfur dioxide gases and to prevent the poisoning of catalysts. This process is called desulfurisation. The sulfur compounds are converted to hydrogen sulfide gas, which is then passed through beds of zinc oxide to convert it to zinc sulfide:

\[ R - SH(g) + H_2(g) \leftrightarrow R - SH(g) + H_2S(g) \]

\[ ZnO(s) + H_2S(s) \leftrightarrow ZnS(s) + H_2O(g) \]

Carbon dioxide is the major gaseous waste product resulting from the production of hydrogen gas from methane. As carbon dioxide is a major greenhouse gas, its release into the atmosphere needs to be restricted.

Carbon dioxide may be collected and sold to soft drink manufacturers, or reacted with ammonia to produce urea, a widely used fertiliser.

Wastage of raw materials is minimised by recycling unreacted gases back into the converter for further passes over the catalyst. In this way, almost complete conversion is achieved.

Heat produced from exothermic processes is recycled and used to maximise energy efficiency. This heat is used to generate steam to drive turbines, compressors and other machines and pre-heat gas mixtures.

Similarly, the heat energy released by the ammonia as it is cooled is collected by heat exchangers for use elsewhere in the process.
HEALTH AND SAFETY

The occupational health and safety issues associated with ammonia production and storage are:

- Fire/explosion injuries
- Poisoning
- Suffocation

Ammonia is a toxic gas that is highly irritating to eyes and lungs. Exposure to high doses can be fatal. Plants must be well ventilated and contain readily available breathing apparatus.

Ammonia reacts readily and explosively with a wide range of chemicals such as acids. Fires and explosions may occur in the parts of the plant where hydrogen is produced, requiring careful design and safety features.

Ammonia boils at –33°C and hence liquid ammonia can cause frostbite and severe burning.

As ammonia is highly soluble in water, it is extremely toxic to the environment, both in its gaseous form and when dissolved in water.

Workers involved in the handling of liquid ammonia storage and transport need to wear impervious gloves, face shields, and rubber boots and aprons.

The carbon monoxide gas produced during reforming is toxic and exposure to this gas must also be carefully monitored.

The site used for ammonia production is often connected directly to the sites of plants synthesising other chemicals, such as urea and nitric acid, thus minimising the hazards and costs associated with transport of the chemical.
MIXED QUESTIONS

QUESTION 1
Describe the theoretical conditions that should be used to maximise the rate of the reaction of nitrogen and hydrogen to produce ammonia. Are these the conditions actually used? If not, why not?

Solution
QUESTION 2
Hydrogen gas is produced industrially by treating natural gas (methane) with steam. Propose a set of production conditions that would maximise the yield of $H_2(g)$, and justify them using Le Chatelier’s principle. What other factors would need to be taken into account in designing a suitable chemical plant?

Solution

QUESTION 3
Explain why ammonia is removed continuously in the Haber process before the system reaches chemical equilibrium.

Solution
QUESTION 4
At 35 000 kPa the equilibrium yield of ammonia in the Haber process at 300ºC is roughly twice that at 500ºC. In view of this fact, explain why the Haber process is normally conducted at a temperature of about 500ºC.

Solution

QUESTION 5
Which of the following equations involving NH₃ results in the production of a fertiliser?

A \[2Li(s) + 2NH_3(aq) \rightarrow 2LiNH_2(aq) + H_2(g)\]
B \[2NH_3(g) + H_2SO_4(l) \rightleftharpoons (NH_4)_2SO_4(s)\]
C \[4NH_3(g) + 3O_2(g) \rightarrow 2N_2(g) + 6H_2O(g)\]
D \[2NH_3(g) \rightarrow N_2(g) + 3H_2(g)\]

QUESTION 6
In which of the following equations is NH₃ not acting as a base?

A \[2NH_3(g) + H_2SO_4(l) \rightleftharpoons (NH_4)_2SO_4(s)\]
B \[2NH_3(g) + HNO_3(l) \rightleftharpoons NH_4NO_3(s)\]
C \[NH_3(aq) + NaOH(aq) \rightleftharpoons NH_4^+(aq) + OH^-(aq)\]
D \[2Li(s) + 2NH_3(aq) \rightarrow 2LiNH_2(aq) + H_2(g)\]
QUESTION 7
Which of the following is not a use of ammonia?

A Manufacture of fertilisers
B Production of TNT
C As a rocket fuel
D Manufacture of plastics

QUESTION 8
The production of ammonia involves a number of steps including steam reforming to produce hydrogen gas, desulphurisation to remove contaminants from the hydrocarbon feedstock and the actual production of ammonia from hydrogen and nitrogen.

Classify each of the reactions involved in the production of ammonia by placing a tick in the appropriate boxes.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Exothermic</th>
<th>Endothermic</th>
<th>Redox</th>
<th>Condensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{CH}_4(g) + \text{H}_2\text{O}(g) \rightleftarrows \text{CO}(g) + 3\text{H}_2(g)$</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\text{N}_2(g) + 3\text{H}_2(g) \rightarrow 2\text{NH}_3(g)$</td>
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<td></td>
</tr>
<tr>
<td>$\text{ZnO}(s) + \text{H}_2\text{S}(g) \rightleftarrows \text{Zn}_3(s) + \text{H}_2\text{O}(g)$</td>
<td></td>
<td></td>
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</tbody>
</table>

QUESTION 9
If you had to transport ammonia by road, which safety sticker would you place on vessel?

A Oxidising agent
B Organic peroxide
C Corrosive
D Flammable solid
QUESTION 10
A typical ammonia plant produces approximately 400,000 t of ammonia per year and the mole ratio of CO₂/NH₃ is 0.500. An ammonia plant also uses about 30.0 GJ of energy per tonne of ammonia produced.

(a) Calculate the mass of CO₂ produced by the ammonia plant each year.

(b) (i) Determine the amount of energy needed to run the plant per year.

(ii) Modern plants can reduce their energy consumption to 27 GJ per tonne of ammonia. How much energy would this plant save if it were able to reduce its energy consumption to this level?

(iii) If the cost of 1 GJ is $40, how much money would the plant save?
(c) Given that yields of 98% are typical, what mass of nitrogen must be used in order to produce 400,000 t of ammonia?
QUESTION 11

(a) Calculate the atom economy of ethylene oxide, created in the following reaction:

\[
2 \text{HO-CHCl-Cl} + \text{Ca(OH)}_2 \rightarrow 2 \text{HO-CH}_2\text{O} + \text{CaCl}_2 + 2\text{H}_2\text{O}
\]

Ethylene oxide

(b) Would this method of production of ethylene oxide be considered as a “Green” process? Give a reason for your answer.

(c) Recently, a method of synthesising ethylene oxide from ethene and oxygen using a silver catalyst was developed. What’s the atom economy of this alternative reaction?

\[
\text{H}_2\text{C}==\text{CH}_2 + \frac{1}{2} \text{O}_2 \xrightarrow{\text{Ag} \text{cat.}} \text{HO-CH}_2\text{O}
\]

Ethylene oxide