

## CONTACT PROCESS

**Sulfuric acid is one of the most important industrial chemicals**

- **Outline three uses of sulfuric acid in industry**

1. The major use of sulfuric acid in Australia is in the manufacture of fertilizers such as ammonium sulfate and superphosphate. Superphosphate is produced by reacting sulfuric acid with rock phosphate. Ammonium sulfate is produced by neutralising ammonia with sulfuric acid.
2. Production of titanium (IV) oxide from titanium minerals eg ilmenite. Titanium is an important lightweight metal used to produce strong alloys and white, opaque pigments.  $H_2SO_4$  is used to leach the titanium from the minerals after mining.
3. Cleaning iron – because very corrosive used to remove the oxide layer from iron or steel before they are galvanised or electroplated.

- **Describe the processes used to extract sulfur from mineral deposits, identifying the properties of sulfur which allow its extraction and analyzing potential environmental issues that may be associated with its extraction**

- Most sulphur is extracted from mineral deposits using the Frasch process. Superheated steam is pumped down the outer of 3 concentric pipes into the sulphur deposit, and since sulphur has a low melting point (119) it is readily melted. At the same time, compressed air is blown down the inner pipe, and because sulphur has a relatively low density, the air is able to force the molten sulphur up the middle pipe to the surface where it resolidifies. The insolubility of sulphur in water means that it separates from any water, leaving 99.5% pure sulphur.
- Sulfur is also obtained from hydrogen sulphide in natural gas and petroleum. Incomplete combustion of  $H_2S$  in a furnace produces  $SO_2$  and S.  
 $3H_2S_{(g)} + O_{2(g)} \rightarrow H_2S_{(g)} + 3S_{(g)} + SO_{2(g)}$   
The mixture is cooled to condense the sulphur.
- Sulfur is also released as sulphur dioxide when metal sulphide ores are smelted.  
Eg.  $ZnS_{(s)} + O_{2(g)} \rightarrow Zn_{(s)} + SO_{2(g)}$

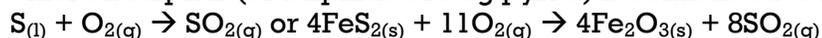
### Environmental Issues:

- Sulfur is easily oxidised to sulphur dioxide or reduced to hydrogen sulfide, both of which are serious air pollutants at quite low concentrations. Care is needed to ensure that there is no inadvertent oxidation or reduction of sulphur
- It is very difficult to back-fill the underground caverns left by extraction of sulphur

- **Outline the steps and conditions necessary for the industrial production of  $H_2SO_4$  from its raw materials**

Today most  $H_2SO_4$  is manufactured by the Contact Process.

Step 1 – molten sulphur (or sulphide ore eg pyrite) is combusted to form  $SO_2$ .

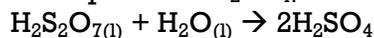


Step 2 –  $SO_2$  gas is transferred to a catalytic converter where it is oxidised to  $SO_3$ .



Conditions necessary include a pressure of 1-2 atmospheres, a small excess of O<sub>2</sub>, a catalyst of vanadium (V) oxide, and temps of 400-500°C.

Step 3 – SO<sub>3</sub> is dissolved in conc H<sub>2</sub>SO<sub>4</sub> to form oleum, H<sub>2</sub>S<sub>2</sub>O<sub>7</sub>. Water is then added to the oleum to produce H<sub>2</sub>SO<sub>4</sub>.



- **Describe the reaction conditions necessary for the production of SO<sub>2</sub> and SO<sub>3</sub>**
  - The production of SO<sub>2</sub> is carried out in a combustion furnace. The exothermic reaction occurs quickly and goes to completion. An excess of dry air is used so that the SO<sub>2</sub> produced is already mixed with O<sub>2</sub> for the next step.
  - To produce SO<sub>3</sub> the reaction conditions necessary include a pressure of 1-2 atmosphere, as small excess of O<sub>2</sub> to increase the yield, temperatures of 400-500°C and a catalyst of V<sub>2</sub>O<sub>5</sub>. The catalyst is needed to increase the reaction rate at moderate temperatures without decreasing the yield.
  - The conditions used are a compromise between reaction rate and equilibrium yield to produce as much SO<sub>3</sub> as possible.
- **Apply the relationship between rates of reaction and equilibrium conditions to the production of SO<sub>2</sub> and SO<sub>3</sub>**

The reaction to produce SO<sub>2</sub> goes to completion.

#### Temperature

A high yield of SO<sub>3</sub> could be achieved at low temps but the rate of the reaction would be very slow. A faster reaction rate will occur at high temps but the yield would be low. The temp chosen is a compromise between reaction rate and yield.

#### Pressure

The rate of formation of SO<sub>3</sub> is increased by increasing the total pressure so that there are more collisions between particles. Increasing the pressure will increase the yield of SO<sub>3</sub> because, according to Le Chatelier's principle, the system will respond by favouring the reaction which produces fewer molecules (3→2). However, the actual reaction takes place at a pressure of 1-2 atmosphere because even at these pressures there is a 99.5% conversion rate.

#### Concentration

The rate of reaction is increased by increasing the concentration of reactants so there are more collisions between reactants. Increasing the concentration will also shift the equilibrium to the right, increasing the yield of SO<sub>3</sub> and so a small excess of O<sub>2</sub> is used because it is cost effective.

<b>Change to reaction conditions</b>	<b>Effect on reaction rate</b>	<b>Effect on yield</b>
Increase pressure	Small increase	Increase
Increase concentration of oxygen	Small increase	Increase
Remove sulphur trioxide from reaction zone	Small increase	Increase
Increase temperature	Increase	Decrease

Use a catalyst	Increase greatly	No change (but produced more quickly)
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- Describe, using examples, the reactions of sulfuric acid acting as:

### **An oxidising agent**

**(put conc H<sub>2</sub>SO<sub>4</sub> above arrows)**

Sulfuric acid is a moderately strong oxidising agent. An oxidising agent is a substance that brings about oxidation.

Concentrated sulfuric acid oxidises many metals with the formation of sulphur dioxide and water. In this case the sulfate ion acts as the oxidant.



Concentrated also oxidises bromine and iodide salts to form free halogens.



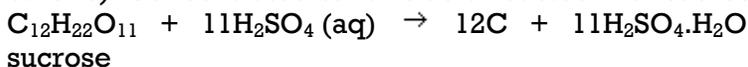
### **A dehydrating agent**

Sulfuric acid has a very strong affinity for water: it absorbs water from mixtures such as moist air and forms an aqueous solution.

Concentrated sulfuric acid will remove the waters of hydration in hydrated salts. Blue copper (II) sulfate crystals are turned to white anhydrous copper sulfate by the removal of water.

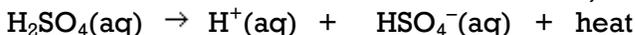


Concentrated sulfuric acid can rapidly dehydrate many organic compounds such as sugars and alcohols. Alcohols are dehydrated to form alkenes (eg converts ethanol to ethene). Concentrated sulfuric acid reacted with sucrose leaves black carbon.



- Describe and explain the exothermic nature of sulfuric acid ionization

The ionisation of sulfuric acid is exothermic, releasing lots of heat.



Sulfuric acid dissociates in two steps.

Notice that sulfuric acid is a strong acid in its first dissociation, but the  $\text{HSO}_4^-$  ion is a weak acid and only dissociates slightly.



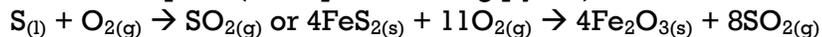
- Identify and describe safety precautions that must be taken when using and diluting concentrated sulfuric acid

- Never add water to acid – reacts with water to produce strongly exothermic reaction. This will produce a dilute solution, releasing only a small amount of heat and any splashes that occur are more likely to be water or dilute acid rather than concentrated acid.
- Slowly and carefully add concentrated sulfuric acid to a large volume of water. Pour acid down the side of the container, stir frequently
- Gloves, lab coat and especially safety glasses must be worn
- Work near supply of running water - if acid is spilled on skin, water must be run over area for many minutes (dehydrate and loose skin)

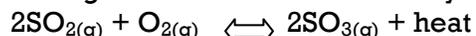
- **Gather, process and present information from secondary sources to describe the steps and chemistry involved in the industrial production of H<sub>2</sub>SO<sub>4</sub> and use available evidence to analyse the process to predict ways in which the output of sulfuric acid can be maximized**

Today most H<sub>2</sub>SO<sub>4</sub> is manufactured by the Contact process.

**Step 1** – molten sulphur (or sulphide ore eg pyrite) is combusted to form SO<sub>2</sub>.

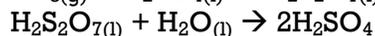
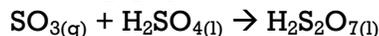


**Step 2** – SO<sub>2</sub> gas is transferred to a catalytic converter where it is oxidised to SO<sub>3</sub>.



The output of H<sub>2</sub>SO<sub>4</sub> can be maximised by maximising the yield of SO<sub>3</sub> produced by carefully controlling conditions. The conditions for maximum yield include a pressure of 1-2 atmosphere, as small excess of O<sub>2</sub> to increase the yield, temperatures of 400-500oC and a catalyst of V<sub>2</sub>O<sub>5</sub>. The catalyst is needed to increase the reaction rate at moderate temperatures without decreasing the yield. The catalyst is also in pellet form which increases its surface area. The SO<sub>2</sub> gas is also passed over several layers of catalyst, cooling the mixture slightly in between each pass, resulting in almost complete conversion of SO<sub>2</sub> to SO<sub>3</sub>.

**Step 3** – SO<sub>3</sub> is transferred to an absorption tower and is dissolved in conc H<sub>2</sub>SO<sub>4</sub> to form oleum, H<sub>2</sub>S<sub>2</sub>O<sub>7</sub>. Water is then added to the oleum to produce H<sub>2</sub>SO<sub>4</sub>.



SO<sub>3</sub> is not directly absorbed in water as this would vaporise the water, produce a dangerous mist of H<sub>2</sub>SO<sub>4</sub> and result in the loss of most of the SO<sub>3</sub>, thus decreasing the yield of H<sub>2</sub>SO<sub>4</sub>.

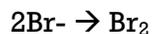
Any unreacted SO<sub>2</sub> is recycled back to the converter so that it can be passed over the catalyst again. The final amounts of SO<sub>3</sub> formed are sent to a second absorption tower. This can increase the conversion of SO<sub>2</sub> to SO<sub>3</sub> to 99.5% resulting in a max output of H<sub>2</sub>SO<sub>4</sub>.

- **Perform first-hand investigations to observe the reactions of sulfuric acid acting as:**

#### **An oxidising agent**

Potassium bromide + H<sub>2</sub>SO<sub>4</sub>

H<sub>2</sub>SO<sub>4</sub> used as oxidising agent – bromine ions become bromine atoms



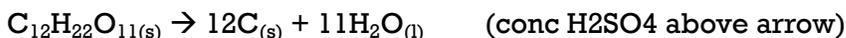
Observation: red/orange vapour/gas forms

#### **A dehydrating agent**

1. Place sugar in beaker (white, crystalline solid)

2. Add concentrated sulfuric acid

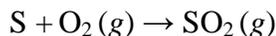
Observation: Solution gradually got darker, steam was released, black column of carbon rose out of beaker



- **Use available evidence to relate the properties of sulfuric acid to safety precautions necessary for its transport and storage.**

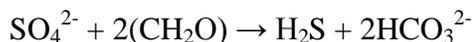
- concentrated sulfuric acid does not attack iron and steel so it can be safely stored or transported in steel containers
- sulfuric acid that has been diluted attacks metals such as iron and steel. Hence dilute sulfuric acid must be stored in glass or plastic containers.
- Care must be taken to avoid contamination with water, because that could set off a vigorous reaction between the acid and the container.

Potential environmental issues associated with the extraction of sulphur are the development of sulphur dioxide or hydrogen sulphide. Sulphur itself is non-volatile and odourless and does not escape into the environment and create a problem. However, sulphur is easily oxidised into sulphur dioxide (SO<sub>2</sub>) at quite low concentration levels. The oxidation process is shown in the reaction below:



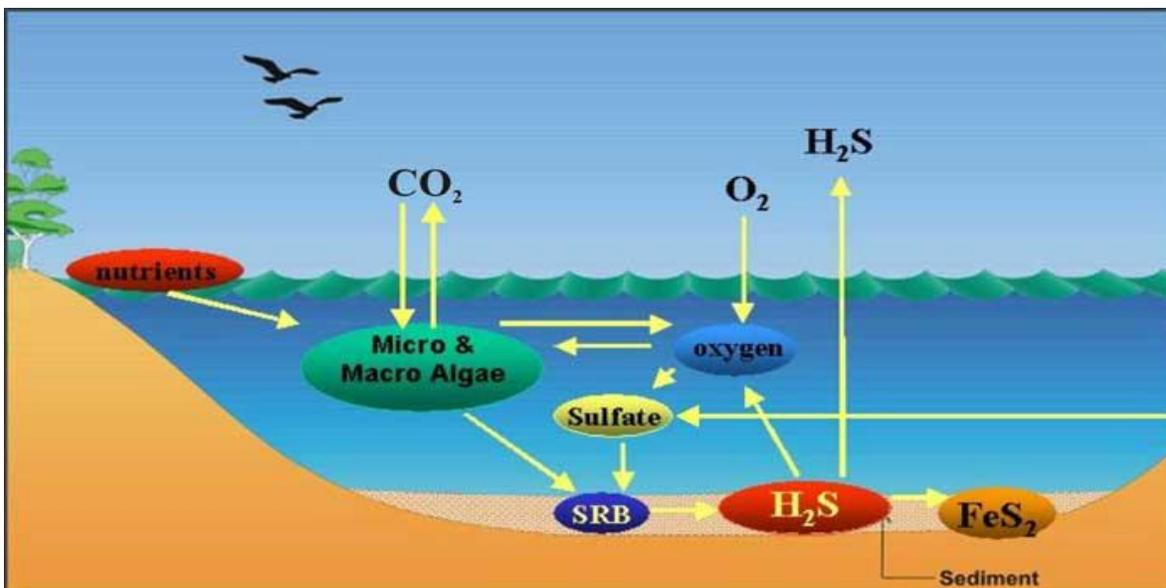
Sulphur dioxide is an irritant to the lungs with short-term exposure linked to wheezing, chest tightness and shortness of breath and longer-term exposure, in conjunction with high levels of particulate soot, causes respiratory illness, alterations in the lungs' defences and aggravation of existing cardiovascular disease. Furthermore, sulphur dioxide is a chief air pollutant as the gas reacts with water and atmospheric oxygen to form sulphurous acid (H<sub>2</sub>SO<sub>3</sub>), causing Acid rain. This is definitely an environmental issue as acid rain acidifies soils, lakes and streams, accelerates corrosion of buildings and monuments, and reduces visibility. Sulphur dioxide also is a major precursor of fine particulate soot, which poses a significant health threat.

Sulphur can also be reduced to hydrogen sulphide (H<sub>2</sub>S), which is a gas fatal at high levels. The reduction equation is shown below:



At low levels, hydrogen sulphide gas has a strong odour similar to rotten eggs. At higher levels, the gas can overwhelm your nose and you cannot smell it. At these higher levels, hydrogen sulphide gas can make you sick and could be fatal. Also, if hydrogen sulphide enters into the water it is toxic to aquatic organisms, meaning a degradation of our waterways. This itself is an environmental issue, which can be potentially caused if sulphur is reduced.

The picture below shows sulphate reduction and hydrogen sulphide and iron sulphide production in a coastal lake. SRB stands for Sulphate reducing bacteria. Taken from [http://www.ozestuaries.org/indicators/Def\\_sulphate\\_reduction.html](http://www.ozestuaries.org/indicators/Def_sulphate_reduction.html)



The water involved in the extraction of sulphur may have dissolved impurities present in the deposit of sulphur, and it is necessary to re-use this water and not discharge it into the environment as it could contaminate the water supply and the process shown in the picture above can occur. Furthermore, it is difficult to back-fill the underground caverns left by sulphur extraction, unlike other underground mining ventures, leading to the possibility of earth subsidence's occurring. The possibility of the soil collapsing is a dangerous factor and an environmental issue. This is another result that can possibly occur from the extraction of sulphur.

It is necessary, therefore, to take care to ensure that sulphur has no inadvertent oxidation or reduction reactions. Adequate precautions need to be taken when leaving the mines that have expired in order to prevent earth subsidence. Finally, the water used in the sulphur extraction process needs to be reused to prevent impurities entering the environment and upsetting the ecosystem, especially that in streams and other waterways.

HSC Course: Conquering Chemistry, Roland Smith, Mc-Graw Hill Book Company, 2000, Sydney, Australia.

[http://en.wikipedia.org/wiki/Hydrogen\\_sulfide](http://en.wikipedia.org/wiki/Hydrogen_sulfide)

[http://en.wikipedia.org/wiki/Sulfur\\_dioxide](http://en.wikipedia.org/wiki/Sulfur_dioxide)

<http://www.alken-murray.com/H2SREM8.HTM>

<http://www.cleanairtrust.org/sulfurdioxide.html>

<http://www.corrosion-doctors.org/Pollution/Acidrain.htm>

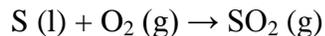
<http://www.idph.state.il.us/envhealth/factsheets/hydrogensulfide.htm>

[http://www.ozestuaries.org/indicators/Def\\_sulphate\\_reduction.html](http://www.ozestuaries.org/indicators/Def_sulphate_reduction.html)

**Question 3.**

Most of the sulfuric acid manufactured is produced using the *Contact Process*, a process involving the catalytic oxidation of sulphur dioxide, SO<sub>2</sub>, to sulphur trioxide, SO<sub>3</sub>.

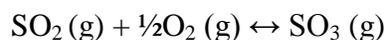
- I. Liquid sulphur is sprayed with excess dry air at atmospheric pressure.



The dry air contains about 33% more oxygen than is needed for conversion of S to SO<sub>2</sub> and to SO<sub>3</sub>. The air is dried by passage through sulfuric acid.

This combustion reaction generates a lot of heat and therefore the reaction needs to be cooled from 1000°C to about 400°C, this allows optimum temperature for admission of the SO<sub>2</sub> to SO<sub>3</sub> converter.

- II. The oxidation of SO<sub>2</sub> to SO<sub>3</sub> is the most difficult part of making sulfuric acid. The reaction is as follows:



This reaction is an exothermic reaction (energy is released), so by Le Chatelier's Principle, higher temperatures will force the equilibrium position to shift to the left of the equation favouring the production of sulphur dioxide. Lower temperatures would favour the production of the product sulphur trioxide and result in a higher yield. However, the rate of reaching equilibrium at the lower temperatures is extremely low. Higher temperature means equilibrium is established more rapidly but the yield of sulphur trioxide is lower. A temperature of 450°C is a compromise whereby a faster reaction rate results in a slightly lower yield.

Similarly, at higher pressures, the equilibrium position shifts to the side of the equation in which there are the least numbers of gaseous molecules.

On the left hand side of the reaction there are 3 moles of gaseous reactants, and the right hand side there are 2 moles of gaseous products, so higher pressure favours the right hand side, by Le Chatelier's Principle. Higher-pressure results in a higher yield of sulphur trioxide.

A vanadium catalyst is also used in this reaction in order to speed up the rate of the reaction.

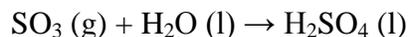
In summary, the conditions used to convert SO<sub>2</sub> to SO<sub>3</sub> is pressure a little above atmospheric, small excess of oxygen, a catalyst of vanadium oxide supported on silica and temperatures of catalyst beds of 550°C (for high rate) and 400°C (for high conversion).

- III. Any unreacted gases from the above reaction are recycled back into the above reaction.

- IV. Sulphur trioxide,  $\text{SO}_3$  (g) is dissolved in 98% (18M) sulfuric acid,  $\text{H}_2\text{SO}_4$ , to produce disulfuric acid or persulfuric acid, also known as fuming sulfuric acid or oleum,  $\text{H}_2\text{S}_2\text{O}_7$ .



This is done because when water is added directly to sulphur trioxide to produce sulfuric acid the reaction is slow and tends to form a mist of sulfuric acid droplets in residual gasses ( $\text{N}_2$  with some  $\text{O}_2$ ) in which the particles refuse to coalesce.

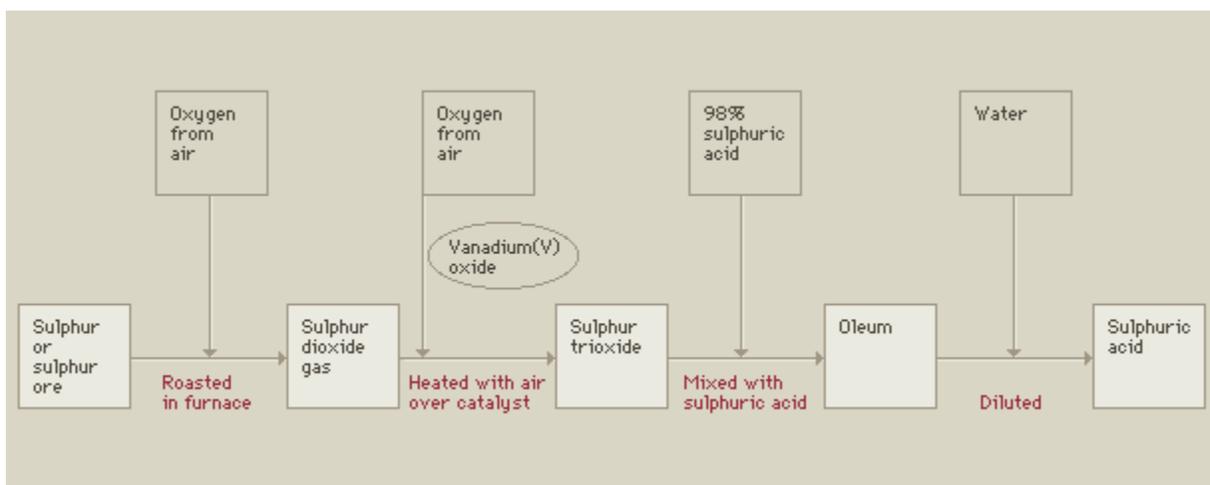


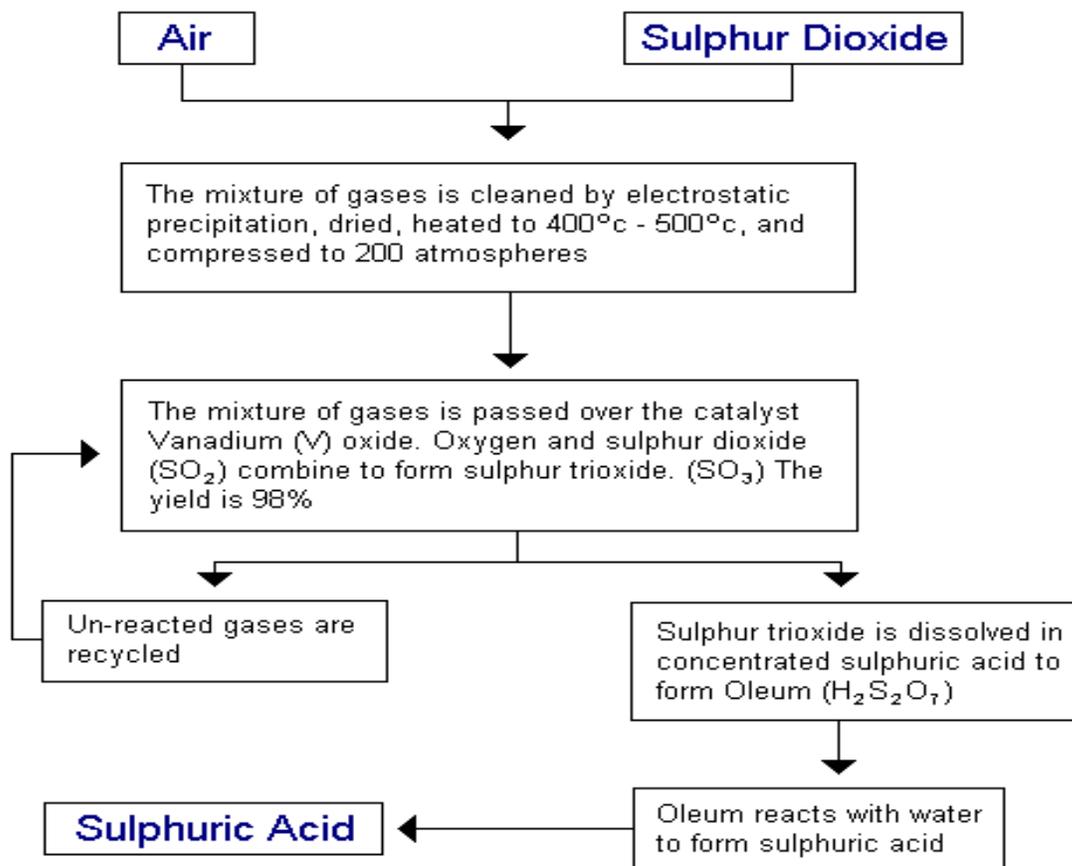
- V. Water is added to the disulfuric acid,  $\text{H}_2\text{S}_2\text{O}_7$ , to produce sulfuric acid,  $\text{H}_2\text{SO}_4$



Two absorbing towers are used, one which absorbs the bulk of the acid formed and which passes the residual gas back to the final catalyst tray of the converter and the second one absorbs the final amounts of then vents the residual gasses mentioned above. The result is 98% sulfuric acid with 2% water drawn off from both absorbers. This is the final product of concentrated sulfuric acid.

Below are flow charts of the “contact process”.





[HSC Course: Conquering Chemistry, Roland Smith, Mc-Graw Hill Book Company, 2000, Sydney, Australia.](#)

[HSC Course: Macmillian Chemistry Pathways 2, Geoffrey Thickett, Macmillan Education Australia Pty Ltd, 2000, Australia.](#)

[http://encarta.msn.com/media\\_461542069\\_761566936\\_-1\\_1/Contact\\_Process.html](http://encarta.msn.com/media_461542069_761566936_-1_1/Contact_Process.html)

<http://www.usetute.com.au/sulfacid.html>

<http://www.enviro-chem.com/plant-tech/3rdtier/sulfcat.html>

[http://www.revisioncentral.co.uk/gcse/chemistry/contact\\_process.html](http://www.revisioncentral.co.uk/gcse/chemistry/contact_process.html)

#### Question 4.

When transporting sulfuric acid, care needs to be taken to avoid it coming into contact with water. As 98% of sulfuric acid is all molecular, having very few ions, it does not attack iron or steel so can safely be stored in steel containers (in a dry, cool, well-ventilated location) or transported in steel tankers. Steel has greater strength when compared to glass and plastic containers (which sulfuric acid also does not react with).

There is however, a problem when it comes to diluted sulfuric acid. The hydrogen ions vigorously attack metals such as iron and steel. This is why diluted acid needs to be stored in glass or plastic containers, also making it more difficult to transport.

When sulfuric acid is stored in steel containers, it needs to be waterproofed to ensure that contamination of water is not possible. If water contaminates the acid, it could set off a vigorous reaction between the acid and the container. Sulfuric acid also decomposes at high temperatures to form poisonous sulfur dioxide and trioxide fumes and for that reason, the container must be kept airtight. These chemicals have also been found to be carcinogenic in nature, through research by the International Agency for Research on Cancer (IARC). They are suspected to cause larynx cancer and lung cancer if inhaled over long periods of time.

Sulfuric acid is a negligible fire hazard when exposed to heat or flame. However, as it is stored in a container it can heat up causing oxidisers to decompose and yield oxygen or other gases, which will increase the burning rate of combustible matter. Contact with easily oxidisable, organic, or other combustible materials may result in ignition, violent combustion or explosion. If this does happen, the fire needs to be fought with dry chemicals or carbon dioxide. If the fire is large, the area of the fire needs to be flooded from a distance. Water needs to be kept out of the storage container and away from spilled material as it will just entice a reaction between the acid and the steel and as it is an exothermic reaction, it will give more heat to the fire.

During transport, if there is a spill there are certain methods that need to be undergone in order to neutralise the spill and prevent the area from being contaminated with sulfuric acid:

- **SOIL SPILL:**

- Dig holding area such as lagoon, pond or pit for containment.

- Dike flow of spilled material using soil or sandbags or foamed barriers such as polyurethane or concrete.

- Use cement powder or fly ash to absorb liquid mass.

- Neutralize spill with slaked lime, sodium bicarbonate or crushed limestone.

- **AIR SPILL:**

- Apply water spray to knock down and reduce vapours. Knockdown water is corrosive and toxic and should be diked for containment and later disposal.

- **WATER SPILL:**

- Neutralize with agricultural lime, slaked lime, crushed limestone, or sodium bicarbonate.

- **OCCUPATIONAL SPILL:**

- Keep combustibles (wood, paper, oil, etc.) away from spilled material. Do not touch spilled material. Do not get water inside container. Stop leak if you

can do it without risk. Use water spray to reduce vapours. Do not put water on leak or spill area. Clean up only under the supervision of an expert. Dike spill for later disposal. Do not apply water unless directed to do so. Keep unnecessary people away. Isolate hazard area and deny entry. Ventilate closed spaces before entering.

It is therefore necessary to take adequate safety precautions when transporting as well as storing sulfuric acid. Due the fact that it reacts with water and then reacts with metals such as steel, it can be difficult to transport. Furthermore, the transport vessel cannot be heated or an explosion could occur which is difficult to put out.

- Outline the steps and conditions necessary for the industrial production of H<sub>2</sub>SO<sub>4</sub> from its raw materials.**
  - This process is called the **Contact Process** (because the SO<sub>2</sub> and O<sub>2</sub> gases must come into contact with a catalyst).
  - 1. Conversion of sulfur to sulfur dioxide:
    - $S + O_2(g) \rightarrow SO_2(g)$
    - When the process starts with pure sulfur, liquid sulfur is sprayed into an excess of dry air at atmospheric pressure. The amount of dry air used is such that it contains about 33% more oxygen than is needed for conversion of S to SO<sub>2</sub> and to SO<sub>3</sub>. The air is dried by passage through sulfuric acid.
  - 2. Conversion of sulfur dioxide to sulfur trioxide:
    - $SO_2(g) + \frac{1}{2}O_2(g) \leftrightarrow SO_3(g) \quad \Delta H = -99 \text{ kJ/mol.}$
    - A pressure of a little above atmospheric.
    - A small excess of oxygen.
    - A catalyst of vanadium (V) oxide supported on silica.
    - Temperature of catalyst beds of 550°C (for high rate) and 400°C (for high conversion).
  - 3. Absorption of sulfur trioxide in water to form sulfuric acid:
    - $SO_3(g) + H_2O(l) \rightarrow H_2SO_4(l)$
    - Because this reaction is so exothermic, spraying water into the SO<sub>3</sub>-containing gas stream produces a fine mist of sulfuric acid droplets in the residual gas (N<sub>2</sub> with some O<sub>2</sub>). It is difficult to separate this sulfuric acid mist from the gas.
    - This is overcome by: in the absorber towers of SO<sub>3</sub> is dissolved in sulfuric acid to form **oleum** (H<sub>2</sub>S<sub>2</sub>O<sub>7</sub>) and water is added at a controlled rate to convert the oleum to sulfuric acid.
      - $SO_3(g) + H_2SO_4(l) \rightarrow H_2S_2O_7(l)$
      - $H_2S_2O_7(l) + H_2O(l) \rightarrow 2H_2SO_4(l)$
- Describe the reaction conditions necessary for the production of SO<sub>2</sub> and SO<sub>3</sub>.**
  - **Equilibrium considerations:** the oxidation of SO<sub>2</sub> to SO<sub>3</sub> is an equilibrium reaction. It is also an exothermic reaction. This means this equilibrium must be forced to the right by using: excess of oxygen (operating at a higher total pressure or by using pure oxygen as reactant instead of air), high pressure and a low temperature.
  - **Compromise conditions:** temperature of 1<sup>st</sup> catalyst bed of 550°C (for high rate, ~70% of conversion). Temperature of 2<sup>nd</sup> catalyst bed of 400°C (for high conversion, ~97% of conversion). The removal of SO<sub>3</sub> from the gas stream then passing the remaining gas mixture over another catalyst bed for final conversion (~99.7%). The remaining 0.3% of the original SO<sub>2</sub> is emitted to the atmosphere.
  - **Energy considerations:** both the burning of sulfur and the conversion of SO<sub>2</sub> and SO<sub>3</sub> are exothermic reactions. Some of the heat released during the process is used to melt the sulfur and the rest is used to form steam for electricity generation. In this way the process can produce a large proportion of the energy needed to operate the plant. Designing energy efficiency into such plants is not only cost effective, but it also minimises environmental damage.

- Apply the relationship between rates of reaction and equilibrium conditions to the production of SO<sub>2</sub> and SO<sub>3</sub>.

	Production of SO <sub>2</sub>	Production of SO <sub>3</sub>
<b>Equation</b>	$S + O_2 (g) \rightarrow SO_2 (g)$	$SO_2 (g) + \frac{1}{2}O_2 (g) \leftrightarrow SO_3 (g)$
<b>Rate Considerations</b>	- As temp ↑ the rate ↑.	- As the temp ↑ the rate ↑. However, since this reaction is exothermic, the prodn of SO <sub>3</sub> ↓ once temp reaches to a certain point and i.e. 400°C. - The use of a catalyst, vanadium (V) oxide, V <sub>2</sub> O <sub>5</sub> , supported on porous silica pellets.
<b>Equilibrium Considerations</b>	- ↑ pressure of O <sub>2</sub> , system will want to counteract the change and ↓ pressure. The equilibrium shift to the right thus the forward reaction will be favoured, prodn of SO <sub>2</sub> will ↑. - The max amount of O <sub>2</sub> is maintained. As the concentration of O <sub>2</sub> ↑, the equilibrium shift to the right. I.e. the forward reaction is favoured and the production of SO <sub>2</sub> ↑.	- ↑ the pressure (concentration) of O <sub>2</sub> , the equilibrium will want to counteract the change and ↓ the concentration of O <sub>2</sub> . The equilibrium shift to the right thus the forward reaction will be favoured, the prodn of SO <sub>3</sub> will ↑. The pressure of oxygen can be ↑ by using pure oxygen as reactant instead of air. - ↑ the total pressure, the equilibrium will want to counteract the change and ↓ the overall pressure. The molar ratio is 1.5:1, the equilibrium shift to the right thus the forward reaction will be favoured, the prodn of SO <sub>3</sub> will ↑.
<b>Thus...</b>	- The pressure of O <sub>2</sub> is the main condition, it must be maintained at its max.	- The compromise conditions are excess of oxygen, high pressure and a moderate temp.

- Describe, using examples, the reactions of sulfuric acid acting as:
  - **An oxidising agent.**
    - Sulfuric acid is a moderately strong oxidising agent.
    - An **oxidising agent** is a substance that brings about oxidation (lose of e-s). It is also called an **oxidant** or an **oxidiser**.
    - The half reaction for sulfuric acid acting as an oxidising agent (absorbing e-s) is:
      - $HSO_4^- + 3H^+ + 2e^- \rightarrow SO_2 + 2H_2O$  (in aqueous solution).
      - $2HSO_4^- + 2H^+ + 2e^- \rightarrow SO_2 + 2H_2O + SO_4^{2-}$  (as concentrated acid)
    - The reactions of sulfuric acid with reactive metals are redox reactions but the oxidant is usually considered to be the hydrogen ion rather than sulfuric acid itself.
    - **Give an example: sugar and sulfuric acid, eqn in prac book.**
  - **A dehydrating agent.**
    - Sulfuric acid has a very strong affinity for water: it absorbs water from mixtures such as moist air and forms an aqueous solution.

- Sulfuric acid can be used to dry gases which do not react with it such as air, helium natural gas or LPG.
  - In addition concentrated sulfuric acid can remove hydrogen and oxygen from compounds as water with which it forms a solution.
  - **Give an example: sugar and sulfuric acid, eqn in prac book.**
- **Describe and explain the exothermic nature of sulfuric acid ionisation.**
    - When sulfuric acid is diluted with water, a large amount of heat is released:
    - $\text{H}_2\text{SO}_4$  (98%)  $\rightarrow$   $\text{H}_2\text{SO}_4$  (very dilute solution)  $\Delta H = -90 \text{ kJ/mol}$
    - This dilution is very **exothermic**.
    - The dilution of sulfuric acid releases much more heat than the dilutions of HCl and nitric acids.
    - The main reason is that diluting concentrated sulfuric acid involves the ionisation of molecular  $\text{H}_2\text{SO}_4$  into hydrated hydrogen and  $\text{HSO}_4^-$  ions:
    - $\text{H}_2\text{SO}_4$  (l) +  $\text{H}_2\text{O}$  (l)  $\rightarrow$   $\text{H}_3\text{O}^+$  (aq) +  $\text{HSO}_4^-$  (aq)
    - Every 100g of 98% sulfuric acid contains 0.1 mol  $\text{H}_2\text{O}$  and 1.0 mol  $\text{H}_2\text{SO}_4$ . Therefore no more than 10% of the  $\text{H}_2\text{SO}_4$  molecules can be ionised. In fact most of the water is tied up as hydrates such as  $\text{H}_2\text{SO}_4 \cdot \text{H}_2\text{O}$  so that there are very few ions in 98% sulfuric acid.
    - When it is added to water, the  $\text{H}_2\text{SO}_4$  molecules can ionise. The ionisation is strongly exothermic and so a large amount of heat is liberated.
    - In concentrated HCl and nitric acids there is sufficient water for all the acid molecules to be already ionised. So adding water to these acids just dilutes the ionic solutions and this releases much less heat.
- **Identify and describe safety precautions that must be taken when using and diluting concentrated sulfuric acid.**
    - Always add acid **slowly** to water, **never** add water to concentrated sulfuric acid. This is because if splashing occurs, the water would be splashed out instead of the acid.
    - Always wear safety goggles because splashes into an eye can cause serious permanent damage).
    - Wear protective gloves and a laboratory coat or apron because sulfuric is very corrosive to skin and clothing.
    - Work near a ready supply of running water to wash off or dilute any splashes to body or clothing.
    - For regular use store the acid in glass bottles no larger than 1L.
    - Wipe off acids with wet tissues because it neutralise the acid.
- **Gather, process and present information from secondary sources to describe the steps and chemistry involved in the industrial production of  $\text{H}_2\text{SO}_4$  and use available evidence to analyse the process to predict ways to which the output of sulfuric acid can be maximised.**

- **Perform 1<sup>st</sup>-hand investigations to observe the reactions of sulfuric acid acting as:**
  - **An oxidising agent.**
  - **A dehydrating agent.**
  - This was a teacher demonstration.
- **Use available evidence to relate the properties of sulfuric acid to safety precautions necessary for its transport and storage.**
  - 98% sulfuric acid is virtually all **molecular** (very few ions).
  - It does not attack iron and steel, so can safely be stored in steel containers or transported in steel tankers.
  - Steel has greater strength than glass and plastic containers.
  - However, diluted sulfuric acid contains hydrogen ions and vigorously attacks metals such as iron and steel. Hence diluted acid must be stored in glass or plastic containers. This is more difficult to transport.
  - When storing or transporting this acid in steel containers, care must be taken to avoid contamination with water, because that could set off a vigorous reaction b/w the acid and the container.