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# *RISK ASSESSMENT OF THE SULPHURIC ACID PLANT AS PART OF THE PROPOSED EXPANSION OF RÖSSING URANIUM MINE, NAMIBIA*

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***January 2008***

***M P Oberholzer***

RISCOM

P O Box 2541, Cresta, 2118
Tel: +27 (0) 82 457 3258
Fax: : 086 624 9423
e-mail: mike@riscom.co.za

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Mike Oberholzer is a Professional Engineer and holds a BSc (Chemical Engineering). He is an approved signatory for MHI risk assessments, thus meeting the competency requirements of SANAS for assessments of hazardous materials covering, fire, explosions and toxic releases.

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# RISK ASSESSMENT OF THE SULPHURIC ACID PLANT AS PART OF THE PROPOSED EXPANSION OF RÖSSING URANIUM MINE, NAMIBIA

# EXECUTIVE SUMMARY

## 1 INTRODUCTION

Rössing Uranium (hereinafter RU) has proposed an expansion of the mining activities. Part of the expansion project is the construction of a Sulphuric Acid Plant. As the accidental release of intermediate products of sulphur dioxide and sulphur trioxide could have offsite consequences, Riscom was commissioned to conduct a risk assessment of the proposed facility to determine the impacts on neighboring facilities and the public.

### 1.1 Terms of Reference

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ii. Are there any factors that will prevent the project from proceeding to the next phase or construction? Alternatively can the project continue under certain conditions or mitigation?
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The scope of the work covered:

1. Developed accidental release and fire scenarios for the proposed sulphuric acid plant, sulphur store and a generic sulphur fire on a stationary rail and road vehicle;
2. Using generic failure rate data (tanks, pumps, valves, flanges, pipe work, gantry, couplings, etc.), determined the probability of each accident scenario.
3. For each incident developed in Step 2, determine the consequences (toxic end points, thermal radiation, domino effect, etc.).
4. Calculated the Maximum Individual Risk (MIR) values taking into account all accidents, worst case meteorological conditions and lethality.
5. Comment of there are any fatal flaws that may prevent the project proceeding to the next phase of the project.

### 1.2 Purpose and Main Activities

Rössing Uranium Mine main activity is the mining and processing of uranium. As part of operations, sulphuric acid will be produced and used in the process

### 1.3 Main Hazard Due To Substance and Process

The main hazards on the facility would be thermal radiation from sulphur fires and toxic vapour clouds from sulphur dioxide and sulphur trioxide.

## 2 ENVIRONMENT

### 2.1 General Background

The Rössing Uranium Mine is located 60 kilometres inland from the coastal town of Swakopmund in the Namib Desert in the Erongo Region in Namibia. Walvis Bay is Namibia's only deepwater harbour, as shown in Fig 1. The town of Arandis is the closest residential area and located approximately 10 km north of the mine. The land around the mine is arid and has low population density.

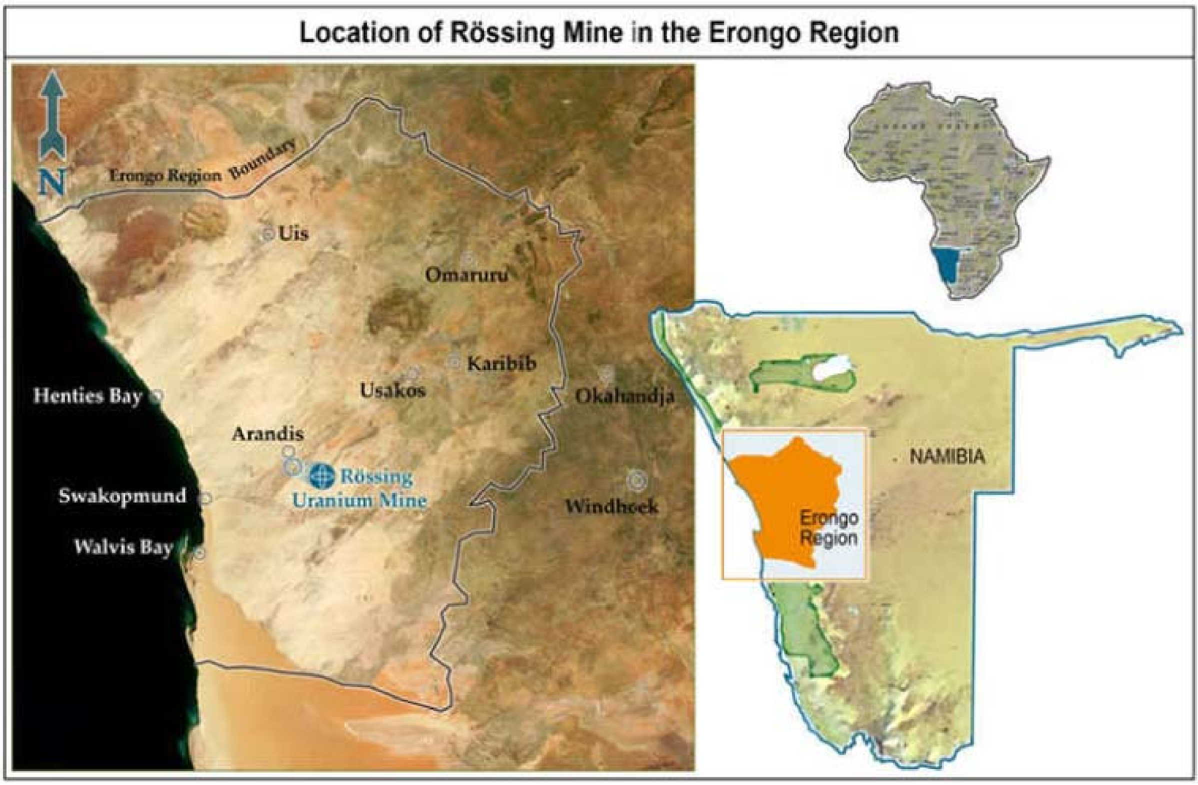


Fig 1 Location of the Rössing Uranium Mine (Courtesy RU)

# 3 PROCESS AND STORAGE TANK FACILITY

## 3.1 Site

The infrastructure on RU site consists of plant offices laboratories and workshops.

## 3.2 Process Nameplate Capacity Study

The production of sulphuric acid would be done by combusting sulphur. RU is currently evaluating a plant with nameplate capacity of 1200 tpa.

## 3.3 Process Description

### 3.3.1 Sulphur Handling and Storage Facilities

Elemental sulphur would be imported at the Port of Walvis Bay, off loaded from the vessel by ship un-loader and then transported by conveyor belt to a closed storage shed within the harbour complex. The maximum inventory of elemental sulphur would be 36 000 t. From the harbour, the sulphur would be loaded onto special designed rail cars and transported by rail to the mine. At the mine the sulphur would be offloaded and stockpiled in a dedicated area. The sulphur storage building at the port would cover a floor area of ~ 6 000 $m^2$ and contain the maximum inventory of 36 000 t. The sulphur storage at the mine would contain 10 000 t of sulphur and would cover a ground area of 5 000 $m^2$.

### 3.3.2 Sulphuric Acid Plant

The manufacture of sulphuric acid at RU would be done via a two-step oxidation process of elemental sulphur (S) to sulphur trioxide ($SO_3$) which would be absorbed into a 98.5% sulphuric acid solution ($H_2SO_4$) as shown below in the simplified Process Flow Diagram of Fig 2.

From the sulphur storage the sulphur would be conveyed to the sulphur melting tank, where the solid sulphur would be melted at a temperature of approximately 145 °C with 7 bar steam. The molten sulphur would then be filtered to remove any solid particles and transferred into the clean sulphur storage tank where the sulphur would be kept molten at approximately 145°C.

The molten sulphur would flow by gravity to the clean sulphur pit from where it would be pumped to the sulphur burner. In the sulphur burner, the molten sulphur would be combusted with dry air to form sulphur dioxide according to the chemical equation below.

$$S \quad + \quad O_2 \quad \rightarrow \quad SO_2 \qquad \Delta H_{rxn} \text{ -ve}$$

The reaction is exothermic and the exit $SO_2$ gas at 1131 °C and 48 kPa would be cooled to 420 °C in a waste heat boiler prior to entering the converter. The function of the converter is to oxidise the $SO_2$ to $SO_3$ using a vanadium catalyst according to the equation below.

$$SO_2 \quad + \quad \tfrac{1}{2}\, O_2 \quad \rightarrow \quad SO_3 \qquad \Delta H_{rxn} \text{ -ve}$$

The $SO_3$ formed in the converter is absorbed into 98.5% sulphuric acid via a 2 stage absorption system according to the equation below.

$$SO_3 + H_2O \rightarrow H_2SO_4 \qquad \Delta H_{rxn} \text{ -ve}$$

The gas leaving the final absorption column would be vented to atmosphere via a stack. The stack would be a self supported steel stack 50 m tall and would have a diameter of ~2 m. The top 2 m of the stack would be a stainless steel cone with an exit diameter of 1.5 m.

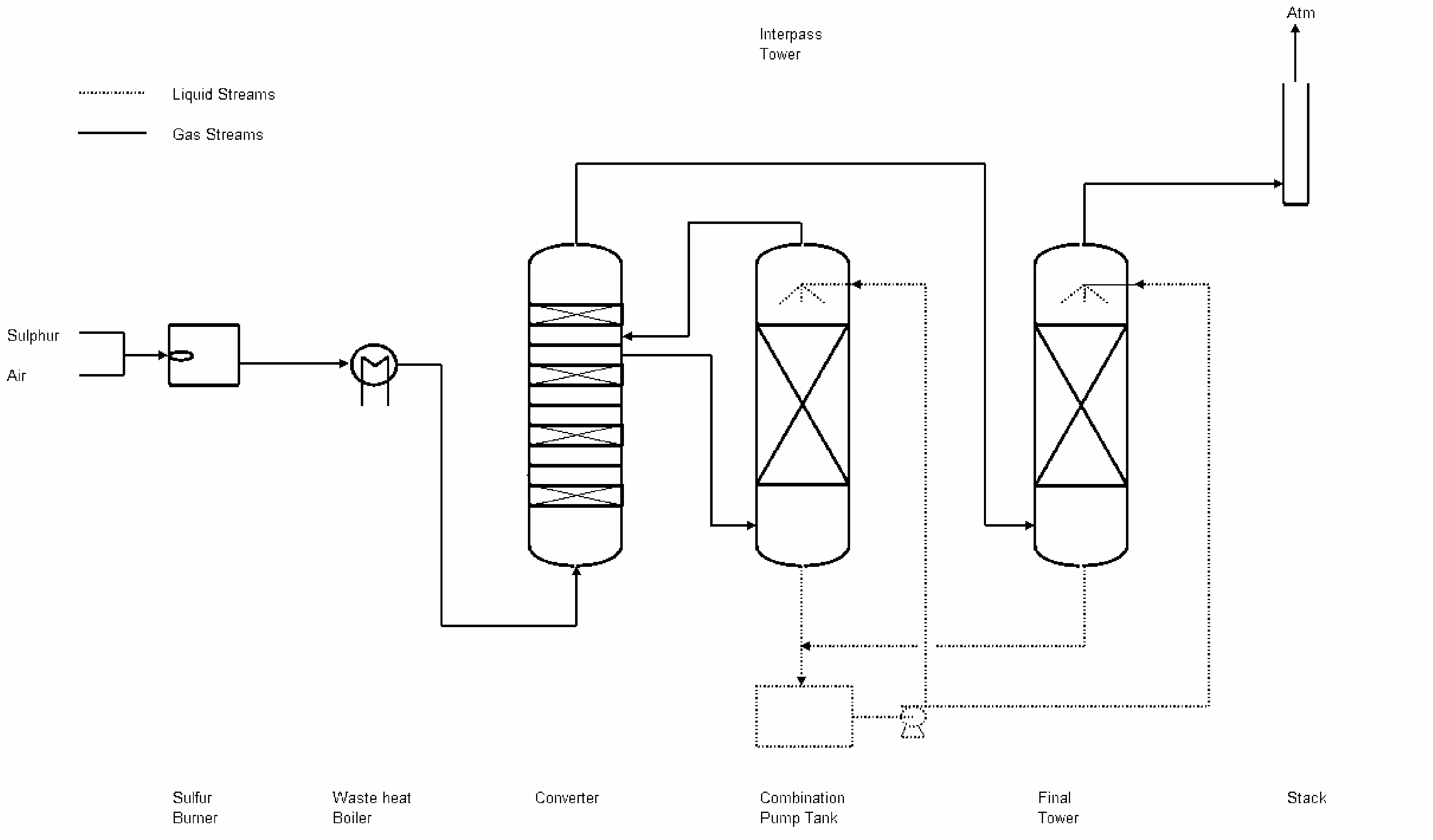


**Fig 2 Simplified Process Flow Diagram (PFD) for the production of sulphuric acid from sulphur**

### 3.4 Summary of Hazardous Materials Inventories

A summary of the proposed hazardous materials inventory required for the expansion project are:

| | | |
|---|---|---|
| Sulphur (solid): | 36 000 t | Walvis Bay |
| | 10 000 t | Mine |
| Sulphur (molten): | 394 t | (Sulphur melting pit) |
| | 1 200 t | (Molten sulphur storage tank) |
| Sulphuric acid (98%) | 1 200 | Metric tons per day |

## 4 HAZARD IDENTIFICATION

The first step in any risk assessment is to identify all hazards. The merits of including the hazard for further investigation are subsequently determined by its significance, normally using a cut-off or threshold quantity. The evaluation methodology assumes that the plant will perform as designed in the absence of unintended events such as component and material failures, human errors, external events and process unknowns.

Once a hazard has been identified, it is necessary to evaluate it in terms of the risk it presents to the employees and the neighbouring community. In principle, both probability and consequence should be considered, but there are occasions where if either the probability or the consequence can be shown to be sufficiently low or sufficiently high, decisions can be made on just one factor.

During the hazard identification component, the following considerations are taken into account:

- Chemical identities;
- Location of facilities that use, produce, process, transport or store hazardous materials;
- The type and design of containers, vessels or pipelines;
- The quantity of material that could be involved in an airborne release; and,
- The nature of the hazard (e.g. airborne toxic vapours or mists, fire, explosion, large quantities stored or processed handling conditions) most likely to accompany hazardous materials spills or releases.

Sulphur was found to be combustible and produces toxic sulphur dioxide when burnt. Sulphur trioxide formed in the Sulphuric Acid Plant is toxic.. Sulphur is explosive under certain conditions.

## 5 CONCLUSIONS

The accuracy of the simulations and risk calculations was determined by the quality of base data and expert judgements. A number of well-known sources of incident data were consulted and applied to obtain the likelihood of an incident to occur. The risk assessment included the consequences of fires and explosions from the proposed project.

The risk assessment was done on the assumption that the proposed project would be maintained to an acceptable level and that all statutory regulations would be applied. It was also assumed that the detailed engineering designs were done by competent people and would be correctly specified for the intended duty. For example it is assumed that the tank walls thickness have been correctly calculated, that the vents have been sized for emergency conditions, that the instrumentation and electrical components comply with the specified electrical area classification, that the material of construction is compatible with the products, etc.

A number of incident scenarios were simulated, and the following conclusions were reached.

### 5.1 Fires

Pool fires were calculated for potential sulphur fires at the molten sulphur tank. The thermal radiation generated from sulphur fires could injure people in the immediate vicinity of the fire. Fires at the sulphur store could damage the storage buildings but should not cause the failure of the structure. Thus the risks from thermal radiation of sulphur fires are acceptable.

Sulphur fires at the rail cars would not be significant with regards to the thermal radiation generated.

### 5.2 Explosions

Sulphur dust explosions were calculated at the storage facilities at Walvis Bay. As the sulphur storage at the mine would be in the open dust explosions would not be expected. A worst case approach was adopted and the mass of material used in the calculations was the volume of the storage facility at the lower explosive limit (LEL). The explosions simulated indicated that fatalities of the public were not expected, but the distance to safety (2 kPa) was calculated at ½ km from the center of the explosion.

### 5.3 Vapour Clouds

Sulphur dioxide and sulphur trioxide are not stored at Walvis Bay or at the RU Mine. Sulphur dioxide would be formed from the combustion of sulphur either at the sulphur storage or in the sulphuric acid plant. The sulphur dioxide is converted to sulphur trioxide in the sulphuric acid plant prior to conversion to sulphuric acid.

In the event of a sulphur fire, the endpoints to the ERPG-2 [1]guideline could extend beyond 10 km downwind of the fire. The risks for a large sulphur fire at Walvis Bay would be acceptable based on expected designs.

Sulphur dioxide and trioxide emissions from the Sulphuric Acid Plant could extend beyond 10 km downwind of the release to the ERPG-2 guidelines. The risks from an accidental release would be acceptable to workers and the public.

1 The ERPG-2 concentration is the maximum air concentration below which it is believed nearly all individuals could be exposed without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action,

# 6 RECOMMENDATIONS

The risk assessment study conducted for the proposed RU sulphur storage and the Sulphuric Acid Plant, did not find any fatal flaws that could prevent the project from proceeding. It is thus recommended that the project proceed provided that:

i. Compliance to all statutory requirements;
ii. Compliance with applicable international recognised codes of best practice for sulphur storage and sulphuric acid plants;
iii. A recognised process hazard analysis (HAZOP, FMEA, etc) should be completed for the proposed plant prior to construction. This is to ensure design and operational hazards have been identified and adequate mitigation put in place. It would be preferable if the study could be facilitated by an independent party that can not benefit financially from offering services, equipment or instrumentation for the project;
iv. Full compliance of IEC 61508 and 61511 (Safety Instrumented Systems) or equivalent, to ensure adequate protective instrumentation is included in the design and determine the required reliability of safety instrumentation for the areas producing sulphur dioxide and trioxide. Compliance with this code would assist in protecting the public for the duration of operation of the hazardous systems within the plant.
v. A safety document detailing safety and design features reducing the impacts from fires, explosions and flammable atmospheres must be prepared and issued. The built facility can be audited against the safety document to ensure compliance with the EIA Terms of Reference. Codes such as IEC 61511 can be used to achieve these requirements. RU and their contractors must demonstrate that sufficient mitigation has been included in the designs to ensure the safety of the surrounding neighbours and the public; and
vi. Emergency response documentation must be done with input from local authorities.

# TABLE OF CONTENTS

# LIST OF FIGURES



# LIST OF TABLES

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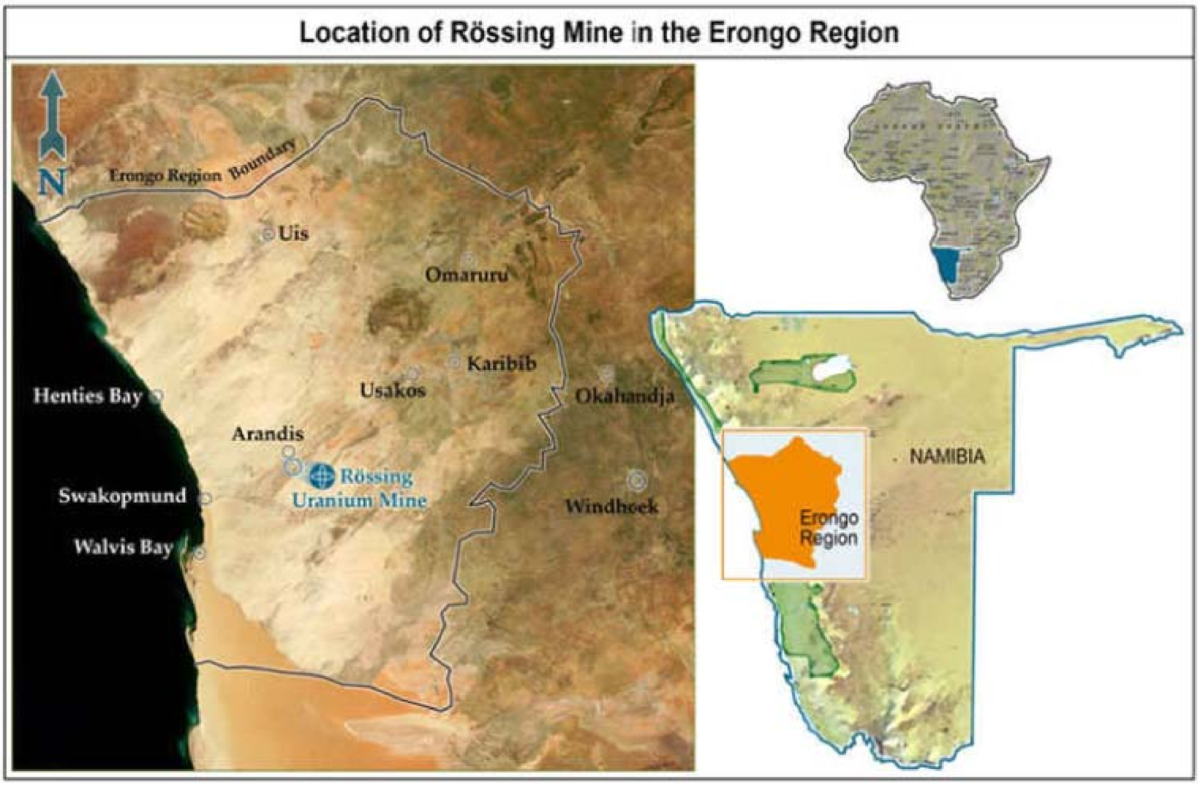


**Figure 2-1 Location of the Rössing Uranium Mine (Courtesy RU)**

# 3 PROCESS AND STORAGE TANK FACILITY

## 3.1 RU Mine

The infrastructure on RU site consists of plant offices, laboratories and workshops. The position of the proposed sulphur storage and acid plant is shown in Figure 3-1

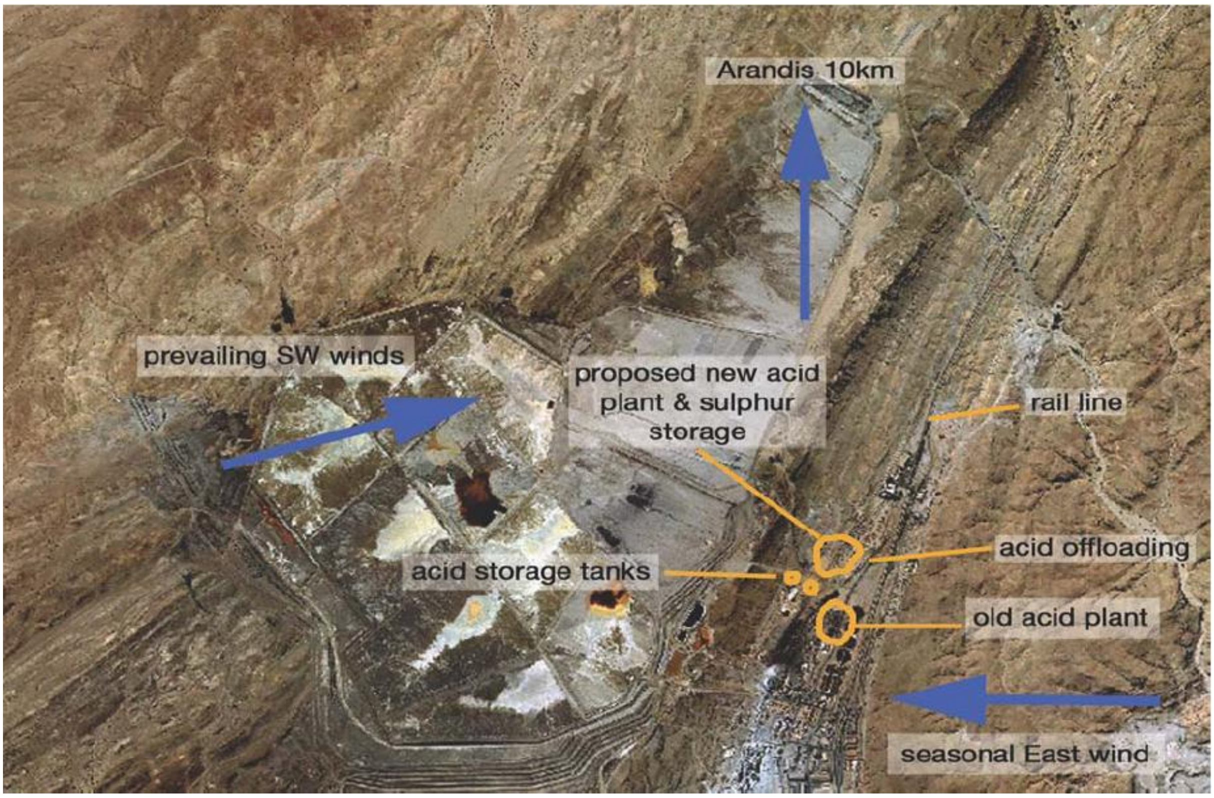


**Figure 3-1 Overlain on an aerial photograph, the proposed location of the new RU acid plant relative to the existing acid plants and other related sulphuric acid producing infrastructure (source: RU public participation material, 2007)**

## 3.2 Walvis Bay

The sulphur storage site at Walvis bay has not been finalized with the preferred site shown in Figure 3-2. The site would consist of a closed warehouse with ship offloading units, conveyors from the ship to the sulphur store and rail loading facilities.


**Figure 3-2 Preferred Sulphur Handling Site**

## 3.3 Process Nameplate Capacity Study

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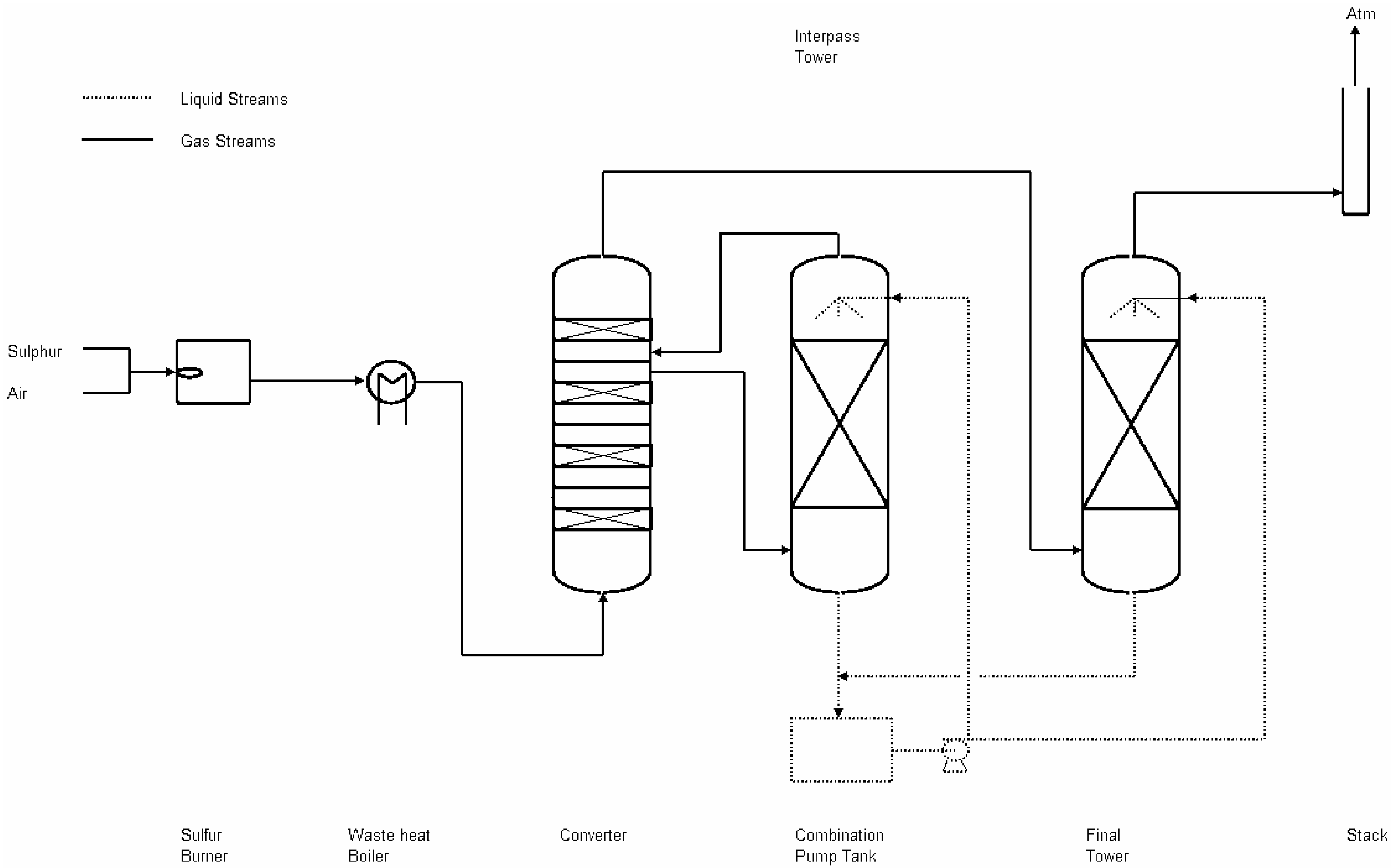


**Figure 3-3 Simplified Process Flow Diagram for the production of sulphuric acid from sulphur**

### 3.5 Summary of Hazardous Materials Inventories

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During the hazard identification component, the following considerations are taken into account:

- Chemical identities;
- Location of facilities that use, produce, process, transport or store hazardous materials;
- The type and design of containers, vessels or pipelines;
- The quantity of material that could be involved in an airborne release; and,
- The nature of the hazard (e.g. airborne toxic vapours or mists, fire, explosion, large quantities stored or processed handling conditions) most likely to accompany hazardous materials spills or releases.

## 4.1 Substance Hazards

All components on the plant were assessed for potential hazards according to the criteria discussed below.

### 4.1.1 Chemical Properties

#### *4.1.1.1 Sulphur*

Sulphur at room temperature is an odourless yellowish solid, often stored as lumps or flakes. With traces of impurities it may impart an oily and/or rotten egg odour.

Sulphur melts at between 107 to 115 ˚C and is often kept as a molten material for downstream processing. Molten sulphur may emit hydrogen sulphide.

Sulphur is a flammable/ combustible material when exposed to heat, sparks or flames, or chemical reaction with oxidisers. It can ignite in air above 261 ˚ C and in oxygen below 260 ˚ C and may burn rapidly with flare-burning effect. The combustion products of sulphur are highly toxic fumes of oxides of sulphur.

Finely divided sulphur dust may form explosive mixtures in air.

Sulphur has a very high reactivity potential with a broad range of chemical compounds and should therefore be handled very cautiously. Should this material be used in conjunction with any other chemical compound make sure that there is no compatibility hazard involved or take the necessary safety measures in order to avoid any hazardous reactions. A few incompatible chemical compounds are: certain hydrocarbons, perchlorates, peroxides, permanganates, chlorates, nitrates, sodium, potassium, lithium, zinc, metal halogenates, charcoal copper and copper alloys.

Exposure to sulphur may result in irritation to lungs, eyes and skin. Sulphur may be harmful if swallowed. Repeated exposure may cause bronchitis to develop with cough, phlegm and or shortness of breath clouding of the eye lens and chronic eye irritation and itching and skin rash.

#### *4.1.1.2 Sulphur Dioxide*

Sulphur dioxide is a colourless gas or compressed liquefied gas with a choking or suffocating odour. It has a boiling point -10°C and is heavier than air. Sulphur dioxide is very toxic.

Sulphur dioxide is acidic and reacts exothermically with bases such as amines, amides, metal oxides, and hydroxides. It is frequently used as a reducing agent although it is not a powerful one. However it can also act as an oxidizing agent. It supports combustion of powdered aluminium and manganese and reacts explosively with fluorine. Readily liquefied by compression. Contact between the liquid and water may result in vigorous or violent boiling and extremely rapid vaporization. If the water is hot an explosion may occur. Pressures may build to dangerous levels if the liquid contacts water in a closed container. Supports incandescent combustion of monocesium acetylide, monopotassium acetylide, cesium oxide, iron (II) oxide, tin oxide, and lead oxide.

Sulphur dioxide can be absorbed into the body by inhalation and a harmful and fatal concentration of this gas in the air will be reached very quickly on loss of containment. Inhalation of the gas may cause lung oedema and may affect respiratory tract, resulting in asthma-like reactions, reflex spasm of the larynx and respiratory arrest.

On exposure, sulphur dioxide may irritate the eyes and the respiratory tract. Rapid evaporation of the liquid may cause frostbite.

#### *4.1.1.3 Sulphuric Acid*

Sulphuric acid is a clear colourless material that may emit choking fumes when hot. The material is non-flammable but when in contact with other flammable materials may result in fires.

Sulphuric acid can result in violent reactions with water and strong bases generating heat. It is not compatible with organic materials, chlorates, carbides, fulminates, and powdered metals. In contact with metal it releases flammable hydrogen gas that will explode if ignited in an enclosed area.

Sulphuric acid is hazardous in contact, inhalation or ingestion. Sulphuric acid can be corrosive to the skin, eyes, nose, mucous membranes, respiratory and gastrointestinal tracts, or any tissue with which it comes in contact. Severe burns can occur with necrosis, scarring and may result in death.

Milder exposures can cause irritation of the eyes, skin, mucous membranes and respiratory and digestive tracts.

Chronic exposure may be associated with changes in pulmonary function, chronic bronchitis, conjunctivitis, and overt symptoms resembling acute viral respiratory tract infection. Discoloration and erosion of dental enamel can occur.

Long term exposure may cause mutations in living cells, bronchitis, emphysema, erosion and pitting of teeth, running nose, upset stomach and tearing of the eyes.

#### *4.1.1.4 Sulphur Trioxide*

Sulphur trioxide is a colourless to white crystalline solid that can also exist as a liquid or gas. It is not combustible but is a fire risk when it comes into contact with organic materials such as wood, cotton, fiberboard, etc. Sulphur trioxide vapours are extremely toxic when inhaled.

Sulphur trioxide has a strong affinity for water and may react with explosive violence with water to generate sulphuric acid. It may dehydrate many organic substances so exothermically that they char and can burn. Sulphur trioxide is acidic and could react exothermically to neutralize bases. The solution in water is a strong acid, it reacts violently with bases and is corrosive to metals forming hydrogen, a flammable/explosive gas. The substance is a strong oxidant and reacts violently with combustible and reducing materials and organic compounds causing fire and explosion hazard.

Acute (short-term) health effects may occur immediately or shortly after exposure to sulphur trioxide. Contact can severely irritate and burn the skin and eyes. Inhalation of sulphur dioxide may irritate the nose and throat and lungs that may cause a build-up of fluid in the lungs (pulmonary edema), a medical emergency, with severe shortness of breath. High exposure to sulphur trioxide can cause headache, nausea and dizziness and possible death.

### 4.1.2 Flammable materials

Flammable materials are those that can ignite to give a number of possible hazardous effects, depending on the actual material and conditions. These are flash fires, explosion, fireball, jet fire or pool fire.

The flammable and combustible materials on site are listed below. All these components have been analysed for fire risks.

**Table 4-1 Flammable and combustible materials on site**

| Compound | Flash Pt. (°C) | Boil Pt. (°C) | Comment |
|---|---|---|---|
| Sulphur | 207 | 444 | Solid at room temperature |

### 4.1.3 Toxic materials

Toxic materials of interest to this study are those that could give dispersing vapour clouds upon release into the atmosphere. These could subsequently cause harm through inhalation or absorption through the skin. Typically the hazard posed by a toxic material will depend both on concentration of the material in the air and the exposure duration. Materials having acute toxicity are listed below in Table 4-2.

**Table 4-2 ERPG guidelines for acute toxic chemicals on the RU site**

| Compound | ERPG-1 | | ERPG-2 | | ERPG-3 | |
|---|---|---|---|---|---|---|
| | mg/m$^3$ | ppm | mg/m$^3$ | ppm | mg/m$^3$ | ppm |
| Sulphuric Acid | 2 | 0.5 | 10 | 2.5 | 30 | 7.5 |
| Sulphur Dioxide | 0.75 | 0.3 | 7.5 | 3 | 40 | 15 |
| Sulphur Trioxide | 2 | 0.5 | 10 | 2.5 | 30 | 7.5 |

NOTE
Emergency Response Planning Guidelines (ERPGs) as developed by the American Industrial Hygiene Association
***ERPG-1:*** Is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odour.
***ERPG-2***: Is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action.
***ERPG-3:*** Is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects.

## 4.2 Generic Equipment Failure Scenarios

In order to characterise the various failure events and assign a failure frequency, fault trees were constructed starting with a final event and working from top down to define all initiating events and frequencies. A summary of this analysis is given in Appendix B. The analysis was completed using published failure rate data. Equipment failures can occur in tanks, pipeline and other items handling hazardous materials. These failures may result in:

- Release of flammable materials and fires upon ignition; and/or,
- Release of toxic materials.

### 4.2.1 Storage Tanks

Incidents involving storage tanks include catastrophic failure leading to product leakage into the bund and a possible bund fire. A tank roof failure could result in a possible tank fire. A fracture of the tank nozzle or the transfer pipeline could also result in product leakage into the bund and a possible bund fire.

Typical failure frequencies for atmospheric tanks and pressure vessels are listed below:

**Table 4-3 Failure frequencies for atmospheric tanks (source TNO "Purple Book")**

| **Event** | Leak Frequency (per item per year) |
|---|---|
| Small leaks | $1x10^{-4}$ |
| Severe leaks | $3x10^{-5}$ |
| Catastrophic failure | $5x10^{-6}$ |

**Table 4-4 Failure frequencies for pressure vessels (source TNO "Purple Book")**

| Event | Failure Frequency (per item per year) |
|---|---|
| Small leaks | $1x10^{-5}$ |
| Severe leaks | $5x10^{-7}$ |
| Catastrophic failure | $5x10^{-7}$ |

### 4.2.2 Process Piping

Piping may fail as a result of corrosion, erosion, mechanical impact damage, pressure surge (water hammer) or operation outside design limitations of pressure and temperature. Corrosion- and erosion-caused failures usually result in small leaks, which are detected early and corrected. For significant failures, the leak duration may be of the order of ten to thirty minutes before detection of such events.

The generic leak frequency data for process piping is generally expressed in terms of the cumulative total failure rate per year for a 10 m section of pipe for each pipe diameter. Furthermore, the failure frequency normally decreases with increasing pipe diameter.

The failure data given in Table 4-5 represent the total failure rate, incorporating all failures of whatever size and due to all probable causes. These frequencies are based on an environment where no excessive vibration, corrosion/ erosion or thermal cyclic stresses are expected. For potential risk causing significant leaks e.g. corrosion, the failure rate will be increased by a factor of 10.

An estimate of the length of the line is obviously required. However as the failure of flanges are assumed to be included in the failure frequency of the pipeline, the minimum length of the pipe is set at 10 m.

**Table 4-5 Failure frequencies for pipes (source TNO "Purple Book")**

| Description | Frequencies of Loss of Containment for Pipes per meter per year | |
|---|---|---|
| | **Full bore rupture** | **Leak** |
| Pipeline < 75 mm | $1x10^{-6}$ | $5x10^{-6}$ |
| Pipeline 75 mm< diameter< 150mm | $3x10^{-7}$ | $2x10^{-6}$ |
| Pipeline >150 mm | $1x10^{-7}$ | $5x10^{-7}$ |

## 4.3 Physical Properties

A summary of relevant physical properties for the identified hazardous substances are summarised in Appendix A.

# 5 PHYSICAL AND CONSEQUENCE MODELLING

In order to establish the impact following an accident, it is necessary to first estimate the physical process of the release (i.e. rate and size), the evaporation from the spill, and the subsequent atmospheric dispersion of the airborne cloud, or in the case of ignition, the burning rate, the resulting thermal radiation or the overpressures from an explosion.

The second step is then to estimate the consequences of a spill on humans, fauna, flora and structures. The consequences would be due to the toxicity, thermal radiation and/or explosion overpressures. The consequences may be described in various formats. The simplest methodology follows a comparison of predicted concentrations (or thermal radiation, or overpressures) to short-term concentration (or radiation or pressure) guideline values. In a different, but more realistic fashion, the consequences may be determined by using a dose-response analysis. Dose-response analysis aims to relate the intensity of the phenomenon that constitutes the hazard to the degree of injury or damage, which it can cause. *Probit Analysis* is possibly the method mostly used to estimate probability of death, hospitalisation or structural damage. The *probit* is a lognormal distribution and represents a measure of the percentage of the vulnerable resource that sustains injury or damage. The probability of injury or death (i.e. *risk level*) is in turn estimated from this *probit* (risk characterisation).

## 5.1 Vapour Clouds

The purpose of considering vapour clouds emanating from toxic material is to identify areas in the community that may be affected or exposed, or individuals in the community who may be subject to injury or death from an accident release of toxic vapours from the facility.

A toxic vapour cloud can occur when:

- a toxic gas is released under pressure,
- when a toxic liquid spills and evaporates
- when material combusts forming toxic gases
- when products react forming toxic gases

The simulations were calculated using the following meteorological conditions:

- Stability Class C and wind speed 1.5 m/s
- Stability Class D and wind speed 5 m/s
- Stability Class D and wind speed 20 m/s

### 5.1.1 Walvis Bay Sulphur Storage

Sulphur dioxide is not stored at the Walvis Bay harbour, but could be produced during a fire when elemental sulphur combusts to form sulphur dioxide. The maximum amount of released sulphur dioxide was calculated at 48 kg/s and would extend beyond 10 km to the ERPG-2 endpoint for the worst weather conditions of a slow wind speed of 1.5 m/s and very stable conditions.

The ERPG-2 concentration is the maximum air concentration below which it is believed nearly all individuals could be exposed without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action.

### 5.1.2 Walvis Bay Rail Transportation

In the event of a railcar fire the combusted sulphur would produce a maximum of 0.2 kg/h of sulphur dioxide. The largest distance to the ERPG endpoint was under neutral conditions and a wind speed of 5 m/s and shown below in Table 5-1.

**Table 5-1 ERPG Endpoints for an accidental sulphur dioxide release**

| | Concentration | Distance to endpoint |
|---|---|---|
| ERPG-1 | 0.75 mg/m$^3$ (0.3 ppm) | 1756 m |
| ERPG-2 | 7.5 mg/m$^3$ (3 ppm) | 441 m |
| ERPG-3 | 40 mg/m$^3$ (15 ppm) | 156 m |

The ERPG-2 concentration is the maximum air concentration below which it is believed nearly all individuals could be exposed without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action, whereas ERPG-3 is the maximum air concentration below which it is believed that nearly all individuals could be exposed without experiencing or developing life-threatening health effects. ERPG-1 is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odour.

The emergency plan must cater for evasive actions up to the ERPG-2 endpoint and could include, but not limited to, evacuation of the public or adequate shelter in place.

The outdoor lethal concentration for a healthy section of the public was not reached at ground level. Thus fatalities are not expected from sulphur dioxide emissions from a fire in a railcar transporting elemental sulphur.

### 5.1.3 Mine Sulphur Storage

The sulphur store at the mine would be slightly smaller than the store at Walvis Bay with 5000 m$^2$ floor coverage. The maximum sulphur dioxide production from a sulphur fire was estimated at 57 kg/s and would extend beyond 10 km to the ERPG-2 endpoint for the worst weather conditions of a slow wind speed of 1.5 m/s and very stable conditions.

### 5.1.4 Sulphuric Acid Plant

The sulphuric acid plant combusts sulphur forming sulphur dioxide. The sulphur dioxide is converted into sulphur trioxide which is converted to sulphuric acid in the adsorption towers. A loss of containment in the plant could result in a release of sulphur dioxide and sulphur trioxide. As both sulphur dioxide and sulphur trioxide are toxic, the release of material at the points shown in Figure 5-1 were simulated to determine the endpoints to the ERPG-2 guideline.

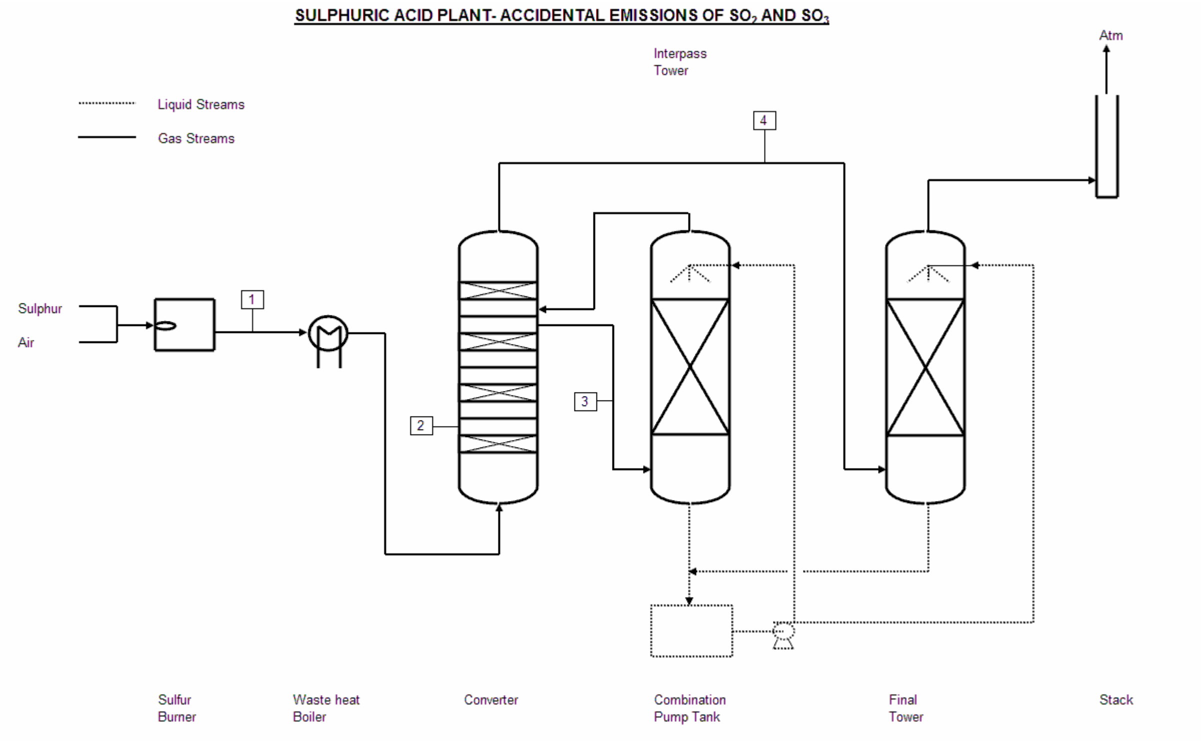



**Figure 5-1 Sulphuric Acid Plant $SO_2$ and $SO_3$ Release Points**

The release rates as well as temperatures and pressures were based on the feasibility report of Read J (2007), ***Feasibility Report for New Sulphuric Acid Plant Final Report to Rössing Uranium Limited Report No. 338126*** ,SNC-LAVALIN FENCO, with a design production capacity of 1200 MTPD (100% $H_2SO_4$ basis) as 98.5% $H_2SO_4$.

The release rates for a full capacity rupture as well as a 10 mm hole are given in Table 5-2 for the points referenced in Figure 5-1. Associated with the amounts released are the maximum expected endpoints to ERPG-2 Guideline.

In some instances the maximum distance occurs during strong wind conditions where the wind forces the buoyant components, due to the relatively high release temperature, to the ground. A large release thus has potential to extend to the town of Arandis and emergency response should ensure adequate protection of the public of Arandis in the event of an emergency.

**Table 5-2 Release Rates from Accidental Ruptures (See Figure 5-1)**

| | | 1 | | 2 | | 3 | | 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Full Bore Rupture | 10 mm Hole | Full Bore Rupture | 10 mm Hole | Full Bore Rupture | 10 mm Hole | Full Bore Rupture | 10 mm Hole |
| $SO_2$ | kg/s | 8.9 | 2.6E-03 | 3.4 | 1.4E-04 | 0.5 | 1.8E-04 | 1.7E-02 | 4.3E-06 |
| $SO_3$ | kg/s | 0.2 | 0.0E+00 | 7.1 | 2.5E-03 | 10.8 | 4.0E-03 | 5.8E-01 | 1.5E-04 |
| T | $^oC$ | 1131 | 1131 | 440 | 440 | 166 | 166 | 135 | 135 |
| P | kPa(g) | 48 | 48 | 33.77 | 33 | 23 | 23 | 4.36 | 4.36 |

Endpoints ERPG-2

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $SO_2$ | m | 5508 | 478 | 2448 | 101 | 7525 | 117 | 1112 | 18 |
| $SO_3$ | m | 516 | 0 | 2363 | 324 | >10000 | 325 | 7274 | 0 |

## 5.2 Fires

Combustible materials within their flammable limits may ignite and burn if exposed to an ignition source of sufficient energy. On process plants this normally occurs as a result of a leakage or spillage. Depending on the physical properties of the material and the operating parameters, the combustion of material in a plant may take on a number of forms i.e. pool fires, jet fires and flash fires.

### 5.2.1 Thermal Radiation

The effect of thermal radiation is very dependent on the type of fire and duration exposure to the thermal radiation. Codes such as API 520 and 2000 suggest the maximum heat absorbed on vessels for adequate relief designs to prevent the vessel from failure due to overpressure. Other codes such as API 510 and BS 5980 give guidelines for the maximum thermal radiation intensity as a guide to equipment layout.

The effect of thermal radiation on human health has been widely studied with many relations developed relating injuries to the time and intensity of the radiation exposure. Two values normally quoted are 1.5 kW/m$^2$ , or “safe” value, where people can be exposed for long period of time and 5 kW/m$^2$ for people performing emergency operation for short periods of time.

**Figure 5-2 Thermal Radiation Guidelines (BS 5980 –1990)**

| Thermal Radiation Intensity (kW/m$^2$) | Limit |
|---|---|
| 1.5 | Will cause no discomfort for long exposure |
| 2.1 | Sufficient to cause pain if unable to reach cover within 40 seconds |
| 4.5 | Sufficient to cause pain if unable to reach cover within 20 seconds |
| 12.5 | Minimum energy required for piloted ignition of wood and melting of plastic tubing |
| 25 | Minimum energy required to ignite wood at indefinitely long exposures |
| 37.5 | Sufficient to cause serious damage to process equipment |

### 5.2.2 Bund and Pool Fires

The pool fires being either tank or bund fires consist of large volumes of flammable material at atmospheric pressure burning in an open space. The flammable material will be consumed at the burning rate depending on factors including the prevailing winds. During combustion heat will be released in the form of thermal radiation. Temperatures close to the flame centre will be high but will reduce rapidly to tolerable temperatures over a relatively short distance. Any plant building or persons close to the fire or within the intolerable zone will experience burn damage with the severity depending on the distance from the fire and the time exposed to the heat of the fire.

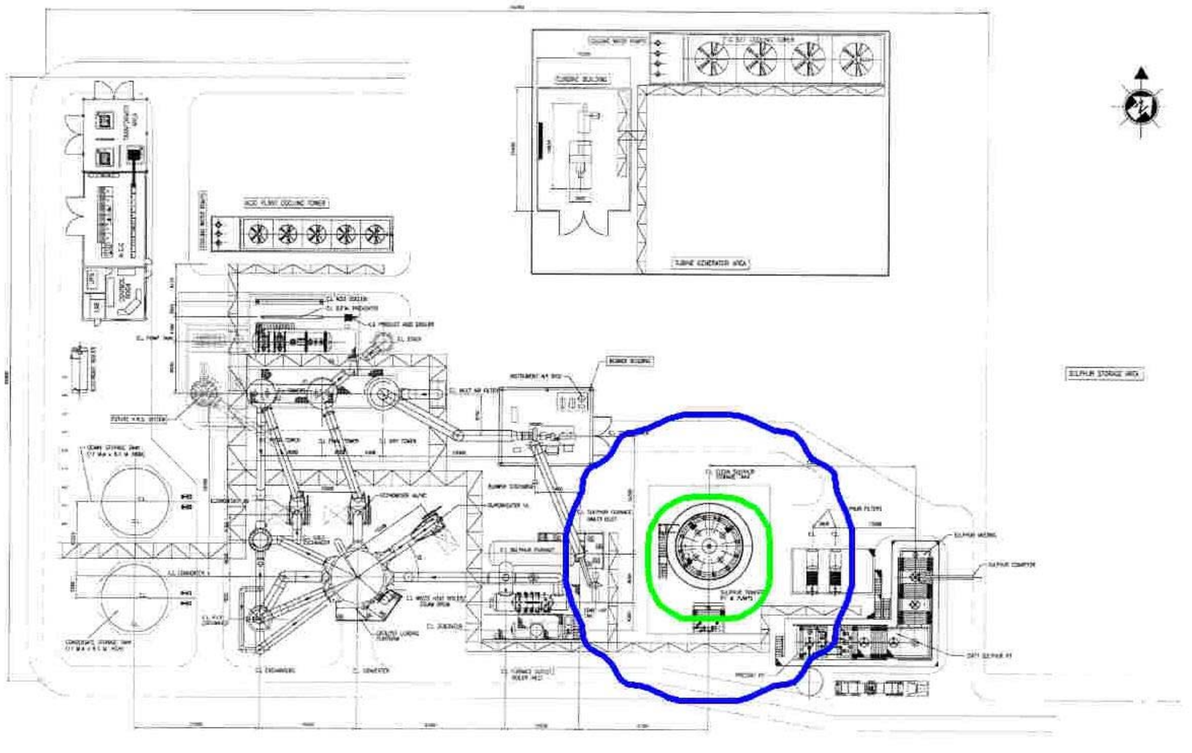
In the event of a pool fire the flames will tilt according to the wind speed and direction. The flame length and tilt angle affect the distance of thermal radiation generated.

### *Sulphur fire*

The lack of a burning rate relationship specifically applicable to sulphur fires necessitated the use of an analogy of hydrocarbon pool fires and applicable to molten sulphur that forms a liquid pool prior to combustion.

Sulphur is normally a solid at ambient conditions and melts at about 113°C. A loss of containment of molten sulphur would result in the rapid cooling down of the molten sulphur forming a solid mass that would be difficult to ignite. Figure 5-3 gives the thermal radiation isopleths (contours) in the event of a molten sulphur fire. The 12.5 kW/m$^2$ would damage plastics and would have a 1% probability of fatality while the 4.73 kW/m$^2$ represents the maximum exposure of an individual for 20 seconds without injury. The isopleths include a solar radiation of 1 kW/m$^2$ which could be experienced on a summer's day. A molten sulphur fire would not damage surrounding equipment and could injure people in the immediate surrounding of the fire only.

Thermal radiation effects from sulphur fires at the storage warehouses would be limited to within the building as the energy released during a fire should not cause the building to fail but may result in minor damages to the cladding painting etc.



LEGEND THERMAL RADIATION (kW/m$^2$)

12.5

4.73

**Figure 5-3 Thermal radiation contours for a molten sulphur fire.**

### 5.2.3 Vapour Cloud Explosion Consequences

A release of combustible gases into the atmosphere could result in the formation of a vapour cloud. The concentration of the combustible component decreases from the point of release to the lower explosive limits (LEL), where the concentration of the component can no longer ignite. The material contained in the vapour cloud between the higher explosive limits (HEL) and the lower explosive limit (LEL), if ignited will form a flash fire or a fireball. The sudden detonation of the explosive mass of material causes an overpressure that can result in injury or damage to property.

An explosion may give rise to any of the following effects:

- Blast damage;
- Thermal damage;
- Missile damage;
- Ground tremors;
- Crater formation; and/or,
- Personal injury

These obviously depend on the pressure waves and proximity to the actual explosion. Of concern in this investigation are the “far distance” effects, such as limited structural damage and the breakage of windows, rather than crater formations. Table 5-3 a give a more detailed summary of the damage produced by an explosion for various over-pressures. The most commonly used overpressure is the “0.3 psi” value. This corresponds to a “Safe Distance”, at which approximately 10% of glass windows are broken.

**Table 5-3 Summary of consequences of blast overpressure (Clancey 1972)**

| Pressure (gauge) | | Damage |
|---|---|---|
| **Psi** | **kPa** | |
| 0.02 | 0.138 | Annoying noise (137 dB), if of low frequency (10 - 15 Hz). |
| 0.03 | 0.207 | Occasional breaking of large glass windows already under strain. |
| 0.04 | 0.276 | Loud noise (143 dB). Sonic boom glass failure. |
| 0.1 | 0.69 | Breakage of windows, small, under strain. |
| 0.15 | 1.035 | Typical pressure for glass failure. |
| 0.3 | 2.07 | ‘Safe distance’ (probability 0.95 no serious damage beyond this value). Missile limit. Some damage to house ceilings; 10% window glass broken. |
| 0.4 | 2.76 | Limited minor structural damage. |
| 0.5 – 1.0 | 3.45 – 6.9 | Large and small windows usually shattered; occasional damage to window frames. |
| 0.7 | 4.83 | Minor damage to house structures. |
| 1.0 | 6.9 | Partial demolition of houses, made uninhabitable. |
| 1.0 – 2.0 | 6.9 – 13.8 | Corrugated asbestos shattered. Corrugated steel or aluminium panels, fastenings fail, followed by buckling. Wood panels (standard housing) fastenings fail, panels blown in. |
| 1.3 | 8.97 | Steel frame of clad building slightly distorted. |
| 2.0 | 13.8 | Partial collapse of walls and roofs of houses. |
| 2.0 – 3.0 | 13.8 - 20.7 | Concrete or cinderblock walls, not reinforced shattered. |
| 2.3 | 15.87 | Lower limit of serious structural damage. |
| 2.5 | 17.25 | 50% destruction of brickwork of house. |
| 3.0 | 20.7 | Heavy machines (1.4 tonne) in industrial building suffered little damage. Steel frame building distorted and pulled away from foundations. |
| 3.0 – 4.0 | 20.7 – 27.6 | Frameless, self-framing steel panel building demolished. |
| 4.0 | 27.6 | Cladding of light industrial buildings demolished. |
| 5.0 | 34.5 | Wooden utilities poles (telegraph, etc.) snapped. Tall hydraulic press (18 tonne) in building slightly damaged. |
| 5.0 – 7.0 | 34.5 – 48.3 | Nearly complete destruction of houses. |
| 7.0 | 48.3 | Loaded train wagons, overturned. |
| 7.0 – 8.0 | 48.3– 55.2 | Brick panels (20 – 30 cm) not reinforced, fail by shearing or flexure. |
| 9.0 | 62.1 | Loaded train boxcars completely demolished. |
| 10.0 | 69.0 | Probable total destruction buildings. Heavy (3 tonnes) machine tools moved and badly damaged. Very heavy (12 000 lb/5443 kg) machine tools survived. |
| 300 | 2070 | Limit of crater lip. |

### 5.2.4 Unconfined Gas Explosions

A flammable gas cloud that detonates within an area that is uncluttered and the expanding gases can easily escape. The maximum overpressure from an unconfined gas explosion is much lower than that of a confined explosion and hence the over pressure distance to safety is lower. As the overpressure from unconfined explosions would not directly result in fatalities, unconfined explosions have not been considered in this study.

### 5.2.5 Confined Gas Explosions

A confined gas explosion is where the exploding gas is restricted from expanding by physical barriers such as walls or equipment and obstacles. The confined gas explosions were modelled using the Multi Energy model of TNO using the explosion class of 10. The multi-energy model uses the energy available for explosions and setting the class between 1 and 10 can determine the effects of a weak deflagration to a confined detonation.

Sulphur dust is known to cause explosions. However dust explosions require dust particles to be a maximum particle size at the concentration within the flammable range with an associated ignition source. As the elemental sulphur used on the plant would be pellets, fines could only be formed from abrasion. The difficulty in determining the consequence from a sulphur explosion is to estimate the amount of sulphur involved in the explosion. The maximum mass of sulphur involved in the explosion would be the volume of the storage at the Lower Explosive Level (LEL).

#### *5.2.5.1 Walvis Bay*

The worst case explosion estimated that 1208 kg of sulphur dust was involved in the explosion. Assuming the central point of the explosion was located within the RU area at the port, the extent of the overpressure isopleths is shown in Figure 5-4. The 2 kPa isopleth or distance to safety was calculated at 511 m from the center of the explosion. This pressure would not cause fatalities but would indicate the extent of the damage such as broken windows. Depending on the location of the sulphur storage this value may just enter residential areas. The 6.9 kPa would not cause direct fatalities but is the recommended distance from the explosion to vulnerable populations such as hospitals, retirement homes, nursery schools etc. The 13.8 kPa is the lowest overpressure that could cause fatalities and should not reach the residential areas.


| LEGEND | Overpressure (kPa) |
|---|---|
| blue line | 2 |
| green line | 6.9 |
| yellow line | 13.8 |

**Figure 5-4 Blast overpressure from a sulphur dust explosion within the storage building at Walvis Bay**

### *5.2.5.2 RU Mine*

The sulphur at the RU mine would be stored in the open and thus a confined explosion is not expected.

# 6 RISK ANALYSIS

## 6.1 Background

It is important to know the difference between hazard and risk. A hazard is anything that has the potential to cause damage to life, the property and the environment. Furthermore, it is a constant parameter (such as petrol, chlorine, ammonia, etc.) that poses the same hazard wherever they are present. Risk, on the other hand, is the probability that a hazard will actually cause damage, and how severe that damage will be. Risk is therefore the probability that a hazard will manifest itself. For instance, the risk of a chemical depends upon the amount present, the process it's used in, the design and safety features of its container, the exposures, the prevailing environmental and weather conditions and so on. Risk analysis thus comprises a judgement of probability based on local atmospheric conditions and generic failure rates, and the severity of consequences based on the best available current technological information.

Risks form an inherent part of modern life. Some risks are readily accepted on a day-to-day basis, while others attract headlines even when the risk is much smaller, particularly in the field of environmental protection and health. For instance, the risk associated with driving a car of *one-in-ten-thousand chance of death per year* is acceptable to most people, whereas the much lower risks associated with nuclear facilities (*one-in-ten-million chance of death per year*) are usually deemed unacceptable.

A report by the British Parliamentary Office of Science and Technology (POST), "*Safety in Numbers?" - Risk Assessment and Environmental Protection*" explains how public perception of risk is influenced by a number of factors in addition to the actual size of the risk. These factors were summarised as follows:

| | |
|---|---|
| ***Control*** | *People are more willing to accept risks they impose upon themselves, or they consider to be "natural", than to have risks imposed upon them.* |
| ***Dread and Scale of Impact*** | *Fear is greatest where the consequences of a risk are likely to be catastrophic rather than spread over time.* |
| ***Familiarity*** | *People appear more willing to accept risks that are familiar rather than new risks* |
| ***Timing*** | *Risks seem to be more acceptable if the consequences are immediate or short-term, rather than if they are delayed - especially if they might affect future generations.* |
| ***Social Amplification and Attenuation*** | *Concern can be increased because of media coverage or graphic depiction of events, or reduced by economic hardship.* |
| ***Trust*** | *A key factor is how far the public trusts regulators, policy makers, or industry. If these bodies are open and accountable (being honest, admitting mistakes and limitations and taking account of differing views without disregarding them as emotive or irrational) then the public is more likely to place credibility in them.* |

The difficulty in communicating an acceptable risk is therefore not trivial. Furthermore, setting acceptable risk criteria for use in quantitative risk assessments may often also result in disagreement between the various affected parties. Nevertheless, sound arguments have lead to the definition of levels of acceptable risks taking into account the need of people to feel safe in their day-to-day activities, and to be protected from risks ranging from unsafe food to radioactivity exposures.

A risk assessment should be seen as an important component of on-going preventative actions aimed at minimising, or hopefully, avoiding accidents. Re-assessments of risk should therefore follow at regular intervals, and/or after any changes that could alter the hazard, so contributing to the overall prevention programme and emergency response plan of the plant. Risks should be ranked in decreasing severity, and the top risk reduced to acceptable levels.

Predictive hazard evaluation procedures have been developed for analysis of processes when evaluating very low probability accidents with very high consequences (for which there is little or no experience), and more likely releases with fewer consequences, but for which there may be more information available. The concept therefore addresses both the probability of an accident and the magnitude and type of the undesirable consequence of that accident. Risk is usually defined as some simple function of both the probability and consequence.

## 6.2 Predicted Risk

The physical and consequence modelling (Section 5) addresses the impact of a release of toxic vapour without taking into account the probability of occurrence. This merely illustrates the significance and the extent of the impact in the event of a release of toxic vapour. This section also contains the possibility of cascading or knock-on effects due to incidents in the facility and the surrounding industries and suburbs. In the following section, the likelihood of various incidents is included, the consequences calculated, and finally the risk for the facility is determined.

## 6.3 Risk Calculations

The previous sections dealt specifically with the predicted zone of impact without taking into account the probability of occurrence and the combined impacts. Risk on the other hand is a product of the likelihood of occurrence and the consequences.

Two types of risk parameters were calculated in this assessment, namely the *maximum individual risk* and the *societal risk*. These are presented below.

## 6.4 Maximum Individual Risk Parameter

Individual risk parameters include "Average Individual Risk", "Weighted Individual Risk", "Maximum Individual Risk" and "Fatal Accident Rate (FAR)". The latter parameter is more applicable to occupational exposures. Only the Maximum Individual Risk (MIR) will be used in this assessment. For this parameter, the frequency of fatality is calculated for an individual who is presumed to be present at some specified location. The parameter is not dependent on the knowledge of the population at risk, and so is an easier parameter to use in the predictive mode than the Average Individual and Weighted Individual risks. The unit of measure is *fatality risk per person per year*.

### 6.4.1 Acceptable Risks

The study of risk, and peoples' reaction to it, has been the subject of numerous studies over the past few decades, including both empirical and philosophical debates. However, there still remains significant controversy regarding basic issues such as the expression or definition of risk, the range of variables which should be taken into account, and the level of acceptance of a risk. Although a number of risk definitions have been proposed, the majority share the common basis of expressing risk as a product of the likelihood of an occurrence and the consequences of the incidence. Goals such as "zero risk" are fundamentally unachievable. Hazards always exist: any activity comes with inherent hazards; those hazards have consequences (safety, environmental, economic); and the hazards have a finite chance of occurring. Therefore, the value of risk must be greater than zero.

Among the most difficult tasks of risk characterisation is the definition of an *acceptable risk*. In this regard, the distinction between risks, which are assumed *voluntarily*, and those, which are borne *involuntarily*, is a crucial one. As an example, the risk to which a member of the public is exposed from an industrial activity is an involuntary one. The personnel employed at the same facility would be exposed to a voluntary risk. In general, people are prepared to tolerate higher levels of risk for hazards to which they expose themselves voluntarily, as shown in Table 6-1. In this table, Kletz (1976) compiled some death rates resulting from well-studied risks. Voluntarily accepted risk levels are typically 100 to 1000-fold more than involuntary risks. For instance, the risk of dying in a car accident in the UK is estimated to be a 17 in 100 000 ($17x10^{-5}$) chance per year, whereas the calculated risk of death from a nuclear power plant (at 1 km from the plant) is 1 in 10 000 000 ($1x10^{-7}$) chance per year.

***Expression of Risk***

*The traditional manner in which risk is defined puts "consequence" and "likelihood" on equal footing, i.e. risk = consequence X likelihood. It therefore implies a linear trade-off between the two. For example, a hazard resulting in one fatality every hundred years has the same objective risk value as a hazard resulting in ten fatalities every thousand years. In both cases the fatality rate is 1 in a hundred years, or 0.01 fatalities per year. However, the two risks are not the same. In general, people find rare, high-consequence accidents less acceptable than more frequent, low consequence accidents. For example an aeroplane crash, during which 200 people may die, would cause a general outcry, but the number of deaths on the road per year, albeit an order more, is perceived as part of functioning in a modern community and so there is little outrage on the part of the public. The difference between the two risks is a perception rooted in emotion.*

*To accommodate this perception difference, the definition of risk could be modified so as to raise the significance of "consequence" over the "likelihood". This may take the form: i.e. risk = consequence$^P$ X likelihood. The exponent P (>1) would therefore force a higher risk with high consequence/low frequency accidents than with low consequence/high frequency accidents.*

Risk management and town planning disciplines tend to favour an objective, neo-mathematical approach, such as expressed above. However, risk perception research has established that members of the public do not think about sources of risk solely, or even substantially, in terms of statistical probabilities (HSE 1998). It further follows that any search for a quantified index of what 'the public' deems to be a statistically acceptable or tolerable level of risk is futile. Risk incorporates a strong subjective component – any attempt to manage risk just "by the numbers" has the potential to fail.

**Table 6-1 Death rates for some voluntary and involuntary risks (after Kletz 1976).**

| Risk | Fatality *(Deaths Per Person Per Year)* |
|---|---|
| ***Voluntary Risk:*** | ($x10^{-5}$) |
| Taking contraceptive pill | 2 |
| Playing football | 4 |
| Rock climbing | 4 |
| Car driving (UK) | 17 |
| Cigarette Smoking (20/day) | 500 |
| ***Involuntary Risk:*** | ($x10^{-7}$) |
| Meteorite | 0.0006 |
| Transport of petrol and chemicals (UK) | 0.2 |
| Aircraft crash (UK) | 0.2 |
| Explosion of pressure vessel (USA) | 0.5 |
| Lightning (UK) | 1 |
| Release from nuclear power station (at 1 km) (UK) | 1 |
| Run over by road vehicle | 600 |
| Leukaemia | 800 |

In an attempt to account for risks in a manner similar to those used in everyday life, the UK HSE developed the “risk ALARP triangle”. This involved deciding:

- Whether a risk is so high that something must be done about it;
- Whether the risk is, or has been made, so small that no further precautions are necessary; or
- If a risk falls between these two states, that it has been reduced to levels as low as reasonably practicable (ALARP).

This is illustrated graphically, in Figure 6-1.

ALARP stands for “As Low As Reasonably Practicable”. As used in the UK, it is the region between that which is intolerable, at $1x10^{-4}$ per year, and the broadly acceptable level of $1x10^{-6}$ per year, with a further lower level of risk of $3x10^{-7}$ per year being applied to either vulnerable or very large populations for land use planning.

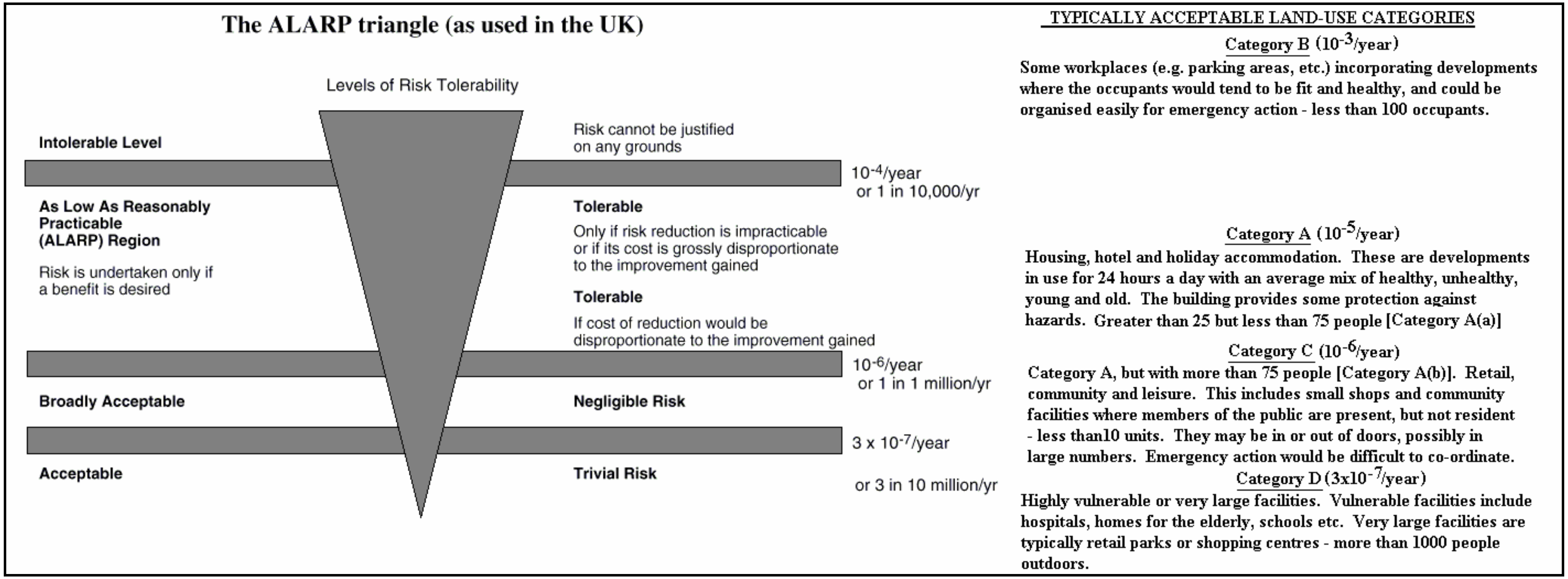



**Figure 6-1 Decision making framework. The UK HSE land-use categories A to D are also included for illustration.**

### 6.4.2 Pool Fires

A pool fire will occur when a pool of combustible material ignites. The cause of this is usually due to an unexpected spillage or leak. As spillages are collected in bunds, the pool fires are most likely to take place within the bunded areas of the storage, filling and loading areas. Events that could result in large fires were developed and summarised in Appendix B.

Sulphur has a relatively low heat of combustion with radiation extending only a short distance from the fire. Thus the risks to the general public of thermal radiation from sulphur fires are acceptable. As workers would be able to escape dangers of a sulphur fire, the risks to workers would be acceptable.

### 6.4.3 Explosions

Fatalities of the general public from sulphur explosions would not be expected and thus the risk level to the general public would be deemed as being acceptable.

#### *6.4.3.1 Lethal Dosages From Accidental Toxic Release*

Quantitative health risk assessment incorporates various distinct stages, including hazard assessment, dose response analysis, exposure assessment, and risk characterisation. The process of hazard assessment is aimed at determining whether particular substances cause adverse impacts on human health.

The quantification of the adverse impacts associated with a substance is made possible through dose response analysis and exposure assessment. By combining information generated through hazard assessment, dose –response analysis, the overall risk posed by a particular pollutant on human health may be characterised.

***Walvis Bay Sulphur Storage***

An adequately designed sulphur handling and storage facility would have a very low probability of a large accidental fire (see Appendix B for the Fault Tree) with the associated sulphur dioxide formation.

As the design of sulphur handling and storage has not been finalised, it would be the responsibility of the engineering contractor to demonstrate that sufficient mitigation has been included in the designs to adequately prevent the occurrence of a large sulphur fire.

***Sulphur Storage at the Mine***

The sulphur storage at the mine would be stored in the open and thus has a different probability of ignition to the sulphur storage at Walvis Bay. Based on the frequency of ignition and propagation into a large fire (see Appendix B), the distances to risks are shown in Table 6-2.

The relatively warm sulphur dioxide formed during the fire is less dense than the surrounding air, and therefore rises. A strong wind that would fan the fire would also force the sulphur dioxide to the ground producing the greatest risk distances. The risks to the workers and public would thus be acceptable with regards to the sulphur dioxide cloud formed during a large fire.

**Table 6-2 Distances to Risk Isopleths from the Center of the Fire**

| Risk (Fatality per person per year) | Distance to Risk Isopleth from the fire edge (m) | Comment |
|---|---|---|
| $1 \times 10^{-4}$ | Not reached | Acceptable to workers |
| $1 \times 10^{-5}$ | 140 | In ALARP region |
| $1 \times 10^{-6}$ | 167 | In ALARP region |
| $3 \times 10^{-7}$ | 194 | Acceptable to vulnerable populations |

***Sulphuric Acid Plant***

The risks from sulphur dioxide and sulphur dioxide releases are shown in Figure 6-2 based on the release scenario given in Appendix B. The risk of $1 \times 10^{-6}$ fatalities per person per year is the lower bounds of acceptability to the public and workers. As the general public are outside of this area, the risks from sulphur dioxide and trioxide are considered acceptable. The overriding scenario causing the extent of the risk is the full bore failure of the piping around the converter and Interpass Absorption Tower. In this instance the sulphur dioxide is the lethal component determining the risks.


LEGEND

1x10$^{-6}$ fatalities per person per year

**Figure 6-2 Lethality from sulphur dioxide and sulphur trioxide releases**

# 7 REDUCTION OF RISK

An Important aspect of any risk assessment is the reduction of risk from identified hazards. Mitigation that can be considered to reduce the risks are listed below. It should be emphasised that suggested mitigation is for consideration only. Riscom does not imply that the suggested mitigation be implemented or that any suggested mitigation is the only measures to reduce risks. Implementation of mitigation should always be done in accordance to recognised engineering practices using applicable codes and standards. Implementation of some or all of the mitigation would not guarantee full compliance of local or statutory requirements. It is the responsibility of RU and their engineering contractor to clearly demonstrate that risks on the site would be adequately mitigated to acceptable levels.

Mitigation for consideration includes:

## 7.1 Codes and Standards

International recognised codes of good design and practice for installations must be incorporated in the designs. This is to prevent a loss of containment of hazardous materials and subsequent initiating event.

## 7.2 Process Hazard Analysis (PHA)

A detailed Process Hazard Analysis (PHA) such as a Hazop, What If? etc. study should be completed prior to construction of the project, with all potential hazards identified, and sufficient mitigation suggested for safe operation. A Process Hazard Analysis is currently not a regulated activity but merely identifies potential hazards and recommends mitigation.

## 7.3 Safety Instrumented Systems

IEC 61508 and 61511 (Safety Instrumented Systems) are codes specifically related to the instrumentation requirements for adequate protection from hazards in chemical plants and applicable for the life cycle of the plant. These codes are aimed at reducing risks of surrounding populations to acceptable levels.

## 7.4 Emergency Planning

Emergency response document for onsite and off-site scenarii must be completed prior to initiating the MHI risk assessment. The emergency plan must include the hazardous scenarii, and address evasive measures. Requirements from local emergency services must be clearly stated in the emergency plan.

# 8 CONCLUSIONS

The accuracy of the simulations and risk calculations was determined by the quality of base data and expert judgements. A number of well-known sources of incident data were consulted and applied to obtain the likelihood of an incident to occur. The risk assessment included the consequences of fires and explosions from the proposed project.

The risk assessment was done on the assumption that the proposed project would maintained to an acceptable level and that all statutory regulations would be applied. It was also assumed that the detailed engineering designs were done by competent people and would be correctly specified for the intended duty. For example it is assumed that the tank walls thickness have been correctly calculated, that the vents have been sized for emergency conditions, that the instrumentation and electrical components comply with the specified electrical area classification, that the material of construction is compatible with the products, etc.

A number of incident scenarios were simulated and the following conclusions were reached.

## 8.1 Fires

Pool fires were calculated for sulphur fire at the molten sulphur tank. The thermal radiation generated from sulphur fires that would injure people in the near vicinity of the fire. Fires at the sulphur store may damage the storage buildings but should not cause the failure of the structure. Thus the risks from thermal radiation of sulphur fires are acceptable.

Sulphur fires at the rail cars would not be significant with regards to the thermal radiation generated.

## 8.2 Explosions

Sulphur dust explosions were calculated at the storage facilities at Walvis Bay. As the sulphur storage at the mine would be in the open dust explosions would not be expected. A worst case approach was adopted and the mass of material used in the calculations was the volume of the storage facility at the lower explosive limit (LEL). The explosions simulated indicated that fatalities of the public were not expected, but the distance to safety (2 kPa) was calculated at ½ km from the center of the explosion.

## 8.3 Vapour Clouds

Sulphur dioxide and sulphur trioxide are not stored at Walvis Bay or at the RU Mine. Sulphur dioxide would be formed from the combustion of sulphur either at the sulphur storage or in the sulphuric acid plant. The sulphur dioxide is converted to sulphur trioxide in the sulphuric acid plant prior to conversion to sulphuric acid.

In the event of a sulphur fire, the endpoints to the ERPG-2 [2]guideline could extend beyond 10 km downwind of the fire. The risks for a large sulphur fire at Walvis Bay would be acceptable based on expected designs.

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2 The ERPG-2 concentration is the maximum air concentration below which it is believed nearly all individuals could be exposed without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action,

Sulphur dioxide and trioxide emissions from the Sulphuric Acid Plant could extend beyond 10 km downwind of the release to the ERPG-2 guidelines. The risks from an accidental release would be acceptable to workers and the public.

# 9 RECOMMENDATIONS

The risk assessment study conducted for the proposed RU sulphur storage and the Sulphuric Acid Plant, did not find any fatal flaws that could prevent the project from proceeding. It is thus recommended that the project proceed provided that:

i. Compliance to all statutory requirements;
ii. Compliance with applicable international recognised codes of best practice for sulphur storage and sulphuric acid plants;
iii. A recognised process hazard analysis (HAZOP, FMEA, etc) should be completed for the proposed sulphur storage and plant prior to construction. This is to ensure design and operational hazards have been identified and adequate mitigation put in place. It would be preferable if the study could be facilitated by an independent party that can not benefit financially from offering services, equipment or instrumentation for the project;
iv. Full compliance of IEC 61508 and 61511 (Safety Instrumented Systems) or equivalent, to ensure adequate protective instrumentation is included in the design and determine the required reliability of safety instrumentation for the areas producing sulphur dioxide and trioxide. Compliance with this code would assist in protecting the public for the duration of operation of the hazardous systems within the plant.
v. A safety document detailing safety and design features reducing the impacts from fires, explosions and flammable atmospheres must be prepared and issued. The built facility can be audited against the safety document to ensure compliance with the EIA Terms of Reference. Codes such as IEC 61511 can be used to achieve these requirements. RU and their contractors must demonstrate that sufficient mitigation has been included in the designs to ensure the safety of the surrounding neighbours and the public; and
vi. Emergency response documentation must be done with input from local authorities.

# 10 ABREVIATIONS AND ACRYNOMNS

| | |
|---|---|
| **Asphixiant** | An asphixiant is a gas that is non-toxic but may be fatal if it accumulates in a confined space and is breathed at high concentrations because it drives out oxygen-containing air. |
| **Blast Pressure** | Measure used in the multi energy method to indicate the strength of the blast, indicated by a number ranging from 1 (for very low strengths up to 10 (for detonative strength. |
| **BLEVE** | **Boiling Liquid Expanding Vapour Explosion** results from the sudden failure of a vessel containing liquid at a temperature above its boiling point. A BLEVE of flammables results in a large fire ball. |
| **Deflagration** | A chemical reaction of a substance in which the reaction front advances into the un-reacted substance at less than sonic velocity |
| **Detonation** | A release of energy caused by the extremely rapid chemical reaction of a substance in which the reaction. |
| **ERPG** | **Emergency Response Planning Guidelines (ERPGs**) as developed by the **American Industrial Hygiene Association**<br>***ERPG-1:*** Is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odour.<br>***ERPG-2***: Is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action.<br>***ERPG-3:*** Is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects |
| **Explosion** | A release of energy that causes a pressure discontinuity or blast wave. |
| **Flammable Liquid** | The Occupational Health and Safety Act 85 of 1993 defines a **flammable liquid** as any liquid which produces a vapour that forms an explosive mixture with air and includes any liquid with a closed-cup flash point of less than 55ºC.<br><br>Flammable products have been classified according to their flash points and boiling points, which ultimately determines the propensity to ignite. Separation distances described in the various codes are dependant on the flammability classification.<br><br>Class Description<br>0 Liquefied Petroleum Gas<br>IA Liquids that have a closed –cup flash point of below 23°C and boiling point below 35°C<br>IB Liquids that have a closed –cup flash point of below 23°C and boiling point of 35°C or above<br>IC Liquids that have a closed –cup flash point of 23°C and above, but below 38°C<br>II Liquids that have a closed –cup flash point of 38°C and above, but below 60.5°C |

| | |
|---|---|
| | IIA Liquids that have a closed –cup flash point of 60.5°C and above, but below 93°C |
| **Flammable Limits** | The range of gas or vapour amounts the air that ill burn or explode if a flame or other ignition source is present. The lower point of the range is called the Lower Flammable Limit. Likewise the upper point of the range is called the Upper Flammable Limit. |
| **Frequency** | The number of times an outcome is expected to occur in a given period of time. |
| **IDLH** | **Immediately Dangerous to Life or Health (IDLH)**.<br>Developed by the National Institute of Occupational Safety and Health (NIOSH). The IDLH value refers to a maximum concentration to which a healthy person may be exposed for 30-minutes and escape without suffering irreversible health effects or symptoms that impair escape (ranging from runny eyes that temporarily impair eyesight to a coma). The IDLHs are intended to ensure that workers can escape from a given contaminated environment in the event of failure of the respiratory protection equipment. |
| **Individual Risk** | The probability that in one year a person will become a victim of an accident if the person remains permanently and unprotected in a certain location. Often the probability of occurrence in one year is replaced by the frequency of occurrence per year |
| **Isopleth** | **See Risk Isopleth** |
| **Jet** | The outflow of material emerging from an orifice with significant momentum. |
| **Jet Fire/Flame** | The combustion of material emerging from an orifice with a significant momentum. |
| **LC** | **Lethal concentration (LC)**.<br>A concentration by which a given percentage of the exposed population will be fatally injured. The $\mathbf{LC_{50}}$, refers to the concentration of airborne material the inhalation of which results in death of 50% of the test group. The period of inhalation exposure could be from 30 min to a few hours (up to 4 hours). |
| **LFL** | Lower Flammable Limit see **Flammable Limits** |
| **LOC** | **Loss of Containment** |
| **Loss of Containment** | The event resulting in a release of material into the atmosphere. |
| **MIR** | The Maximum Individual Risk see **Individual Risk** |
| **QRA** | **See Quantitative Risk Assessment** |
| **Quantitative Risk Assessment** | The process of hazard identification followed by a numerical evaluation of effects of incidents, and consequence and probabilities, and their combination into overall measure of risk. |
| **Risk** | A measure of the consequence of a hazard and the frequency with which it is likely to occur. Risk is expressed mathematically as:<br>**Risk = Consequence x Frequency of Occurrence** |
| **Risk Contour** | **See Risk Isopleth** |
| **Risk Isopleth** | Line drawn around a facility connecting all points having the same level of risk. |
| **TEEL** | **Temporary Emergency Exposure Limits (TEEL-0, TEEL-1, TEEL-2 and TEEL-3).**<br>The USA DOE Emergency Management Advisory Committee's |

| | |
|---|---|
| | Subcommittee on Consequence Assessment and Protective Action developed TEELs as an interim method to allow for the preliminary identification of hazardous or potentially hazardous situations for emergency planning. The definition of each of the four TEELs are given as follows:<br>***TEEL-0:*** The threshold concentration below which most people will experience no appreciable risk of health effects.<br>***TEEL-1:*** The maximum concentration in air below which it is believed nearly all individuals could be exposed without experiencing other than mild, transient adverse health effects or perceiving a clearly defined objectionable odour.<br>***TEEL-2:*** The maximum concentration in air below which it is believed nearly all individuals could be exposed without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action.<br>***TEEL-3***: The maximum concentration in air below which it is believed that nearly all individuals could be exposed without experiencing or developing life-threatening health effects. |
| **TLV-STEL** | **Short Term Exposure -Threshold Limit Values (TLV-STEL)**.<br>The concentrations to which workers can be exposed continuously for a short period (15 minutes) of time without suffering from (1) irritation, (2) chronic or irreversible tissue damage, or (3) narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue or materially reduce work efficiency, and provided that the daily TLV-TWA is not exceeded. |
| **TLV-TWA** | **Time-Weighted Average – Threshold Limit Values (TLV-TWA)**.<br>This refers to the concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effects. |
| **UFL** | Upper Flammable Limit see **Flammable Limits** |
| **Vapour Cloud Explosion** | The explosion resulting from ignition of a pre-mixed cloud of a flammable vapour, gas or spray with air, in which flames accelerates to sufficiently high velocities to produce significant overpressure. |
| **VCE** | See **Vapour Cloud Explosion** |

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# 12 APPENDIX A: PHYSICAL AND TOXICOLOGICAL PROPERTIES

**Table 12-1 Thermodynamic Properties of Sulphur**

| Parameter | Sulphur |
|---|---|
| Molecular Weight | 32.07 |
| Normal Boiling Point (K) | 717.75 |
| Melting Point (K) | 385.95 to 393.15 |
| Critical Temperature (K) | 1 314 |
| Critical Pressure (kPa) | 20 700 |
| Heat Capacity : Vapour (J/kg.K) | 670 |
| : Liquid (J/kg.K) | 997 |
| Density : Vapour (kg/m$^3$) | 1.3 |
| : Liquid (kg/m$^3$) | 1 960 |
| : Solid (kg/m$^3$) | 2 070 |
| Viscosity : Vapour (cP) | NA |
| : Liquid (cP) | NA |
| Thermal Conductivity : Liquid (W/m.K) | 0.129 |
| : Solid (W/m.K) | 0.168 |
| Surface Tension (N/m) | NA |
| Vapour Pressure (kPa) | 1.3 at 519.15 K |
| | 13.3 at 606.15 K |
| | 53.3 at 680.15 K |
| Antoine Coefficients : A (Pa) | 24.1596 (est) |
| : B (K) | 9828.718 (est) |
| : C (K) | 60.2228 (est) |
| Heat of Vaporisation (kJ/kg) | 287.2 |
| Heat of Fusion (kJ/kg) | 8.59 |
| Heat of Combustion (kJ/kg) | -9256 |
| Flash Point (K) | 480.15 |
| Ignition Temperature in Air (K) | 505.15 |
| Maximum Flame Temperature (K) | 1 650 |
| Explosion Limits in Air (%v/v) – Lower | 35 g/m$^3$ (dust) |
| – Upper | 1.4 kg/m$^3$ (dust) |

**Table 12-2 Physical Properties of Sulphur Dioxide**

| Parameter | Value |
|---|---|
| Molecular Weight | 64.06 |
| Normal Boiling point | 263.13 K (10˚C) |
| Melting Point | 200 K (-73 C) |
| Critical Temperature | 430.75 K |
| Critical Pressure | 0.788 x $10^7$ Pa |
| Critical Volume | 0.122 $m^3$/kmol |
| Specific Heat : Vapour at 20 $^oC$ | 0,62 kJ/kg K |
| Density : Vapour at 1 atm | 2.25 (air=1) |
| Vapour Pressure at 20 $^oC$ | 334.7 kPa |
| Heat of Vaporization | 393.5 kJ/kg |
| Heat of Combustion | Non-combustible |
| Flash Point | N/A |
| Explosion Limit : Lower | N/A |
| : Upper | N/A |
| Solubility in Water : at 25 $^oC$ | 8.6ml/100 ml |

**Table 12-3 Physical Properties of Sulphur Trioxide**

| Parameter | Units | SULFUR TRIOXIDE |
|---|---|---|
| Molecular Weight | g/mol | 80.1 |
| Normal Boiling Point | K | 317.9 |
| Melting Point | K | 290.0 |
| Critical Temperature | K | 490.9 |
| Critical Pressure | Pa | 8210000.0 |
| Heat Capacity : Vapour | J/kg K | 0.0 |
| : Liquid | J/kg K | 1.0 |
| Density : Vapour (STP) | (kg/$m^3$) | 3.40 |
| : Liquid | (kg/$m^3$) | 1780.0 |
| Vapour Pressure @ 20 $^oC$ | kPa | 25.7 |
| Antoine Coefficients : A | Pa | 25.7 |
| : B | K | 3995.7 |
| : C | K | -36.7 |
| Heat of Vaporisation | kJ/kg | 507.8 |
| Heat of Combustion | kJ/kg | 1776.1 |
| Flash Point | K | N/A |
| Ignition Temperature in Air | K | 595.0 |

**Table 12-4 Toxicological (inhalation) Properties of Sulphuric Acid Vapour and sulphur trioxide**

| Physiological/Toxic Effects | Concentration ($mg/m^3$) | Exposure Period |
|---|---|---|
| Odour Threshold | 3 | |
| Increased pulmonary air flow resistance (shallow breathing) | 0.35 - 5 | |
| 8-hour Time Weighted Threshold Limit Value (TLV-TWA). | 1 | 8 h/d,40 h/week |
| ERPG-1 | 2 | 1 h |
| 15 Minute Short Term Exposure Threshold Limit (TLV-STEL) | 3 | 15 min |
| ERPG-2 | 10 | 1 h |
| IDLH | 15 | 30 min |
| ERPG-3 | 30 | 1 h |
| $LC_{50}$ (mouse) | 320 | 2 h |
| $LC_{50}$ (rat) | 510 | 2 h |
| $LC_{50}$(human, 30 min), derived from animal studies | 575 | 30 min |

**Table 12-5 Toxicological (inhalation) Properties of Sulphur Dioxide**

| Physiological/Toxic Effects | Concentration (ppm) | Exposure Period |
|---|---|---|
| ERPG-1 | 0.3 | 1 h |
| Normal Detectable Odour Range | 0.7 | |
| 8-hour Time Weighted Threshold Limit Value (TLV-TWA) | 2 | 8 h/d, 40 h/week |
| Minor Eyes, Nose and Throat Irritation | 2 | |
| ERPG-2 | 3 | 1 h |
| 15-minute Short Term Exposure Threshold Limit Value (TLV-STEL) | 5 | 15 min |
| Respiratory irritation and nosebleeds | 10 | |
| Bronchospasms in normal individuals | 10 – 20 | |
| ERPG-3 | 15 | 1 h |
| Eye irritation and may lead to chronic respiratory symptoms | 20 | |
| IDLH | 100 | 30 min |
| $LC_{50}$(human, 30 min), derived from animal studies | 400 - 2 200 | |

# 13 APPENDIX B: INCIDENT SCENARII

## 13.1 Pool Fire Incident Scenarii

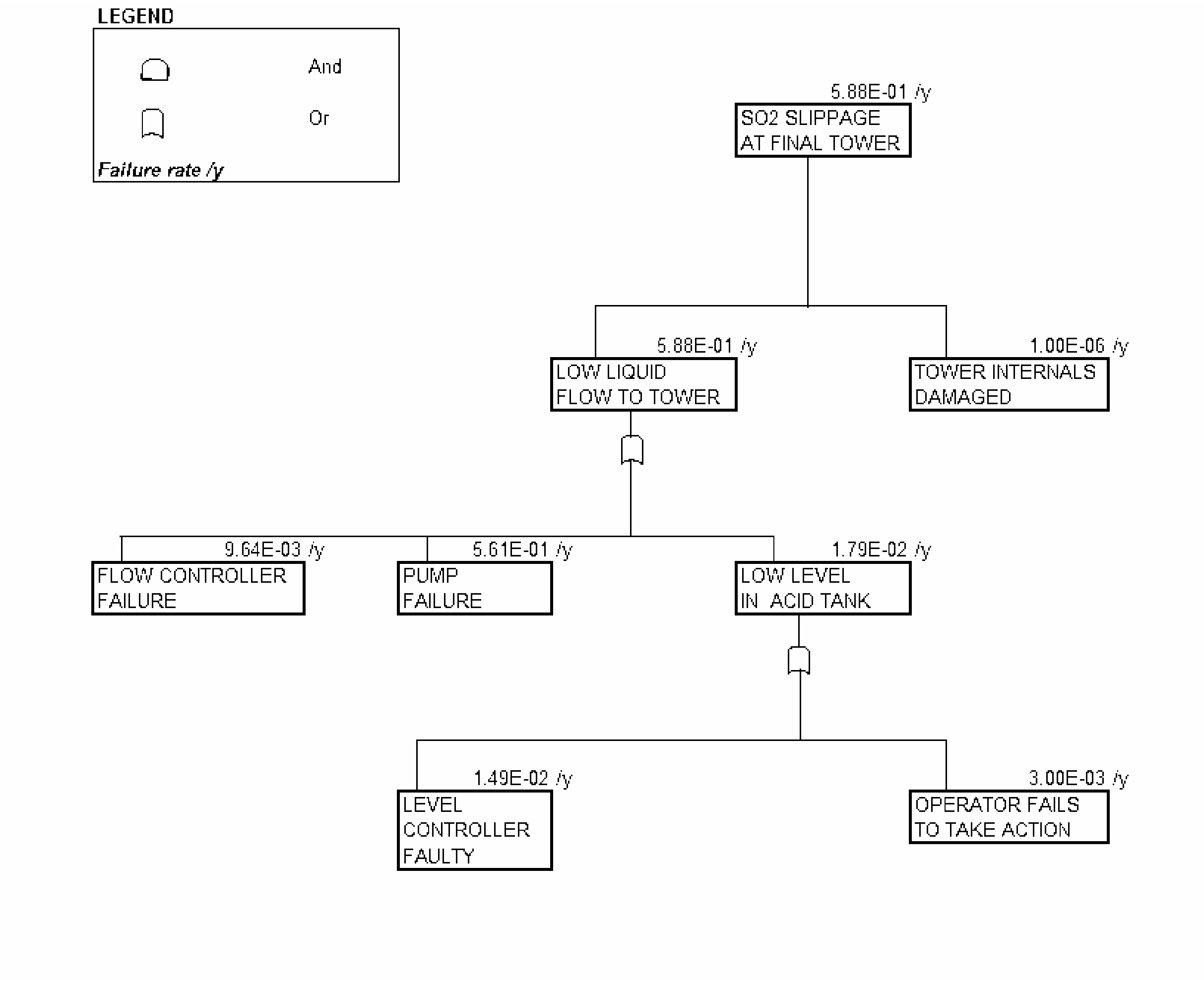
| Scenario | Component | Frequency of Fire Per Annum | Amount Released (kg) | Area of Release ($m^2$) |
|---|---|---|---|---|
| Vessel Failure | Sulphur | 3.25E-08 | 1206874 | 480 |
| Overfill | Sulphur | 2.09E-04 | 19600 | 480 |
| Valve & Pipework failure | Sulphur | 3.98E-06 | 1206874 | 480 |
| Tank Top Fire | Sulphur | 3.90E-08 | 1206874 | 154 |

## 13.2 Release Scenarii from the Sulphuric Acid Plant

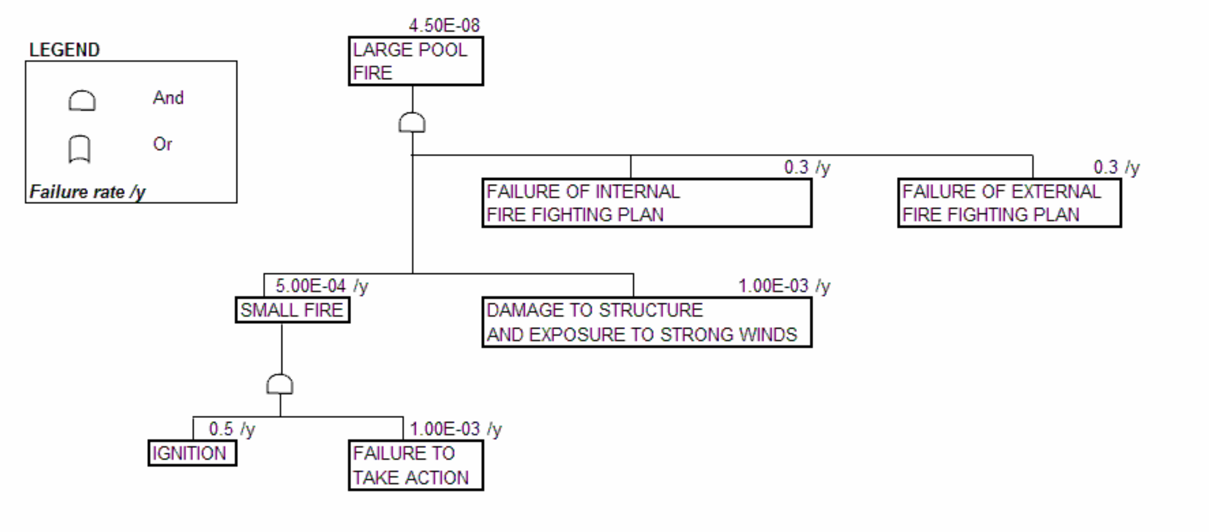
| Event | Scenario | Component | Releases Quantity (kg/s) | Duration (min) | Approx Height of Release(m) | Failure freq/m/y | Approx. length (m) | Frequency (event/annum) |
|---|---|---|---|---|---|---|---|---|
| 10 | **Pipe Failure After $SO_2$ Burner** | | | | | | | |
| 11 | Full bore pipe failure | $SO_2$ | 8.92E+00 | 30 | 1 | 1.00E-07 | 6.00E+01 | 6.00E-06 |
| 12 | Full bore pipe failure | $SO_3$ | 2.10E-01 | 30 | 1 | 1.00E-07 | 6.00E+01 | 6.00E-06 |
| 13 | 10 mm hole | $SO_2$ | 2.64E-03 | 30 | 1 | 5.00E-07 | 6.00E+01 | 3.00E-05 |
| 14 | 10 mm hole | $SO_3$ | 0.00 | 30 | 1 | 5.00E-07 | 6.00E+01 | 3.00E-05 |
| | | | | | | | | |
| 20 | **Failure of the Converter Shell and Piping** | | | | | | | |
| 21 | Full bore pipe failure | $SO_2$ | 3.40E+00 | 30 | 3 | 1.00E-07 | 6.00E+01 | 6.00E-06 |
| 22 | Full bore pipe failure | $SO_3$ | 7.11E+00 | 30 | 3 | 1.00E-07 | 6.00E+01 | 6.00E-06 |
| 23 | 10 mm hole | $SO_2$ | 1.37E-04 | 30 | 3 | 5.00E-07 | 6.00E+01 | 3.00E-05 |
| 24 | 10 mm hole | $SO_3$ | 2.54E-03 | 30 | 3 | 5.00E-07 | 6.00E+01 | 3.00E-05 |
| | | | | | | | | |
| 30 | **Failure Of Piping At The Interpass Tower** | | | | | | | |
| 31 | Full bore pipe failure | $SO_2$ | 4.77E-01 | 30 | 3 | 1.00E-07 | 6.00E+01 | 6.00E-06 |
| 32 | Full bore pipe failure | $SO_3$ | 1.08E+01 | 30 | 3 | 1.00E-07 | 6.00E+01 | 6.00E-06 |
| 33 | 10 mm hole | $SO_2$ | 1.77E-04 | 30 | 3 | 5.00E-07 | 6.00E+01 | 3.00E-05 |
| 34 | 10 mm hole | $SO_3$ | 3.99E-03 | 30 | 3 | 5.00E-07 | 6.00E+01 | 3.00E-05 |
| | | | | | | | | |
| 40 | **Failure Of Piping At The Final Tower** | | | | | | | |
| 41 | Full bore pipe failure | $SO_2$ | 1.67E-02 | 30 | 3 | 1.00E-07 | 6.00E+01 | 6.00E-06 |
| 42 | Full bore pipe failure | $SO_3$ | 5.77E-01 | 30 | 3 | 1.00E-07 | 6.00E+01 | 6.00E-06 |
| 43 | 10 mm hole | $SO_2$ | 4.28E-06 | 30 | 3 | 5.00E-07 | 6.00E+01 | 3.00E-05 |
| 44 | 10 mm hole | $SO_3$ | 1.48E-04 | 30 | 3 | 5.00E-07 | 6.00E+01 | 3.00E-05 |
| | | | | | | | | |
| | | | | | | | | |

| Event | Scenario | Component | Releases Quantity (kg/s) | Duration (min) | Approx Height of Release(m) | Failure freq/m/y | Approx. length (m) | Frequency (event/annum) |
|---|---|---|---|---|---|---|---|---|
| 50 | **Failure Of Interpass Tower Shell** | | | | | | | |
| 51 | Full bore pipe failure | $SO_2$ | 4.77E-01 | 30 | 3 | 5.00E-06 | 1 | 5.00E-06 |
| 52 | Full bore pipe failure | $SO_3$ | 1.08E+01 | 30 | 3 | 5.00E-06 | 1 | 5.00E-06 |
| 53 | 10 mm hole | $SO_2$ | 1.77E-04 | 30 | 3 | 1.00E-04 | 1 | 1.00E-04 |
| 54 | 10 mm hole | $SO_3$ | 3.99E-03 | 30 | 3 | 1.00E-04 | 1 | 1.00E-04 |
| | | | | | | | | |
| 60 | **Failure Of The Final Tower Shell** | | | | | | | |
| 61 | Full bore pipe failure | $SO_2$ | 1.67E-02 | 30 | 3 | 5.00E-07 | 1 | 5.00E-07 |
| 62 | Full bore pipe failure | $SO_3$ | 5.77E-01 | 30 | 3 | 5.00E-07 | 1 | 5.00E-07 |
| 63 | 10 mm hole | $SO_2$ | 4.28E-06 | 30 | 3 | 1.00E-04 | 1 | 1.00E-04 |
| 64 | 10 mm hole | $SO_3$ | 1.48E-04 | 30 | 3 | 1.00E-04 | 1 | 1.00E-04 |
| | | | | | | | | |
| 70 | **High Concentration of Pollutants Venting at The Stack** | $SO_2$ | 1.67E-02 | 30 | 100 | 5.88E-01 | 1 | 5.88E-01 |
| 7.1 | Slippage | $SO_3$ | 5.77E-01 | 30 | 100 | 5.88E-01 | 1 | 5.88E-01 |

## 13.3 Fault Tree –Final Scrubber




## 13.4 Fault Tree – Sulphur Fire at the Walvis Bay Storage



## 13.5 Fault Tree- Sulphur Fire at the Mine