



AIR POLLUTION FROM IGNITED AND UNIGNITED ACID GAS FLARES IN QATAR

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Qatar, one of the Gulf States, possesses one of the world's largest non-associated gas fields. Most of the country's development plans are based on the preparation of natural gas for export and local use.

Under normal operation of gas processing plants, the residual, H₂S-rich Acid Gas is treated in a sulfur recovery unit to produce pure sulfur. However, under abnormal situations, the acid gas is burned in incinerators or flares releasing SO₂-rich combustion products. Under severe weather conditions, such a flare may get extinguished and the acid gas is released unignited into the atmosphere. This paper studies the environmental hazards due to the release of such dangerous gases. Dispersion models developed by the US EPA have been used to determine the size and map location of the dangerous zones.

For ignited acid gas, the results indicated the possible formation of SO₂-toxic clouds extending to 110 km in the downwind direction from the flare location and 210 m above ground level. For the less common case of releasing unignited acid gas, the H₂S-toxic cloud may extend to 20 km and 110 m in the downwind and vertical directions, respectively. A parametric study has been conducted to consider the effects of some meteorological conditions (wind speed and atmospheric stability) as well as the number of operating trains in a typical gas processing plant.

Keywords: Risk assessment, Environmental impact, Gas processing plants, Hazardous gases, Toxic clouds, Health and safety.

1. INTRODUCTION

Like other developing countries, Qatar (one of the Gulf States) has been moving forward launching a development plan based on the utilization of its oil and gas resources. As an example, the North Field is recognized as one of the world's largest non-associated gas fields, with total reserves in excess of 500 trillion SCF. Thus, natural gas has become the most important source of income for the State of Qatar. As a clean and relatively cheap source of energy, natural gas is used locally to generate power and to operate industrial plants. Also it is used as a feedstock for local petrochemical industry. The larger remaining amount of natural gas is liquefied and stored in huge tanks awaiting export.

2. DESCRIPTION OF THE PROBLEM

In a typical natural gas processing plant, the raw sour gas is treated into successive steps to produce sweet dry gas suitable for injection into the pipeline network for distribution to local customers and/or liquefaction for export purposes. Natural gas condensates are collected in low and high pressure separators. The feed gas is then treated in di-ethanol-amine units (DEA) to separate H₂S by reaction with

DEA and produce sweet gas. The residual gas is directed to a regenerator where the amine is separated and taken back to a storage tank. Under normal operation, the H₂S-rich remaining gas (called Acid Gas) is sent to a sulfur recovery unit (SRU) where the sulfur is separated and liquefied. However, during abnormal situations such as emergency shutdown of the SRU, the acid gas (containing about 30 % H₂S) is burned in incinerators or flares releasing SO₂-rich combustion products. Having a high temperature and a density lower than that of air, such products form a plume that diffuses by passive dispersion. Another hazardous situation may develop if the flare is extinguished due to atmospheric wind or other severe meteorological conditions. In such a case, the acid gas at ambient temperature is released into the atmosphere. Being denser than air, the acid gas diffuses downwards due to negative buoyancy and attacks the ground.

3. AIR POLLUTION

In the two situations mentioned above, very hazardous gases (SO₂ or H₂S) are released in the atmosphere causing air pollution. It is recognized that there is a strong relationship between environmental pollutants and dangerous diseases such as cancer [1]. Hydrogen sulfide (H₂S) is toxic, corrosive if moist, and flammable. At concentrations of 10-500 PPM, it causes headaches, coughing and pain in the respiratory tract, dizziness, nausea, and eye irritation. Exposure to 500-700 PPM causes moderate poisoning. Inhalation of concentrations higher than 700 PPM causes respiratory arrest, anoxia and death [2]. On the other hand, sulfur dioxide (SO₂) is very irritant due to its formation of sulfurous and sulfuric acids on contact with moist tissues and mucous membranes. Acute exposures are fortunately rare but give rise to intense irritation of the eye and upper respiratory system, followed by dyspnoea and cyanosis, and unconsciousness. Death can result from reflex spasm of the larynx causing suffocation and circulatory failure. Sulfur trioxide (SO₃) behaves in a similar way but it is much more chemically active [2].

4. RISK ASSESSMENT

In order to reduce the environmental impact of such abnormal situations, the size of the problem and the consequences of the propagation should be studied. For example, the US EPA Clean air Act (section 112R) requires facilities that manufacture, process, use, store, or otherwise handle certain amounts of toxic substances to submit a Risk Management Plan (RMP) to local emergency management authorities. An important element of the RMP is the determination of consequence distances for worst case and alternative release scenarios.

Risk analysis is an engineering decision to insure safety. The various steps in the risk analysis process can be grouped in the two major areas of Risk Assessment and Risk Management. The end result of risk assessment is an expression of risk that defines the probability of harm which could result from a given action or situation. The expression should combine all elements included in the risk assessment, such as extent or concentration of the hazard, effect or consequence of exposure to the hazard, and possibility of exposure. All of these factors are combined to describe the nature and magnitude of the risk along with all uncertainties associated with the entire process.

Using the risk value obtained from the risk assessment procedure to decide what action to take is called risk management. It involves weighing the calculated risk against benefits, desired results, or requirements and then selecting a cost-effective alternative to achieve the best risk/benefit ratio. The risk management process is based on the premise that no action is totally risk free; there are no rewards without risks, no operating systems without potential failures. Accordingly, the present study can be classified as a part of the risk assessment process.

5. METEOROLOGY AND AIR POLLUTION

The degree to which air pollutants discharged from various sources concentrate in a particular area depends on the meteorological conditions. Even if the total discharge of contaminants into the atmosphere in a given area remains constant from day to day, the degree of air pollution may vary widely because of differences in meteorological conditions and only the weather that can trigger an air pollution episode in such a situation. Thus, for the application of dispersion theory, knowledge of local weather conditions and

some meteorological conditions is necessary to evaluate the intensity of air pollution. The important meteorological conditions that influence air pollution are [3]:

1. Wind direction and speed: The wind at or near the point of discharge carries the pollutants away from the source and causes air entrainment. The wind speed is the prime source of horizontal dispersion.
2. Mixing height: The mixing height can be defined as that height above the earth's surface to which related pollutants will extend, primarily through the action of atmospheric turbulence.
3. Atmospheric stability and temperature: Under normal conditions the temperature decreases in the upward direction. This causes the buoyant motion of the air, which enhances atmospheric instabilities, mixing, and dispersion of pollutants in the vertical direction. If this is not the case, there will be no or less motion and the pollutants will be kept at the ground level. The atmospheric stability class ranges from A to F where A: extremely unstable, B: moderately unstable, C: slightly unstable, D: neutral, E: stable, and F: very stable.

6. OBJECTIVES

The present paper touches on the assessment of risks of handling dangerous gases within local gas processing plants. To be more specific, the main objective of this work is to predict the size and location of the toxic zone formed due to the release of acid gas from ignited and unignited flares and the subsequent dispersion in the surrounding atmosphere. Table 1 shows the air pollutants considered in this study, along with the different levels of toxicity and their adverse effects [2, 4].

Table 1 Pollutants and their different toxic limits [2, 4] (all units are in PPM)

CHEMICAL	CEILING	IDLH	TWA	STEL	TOXIC ENDPOINT
Hydrogen sulfide	10	100			28
Sulfur dioxide			2	5	

Where:

Ceiling: An exposure limit set by NIOSH and OSHA that must not be exceeded during any part of the workday.

IDLH: Immediately Dangerous to Life and Health Limit. Levels established by NIOSH "from which one could escape within 30 minutes without any escape-impairing symptoms or any irreversible health effects."

TWA: The time-weighted average concentration for a normal 8-hour workday and a 40-hour workweek, to which all workers may be exposed without adverse health effects.

STEL: Short Term Exposure Limit. A time-weighted average concentration to which workers would not be exposed for longer than 15 minutes and which should not be repeated more than four times a day, with at least 60 minutes between successive exposures.

Toxic Endpoint: The threshold for serious injury from exposure to a toxic substance in the air.

7. PROCEDURES AND TOOLS

The objectives of this study are achieved partially by the use of Atmospheric Dispersion software containing two EPA-developed dispersion models explained in the following sections.

The AFFTOX Dispersion Model:

AFTOX [5] is a Gaussian puff/plume model developed by the U.S. Air Force to model neutrally buoyant gaseous releases from both gas and liquid sources. The model assumes a Gaussian concentration distribution within the puff. For the steady state situations considered in this study, such distribution is represented mathematically by the following relation:

$$C(y,z) = (Q/2\pi\sigma_x\sigma_y u) \cdot \exp(-0.5(y/\sigma_y)^2) \cdot \{\exp(-0.5((z-H)/\sigma_z)^2) + \exp(-0.5((z+H)/\sigma_z)^2)\}$$

Where C is the concentration in the puff at a given point, Q is the total mass of the puff, σ_x , σ_y , σ_z are the dispersion coefficients, H is the height of the source point, and u is the wind speed at the standard height ($z = 10\text{m}$). It assumes $\sigma_x = \sigma_y$ while σ_y , σ_z are affected by the downwind distance (x) and the atmospheric stability.

The DEGADIS+ Dispersion Model:

DEGADIS+ [6] is a dense-gas dispersion model developed by the U.S. Coast Guard. It is used to determine hydrocarbon flammability levels and toxic concentrations from episodic dense-gas/aerosol releases. The model describes the dispersion processes, which accompany the ensuing of the heavier-than-air flow and its entrainment into the atmospheric boundary layer. The heavy gas is first treated as a jet moving upwards until its kinetic energy is zero; a point at which it starts moving downwards (by gravity) until it hits the ground and forms a blanket acting as a secondary source. The concentration distribution is represented by:

Within the secondary source:

$$C(x,y,z) = C_c(x) \cdot \exp[-(z/\sigma_z)^{1+\alpha}]$$

Outside the secondary source:

$$C(x,y,z) = C_c(x) \cdot \exp[-(\{y-b(x)\}/\sigma_y)^2 - (z/\sigma_z)^{1+\alpha}]$$

Where $C_c(x)$ is the centerline concentration, $b(x)$ is the secondary source width, and α is an empirical coefficient.

The sources considered by the two models may be treated as continuous, finite duration, or instantaneous releases. The models allow for a single-source release over flat terrain. A single meteorological condition is specified for the duration of the release.

For a given set of conditions, the models predict the 3D concentration distribution of the pollutant. Figure 1 is an example of a predicted concentration profile in the downwind direction. Moreover, the used dispersion software has the capability of plotting the projection of the toxic cloud on a map provided the source point and wind direction are specified. In addition to showing a contour line for each specified concentration limit (e.g. ceiling, IDLH....) with its centerline along the wind direction, the software draws circles indicating possible hazardous zones just in case if the wind changes its direction suddenly (e.g. figure 2).

8. RESULTS AND DISCUSSION

As mentioned earlier, the release of toxic gases may have a serious impact on the environment. This study will focus on the size of the dangerous cloud of the released gas as well as its location relative to the source point. It should be emphasized that the aim is not to investigate or criticize a specific installation. However, the study tries to consider data similar to real situations that may develop in an industrial plant within the country. Thus, the study may be useful and beneficial to the local industrial sector. It should be also emphasized that the results of this study are purely computational and have not been verified

experimentally. However, some researchers have conducted experiments in China Town, Nevada, USA and verified successfully the DEGADIS+ model [6].

Both situations of ignited and unignited flares from the Sulfur Recovery Unit of a typical gas processing plant with a maximum of six operating trains (production lines) are studied. Different values of the meteorological parameters wind speed and atmospheric stability class as well as the number of operating trains are considered. The base case deals with a wind speed of 1.5 m/s, a stability class F (very stable), and three operating trains. In order to emphasize the environmental impact on the relatively populated areas in Qatar (e.g. cities of Doha and Al-Khawr), the source point is assumed to be in the industrial city of Ras Laffan (north east of Qatar) and the wind is assumed to blow from the north.

Generally, the acid gas is a mixture of H₂S and CO₂ with small fractions of H₂O and other hydrocarbons. For the two scenarios considered in a typical gas processing plant, the acid gas data is:

Unignited Acid Gas Flare:

- Composition (by volume): 30% H₂S and 70 % CO₂
- Temperature: 308 K
- Density: 1.618 Kg/m³
- Flow rate (ONE TRAIN): 8.7 Kg/s
- Toxic limits of H₂S: Ceiling 15 mg/m³ (10 PPM), Toxic end point 42 mg/m³ (28 PPM), and IDLH 142 mg/m³ (100 PPM) [4].

For ignited Flares, the acid gas is assumed to burn completely with the stoichiometric amount of air. Applying the principles of thermo-chemistry, the products of combustion are found to have the following data:

Ignited Acid Gas Flare:

- Composition (by volume): 10% SO₂, 10%H₂O, 23.4%CO₂, 56.6%N₂.
- Temperature: 900 K
- Density: 0.439 Kg/m³
- Flow Rate (ONE TRAIN): 22 Kg/s
- Toxic limits of SO₂: TWA 5 mg/m³ (2 PPM) and STEL 13 mg/m³ (5 PPM) [4].

The DEGADIS+ and AFTOX models are used to predict the size of the toxic clouds caused by the release of the unignited acid gas (heavier than air) and ignited acid gas (lighter than air), respectively. In addition to summarizing them in a written report, the used software presents the output results in three graphs: the concentration profile along the downwind direction, a 2D plan of the toxic cloud (downwind and crosswind directions) that can be superimposed on an area map, and a 2D side view (downwind and vertical directions). Figures 1, 2, and 3 are examples of such results for an ignited flare from ONE TRAIN only for a highly stable atmosphere (class F) and a wind speed of 1.5 m/s. The concentration profile of sulfur dioxide (fig.1) has the well-known Gaussian shape with its peak shifted slightly downwind from the source point. This slight shift is a function of wind speed and plume shape factor. Moreover, the figure depicts the exponential variation of the concentration with the downwind distance indicating the formation of STEL and TWA sulfur dioxide toxic clouds extending to about 15 and 32 Km, respectively. Figure 2 shows the projection of such toxic clouds on the map of Qatar indicating the possibility of reaching the nearest populated town, Alkhour. Furthermore, the side view of the toxic cloud (fig.3) indicates a vertical rise of about 115 and 140 m for the STEL and TWA toxic limits, respectively.

A parametric study is conducted for one operating train to show the effects of stability class and wind speed. Both parameters contribute to the mixing intensity. Wind speed affects the mixing in the downwind direction while atmospheric instability affects mixing in the vertical and crosswind directions. As atmospheric instability becomes stronger the mixing intensity increases, and thus the plume released at high level (48 m) has better chances to reach the ground level at shorter distances from the source, as shown in figure 4. Meanwhile, dilution and air entrainment help to reduce the pollutant concentration and thus shortens the size of the toxic cloud in the downwind direction. Figure 5 depicts an exponential reduction in the toxic cloud size in the downwind direction with the increase in atmospheric instabilities. Similarly, figure 6 shows that the enhanced mixing intensity due to a higher wind speed reduces the toxic

cloud size at ground level. In addition to its effect on the size of the toxic cloud, the higher wind speed carries the entire cloud to further distances from the source point at ground level, as shown in figure 7.

The typical situation of having three operating trains (figures 8 & 9) produces a TWA toxic zone extending to about 65 km and 185 m in the downwind and vertical directions; respectively. The results presented in figure 10 for a gas processing plant operating at full load (i.e. six trains) show a toxic zone extending to about 110 km. This situation is extremely dangerous since the toxic cloud may reach the capital city Doha and the neighboring country Bahrain. Such a cloud is found to extend vertically to about 230 meters.

For the less common situation of unignited flare, the CEILING concentration of H₂S (15 mg/m³ or 10 PPM) has been used to predict the worst scenario. Figure 11 depicts the toxic cloud for the base case of three operating trains. The size of the toxic cloud is about 13.7 km and 95 m in the downwind and vertical directions; respectively. For full load operation of a typical gas processing plant with six trains, the toxic cloud extends to about 20 km in the downwind direction, as shown in figure 12.

Figure 13 shows the results of a parametric study of the effects of atmospheric stability on the size of the toxic zone due to the release of unignited acid gas for three operating trains and a wind speed of 1.5 m/s. For unstable atmospheres (class A, B, and C), the figure indicates safe conditions at ground level. Although it is heavier than air, the plume for such situations is diluted due to strong atmospheric instabilities and thus does not touch the ground level. Similar results (safe conditions at ground level) have been obtained for wind speeds higher than 2 m/s. This is also explained by the relatively strong mixing intensity.

This study should be considered as a first stage of a more comprehensive project aiming at better understanding and determination of environmental impact of abnormal release of dangerous industrial gases. Civil defense centers and related industrial corporations should work together to generate databases for such environmentally hazardous situations. Action plans (e.g. emergency evacuation) should be prepared accordingly.

SUMMARY

The main objective of this paper is to help in the risk assessment of abnormal release of toxic gases from ignited and unignited flares found in local gas processing plants. A software based on some US EPA-developed dispersion models has been utilized to predict the size of the toxic clouds in the downwind and vertical directions. AFTOX and DEGADIS+ models have been used for the neutrally buoyant ignited flare and the heavier-than-air unignited flare; respectively.

The unignited flare (raw acid gas) has about 30 % hydrogen sulfide. For the ignited flare, on the other hand, burning of the acid gas produces a buoyant plume containing about 10 % sulfur dioxide. Considering worst case scenario, the sizes of the formed toxic clouds of both cases in the downwind and vertical directions for different numbers of operating trains are given below:

	3 Trains		6 Trains	
	Downwind	Vertical	Downwind	Vertical
<i>Ignited</i>	65 km	185 m	110 km	230 m
<i>Unignited</i>	13.7 km	95 m	20 km	110 m

The considered parametric studies show the effect of the intensity of mixing produced by atmospheric instability and wind speed. For an ignited flare of one operating train, the size of the toxic cloud at ground level in the downwind direction varies from 33 km to 2 km when the atmospheric conditions change from very stable to extremely unstable ones. Similarly, the toxic cloud size varies from 33 km to 8 km when

the wind speed changes from 1.5 m/s to 7 m/s. For unignited flares, on the other hand, the effects of mixing intensity are stronger. Mixing processes for both unstable atmospheres (stability classes A, B, & C) and wind speeds higher than 2 m/s are strong enough to dilute the unignited plume of three operating trains such that no toxic zones are produced at ground level.

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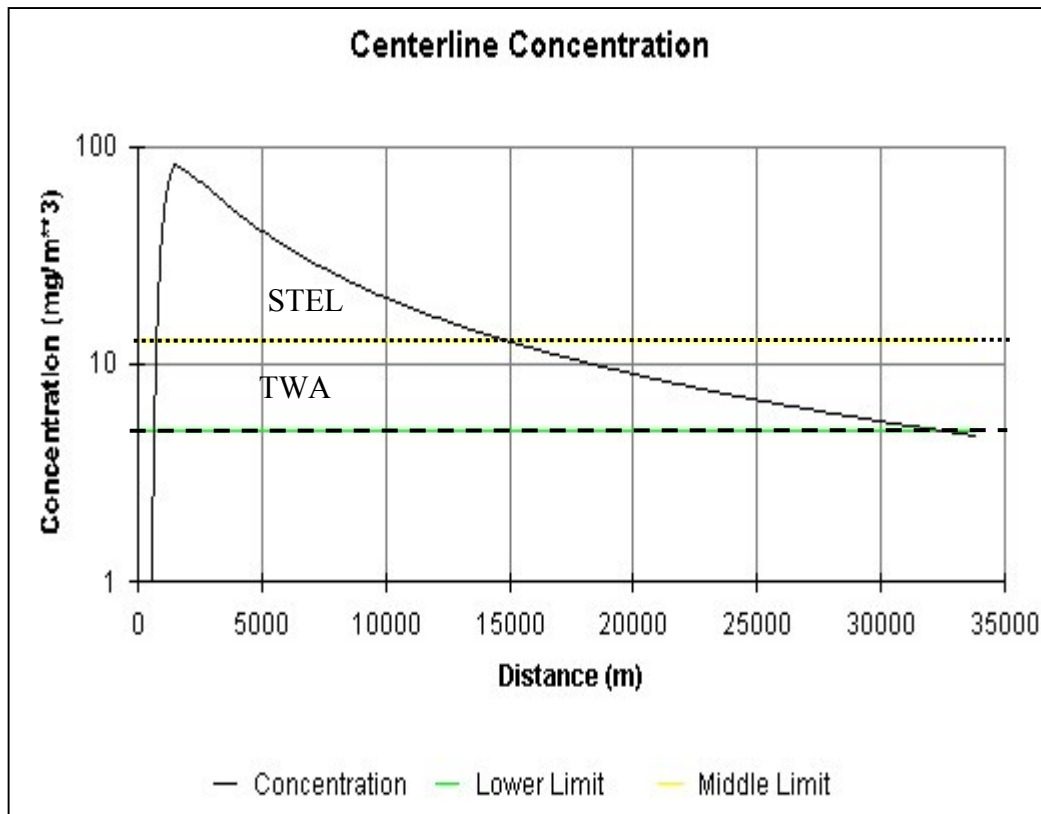


Figure 1 SO₂ concentration vs. downwind distance at ground level for the release of ignited acid gas (1 train)

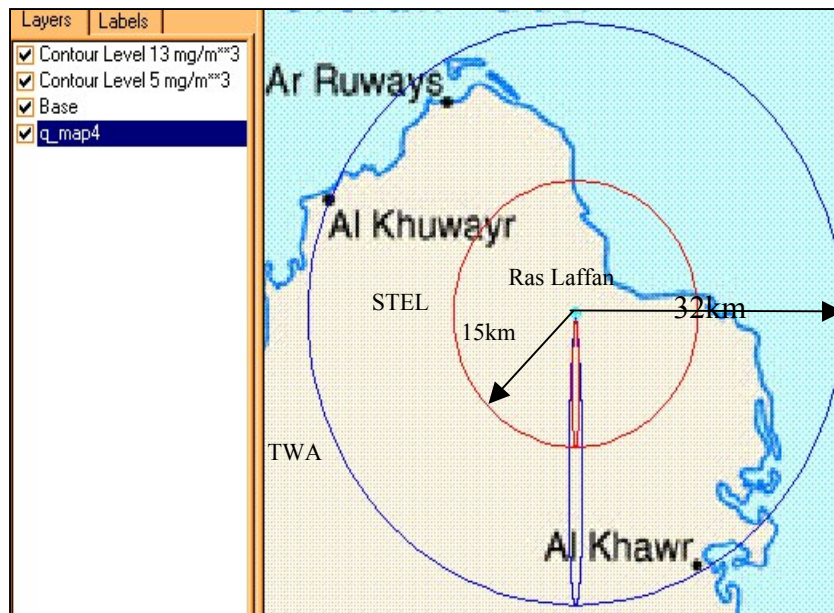


Figure 2 Ground level toxic zone on Qatar map due to the release of ignited acid gas (1 train)

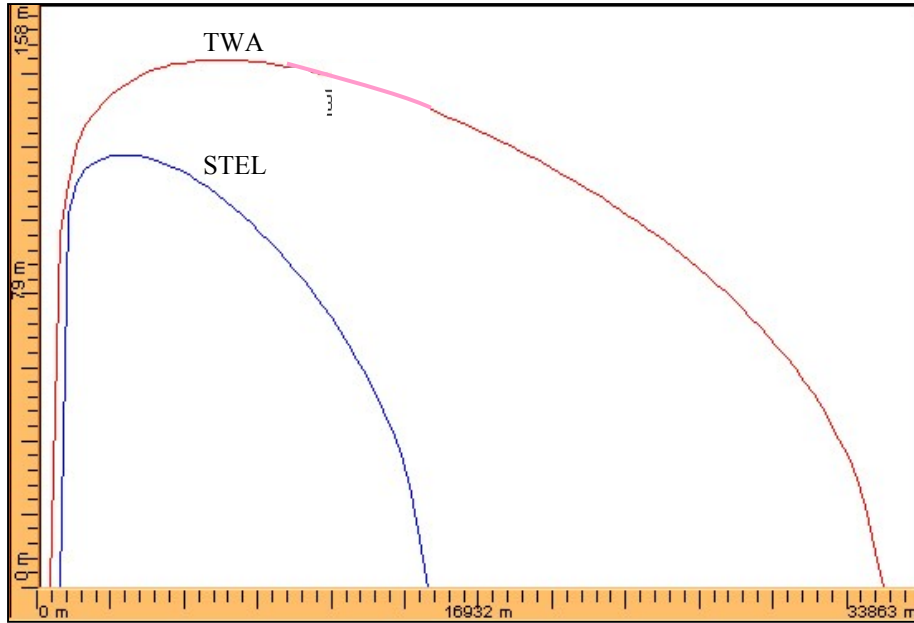


Figure 3 Side view of the toxic cloud (vertical height vs. downwind distance) for the release of ignited acid gas (1 train)

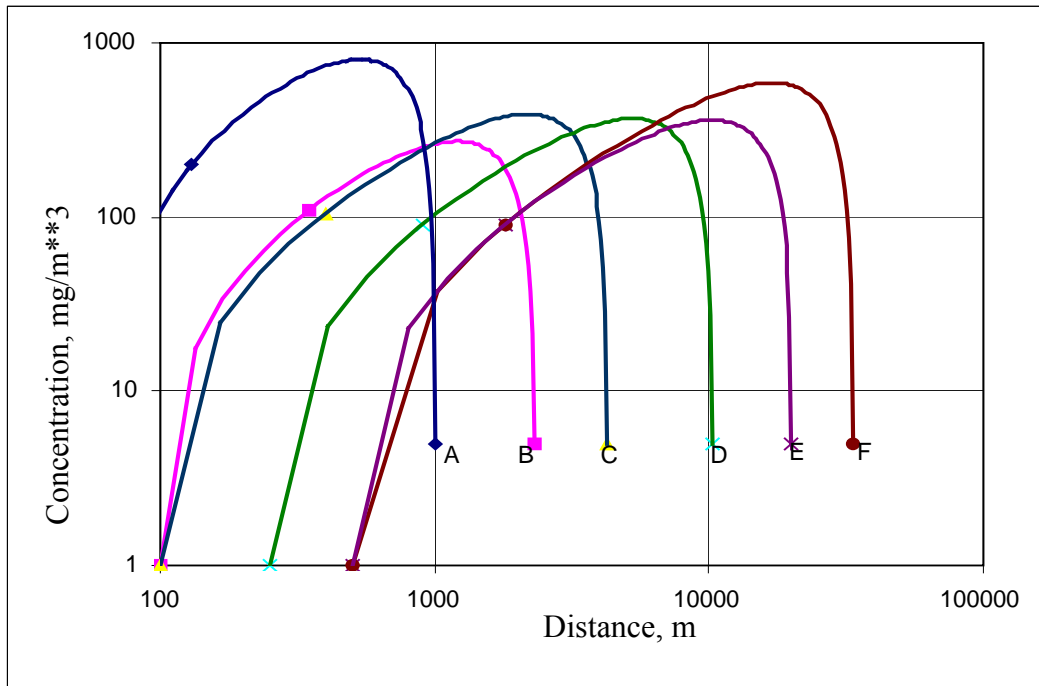


Figure 4 SO₂ concentration vs. downwind distance for different stability classes for the release of ignited acid gas (1 train)

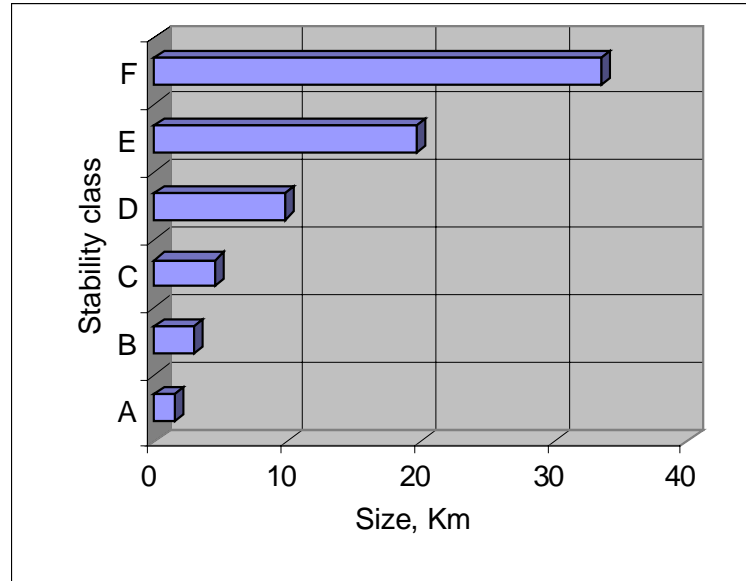


Figure 5 Size of toxic zone vs. stability class for the release of ignited acid gas (1 train)

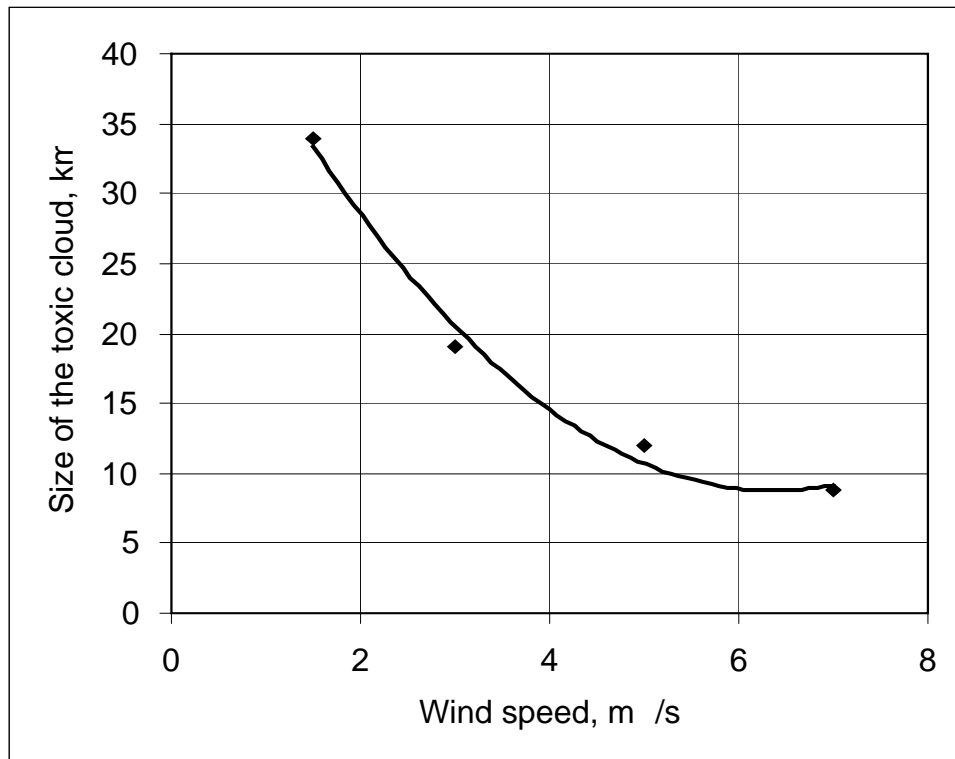


Figure 6 Effect of wind speed on the toxic zone size for the release of ignited acid gas (1 train)

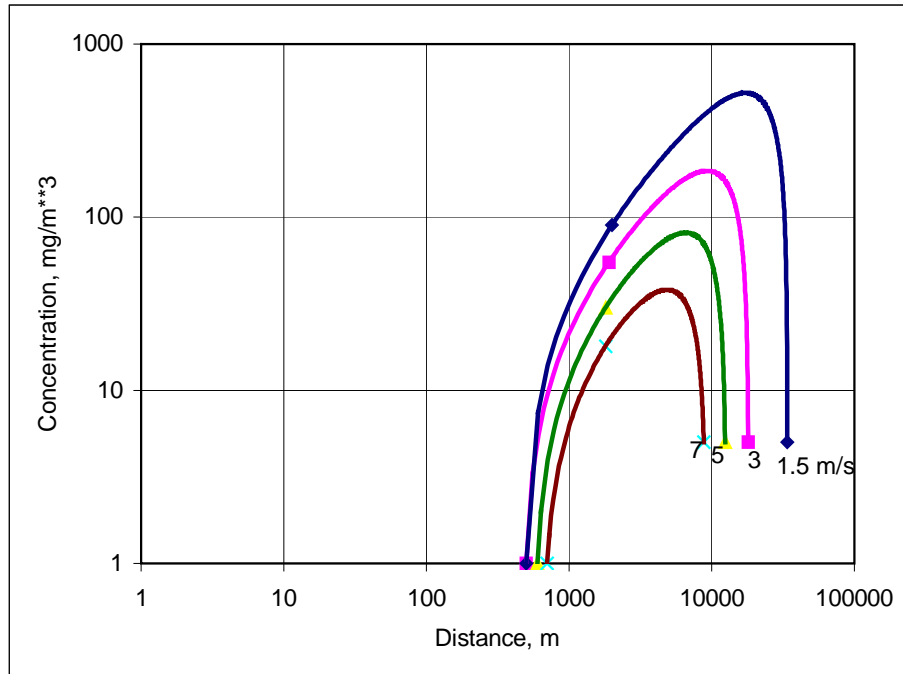


Figure 7 SO₂ concentrations vs. downwind distance for different wind speeds for the release of ignited acid gas (1 train)

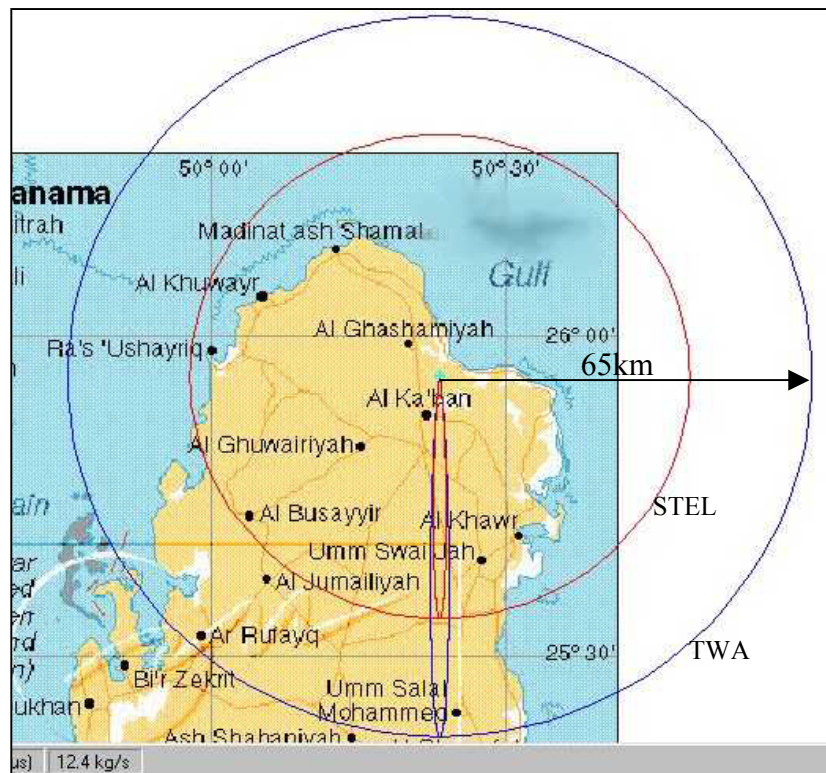


Figure 8 Toxic zones due to the release of ignited acid gas (3 trains)

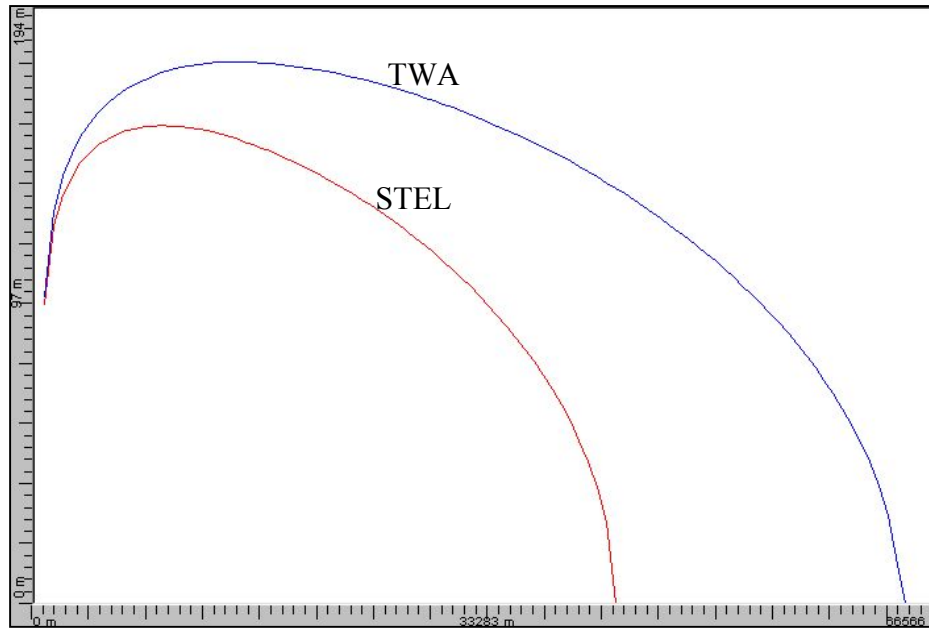


Figure 9 Side view of the toxic cloud for the release of ignited acid gas (3 trains)

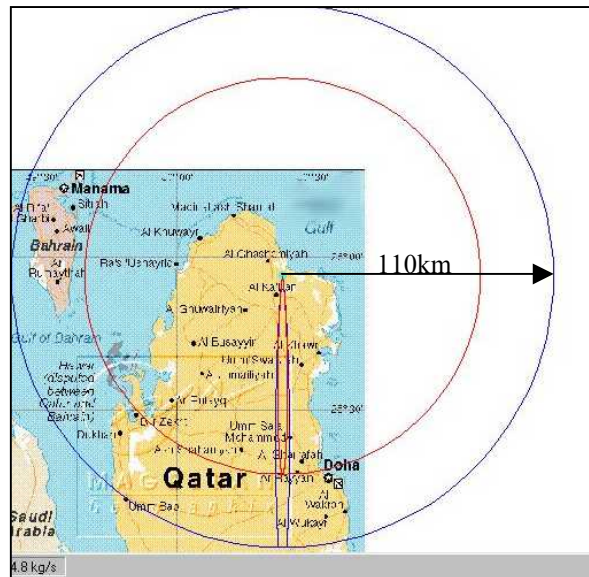


Figure 10 Toxic zones due to the release of ignited acid gas (6 trains)

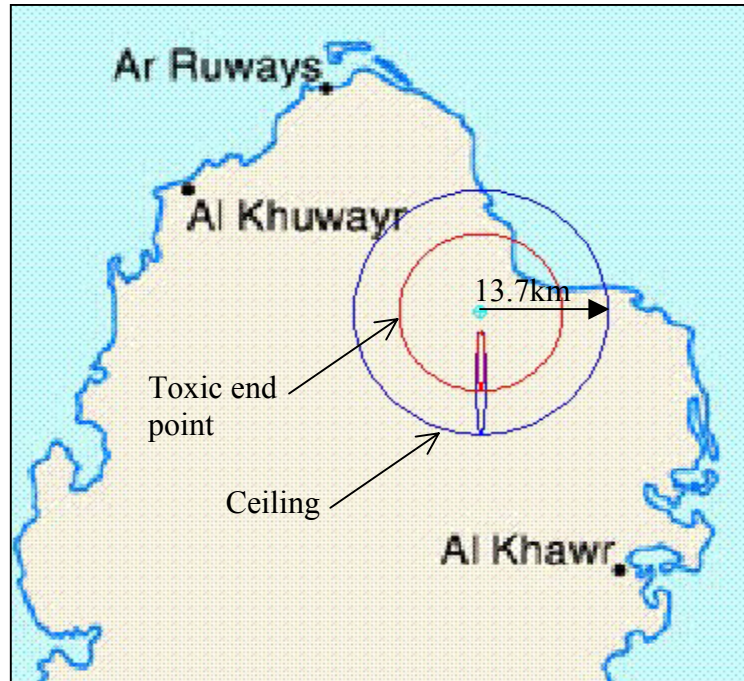


Figure 11 Toxic zones due to the release of unignited acid gas (3 trains)



Figure 12 Unignited acid gas toxic zones (6 trains)

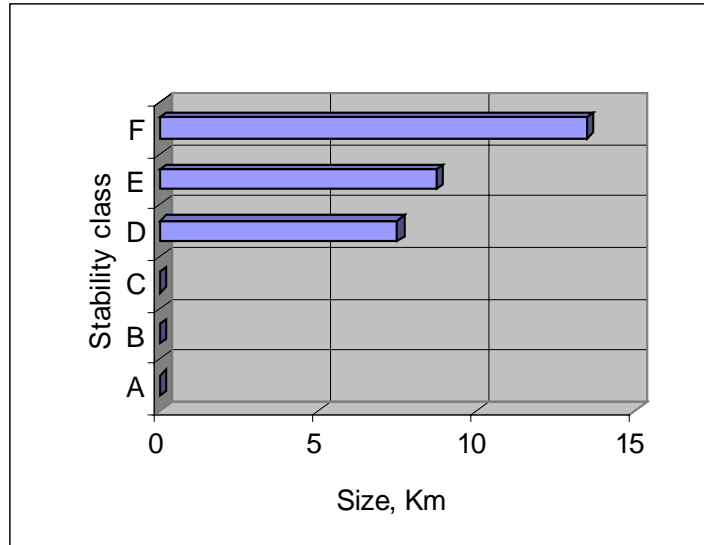


Figure 13 Size of toxic zone vs. stability class for the release of unignited acid gas (3 trains)