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# Emission Inventories from Kuwait Petroleum Refineries and Respective Ground Level Concentration of Pollutants in the Neighboring Residential Area

By

Salwa Farhan Alanezi

A doctoral thesis submitted in partial fulfillment of the
requirements for the award of the Doctor Philosophy Degree of
Loughborough University
December, 2012

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# DEDICATION

The work of this Thesis is dedicated to my family.

To my mother, for her great love, and for supporting me since I were a child, for believing in me, for raising me on a principle that everything is possible in this world if we insist, and only sky is the limit.

To my beloved husband Khalifa, my soul mate for showing faith in me, for his love which allowed me to continue to achieve my goals. For his friendship when I need a friend, for his parental caring when I need my father support and love. I'm lucky to be his wife.

To my sisters and brothers, for the encouragement, love and support they offered me throughout my life generally and in my study specifically.

Finally, to my lovely children Khaled, Haya, Dalal, Ali and Yousuf who were brave, strong and dutiful, their braveness gave me the real chance to work on this study and made it manageable to handle a family and a research at the same time. I'm gifted to have them.

# ACKNOWLEDGEMENTS

I appreciate the great contribution of Prof. Vahid Nassehi as a supervisor of this study; his encouragement, assistance and guidance to me. I acknowledge his knowledge, patience and kindness when I need his advice.

I am really grateful to my closest friend Suzan who encouraged me when I need her help and support.

I need to thank people who made my study easier by their technical IT support such as Paul Izzard.

A big thank you to my colleagues, Mahdi and Khayreia, who were always supportive and created a nice studying environment to keep me going forward to my goal.

Finally, a special thank you to people who appeared in a special moments during my study and supported me by offering their knowledge, kindness, advice and love. Those who were carrying messages from god telling me don’t stop and keep going, things are just fine. Thank you, Prof. Vahid Nassehi and my colleague Kheyreia.

# ABSTRACT

The State of Kuwait has three large refineries, namely, Mina Al Ahmadi Refinery, Mina Abdullah Refinery and Shuaiba Refinery. These refineries process and refine Kuwait Crude Oil through different process units.

There are many heaters, boilers and flares that form a part of the complicated equipment which enhance the different petroleum processes. Fuel gas is used as a firing fuel for those heaters and boilers. As a result, stack emissions like $SO_2$, $NO_x$, CO are predominantly present in the flue gases and this study focuses on those emissions and their impact on the surrounding residential area. The area of interest will be Umm Al-Hyman residential area.

This study accumulates emission inventories from the three refineries and the respective ground level concentration of the pollutants in the neighboring residential area. It also focuses on the impact of emissions from the refinery operations on the ground level concentrations in the surrounding areas by using the inventory model and latest emission factors to provide accurate emission estimates. The models were developed and the results were verified with the actual data from the area of impact.

As a result of the findings of the major pollutants, namely $SO_2$, $NO_x$ & CO, it is found that $SO_2$ and CO are not exceeding Kuwait EPA Ambient Air Quality Standards for Residential Areas normally. However, $NO_x$ is observed to exceed occasionally. Even though, $NO_x$ emissions from refineries sources represented by plume models were much less, there is a consistent increase in the measured $NO_x$. Furthermore, in 2007, the measured hourly, daily and annual $NO_x$ concentration exceeded the international standard many times. The increasing trend in $NO_x$ is attributed to continuous increase in population and the number of motor vehicles.

The study will go further step in recommending engineering solutions and best practices to reduce the pollutants concentrations which will help in the reduction of human health risks and protect the environment.

KEYWORDS: Air dispersion models, Refinery air emissions, Emission Inventories, AERMOD Plume, Ground level concentration, Point source, air pollution, point sources.

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# *Chapter 1*

# *General Introduction*

## 1.1 Introduction

A petroleum refining industry converts crude oil into more than 2500 refined products, including liquefied petroleum gas, gasoline, kerosene, aviation fuel, diesel fuel, fuel oils, lubricating oils and feed stocks for the petrochemical industry. Petroleum refinery activities start with the receipt of crude for storage at the refinery, includes all petroleum handling and refining operations, and they terminate with storage preparatory to shipping the refined products from the refinery.

Petroleum refineries use and generate an enormous number of chemicals, many of which leave the facilities as discharges of air emissions, wastewater, or solid waste. Discharge materials generated typically include, volatile organic carbons (VOCs), carbon monoxide (CO), sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), particulates, ammonia ($NH_3$), hydrogen sulphide ($H_2S$), metals, spent acids and chemicals, spent catalysts, and numerous toxic organic compounds.

Air emissions from refineries includes fugitive emissions of the volatile constituents in crude oil and its fractions, emissions from the burning of fuels in process heaters, and emissions from the various refinery processes themselves. Fugitive emissions occur throughout refineries and arise from the thousands of potential fugitive emission sources such as valves, pumps, tanks, pressure relief valves, flanges, etc. While individual leaks are typically small, the sum of all fugitive leaks at a refinery can be one of its largest emission sources. Fug emissions can be reduced through a number of techniques, including improved leak resistant equipment, reducing the number of tanks and other potential sources and perhaps the most effective method of **L**eak **D**etection **a**nd **R**epair (LDAR)[28] program.

The numerous process heaters used in refineries to heat process streams or to generate steam (boilers) for heating or steam stripping, can be potential sources of $SO_x$, $NO_x$, CO, particulates and hydrocarbons emissions. When operating properly and when burning cleaner fuels such as, refinery fuel gas, fuel oil or natural gas, these emissions are relatively low. If, however, combustion is not complete, or heaters are fired with refinery fuel pitch or residuals, emissions can be significant.

The majority of gas streams exiting from each refinery process contain varying amounts of refinery fuel gas, hydrogen sulfide and ammonia. To recover the refinery fuel gas and sulfur, these streams are collected and sent to the gas treatment and sulfur recovery units. Emissions from the sulfur recovery units typically contain $H_2S$ and $SO_x$. Other emissions sources from refinery processes arise from periodic regeneration of catalysts. These processes generate streams that may contain relatively high levels of carbon monoxide (CO), particulates and VOCs. Before being discharged to the atmosphere, such off-gas streams maybe treated first through a carbon monoxide boiler to burn carbon monoxide and any VOCs and then through an electrostatic precipitator or cyclone separator to remove particulates.

In addition to the process units and other facilities in the refinery, there are amenities like clinics, canteens, storage yard, warehouse, workshops and fire station. Other than air emissions generated due to a refinery activity, there are solid waste generations from these facilities. These include, medical waste, petroleum sludge, oily waste, asbestos waste, used filters, welding material scrap, refractory waste, used insulation materials, spent catalyst, empty chemical drums, expired/unused chemicals, plant trash (rags/personal protection equipment), used batteries, office waste, rubber waste, metal waste (from welding shop), packing materials, wooden pallets, construction debris, canteen waste and house hold waste.

Wastewater, which is the third form of refinery wastes, is usually produced from various units/equipment like Desalters, Strippers, etc. In general, the Industrial wastewater from a refinery is the contaminated water streams being discharged to water body after treatment (or without treatment) and is governed by effluent discharge standards.

## 1.2 Objectives of the current research

The main objective of the current research is to develop emission inventories for three air pollutants namely NOx, $SO_2$, and CO from Kuwait National Petroleum Company (KNPC) Refineries operations and evaluate the impact of these emissions in surrounding areas. Specific objectives of the study are as follows:

1. To present a complete description and estimation for the three pollutants emissions from KNPC.

2. To bring into focus the Air pollution issues currently faced in Kuwait and present the importance of weather conditions on dispersion of the pollutants.
3. To establish dispersion patterns of $SO_2$, CO and $NO_x$ from KNPC operations using AERMOD View (U.S. EPA, 1995) [1,2,3] dispersion module.
4. To assess the impact of $SO_2$, CO & $NO_x$ emitted from KNPC refineries on Umm-Alhyman residential area in the state of Kuwait.

## *1.3 Significance of this research to KNPC*

The emission inventory developed in this study will serve as a baseline for further improvement of the Environment Management Goals, Objectives and Performance of KNPC. The key benefits to KNPC are as below:

- Provide basis for understanding environmental impact of emissions from KNPC.
- Provide a ready reference as a source of data for emission from KNPC.
- Understand and identify key focus areas for emission control.
- Provide baseline data for future studies.
- Enable benchmarking with other companies.

## *1.4 Research Methodology*

The process flow or methodology of this research study has four steps. The initial step is to collect sufficiently verified information and data of various emission sources from KNPC operations. The next step involves selection of an Air Quality model and applying suitable emission factors to calculate air emissions. Following this step will be the process of running the model and establishing emission patterns. Finally, establishing source-receptor relationship for various emission sources from the refineries will bring the study to conclusion.

### 1.4.1 Literature Survey

A detailed review of available literature on the subject of the research study has been carried out during the initial phase of the study. During the progress of the study, developments in the area of study have been regularly reviewed to keep the study objectives in perspective. Literature review focuses on the following:

- Available literatures from relevant publications concerning annual emission quantities from Refinery Operations across the world.
- Literatures on the emission characteristics from refineries.
- Literatures on emissions from Flaring, Boilers, Process Heaters and Sulfur Recovery units.
- Literatures on meteorological parameters for modeling emissions from refineries with respect to impact on surrounding residential populations.
- Literatures on available air models to assess the impact of emissions from refineries.
- Literature survey of Air quality data and information specifically for

Kuwait.

- Literatures of emission control strategies in Petroleum refineries.

### 1.4.2 Data collection and analysis

Different types of data that are required for the purpose of developing emission inventories and modeling dispersion of $SO_2$, CO and $NO_x$ from emission sources in KNPC were collected. Specifically, these include:

- Source Information.
- Location of KNPC Refineries, various sources of emission from refineries, coordinates for point sources, emission rate, flue gas velocities, stack details like diameter, height etc.
- Geographical Information.
- Data regarding terrain elevation coordinates for KNPC refineries and adjoining residential areas were obtained.
- Meteorological Information of Kuwait.
- Meteorological data including wind velocity, wind direction, air temperature, cloud cover, stability class were obtained as a package.

### 1.4.3 Modeling and Simulation

#### *1.4.3.1 Air Dispersion Modeling Software*

The Objective of an Air Modeling System:

An XYZ Company wants to obtain a permit to operate a chemical plant in a rural area. The effluent from the facility ($SO_2$) is released to the atmosphere through two stacks. A building is located close to the stacks. An air dispersion modeling study usingan air dispersion model software like the U.S. EPA **AERMOD** model needs to be conducted to find out the impact from the chemical plant emissions to the atmosphere, the significance of these impacts and the area being impacted.

**AERMOD** Software [5,6]

The U. S. Environmental Protection Agency (EPA), together with the American Meteorological Society (AMS), developed a new air quality dispersion model called the AMS/EPA Regulatory Model (AERMOD). **AERMOD** is designed to calculate air pollutant concentrations in all types of terrain, from flat prairie to complex mountainous situations. **AERMOD** is a modeling system which contains: 1) an air dispersion model, 2) a meteorological data preprocessor called **AERMET**, and 3) a terrain data preprocessor called **AERMAP**.

##### *1.4.3.1.1 AERMET*

The **AERMET** module is basically a meteorological preprocessor which formulates hourly surface data and upper air data for use in the **AERMOD** short-term air quality dispersion model. **AERMET** was designed to allow for future enhancements to process other types of data and to compute boundary layer parameters with different algorithms.

**AERMET** processes meteorological data in three stages and from this process two files are generated for use with the **AERMOD** model:

- Surface File (*.SFC) : Hourly boundary layer parameters estimates
- Profile File (*.PFL): Multiple-level detection of temperature, wind speed, wind direction and standard deviation of the fluctuating wind components.

Minimum **AERMET** Input Data Requirements :

When preprocessing meteorological data for use with the **AERMOD** model, the following are the minimum data input requirements for **AERMET** View:

- Hourly surface observations of
  1. Wind Speed
  2. Wind Direction
  3. Dry Bulb Temperature
  4. Cloud Cover

#### *1.4.3.1.2 AERMOD*

The AMS/EPA Regulatory Model (**AERMOD**) was specially designed to support the EPA’s regulatory modeling programs. **AERMOD** is a regulatory steady-state plume modeling system with three separate components, namely, **AERMOD**

(**AERMIC** Dispersion Model), **AERMAP** (**AERMOD** Terrain Preprocessor), and **AERMET** (**AERMOD** Meteorological Preprocessor). The **AERMOD** model includes a wide range of options for modeling air quality impacts of pollution sources, making it a popular choice among the modeling community for a variety of applications. **AERMOD** contains basically the same options as the ISCST3 model.

Some of the salient Features of **AERMOD** are:

- **AERMOD** requires two types of meteorological data files, a file containing surface scalar parameters and a file containing vertical profiles. These two files are provided by the U.S. EPA AERMET meteorological preprocessor program.
- PRIME building downwash algorithms based on the ISC-PRIME model have been added to the AERMOD model.
- Use of locatable arrays for data storage.
- Integration of event processing for evaluating short-term source culpability.
- Post-1997 PM10 processing.
- A non-regulatory default TOXICS option that includes optimizations for area sources and the Sampled Chronological Input Model (SCIM) option.
- Clear evaluation of multiple-year meteorological data files including the ANNUAL average.
- Options to specify emissions that vary by season, hour-of-day and day-

of- week.

- For applications involving elevated terrain, the user must also input a hill height scale along with the receptor elevation. The U.S. EPA **AERMAP** terrain preprocessing program can be used to generate hill height scales as well as terrain elevations for all receptor locations.
- Deposition algorithms have been implemented in the **AERMOD** model - results can be output for concentration, total deposition flux, dry deposition flux, and/or wet deposition flux.
- The model contains algorithms for modeling the effects of settling and removal (through dry deposition) of large particulates and for modeling the effects of precipitation scavenging for gases or particulates.
- Two types of files of intermediate results for debugging purposes can be requested: one containing information related to the model results and the other containing gridded profiles of meteorological variables.
- **AERMOD** does not make any distinction between elevated terrain below release height (simple terrain) and terrain above release height (complex terrain).
- **AERMOD** does not support the Open Pit type source.
- The Polar Plant Boundary receptor type is not available in **AERMOD**. A new type of receptor was included, the discrete Cartesian receptors that allows for grouping of receptors, e.g., along arcs. This receptor option was designed to be used with the EVALFILE option which is

described below.

- Two additional output file options were included in **AERMOD**. One type of file lists concentrations by rank (RANKFILE). The other type of output file (EVALFILE) provides arc maxima results along with detailed information about the plume characteristics associated with the arc maximum.

**AERMOD** View

**AERMOD** View is a complete and powerful air dispersion modeling package that seamlessly incorporates the popular U.S. EPA models, ISCST3, ISC-PRIME and AERMOD and related pre- and postprocessors under one integrated interface without any modifications to the models. These models are used extensively to assess pollution concentration and deposition from a wide variety of sources.

**Features:**

- Impressive presentations of the model results can be created with the easy and intuitive graphical interface of **AERMOD** View. User can customize the project using display options such as transparent contour shading, annotation tools, various font options, and specify compass directions.
- Model objects such as sources, receptors and buildings can be specified graphically. After defining an object graphically, user automatically has access to the related text mode lists in which user can further modify parameters.

- Automatic elimination of receptors within the facility property line is possible.
- User can import base maps in a variety of formats for easy visualization and source identification.
- Use of the major digital elevation terrain formats - USGS DEM, GTOPO30 DEM, UK DTM, UK NTF, XYZ Files, CDED 1-degree, AutoCAD DXF is possible.
- User can interpret the effects of topography by displaying model results with 3D terrain using the powerful 3D visualization built right into the interface.
- User can complete building downwash analysis effectively and quickly using the necessary tools that **AERMOD** View provides.
- User can prepare the meteorological data quickly and accurately using the step-by-step meteorological preprocessing interface.
- User can summarize the modeling inputs in professionally designed reports using report-ready formats.
- **AERMOD** View can be used to its full potential and to user's best advantage by accessing context-sensitive "Help that really helps", which provides user with a clear explanation of the modeling requirements.

#### ***1.4.3.1.3 AERMAP***

Regulatory dispersion models applicable for simple to complex terrain situations require information about the surrounding terrain. **AERMOD** does not process its own terrain. A preprocessor program, **AERMAP**, has been developed to process the terrain data in conjunction with a layout of receptors and sources to be used in **AERMOD** control files.

**AERMAP** has been designed

- to process several of the standardized terrain data formats.
- with the expectation that terrain will impact air quality concentrations at each individual receptor. **AERMAP** first determines the base elevation at each receptor and source.
- for complex terrain situations, **AERMOD** captures the essential physics of dispersion in complex terrain and therefore needs elevation data that convey the features of the surrounding terrain. In response to this need, **AERMAP** searches for the terrain height and location that has the greatest influence on dispersion for each individual receptor. This height is the referred to as the hill height scale.
- both the base elevation and hill height scale data are produced by **AERMAP** as a file or files which can be directly inserted into an **AERMOD** input control file.

#### *1.4.3.2. Steps in the development of Air Dispersion Modeling*

To develop an Air Dispersion model, the **AERMOD** View has the following steps, which should be followed in the order provided:

- The Problem
    - This implies the identification of the air pollutants or emission types which will be calculated for this project, the stacks or point sources locations, the amount of each pollutant produced from the point source in grams per second (g/s), and receptors locations.
- Creating an AERMOD View Project
    - This can be accomplished by using the AERMOD View and open a new project as per procedure.
- Defining Buildings
    - To define the buildings located in the premises of the project area. There are three ways to define the location and dimensions of the buildings: a) Graphical Mode, b) Text Mode, and c) Import from an AutoCAD DXF File.
- Defining Stacks
    - By defining the stacks (point sources). This can be done by three ways: a) Graphical Mode, b) Text Mode, and c) Import Mode. If you have a base map of your facility, then it’s more efficient to use the graphical mode and also faster than the text mode.
- 3D View

  - AERMOD View offer two ways to visualize your project in 3D: a) Lakes Environmental 3D Visualization application - 3D View, and b) Exporting to Google Earth ( this requires that you have installed Google Earth in your machine).
- Control Pathway
  - In the Control Pathway the overall job control options are specified such as dispersion options, pollutants, and averaging times.
- Source Pathway
  - The Source Pathway allows you to specify the source input parameters and source group information such as source types, building downwash, and variable emissions.
- Receptor Pathway
  - The Receptor Pathway allows you to specify the receptor locations for a particular run define the number and type of receptors in project, define receptor groups, and flagpole options.
- Meteorology Pathway
  - The Meteorology Pathway allows for the specification of input meteorological data file and other variables, including the period to process the meteorological files.
- Output Pathway
  - The Output Pathway allows you to specify the output

  options for a particular run such as contour plot files and threshold violation files.

- Terrain Processor
    - This step is to specify the digital terrain files that cover the modeling domain and process it using the AERMAP model. In AERMOD View this is done within the Terrain Processor window.
- Running BPIP
    - BPIP(US EPA Building Input Profile Program. After checking the 3D visualization to see if the buildings and stacks were properly defined, it's time to run the BPIP to obtain building downwash calculation results.
- Running the AERMOD Model
    - The project should be complete by completing the above steps. Before running the project, it is suggested to check the status of the project to make sure the options are correct.
- Post-Processing of Results
    - Results from the model run are displayed in the drawing area. The plots tab is added to the tree view after successfully running the module. This tab lists all available plot files generated for the current run, grouped by source group and high value.

- Exporting to Google Earth
    - The software provides a means of exporting to Google Earth program. This is done by selecting the 3D View button followed by selecting Google Earth (from the pop-up menu). The Export to Google Earth dialog is displayed. Then to press the Export button. Google Earth will be automatically launched and it will be easy to visualize the entire project (building, stacks, grids, terrain contours, and concentration contours. To get the exact view in Google Earth, the contour settings in AERMOD View should be adjusted before exporting. Also, it’s possible to control which layers are displayed in Google Earth by unchecking layers in the Places list.
- Comparison of Model Results
    - After obtaining the Ground Level Concentrations on the targeted area and receptors, it is recommended to compare the results with the results or readings of the ambient air monitoring fixed stations in the same area, usually those fixed stations are distributed in the area by the local environmental protection agency of the country.

### 1.4.4 Findings of the Model and Impact Analysis

A detailed analysis of the plume models developed using AERMOD and the impact on the chosen surrounding area is very important and will be studied in detail. This is vital in establishing the facts and would pave the way in bridging the gap between industries and government agencies for the enforcement of effective regulatory mechanisms.

### 1.4.5 Recommendations & Conclusions

The study will go further step in recommending engineering solutions and best practices to reduce the pollutants concentrations which will help in the reduction of human health risks and protect the environment.

The rest of this thesis will be as follows. Immediately following this introduction chapter will be a chapter on review of literature which will detail a collection of previous research carried out in the subject of study.

Chapter 2 will discuss an inventory of emissions related to this study. An inventory is a database that catalogs the air emissions for various pollutants from various sources during a specified time period. The aim is to be able to list and hence prioritize sources of air contaminants.

Chapter 4 will highlight various available air dispersion models and discussing their qualities and limitations. The chapter will then dovetail into the Air Pollution Dispersion Model (AERMOD) utilized in this research. Its properties and use will be discussed including input and output parameters.

Chapter 5 is the results chapter. The results from implementing the AERMOD will be shown and subsequently followed by discussion of the results.

Chapter 6 will do a comparison of the results from the summer and winter data from the three refineries under focus with a view of testing their sensitivity.

Chapter 7 will be the concluding chapter and it will discuss the highpoints from this research and list out some short comings of the research whilst also making recommendations for suture research.

# Chapter 2

# Literature Survey & Emissions from KNPC Specific Sources

## *2.1. Literature Survey*

### 2.1.1 Petroleum Refining

The petroleum industry is organized into four broad sectors: exploration and production of crude oil and natural gas; transportation; refining; and marketing and distribution. This guideline only addresses the petroleum refining sector.

Crude oil is fractionated into liquefied petroleum gas, naphtha (used to produce gasoline by blending with octane boosters), kerosene / aviation turbine fuel, diesel oil, and residual fuel oil. Catalyst cracking and reforming, thermal cracking, and other secondary processes are used to change the chemical composition of straight run fractions into salable products such as fractions or cuts for gasoline or diesel fuel blending. Finishing processes are used to achieve the desired product specifications. Certain refineries also produce feed stocks for the manufacture of lube oils and bitumen. Some refineries also manufacture coke.

### 2.1.2 Emissions Characteristics[32]

Boilers, process heaters, and other process equipment are responsible for the emission of particulates, carbon monoxide, nitrogen oxides ($NO_{x)},$ Sulfur oxides ($SO_{x)},$ and carbon dioxide. Sulfur recovery units combustion units and flares release $SO_{x.}$ Catalytic cracking regenerators release particulates, $NO_x$ and $SO_{x.}$ Catalyst changeovers and cokers release particulates. Volatile organic compounds (VOCs) such as benzene, toluene, and xylene are released from storage, product loading and handing facilities, oil / water separation system, and as fugitive emissions from flanges, valves, seals, and drains. For each ton of crude processed, refineries may emit about:

- 0.8 kg (ranging from less than 0.1 to 3kg ) of particulate matter;
- 1.3 kg of SOx. (ranging 0.2 - 6 kg and 0.1 kg with Claus sulfur recovery process;
- 0.3. kg of NOx (ranging 0.06 - 0.5 kg); and
- 2.5g of BTX (benzene, toluene, xylene) (ranging from 0.75 to 6) and 1g with Claus sulfur recovery process.

From the outlined quantities, about 0.14g of benzene, 0.55g of toluene, and 1.8g of xylene may be released per ton of crude processed.

VOC emissions depend upon the production techniques, emission control techniques, equipment maintenance, and climate conditions and may be 1 kg per ton (with a range of 0.5 to 6 kg/t of crude processed.

Petroleum refineries use relatively large volumes of water especially for cooling systems. Surface water runoff, and sanitary wastewaters are also generated. The quantity of wastewaters generated and its characteristics depend on the process configuration. As a general guide, approximately 3.5-5 $m^3$ of wastewater per ton of crude is generated when cooling water are recycled. Refineries generate polluted wastewaters, containing BODs and COD levels of approximately, 150-250 mg/L and 300-600 mg/L, phenol level 20-200 mg/L; oil levels of 100 to 300 mg/L in Desalters water and up to 5,000 mg/L in tank bottoms; benzene levels of

1 to 100 mg/L benzopyrene level of less than 1 to 100 mg/L, heavy metals (chrome and lead levels of 0.1-100 and 0.2-10 mg/L respectively), and other pollutants. The refineries also generate solid wastes and sludge (with a range of 3-5 kg per ton of crude processed), 80% of which may be considered hazardous because of the presence of toxic organics and heavy metals.

Accidental discharge of large quantities of pollutants can occur as a result of abnormal operation in a refinery and potentially pose a major local environment hazard.

### 2.1.3 Pollution Prevention and Control

Petroleum refineries are complex plants, where the combination and sequence of processes is usually very specific to the characteristics of the raw materials (crude oil) and the products. Specific pollution prevention or source reduction measures can often only be determined by the technical staff. However, there are a number of broad areas where improvements are often possible and site specific waste reduction measures in these areas should be designed into the plant and targeted by management of operating plants. Areas where efforts should be concentrated include:

### 2.1.4 Reduction

- Minimize losses from storage tanks and product transfer areas by methods such as vapor recovery system and double seals.
- Minimize sulfur oxide emissions by either desulfurization of fuels (to the

extent feasible) or directing the use of high sulfur fuels to units equipped with sulfur oxide emission controls.

- Recover sulfur from tail gases in high efficiency sulfur recover units.
- Recover non silica based (i.e., metallic) catalysts and reduce particulate emissions.
- Use low NOx burners to reduce NOx emissions
- Avoid and limit fugitive emissions by proper process design and maintenance.
- Maintain fuel usage to a minimum.

### 2.1.5 Target Pollution Loads

Implementation of pollution prevention measures can provide both economic and environmental benefit. However, a balance on energy usage and environmental impacts may have to be arrived at. The following production-related targets can be achieved by measures such as those detailed in the previous section. The values relate to the production processes before the addition of pollution control measures.

New refineries should be designed to maximize energy conservation, and reduce hydrocarbon losses. A good practice target for simple refineries (i.e. refineries with distillation, catalytic reforming, hydrotreating and off-site facilities) is that the total quantity of oil consumed as fuel and lost in production operations should not exceed 3.5% of the throughput. For refineries with secondary conversion units (i.e., hydrocrackers, lube oil units, the target should be 5 to 6% (and in some cases, up to 10%) of the throughput. Fugitive VOC emissions from the process units can be reduced to 0.05% of the throughput with total VOC emissions of less than 1 kg/ton of crude (or 0.1% of the throughput). Method of estimating these figures include emissions monitoring, mass balance, and inventories of emissions sources. Design assumptions should be recorded to allow for subsequent computation and reduction of losses. Vapor recovery system to control losses of $VOC_s$ from storage tanks and loading areas should achieve 90 to 100% recovery.

Plant operator should aim at using fuel with less than 0.5% sulfur (or an emission level corresponding to 0.5% sulfur in fuel.) High sulfur fuels should be directed to units equipped with sulfur oxide controls. Fuel blending is another option. A sulfur recovery system with at least 97 percent but preferably over 99% sulfur recovery should be used when the hydrogen sulfide concentration in tail gases exceeds 230 $mg/Nm^3$. The total release of sulfur dioxide should be below 0.5 kg/ton for a hydro skimming refinery and below 1 kg/ton for a conversion refinery.

A wastewater generation rate $0.4m^3/t$ of crude processed is achievable with good design and operation and new refineries should achieve this target as minimum. The generation rate of solid wastes and sludge should be less than 0.5% of the crude processed and should aim for 0.3%.

## 2.1.6 Treatment Technologies

### 2.1.6.1 Air Emissions

Control or air emission normally includes the capturing and recycling or combustion of emission from vents, product transfer points, storage tanks, and other handling equipment. Boilers, heaters, other combustion devices, cokers, and catalytic units may require particulate matter controls. Carbon monoxide boilers are normally a standard practice in fluidized catalytic cracking units. Catalytic cracking units should be provided with particulate removal devices. Steam injection in flaring stacks can reduce particulate matter emissions.

### 2.1.6.2 Emission Guidelines

Emission levels for the design and operation of each project must be established through the Environmental Assessment (EA) process, based on country legislation and the Pollution. The following guidelines present emission levels normally acceptable to the World Bank Group in making decision regarding provision of World Bank Group. The guidelines are shown as concentrations to enable monitoring. Dilution of air emissions or effluents to achieve these guidelines is unacceptable. All of the maximum level should be achieved for at least 95% of the time that the plant or unit is operating, to be calculated as a proportion of annual operating hours.

The following emissions levels should be achieved:

**Table 2.1: Emissions from the Petroleum Industry**

| **Maximum value milligrams per normal Cubic meter (mg/Nm$^3$)** | **Parameter** |
|---|---|
| 50 | Particulate matter (PM) |
| 460 | Nitrogen oxide |
| 150 for sulfur recovery units and 500 for other units | Sulfur oxide ($SO_x$)* |
| 2 | Nickel and Vanadium (combined) |
| 15 | Hydrogen sulfide |

- Excluding $NO_x$ emission from catalytic units.

### 2.1.7 Monitoring and Reporting

Frequent sampling may be required during start-up and upset conditions. Once a record of consistent performance has been established, sampling for the parameters listed above should be as detailed below.

Air emissions from stacks should be monitored once every shift not continuously for opacity (a maximum level of 10%). Air emission of hydrogen sulfide from a sulfur recovery unit should be monitored on a continuous basis. Annual emissions monitoring of combustion sources should be carried out for $SO_x$ (sulfur content of the fuel with monitored on a supply tank basis) and $NO_x$.

Liquid effluents should be monitored daily for all the parameters citied above except for metal which should be monitored on at least a monthly basis.

Monitoring data should be analyzed and reviewed at regular intervals and compared with the operating standards so that any necessary corrective actions can be taken. Records of monitoring results should be kept in an acceptable format. These should be reported to the responsible authorities and relevant parties, as required.

### 2.1.8 Control Practices

The following issues summarize the key production and control practices that will lead to compliance with emissions guidelines.

- Use vapor recovery system to reduce VOC emissions.
- Install sulfur recovery system, where feasible.
- Use low NOx burners.
- Maintain fuel and losses to 3.5% for simple refineries and below 6% (with 10% as maximum) for refineries with secondary processing.
- **Cap-and-trade system**[33]
    - Cap-and-trade system is a form of trading that sets a cap on emissions from companies and industries in an area and lets them trade emissions authorizations. One option that might facilitate reduced emissions could be to increase the levy as high as the estimated marginal abatement costs. Nashina Shariff (June 2011) discussed about this in a policy brief on Sustainable Prosperity.
    - Emissions' trading is likely considered to be an attractive tool for

emissions control and environmental management, mostly in countries where a high pollution reduction goals are set that necessarily would include making major new pollution control investments.

- No environmental regulatory program works without a system to safeguard compliance. A strong compliance program has several features, all of which are designed to ensure that emission sources will comply with rules and be treated fairly through fixed procedures that are transparent, clear and consistently applied. A number of environmental technical programs should be planned to help manage disputes and to encourage industries to comply with the rules.

- It is useful to review the experience of the successful $SO_2$ trading program in the United States. The U.S. program was followed by years of theoretical and empirical analyses of suitable design features for a trading program, as well as more than 10 years of experiments with less sophisticated market-based tools. While the experiments at the U.S. EPA with offsets and other forms of economic incentives had only limited success, the lessons fed directly into a political debate over how to reduce $SO_2$ emissions of existing power plants—a debate that in 1990 led to the creation of the $SO_2$ Allowance Trading Program in the Clean Air Act Amendments. This was followed by a four-year lead-in period in which the U.S. EPA wrote implementing regulations using notice-and-comment rulemaking procedures that required extensive solicitation of public views, followed by the formal establishment of the emissions trading program. The U.S. program was built on an existing, well-established regime for environmental enforcement. Such a regime needs to be investigated in Kuwait or maybe in the Arabian Gulf Area.

- Also, it is proposed to develop and demonstrate various computer-based tools; most of the tools exist at KNPC to facilitate to manage the allowances (Emissions Tracking and Allowance Tracking Systems) between the three refineries, as an example for a bigger country wide program.
- All these will help in the reduction of human health risks and protect the environment in Kuwait.

### 2.1.9 Environmental Legislation

Kuwait Environment Public Authorities was established 1995, and the regulations came into 2001. Before 1995 Shuaiba Area Authority regulations were enforce, current limitations are provided in the following tablets.

**Table 2.2: Kuwait EPA Standards for Ambient Air Quality in Residential Areas**

**(in part per billion (ppb))**[27]

(Gazette No. 533 Dt. 2/10/2001 Official Magazine, State of Kuwait)

| **Annual** | **24-Hous** | **8-Hours** | **1-Hours(1)** | **Pollutant** | **Sr. No.** |
|---|---|---|---|---|---|
| **Ppb** | **Ppb** | **ppb** | **ppb** | | |
| 30 | 60 | - | 170 | $SO_2$ | 1 |
| 6 | 30 | - | 140 | $H_2S$ | 2 |
| 30 | 50 | - | 100 | $NO_2$ | 3 |
| - | 8000 | 10000 | 30000 | CO | 4 |
| - | - | 60 | 80 | $O_3$ | 5 |
| 140 | - | - | 800(3) | $NH_3$ | 6 |
| One tenth (1/10) of the indoor limit or 0.24 ppm for period of 3 hours from 6.00-9.00 AM | | | | NMHC* | 7 |
| 90 | 350 | - | - | SPM(PM-10) ($\mu g/m^3$) | 8 |
| 7.5 Tons/Km$^2$ | - | - | - | Dust Fall | 9 |
| 1.5 | - | - | - | Lead<br>($\mu g/m^3$) | 10 |
| - | 0.01 ppm | - | 0.03 ppm<br>(for 30 min) | Chlorine | 11 |

**Note:**

Not to be exceeded more than twice within 30 days at same site

Not to be exceeded more than once within one year.

Not to be exceeded more than once during a year.

*NMHC: Non-Methane Hydrocarbons.

## Table 2.3: Kuwait EPA Standards for Emissions from Fixed & Moving Sources[27]

(Gazette No. 533 Dt. 2/10/2001 Official Magazine, State of Kuwait)

| **Max. allowed emissions** | **Pollutant** | **Source** |
|---|---|---|
| **Fixed Source** | | |
| **1. All Industrial Facilities** | | |
| Darkness level should not exceed 20 %( max. Limit). | Particulate | 1.1 All emission sources |
| No emissions are allowed. | Asbestos | |
| Darkness level should not exceed 20 %( max. Limit) 115 mg/m3. | Particulate | 1.2 Stacks of products |
| Darkness level must not exceed 20 %( max. l Limit) | Particulate | 1.3 Stacks |
| **2. Facilities Operated by Combustion** | | |
| 43 Nano grams/Joule | Particulate | Fossil fuel Boilers and Furnace with heat energy input more than 30 MW(100 MBTU/hr) |
| 512 Nano grams/Joule | 0 | |
| 86 Nano grams/Joule facilities burning natural gases | $NO_X$ | |
| 130 Nano grams/Joule facilities burning fuel oil | $NO_X$ | |
| Should not exceeded more than 20 %(max. limit) | Darkness | |
| **3. Petroleum Refineries** | | |
| 1.0 Kg/metric ton coke burn off | Particulate | 3.1 FCC Unit |
| 9.8 Kg/metric ton per coke burn off | 0 | (With incinerator or waste heat boiler) |
| 500 ppm ( volume) | CO | 3.2 Fuel gas combustion |
| 30% except 6 minutes per hour | Darkness | 3.3 Claus Unit for Sulfur recovery and capacity exceeding 20 T/day. |
| 230 mg/m3 dry measurement | $H_2S$ | |
| 250 ppm with oxidation or reduction and incineration. | 0 | |

In India, Environmental legislation dates back to 1853, when the Shore Nuisance (Bombay and Colaba) Act came into being. Subsequently, the Bengal Smoke

Nuisance Act-1905, Orissa River pollution Act-1953, Gujarat Smoke Nuisance Act-1963 and Maharashtra prevention of pollution Act-1969 came into effect. However, countrywide regulatory mechanism for control of pollution came into effect in real sense with the enactment of water (Control and prevention of pollution) Act in 1974. Under the provisions of this act, pollution Control Boards were formed in the Central and the State which laid down standards for discharge of effluent from industries. In 1977 the water Cess Act came into being with something similar to the “polluter pay” principle, whereby Cess collect could be utilized by the SPCBs. In 1981, the Air (Control and prevention of pollution) Act was passed.

Subsequently, in 1986, the Environment (protection) Act was passed giving wide-ranging powers to the Ministry of Environment and Forests (MOEF), Govt. of India to implement measures for environment protection in the country. The rules and standards notified by the Ministry of Environment and Forest (MOEF) under this act covers all aspects of environmental management including water, air noise, hazardous wastes and chemicals, procedures for environmental clearance for projects etc.

Environmental management in India Industry is governed by the rules and standards notified under all the above four acts apart from the Factories Act-1948. In 1987 this act was revised which includes stipulation for occupational health and standards.

In the USA, the Clean Air Act – 1963, the Clean Water Act and the Resource Conservation and Recovery Act-1976 govern the environment protection regulations. Besides, the Occupational Health and Safety Administration (OSHA) laid down the Occupational Health related standards.

The US Environment Protection Agency (EPA) was established in 1970, the same year when the first Clean Air Act Amendment was passed. The EPA in USA is the federal regulatory agency which is akin to MOEF in India. The MOEF is assisted by CPCB in formulating rules and standards. Similarly, individual US States are having regulatory agencies to oversee the implementation of federal regulations as is being done by State Pollution Control Boards in India for implementation of notified standards. It is pertinent to note that in both the countries the State Regulatory agencies/SPCBs can formulate more stringent rules and standards, but are not empowered to relax those fixed by the EPA/MOEF, as the case may be.

#### 2.1.9.1 Ambient Air Quality Standard

In India, as well as the USA, maintenance of ambient air quality within the laid down standard is the responsibility of State regulatory agencies. The major control strategies are fixing of emission limits from industries and operations and relocations of residential, commercial or industrial facilities. In the USA simulations models are used extensively to predict air quality due to future development in a particular area and accordingly formulate plants for maintenance of ambient air quality. This approach was first applied in India in late 70’s in connection with setting up of Mathura Refinery. Dispersion modeling studies were carried out by M/s India Metrology Dept. as well as M/s Techneco of Italy to predict impact of the refinery emission on the Taj Mahal located in Agra 40 km south east of Mathura. Similar studies are now carried out for major project in the country. The Indian and US ambient air quality standards are given in table.

**Table 2.4: Indian and US ambient air quality standards**

| Concentration, micro gm/m$^3$ | | | | Pollutant |
|---|---|---|---|---|
| Indian Standards | | | US Standards | |
| Sensitive Area | Residential & Rural Area | Industrial Area | | |
| | | | | $SO_2$ |
| 15 | 60 | 80 | 80 | Annual Avg. |
| 30 | 80 | 120 | 365 | 24 Hrs |
| - | - | - | 1300 | 3 Hrs |
| | | | | $NO_X$ as $NO_2$ |
| 15 | 60 | 80 | 100 | Annual Avg. |
| 30 | 80 | 120 | - | 24 Hrs |
| | | | | SPM |
| 70 | 140 | 360 | - | Annual Avg. |
| 100 | 200 | 500 | - | 24 Hrs |
| | | | | RPM( $PM_{10}$) |
| 50 | 60 | 120 | 50 | Annual Avg. |
| 75 | 100 | 150 | 150 | 24 Hrs |
| | | | | Lead |
| 0.5 | 0.75 | 1 | - | Annual Avg. |
| 0.75 | 1 | 1.5 | - | 24 Hrs |
| - | - | - | 1.5 | Quarterly Avg. |
| | | | | CO |
| 1000 | 2000 | 5000 | 10000 | 8 Hrs. |
| 2000 | 4000 | 10000 | 40000 | 1 Hr. |
| | | | | Ozone |
| - | - | - | 235 | 1 Hr |

Compliance requirement for the US air quality standards are as follows:

- Continuous monitoring with laid down quality assurance procedure
- PM10 to be done every 6th day in the year.
- Ozone to be done during summer months only
- Minimum 80% (75% for NO2) valid hourly/24 hourly data for averaging periods of 24 hours/annual average
- Maximum (Short-term i.e. 1 hour/8 hours/24 hours) concentration not to exceed more than once a year

Compliance requirement of Indian standards are as follows:

- Minimum 104 measurements in a year taken twice in a week 24 hours for annual average
- 24 hourly/8 hourly values should be met 98% of the time. However, 2% of the time it may exceed but not in two consecutive readings

It may be seen that Indian ambient air quality standards are more stringent than the US standards.

### 2.1.9.2 Stack Emission Standard

The stack Emission standards for refinery units in India and the USA are as given in the following table:

**Table 2.5: Stack emission standards for Indian & USA refinery**

| Indian standard | US standard | Pollution | Emission Source |
|---|---|---|---|
| 0.25 kg $SO_2$/MT feed in Distillation unit stack. | Max.230 mg/dscm $H_2S$ in gas ( 0.018% wt.) | $SO_2$ | Fuel gas Combustion Device (Furnace / Boiler / Flares) |
| $H_2S$ in desulfurized traces. Natural Gas in India also contains negligible amount of $H_2S$. | | | |
| 1.0% vol max. in flue gas (as per general Emission Standard.) | 0.05% vol max in flue gas | CO | FCCU |
| 150 mg/NM$^3$ in flue gas (as per General Emission Standard) | 1.0 kg/MT coke burn off | Particulate Matter | |
| 2.5 kg/MT feed equivalent to 55 kg/MT coke burn off assuming 4.5% coke yield. | 9.8 kg/MT coke burn off | $SO_2$ | |
| | Or | | |
| | Feed sulfur 0.3% max. | | |
| 120 kg/MT in feed equivalent to 94% conversion efficiency in SRU. | 0.025% vol in flue gas equivalent to over 99.5% efficiency. | $SO_2$ | SRU |

The refineries in the USA use Natural Gas predominantly in the process furnaces along with desulfurized refinery fuel gas. In India however, all refineries except Digboi refinery use refinery fuel gas along with oil in its furnaces. While at Mathura refinery low sulfur fuel oil (less than 0.5% S) obtained from processing BH or other low S crudes is used, refineries like Haldia has to use high S fuel oil in its furnaces due to processing of only high S imported crude.

In case of boilers the Indian standard ( re: Notification no GSR 422 (E) dt. 19.5.94 and its amendment no. GSR 801 (E) dt 31.12.94 is in terms of stock height based on steam generating capacity or by using a stack height formula (height, m=14 * ($SO_2$ emission, kg/hr) to the power 0.3) if steam generation capacity is greater than 30 MT/hr.

**Table 2.6: The US standard for boilers on liquid fuel firing :( ref: 40 CFR Ch. (part 60 sub-part Db July'90)**

| | |
|---|---|
| Max 10% of potential theoretically calculated emission (i.e. 90% reduction) and not exceeding the limit of 340 Nano gram/joule ( 1.42 kg/mil kcal) of heat input. In case very low S fuel oil is used (S = 0.5 Max), percent reduction limit is not applicable and $SO_2$ emission should not exceed 215 Nano gram/joule of (0.90 kg/mil kcal) heat input. | $SO_2$ |
| 170 Nano gram/joule (0.71 kg/mil kcal) of heat input for high heat release residential fuel oil. | $NO_X$ |
| 86 Nano gram/joule ( 0.36 kg/mil kcal) of heat input in case of high heat release natural gas or distillate oil. | |
| 43 Nano gram/joule (0.018 kg/mil kcal) of heat input | SPM |

### 2.1.9.3 World Bank and pollutant Standard

On a benchmark with the maximum emission levels defined in the guidelines set out by the World Bank for all new refinery projects. For all, significant pollutants are not regulated by the World Bank. These levels are presented in the table.

**Table 2.7 World Bank benchmark for emission levels**

| Maximum emission levels<br>In mg/Nm$^3$ to 15% dry $O_2$) | Pollutant |
|---|---|
| 500 (note-1)<br>150 for desulfurization equipment | $SO_2$ |
| 460 | $NO_X$ (expressed as $NO_2$) |
| 50 | Particulate matter |
| 150 (note-2) | VOCs except methane |
| 50 (note-2) | $NH_3$ |
| 2 | Nickel and Vanadium |

(note-1): this level can be adapted to local conditions, provided it is justified by a risk analysis in the impact review.

(note-2): level defined in the order of Feb. 2nd 1998, governing ICPEs (classified installations for the protection of the environment) which are regulated.

**Table 2.8 Maximum concentration levels defined by WHO guidelines**

| Average over: | Maximum level (µg/m$^3$) | Pollutant |
|---|---|---|
| 15 minutes | 100,000 | CO |
| 30 minutes | 60,000 | |
| 1 hour | 30,000 | |
| 8 hours | 10,000 | |
| 1 hour | 200 | $NO_X$ |
| I year | 40 | |
| 8 hours | 120 | Ozone |
| 10 minutes | 500 | $SO_2$ |
| 24 hours | 125 | |
| I year | 50 | |

Maximum concentration levels defined by World Bank guidelines

| Average over | Maximum level(µg/$m^3$) | Pollutant |
|---|---|---|
| 1 year | 50 | Particulate matter |
| 1 day | 70 | |
| 1 day | 150 | $NO_X$ |

### Table 2.9: Impact factor – Atmospheric emissions – Summary

| Best practice criteria | Target criteria | Reference criteria |
|---|---|---|
| Compliance with the following specific flows: | Compliance with maximum emission levels set by French legislation for VOCs and $NH_3$. | Compliance with maximum emission levels defined in the World Bank guidelines. |
| $SO_2$ < 0.2 kg/t of crude | Modeling survey of impact on air quality. | Assessment of fugitive VOC emission in order to minimize them whenever feasible |
| $NO_X$< 0.15 kg/t of crude | Compliance with maximum air concentration levels set by the WHO and World Bank. | Regular monitoring of the emission of pollutions |
| Avoidance of burning in flaring stacks and recovery of gases when possible. | | |

### Table 2.10: Kuwait EPA Ambient Air Quality Standards for Residential Areas (in mg/$m^3$)[27]

| Year | Day** | 8 hours | 1 hour* | Pollutant |
|---|---|---|---|---|
| mg/$m^3$ | mg/$m^3$ | mg/$m^3$ | mg/$m^3$ | Unit |
| 80 | 157 | - | 444 | Sulfur Dioxide ($SO_2$) |
| 8 | 40 | - | 200 | Hydrogen Sulphide ($H_2S$) |
| 67 | 112 | - | 225 | Nitrogen Dioxide($NO_2$) |
| - | 9000 | 11500 | 34000 | Carbon Monoxide(CO) |
| - | - | 120 | 157 | Ozone ($O_3$) |

| | | | | |
|---|---|---|---|---|
| 148 | - | - | 850 | Ammonia (NH3) |
| 1/10 from specified rate in works environment (TLV's). | | | | Hydrocarbon Compound without Methane |
| 90 | 350 | - | - | Suspended Particulate Matter(PM-10) |
| 7.5 Ton/$Km^2$ | - | - | - | Dust Fall out Matter |
| 1.5 | - | - | - | Lead |
| - | 30 | - | 100 | Chlorine |

### 2.1.10 Air Dispersion Models:

Air dispersion models are computer programs that use mathematical algorithms to simulate how pollutants and species like $SO_X$, $NO_X$, CO, $CO_2$ etc. in the ambient air atmosphere are disperse.

Many of the dispersion models are developed by U.S. Environmental Protection Agency (EPA), some dispersion models are developed by others but accepted by U.S. Environmental Protection Agency (EPA), those dispersion models are accepted for use in many other countries as well. Those EPA models are categorized into four groups:

#### 2.1.10.1 The recommended and preferred models:

**AERMOD** – This atmospheric dispersion model based on atmospheric boundary layer turbulence structure and scaling concepts, it includes multiple ground-level and elevated points, sources such as area, volume and line sources. It can handle complex or flat, urban or rural terrain and also includes algorithms for building effects and plume penetration of inversions aloft. It uses Gaussian dispersion for low turbulence i.e. stable atmospheric conditions, and non-Gaussian dispersion for unstable conditions (high turbulence). The module includes Algorithms for plume depletion by wet and dry deposition. It took 14 years to develop this model before accepting it officially by U.S. EPA.

**CALPUFF** – It's a non-steady-state dispersion model that simulates the effects of space and time, meteorological conditions on pollution transformation, transport and removal. CALPUFF can be applied for complex terrain and for long-range transport.

**BLP** – It's an air dispersion model based on Gaussian plumes designed to handle specific modeling problems which arise from industrial sources related to downwash and plume rise effects from stationary line sources.

**CALINE3** – A steady-state dispersion model based on Gaussian dispersion, it determines pollution concentrations at receptors located downwind of highways which are in relatively simple and uncomplicated terrain.

**CAL3QHC** and **CAL3QHCR** – The CAL3QHC is simply a CALINE3 based model with series calculations and a traffic model designed for calculating delays and queues that occur at intersections. CAL3QHCR is an advanced dispersion model built on CAL3QHC which needs meteorological data.

**CTDMPLUS** – It's a Complex Terrain Dispersion Model (CTDM) using algorithms suitable for unstable situations means turbulent atmospheric conditions. It is an advanced Gaussian air dispersion model based on point source to be used in all stability conditions including all conditions of atmospheric turbulence.

**OCD** - Offshore and Coastal Dispersion Model (OCD), it’s a Gaussian dispersion model established to determine the effect of offshore emissions from line or area or point sources on the quality of the air in the coastal areas.

#### 2.1.10.2 Alternative models:

**ADAM** – It's an air Force Dispersion Assessment Model (ADAM), a Gaussian dispersion model which includes the effects of heat transfer, thermodynamics, aerosol loading, chemistry, and dense gas.

**ADMS-3** – It's an atmospheric Dispersion Modeling System (ADMS-3), it is a dispersion model which is advanced and developed to calculate concentrations of pollutants produced either continuously from volume, area, line, and point sources, or individually from point sources.

**AFTOX** – It's a dispersion model based on Gaussian plumes that deals with puff or continues gas or liquid, surface or elevated emissions from area or point sources.

**SLAB** – It's a model for dense releases which are denser-than-air gaseous plume releases, it utilizes the one-dimensional equations of momentum, conservation of energy and mass, and the equation of state. SLAB accepts point source from ground-level releases, releases from volume sources, jet releases which are elevated, and emissions produced from volatile liquid compounds.

**DEGADIS** - Dense Gas Dispersion (DEGADIS), this model deals with flat and level terrain and it simulates the dispersion at ground level of area source vapors of denser-than-air gases which has zero momentum into the atmosphere.

**HGSYSTEM** - A group of computer programs made by Shell Research Ltd. and designed to calculate the dispersion produced from chemical releases accidently emphasizing on the dense behavior of gases.

**HOTMAC** and **RAPTAD** - These models are used for complex terrain, coastal regions, urban areas, and around buildings where other modules fail. HOTMAC is a model used for weather forecasting in combination with RAPTAD which is considered a puff dispersion model.

**HYROAD** - The Roadway Model simulating the dispersion of gas pollutant emissions from vehicular traffic. It’s a puff dispersion module that calculates concentrations of gaseous pollutants like carbon monoxide (CO) and particulate matter (PM) produced from vehicle emissions within 500 meters of the roadway intersections.

**ISC3** – It’s a model based on Gaussian dispersion modeling and consider long-term and short-term modes. It’s used to predict the concentration of pollutants which are produced from variety of sources related to industries. This model deals with point, area, line, and volume sources and has limited terrain adjustment.

**OBODM** – It’s a model for evaluating the impacts on air quality of the open burning and detonation (OB/OD) of obsolete weapons and solid propellants. It uses dispersion and deposition algorithms taken from existing models to predict the transport and dispersion of pollutants emitted by the open burning and detonation different operations.

**PLUVUEII** – It's a model that predicts the degradation of the atmospheric visibility and atmospheric discoloration produced by plumes occasioning from the emissions of sulfur oxides, particles and nitrogen oxides. The model cover single or area source and it estimates the dispersion, chemical reactions, transport, optical effects and surface deposition of gas emissions.

**SCIPUFF** – It's a puff dispersion model that uses a group of Gaussian puffs to estimate three-dimensional, time-dependent pollutant concentrations. In addition to the average concentration value, this model predicts the statistical difference in the concentrations resulting from the effect of random variations of the wind.

**SDM** - Shoreline Dispersion Model (SDM) is a dispersion model based on Gaussian plumes used to estimate pollutants ground-level concentrations produced from tall stationary point source emissions near a shoreline.

#### 2.1.10.3 Screening models:

These models are often used before applying an advanced air dispersion model to decide if advanced modeling is required.

**AERSCREEN** – It's considered the screening version of AERMOD. It produces approximations of pollutants concentrations, without using the meteorological data. This model is under development and is not released to be used by public.

**CTSCREEN** – It’s the screening version of CTDMPLUS.

**SCREEN3** – It’s the screening version of ISC3.

**TSCREEN** - Toxics Screening Model (TSCREEN) is a Gaussian based model to screen air pollutant emissions which are toxic and their dispersion from possible releases. It contains 3 modules: RVD (Relief Valve Discharge), SCREEN3 and PUFF.

**VALLEY** – It’s a screening, complex terrain using Gaussian dispersion model for predicting annual or 24-hour concentrations produced from up to 50 point and area emission sources.

**COMPLEX1** – it’s a model deals with a multiple point sources with terrain adjustment that uses the plume impaction algorithm of the VALLEY model.

**RTDM3.2** - Gaussian Rough Terrain Diffusion Model (RTDM3.2) for predicting ground-level concentrations of one or more point sources in rough (or flat) terrain.

**VISCREEN** - A model that estimates the specified emissions impact related to specific transport and dispersion conditions.

#### 2.1.10.4 Photochemical models:

Photochemical models for air quality are widely utilized tools for measuring the effectiveness of the strategies used to control pollution which are adopted by regulatory agencies. These are large-scale air quality models that simulate the pollutant concentrations changes in the atmosphere by identifying the chemical and physical characteristics of processes in the atmosphere. These models are applied in a large scale ranging from local and regional to national and global.

**Models-3/CMAQ** – This model has state-of-the-science capabilities, it's considered the latest version of the Community Multi-scale Air Quality (CMAQ) model and it's used for conducting urban to regional scale simulations of various air quality issues, including toxics, visibility degradation, acid deposition, fine particles, and tropospheric ozone.

**CAMx** – It's an air quality Model but a Comprehensive model with extensions which simulates air quality over various geographic scales. It handles a range of inert and chemically active pollutants, including particulate matter, ozone, mercury, inorganic and organic PM2.5/PM10, and other toxics.

**REMSAD** – It's the suitable Regional Modeling System developed manly for Aerosols and Deposition, it is capable to estimates the concentrations of inert substances as well as the chemically reactive pollutants. This is done by simulating the atmospheric processes which affect pollutant concentrations in regional scales. The pollutants or processes as particulate matter is considered a regional processes, processes relevant to regional haze and other pollutants including mercury and soluble acidic components.

**UAM-V** – It's an urban air quality model and was widely used in 1970s for air quality studies focusing on ozone.

#### 2.1.10.5 Other models developed in the United States:

**PUFF-PLUME** - It was first developed by the Pacific Northwest National Laboratory (PNNL) in the 1970s and considered a Gaussian chemical and radionuclide dispersion model. It includes wet and dry deposition and it handles a real-time input of meteorological observations and forecasts, dose estimates from inhalation and gamma shine.

**Puff model** – It was developed at the University of Alaska Fairbanks. Puff is a volcanic ash tracking model. The ash particles are initiated at the volcano's location and then allowed to advent, diffuse, and settle within the atmosphere. The model can locate the particles at any time after the eruption and can be viewed.

**ADMS-3** – It was explained above and it belongs to the Alternative Models section of the models accepted by the U.S. EPA.

**ADMS-URBAN** – It's a dispersion model for simulating the dispersion on scales ranging from a street scale to county-wide scale, its capable to handle most related emission sources such as industrial, traffic, commercial, and domestic sources. This model is used for air quality management and assessments of current and future air quality vis-a-vis national and regional standards in Europe and other countries.

**ADMS-Roads** - A dispersion model for simulating plumes of the pollutant emissions produced from vehicles using small road networks in combination with emissions from industrial plants. It deals with multiple road sources as well as multiple point, area or line emission sources. The basis of this model is similar to the other ADMS bases.

**ADMS**-Screen - A screening model for fast assessment of the impact on air quality from a single industrial stack to decide if more thorough modeling is needed. It requires minimal input data and combines the dispersion modeling algorithms of the ADMS models with a user interface.

**GASTAR** - A model for simulating releases produced accidently of denser-than-air toxic and flammable gases. It deals with continuous releases as well as instantaneous releases. The source of releases could be jet sources or evaporation of volatile liquid pools, the model accepts ground roughness, variable terrain slopes, it handles difficult situation such as buildings and fences, and even time-varying releases.

**NAME** - Numerical Atmospheric-dispersion Modeling Environment, this model has a large scale from local to global and it was developed at UK. It is an integrated model, this model includes boundary layer dispersion modeling It can be used for: air quality forecasting, dispersion of air pollution, and acid rain; it can track radioactive emissions and ash discharged from volcanoes; it can analyze the accidental air pollutant releases and help to take decision in emergency response by its assessment; it helps in doing analysis of long-term environmental impact.

**UDM** - Urban Dispersion Model, it is a puff Gaussian model for estimating the atmospheric pollutants dispersion in a limited range from 10m to 25 km in the urban environment area. It is developed for the UK Ministry of Defense by the

Defense Science and Technology Laboratory. It handles variety of releases including instantaneous, continuous, and pool releases, gases, liquids, and particulates. The model has a three system arrangement: that of single building where area density is less than 5%, urban areas where area density is more than 5% and open areas. The model can be joined with the SCIPUFF which is the US model to extend the prediction range of the model and to replace the open system.

#### 2.1.10.6 Models developed in Europe:

The European Topic Centre on Air and Climate Change is part of the European Environment Agency (EEA) and it has an online Model Documentation System (MDS). This system includes information and descriptions for all the dispersion models which been developed by European countries. In September 2010 the MDS contain about 140 models developed in Europe (excluding the United Kingdom). Some of those 140 models are mentioned below.

Many of the models include a pre-processor module for the input of meteorological and other data, and many also include a post-processor module for graphing the output data and/or plotting the area impacted by the air pollutants on maps.

The country of origin is included for the each of the European models listed below.

**AEROPOL (Estonia)** - The AERO-POL model is a Gaussian plume dispersion model developed for simulating the dispersion of continuous, buoyant plumes from fixed point, area and line sources. It handles flat terrain on a local to regional scale. It includes plume depletion by wet and/or dry deposition. It handles also the effects of buildings.

**ATSTEP (Germany)** – it's a Gaussian Puff Dispersion and Deposition model used mostly in RODOS which is the decision support system (Real-time On-line Decision Support) for management of nuclear emergency. RODOS is operational in Germany and test-operational in many other European countries.

**AUSTAL2000 (Germany)** - This air dispersion model is used for industrial sources emissions by the German Federal Environmental Agency. It handles area, line, point and volume sources of plumes. It can handle also building effects, simple and complex terrain, plume depletion by dry or wet deposition.

**BUO-FMI (Finland)** - This model was developed for the emissions from fires in warehouses and chemical stores by the Finnish Meteorological Institute (FMI) and its specifically for estimating the atmospheric dispersion of neutral or buoyant plume gases and particles produced from the previous mentioned fires. It is a hybrid of two models the first one is a local scale Gaussian plume model and the another model type. Depletion of Plumes is based on dry deposition in this model but wet deposition is not included.

**CAR-FMI (Finland)** - This model is specially for estimating chemical transformation and atmospheric dispersion of emissions produced from vehicles of inert gases (NOx, CO) and reactive gases($O_3$,NO, $NO_2$) from a road network of line sources on a local scale and it was developed by the Finnish Meteorological Institute (FMI). It is a typical Gaussian line source model which includes an analytical solution for the chemical cycle $NO-O_3-NO_2$.

**CAR-International (The Netherlands)** – this model is for calculation of Air pollution from Road traffic(CAR-International), it's an atmospheric dispersion model and it's developed by the Netherlands Organization for Applied Scientific Research. It simulates the dispersion of emissions produced from vehicles in roadway traffic.

**DIPCOT (Greece)** - Dispersion over Complex Terrain, this model simulates the dispersion of plumes from multiple point sources over complex terrain. It is a model developed in the National Centre of Scientific Research "DEMOKRITOS" of Greece and it handles a local to regional scale but it does not include wet deposition only dry deposition, it does not handle chemical reactions.

**DISPERSION21 (Sweden)** - This model developed for evaluating air pollutant emissions from planned or existing urban or industrial sources and it handles local scale. It was built by the Meteorological and Hydrological Institute in Sweden (SMHI). It is considered a Gaussian plume model for area, point and line vehicular traffic sources. It handles building effects, plume penetration of inversions aloft, chemistry of NOx . It does not include dry or wet deposition or the effects of complex terrain.

**DISPLAY-2 (Greece)** – it's a vapor cloud dispersion model and this kind of models is for neutral or denser-than-air pollution plumes over a complex, irregular, obstructed terrain and it handles local scale only. It accepts jet releases and the two-phase (i.e., liquid-vapor mixtures) releases. This model was developed at the National Centre of Scientific Research "DEMOKRITOS" of Greece.

**EK100W (Poland)** – it’s a Gaussian plume model developed for air quality impact assessments of pollutants produced from industrial point sources and also for urban air quality researches on a local scale. It includes dry and wet deposition but cannot handle complex terrain.

**FARM (Italy)** - The Flexible Air quality Regional Model (FARM), it's an atmospheric dispersion model developed for the pollution forecasts and the evaluation of the effects of regional emission control policies in complex situations. It handles point and area sources, and includes plume depletion by wet and dry deposition and photochemistry.

**FLEXPART (Austria/Germany/Norway)** – This model considered an efficient and flexible model to deal with particle transport and diffusion phenomena and it covers regional to global applications. It was developed at BOKU Vienna, TU München, and NILU.

**GRAL (Austria)** - The GRAz Lagrangian model was developed in Austria at the Graz University of Technology. It’s a dispersion model handles the buoyant plumes created from emissions from multiple points, line and tunnel portal sources. It handles flat as well as complex terrain but it has no deposition or chemistry capabilities.

**HAVAR (Czech Republic)** – It’s a model developed by the Czech Academy of

Sciences and it’s a Gaussian plume model built with a puff model and a hybrid plume-puff model. It is specially used for routine and accidental releases of radio nuclides from single point sources within nuclear power plants. The model handles radioactive plume depletion by radioactive decay and also by wet and dry deposition. In case of the decay of some nuclides, the creation of daughter products that then grow into the plume is taken into account.

**IFDM (Belgium)** - The Immission Frequency Distribution Model, developed at the Flemish Institute for Technological Research (VITO). This model is a Gaussian dispersion model used for point as well as area sources. It handles only flat terrain and a local scale. The model includes plume depletion by wet and dry deposition but cannot handle complex terrain, building effects and chemical transformations.

**INPUFF-U (Romania)** - This model was developed in Romania by the National Institute of Meteorology and Hydrology in Bucharest. It is a puff Gaussian model for estimating the dispersion of radio nuclides produced from passive emission plumes on a range vary from local to urban scale. It handles accidental or continuous releases from mobile or stationary point sources. It includes dry and wet deposition, buoyancy effects, building effects, chemical reactions but effects of complex terrain are not included.

**LOTOS-EUROS (The Netherlands)** - The Long Term Ozone Simulation - European Operational Smog (LOTOS) was designed for modeling the dispersion of pollutants (such as: photo-oxidants, aerosols, heavy metals) over all of Europe.

This model was developed by the Netherlands National Institute for Public Health and Environment (RIVM). It includes wet and dry deposition and simple reaction chemistry.

**MEMO (Greece)** – This model is for wind flow simulation, it's an Eulerian non-hydrostatic prognostic mesoscale model. It was developed by the Aristotle University of Thessaloniki in cooperation with the Universität Karlsruhe (Karlsruhe Institute of Technology). This model is developed for describing the phenomena of atmospheric transport in the range from local-to-regional scale, often referred to as mesoscale air pollution models.

**MERCURE (France)** – It's an atmospheric dispersion model CFD code designed by Electricite de France (EDF) and distributed by ARIA Technologies, which is a French company. The code is a version of the CFD software ESTET, designed by EDF's Laboratoire National d'Hydraulique.

**MODIM (Slovak Republic)** – This model intended for regulatory and planning purpose and it handles local to regional scales. It was developed for estimating the dispersion of continuous, neutral or buoyant plumes. It integrates a Gaussian plume model which accept single or multiple point and area sources with a numerical model for line sources, street canyons and street networks.

**MUSE (Greece)** – It's a type of photochemical dispersion model and it took its name from the Professor who developed this model, professor Nicolas Moussiopoulos, he developed it at the Aristotle University of Thessaloniki in Greece. It is designed for the purpose of studying the photochemical smog formation in urban areas and to support the assessment of control strategies on a local to regional scale. It can simulate dry deposition and transformation of pollutants which can be treated using any appropriate chemical reaction mechanism.

**OML (Denmark)** – The model was developed by the National Environmental Research Institute of Denmark. It’s a dispersion model developed for calculations of continuous neutral as well as buoyant plumes from single, multiple, stationary point and area sources. It has some simple systems for handling complex terrain and photochemistry (primarily for $NO_2$).

**ONM9440 (Austria)** – Its considered a Gaussian air dispersion model for continuous as well as buoyant plumes from stationary sources which handles flat terrain areas. It handles also plume depletion by dry deposition of solid particulates.

PROKAS-V (Germany) - A Gaussian air dispersion model for assessing the air dispersion of gas pollutants produced from vehicular traffic of line sources on a road network on a local scale.

**OSPM (Denmark)** – It’s the Operational Street Pollution Model which was developed by the National Environmental Research Institute of Denmark and it’s considered a practical street network pollution model. OSPM has been regularly used in lots of countries for doing researches on traffic pollution, doing analyses of field campaign measurements, studying the effectiveness of pollution control strategies, doing exposure assessments. This model is considered the state-of-the-art dispersion model in applied street pollution modeling.

**POLGRAPH (Portugal)** - This model was designed at the University of Aveiro, Portugal by a Professor called Carlos Borrego. It was developed for evaluating the effect of industrial pollutant emissions as well as air quality assessments. It's considered a Gaussian plume dispersion model handles flat or gently rolling terrain for continuous and elevated point sources which can be used on a local scale.

**RADM (France)** - The Random-walk Advection and Dispersion Model (RADM) was designed by an independent research and development organization in France called ACRI-ST. This model can handle gas plumes and particles from single or multiple sources, stationary or mobile, or area sources. It can handle also chemical reaction, deposition, radioactive decay, inversion conditions and complex terrain.

**RIMPUFF (Denmark)** – It’s a model which can handle a local and regional scale and considered a real-time puff diffusion model. It was developed by Risø National Laboratory for Sustainable Energy, Technical University of Denmark. This model is an operational emergency response model need to be used for assisting emergency management organizations dealing with nuclear, chemical, biological and radiological releases to the atmosphere. RIMPUFF is been used in many European national emergency centers for readiness and calculation of nuclear accidental releases (RODOS, EURANOS, ARGOS), chemical gas releases (ARGOS), and helps also as a decision making tool during active combating of airborne diffusion of different biological infections.

**SAFE AIR II (Italy)** – This dispersion model simulation the air pollution from emissions II (SAFE AIR II), it was designed at University of Genoa, Italy. It handles a complex terrain at local to regional scales. It can handle as well line, point, area and volume sources, it accommodates continuous plumes as well as puffs. It includes first-order chemical reactions and plume depletion by dry and wet deposition, but it does not include any photochemistry.

**SEVEX (Belgium)** - The model's name refer to the major disaster happened for highly toxic gases releases that occurred in 1976 in Seveso, Italy. This dispersion model simulates the accidental release of toxic or flammable materials. It handles flat or complex terrain and deals with emissions from evaporation of volatile liquid spill pools as well as from multiple pipe and vessel sources. The accidental releases may be continuous, transient or disastrous. The integrated model can handle denser-than-air gases as well as neutral gases. It does not include handling of multi-component material, nor does it provide for chemical transformation of the releases.

**STACKS (The Netherlands)** – It's a Gaussian plume dispersion model handles point and area buoyant plumes can be used over flat terrain on a local scale. It includes $NO_2$ chemistry, building effects and plume depletion by deposition. It is manly developed for environmental impact studies and assessing the emission control strategies.

**STOER.LAG (Germany)** – An air dispersion model developed to evaluate releases happened accidentally of hazardous or flammable substances from area or point sources from ground-level or elevated sources from industries. It can handle neutral and denser-than-air gases or aerosols emissions. The model accommodates terrain and building effects, evaporation of volatile liquids produced from spill pools, and combustion or explosion of flammable gas-air mixtures including the effect of pressure and heat waves caused by a fire or explosion.

**SYMOS'97 (Czech Republic)** – It's a dispersion model, designed by the Czech Hydro meteorological Institute, for calculations of continuous buoyant or neutral plumes from multiple or single point, area or line sources. It can handle complex terrain and it can also be used to simulate the dispersion of cooling tower plumes.

**UDM-FMI (Finland)** - This model was designed by the Finnish Meteorological Institute (FMI) as a Gaussian dispersion model for urban scale used for regulatory pollution management and control. It handles multiple area, line, point and volume sources and it covers chemical transformation (for $NO_2$), dry and wet deposition (for $SO_2$), and downwash effect (but no building effects).

### 2.1.10.7 Models developed in the United Kingdom

**ADMS-3** – This dispersion model is descripted in the Alternative Models section of the models which are accepted by the U.S. EPA

**ADMS-URBAN** – This model developed for simulating dispersion on scales ranging from a street scale to county-wide scale, it is capable for handling most relevant emission sources such as industrial, traffic, domestic and commercial, sources. It is used also for air quality assessment and management of current and future air quality, also national and regional standards in Europe and anywhere else.

**ADMS-Roads** – This model for simulating the dispersion of pollutant emitted from vehicles from road networks in combination with emissions emitted from industrial plants. It handles multiple point as well as multiple road sources, area or line emission sources. The model operation is similar to the other ADMS models.

**ADMS-Screen** – This is a screening model to be used for rapid assessment of the air quality impact of a specific single stack in an industry to determine if more detailed modeling is required. It also combines the dispersion modeling algorithms of the ADMS models with a user interface which require minimal input data.

**GASTAR** - This model is used for simulating releases produced accidently of toxic and denser-than-air flammable gases. It handles continuous and instantaneous releases, releases produced from jet sources, releases produced from evaporation of volatile liquid areas and pools, variable ground roughness and terrain slopes , obstacles such as buildings and fences, and releases related to time-varying.

**NAME** – This is the Numerical Atmospheric dispersion Modelling Environment. It is a local to global scale model and it was developed by the UK's Meteorological Office. It's designed to be used for: air pollution dispersion, forecasting of air quality, and acid rain; for tracking volcanic ash and radioactive emissions discharges; analysis of air pollutant releases produced accidently and it helps in assisting in emergency response; and the environmental impact analysis for long term planning. It is an integrated model which includes boundary layer dispersion modeling.

**UDM** – This is the Urban Dispersion Model which is a Gaussian puff based model, it is for predicting the dispersion of atmospheric pollutants in a specified range from 10m to 25 km for the urban environment. The Defense Science and Technology Laboratory developed this model for the UK Ministry of Defense. It is capable to handle continuous, instantaneous and pool releases, and it is capable to model liquids, gases, and particulates. This model has a three system structure: that of single building (where the area density less than 5%), urban array (where the area density more than 5%), and open. This model can be combined with the US model SCIPUFF to replace the open system and increase or extend the model's prediction range.

### 2.1.10.8 Models developed in Australia:

**AUSPLUME** – It's an air dispersion model that was developed as the main model accepted by the Environmental Protection Authority (EPA) of the Australian, state of Victoria.

**LADM** - An advanced air dispersion model designed by Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) for calculating the dispersion of buoyant pollution plumes and estimating the photochemical creation of smog over complex terrain on a scale vary from local to regional. The model deals with fumigated plumes.

**TAPM** – It is considered an advanced air dispersion model integrated with a pre-processor for accommodating meteorological data inputs. It can handle multiple pollutants, and deal with sources like point, line, area and volume sources on a scale range from local and city to regional scale. The model capabilities include plume depletion by deposition, building effects, and a photochemistry. This model was designed by Australia's Commonwealth Scientific and Industrial Research Organization.

**DISPMOD** – It’s a Gaussian air dispersion model for point sources specially for coastal regions. It was developed specifically by the Western Australian Department of Environment to estimate the plume fumigation that form when an elevated onshore pollution plume intersects a growing thermal internal boundary layer (TIBL) contained within offshore air flow coming onshore.

**AUSPUFF –** It is a Gaussian puff dispersion model developed for regulatory purposes used by CSIRO. It consists of some simple algorithms for the chemical transformation of reactive air pollutants.

## *2.2 Kuwait National Petroleum Company*[7]

One of the largest oil complexes in the world, KNPC houses three major oil refineries which are Mina Abdulla, Mina Al-Ahmadi and Shuaiba. Kuwait National Petroleum Company established in October 1960 as a shareholder company owned by the Government and the Private Sector. In 1975, the Company became a fully owned state company. After the creation of Kuwait Petroleum Corporation (KPC) in 1980, KNPC became a fully owned by KPC which itself is owned by the State of Kuwait. The three refineries and their interaction are depicted below. The unit used to describe the refineries capacity is thousand barrels per day (MBPD).

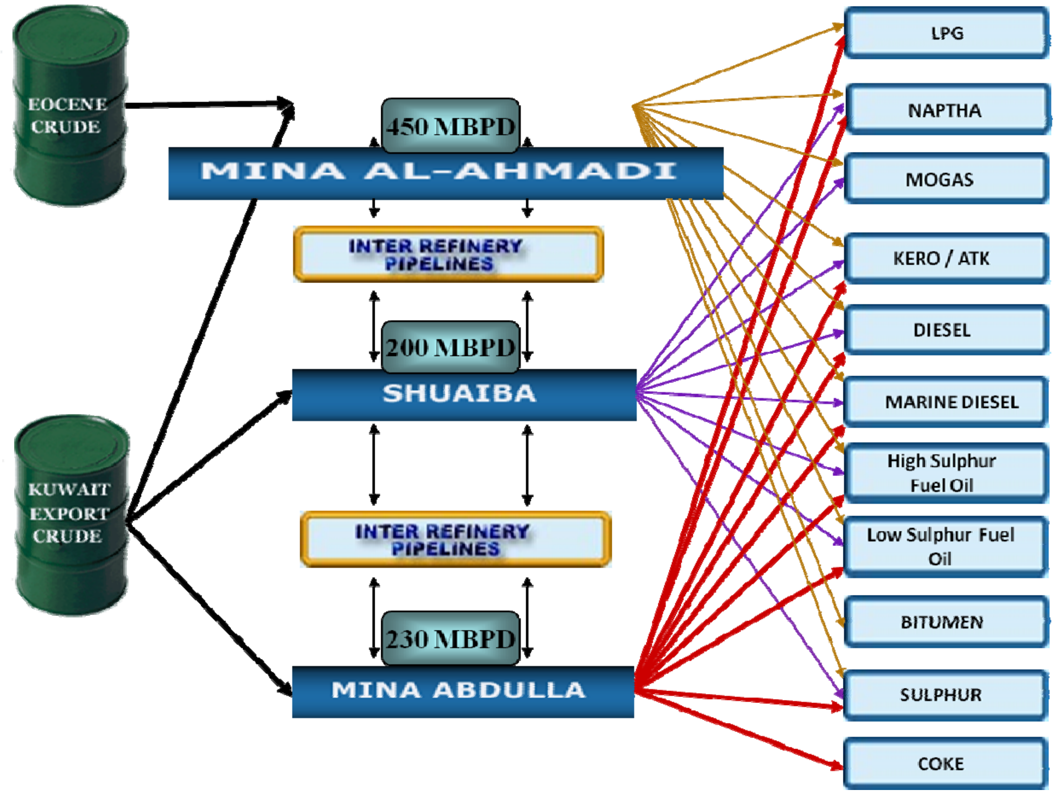

**Figure 2.1: KNPC's Three Refineries Diagram**

**Mina Abdulla Refinery** (with a total capacity of 230,000 BPD) located South of

Kuwait City, the total area covered by its installations, is 7,835,000 $m^2$. This refinery was built in 1958 during the rule of the late Sheik Abdulla Al-Salem Al-Sabah, by the American Independent Oil Company. It was, at that time, a simple refinery that contained one crude oil refining unit with a capacity of approximately 30,000 BPD.

Following several expansion projects, its refining capacity rose to approximately 145,000 BPD. When the State of Kuwait acquired full control of its oil wealth in 1975, ownership of Mina Abdulla Refinery passed to the State and following a transition period during which the refinery belonged to a national company under the name of "Wafra Oil Company", ownership of the refinery transferred to KNPC in 1978. In line with the strategy adopted in the early 1980's to modernize Mina Abdulla refineries, KNPC executed the Mina Abdulla Refinery Modernization Project.

Mina Abdulla Refinery Modernization Project, the plan to modernize Mina Abdulla Refinery was a part of a strategy concerning energy in the country and the need of liquid fuel to feed its power generation stations and other installations, cater to the country's demand for petroleum products and create stable foreign markets for Kuwaiti export high grade petroleum products. Furthermore, the need to provide the local market with petroleum products with a low content of pollutants and conform with the strict anti-pollution requirements of many countries with regard to petroleum products, necessitated the introduction of new technologies that would increase the ability of the Kuwaiti petroleum products to compete in the world market and to satisfy environmental regulations.

The high technology used in the construction of the new refinery was the best oil refining technology known at the time. Upon the completion of its modernization project, Mina Abdulla Refinery became one of the worlds most sophisticated and modern oil refineries.

### *Units of Mina Abdulla Refinery*

Mina Abdulla Modernization Project consisted of 15 new process units and the modernization of existing units such as the crude distillation, hydrogen production units, sulfur recovery units and others. Among the most important units at Mina Abdulla Refinery are two crude distillation units, four hydrogen production units, two atmospheric residue desulfurization units, two vacuum distillation unit, two delayed coker units, a hydro-cracking unit and several other support facilities and utilities.

**SHU Refinery** was commissioned in 1968 at 95000 BBLS/D Crude oil processing capacity. In mid-60’s, Shuaiba Refinery process Units were designed with high level of technology and techniques available at that time.

The refinery was capable to handle relatively high sulfur heavy crude oils, which necessitated special processing technology. SHU Refinery considered the world’s first all-Hydrogen refinery at that time with full usage of Hydrogen gas manufactured from natural gas in process units. The hydrogen gas plays a significant role in removing/reducing sulfur and nitrogen impurities from products as well as upgrading products quality to meet the required international products specification.

SHU Refinery produces wide range of products, i.e., Naphtha as raw material for petrochemical industries, high octane Gasoline for Internal Combustion Engines, Aviation Turbine Kerosene for airplanes, Diesel fuels and fuel oil engines and furnaces. SHU Refinery uses a technology called the Hydro-cracking technology to produce high quality light products converted from heavy oils.

In 1975, SHU Refinery was revamped to 195000 BBLS/D Crude oil processing capacity utilizing the most updated process technology in order to meet/achieve the needs of products quality and maximize refinery profitability.

Presently SHU Refinery is operating at 200000 BBLS/D Crude oil processing on sustained basis. New plant facilities are being added to improve performance and comply with Environmental requirement introduced at various stages.

### *Units of SHU Refinery*

SHU Refinery consists of 20 process units, i.e., Crude Distillation unit, Hydrogen Manufacturing units, Catalytic Reforming unit, Isocracker unit, Isomax unit, H-Oil unit, Burgan Gas unit, Naphtha Fractionation unit, Naphtha Unifining unit, Kerosene Unifining unit, Light Diesel Unifining unit, Heavy Diesel Unifining unit, Amine Treating unit, Kerosene Merox unit, Sulfur Recovery Plant, Tail Gas Treating unit, Acid Gas Removal plant (AGRP), Ammonical Water Treating units, Utilities and Flare Gas Recovery unit.

**Mina Al-Ahmadi Refinery** was built in 1949 as a simple refinery with a refining capacity of 25000 BPD to fulfill the local market needs of gasoline, kerosene and diesel. The refinery is located 45 km to the south of Kuwait city on the Arabian Gulf coast. It covers a total area of 10,533,400 $m^2$.

Following the establishment of KPC and the restructuring of the Kuwait oil sector, ownership of the refinery passed from Kuwait Oil Company to KNPC. KNPC was given the responsibility of oil refining and gas liquefaction operations as well as the distribution of petroleum products to the local/world market on behalf of KPC.

One of the most important facilities in the oil industry in Kuwait, is the Gas Project, Liquefied Petroleum Gas (LPG) plant. The Gas Plant had been designed and commissioned in 1979 in order to process all associated gas/ condensate collected from oil field operated by Kuwait Oil Company (KOC), another KPC company which is responsible for oil/ gas exploration and extraction. It consists of three identical trains with a total processing capacity of 1.68 billion SCF / day (including 80,000 BPD of hydrocarbon condensate). While the LPG plant essentially produces liquefied propane, liquefied butane which is stored in refrigerated tanks and Kuwait Natural Gasoline (KNG), it also produces high-pressure (HP) and low pressure (LP) lean gases.

It may be noted that the LPG plant plays a significant role as primary energy supplier to power stations, KNPC refineries and PIC. It is also the only petrochemical feed stock supplier of ethane gas to Equate for the manufacture of polyethylene.

In the early 1980’s as part of an overall plan to upgrade the oil refining industry and expand the refineries, KNPC – MAA Refinery had added major facilities. While the Refinery Modernization Project (RMP) was completed in 1984, the further upgrading project (FUP) was completed in 1986.

In order to meet the new unleaded gasoline specification as well as to upgrade cracked LPG from the FCC unit, new facilities were added downstream of the FCC unit. These units together called the MAFP block and commissioned in 1997, including facilities to supply propylene product to PIC for the manufacture of polypropylene and to produce Alkylate and MTBE, which are both mogas components.

The Acid Gas Removal Project (AGRP) was installed in year 2000 in order to treat associated sour gas from the oil fields. In order to meet latest diesel qualities, a new Gas Oil Desulfurization unit was added to the refinery configuration in year 2002.

Further, two UNITS for Naphtha Continuous Catalyst Reforming (CCR) were built and commissioned in the 2003. MAA Refinery also houses the control of sulfur solidification and granulation facilities, which serves all the three KNPC refineries.

### *Units of Mina Al-Ahmadi Refinery*

The following are the units of Mina Al-Ahmadi refinery. Crude Distillation unit 03, ATK Merox, Bitumen, AGRP, Desalination Plant, Boilers, LPG Trains 1,2 and 3, Eocene, Crude Distillation unit 04, RMP Atmospheric Residue Desulfurization units, Kerosene Desulfurization unit, Gas Oil Desulfurization unit, MTBE, Alkylation, Sulfuric Acid, RMP Hydrogen Production units, RMP Hydrogen Sulfide Recovery unit, RMP Sulfur Recovery units, RMP Tail Gas Treating units, RMP Sewer Water Treating unit, Waste Water Treating Facilities, Sulfur Handling, Crude Distillation unit 05, FUP Atmospheric Residue Desulfurization units, Vacuum Rerun, Hydro Cracker unit, PRU, Fluidized Catalytic Cracking (FCC) unit, FCC LPG Treating unit, FUP Hydrogen Production units, FUP Hydrogen Sulfide Recovery unit, FUP Sulfur Recovery units, FUP Tail Gas Treating unit, FCC LT. & HVY. Gasoline Merox, FCC SWT, FUP SWT and Hydrogen Recovery unit.

### 2.2.1 Environmental Issues [8]

Refinery Operations have Environmental impacts on all major elements of the Environment viz., Air, Water, Land, Flora and Fauna. The significant Environmental aspects associated with KNPC refinery are as indicated below:

- $SO_2$, $NO_x$, CO and Particulate emissions from Boiler and Heater stacks
- Flaring
- Release of Ozone Depleting Substances, viz., Halons, Refrigerants to atmosphere
- Fugitive emission from the units and tanks
- Treated effluent discharge to sea

- Containment failure, oil spill
- Disposal of Hazardous waste, viz., Oily Sludge, Spent Catalyst and contaminated soil/waste
- Utilization of power, water and fuel
- Indirect impacts from Products like $SO_2$, particulate from Gasoline, Diesel combustion

These environmental aspects have an impact on the surrounding area. The extent of their impacts needs to be studied to prioritize control strategies.

### *2.2.2 Flaring*

#### *2.2.2.1 Introduction*

Flaring is an oxidation process which requires a high-temperature and is used to burn combustible components, mostly hydrocarbons, of waste gases from industrial operations. Natural gas, propane, ethylene, propylene, butadiene and butane constitute over 95 percent of the waste gases flared. In combustion, gaseous hydrocarbons react with atmospheric oxygen to form carbon dioxide ($CO_2$) and water. In some waste gases, carbon monoxide (CO) is the major combustible component.

Flares used extensively to dispose of (1) purged and wasted products from refineries, (2) unrecoverable gases emerging with oil from oil wells, (3) vented gases from blast furnaces, (4) unused gases from coke ovens, and (5) gaseous wastes from chemical industries. Gases flared from refineries, petroleum production, chemical industries, and to some extent, from coke ovens, are composed largely of low molecular weight hydrocarbons with high heating value.

### 2.2.2.2 Flare Process Description

The typical flare system consists of

- a gas collection header and piping for collecting gases from processing units,
- a knockout drum to remove and store condensable and entrained liquids,
- a proprietary seal, water seal or purge gas supply to prevent flash-back,
- a single- or multiple-burner unit and a flare stack,
- gas pilots and an igniter to ignite the mixture of waste gas and air, and, if required,
- a provision for external momentum force (steam injection or forced air) for smokeless flaring.

Natural gas, fuel gas, inert gas or nitrogen is used as purge gas. Complete combustion requires sufficient and proper mixing combustion air and waste gas. Smoking may result from combustion, depending upon waste gas components and the quantity and distribution of combustion air. Waste gases containing methane, hydrogen, CO and ammonia usually burn without smoke. Waste gases containing heavy hydrocarbons such as paraffin (above methane), olefins and aromatics cause smoke. An external momentum force, such as steam injection or blowing air is used for efficient air/waste gas mixing and turbulence, which promotes smokeless flaring of heavy hydrocarbon waste gas.

Steam injection is accomplished either by nozzles on an external ring around the top of the flare tip or by a single nozzle located concentrically within the tip. At installations where waste gas flow varies, both are used. The internal nozzle provides steam at low waste gas flow rates and the external jets are used with large waste gas flow rates.

#### *2.2.2.3 Types of Flares*

There are two types of flares, elevated and ground flares[29]. Elevated flares, the more common type, have larger capacities than ground flares. In elevated flares, a waste gas stream is fed through a stack anywhere from 10 to over 100 meters tall and is combusted at the tip of the stack (as shown in Figure 2.2). The flame is exposed to atmospheric disturbances such as wind and precipitation. In ground flares, combustion takes place at ground level. Ground flares vary in complexity and they may consist either of conventional flare burners discharging horizontally with no enclosures or of multiple burners in refractory-lined steel enclosures (as shown in Figure 2.3). Ground flares are present only in MAA refinery in KNPC.

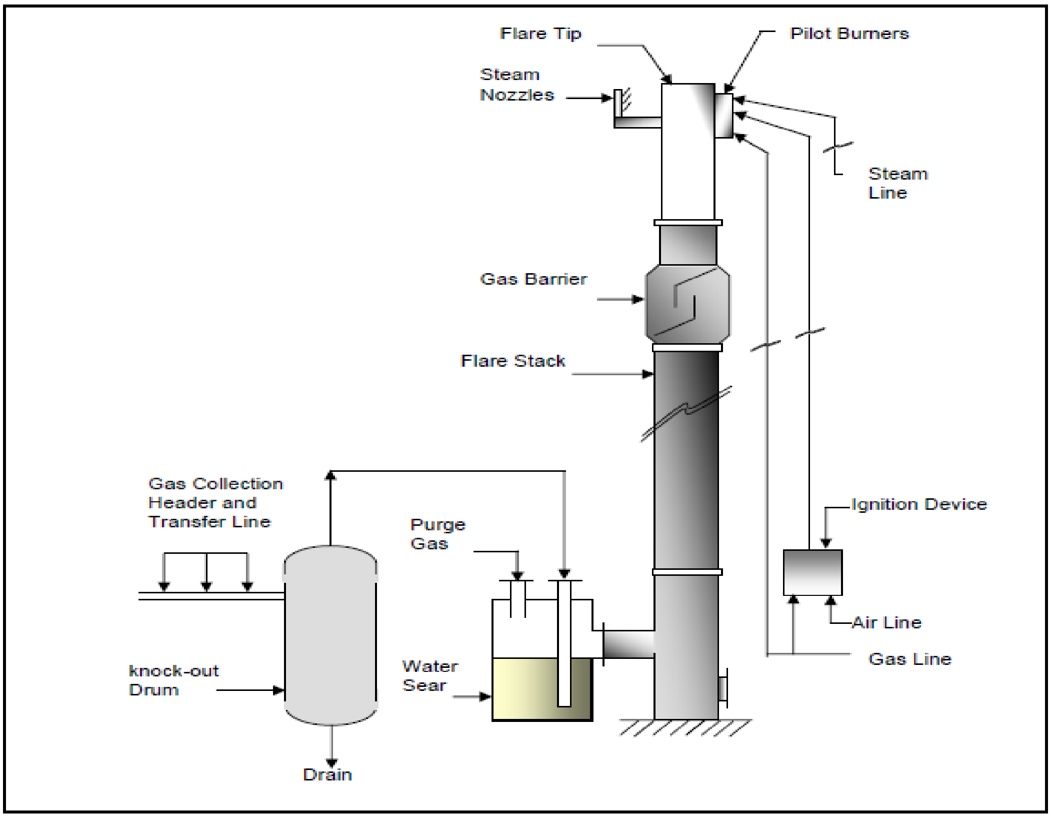

Figure 2.2: Steam assisted Elevated Flare System

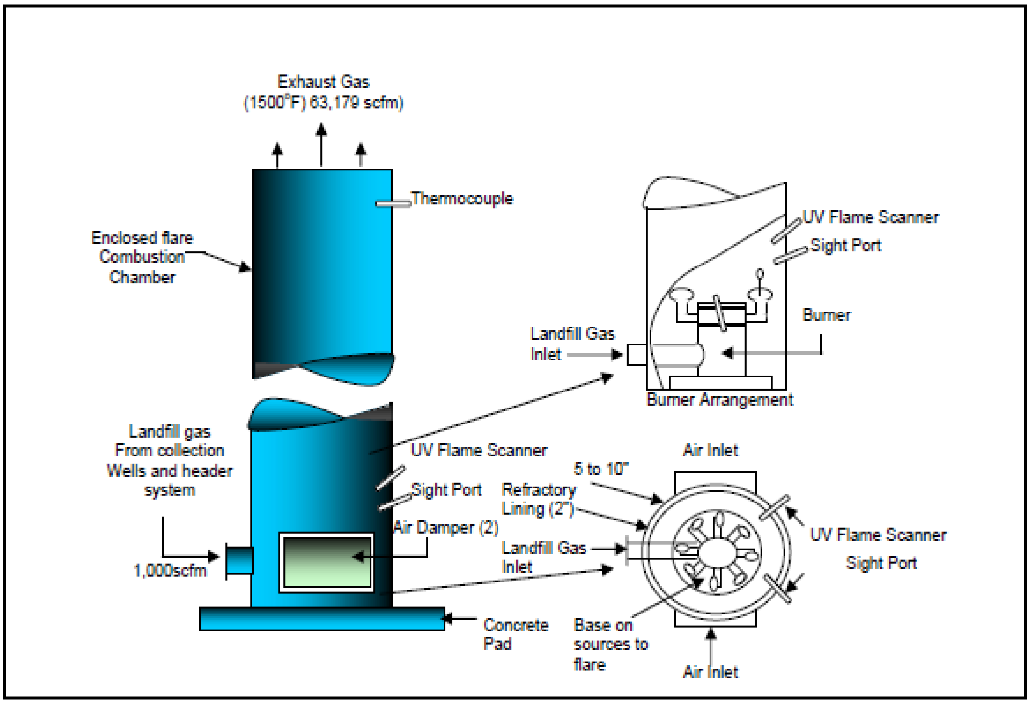

Figure 2.3: Typical Enclosed Ground Flare System

### *2.2.2.4 Atmospheric Flare emissions*

Emissions from flaring include carbon particles (soot), unburned hydrocarbons, CO and other partially burned and altered hydrocarbons. Also emitted are $NO_x$ and if sulfur-containing material such as hydrogen sulfide or mercaptans is flared, sulfur dioxide ($SO_2$). The quantities of hydrocarbon emissions generated relate to the degree of combustion. The degree of combustion depends largely on the rate and extent of fuel-air mixing and on the flame temperatures achieved and maintained. Properly operated flares achieve at least 98 percent combustion efficiency in the flare plume.

### *2.2.2.5 Environmental Issues*

Emissions from flaring contribute significantly to global warming from Refineries due to the presence of $CO_2$ and Methane, which are significant greenhouse gases. $SO_2$ emissions are the next significant contributor to environmental pollution in gases containing $H_2S$ or sulfur. $SO_2$ has direct health effects, causes respiratory illnesses and contributes to acid deposition which can impact marine and terrestrial environment. CO has direct effects on human health and vegetation. It acts as an azphixiant when inhaled in large volumes. CO may also contribute indirectly to global warming. VOC's from flaring cause eye irritation and coughing. Some are also carcinogenic. VOC's also acts as a pre-cursor to low level Ozone formation. $N_2O$ is a potent greenhouse gas. Smoky flares may also cause emission of particulates, which can affect respiratory system of human beings.

### 2.2.3 Boilers

Any Steam System in a Refinery consists of Steam generators known as Boilers and distribution network at different pressure levels to meet the process and utility requirements in the refinery. There are a few fundamental types of boilers and many variations of each type. Boilers are generally classified according to the relative position of combustion gases and water as either fire tube or water tube. Boilers are also classified by the form of energy produced; low or high pressure steam; low, medium or high temperature water.

#### *2.2.3.1 Boiler Operation*

A typical boiler consists of facilities to preheat the incoming boiler feed water, a firebox for fuel combustion, and tubes within the firebox and convection sections to transfer the heat and make steam. Separation of the steam and water is done in unfired pressure vessels called steam drums. Many boilers also have a lower drum (called a mud drum) to allow sediment to settle out and be separated. Water circulation within the boiler may be either from natural circulation in the generating coils or forced by a circulation pump. Natural circulation takes place in the tubes between the steam and mud drums. The incoming flue gas boils the water in the first tubes it contacts, causing the average density of the water in the tube to decrease as steam vapor displaces liquid. This causes a pressure differential with the water column in the rear tubes and allows the water to circulate down the rear tubes (called down comer tubes) to the mud drum and back up the front tubes (called generating tubes) making steam.

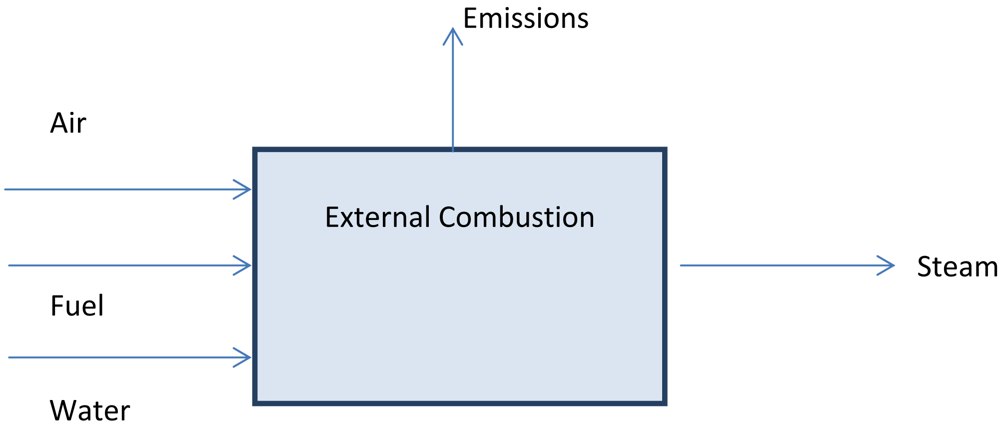

Figure 2.4: Process Flow Diagram for Boilers

### *2.2.3.2 Atmospheric emissions*

Combustion of natural gas in boilers generates emissions of criteria pollutants ($NO_x$, CO, $SO_2$, PM, VOC's) and small quantities of Hazardous Air Pollutants (HAP).

#### *2.2.3.3 Environmental Issues*

Control of pollutants from the combustion of fossil fuels in the boilers operating in an industrial facility is highly required. Boiler plant emission regulations are typically issued by local environmental agencies, with the most stringent regulation usually being imposed. Two general types of regulations exist: Point source regulations and ambient air quality standards. Following control measures are typically inbuilt in the design and operation of boilers:

- Stack opacity monitors are common. Regulated pollutants such as NOx, SOx and CO may be monitored by continuous analyzers on the stack. Adjusting boiler performance to change these emissions is done through burner controls. Optimum boiler operation is usually controlled by reducing the excess air until the CO emissions rise to a easily detected level (typically 100 ppm to 300 ppm).
- Proper burner adjustment is an important part of managing the boiler. Generation of NOx and soot (particulates < 10 microns) is controlled by how aggressively air is mixed with the burner fuel. Rapid mixing creates a short, high temperature flame and results in higher NOx emissions. Slower mixing results in longer flames that may form soot. Optimum performance is a balance between the two and varies for each boiler.

## 2.2.4 Process Heaters

An industrial furnace or direct fired heater is an equipment used to provide heat for a process or can serve as reactor which provides heats of reaction. Furnace designs vary as to its function, heating duty, type of fuel and method of introducing combustion air. However, most process furnaces have some common features.

Fired heaters are used throughout hydrocarbon and chemical processing industries such as refineries, gas plants, petrochemicals, chemicals and synthetics, olefins, ammonia and fertilizer plants. Most of the unit operations require one or more fired heaters as start-up heater, fired reboiler, cracking furnace, process heater, process heater vaporizer, crude oil heater or reformer furnace.

### *2.2.4.1 Process heater Operation*

In a Fired Heater, fuel flows into the burner and is burnt with air provided from an air blower. There can be more than one burner in a particular furnace which can be arranged in cells which heat a particular set of tubes. Burners can also be floor mounted, wall mounted or roof mounted depending on design. The flames heat up the tubes, which in turn heat the fluid inside in the first part of the furnace known as the radiant section or firebox. In this chamber where combustion takes place, the heat is transferred mainly by radiation to tubes around the fire in the chamber. The heating fluid passes through the tubes and is thus heated to the desired temperature. The gases from the combustion are known as flue gas. After the flue gas leaves the firebox, most furnace designs include a convection section where more heat is recovered before venting to the atmosphere through the flue gas stack.

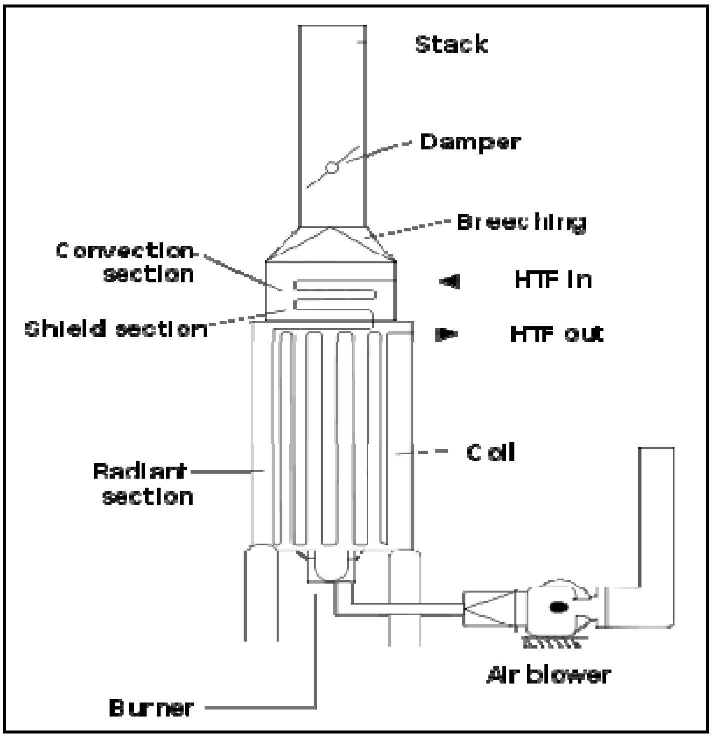

Figure 2.5: Illustration of a Fired Heater

### *2.2.4.2 Emissions from Heaters*

Almost all refinery heaters have double service burners. That is the heater burners can fire fuel gas or fuel oil. The fuel gas stream will usually have been treated for the removal of sulfur in the gas treating plant. So normally, this fuel source is not a major pollutant problem. However, all refineries have a “waste liquid” pool and this is used as the fuel oil stream to the heaters. Unless, properly treated either in terms of the streams that are routed to this pool or indeed the fuel oil pool itself, it becomes the source of $SO_2$ pollution.

The high temperature in the flame and radiant section, together with combustion turbulence at the burners, causes reaction of oxygen with nitrogen forming NO (nitric oxide) and $NO_2$ (nitrogen dioxide) from the fired heater stacks. Low excess air firing (LEA) is the simplest way to reduce NOx formation and improve efficiency. The more excess air, the more oxygen is available to produce NOx. Low NOx burners stage the combustion reducing the available oxygen, temperature or residence time to limit the formation of NOx.

#### *2.2.4.3 Environmental Issues*

Almost all refineries today hydro treat most product streams for the removal of sulfur and nitrogen except perhaps the very heavy residue stream. Where these residue streams are used as part of the fuel oil pool they are usually blended with hydro treated middle distillate streams (gasoil or even kerosene) to reduce the total stream sulfur. The individual refinery planning schedules will be tailored to meet these refinery fuel criteria.

Stringent emission limits require greater control of NOx and other stack components. Operating the heater at optimum efficiency, with low excess air firing is the simplest and least expensive way to reduce NOx emissions. Modern refinery design engineering takes note of the stack height requirements so that the emission fall out avoids populated areas as much as possible.

## 2.2.5 Sulfur Recovery Units

### 2.2.5.1 Introduction

In general, SRUs extract sulfur from $H_2S$ rich streams through either a wet or dry bed process. The most common process utilized is a staged Claus unit often followed by a tail gas treating system. Both natural gas and crude oil contain measurable quantities of sulfur compounds including hydrogen sulfide ($H_2S$). Although the magnitude of sulfur handled at gas plants and refineries may vary widely, there are some common concerns relative to their stable operation. The removal of sulfur from the feedstock is an important part of the refinement necessary to make a usable, saleable product. Because of the extremely toxic nature of $H_2S$, it is not permissible to vent the acid gas to atmosphere. The recovery of elemental sulfur is the preferred treatment of the acid gas streams formed from desulfurization. However, in some cases it may be acceptable to oxidize this stream into sulfur dioxide ($SO_2$).

### 2.2.5.2 SRU Operation

A typical Claus unit design can be separated into a thermal reaction followed by a catalytic reaction. The key reactions to the Claus process are identified below:

$H_2S + 3/2\ O_2 \rightarrow SO_2 + H_2O$ burns one-third of the $H_2S$ to $SO_2$

$2H_2S + SO_2 \rightarrow 3/2S_2 + 2H_2O$ Claus conversion of $H_2S$ and $SO_2$

Typically, a reaction furnace is followed by a thermal reactor (or waste heat boiler), which in turn is followed by three catalytic beds. The Claus (catalytic) reaction requires two moles of $H_2S$ to react with one mole of $SO_2$. For this reason, only one third of the $H_2S$ stream is burned in the reaction furnace, leaving two-thirds to react with the $SO_2$ in the thermal reactor. The Claus reaction in the thermal region yields an approximate 70% conversion of $H_2S$ to sulfur vapor. To collect this sulfur, the gases exiting the waste heat boiler routed to a condenser where the gases are cooled to collect approximately 50-65% of the total sulfur production.

After the condenser, the gas is at its dew point and generally contains some liquid entrainment as well. After the stream exits a sulfur condenser, the stream must be reheated prior to entering the next catalytic reactor to prevent the liquid sulfur from plugging individual catalyst pores, thereby deactivating the catalyst. The reheated gas usually sent through three catalytic stages, each followed by a cooling/condensation-reheat step. Reheat may be provided by direct fired heaters, indirect heat (such as heat exchangers) or hot gas by-pass. Direct heat is the mixing of the reactor feed and the combustion products resulting from a fired heater burning either fuel gas or acid gas. Indirect reheat methods include the use of a steam-heated heat exchanger or a direct fired heater installed between each sulfur condenser and the catalytic reactor where the combustion products are routed through a heat exchanger and are not mixed with the reactor feed. Hot gas by-pass involves the mixing of a hot gas slip stream from the waste heat boiler into the sulfur condenser outlet gases upstream of the catalytic reactor. The effluent gas from the final Claus stage (called the tail gas) is either, routed directly to an incinerator (thermal oxidizer) or to a tail gas treating system.

### 2.2.5.3 Emissions from SRU

The major air pollutant emitted from SRU's are $SO_2$. Claus units generally operate at approximately 95-96% recovery efficiency without a tail gas treating unit (TGTU). TGTUs increase the efficiency of Sulfur recovery to 98-99.99 %. Depending on the emission control equipment installed, the $SO_2$ emissions will vary.

### 2.2.5.4 Environmental Issues

As stated in section 2.2, $SO_2$ emissions are the next significant contributor to environmental pollution in gases containing $H_2S$ or sulfur. $SO_2$ has direct health effects, causes respiratory illnesses and also contributes to acid deposition which can impact marine and terrestrial environment.

# *Chapter 3*

# *Emission Inventories*

## 3.1 Introduction

An inventory of emissions is a database that catalogs the air emissions for various pollutants from various sources during a specified time period. Developing emission inventories for different sources is the first and foremost step in an Air Quality Management Process.

Establishing Emission inventories help in establishing and prioritizing sources of air pollutants. It helps in regulations management, predictive emission targeting, land use planning, urban planning and envisaging appropriate controls to achieve best possible pollution reduction from sources. Generally, all regulated pollutants are included in a completed emission inventory. However, emission inventories may also be developed for specific purpose for targeted pollutants.

Various methods and procedures are available to quantify emissions from sources in Refineries. Soetjiptono, T.E. (1996)[10] have presented various methods and procedures to quantify the emissions from the sources.

## 3.2 Emission Inventory Objectives

Emission inventories play an important role in developing strategies for air quality management and form the basis of assessment of the success of such strategies. As shown in Fig 3.1, Emission inventories play a major role in developing air quality management strategies. Major interactions exist between modeling, monitoring and developing emission inventories.

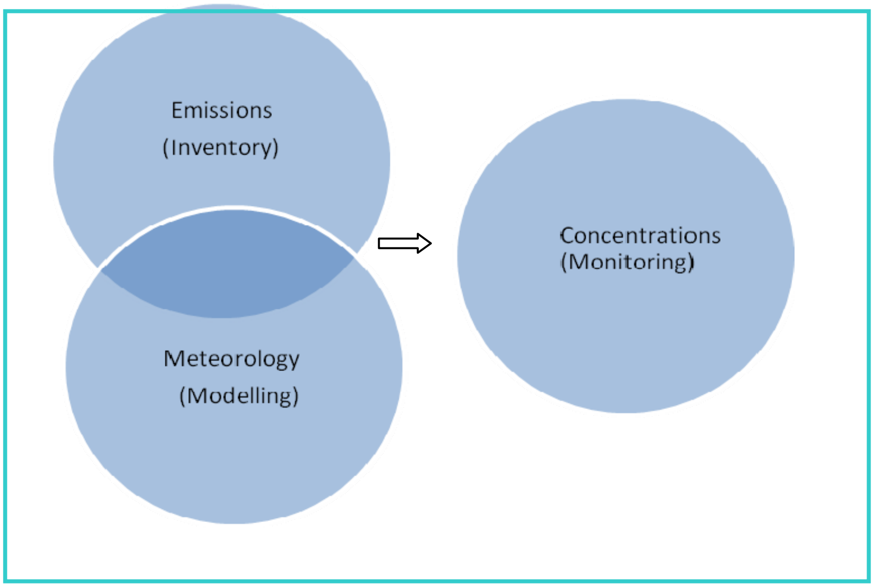

Figure 3.1: Air Quality Management Strategy

## 3.3 Air Quality Monitoring

As seen in Fig 3.1, Air quality monitoring is a vital element of managing air quality by providing necessary information for regulatory framework, policy setting, development of strategy, setting goals, assurance of compliance etc.

## 3.4 Emission inventories and source studies

Emission inventories help in estimating quality of pollutants emitting from specific sources and in the establishment of the combined emissions from all identified sources. Depending on the quantity of the contaminant, average emission rate for each of the source is used to develop inventories. It is necessary to keep in perspective that emission inventories are not actual emissions for a day but represent average emissions for a given period.

## 3.5 Atmospheric Dispersion Modeling

Atmospheric dispersion modeling of the various pollutants in a particular area of interest of study gives a clear understanding of the pollutant concentration level and the effect of meteorology on the dispersion of pollutants. It also gives an idea on the impact of pollutants on the population neighborhoods and helps in estimating the chronic health effects. Atmospheric dispersion modeling results can be used by regulatory agencies in formulating control strategies after validating with the real-world monitoring data from the various monitoring stations.

## 3.6 Managing an emission Inventory study

An emission inventory study involves systemic method of applying scientific principles in managing emission. The following flowchart typically illustrates the various steps involved in managing an emission inventory study.

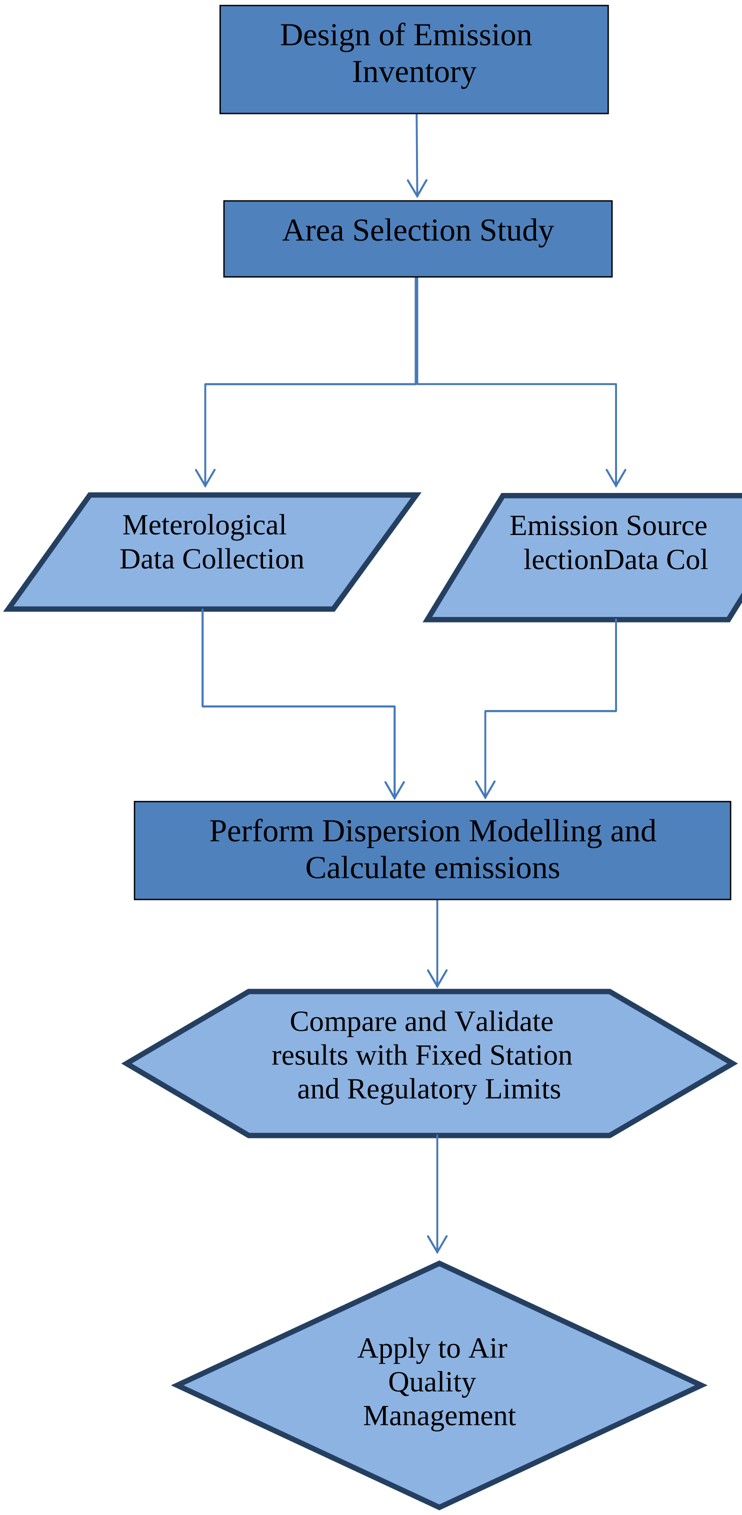

Figure 3.2: Flow Diagram for the Management of Emissions Inventory Study

### 3.6.1 Emission Inventory design

The foremost step involves a conceptual design phase wherein the tasks associated with emission inventory are enumerated stepwise. This includes the following:

- Formulation of Scope and Objectives of an emission inventory.
- Identification of emission sources
- Identification of the contaminants
- The area of study of interest and the impact potential.
- Analysis and presentation of the Report.

### 3.6.2 Data collection

An important step in inventory design is collecting the adequate and representative emission data of various pollutants in the vicinity of the area identified. An emission inventory would typically include emission estimates for various pollutants like $SO_x$, $NO_{x,}$ VOCs, CO, $CO_2$ and Particulate Matters etc. Data are represented for a number of different timestamps namely, hourly, 8 hourly, 24-hourly, monthly, seasonally and annually. Also, the meteorological data encompassing a wider span of period would help in covering most of the weather pattern.

### 3.6.3 Obtaining Emission data

Emission data are available in various forms, the most common of which are an emission factor. An emission factor is the rate of emission per unit of activity for a particular process. The unit of activity varies with the discharge type, but would typically be either hour of discharge (e.g., g/hour) or quantity of product (e.g. g/ton). Real data from industrial discharges is also captured in Environment Management Systems (EMS), which can be a good source of emission data. Other forms of data that include:

- Data from Continuous Emission Monitoring devices
- Periodic Stack sampling data
- Process Material Balance calculations
- Average emission rate estimated from a process etc.

In most of the cases, the emission factors are an average of all available data of acceptable quality and are generally representative of long-term averages of all emission sources in a facility.

### 3.6.4 Emission Calculations

Different methods for calculating the emission inventories are available and the selection depends on the availability of data and time. The methods include usage of Continuous Emission Monitoring devices, extrapolating the results of short-term source emission tests and using published emission factors from known sources of activity levels etc.

The most accurate way of estimating a source's emissions is directly measuring the concentration of air pollutants in the stack gas. A long-term average (e.g. yearly or daily) of emissions would fairly be a representative of the source's routine operating conditions.

A mass balance is a method that estimates emissions by accounting of all the inputs and all possible outputs including air emissions. This approach can provide reliable average emission estimates for specific emission units. Also, it is to be noted that this method may not be generally feasible where the losses are too small to be measured. In these cases, emission factors can be used.

### *3.6.4.1 Emission Factors and Emission Models*

An emission factor is a value that relate the quantity of a pollutant released to the atmosphere with an activity which is produces that pollutant. An emission factor is a ratio of the amount of a pollutant emitted per specific unit feed of the material. It is founded on the premise that there exists a linear relationship between the pollutant and the activity level.

An emission model can be developed based on the following general equation for calculating emissions using an emission factor. It was used in the "Compilation of Air Pollutant Emission Factors" (AP-42) which has been published by the U.S. Environmental Protection Agency (EPA) since 1972.

$$E = A \times EF \times (1 - ER/100)$$

where

E = emissions; A = activity rate; EF = emission factor, and ER =overall emission reduction efficiency (%)

Emission factors can be used to derive estimates of gas emissions based on the amount of fuel combusted in an industrial production level.

#### *3.6.4.2 Limitations of Emission Factors*

Emission data from the Continuous Emission Monitoring Systems are usually chosen since they provide the best representation of the source's emission. However, in real life, test data from individual sources are not always available and sometimes, may not reflect the variability of actual emissions over time. The emissions source variability even among similar individual sources is mainly due to inherent variations in the process, control system and the pollutant. Even though these variations are taken into account while developing emission factors, they are not often reported in the test reports used to develop emission factors. Hence, some emission factors derived from source tests may vary by an order of magnitude.

### 3.6.5 Methods for estimating air emissions from refineries

There are several methodologies available for calculating emissions from refining process and operations. The method used is dependent upon available data, available resources and the degree of accuracy required in the estimate. Common methods available for calculating emissions from refinery processes are discussed below:

### Stack Sampling by Orsat Apparatus Method:

Samples are collected from the stack using probes inserted through a port in the heater and boiler stacks and pollutants are collected in rubber bladders and sent to laboratory for complete flue gas analysis. Emissions are then determined by multiplying the pollutant concentration by the volumetric stack gas flow rate. As the heaters and boilers convection zones are often deprived of air leak proof, many of these samples lead to erroneous results due to air ingression & improper sampling.

### Use of Continuous Online Analyzers:

Many heaters and boilers are provided with continuous stack emission analyzers which gives composition of the flue gases in a dynamic environment. Emissions are then determined by multiplying the pollutant concentration by the volumetric stack gas flow rate. These data are then fed to Environment Management Systems (EMS), which can be a good source of emission data. Often Sulphur and TGTU plants are provided with continuous online $SO_2$ & $H_2S$ analyzers, which are good sources for estimating emissions.

### 3.6.6 Quality Assurance

Quality assurance is integrated into the process of preparing an emission inventory at all stages. Good quality assurance gives confidence in the inventory and any resulting regulatory provisions. Any evaluation process involves quality check at various stages, these include, checks on the bad data to do slicing, outlier limits and validation etc.

Nowadays, various softwares are being used for data handling. This minimizes errors by avoiding duplicate data input, provision for bad data slicing, fixing outlier limits etc. Various statistical methods are in-built in these software, which help in ensuring the quality of the fed data for model development.

# *Chapter 4*

# *Air Pollution Dispersion Model*

## 4.1 Introduction

This chapter will be reviewing the Air Pollution Dispersion Model. In general, the chapter will outline various air dispersion models with the view of highlighting their qualities and limitations. Based on this outline, a modeling technique will be chosen and justified. In addition, factors affecting dispersion will also be highlighted. The chapter will conclude by modeling the data based on chosen model and then displaying the results.

## 4.2 Atmospheric Dispersion Modeling

In simple terms, a model can be described as a physical or mathematical representation of a real life system. It may not contain all the features of the system but a good model should have all the necessary features needed for the problem at hand. In atmospheric dispersion, unwanted particles are dispersed through the atmosphere over long distances usually via turbulence. These particles are thus mixed with clean air during travel. It is important to be able to understand the physics of the dispersion in order to estimate the amount of contaminants in air. To properly understand this, modeling of the dispersion of contaminants is thus necessary.

In line with the definition of modeling, one could then explain Atmospheric dispersion modeling as the mathematical modeling or representation of how air contaminants disperse in the atmosphere or more formally, it can be described as *the mathematical simulation of the physics and chemistry governing the* *transport, dispersion and transformation of pollutants in the atmosphere*[1].

Typically, dispersion models are developed using user friendly computer software programs which solve the mathematical equations and algorithms, governing pollutant dispersion. The dispersion models are used to estimate or to predict the downwind concentration of air pollutants emitted from sources such as industrial plants and vehicular traffic. Such models are important to governmental agencies tasked with protecting and managing the ambient air quality. They are used to predict impacts of new projects and helps in permitting new projects.

Therefore, the output of a dispersion model software is the pollutant concentration downwind whilst the inputs are:

- Meteorological conditions such as wind speed and direction, the amount of atmospheric turbulence (as characterized by what is called the "stability class"), the ambient air temperature and the height to the bottom of any inversion aloft that may be present
- Emissions parameters such as source location and height, source vent stack diameter and exit velocity, exit temperature and mass flow rate
- Terrain elevations at the source location and at the receptor location
- The location, height and width of any obstructions (such as buildings or other structures) in the path of the emitted gaseous plume

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[1] Good Practice Guide for Atmospheric Dispersion Modelling (2004) published by the Ministry of Environment, New Zealand

Figure 4.1 shows how the inputs to a model are used by an air pollution modeling software.

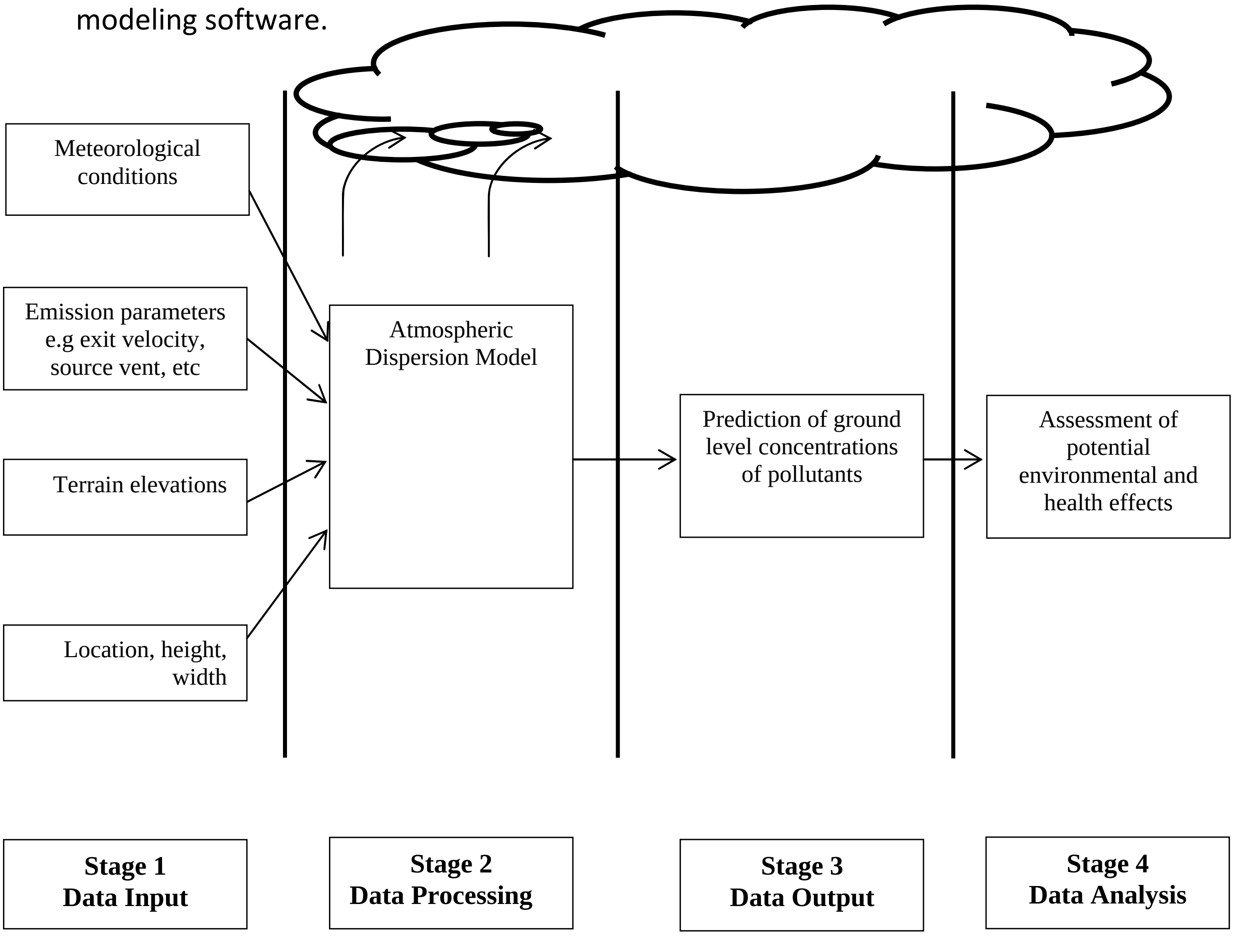


Figure 4.1 Application of inputs in an Air Dispersion model

In this research, the impact of combustion from the various point sources of emission in the Kuwait refineries has been assessed using the dispersion of methane, non-methane hydrocarbons and $SO_2$ pollutants. Al Jadidi, (2003)[18] has presented a computer simulation of Air Pollution in Dalan Refinery which is located in Farashband area at 200 km from southwest of Shiraz city. All the refining operations were simulated using steady state simulation software.

## 4.3 Types of Atmospheric dispersion Models

The selection of a tool for modeling air dispersion is dependent on two important factors – the size or scale of the potential effects of the dispersion on the environment and the complexity of the dispersion[1].

From literature, three primary models exist for air dispersion. These are Gaussian, Langrangian and Eulerian models (Bosanquet and Pearson, 1936).

### 4.3.1 Gaussian model

The Gaussian model is perhaps the oldest and perhaps the most commonly used model type. It assumes that the air pollutant dispersion has a Gaussian distribution, meaning that the pollutant distribution has a normal probability distribution. Gaussian models are most often used for predicting the dispersion of continuous, buoyant air pollution plumes originating from ground-level or elevated sources. Gaussian models may also be used for predicting the dispersion of non-continuous air pollution plumes (called puff models). The primary algorithm used in Gaussian modeling is the Generalized Dispersion Equation for a Continuous Point-Source Plume.

### 4.3.2 Lagrangian model

The Lagrangian dispersion model can be analytically modeled after the pollution plume particles as the particles move in the atmosphere and they model the motion of the parcels as a random walk process. The Lagrangian model then calculates the air pollution dispersion by computing the statistics of the trajectories of a large number of the pollution plume parcels. A Lagrangian model uses a moving frame of reference as the parcels move from their initial location. It is said that an observer of a Lagrangian model follows along with the plume.

### 4.3.3 Eulerian model

Eulerian dispersions model is similar to a Lagrangian model in that it also tracks the movement of a large number of pollution plume parcels as they move from their initial location. The most important difference between the two models is that the Eulerian model uses a fixed three-dimensional Cartesian grid as a frame of reference rather than a moving frame of reference. It is said that an observer of an Eulerian model watches the plume go by.

### 4.3.4 Dense gas model

Dense gas models are models that simulate the dispersion of dense gas pollution plumes (i.e., pollution plumes that are heavier than air).

In this report, the Gaussian-Plume model which is a hybrid of the Gaussian model is adopted. This is because of its ease of use, international and widespread approval and ease of understanding. In general, Gaussian-plume models have assumptions and uncertainties which are well understood. The next section will discuss Gaussian-Plume models.

### 4.3.5 Gaussian –Plume Models

Gaussian plume models have Gaussian distribution of concentrations in both the horizontal and vertical directions, hence the name. Two types of parameters typically influence the dispersion of pollutants – meteorological and source parameters. In Gaussian-Plume models, although meteorological parameters change from time to time, the model calculations at a particular time instance is independent of calculations at other time instances. As a result, the meteorological parameters are theoretically said to remain the same during dispersion thus assuming a steady state condition.

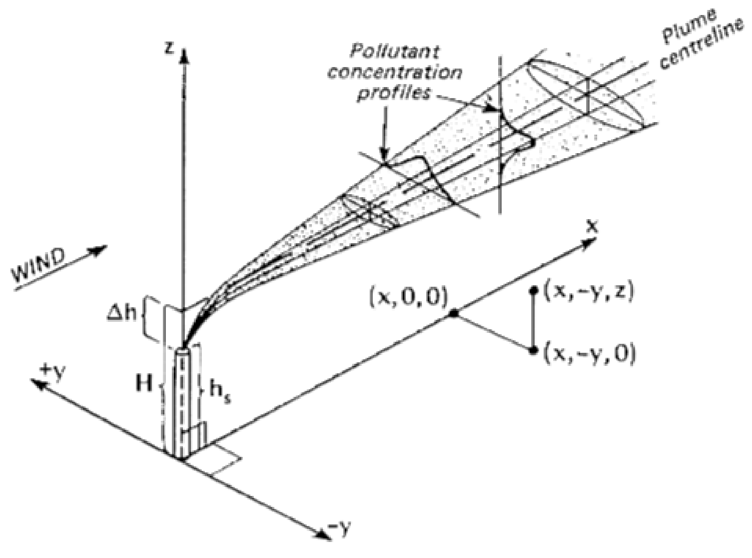


Figure 4.2 Plume from an elevated point source (Oke, 1987, Good Practice Guide for Atmospheric Dispersion Modeling, 2004)

Gaussian Plume models are typically common and widely used for various reasons including –

1. The models are easy to use due to the user friendly user interface with little required of the user
2. Widespread ensures that knowledge on application can be easily sourced and shared with other users.
3. They do not consume too much computational resources
4. The meteorological requirements are easily acquired.

## 4.4 Pollutant Dispersion parameters

There are two factors which affect pollutant dispersion. These factors are - Source parameters and Meteorological parameters.

- **Source parameter**

  The amount of pollutant, which is emitted, is proportional to the concentrations. Various parameters like particle size for dust, exhaust gas temperatures, exhaust gas velocities, stack heights, and stack diameter affects dispersion.

- **Meteorological parameters**

  Wind speed and direction, vertical thermal profiles affect dispersion. The pollutant concentration is proportional to the reciprocal of wind speed. This is mainly due to the accelerated transport. Moreover, turbulent mixing increases with growing wind speed. As so-called inversions (i.e., situations where temperature is increasing with height) hinder turbulent mixing, maximum surface concentrations are observed during highly stable stratification. On the contrary, convective situations intensify vertical mixing and therefore show the lowest concentration values.

## 4.5 Factors affecting Dispersion

The meteorological parameters like winds, turbulence and temperature in the atmosphere have a great influence on the dispersion of the pollutants. The parameters affecting the transport and dispersion of pollutants include cloud cover, relative humidity and radiation to or from earth's surface.

### 4.5.1 Wind velocity

The wind within the planetary boundary layer will have a greater speed at farther heights from the ground surface. One of the effects of wind speed is to dilute continuously released pollutants at the point of emission. This dilution takes place in the direction of plume transport and at the top of the stack. As a result, wind speeds used in estimating plume dispersion are generally estimated at stack top. In addition, wind speed affects the plume rise in a way that fast wind bends the plume faster and increases the rate of dilution.

### 4.5.2 Wind Direction

The initial transport direction of pollutants from their sources is determined by the wind direction at the source. The wind direction significantly affects pollutants from point sources more than any other meteorological factor. The direction of plume transport is very important in assessing source impact assessment where there are sensitive receptors or two or more sources, and in trying to assess the performance of model through comparison of measured air quality with model estimates.

Pollutant dispersion is also affected by variability in wind direction. Thus, if the wind direction is constant, the area will be covered by high level of pollutant concentrations. However, if direction is constantly shifting then there will be dispersion over a larger area. Wind direction and frequency for a given period can be determined by constructing a wind rose.

### 4.5.3 Temperature

The temperature normally decreases with increasing altitude at a rate of -6.5$^{o}$C/m, because of the decrease in pressure with height. This temperature profile has an important effect on wind structure and turbulence in the planetary boundary layer. Due to the influence of surface heating as well as local weather influences, the temperature profile is usually different from a normally observed profile. This phenomenon often plays an important role in determining the rate of dispersal of pollutants.

### 4.5.4 Turbulence

The pollutants get transported along the direction of wind. But it is the atmospheric turbulence that determines the lateral and vertical spread of the pollutants. Stability assumes a critical role in determining the amount of turbulence in the atmosphere and thus directly affects the level of dispersion. Turbulence can be of two types:

- **Mechanical Turbulence**
    - Caused by air moving over and around structures/vegetation
    - Increases with wind speed

- Affected by surface roughness

- **Thermal Turbulence**
    - Caused by heating/cooling of the earth's surface
    - Flows are typically vertical
    - Convection cells of upwards of 1000 - 1500 meters

### 4.5.5 Stability Class

Atmospheric stability is related to the vertical profile of density in the atmosphere. Spatial variation of temperature and specific humidity leads to a corresponding variation of density, which is known as density stratification. If cooler (and hence heavier) parcels of air reside above hotter (and hence lighter) parcels, then there is always a tendency of the heavier parcels to move down and the lighter parcels to move up. This kind of stratification is not stable and the related turbulence is also higher. Stable stratification is a result of lighter parcels residing on top of heavier parcels and is characterized by low turbulence. Uniform density of air results in neutral stratification. Stability plays a direct role in the amount of turbulence present in the atmosphere and therefore significantly affects atmospheric dispersion.

## 4.6 Overview of Models

### 4.6.1 Industrial Source Complex Short Term Model 1,2,3

The Industrial Source Complex Short Term (ISCST3) model is the US EPA's current regulatory model for many New Source Review (NSR) and other air permitting applications. The ISCST3 model is based on a steady-state Gaussian plume algorithm, and is applicable for estimating ambient impacts from point, area, and volume sources out to a distance of about 50 kilometers. ISCST3 includes algorithms for addressing building downwash influences, dry and wet deposition algorithms, and also incorporates the complex terrain screening algorithms from the COMPLEX1 model.

The ISCST model was originally developed in the 1970's. The ISCST2 model was developed by PES under contract to the US EPA between 1989 and 1992, and represented a major restructuring and reprogramming of the model code. PES has continued to support EPA's maintenance and further development of the ISCST3 model for the past decade. Major enhancements to the model that were implemented by PES include an improved area source algorithm, the complex terrain screening algorithms from COMPLEX1, a revised dry deposition algorithm, a wet deposition algorithm, a pit retention algorithm, conversion of the code to Fortran 90, and several enhancements and optimizations intended for air toxics applications. The conversion of the code to Fortran 90 allowed the introduction of dynamically allocatable array storage so that users no longer need to recompile the model to modify the limits on the number of sources, receptors, etc., that can be modeled.

The ISCST3 model utilizes hourly meteorological data that have been preprocessed using the PCRAMMET[5] program for National Weather Service (NWS) data, and the Meteorological Processor for Regulatory Models (MPRM) for on-site data. The accuracy of the model built is evaluated through comparisons between statistical parameters and standard deviation of the predicted and observed concentrations. An investigation of the performance of the ISCST3 model under the prevailing meteorological conditions in Kuwait was conducted by M.S.Al-Rashidi, et. al.(2005)[23].

### 4.6.2 Equations

The short term concentration model for pollutant sources uses the steady-state Gaussian Plume equation for a continuous elevated source. For each source and each hour, the origin of the source's coordinate system is placed at the ground surface at the base of the source. The x-axis is positive in the downwind direction, the y-axis is crosswind to the axis and the z-axis extends vertically. The fixed receptor locations are converted to each source's coordinate system for each hourly concentration calculation. The hourly concentrations predicted for each source at every receptor are summed to obtain the total concentration produced at each receptor by the combined source emissions.

The crosswind distance y (meters) and the concentration rate on an hourly basis at downwind distance x (meters) is given as follows:

$$C(x,y,z) = \frac{Q}{(2\pi)\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^{\,2}}\right] + exp\left[\frac{-(z+H)^2}{2\sigma_z^{\,2}}\right]\right\} \quad (4.2)$$

where,

Q = pollutant emission rate (mass per unit time)

$\sigma_y, \sigma_z$ = standard deviation of lateral and vertical concentration distribution (m)

u = mean wind speed (m/s) at release height

H = source height (m)

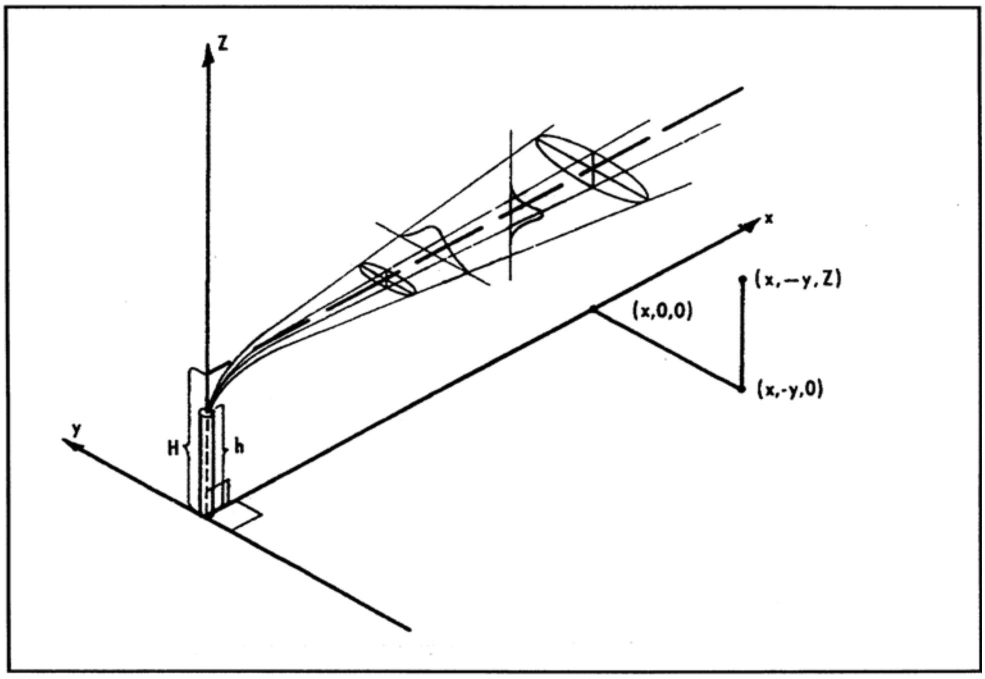


Figure 4.3: Coordinate system of the Gaussian Theory

## 4.7 Emission Inventory Analysis & Modeling:

As discussed in the previous section, in order to conduct air dispersion modeling using AERMOD, it is important to process the meteorological data to be representative of the general area being modeled.

### 4.7.1 Fixed Ambient Air Monitoring Stations in the State of Kuwait

Kuwait EPA has a few fixed stations to monitor air quality in urban areas and collect the related data. The fixed monitoring stations measure the level of concentration of pollutants such as $NO_2$, CO, NO, $SO_2$, $CO_2$, $O_3$, $H_2S$ and TSP ( total suspended particulate) continuously. These fixed monitoring stations are suitable for urban areas and are distributed in the residential areas except for one station which is located in the north part of Kuwait, where there is no residential areas.

### 4.7.2 Meteorological Data Analysis of the State of Kuwait9

The area of Kuwait is 17,818 $km^2$. It has a desert climate, hot and dry climate in summer and cold in winter. Rainfall varies mostly from 75 to 150 millimeters yearly across the country. In some years, it was recorded that rainfall reached a range from 25 to 325 millimeters.

The average daily temperature in summer ranges from 42°C to 46°C with the highest recorded temperature of 51.5°C. In summer, there are always dust storms especially in June and July. In winter, the range of temperature is from -2°C to 27°C with an average temperature of around 13°C. The spring in Kuwait is pleasant, the Surface coastal water temperature range from 15°C to 35°C in the year usually in February and August respectively. Sandstorms occur mostly in spring season.

It is well known that the meteorological conditions control the pollutants dispersion patterns. For AERMOD View dispersion model which is used for this study, the real meteorological conditions were used. Five years hourly record of the surface and upper air meteorological data for years 2003, 2004, 2005, 2006 and 2007 obtained from Kuwait International Airport (KIA) weather station has been pre-processed in the AERMET program of AERMOD software. This has been preprocessed by M/s. Lakes Environment Co. and is used in the study for calculating the dispersion of $NO_2$, $SO_2$ and CO which are the subject pollutants of the present study. The prevailing wind in Kuwait is along the north westerly quadrant most of the year with an average wind speed of 4.35 m/s.

### 4.7.3 Mathematical Model (AERMOD View Dispersion Model Software)[6]

The AERMOD View dispersion model developed in 1995 by a joint committee comprising of the American Meteorological Society (AMS) and the United States Environmental Protection Agency (US EPA) EPA called the Regulatory Model Improvement Committee (AERMIC) with a review in 1998. The committee developed the AERMOD following 7 steps:

1. Initial Model Formulation
2. Developmental Evaluation
3. Internal peer review and beta testing
4. Revised model formulation
5. Performance evaluation and sensitivity testing
6. External peer review
7. Submission to EPA office for AIR Quality Planning and Standards (OAQPS)

for consideration as a regulatory model.

It serves as a replacement for the ISCST3 2000 and is the model of choice adopted in the present study. This algorithm model is based on a Gaussian plume dispersion model discussed in section 4.2.1. It handles the steady state Gaussian plumes equations and calculates a short term pollutants concentrations from multiple point sources at a specified receptor grid on a level terrain or slightly slope terrain. It requires 3 main input data, namely:

**Source Information:** the source emitting rate (g/s). In the present study, there are 151 point sources from 3 KNPC refineries, the coordination of the each point source (UTM), source height (m), source base height above sea level (m), exit inner diameter (m), exit gas speed (m/s) and exit gas temperature (°C) etc.

**Receptor Information:** The receptors location should be specified in the model. In this case, the area chosen for the impact of study is **Umm-Alhyman area**.

**Meteorological Information:** Several meteorological data required like anemometer height (m), wind speed (m/s), wind direction, air temperature, total and opaque cloud cover (%), stability class at the hour of measurement and mixing height (m) etc.

A typical AERMOD supports three main modules namely:

- A steady-state dispersion model which is designed for short-range dispersion of air contaminants of up to about 30 miles dispersion typically from stationary industrial sources.

- A meteorological data pre-processor called the AERMET. This data pre-processor accepts input data in the form of air soundings and meteorological data from on-site instrument towers and outputs parameters needed by the dispersion model.

- A terrain pre-processor called the AERMAP. This pre-processor provides a connection between the terrain features and the air contaminants plume behaviour. It then uses this to create location and height data for each receptor location. It can also use this data to provide information which enables the dispersion model to simulate the effects of air flowing over hills.

A conventional Data Flow system for the AERMOD is shown in figure 4.4

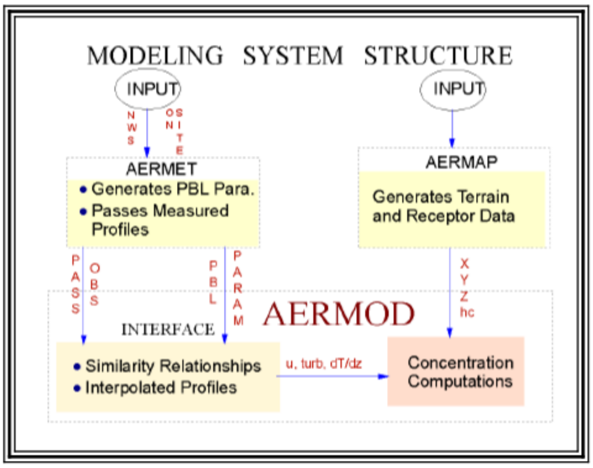


Figure 4.4: Data Flow for AERMOD System

The Data flow shows the two meteorological and terrain data pre-processors i.e. the AERMET and the AERMAP. The AERMET receives input in the form of meteorological observations, surface roughness and characteristics and then evaluates the boundary layer parameters. These parameters include - convective velocity scale ($w_*$), friction velocity ($u_*$), surface heat flux ($H$), mixing height ($z_i$), temperature scale ($\vartheta_*$) and the Monin-Obukhov length ($L$). These parameters are then used by the AERMOD interface to generate the profiles of potential temperature gradient ($d\vartheta/dz$), lateral and vertical turbulent fluctuations ($\varepsilon_v$,$\varepsilon_w$), wind speed ($u$), and potential temperature ($\vartheta$).

The AERMAP, which is the terrain pre-processor, receives input from the Digital Elevation Model (DEM) data to produce gridded terrain data which are then used to evaluate terrain height scale parameter ($h_c$). In addition, the AERMAP also produces receptor grids. The receptor parameters – its vertical and horizontal location (x, r), its vertical height above sea level (z) and its terrain height scale ($h_c$) are passed on to the AERMOD as shown in figure 4.4.

***Calculation of Parameters***

The energy balance in the PBL is defined by the equation:

$$R_n = H + \lambda E + G \tag{4.3}$$

where $R_n$ is the net radiation,

H is the sensible heat flux,

λE is the latent heat flux and

G is the soil heat flux.

Introducing the Bowen ration ($B_o$) as the ratio of the sensible heat flux to the latent heat flux, ($H/\lambda E$). Then equation (4.3) becomes

$$R_n = H + (H/B) + G \qquad (4.4)$$

In addition, parameterizing the soil heat flux as $G = 0.1R_n$ gives

$$R_n = H + (H/B) + 0.1R_n \qquad (4.5)$$

Thus,

$$H = \frac{0.9R_n}{1+\frac{1}{B_0}} \qquad (4.6)$$

This *H* value is then used to evaluate the friction velocity (*u**) and the Monin Obukhov length (*L*) according to equation (4.7).

$$u_* = \frac{ku_{ref}}{\ln\left(\frac{z_{ref}}{z_0}\right) - \Psi_m\left\{\frac{z_{ref}}{L}\right\} + \Psi_m\left\{\frac{z_0}{L}\right\}} \qquad (4.7)$$

$z_{ref}$ is the reference measurement height,

$u_{ref}$ is the speed of the wind at the reference height,

k = 0.4 is the VonKarman constant

$z_0$ is the roughness length

The $\Psi_m$ (.) are stability terms and are calculated as:

$$\Psi_m\left(\frac{z_{ref}}{L}\right) = 2\ln\left(\frac{1+\mu}{2}\right) + \ln\left(\frac{1+\mu^2}{2}\right) - 2tan^{-1}\mu + \frac{\pi}{2} \qquad (4.8)$$

and

$$\Psi_m\left(\frac{z_0}{L}\right) = 2\ln\left(\frac{1+\mu_0}{2}\right) + \ln\left(\frac{1+\mu_0{}^2}{2}\right) - 2tan^{-1}\mu_0 + \frac{\pi}{2} \qquad (4.9)$$

where

If $\rho$ is the density of air, $c_p$, the specific heat capacity of air at constant pressure, $T_{ref}$, the ambient temperature of the surface layer and $g$ the acceleration due to gravity, then the length $L$ can be calculated according to equation (4.10)

$$L = \frac{\rho c_p T_{ref} u_*^3}{kgH} \qquad (4.10)$$

In general, the AERMOD assumes that the concentration distribution is Gaussian in both the x and the y directions in the Stable Boundary Layer (see figure 4.2) however, in the convective boundary layer, the vertical concentration distribution is bi-Gaussian (Willis and Deardorff, 1981; Briggs, 1993).

The geographical locations of the point emission sources of three KNPC refineries[7], namely, Mina-Al Ahmadi, Mina Al-Abdullah and Mina Al-Shuaiba in the State of Kuwait has been presented in the figures below:

Figure 4.5: KNPC's MAA Refinery

Figure 4.6: KNPC's MAB Refinery

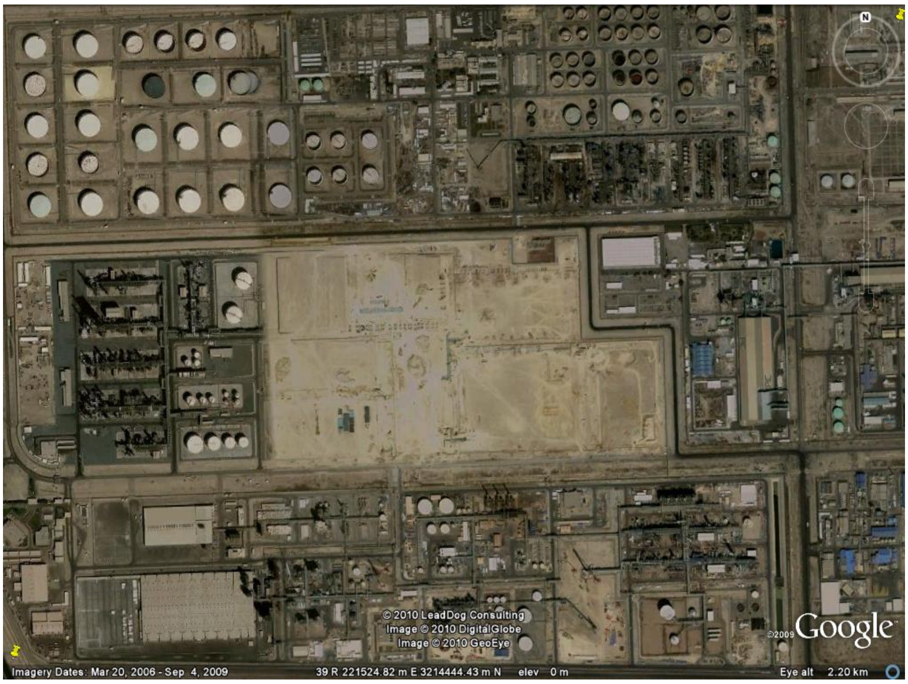


Figure 4.7: KNPC’s SHU Refinery

Figure 4.8: KNPC’s whole Refinery Areas with Umm-Alhyman Residential Area

The monthly average point source emission inventories from the three KNPC refinery stacks for the year 2007 have been used to feed the AERMOD View. The emissions inventory data is in g/sec. The details of these point sources and the emission data have been presented refinery wise in Appendix.

The concentration of three pollutants, namely, $SO_2$, $NO_x$ and CO has been chosen as pollutants of interest affecting the study area. The distribution pattern of these pollutants from these point sources refinery wise as well as point source type wise has been presented in the following figures.

Figure 4.9 below shows the total CO emissions in g/sec from the three Kuwait National Petroleum Company refineries (KNPC) point sourced using AP-42 emission factors for natural gas which has been published by the U.S. Environmental Protection Agency (EPA) since 1972.

MAA Refinery is producing 64 % from the total CO emissions, MAB Refinery is producing 25 % from the total CO emissions, and SHU Refinery is producing the rest 11 % CO emissions.

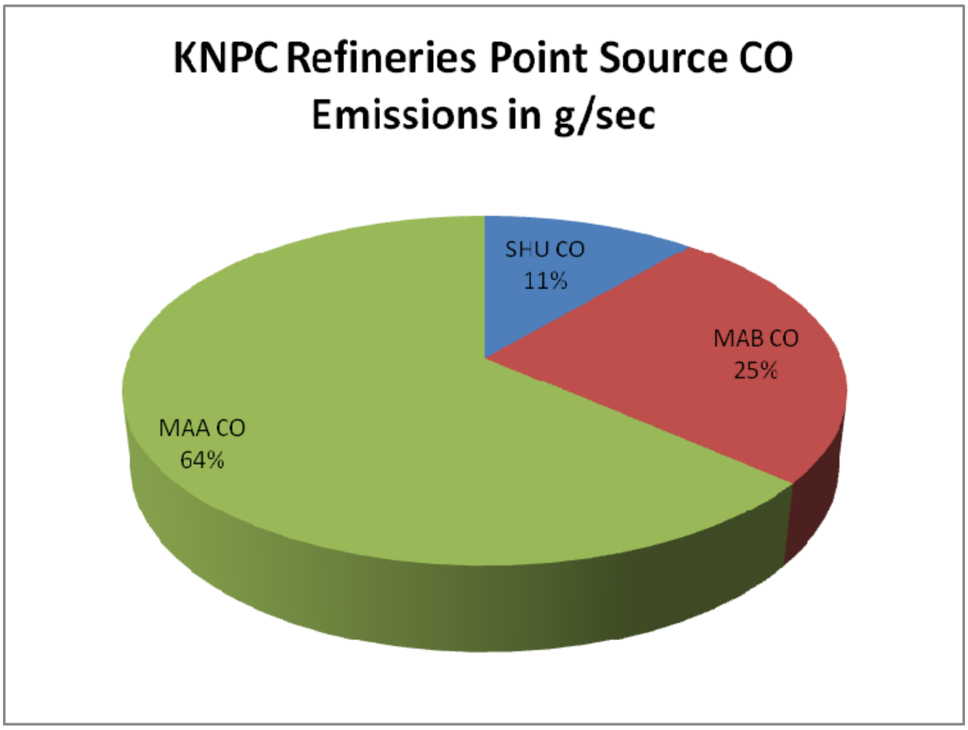


Figure 4.9: KNPC' s whole Refinery Point Source CO Emissions in g/sec

Figure 4.10 below shows the total NOx emissions in g/sec from the three Kuwait National Petroleum Company refineries (KNPC) point sourced using AP-42 emission factors for natural gas. MAA Refinery is producing 63 % from the total NOx emissions, MAB Refinery is producing 20 % from the total NOx emissions, and SHU Refinery is producing the rest 17 % NOx emissions.

Figure 4.11 below shows the total $SO_2$ emissions in g/sec from the three Kuwait National Petroleum Company refineries (KNPC) point sourced using AP-42 emission factors for natural gas. MAA Refinery is producing 69 % from the total $SO_2$ emissions, MAB Refinery is producing 8 % from the total $SO_2$ emissions, and SHU Refinery is producing the rest 23 % $SO_2$ emissions.

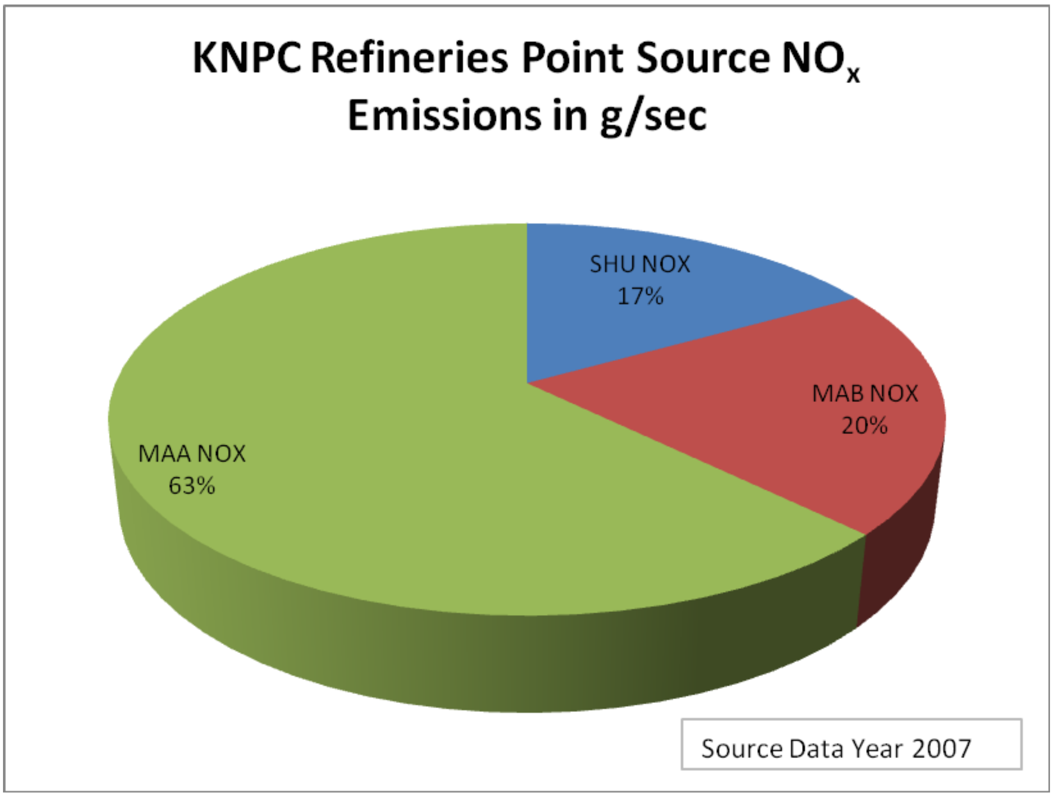


Figure 4.10: KNPC's whole Refinery Point Source $NO_x$ Emissions in g/sec

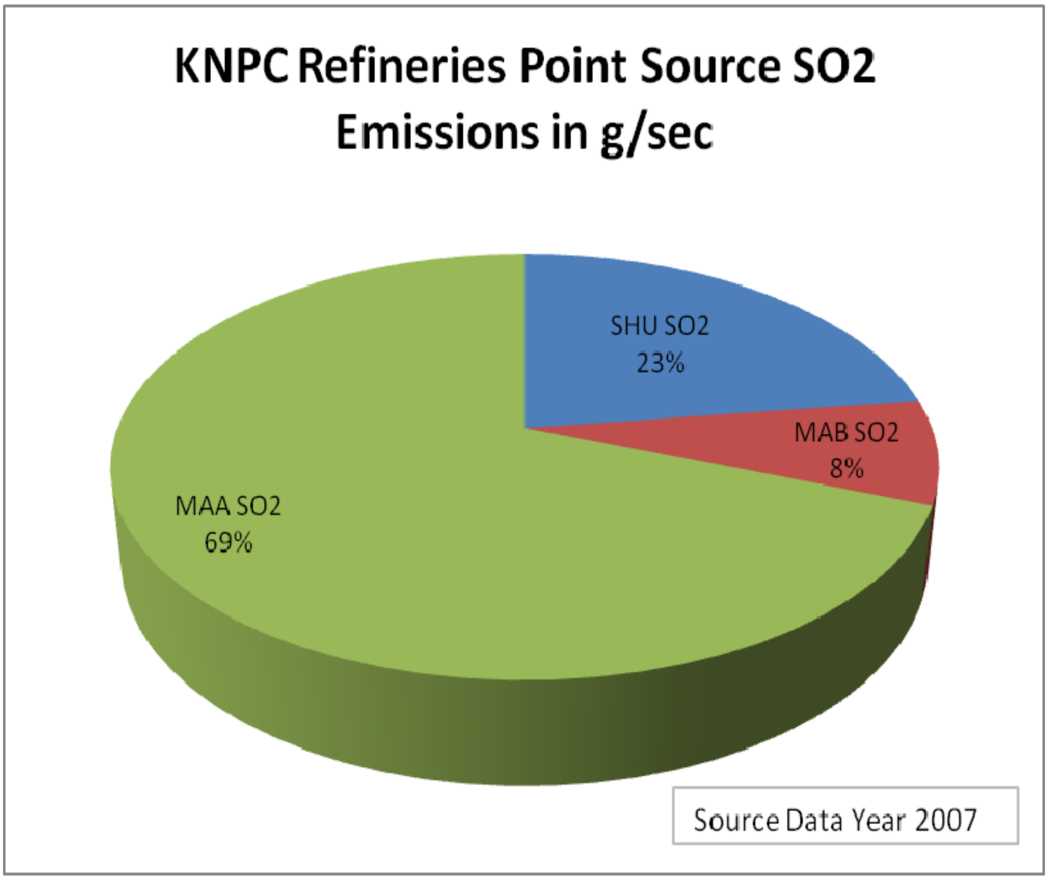


Figure 4.11: KNPC' s whole Refinery Point Source $SO_2$ Emissions in g/sec

Figure 4.12 shows the emissions produced from Boilers at KNPC refineries in (grams/s) using AP-42 emission factors for natural gas. SHU Refinery is producing 7.1 (g/s) CO emissions, 23.6 (g/s) NOx emissions, and 8.5 (g/s) $SO_2$ emissions. In the same way, MAB Refinery is producing 9.4 (g/s) CO emissions, 16.3 (g/s) NOx emissions, and 2.4 (g/s) $SO_2$ emissions. Finally, MAA Refinery is producing 32 (g/s) CO emissions, 106.8 (g/s) NOx emissions, and 27.9 (g/s) $SO_2$ emissions.

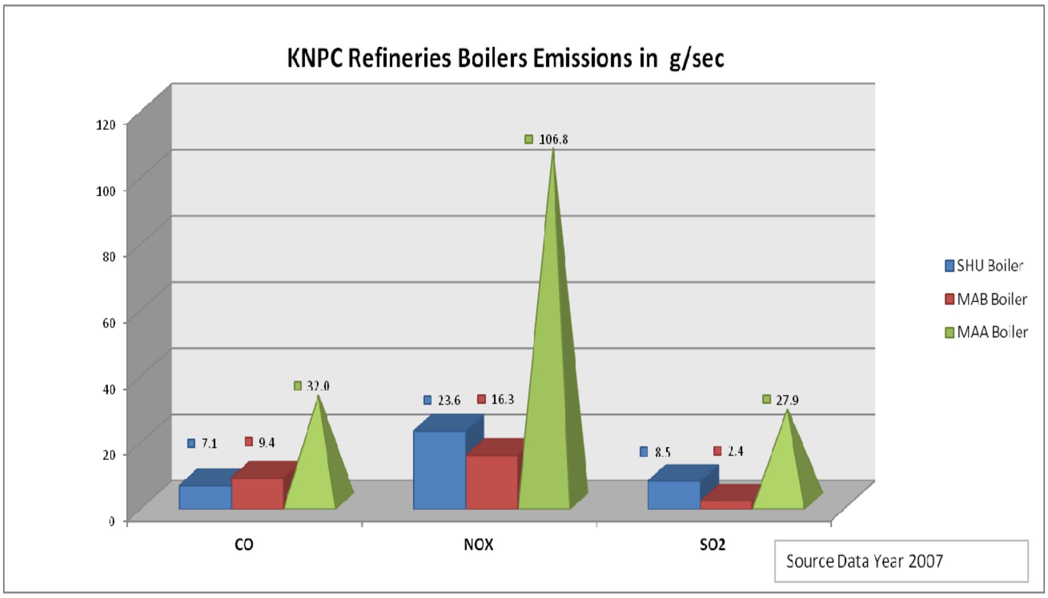


Figure 4.12: KNPC' s whole Refineries Boilers Emissions in g/sec

Figure 4.13 shows in the same way the emissions produced from Flares at KNPC refineries in (grams/s)

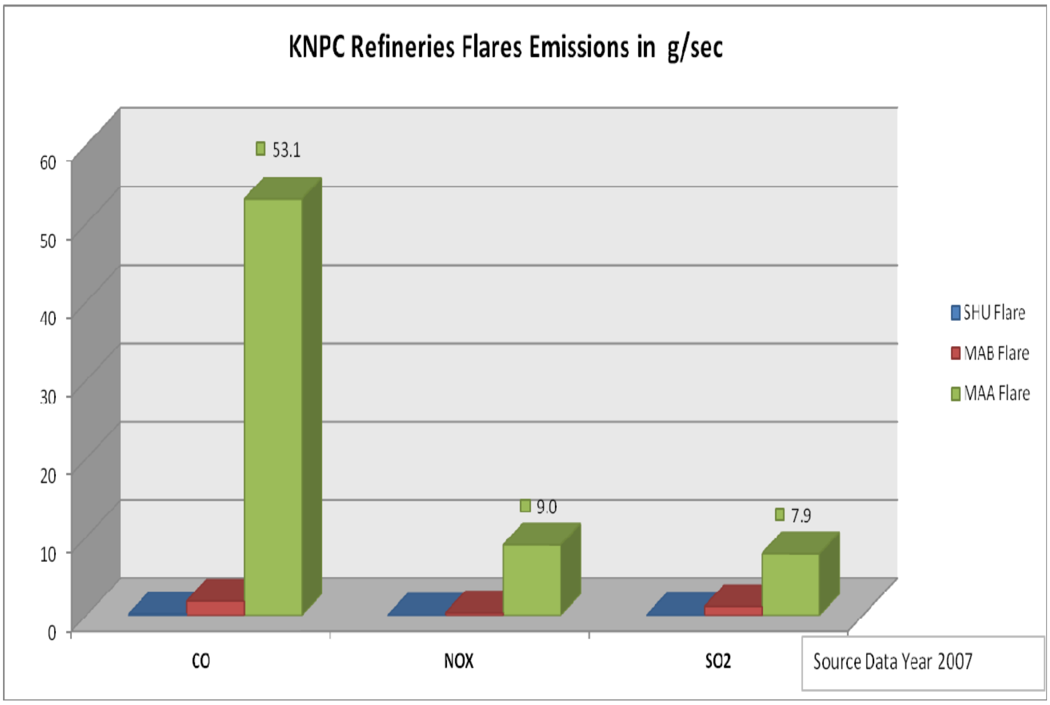


Figure 4.13: KNPC's whole Refineries Flares Emissions in g/sec

Figure 4.14 shows in the same way the emissions produced from Process Heaters at KNPC refineries in (grams/s)

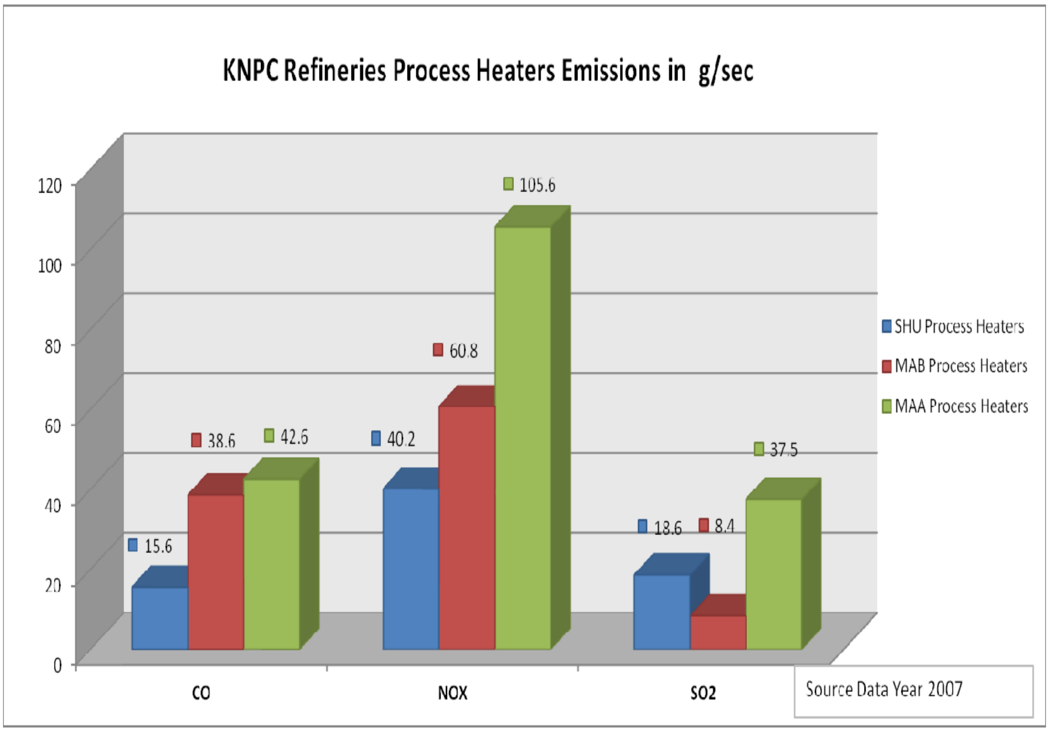


Figure 4.14 : KNPC' s whole Refineries Process Heaters Emissions in g/sec

Figure 4.15 shows the Fluidized Catalytic Cracking unit (FCC unit) $SO_2$ emissions, this unit is located at MAA Refinery in (grams/s)

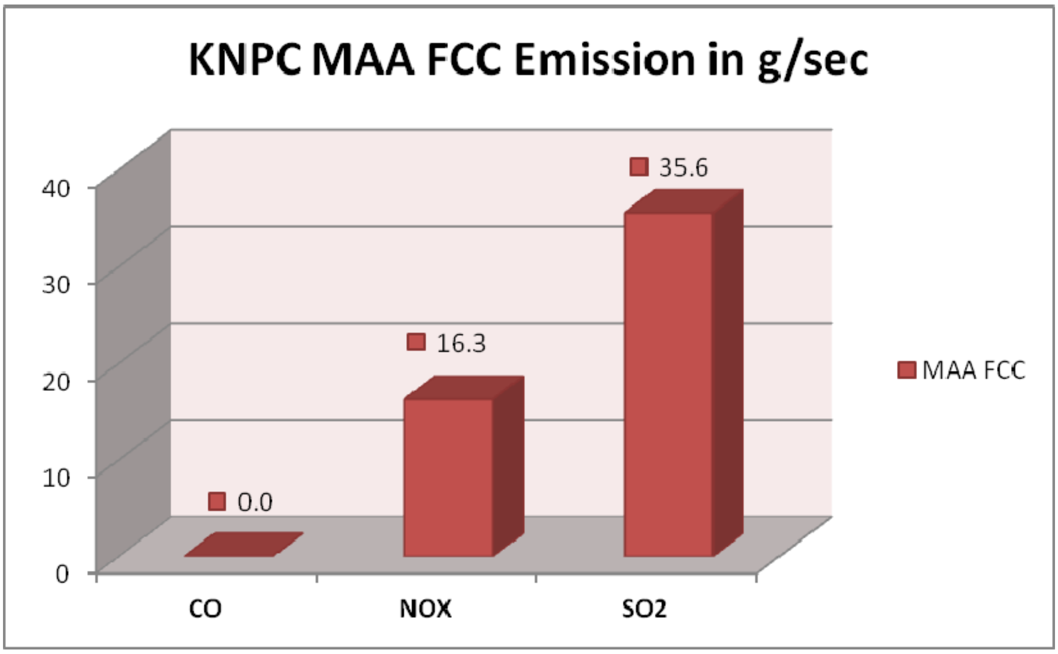


Figure 4.15: KNPC's MAA Refinery's FCC Stack Emissions in g/sec

Figure 4.16 shows the $SO_2$ emissions produced from the three KNPC refineries Tail Gas Treating Units (TGT Units) in (grams/s).

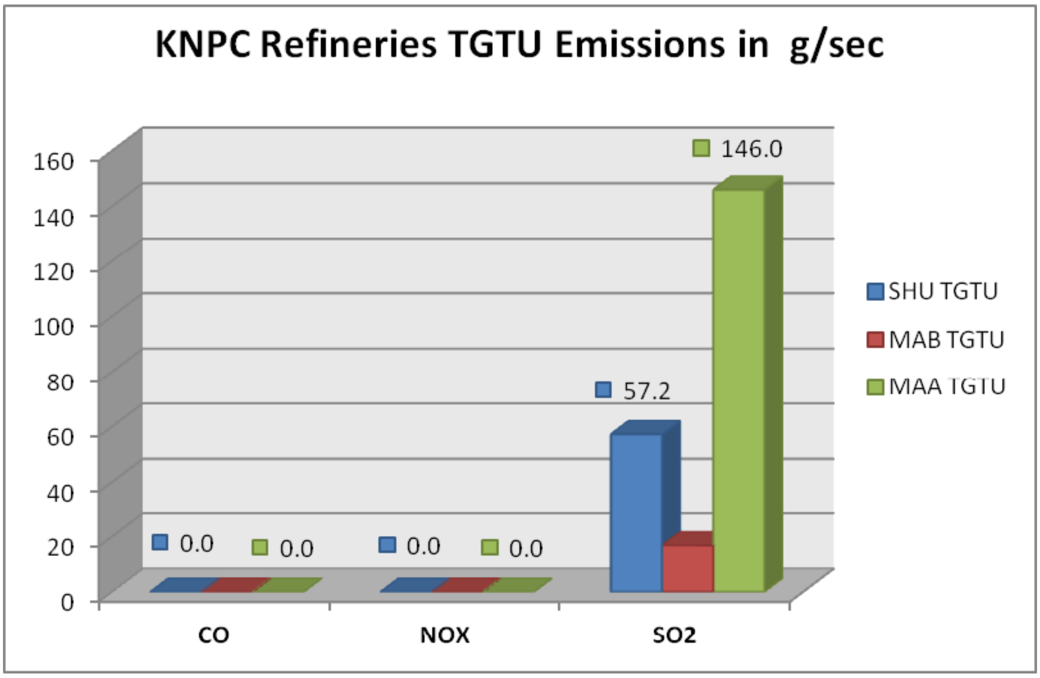


Figure 4.16: KNPC's whole Refinery TGTU Stack Emissions in g/sec

KNPC refineries have been conscious of these pollutants and considerably taken measures to reduce the emission of them by implementing various projects.

**Umm-Alhyman Residential Area Map**[7]

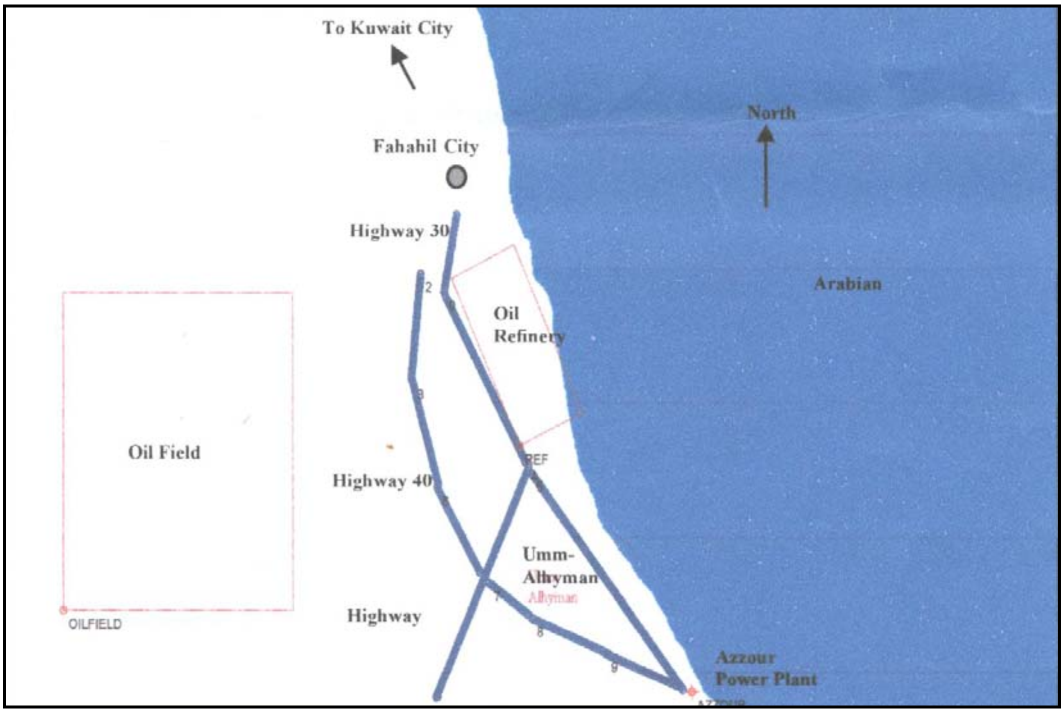


Figure 4.17 Umm-Alhyman area – Receptor Source

This area has been chosen as study of interest due to its close proximity with the neighboring industrial areas containing various industries comprising oil fields of KOC, three refineries of KNPC, Petrochemical complexes of Equate and Power station at Al-Zour area nearby. Kuwait Oil Company, KOC is the heart of the petroleum production in Kuwait. The oilfields involve various types of industrial operations and activities, such as production of crude, flaring of gases, drilling and fuel combustion which emits polluting gases to atmosphere.

This area has been consistently affected by the pollutants from these industries and there have been numerous complaints by the local population. Recent media reports on the extent of pollution impact have been presented:

مشاركة طلابية / الموت البطيء... «أم الهيمان»

| بقلم بدر البرير |

*

ضاحية علي صباح السالم (ام الهيمان) لا تعاني من التلوث الهوائي السام - والذي يفتك بأرواح ما يزيد على 45 الف روح يسكنون هذه الضاحية المنكوبة - فحسب، ولا التلوث الكهرومغناطيسي المدمر لاطفالنا ونسائنا والذي ينبعث من ابراج الضغط العالي الملاصقة لبيوت الضاحية والتي لا تبعد اكثر من 30 متراً فقط عن المسكن، بل ان هناك معاناة اخرى ولا تقل ضراوة وفتكا بنا بل تتعدى الى اجيال واجيال، ولا تضر البشر فقط بل ان اثرها المدمر يقع على جميع الاحياء برية وبحرية.

ان هذه المعاناة سببها الماء الملوث الذي تخرجه هذه المصانع المجاورة للضاحية وكأن البلاد بلا قانون ولا رقابة، وكيف لا واصحاب هذه المصانع والمتنفذون المتاجرون بأرواحنا يرون هذا التراخي في التعاطي الحكومي الهزيل مع قضية عمرها 10 سنوات من المعاناة والتي راح فيها من الضحايا ما لا يعلمه الا المولى عز وجل.

وان هذه المصانع لا تنفث سمومها في الهواء فقط، بل تسرب لنا المياه التي تخرج منها والتي تحمل الكثير من السموم والتي لا تقل ضراوة عن سموم الهواء، فطبقاً لاخر تقرير صدر في 2010 من لجنة حكومية مشتركة من مجلس الوزراء الذي اقر بوجود مواد كيميائية تم رصدها والتي تشكل خطراً على الاحياء ومن هذه المواد الزئبق الذي سنذكر من اثاره انه يسبب الفشل الكلوي ويؤثر على الجهاز العصبي وهناك ايضاً من المواد التي تم اكتشافها البكتيريا القولونية والبرازية ومواد عضوية غير محللة وكذلك الفورمالديهايد والنيترات، والسؤال هو: إلى متى؟؟

* جامعة الكويت - مقرر تربية بيئية

تعليق على المقال

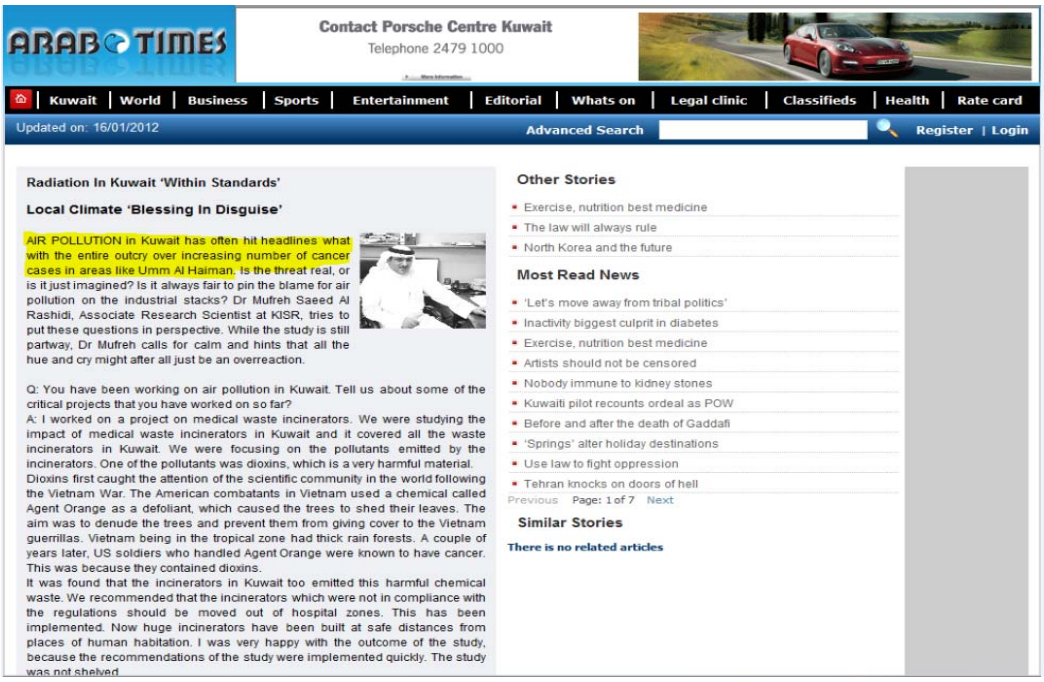
الإسم

البريد الإلكتروني

عنوان التعليق

" Umm-Alhyman area not only suffers from the poisonous air pollution which is harming more than 45000 persons who are living in this area, but also from an electromagnetic pollution from the adjacent high tension power transmission…." - ALRAI Newspaper on 3rd January 2012.

Figure 4.18: Newspaper Article-1 on the effect of pollutants on the area



**Radiation In Kuwait 'Within Standards'**

**Local Climate 'Blessing In Disguise'**

AIR POLLUTION in Kuwait has often hit headlines what with the entire outcry over increasing number of cancer cases in areas like Umm Al Haiman. Is the threat real, or is it just imagined? Is it always fair to pin the blame for air pollution on the industrial stacks? Dr Mufreh Saeed Al Rashidi, Associate Research Scientist at KISR, tries to put these questions in perspective. While the study is still partway, Dr Mufreh calls for calm and hints that all the hue and cry might after all just be an overreaction.

Q: You have been working on air pollution in Kuwait. Tell us about some of the critical projects that you have worked on so far?
A: I worked on a project on medical waste incinerators. We were studying the impact of medical waste incinerators in Kuwait and it covered all the waste incinerators in Kuwait. We were focusing on the pollutants emitted by the incinerators. One of the pollutants was dioxins, which is a very harmful material.
Dioxins first caught the attention of the scientific community in the world following the Vietnam War. The American combatants in Vietnam used a chemical called Agent Orange as a defoliant, which caused the trees to shed their leaves. The aim was to denude the trees and prevent them from giving cover to the Vietnam guerrillas. Vietnam being in the tropical zone had thick rain forests. A couple of years later, US soldiers who handled Agent Orange were known to have cancer. This was because they contained dioxins.
It was found that the incinerators in Kuwait too emitted this harmful chemical waste. We recommended that the incinerators which were not in compliance with the regulations should be moved out of hospital zones. This has been implemented. Now huge incinerators have been built at safe distances from places of human habitation. I was very happy with the outcome of the study, because the recommendations of the study were implemented quickly. The study was not shelved

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Figure 4.19: Newspaper Article-2 on the effect of pollutants on the area

# *Chapter 5*

# *Model Analysis*

## 5.1 Introduction

AERMOD – Gaussian plume air dispersion model was used to simulate the plume level concentrations of $SO_2$, $NO_x$ and CO pollutants emitted from various point emission sources of three refineries from KNPC. The impact of the plume on the nearby residential area Umm-Alhyman was studied in detail.

Figure 5.1 Map of State of Kuwait

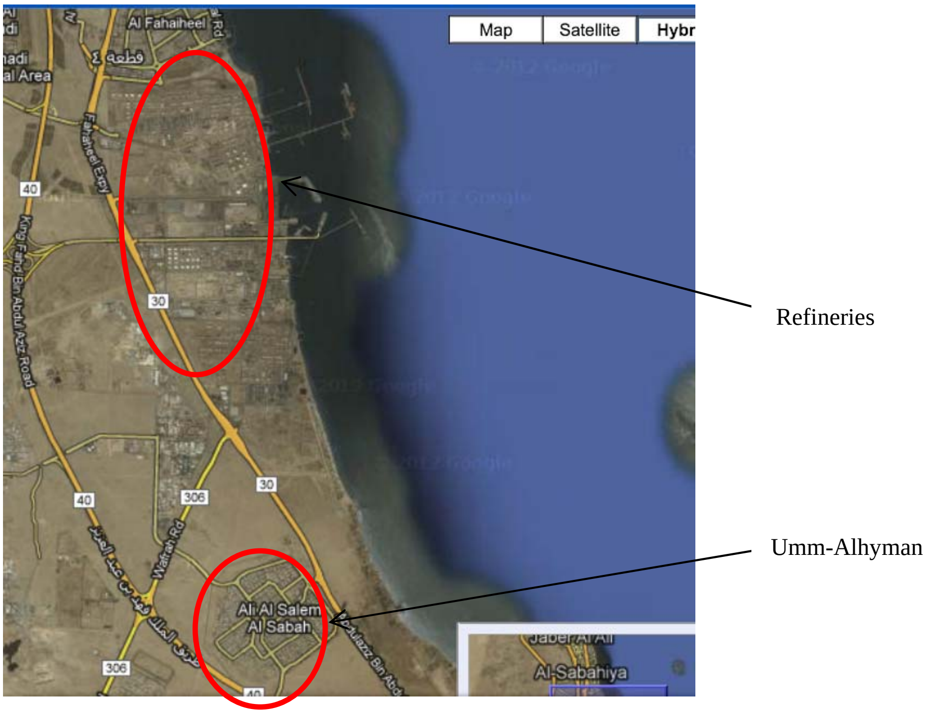

Figure 5.2 Map of the area showing the refineries and Umm-Alhyman area

## 5.2 AERMOD Dispersion Plume Models

The hourly, daily and annual average maximum ambient air quality concentrations of $SO_2$, $NO_x$ and CO were predicted from AERMOD and the output results are shown in the following figures:

Figure 5.3 shows Umm-Alhyman area at the south of the map. The highest hourly SO2 concentration calculated by the AERMOD View model is 809.7 mg/m$^3$ and the lowest is 30.9 mg/m$^3$ . It is clear how the plumes are covering Umm-Alhyman residential area and from the color code the range of the plumes concentration of the subject pollutant is changing gradually from 723 mg/m$^3$ to 204 mg/m$^3$. The concentration records of the fixed station will be explained later and all of its readings are below 444 mg/m$^3$ which might be strongly related to the position of this fixed station from Umm-Alhyman residential area. It's noticed from Fig.5.3

that the highest concentration plume are in the east side of the area and the lowest concentration plume are in the west side of the area.

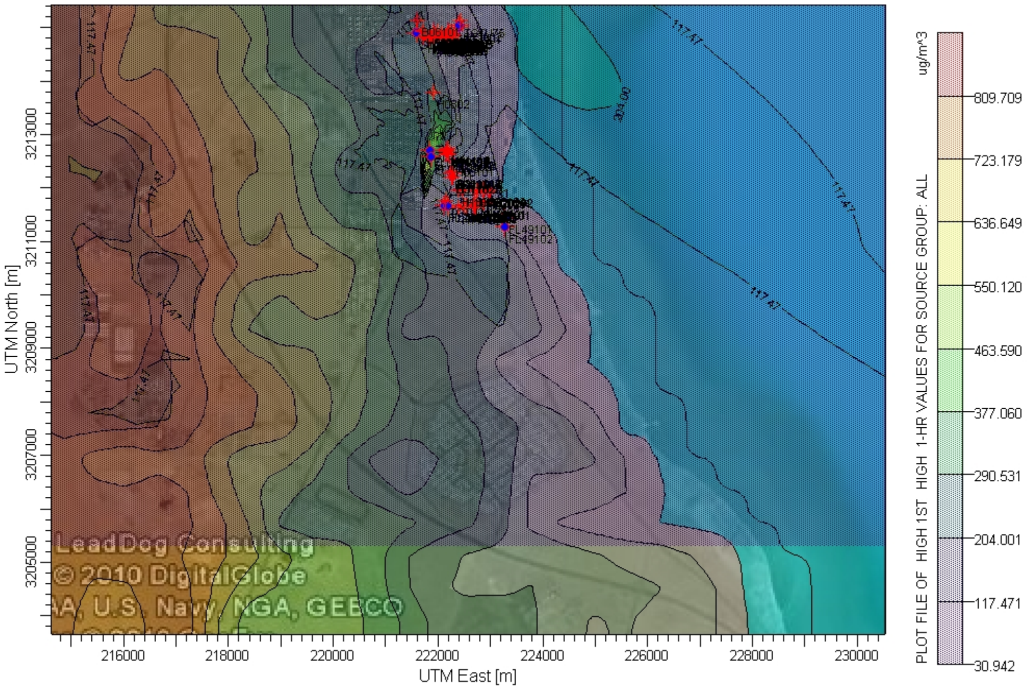

Figure 5.3: AERMOD plume output results for $SO_2$ Hourly concentration. (Umm-Alhyman Area at the South)

Figure 5.4 shows Umm-Alhyman area at the south of the map. The highest daily SO2 concentration calculated by the AERMOD View model is 84.4 mg/$m^3$ and the lowest is 3.7 mg/$m^3$ and the plume affecting Umm-Alhyman residential area concentration is 30.6 mg/$m^3$

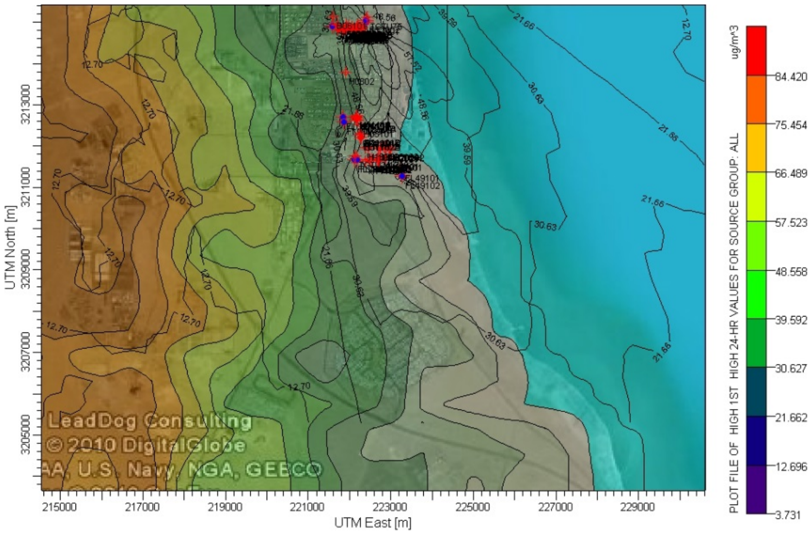

Figure 5.4: AERMOD plume output results for $SO_2$ Daily concentration. (Umm-Alhyman Area at the South)

Figure 5.5 shows Umm-Alhyman area at the south of the map. The highest annual SO2 concentration calculated by the AERMOD View model is 20.2 mg/$m^3$ and the lowest is 0.261 mg/$m^3$ and the plume affecting Umm-Alhyman residential area concentration is 6.9 mg/$m^3$

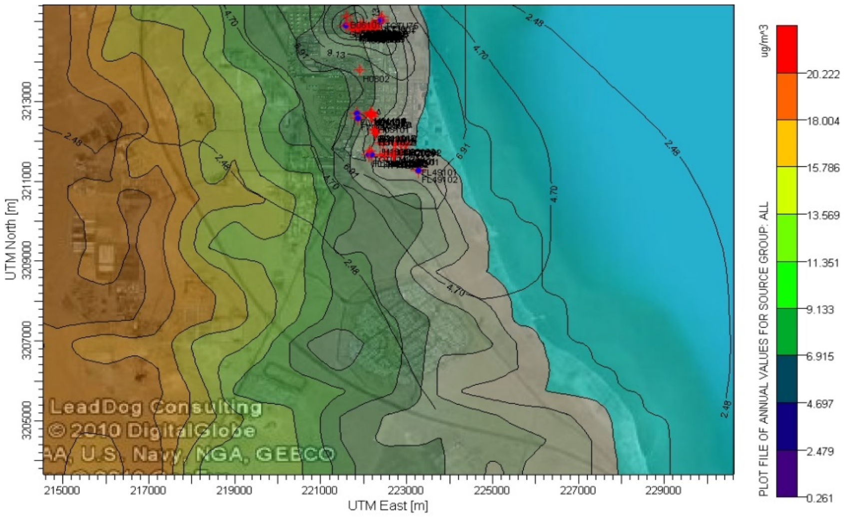

Figure 5.5: AERMOD plume output results for $SO_2$ Annual concentration. (Umm-Alhyman Area at the South)

Figure 5.6 shows Umm-Alhyman area at the south of the map. The highest hourly NOx concentration calculated by the AERMOD View model is 5951 mg/m$^3$ and the lowest is 69.9 mg/m$^3$ but the plumes are not affecting Umm-Alhyman residential area.

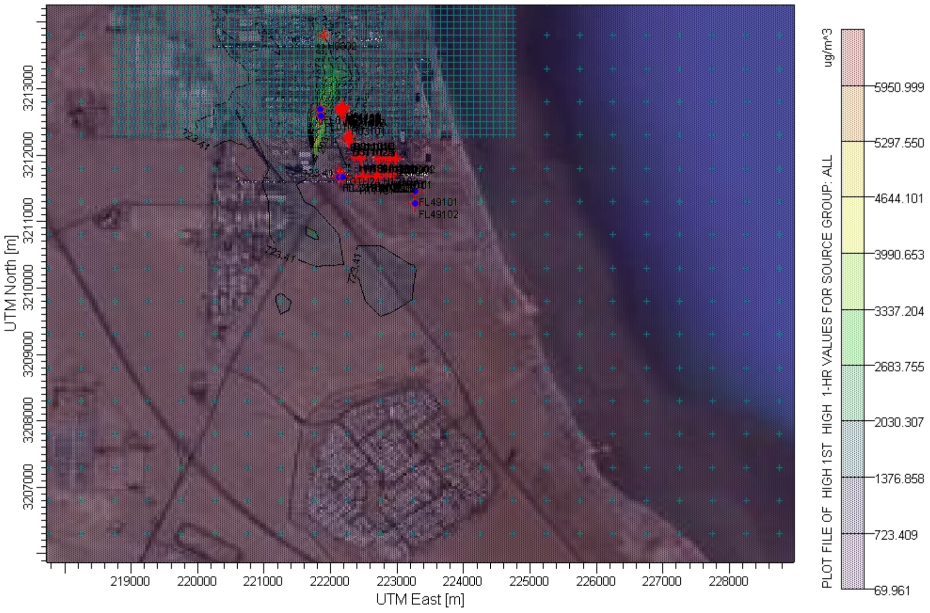

Figure 5.6: AERMOD plume output results for NOx Hourly concentration. (Umm-Alhyman Area at the South)

Figure 5.7 shows Umm-Alhyman area at the south of the map. The highest daily NOx concentration calculated by the AERMOD View model is 389.4 mg/m$^3$ and the lowest is 6.0 mg/m$^3$ and the plume touching the corner of Umm-Alhyman residential area concentration is 48.6 mg/m$^3$

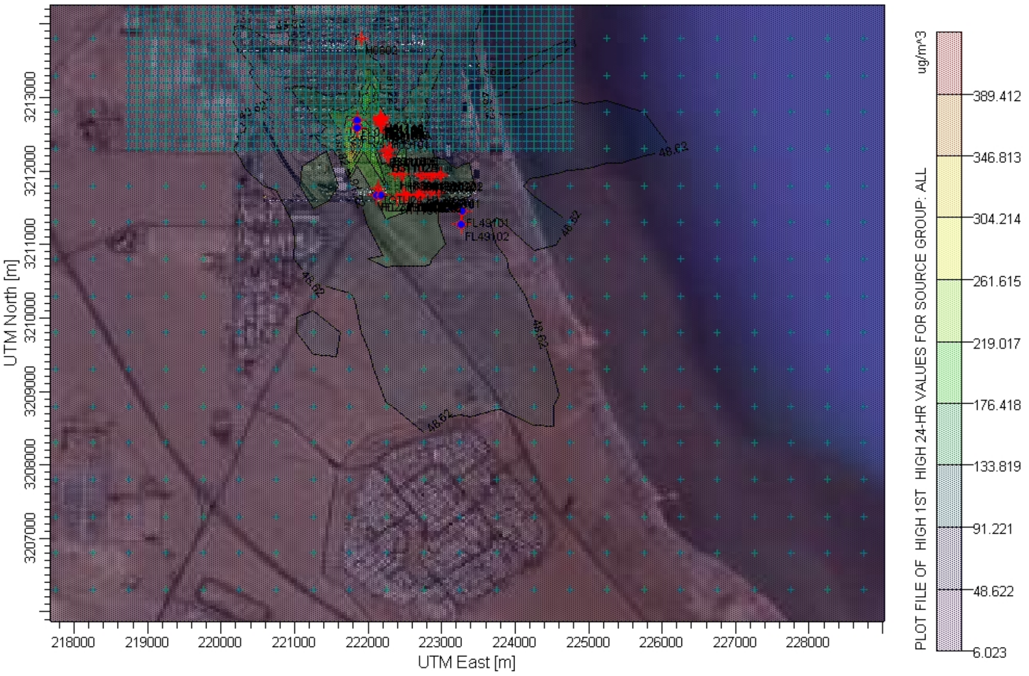

Figure 5.7: AERMOD plume output results for Pollutant NOx Daily concentration. (Umm-Alhyman Area at the South)

Figure 5.8 shows Umm-Alhyman area at the south of the map. The highest annual NOx concentration calculated by the AERMOD View model is 48.8 mg/m$^3$ and the lowest is 0.48 mg/m$^3$ and the plumes affecting Umm-Alhyman residential area concentration is 5.86 mg/m$^3$

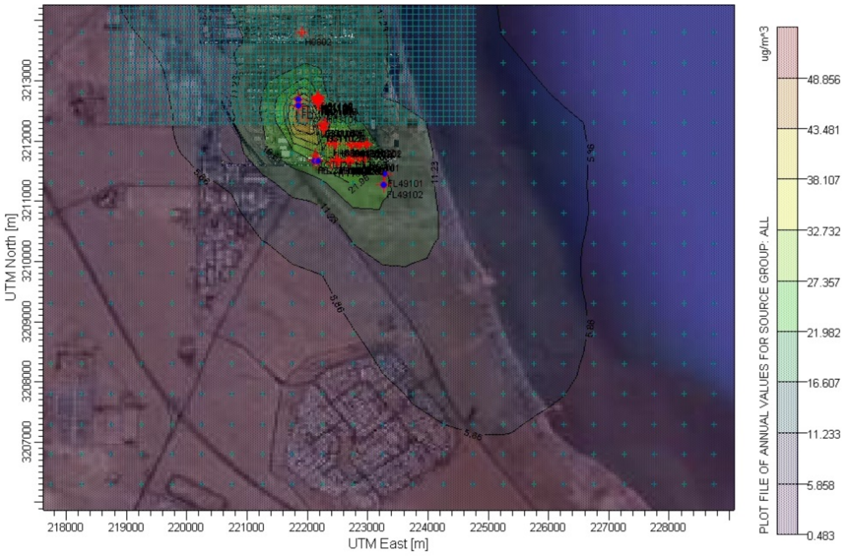

Figure 5.8: AERMOD plume output results for NOx Annual concentration. (Umm-Alhyman Area at the South)

Figure 5.9 shows Umm-Alhyman area at the south of the map. The highest hourly CO concentration calculated by the AERMOD View model is 3604.3 mg/m$^3$ and the lowest is 47.8 mg/m$^3$ and the plumes are not affecting Umm-Alhyman residential area.

Figure 5.9: AERMOD plume output results for CO Hourly concentration. (Umm-Alhyman Area at the South)

Figure 5.10 shows Umm-Alhyman area at the south of the map. The highest 8-hourly CO concentration calculated by the AERMOD View model is 982.2 mg/m$^3$ and the lowest is 12.6 mg/m$^3$ and the plumes are not affecting Umm-Alhyman residential area.

Figure 5.10: AERMOD plume output results for CO - 8 Hourly concentrations.

(Umm-Alhyman Area at the South)

Figure 5.11 shows Umm-Alhyman area at the south of the map. The highest daily CO concentration calculated by the AERMOD View model is 408.8 mg/m$^3$ and the lowest is 5.34 mg/m$^3$ and the plumes are not affecting Umm-Alhyman residential area.

Figure 5.11: AERMOD plume output results for CO Daily concentration. (Umm-Alhyman Area at the South)

## 5.3 Model Performance and Results Validation

The hourly, 8-hourly, daily and annual average maximum ambient air quality concentrations of $SO_2$, $NO_x$ and CO were predicted from AERMOD and the output results were compared with fixed monitoring stations of Umm-Alhyman area receptors.

The performance of the model was analyzed and it is clear that the model predictions are in good agreement with the observed data with accuracy of 74-77% at the monitoring station used by Kuwait EPA.

A table comparing the model results with receptors data along with the allowable levels of pollutants as regulated by Kuwait-EPA has been presented for comparison in the Appendix.

Figure 5.12 shows a comparison between the results of the fixed station (blue spikes) for hourly SO2 emissions and Kuwait EPA limit which is 444 mg/m$^3$ (orange horizontal line) which is higher than the fixed station results and this might be related to the position of the fixed station.

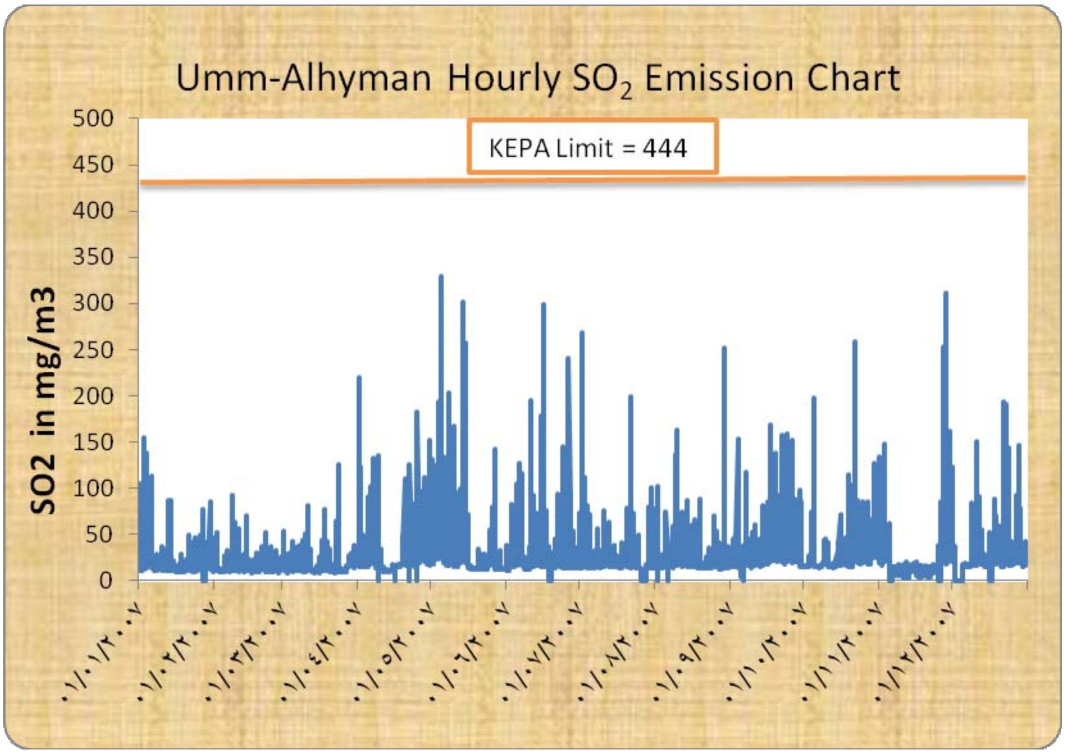

Figure 5.12: Umm-Alhyman Area $SO_2$ Hourly Emission Chart.

Figure 5.13 shows a comparison between the results of the fixed station and the air dispersion model AERMOD View for daily SO2 emissions. The plume affecting Umm-Alhyman area concentration is 30.6 mg/m$^3$. Kuwait EPA limit is 157 mg/m$^3$ which is higher than the fixed station results and the plume concentration.

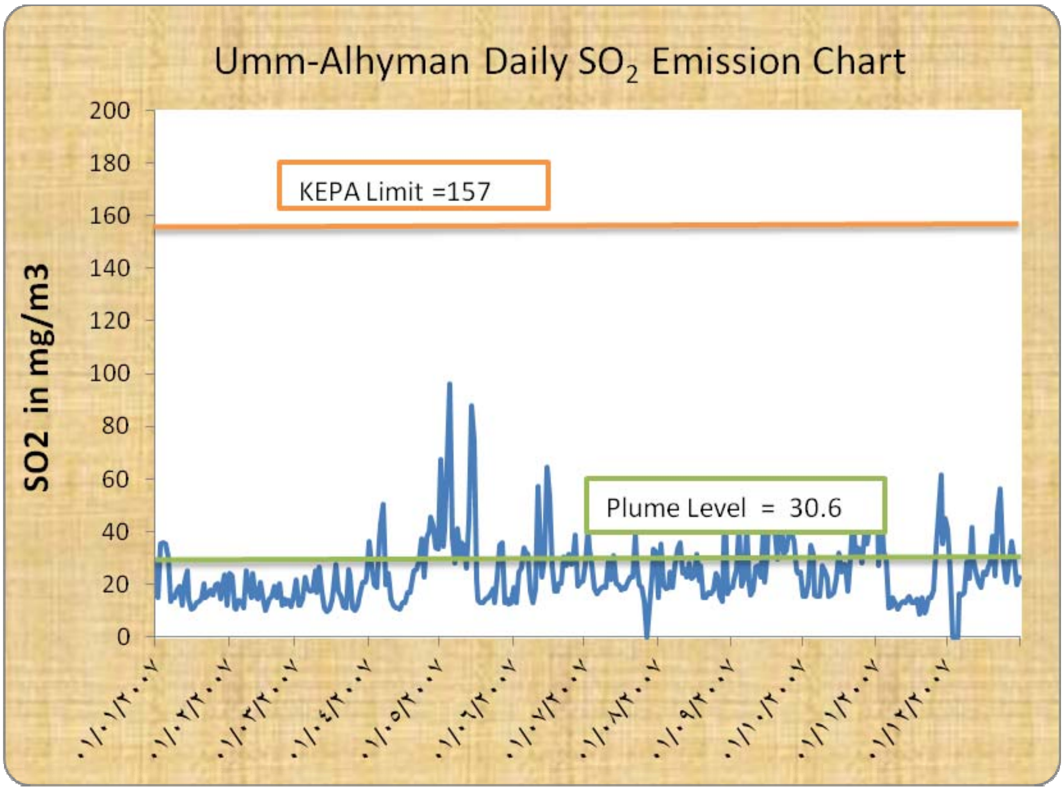

Figure 5.13: Umm-Alhyman Area $SO_2$ Daily Emission Chart

Figure 5.14 shows a comparison between the results of the fixed station and the air dispersion model AERMOD View for annual SO2 emissions. The plume affecting Umm-Alhyman area concentration is 6.9 $mg/m^3$. Kuwait EPA limit is 80 $mg/m^3$ which is higher than the fixed station results and the plume concentration.

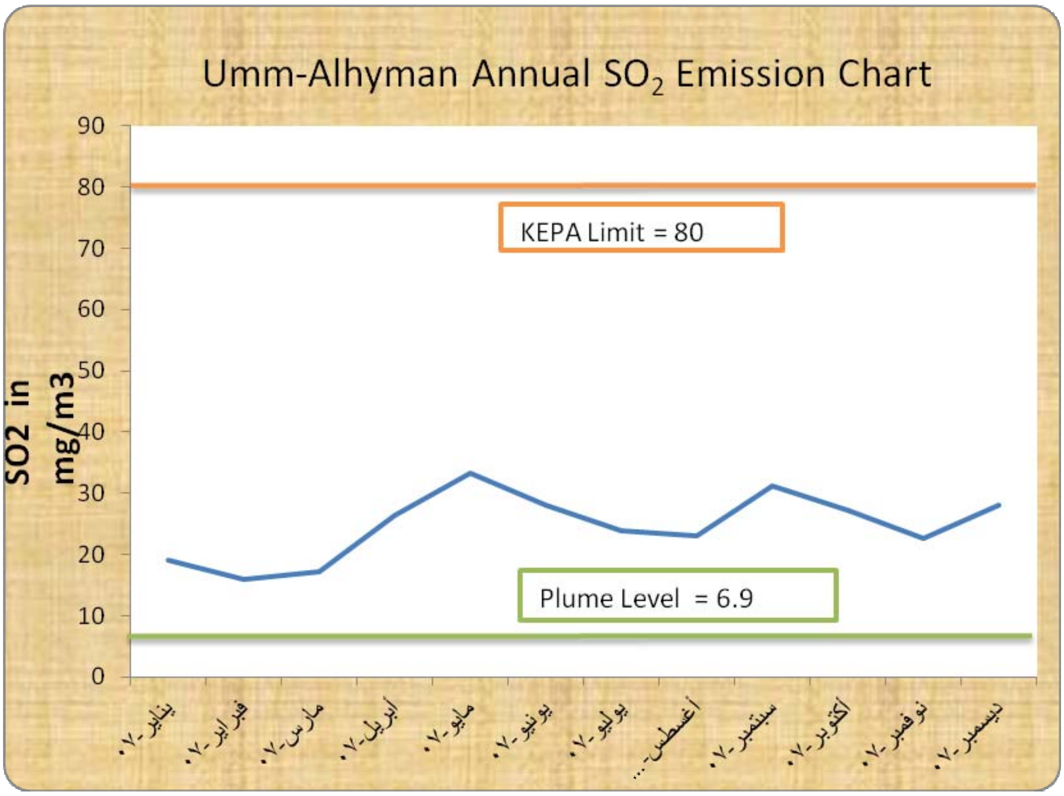

Figure 5.14: Umm-Alhyman Area $SO_2$ Annual Emission Chart

Figure 5.15 shows a comparison between the results of the fixed station and the air dispersion model AERMOD View for hourly NOx emissions. The plumes did not affect Umm-Alhyman area. Kuwait EPA limit is 225 mg/m$^3$.

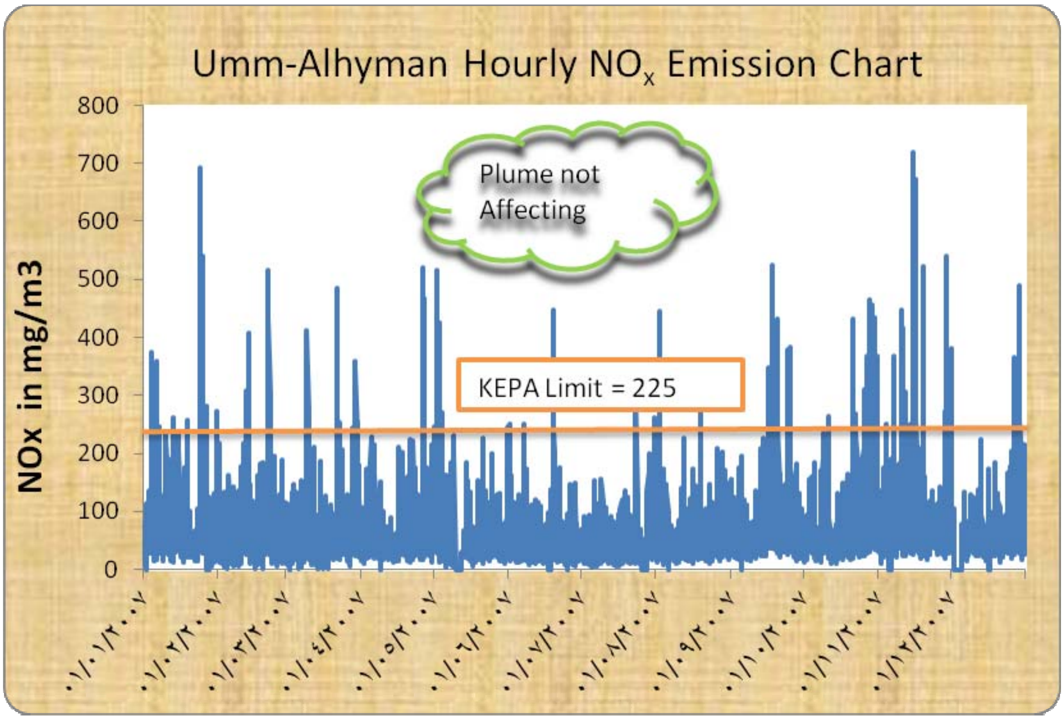

Figure 5.15: Umm-Alhyman Area NOx Hourly Emission Chart

Figure 5.16 shows a comparison between the results of the fixed station and the air dispersion model AERMOD View for daily NOx emissions. The plume affecting Umm-Alhyman area concentration is 48.6 mg/m$^3$. Kuwait EPA limit is 112 mg/m$^3$.

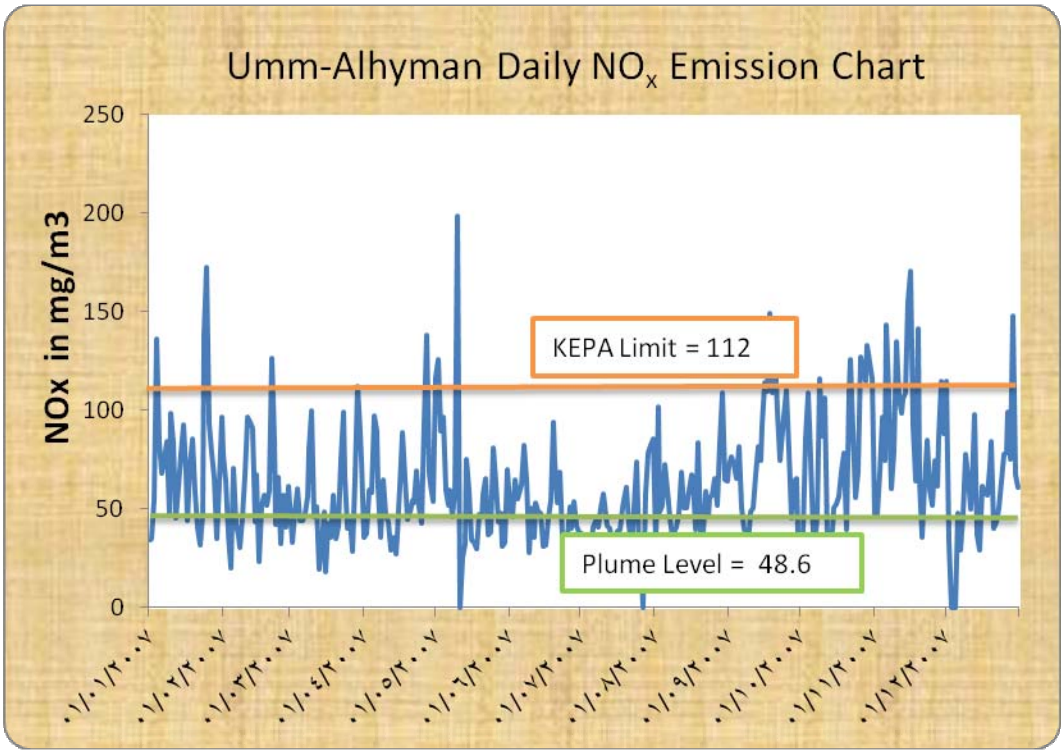

Figure 5.16: Umm-Alhyman Area NOx Daily Emission Chart

Figure 5.17 shows a comparison between the results of the fixed station and the air dispersion model AERMOD View for annual NOx emissions. Kuwait EPA limit is 67 mg/m$^3$. The plume affecting Umm-Alhyman area concentration is 5.9 mg/m$^3$ which is lower than Kuwait EPA limit and the readings of the fixed station results. This could be related to the NOx emittions from motor vehicles using the highway near Umm-Alhyman area as well as the NOx emissions produced from Al-Zour power station which is located south east of Umm-Alhyman area as shown in Fig.4.17.

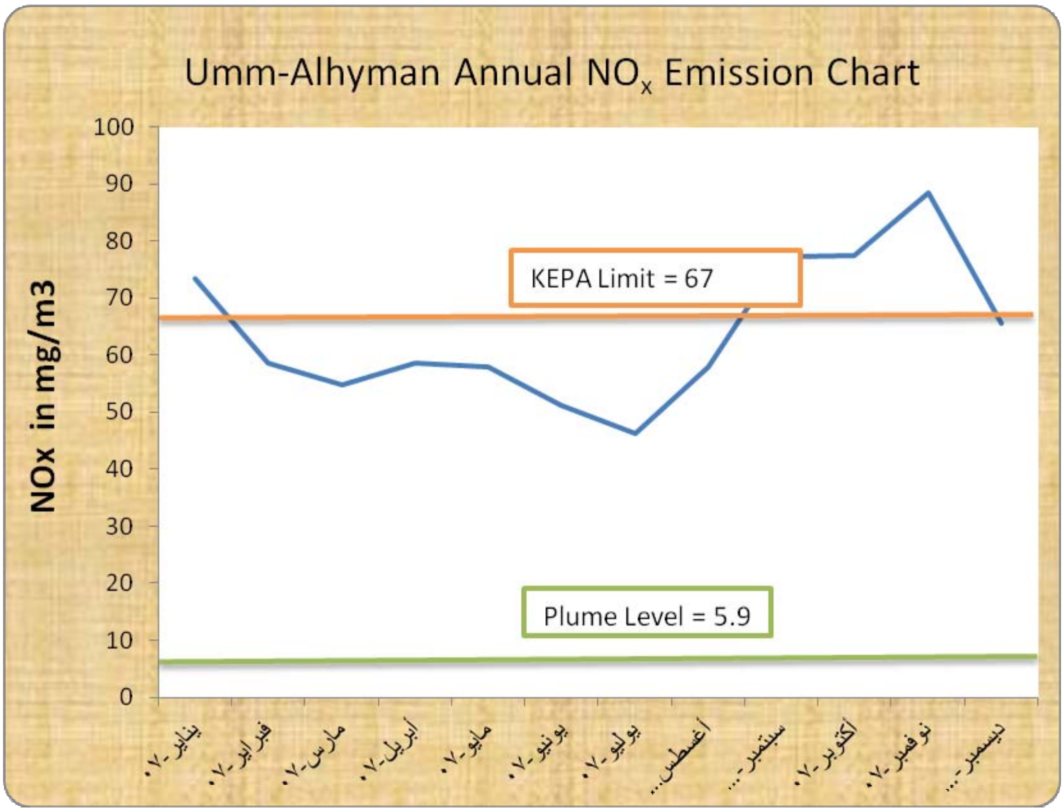

Figure 5.17 Umm-Alhyman Area NOx Annual Emission Chart

Figure 5.18 shows a comparison between the results of the fixed station and the air dispersion model AERMOD View for hourly CO emissions. Kuwait EPA limit is 34000 mg/$m^3$. The plume did not affect Umm-Alhyman area. The fixed station results are less than 6000 mg/$m^3$.

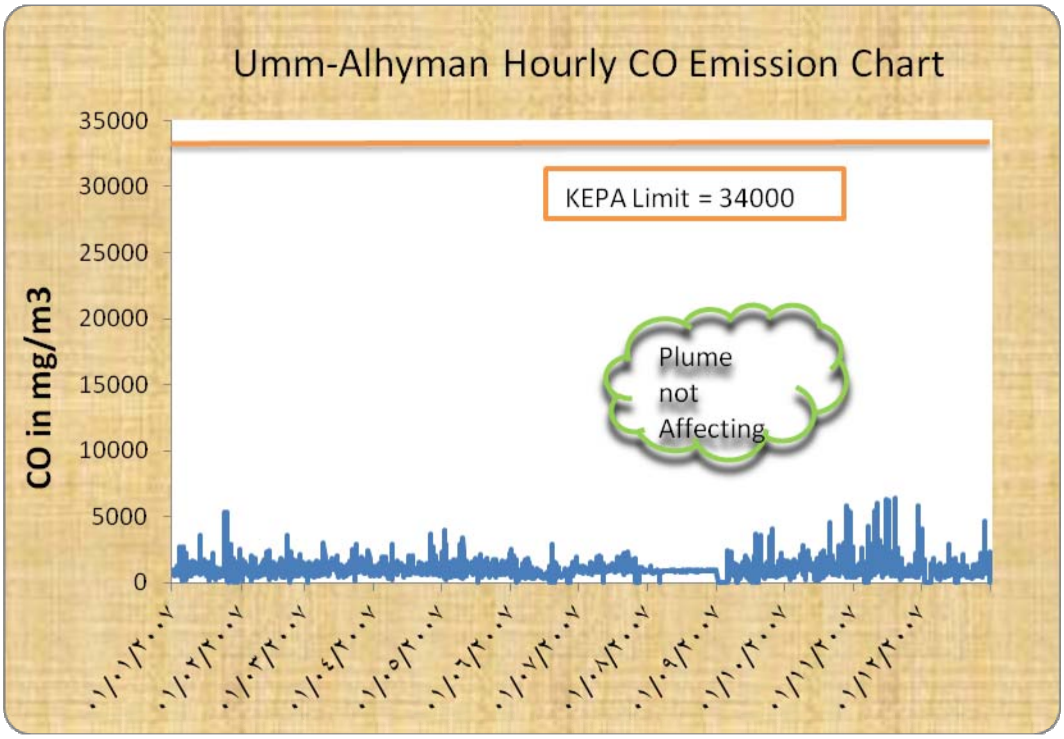

Figure 5.18: Umm-Alhyman Area CO Hourly Emission Chart

Figure 5.19 shows a comparison between the results of the fixed station and the air dispersion model AERMOD View for daily CO emissions. Kuwait EPA limit is 9000 mg/m$^3$ . The plume did not affect Umm-Alhyman area. The fixed station results are less than 2000 mg/m$^3$.

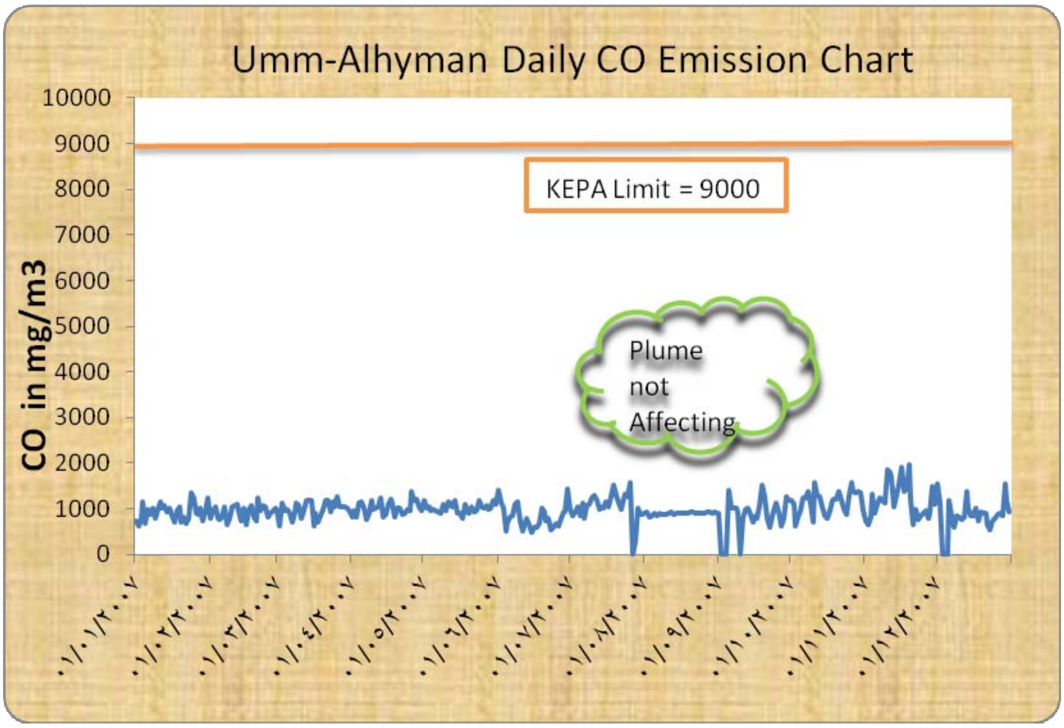

Figure 5.19: Umm-Alhyman Area CO Daily Emission Chart

Figure 5.20 shows a comparison between the results of the fixed station and the air dispersion model AERMOD View for 8-hourly CO emissions. Kuwait EPA limit is 11500 mg/m$^3$ . The plume did not affect Umm-Alhyman area. The fixed station results are less than 1200 mg/m$^3$.

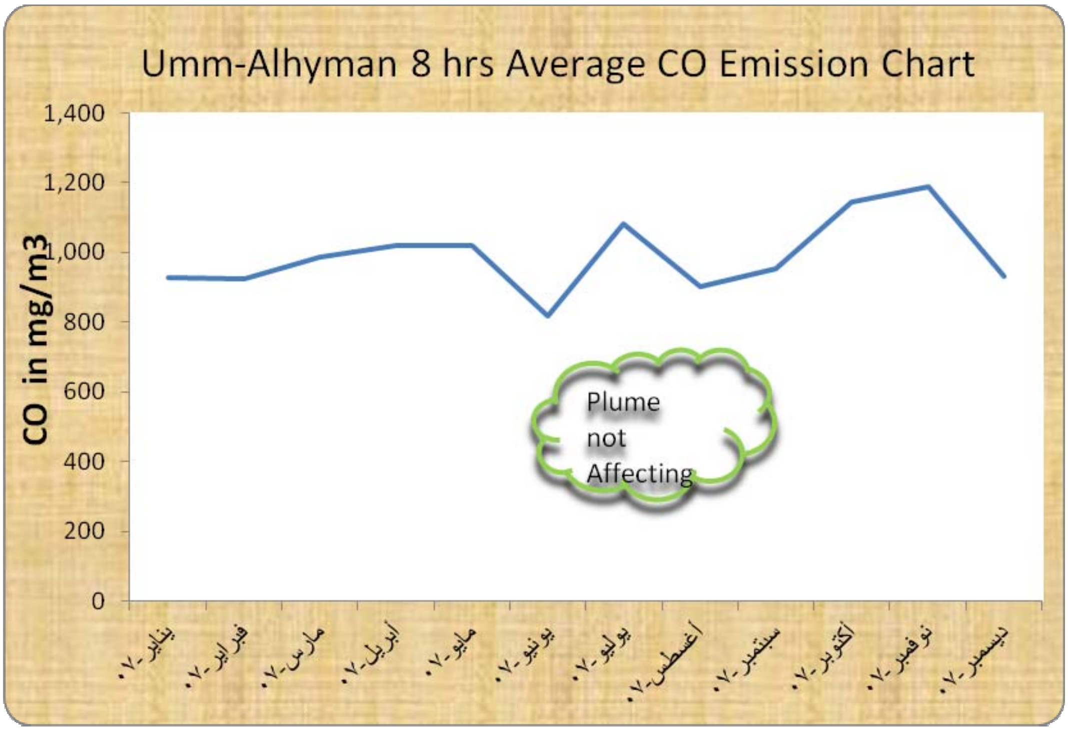

Figure 5.20: Umm-Alhyman Area CO 8 hours Emission Chart

As a result of the findings of the major pollutants, namely $SO_2$, NOx & CO, it is found that $SO_2$ and CO are not exceeding Kuwait EPA Ambient Air Quality Standards for Residential Areas normally. However, NOx is observed to exceed occasionally. Even though, the NOx emissions from refinery sources represented by plume models were much less, there is a consistent increase in the measured NOx. Furthermore, in 2007, the measured hourly, daily and annual NOx concentration exceeded the international standard many times. The increasing trend in $NO_x$ is attributed to continuous increase in population and the number of motor vehicles[22].

## 5.4 Discussions

The results presented in this thesis are based on measurements and data taken in this particular environment of Kuwait. However, similar analyses have been done at different parts of the world.

Depending on various conditions and background, the actual use of such results to solve air pollution problems can be different to suit different places. The following provides list of various strategies which have been developed and adopted by industries to reduce environmental air pollution at different parts of the world.

Richard D. Morgenstern April,2004[30] and his colleagues in their discussion paper talked about the possibility to improve environmental quality in china by the emission trading rather than the conventional administrative approaches which depends on monitoring and enforcement.

The Asian Development Bank (ADB) encouraged studies in this field especially after the effect of the new coal-fired power plants in China. The People’s Republic of China (PRC) calls in its 10th Five Year Plan (2000 – 2005) for major emissions reductions, this encouraged some chines officials to look into a new cap-and-trade system to meet the goal of that five year plan. This system is a form of trading that sets a cap on emissions from companies and industries in an area and lets them trade emissions authorizations.

Taiyuan, the capital of Shanxi Province was the first on the World Bank list of the most polluted cities in the world, this city municipality officials were forced to participate in the study. The project study should address three key areas of focus: emissions trading, Taiyuan, and sulfur dioxide (SO2) emissions. New analyses showed that savings from the use of emissions trading to manage acid rain in the United States at 40 percent or more below the cost of conventional approaches. The levy system relies on price signals to induce reductions in emissions but the trading system sets emissions quantity targets, distributes permits to the polluting firms, and allows trading of the permits among firms in the system.

Higher-cost sources benefit by saving money; they pay lower-cost sources less than it would cost to make the reduction on their own by using control technologies or process changes. In the same way, sources which cost less, gain by receiving compensation from sources which cost more for their excess reductions. Society do benefit from the transaction because at the end it achieves the required emissions reductions.

Emissions trading are likely considered to be an attractive tool for emissions control and environmental management, mostly in countries where a high pollution reduction goals are set that necessarily would include making major new pollution control investments. However, whether this tool can work in countries in which legal and official measures to ensure compliance still applied is doubtable. For example, it is not clear that state-owned enterprises (SOEs) like Kuwait National petroleum company (KNPC) have any real incentive to pursue new cost-effective emissions reduction strategies such as emissions trading.

SOEs are accustomed to negotiating their compliance with governmental agencies case-by-case and have not been subjected to aggressive enforcement.

The table below shows the cost of reducing $SO_2$ emissions by different strategies in Taiyuan by Richard D. Morgenstern and his team.

**Table 5.1: $SO_2$ Control Measures Planned or in Use in Taiyuan, 2001–2002**

| **Cost-effectiveness (RMB/ton) (US$)** | **Where applied** | **Status** | **Control measure** |
|---|---|---|---|
| Unknown | City-wide | Done | Close small boilers |
| 500–1,100 ($60–130)* | Taiyuan District Heating,<br>Xishan thermal plant, Jinxi | In use | Wet method |
| 667 ($85) | Taiyuan #1, #2, Taiyuan Iron and Steel, others | In use | Lower sulfur coal (~1.3%) |
| 1,070 ($130) | Coal gasification power plant | Planned | Add limestone to fuel |
| 1,300–1,667 ($150–200)* | Taiyuan #1, #2 | Planned | Full FGD1 |
| 2,000 ($240)** | Taiyuan #1 | In use | Simple FGD |
| 2,800 ($340) | Coking plants | Limited use | Coal washing |

1FGD = flue gas desulfurization

* As estimated by plant officials.

** Plus unspecified investment costs.

### 5.4.1 Reduction of SO2 and other pollutants

Power plants were required in Taiyuan city to upgrade their sulfur removal technologies by, for example, mixing limestone with the coal prior to combustion or by installing flue gas desulfurization (FGD). All boilers with thermal capacity greater than 10 tons of steam per hour are required to use coal with sulfur content of 1 percent or less. In addition, both of the large power plants in Taiyuan have closed several small boilers to avoid installing FGD for big number of boilers.

A primary way to reduce the emissions from Kuwait refineries is to increase the height of the stacks to the minimum standard height which is 65 meters (213 feet) measured at the base of the stack to the tip of the stack.

"Geir Husdal in 1994 commented in his paper[26]on the Offshore oil and gas production industry gas emissions and in his research, he focused on many emissions like Volatile Organic Compounds (VOC), $CO_2$ and methane besides the NOx and $SO_2$ . He explained that the potential threats of those gases are being considered by government and public as well. He mentioned that the acid rain and smog as some of the environmental problems resulted from industrial air emissions."

The Geneva Convention through its three protocols; the Helsinki protocol (1985), the Sofia Protocol (1988), and the Geneva Protocol (1991), signed by almost all industrial countries in Europe and North America, imposes obligations on the signature nations to control and reduce their emissions of $SO_2$, NOx and VOC. As a result, many countries including USA and especially after climate change convention 1992, adopted strategies to reduce greenhouse gases and their emissions such as NOx and $SO_2$.

# Chapter 6

# Sensitivity Analysis

#

Summer and winter season’s data for the three refineries will be used in the AERMOD View dispersion model and results will be compared in this chapter to test their sensitivity. The yearly data for each refinery separately will be used in the model in the next part of this chapter. Two sets of data are presented, - the season/yearly meteorological data and the average concentration of each pollutant related to the season/year. The aim is to understand and highlight the results of the AERMOD View air dispersion model at summer in comparison to results in winter for the three refineries. In addition, the chapter also aims to compare the effect of each refinery separately on the area and compare the effect to the capacity of that refinery. MAA refinery capacity is almost double MAB refinery and double SHU refinery also. For summer season, June, July, and August data were used. For winter season, December, January, and February related data were used.

## 6.1 SUMMER PLOT ANALYSIS: (June, July & August 2007 data)

Figure 6.1 shows the plumes patterns for NOx hourly concentration from the three KNPC refineries in summer. The highest concentration is 4048.2 mg/m$^3$ and the lowest is 45.3 mg/m$^3$.

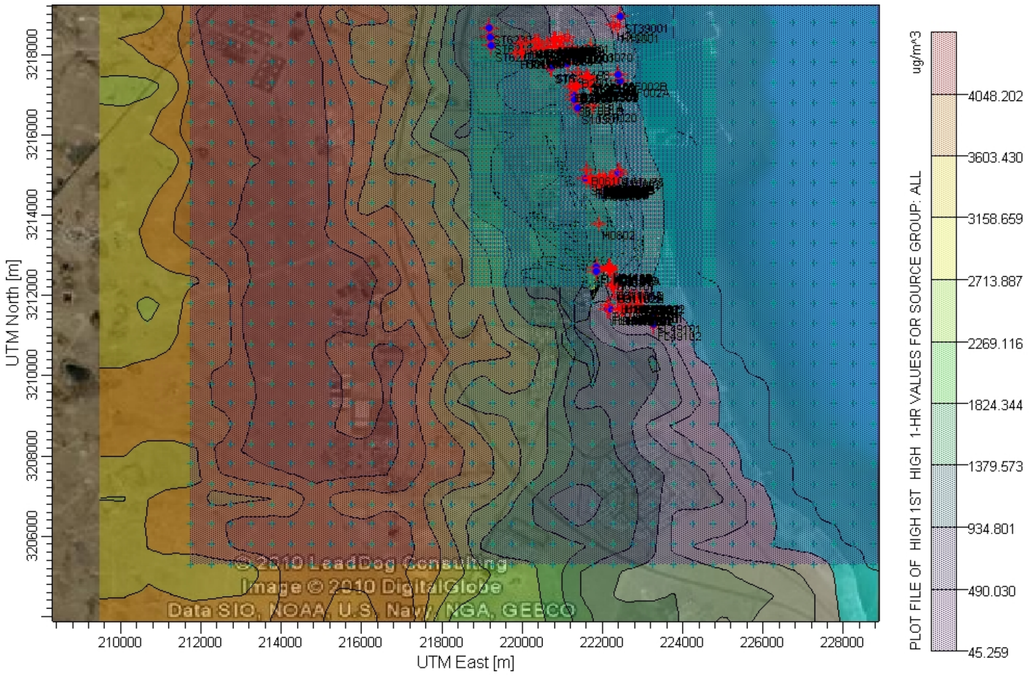

Figure 6.1: Summer plumes for NOx hourly concentration.

Figure 6.2 shows the plumes patterns for NOx daily concentration from the three KNPC refineries in summer. The highest concentration is 213.3 mg/m$^3$ and the lowest is 3.7 mg/m$^3$.

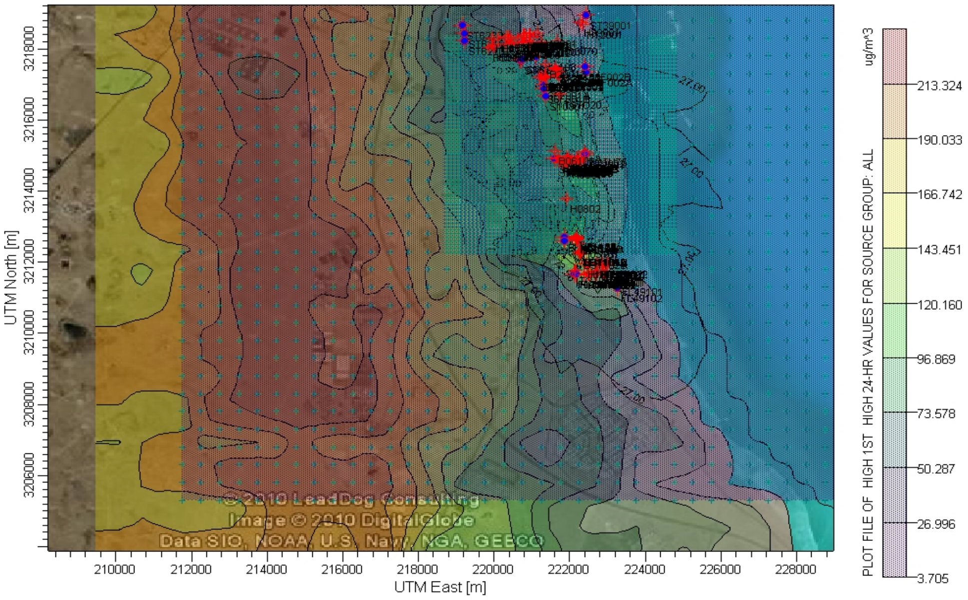

Figure 6.2: Summer plumes for NOx daily concentration.

Figure 6.3 shows the plumes patterns for $SO_2$ hourly concentration from the three KNPC refineries in summer. The highest concentration is 525.3 mg/m$^3$ and the lowest is 30.0 mg/m$^3$.

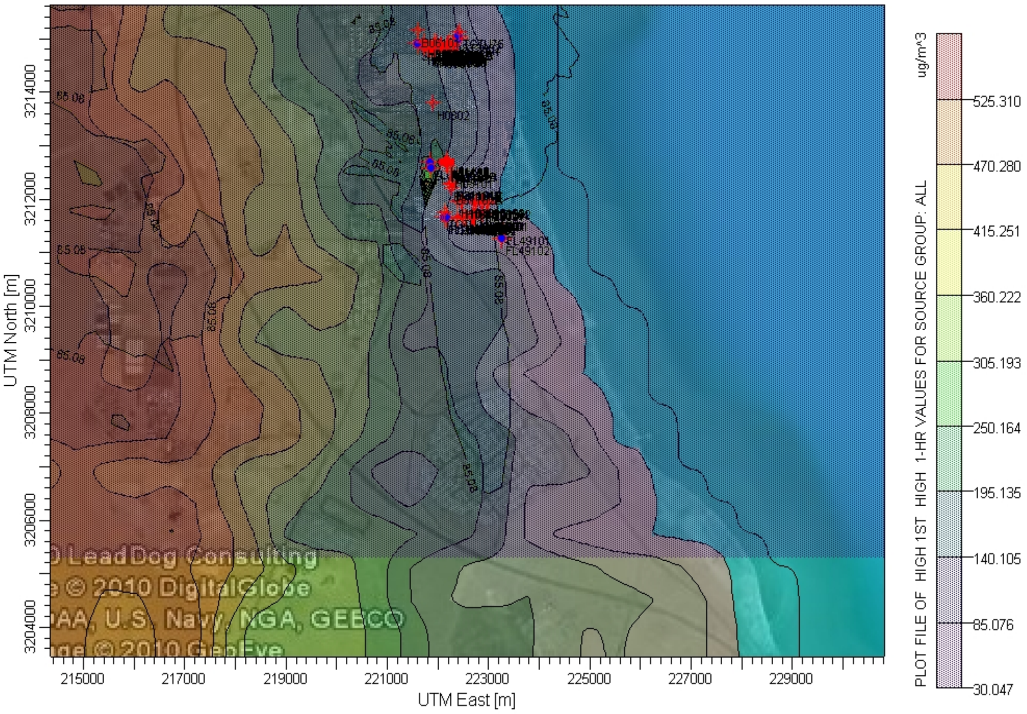

Figure 6.3 Summer plumes for $SO_2$ hourly concentration.

Figure 6.4 shows the plumes patterns for $SO_2$ daily concentration from the three KNPC refineries in summer. The highest concentration is 80.6 mg/m$^3$ and the lowest is 2.5 mg/m$^3$.

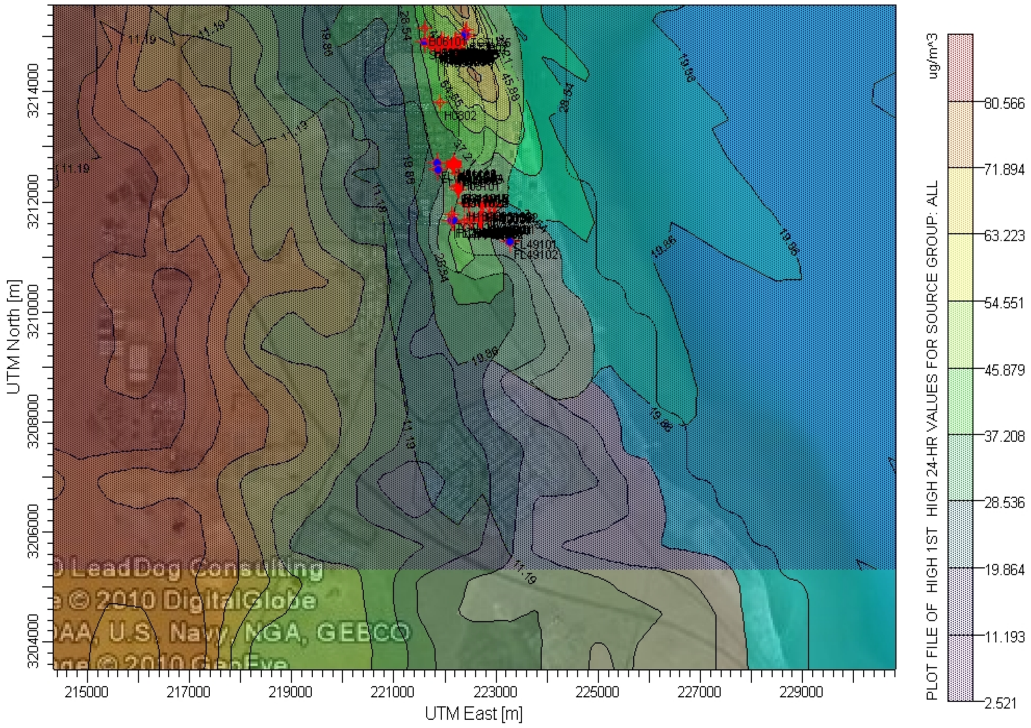

Figure 6.4 : Summer plumes for $SO_2$ daily concentration.

## 6.2 WINTER PLOT ANALYSIS: (December 2006, January & February 2007 data)

Figure 6.5 shows the plumes patterns for NOx hourly concentration from the three KNPC refineries in winter. The highest concentration is 4193.1 mg/$m^3$ and the lowest is 32.8 mg/$m^3$.

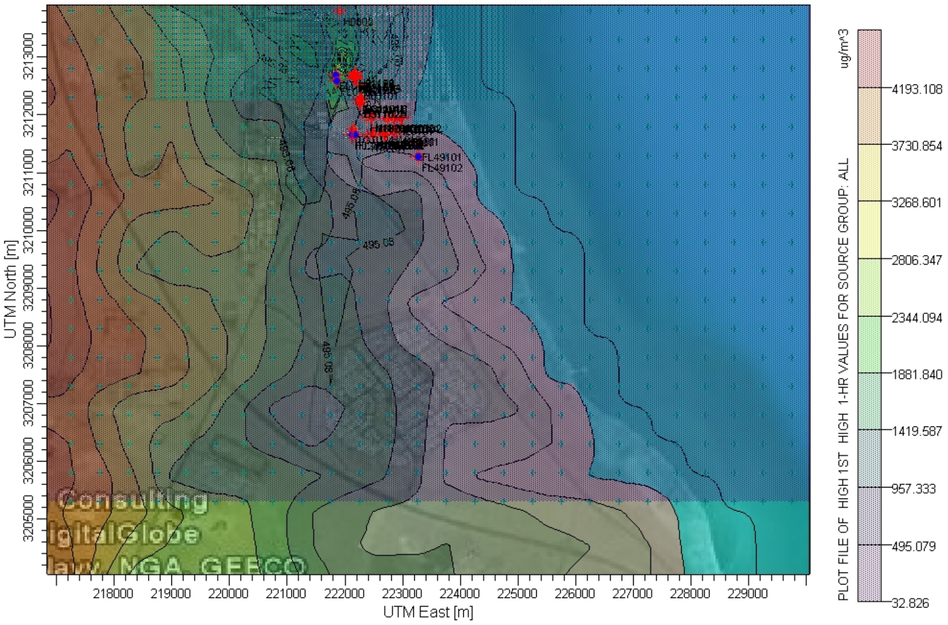

Figure 6.5: Winter plumes for NOx hourly concentration.

Figure 6.6 shows the plumes patterns for NOx daily concentration from the three KNPC refineries in winter. The highest concentration is 254.3 mg/m$^3$ and the lowest is 2.7 mg/m$^3$.

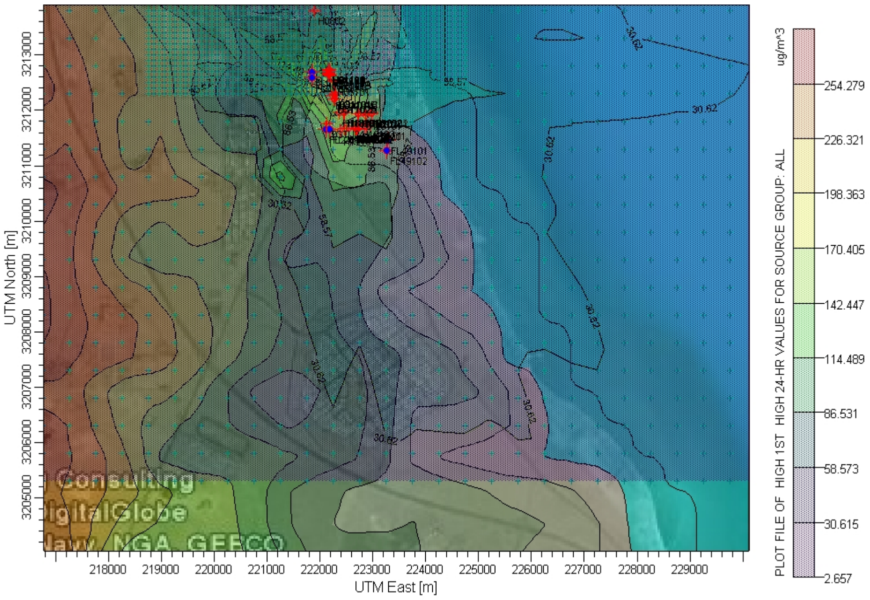

Figure 6.6: Winter plumes for NOx daily concentration.

Figure 6.7 shows the plumes patterns for $SO_2$ hourly concentration from the three KNPC refineries in winter. The highest concentration is 545.9 mg/m$^3$ and the lowest is 21.0 mg/m$^3$.

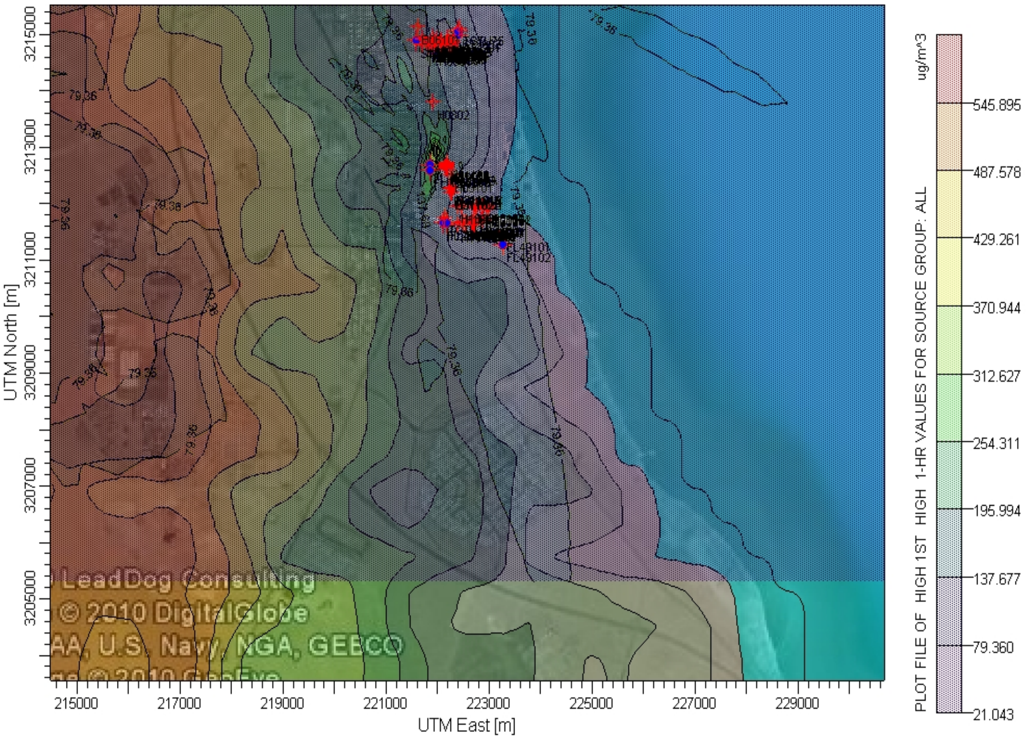

Figure 6.7: Winter plumes for $SO_2$ hourly concentration.

Figure 6.8 shows the plumes patterns for $SO_2$ daily concentration from the three KNPC refineries in winter. The highest concentration is 71.9 mg/m$^3$ and the lowest is 1.7 mg/m$^3$.

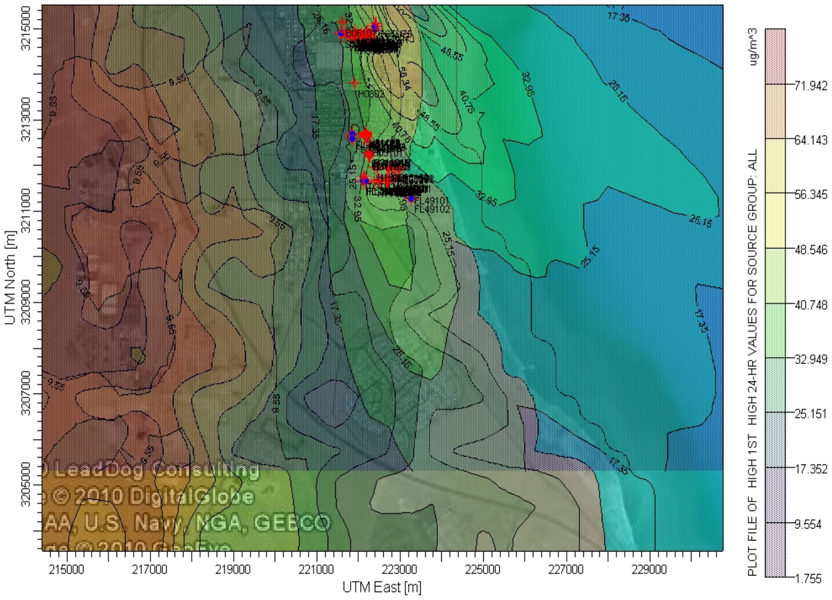

Figure 6.8: Winter plumes for $SO_2$ daily concentration.

## 6.3 KNPC Refineries Plume Pattern for each refinery

### 6.3.1 KNPC MAA, Refinery

Figure 6.9 shows the plumes patterns for $SO_2$ hourly concentration from MAA refinery. The highest concentration is 244.6 mg/m$^3$ and the lowest is 29.6 mg/m$^3$.

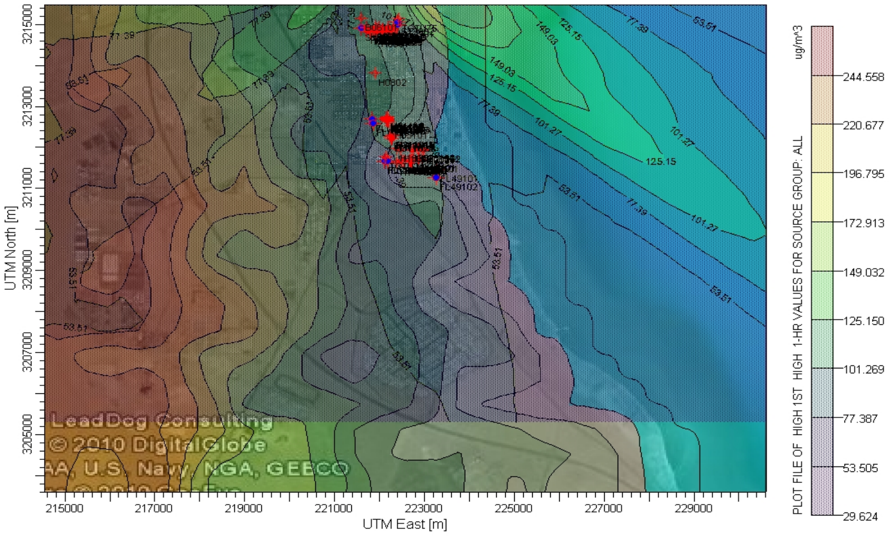

Figure 6.9: MAA plumes for $SO_2$ hourly concentration.

Figure 6.10 shows the plumes patterns for $SO_2$ daily concentration from MAA refinery. The highest concentration is 70.6 mg/$m^3$ and the lowest is 2.8 mg/$m^3$.

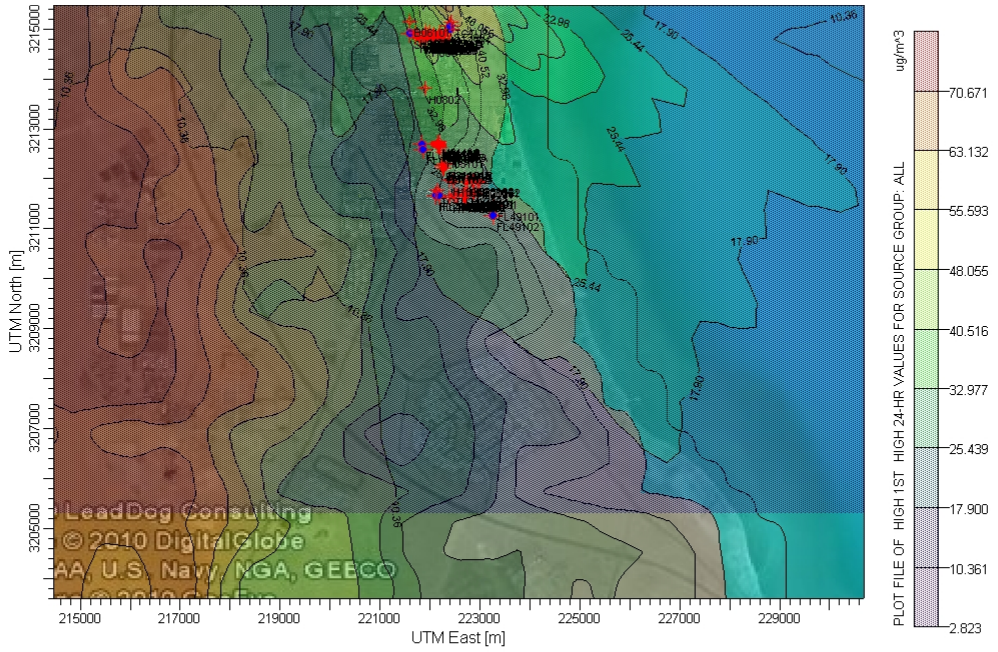

Figure 6.10: MAA plumes for $SO_2$ daily concentration.

Figure 6.11 shows the plumes patterns for $SO_2$ annual concentration from MAA refinery. The highest concentration is 18.6 mg/$m^3$ and the lowest is 0.14 mg/$m^3$.

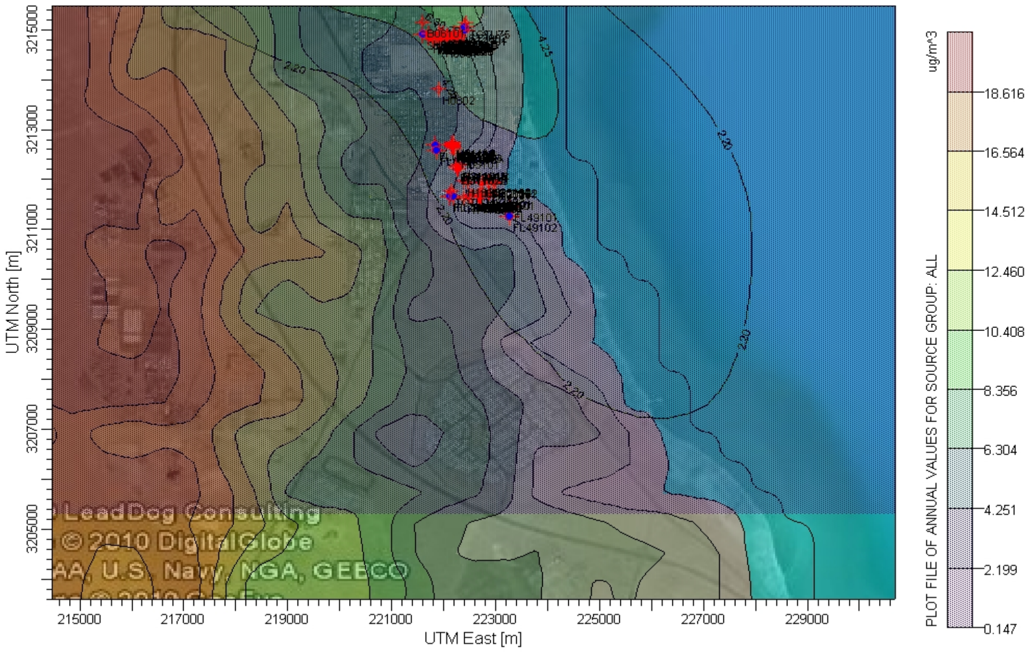

Figure 6.11: MAA plumes for $SO_2$ Annual concentration.

Figure 6.12 shows the plumes patterns for NOx hourly concentration from MAA refinery. The highest concentration is 487.5 mg/m$^3$ and the lowest is 37.5 mg/m$^3$.

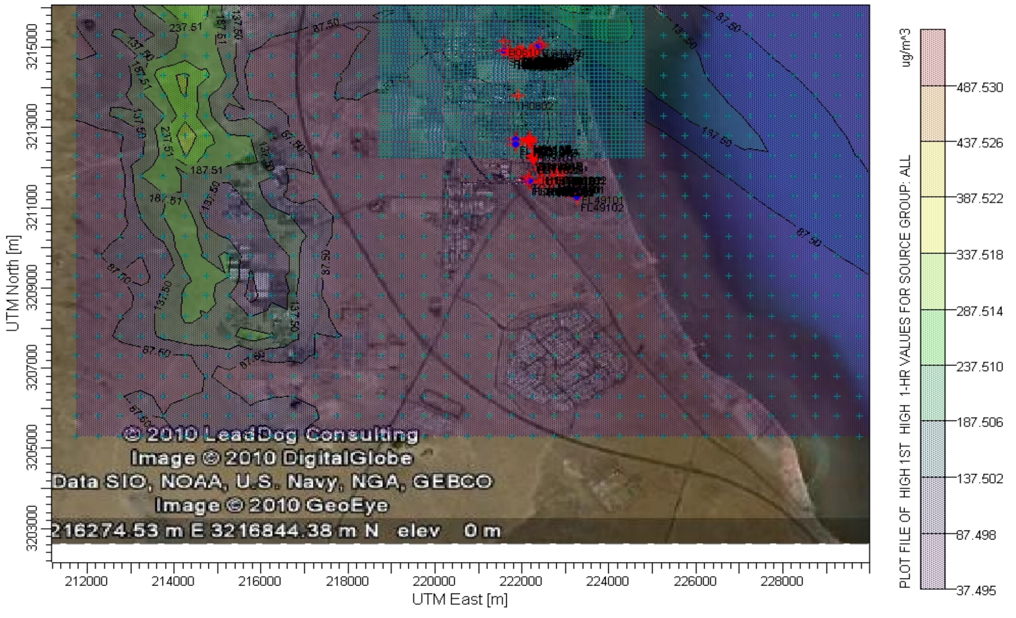

Figure 6.12: MAA plumes for NOx hourly concentration.

Figure 6.13 shows the plumes patterns for NOx daily concentration from MAA refinery. The highest concentration is 114.1 mg/m$^3$ and the lowest is 3.1 mg/m$^3$.

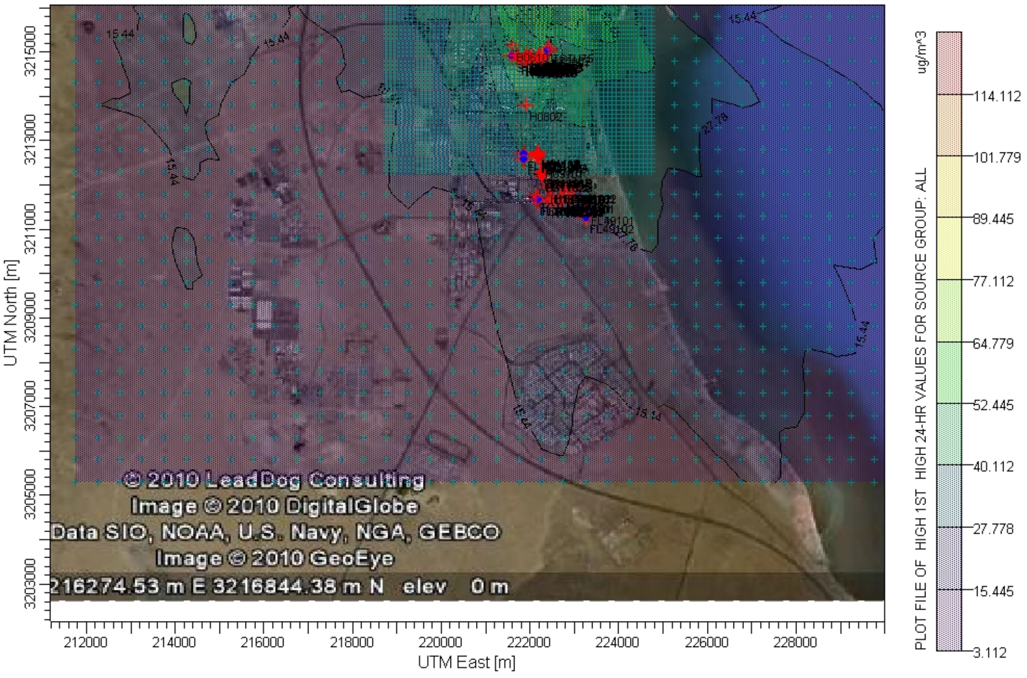

Figure 6.13: MAA plumes for NOx daily concentration.

Figure 6.14 shows the plumes patterns for NOx annual concentration from MAA refinery. The highest concentration is 25.1 mg/m$^3$ and the lowest is 0.17 mg/m$^3$.

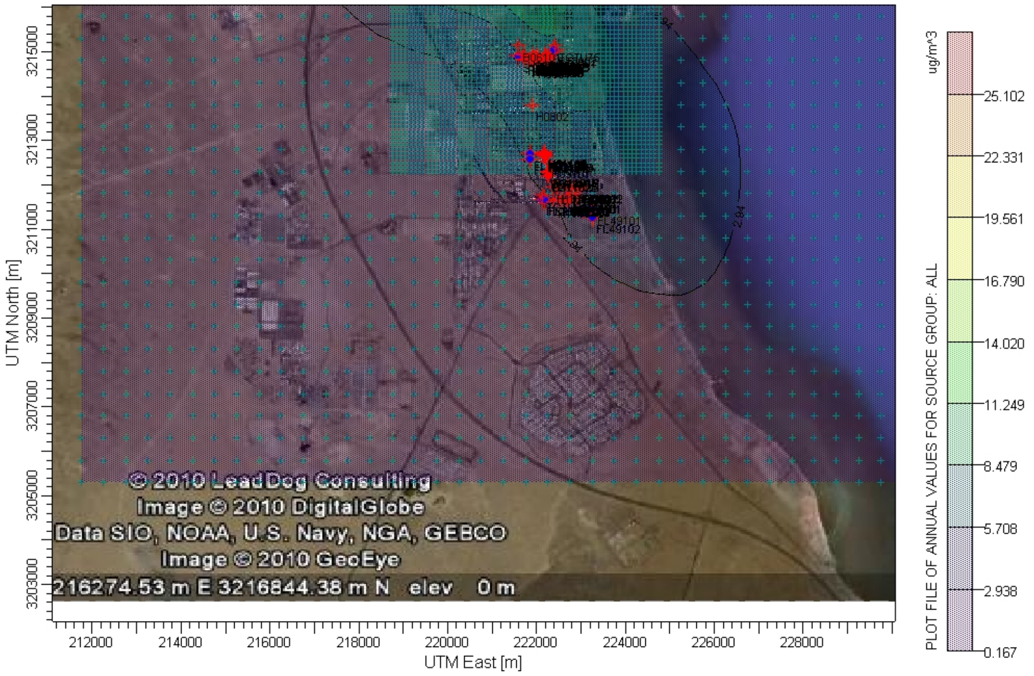

Figure 6.14: MAA plumes for NOx Annual concentration.

### 6.3.2 KNPC MAB, Refinery

Figure 6.15 shows the plumes patterns for $SO_2$ hourly concentration from MAB refinery. The highest concentration is 809.7 mg/m$^3$ and the lowest is 11.0 mg/m$^3$.

Figure 6.16 shows the plumes patterns for $SO_2$ daily concentration from MAB refinery. The highest concentration is 49.9 mg/m$^3$ and the lowest is 0.91 mg/m$^3$.

Figure 6.17 shows the plumes patterns for $SO_2$ annual concentration from MAB refinery. The highest concentration is 7.6 mg/m$^3$ and the lowest is 0.05 mg/m$^3$.

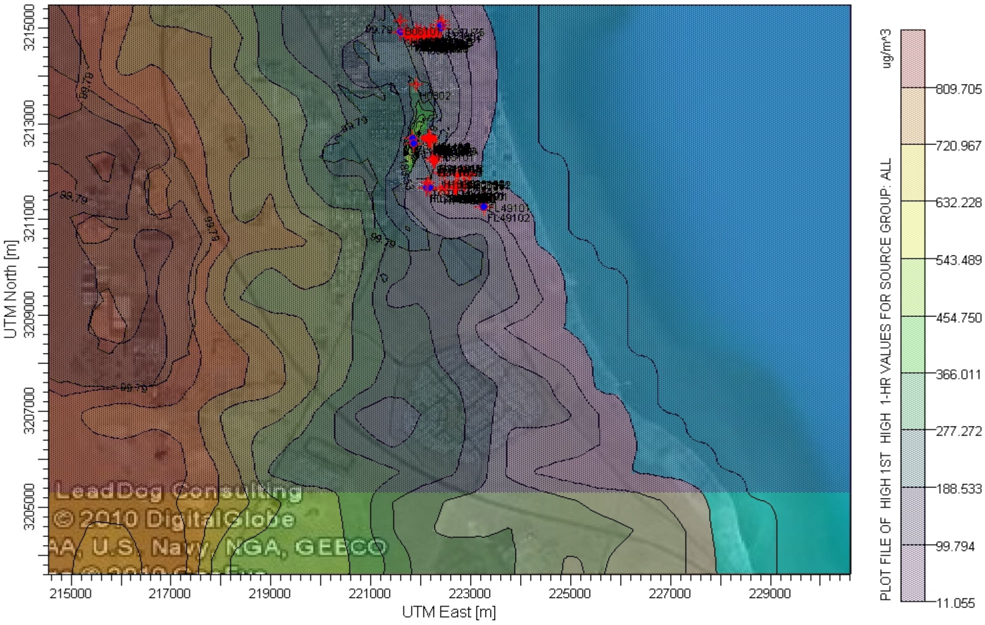

Figure 6.15: MAB plumes for $SO_2$ Hourly concentration.

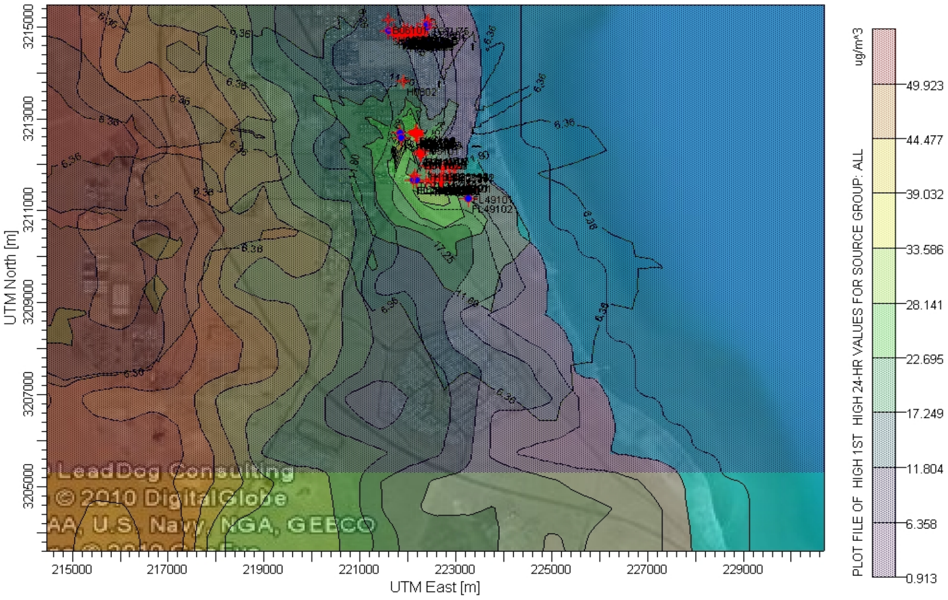

Figure 6.16: MAB plumes for $SO_2$ daily concentration

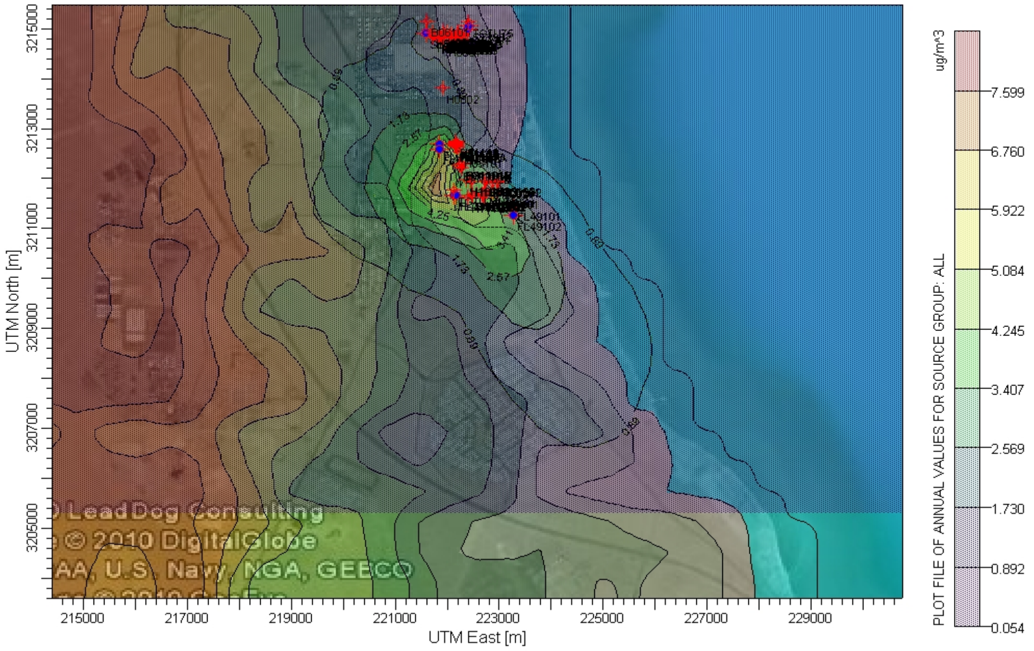

Figure 6.17: MAB plumes for $SO_2$ Annual concentration.

Figure 6.18 shows the plumes patterns for NOx hourly concentration from MAB refinery. The highest concentration is 5950.9 mg/m$^3$ and the lowest is 69.9 mg/m$^3$.

Figure 6.19 shows the plumes patterns for NOx daily concentration from MAB refinery. The highest concentration is 384.0 mg/m$^3$ and the lowest is 3.6 mg/m$^3$.

Figure 6.20 shows the plumes patterns for NOx annual concentration from MAB refinery. The highest concentration is 44.2 mg/m$^3$ and the lowest is 0.26 mg/m$^3$.

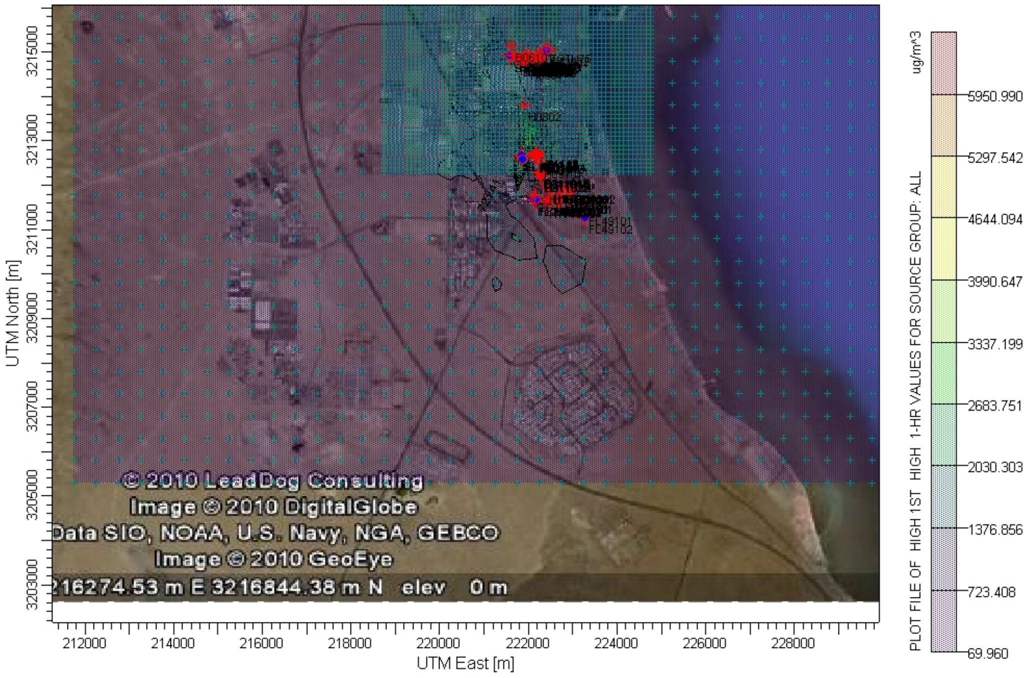

Figure 6.18: MAB plumes for NOx Hourly concentration.

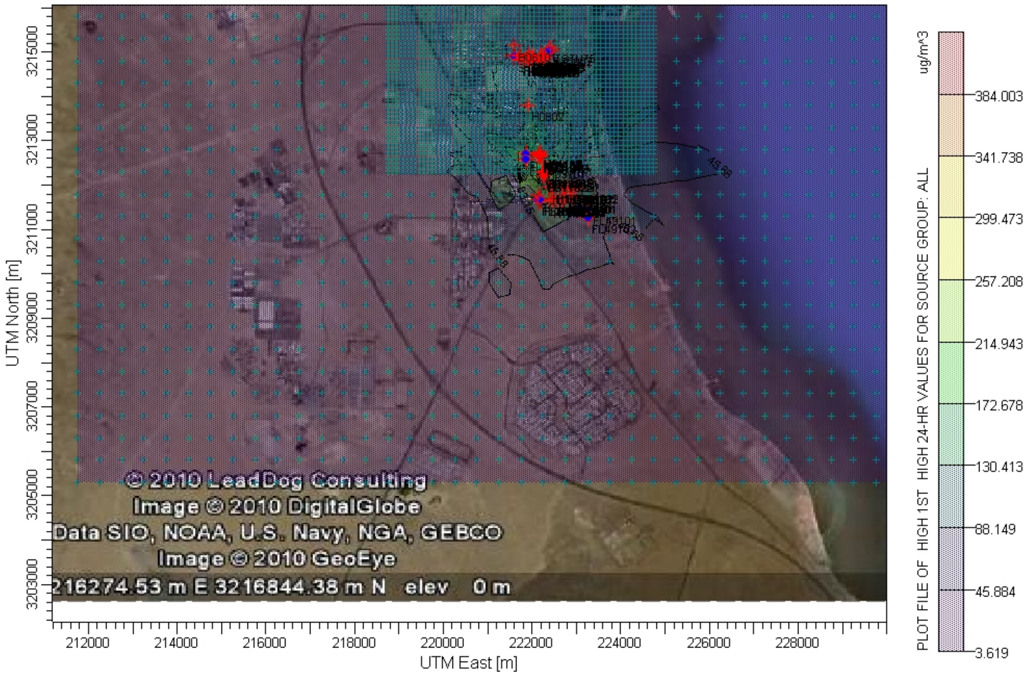

Figure 6.19: MAB plumes for NOx daily concentration

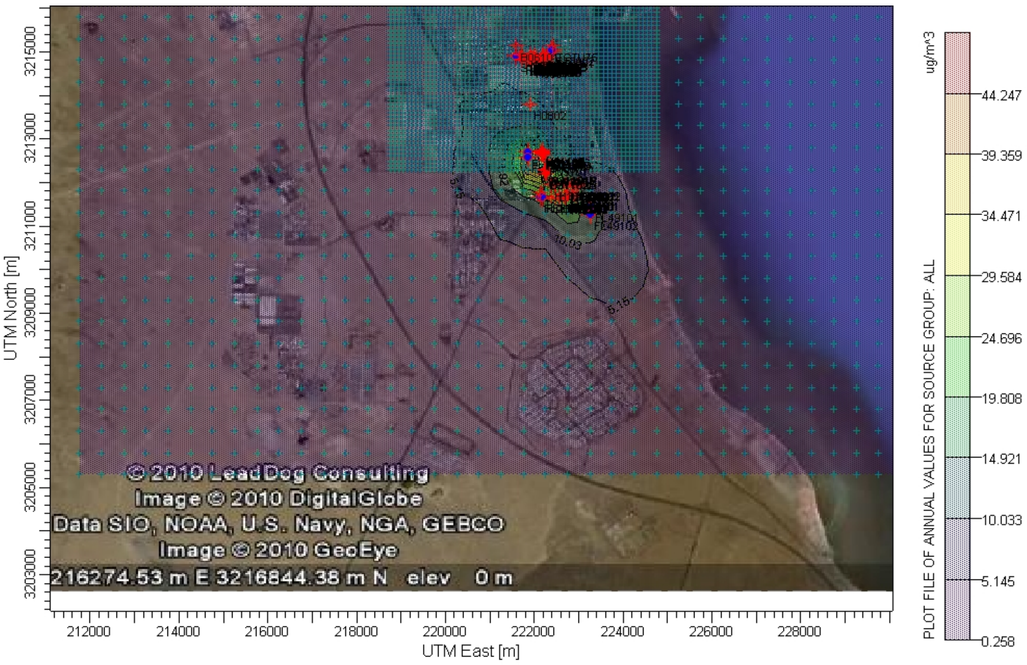

Figure 6.20: MAB plumes for NOx Annual concentration.

### 6.3.3 KNPC SHU, Refinery

Figure 6.21 shows the plumes patterns for $SO_2$ hourly concentration from SHU refinery. The highest concentration is 213.3 mg/$m^3$ and the lowest is 15.3 mg/$m^3$. Figure 6.22 shows the plumes patterns for $SO_2$ daily concentration from SHU refinery. The highest concentration is 46.8 mg/$m^3$ and the lowest is 1.3 mg/$m^3$. Figure 6.23 shows the plumes patterns for $SO_2$ annual concentration from SHU refinery. The highest concentration is 12.1 mg/$m^3$ and the lowest is 0.1 mg/$m^3$.

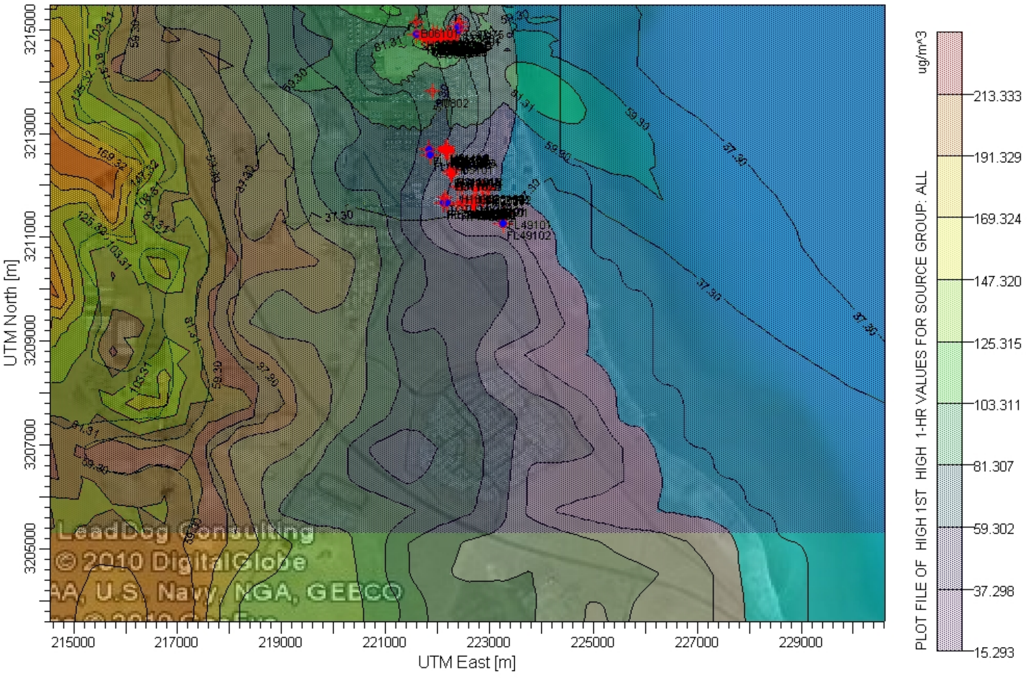

Figure 6.21: SHU plumes for $SO_2$ Hourly concentration.

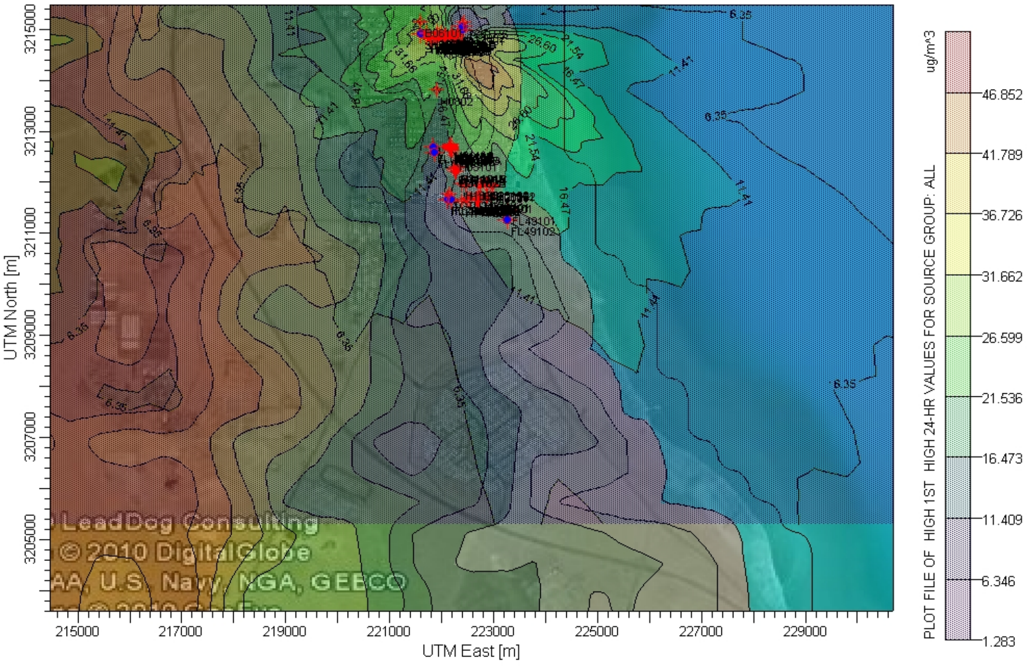

Figure 6.22: SHU plumes for $SO_2$ daily concentration.

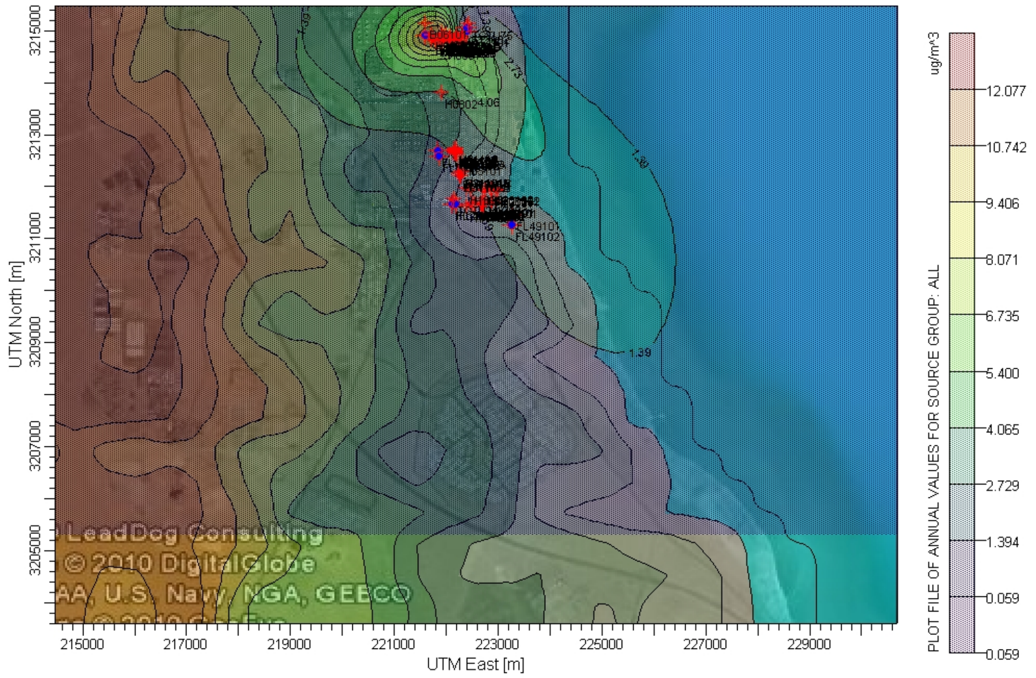

Figure 6.23: SHU plumes for $SO_2$ Annual concentration.

Figure 6.24 shows the plumes patterns for NOx hourly concentration from SHU refinery. The highest concentration is 214.0 mg/m$^3$ and the lowest is 15.6 mg/m$^3$. Figure 6.25 shows the plumes patterns for NOx daily concentration from SHU refinery. The highest concentration is 60.7 mg/m$^3$ and the lowest is 0.98 mg/m$^3$. Figure 6.26 shows the plumes patterns for NOx annual concentration from SHU refinery. The highest concentration is 0.05 mg/m$^3$ and the lowest is 0.26 mg/m$^3$.

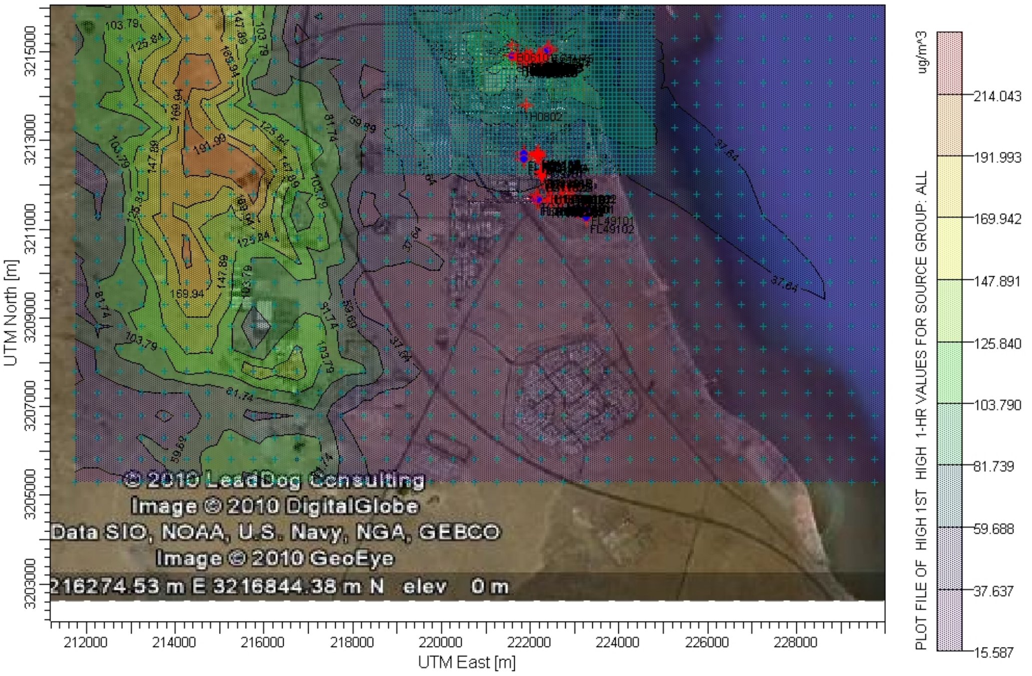

Figure 6.24: SHU plumes for NOx Hourly concentration.

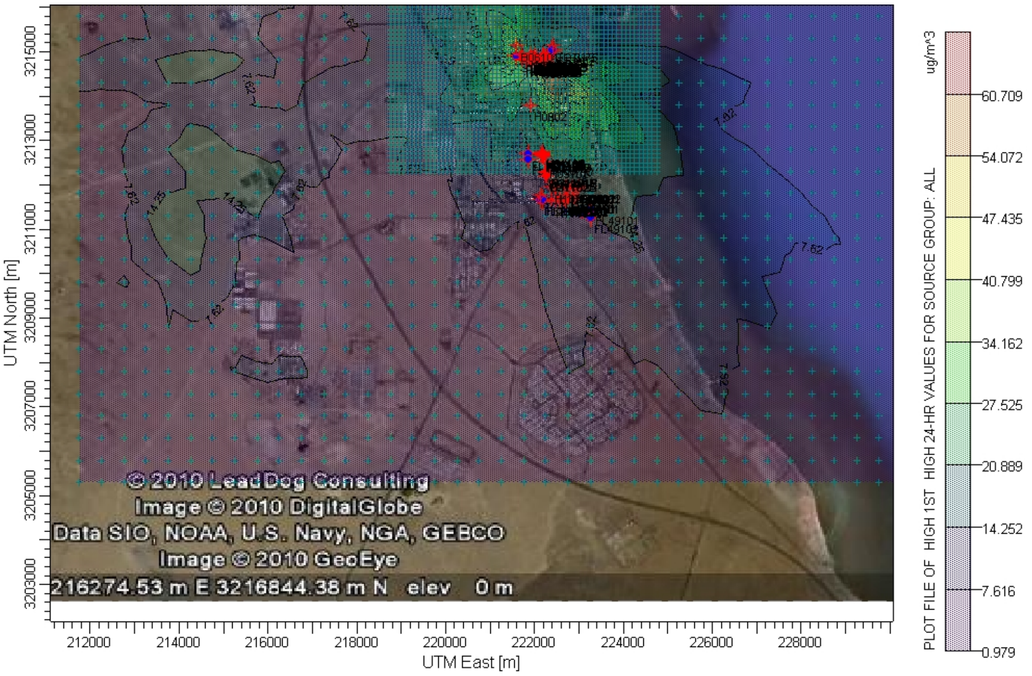

Figure 6.25: SHU plumes for NOx daily concentration.

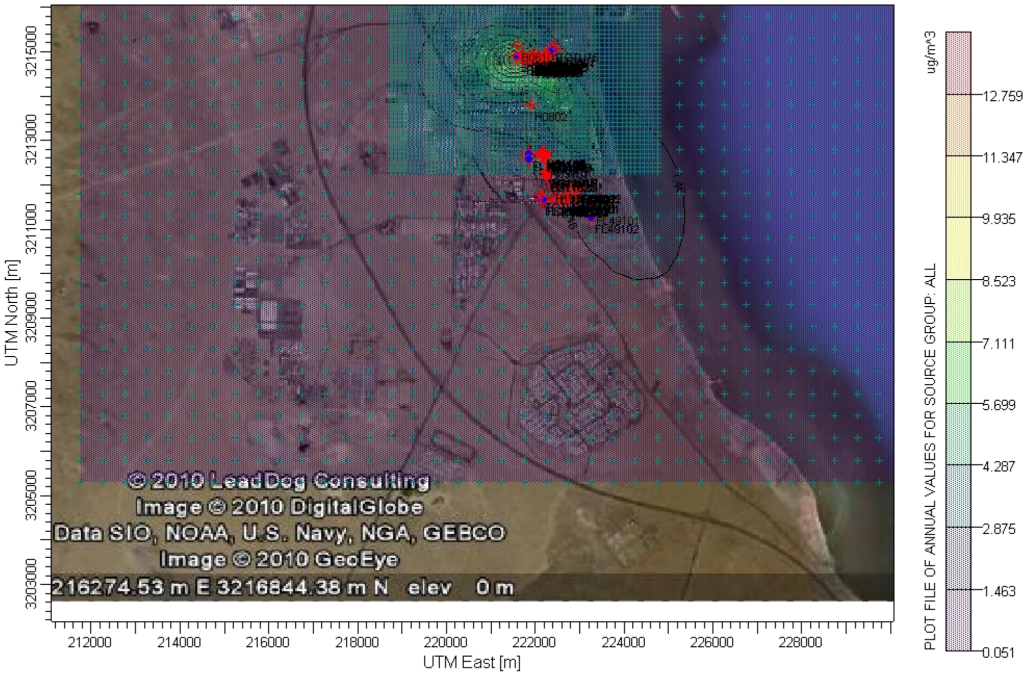

Figure 6.26: SHU plumes for NOx Annual concentration

# *Chapter 7*

# *Conclusions and Recommendations for Future Work*

## 7.1 Conclusions

Almost all of the objectives of the present project as stated in the introduction to this thesis have been achieved. The main conclusion is that the use of computer modeling is appropriate for the prediction of ground level concentration of pollutants in urban environments which are located in the vicinity of major petroleum refineries. As is discussed in the previous chapters this investigation has provided a convenient means to quantitatively analyze effects of refinery emissions on ground level concentration of pollutants. It has also been possible to include contributions from all of pollution sources such as industry, urban transportation traffic, etc. to evaluate the impact of various sources on the air quality of residential areas.

However, the AERMOD software comes with its limitations. Some of the observed draw backs include:

1. The huge amount of parameters needed as input data could cause some errors with the results if there is a systematic error with any of the parameters. The larger the amount of parameters, the more prone to this type of error
2. At the moment, the module does not have the option of automatically comparing the air dispersion model results with the fixed station results. Ability to do this will greatly aid the comparison and thus save on time and accuracy.

Despite these limitations, it should be said that the software performed optimally for what was required in this project.

In view of the results obtained in this project the following practical conclusions have also been made which make it possible to formulate a number of recommendations for the reduction of ground level pollution in the residential areas located in the vicinity of petroleum refineries. Therefore engineering solutions listed below are recommended:

- To adopt methodologies which lead to the reduction of $SO_2$, CO and NOx emissions from KNPC refineries. In this way the pollutants load is reduced which makes the task of environmental management much easier.
- To work with environmental agencies to set targets for emissions as limits that should not be exceeded. These limits should reflect the number of industries in the area, their emission sizes and desirable ambient air standard for residential areas.
- To create an awareness and educate civil and industry leadership about the benefits of adopting limits for pollutants emissions.
- The specific technique of the installation of catalytic convertors in the outlet stacks of pollutants will be very useful for NOx reduction and should be employed by refineries.
- In the case of refineries studied in this project upgrading of the existing

old burners in heaters and boilers to more modern Ultra NOx burners will dramatically reduce the emission levels.

## 7.2 Recommendations for future work

Although every effort has been made to include all of the relevant factors which influence the outcome of the present investigation there are a number of areas which have remained relatively unexplored and should be considered in future projects. In the present work the main focus has been on the investigation of the impact of current practices in the context of an existing refinery complex. Therefore, this study does not include prediction of the impact of introducing different and more modern petroleum refining processes. As it is clearly concluded by the present work, the impact of introducing features such as catalytic convertors on the effects of emissions on environment can be very significant. It is, hence, useful to numerically quantify the effects of such up-grading by further simulations by the computer model. Another aspect of future work is the inclusion of NOx emissions from motor vehicles which was not considered in this research. This would ensure the robustness of the future research.

Finally, in this study the ground level concentration of three major pollutants, i.e. NOx, SO2 and CO, have been investigated. However, in a complex operation such as petroleum refining other pollutants are also produced and emitted to environment and levels and impact of such pollutants should also be investigated in future studies.

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# *Appendix*

**Table A1: MAA REFINERY POINT SOURCES**

| **PROCESS HEATERS (Equipment ID)** | |
|---|---|
| H-84-100 | 31-2F101 |
| H-84-200 | 31-2F102 |
| 41-H001 | 31-2F103 |
| 41-H002 | 31-3F101 |
| 41-H003 | 31-3F102 |
| 42-H001 | 32-2F201 |
| 42-H002 | 32-2F202 |
| 81-H001 | 32-2F203 |
| 81-H002 | 32-3F201 |
| 81-H003 | 32-3F202 |
| 82-H001 | 33-2F301 |
| 82-H002 | 33-2F302 |
| H-03-070 | 33-2F303 |
| H-40-001 | 33-3F301 |
| H-80-001 | 33-3F302 |
| H-39-001 | H-48-001 |
| H-12-001 | H-49-001 |
| H-43-001 | H-88-001 |
| H-44-001 | H-89-001 |
| H-58-001 | H-83-001 |
| | H-84-320 |
| **BOILERS (Equipment ID)** | |
| B-29-001 | B-29-011 |
| B-29-101 | B-29-012 |
| B-29-701 | B-29-013 |
| | B-29-014 |
| **SULFUR RECOVERY UNIT (Equipment ID)** | |
| SRU-92 | SRU-51 |

| | |
|---|---|
| 20-500 | SRU-52 |
| 21-500 | SRU-91 |
| **FLUIDIZED CATALYTIC CRACKING UNIT (Equipment ID)** | |
| **FCC-UNIT-86 - FLARE** | |
| ST-62-102 | ST-62-401 |
| ST-62-301 | ST-62-001 |
| ST-11-9800 | ST-62-101 |
| 36 F 001 A | ST-39-001 |
| 36 F 001 B | S-10-301 |
| 36 F 002 A | S-10-302 |
| 36 F 002 B | 36 F 006 A |
| 36 F 004 A | 36 F 006 B |
| | 36 F 004 B |

## Table A2: MAB REFINERY POINT SOURCES

| **PROCESS HEATERS (Equipment ID)** | |
|---|---|
| H-12-202 | H-01-101 |
| H-12-103 | H-01-102 |
| H-13-101 | H-01-104 |
| H-13-201 | H-01-105 |
| H-14-101 | H-01-106 |
| H-14-102 | H-01-107 |
| H-14-103 | H-01-108 |
| H-15-101 | H-01-109 |
| H-16-101 | H-01-110 |
| H-17-101 | H-02-101A |
| H-18-101 | H-02-101B |
| H-18-201 | H-02-102 |
| H-18-301 | H-03-101 |
| H-20-101 | H-11-101 |
| H-20-102 | H-12-101 |
| H-20-201 | H-12-102 |
| H-20-202 | H-12-201 |
| **BOILERS (Equipment ID)** | |
| B-31-101C | B-06-101 |
| B-31-102A | B-31-101A |
| B-31-102B | B-31-101B |
| **SULFUR RECOVERY UNIT (Equipment ID)** | |
| FL-24-201 | FL-24-101 |
| **FLARE** | |
| FL-01-103 | FL-49-101 |
| FL-23-101 | FL-49-102 |
| FL-23-102 | FL-01-102 |

## Table A3 : SHU REFINERY POINT SOURCES

| **PROCESS HEATERS (Equipment ID)** | |
|---|---|
| H-11-04 | H-05-01 |
| H-11-05 | H-06-01 |
| H-11-06 | H-06-02 |
| H-12-01 | H-06-03 |
| H-12-03 | H-06-04 |
| H-12-04 | H-07-01A |
| H-13-01 | H-07-02A |
| H-13-03 | H-07-01B |
| H-63-01 | H-07-02 B |
| H-68-01 | H-08-01 |
| H-68-02 | H-08-02 |
| H-02-01 | H-09-01 |
| H-05-51 | H-10-01 |
| H-62-01 | H-11-02 |
| | H-11-03 |
| **BOILERS (Equipment ID)** | |
| B-20-01 C | B-20-01A |
| B-20-01 D | B-20-01 B |
| **SULFUR RECOVERY UNITS (Equipment ID)** | |
| | Unit 75 |
| **FLARE** | |
| ST-29-03 | ST-29-01 |
| | ST-29-02 |

## Table A4: The AERMOD data input for NOx Dispersion Module

| source type | source ID | x coordinates | y coordinates | base elevation | release height | gas exit temp | stack inside dia | Emission Rate |
|---|---|---|---|---|---|---|---|---|
| | | M | m | m | m | k | m | |
| point | B2001A | 222203.18 | 3214937.84 | 12.8 | 18.3 | 675.7 | 2.97 | 6.275633937 |
| | B2001B | 222200.25 | 3214928.67 | 12.96 | 18.3 | 648.556 | 2.97 | 6.221174748 |
| | B2001C | 222202.51 | 3214910.13 | 13.1 | 18.3 | 659.111 | 2.97 | 6.582511725 |
| | B2001D | 222204.92 | 3214897.74 | 13.16 | 18.3 | 677.444 | 2.97 | 4.536557821 |
| | ST2901 | 222396.9 | 3214997.87 | 8.18 | 73.446 | 1144.111 | 0.915 | 0.014205502 |
| | ST2902 | 222400.95 | 3215053.24 | 7.93 | 73.446 | 1144.111 | 0.915 | 0.014239948 |
| | ST2903 | 221593.02 | 3214903.31 | 26.22 | 101.224 | 1144.111 | 0.915 | 0.013890222 |
| | H0201 | 221896.921 | 3214815.84 | 20.39 | 52.2 | 699.66667 | 3.66 | 0.902002839 |
| | H0251 | 221837.229 | 3214811.12 | 21.51 | 52.2 | 699.66667 | 3.66 | 0.942332754 |
| | H0501 | 222183.515 | 3214796.58 | 14.45 | 24.7 | 977.44444 | 3.05 | 0.057015205 |
| | H0601 | 221920.884 | 3214910.78 | 19.25 | 44.2 | 623.55556 | 1.98 | 8.272208458 |
| | H0602 | 221919.692 | 3214861.51 | 19.27 | 40.6 | 738 | 1.45 | 5.907916329 |
| | H0603 | 221919.221 | 3214953.96 | 18.77 | 45 | 697.44444 | 2.27 | 11.61517448 |
| | H0604 | 221908.717 | 3214855.61 | 19.82 | 26.1 | 798 | 1.71 | 0.78031757 |
| | H0701A | 221949.538 | 3214863.86 | 18.96 | 27.4 | 970.22222 | 1.3 | 0.375502773 |
| | H0701B | 222021.72 | 3214825.14 | 17.33 | 29 | 924.66667 | 1.75 | 0.34493089 |
| | H0702A | 221951.425 | 3214829.92 | 19 | 27.4 | 966.33333 | 1.3 | 0.048898167 |
| | H0702B | 222055.018 | 3214858.23 | 16.88 | 29 | 865.22222 | 1.75 | 0.045406462 |
| | H0703 | 221988.994 | 3214927.62 | 17.63 | 14.7 | 711.33333 | 1.22 | 0.213433363 |
| | H0704 | 222072.002 | 3214888.63 | 16.05 | 56.4 | 616.33333 | 1.68 | 0.03201116 |
| | H0801 | 221952.417 | 3214759.03 | 19.54 | 35.4 | 1009.1111 | 1.22 | 0.020756514 |
| | H0802 | 221904.743 | 3213803.32 | 25.75 | 40.4 | 926.33333 | 2.44 | 0.945908168 |
| | H0901 | 222293.34 | 3214858.63 | 11.57 | 40.4 | 960.77778 | 2.44 | 3.534102257 |
| | H1001 | 222165.538 | 3214837.07 | 14.17 | 30.8 | 1021.8889 | 1.52 | 0.017305108 |
| | H1102 | 222203.95 | 3214857.71 | 13.63 | 32.9 | 839.66667 | 1.62 | 0.616487159 |
| | H1103 | 222206.88 | 3214866.88 | 13.55 | 30.5 | 875.77778 | 1.37 | 0.360051266 |
| | H1104 | 222248.844 | 3214810.4 | 12.73 | 33.8 | 1005.2222 | 1.68 | 0.690414705 |
| | H1105 | 222259.298 | 3214794.74 | 12.74 | 35.1 | 1005.2222 | 1.98 | 0.905392464 |
| | H1106 | 222191.311 | 3214894.99 | 13.46 | 31.4 | 830.77778 | 1.37 | 0.233681919 |
| | H1201 | 222210.283 | 3214783.6 | 13.76 | 30.5 | 901.33333 | 1.98 | 0.527565986 |
| | H1203 | 222207.104 | 3214876.12 | 13.22 | 28.5 | 899.66667 | 1.37 | 0.276309239 |
| | H1204 | 222196.426 | 3214882.54 | 13.54 | 27.9 | 896.88889 | 1.4 | 0.384875373 |
| | H1301 | 222202.882 | 3214925.53 | 13.03 | 30.5 | 896.88889 | 1.22 | 0.580710054 |
| | H1303 | 222194.167 | 3214901.09 | 12.96 | 30.5 | 776.88889 | 1.37 | 0.382864429 |
| | H6201 | 221804.825 | 3214814.98 | 22.2 | 52.2 | 699.66667 | 3.66 | 0.909900678 |
| | H6301 | 221713.08 | 3214940.46 | 23.72 | 66.5 | 505.22222 | 1.75 | 0.014159795 |
| | H6801 | 221718.589 | 3214832.48 | 23.98 | 33.8 | 741.33333 | 1.52 | 0.002026352 |
| | H6802 | 221709.851 | 3214918.97 | 23.55 | 49.1 | 644.11111 | 1.75 | 0.234126169 |
| | TGTU75 | 222413.561 | 3215126.89 | 7.12 | 61 | 849.66667 | 2.74 | 0 |
| | B-06-101 | 221601.626 | 3215146.53 | 25.3 | 18.293 | 463.55556 | 1.5243902 | 1.415078935 |
| | B-31-101A | 222236.397 | 3212277.81 | 8.34 | 18.2 | 255.22222 | 1.8292683 | 3.013726212 |
| | B-31-101B | 222274.817 | 3212298.45 | 7.4 | 18.29 | 255.22222 | 1.8292683 | 2.877771585 |
| | B-31-101C | 222296.325 | 3212291.77 | 6.47 | 18.29 | 255.22222 | 1.8292683 | 2.668602494 |
| | B-31-102A | 222261.757 | 3212206.33 | 7 | 30.488 | 255.22222 | 1.6996951 | 2.978298833 |
| | B-31-102B | 222278.074 | 3212209.01 | 6.4 | 30.488 | 255.22222 | 1.6996951 | 3.353656856 |
| | FL-01-102 | 221848.283 | 3212693.93 | 25.95 | 79.9 | 1644.1111 | 0.9146341 | 0.082888268 |
| | FL-01-103 | 221856.578 | 3212588.97 | 25.06 | 79.9 | 1644.1111 | 0.9146341 | 0.082888268 |

## Table A4 continued

| source type | source ID | x coordinates | y coordinates | base elevation | release height | gas exit temp | stack inside dia | Emission Rate |
|---|---|---|---|---|---|---|---|---|
| | | M | m | m | m | k | m | |
| | FL-23-101 | 222124.06 | 3211664.25 | 8.73 | 92.03 | 1644.1111 | 0.6097561 | 0.002665874 |
| | FL-23-102 | 222178.28 | 3211666.02 | 7.4 | 92.06 | 1644.1111 | 0.6097561 | 0.002665874 |
| | FL-49-101 | 223275.837 | 3211460.85 | 1 | 110.455 | 1644.1111 | 1.5243902 | 0.082888268 |
| | FL-49-102 | 223265.977 | 3211276.2 | 2.08 | 110.445 | 1644.1111 | 1.5243902 | 0.082888268 |
| | H-01-101 | 222167.935 | 3212695.45 | 17.36 | 20.96 | 755.22222 | 1.5243902 | 0.446666957 |
| | H-01-102 | 222170.494 | 3212689.23 | 17.16 | 20.96 | 755.22222 | 1.5243902 | 0.500711083 |
| | H-01-104 | 222170.345 | 3212683.07 | 17.05 | 20.96 | 755.22222 | 1.5243902 | 0.49665623 |
| | H-01-105 | 222170.122 | 3212673.83 | 16.89 | 20.96 | 755.22222 | 1.5243902 | 0.460297607 |
| | H-01-106 | 222168.456 | 3212717.01 | 17.7 | 20.96 | 727.44444 | 1.5243902 | 0.296267406 |
| | H-01-107 | 222168.531 | 3212720.09 | 17.7 | 20.96 | 755.22222 | 1.5243902 | 0.605149989 |
| | H-01-108 | 222168.605 | 3212723.17 | 17.8 | 20.96 | 755.22222 | 1.5243902 | 0.565790877 |
| | H-01-109 | 222168.828 | 3212732.41 | 17.99 | 20.96 | 755.22222 | 1.5243902 | 0.57530519 |
| | H-01-110 | 222177.173 | 3212741.45 | 17.8 | 20.96 | 755.22222 | 1.5243902 | 0.623099138 |
| | H-02-101A | 222172.308 | 3212652.21 | 16.4 | 19.817 | 783 | 2.2865854 | 0.500141935 |
| | H-02-101B | 222158.549 | 3212643.29 | 16.6 | 19.817 | 783 | 2.2865854 | 0.44639857 |
| | H-02-102 | 222193.294 | 3212623.97 | 15.5 | 19.817 | 783 | 2.2865854 | 2.448891396 |
| | H-03-101 | 222258.59 | 3212523.78 | 12.07 | 43.14 | 560.77778 | 2.7439024 | 9.835316275 |
| | H-11-101 | 222383.363 | 3211633.34 | 3 | 70.122 | 449.66667 | 2.4390244 | 7.599989807 |
| | H-12-101 | 222668.962 | 3211681.91 | 2 | 55.79 | 505.22222 | 2.1097561 | 0.149590685 |
| | H-12-102 | 222687.765 | 3211675.3 | 2 | 55.79 | 505.22222 | 2.1097561 | 0.181359014 |
| | H-12-103 | 222738.722 | 3211766.51 | 2 | 36.585 | 677.44444 | 1.0670732 | 0.137313529 |
| | H-12-201 | 222714.392 | 3211656.17 | 2 | 55.79 | 505.22222 | 2.1097561 | 0.123545388 |
| | H-12-202 | 222692.585 | 3211650.53 | 2 | 55.79 | 505.22222 | 2.1097561 | 0.193644171 |
| | H-13-101 | 222707.834 | 3211945.97 | 2 | 51.829 | 449.66667 | 1.9817073 | 5.235746717 |
| | H-13-201 | 222740.172 | 3211939.03 | 2 | 51.82 | 449.66667 | 1.9817073 | 5.593440128 |
| | H-14-101 | 222473.817 | 3211677.38 | 3 | 38.11 | 527.44444 | 1.3719512 | 0.375626188 |
| | H-14-102 | 222495.327 | 3211670.69 | 3 | 38.11 | 527.44444 | 1.3719512 | 0.332507947 |
| | H-14-103 | 222546.764 | 3211669.45 | 2.67 | 53.35 | 449.66667 | 1.625 | 4.411389144 |
| | H-15-101 | 222948.848 | 3211718.31 | 1.73 | 38.11 | 647.44444 | 1.2195122 | 0.170606548 |
| | H-16-101 | 222883.948 | 3211722.95 | 2 | 38.11 | 688.55556 | 1.1432927 | 0.189385898 |
| | H-17-101 | 222851.239 | 3211714.5 | 2 | 30.488 | 455.22222 | 0.9146341 | 0.111979982 |
| | H-18-101 | 222466.894 | 3211951.78 | 3 | 79.268 | 394.11111 | 3.0243902 | 4.424250634 |
| | H-18-201 | 222450.651 | 3211952.18 | 3 | 79.26 | 394.11111 | 3.0243902 | 6.126907752 |
| | H-18-301 | 222372.291 | 3211960.23 | 3 | 79.26 | 394.11111 | 3.0243902 | 5.416595551 |
| | H-20-101 | 222861.402 | 3211911.46 | 2 | 60.97 | 449.66667 | 1.8810976 | 0.577173754 |
| | H-20-102 | 222862.589 | 3211960.73 | 2 | 60.97 | 449.66667 | 1.8810976 | 0.559194603 |
| | H-20-201 | 222975.698 | 3211933.35 | 1.47 | 60.97 | 449.66667 | 1.8810976 | 0.5528279 |
| | H-20-202 | 222986.972 | 3211951.57 | 1.33 | 60.97 | 449.66667 | 1.8810976 | 0.498540721 |
| | TGTU-24 | 222137.344 | 3211765.61 | 8.91 | 38.11 | 538.55556 | 2.1341463 | 0 |
| | B-29-001 | 221364.36 | 3217187.3 | 21.77 | 45.7 | 472 | 2.3 | 18.95482615 |
| | B-29-011 | 221348.58 | 3217250.8 | 20.59 | 45.7 | 472 | 2.3 | 13.99185852 |
| | B-29-012 | 221352.04 | 3217237.2 | 20.58 | 45.7 | 472 | 2.3 | 14.51718051 |
| | B-29-013 | 221370.61 | 3217567.3 | 15.84 | 45.7 | 472 | 2.3 | 10.3978025 |
| | B-29-014 | 221359.93 | 3217205.2 | 21.46 | 45.7 | 466 | 2.3 | 17.4036019 |
| | B-29-101 | 221256.14 | 3217224.1 | 21.7 | 45.7 | 466 | 2.3 | 15.43401089 |
| | B-29-151 | 221186.29 | 3217224.2 | 22.23 | 45.7 | 466 | 2.3 | 16.05436363 |
| | FCC UNIT 86 | 219853.3 | 3218032.3 | 34.21 | 79.3 | 547 | 2.3 | 16.28021297 |
| | 36 F 001 A | 221309 | 3216986 | 25.21 | 94.03 | 1033.2 | 1.22 | 0.037986727 |

## Table A4 continued

| source type | source ID | x coordinates | y coordinates | base elevation | release height | gas exit temp | stack inside dia | Emission Rate |
|---|---|---|---|---|---|---|---|---|
| | | M | m | m | m | k | m | |
| | 36 F 001 B | **221306** | **3216886** | **26.49** | **94.03** | **1033.2** | **1.22** | **0.037986727** |
| | 36 F 002 A | **222432.76** | **3217332.4** | **2.73** | **62.82** | **1033.2** | **1.22** | **0.017548901** |
| | 36 F 002 B | **222392.73** | **3217502.2** | **3.59** | **62.82** | **1033.2** | **1.22** | **0.019156411** |
| | S-10-301 | **221372.05** | **3216656.1** | **25.61** | **91.44** | **1033.2** | **1.01** | **2.066109194** |
| | ST-11-9800 | **221110.46** | **3217780.4** | **11.54** | **73.15** | **1033.2** | **0.76** | **0.098075314** |
| | ST-39-001 | **222435.86** | **3218949.4** | **1.69** | **85.7** | **1033.2** | **0.55** | **4.386954913** |
| | ST-62-001 | **220694.6** | **3217691.6** | **17.2** | **88.8** | **1033.2** | **1.01** | **1.422122201** |
| | ST-62-101 | **219212.47** | **3218442.4** | **29.94** | **79.7** | **1033.2** | **0.76** | **0.231862321** |
| | ST-62-102 | **219220.51** | **3218217.6** | **32.37** | **79.7** | **1033.2** | **0.76** | **0.236996575** |
| | ST-62-301 | **219167.1** | **3218657.1** | **28.23** | **80.225** | **1033.2** | **0.76** | **0.382706123** |
| | ST-62-401 | **220737.97** | **3217715.8** | **15.87** | **110.52** | **1033.2** | **0.71** | **0.003773945** |
| | 31-2F101 | **221621.22** | **3217473.8** | **16.79** | **58.8** | **533** | **3** | **1.517617868** |
| | 31-2F102 | **221624.7** | **3217461** | **16.92** | **52.7** | **533** | **2.8** | **1.800233733** |
| | 31-2F103 | **221629.4** | **3217453.5** | **17** | **58.8** | **533** | **2.4** | **1.800233733** |
| | 31-3F101 | **221626.07** | **3217439.1** | **17.16** | **36.9** | **533** | **1.1** | **0.642937444** |
| | 31-3F102 | **221627.52** | **3217432** | **17.24** | **36.9** | **533** | **1.1** | **0.642937444** |
| | 32-2F201 | **221659.08** | **3217371.5** | **17.88** | **58.8** | **533** | **3** | **1.288891896** |
| | 32-2F202 | **221661.21** | **3217358.8** | **18.02** | **52.7** | **533** | **2.8** | **1.288891896** |
| | 32-2F203 | **221665.81** | **3217347.6** | **18.14** | **58.8** | **533** | **2.4** | **1.288891896** |
| | 32-3F201 | **221662.56** | **3217336.2** | **18.26** | **36.9** | **533** | **1.1** | **0.460337313** |
| | 32-3F202 | **221664.99** | **3217335.9** | **18.27** | **36.9** | **533** | **1.1** | **0.460337313** |
| | 33-2F301 | **221697.44** | **3217267.3** | **18.57** | **58.8** | **533** | **3** | **2.96032472** |
| | 33-2F302 | **221700.4** | **3217255.2** | **18.62** | **52.7** | **533** | **2.8** | **2.96032472** |
| | 33-2F303 | **221705** | **3217244** | **18.62** | **58.8** | **533** | **2.4** | **2.96032472** |
| | 33-3F301 | **221701.73** | **3217232.1** | **18.83** | **36.9** | **533** | **1.1** | **1.057307816** |
| | 33-3F302 | **221703.47** | **3217225.6** | **18.85** | **36.9** | **533** | **1.1** | **1.057307816** |
| | 41-H001 | **220953.03** | **3218187.3** | **13.76** | **61** | **466** | **1.7** | **0.503987366** |
| | 41-H002 | **220949** | **3218177.5** | **13.65** | **62.5** | **466** | **2.1** | **1.984398483** |
| | 41-H003 | **220914.77** | **3218373.1** | **15.76** | **54.9** | **466** | **1.2** | **0.167925414** |
| | 42-H001 | **220805.27** | **3218200.8** | **15.96** | **61** | **466** | **1.7** | **0.513236032** |
| | 42-H002 | **220807.48** | **3218180.4** | **15.68** | **62.5** | **466** | **2.1** | **2.073580931** |
| | 81-H001 | **220463.01** | **3218165.7** | **23.9** | **61** | **466** | **1.7** | **0.386216273** |
| | 81-H002 | **220461.18** | **3218146** | **23.72** | **62.5** | **466** | **2.1** | **1.87921301** |
| | 81-H003 | **220432.31** | **3218339** | **25.37** | **54.9** | **466** | **1.2** | **0.109216249** |
| | 82-H001 | **220314.38** | **3218154.5** | **27.43** | **61** | **466** | **1.7** | **0.472242964** |
| | 82-H002 | **220317.45** | **3218136.2** | **27.14** | **61** | **466** | **2.1** | **1.85753866** |
| | H-03-070 | **221685.64** | **3218221** | **12.75** | **62.5** | **533** | **3** | **4.761819053** |
| | H-12-001 | **222354.96** | **3218693.8** | **3.12** | **32** | **1033** | **2.6** | **0.297779428** |
| | H-39-001 | **222265.64** | **3218739.4** | **4.23** | **61** | **489** | **2.4** | **0.182572796** |
| | H-40-001 | **221130.29** | **3218418.1** | **15.3** | **80.8** | **455** | **2.9** | **8.615752816** |
| | H-43-001 | **221038.67** | **3218335.6** | **15.08** | **45.7** | **672** | **1.2** | **0.000383728** |
| | H-44-001 | **220963.48** | **3218383** | **15.88** | **61** | **455** | **1.8** | **0.58512893** |
| | H-48-001 | **220845.46** | **3218372.7** | **16.95** | **79.3** | **394** | **3.6** | **11.44807564** |
| | H-49-001 | **220803.63** | **3218367.2** | **17.82** | **79.3** | **394** | **3.6** | **9.482064556** |
| | H-58-001 | **220771.42** | **3218389.9** | **18.48** | **50.6** | **438** | **2** | **0.838805535** |
| | H-80-001 | **221259.79** | **3218188.2** | **13** | **61** | **444** | **3** | **4.517643944** |
| | H-83-001 | **220093.2** | **3218299.5** | **32.69** | **61** | **444** | **2.9** | **6.839558769** |
| | H-84-100 | **219972.24** | **3218068.8** | **34** | **44.8** | **477** | **1.4** | **0.758532324** |

## Table A4 continued

| source type | source ID | x coordinates | y coordinates | base elevation | release height | gas exit temp | stack inside dia | Emission Rate |
|---|---|---|---|---|---|---|---|---|
| | | M | m | m | m | k | m | |
| | H-84-200 | **220006.64** | **3218069.5** | **34** | **44.8** | **477** | **1.4** | **0.757206906** |
| | H-84-320 | **219952.01** | **3218305.1** | **33** | **61** | **433** | **2.4** | **5.548535551** |
| | H-88-001 | **220355.76** | **3218330.7** | **27.25** | **79.3** | **394** | **3.6** | **9.758445207** |
| | H-89-001 | **220311** | **3218327.1** | **28.17** | **79.3** | **394** | **3.6** | **9.098958926** |
| | TGTU-55 | **220643.07** | **3218132.9** | **19.14** | **79.3** | **600** | **1.2** | **0** |
| | TGTU-93 | **220637.7** | **3218268.3** | **20.27** | **79.3** | **593** | **1.5** | **0** |
| | TGTU-20-400 | **221741** | **3216733** | **20.19** | **79.3** | **588** | **1.83** | **0** |
| | TGTU-54 | **220643.07** | **3218132.9** | **19.14** | **79.3** | **600** | **1.2** | **0** |

## Table A5: The AERMOD data input for CO dispersion module

| source type | source ID | x coordinates | y coordinates | base elevation | release height | gas exit temp | stack inside dia | Emission Rate |
|---|---|---|---|---|---|---|---|---|
| | | m | m | m | m | k | m | g/s |
| point | B2001A | **222203.18** | **3214937.84** | **12.8** | **18.3** | **675.7** | **2.97** | **1.88269553** |
| | B2001B | **222200.25** | **3214928.67** | **12.96** | **18.3** | **648.556** | **2.97** | **1.86634315** |
| | B2001C | **222202.51** | **3214910.13** | **13.1** | **18.3** | **659.111** | **2.97** | **1.9747552** |
| | B2001D | **222204.92** | **3214897.74** | **13.16** | **18.3** | **677.444** | **2.97** | **1.36096562** |
| | ST2901 | **222396.9** | **3214997.87** | **8.18** | **73.446** | **1144.111** | **0.915** | **0.07737443** |
| | ST2902 | **222400.95** | **3215053.24** | **7.93** | **73.446** | **1144.111** | **0.915** | **0.0773734** |
| | ST2903 | **221593.02** | **3214903.31** | **26.22** | **101.224** | **1144.111** | **0.915** | **0.07587678** |
| | H0201 | **221896.9213** | **3214815.835** | **20.39** | **52.2** | **699.66667** | **3.66** | **0.27002202** |
| | H0251 | **221837.2285** | **3214811.118** | **21.51** | **52.2** | **699.66667** | **3.66** | **0.28268728** |
| | H0501 | **222183.5153** | **3214796.576** | **14.45** | **24.7** | **977.44444** | **3.05** | **0.0171268** |
| | H0601 | **221920.8843** | **3214910.779** | **19.25** | **44.2** | **623.55556** | **1.98** | **2.48163068** |
| | H0602 | **221919.6916** | **3214861.505** | **19.27** | **40.6** | **738** | **1.45** | **1.77235684** |
| | H0603 | **221919.2213** | **3214953.958** | **18.77** | **45** | **697.44444** | **2.27** | **3.48459709** |
| | H0604 | **221908.7165** | **3214855.608** | **19.82** | **26.1** | **798** | **1.71** | **0.65546313** |
| | H0701A | **221949.5379** | **3214863.864** | **18.96** | **27.4** | **970.22222** | **1.3** | **0.31543819** |
| | H0701B | **222021.7196** | **3214825.141** | **17.33** | **29** | **924.66667** | **1.75** | **0.2897381** |
| | H0702A | **221951.4245** | **3214829.923** | **19** | **27.4** | **966.33333** | **1.3** | **0.04111115** |
| | H0702B | **222055.0175** | **3214858.23** | **16.88** | **29** | **865.22222** | **1.75** | **0.03810629** |
| | H0703 | **221988.994** | **3214927.619** | **17.63** | **14.7** | **711.33333** | **1.22** | **0.06400936** |
| | H0704 | **222072.0016** | **3214888.633** | **16.05** | **56.4** | **616.33333** | **1.68** | **0.00964951** |
| | H0801 | **221952.4169** | **3214759.027** | **19.54** | **35.4** | **1009.1111** | **1.22** | **0.01745734** |
| | H0802 | **221904.7427** | **3213803.32** | **25.75** | **40.4** | **926.33333** | **2.44** | **0.28375698** |
| | H0901 | **222293.3396** | **3214858.63** | **11.57** | **40.4** | **960.77778** | **2.44** | **1.06028845** |
| | H1001 | **222165.5378** | **3214837.069** | **14.17** | **30.8** | **1021.8889** | **1.52** | **0.01455678** |
| | H1102 | **222203.9503** | **3214857.71** | **13.63** | **32.9** | **839.66667** | **1.62** | **0.51792322** |
| | H1103 | **222206.8802** | **3214866.883** | **13.55** | **30.5** | **875.77778** | **1.37** | **0.30246417** |
| | H1104 | **222248.8442** | **3214810.403** | **12.73** | **33.8** | **1005.2222** | **1.68** | **0.5799683** |
| | H1105 | **222259.2981** | **3214794.744** | **12.74** | **35.1** | **1005.2222** | **1.98** | **0.7605526** |
| | H1106 | **222191.3113** | **3214894.992** | **13.46** | **31.4** | **830.77778** | **1.37** | **0.19629856** |
| | H1201 | **222210.2828** | **3214783.603** | **13.76** | **30.5** | **901.33333** | **1.98** | **0.44316325** |
| | H1203 | **222207.1035** | **3214876.122** | **13.22** | **28.5** | **899.66667** | **1.37** | **0.23210708** |
| | H1204 | **222196.4264** | **3214882.543** | **13.54** | **27.9** | **896.88889** | **1.4** | **0.32328713** |
| | H1301 | **222202.882** | **3214925.526** | **13.03** | **30.5** | **896.88889** | **1.22** | **0.487809** |
| | H1303 | **222194.1667** | **3214901.086** | **12.96** | **30.5** | **776.88889** | **1.37** | **0.32160895** |
| | H6201 | **221804.8247** | **3214814.984** | **22.2** | **52.2** | **699.66667** | **3.66** | **0.27296651** |
| | H6301 | **221713.08** | **3214940.461** | **23.72** | **66.5** | **505.22222** | **1.75** | **0.01193217** |
| | H6801 | **221718.5887** | **3214832.479** | **23.98** | **33.8** | **741.33333** | **1.52** | **0.00170878** |
| | H6802 | **221709.8513** | **3214918.97** | **23.55** | **49.1** | **644.11111** | **1.75** | **0.07020064** |
| | TGTU75 | **222413.5613** | **3215126.886** | **7.12** | **61** | **849.66667** | **2.74** | **0** |
| | B-06-101 | **221601.6259** | **3215146.534** | **25.3** | **18.293** | **463.55556** | **1.5243902** | **0.47885954** |

## Table A5 continued

| source type | source ID | x coordinates | y coordinates | base elevation | release height | gas exit temp | stack inside dia | Emission Rate |
|---|---|---:|---:|---:|---:|---:|---:|---:|
| | | m | m | m | m | k | m | g/s |
| | B-31-101A | **222236.3967** | **3212277.81** | **8.34** | **18.2** | **255.22222** | **1.8292683** | **1.80828684** |
| | B-31-101B | **222274.817** | **3212298.452** | **7.4** | **18.29** | **255.22222** | **1.8292683** | **1.72665806** |
| | B-31-101C | **222296.3252** | **3212291.77** | **6.47** | **18.29** | **255.22222** | **1.8292683** | **1.60116751** |
| | B-31-102A | **222261.7573** | **3212206.326** | **7** | **30.488** | **255.22222** | **1.6996951** | **1.78703659** |

| | | | | | | | | |
|---:|---:|---:|---:|---:|---:|---:|---|---|
| **2.01218234** | **1.6996951** | **255.22222** | **30.488** | **6.4** | **3212209.013** | **222278.0744** | B-31-102B | |
| **0.45024637** | **0.9146341** | **1644.1111** | **79.9** | **25.95** | **3212693.934** | **221848.2828** | FL-01-102 | |
| **0.45024637** | **0.9146341** | **1644.1111** | **79.9** | **25.06** | **3212588.966** | **221856.5781** | FL-01-103 | |
| **0.01500163** | **0.6097561** | **1644.1111** | **92.03** | **8.73** | **3211664.249** | **222124.0598** | FL-23-101 | |
| **0.01500163** | **0.6097561** | **1644.1111** | **92.06** | **7.4** | **3211666.021** | **222178.2795** | FL-23-102 | |
| **0.45024637** | **1.5243902** | **1644.1111** | **110.455** | **1** | **3211460.846** | **223275.8369** | FL-49-101 | |
| **0.45024637** | **1.5243902** | **1644.1111** | **110.445** | **2.08** | **3211276.203** | **223265.9774** | FL-49-102 | |
| **0.37524676** | **1.5243902** | **755.22222** | **20.96** | **17.36** | **3212695.45** | **222167.9353** | H-01-101 | |
| **0.42067315** | **1.5243902** | **755.22222** | **20.96** | **17.16** | **3212689.225** | **222170.4935** | H-01-102 | |
| **0.41719552** | **1.5243902** | **755.22222** | **20.96** | **17.05** | **3212683.066** | **222170.3447** | H-01-104 | |
| **0.38658926** | **1.5243902** | **755.22222** | **20.96** | **16.89** | **3212673.827** | **222170.1215** | H-01-105 | |
| **0.24884444** | **1.5243902** | **727.44444** | **20.96** | **17.7** | **3212717.007** | **222168.4562** | H-01-106 | |
| **0.50833068** | **1.5243902** | **755.22222** | **20.96** | **17.7** | **3212720.087** | **222168.5306** | H-01-107 | |
| **0.47527953** | **1.5243902** | **755.22222** | **20.96** | **17.8** | **3212723.166** | **222168.605** | H-01-108 | |
| **0.4832856** | **1.5243902** | **755.22222** | **20.96** | **17.99** | **3212732.405** | **222168.8283** | H-01-109 | |
| **0.52339802** | **1.5243902** | **755.22222** | **20.96** | **17.8** | **3212741.447** | **222177.1726** | H-01-110 | |
| **0.42010437** | **2.2865854** | **783** | **19.817** | **16.4** | **3212652.205** | **222172.3076** | H-02-101A | |
| **0.3751129** | **2.2865854** | **783** | **19.817** | **16.6** | **3212643.293** | **222158.5492** | H-02-101B | |
| **0.73467635** | **2.2865854** | **783** | **19.817** | **15.5** | **3212623.965** | **222193.2942** | H-02-102 | |
| **2.95056565** | **2.7439024** | **560.77778** | **43.14** | **12.07** | **3212523.784** | **222258.5899** | H-03-101 | |
| **4.55996169** | **2.4390244** | **449.66667** | **70.122** | **3** | **3211633.337** | **222383.3626** | H-11-101 | |
| **0.25117489** | **2.1097561** | **505.22222** | **55.79** | **2** | **3211681.912** | **222668.9623** | H-12-101 | |
| **0.30462446** | **2.1097561** | **505.22222** | **55.79** | **2** | **3211675.296** | **222687.7646** | H-12-102 | |
| **0.23022866** | **1.0670732** | **677.44444** | **36.585** | **2** | **3211766.508** | **222738.7221** | H-12-103 | |
| **0.20751543** | **2.1097561** | **505.22222** | **55.79** | **2** | **3211656.166** | **222714.3917** | H-12-201 | |
| **0.32532208** | **2.1097561** | **505.22222** | **55.79** | **2** | **3211650.529** | **222692.5851** | H-12-202 | |
| **3.14144202** | **1.9817073** | **449.66667** | **51.829** | **2** | **3211945.972** | **222707.8344** | H-13-101 | |
| **3.35607005** | **1.9817073** | **449.66667** | **51.82** | **2** | **3211939.029** | **222740.1722** | H-13-201 | |
| **0.63115854** | **1.3719512** | **527.44444** | **38.11** | **3** | **3211677.375** | **222473.8171** | H-14-101 | |
| **0.55867198** | **1.3719512** | **527.44444** | **38.11** | **3** | **3211670.693** | **222495.3265** | H-14-102 | |
| **2.64678088** | **1.625** | **449.66667** | **53.35** | **2.67** | **3211669.452** | **222546.7644** | H-14-103 | |
| **0.28665672** | **1.2195122** | **647.44444** | **38.11** | **1.73** | **3211718.306** | **222948.8476** | H-15-101 | |
| **0.31812629** | **1.1432927** | **688.55556** | **38.11** | **2** | **3211722.951** | **222883.9481** | H-16-101 | |
| **0.18804574** | **0.9146341** | **455.22222** | **30.488** | **2** | **3211714.495** | **222851.2386** | H-17-101 | |
| **2.654569** | **3.0243902** | **394.11111** | **79.268** | **3** | **3211951.783** | **222466.8943** | H-18-101 | |
| **3.67616327** | **3.0243902** | **394.11111** | **79.26** | **3** | **3211952.175** | **222450.6512** | H-18-201 | |
| **3.249996** | **3.0243902** | **394.11111** | **79.26** | **3** | **3211960.229** | **222372.2912** | H-18-301 | |
| **0.96971851** | **1.8810976** | **449.66667** | **60.97** | **2** | **3211911.457** | **222861.4021** | H-20-101 | |

## Table A5 continued

| Emission Rate | stack inside dia | gas exit temp | release height | base elevation | y coordinates | x coordinates | source ID | source type |
|---|---|---|---|---|---|---|---|---|
| g/s | m | k | m | m | m | m | | |
| 0.93944501 | 1.8810976 | 449.66667 | 60.97 | 2 | 3211960.73 | 222862.5894 | H-20-102 | |
| 0.92871677 | 1.8810976 | 449.66667 | 60.97 | 1.47 | 3211933.354 | 222975.6977 | H-20-201 | |
| 0.83758872 | 1.8810976 | 449.66667 | 60.97 | 1.33 | 3211951.57 | 222986.9715 | H-20-202 | |
| 0 | 2.1341463 | 538.55556 | 38.11 | 8.91 | 3211765.614 | 222137.3438 | TGTU-24 | |
| 5.68647386 | 2.3 | 472 | 45.7 | 21.77 | 3217187.3 | 221364.36 | B-29-001 | |
| 4.19756931 | 2.3 | 472 | 45.7 | 20.59 | 3217250.8 | 221348.58 | B-29-011 | |
| 4.3550928 | 2.3 | 472 | 45.7 | 20.58 | 3217237.2 | 221352.04 | B-29-012 | |
| 3.11931193 | 2.3 | 472 | 45.7 | 15.84 | 3217567.3 | 221370.61 | B-29-013 | |
| 5.22107452 | 2.3 | 466 | 45.7 | 21.46 | 3217205.2 | 221359.93 | B-29-014 | |
| 4.63025352 | 2.3 | 466 | 45.7 | 21.7 | 3217224.1 | 221256.14 | B-29-101 | |
| 4.8162955 | 2.3 | 466 | 45.7 | 22.23 | 3217224.2 | 221186.29 | B-29-151 | |
| 0.02642784 | 2.3 | 547 | 79.3 | 34.21 | 3218032.3 | 219853.3 | FCC UNIT 86 | |
| 0.20642914 | 1.22 | 1033.2 | 94.03 | 25.21 | 3216986 | 221309 | 36 F 001 A | |
| 0.20642914 | 1.22 | 1033.2 | 94.03 | 26.49 | 3216886 | 221306 | 36 F 001 B | |
| 0.0958348 | 1.22 | 1033.2 | 62.82 | 2.73 | 3217332.4 | 222432.76 | 36 F 002 A | |
| 0.10454751 | 1.22 | 1033.2 | 62.82 | 3.59 | 3217502.2 | 222392.73 | 36 F 002 B | |
| 11.2417457 | 1.01 | 1033.2 | 91.44 | 25.61 | 3216656.1 | 221372.05 | S-10-301 | |
| 0.53366208 | 0.76 | 1033.2 | 73.15 | 11.54 | 3217780.4 | 221110.46 | ST-11-9800 | |
| 23.8704942 | 0.55 | 1033.2 | 85.7 | 1.69 | 3218949.4 | 222435.86 | ST-39-001 | |
| 7.73864853 | 1.01 | 1033.2 | 88.8 | 17.2 | 3217691.6 | 220694.6 | ST-62-001 | |
| 1.26233575 | 0.76 | 1033.2 | 79.7 | 29.94 | 3218442.4 | 219212.47 | ST-62-101 | |
| 1.28963869 | 0.76 | 1033.2 | 79.7 | 32.37 | 3218217.6 | 219220.51 | ST-62-102 | |
| 2.08219082 | 0.76 | 1033.2 | 80.225 | 28.23 | 3218657.1 | 219167.1 | ST-62-301 | |
| 0.02102616 | 0.71 | 1033.2 | 110.52 | 15.87 | 3217715.8 | 220737.97 | ST-62-401 | |
| 0.45533077 | 3 | 533 | 58.8 | 16.79 | 3217473.8 | 221621.22 | 31-2F101 | |
| 0.54010568 | 2.8 | 533 | 52.7 | 16.92 | 3217461 | 221624.7 | 31-2F102 | |
| 0.54010568 | 2.4 | 533 | 58.8 | 17 | 3217453.5 | 221629.4 | 31-2F103 | |
| 0.54010568 | 1.1 | 533 | 36.9 | 17.16 | 3217439.1 | 221626.07 | 31-3F101 | |
| 0.54010568 | 1.1 | 533 | 36.9 | 17.24 | 3217432 | 221627.52 | 31-3F102 | |
| 0.38667452 | 3 | 533 | 58.8 | 17.88 | 3217371.5 | 221659.08 | 32-2F201 | |
| 0.38667452 | 2.8 | 533 | 52.7 | 18.02 | 3217358.8 | 221661.21 | 32-2F202 | |
| 0.38667452 | 2.4 | 533 | 58.8 | 18.14 | 3217347.6 | 221665.81 | 32-2F203 | |
| 0.38667452 | 1.1 | 533 | 36.9 | 18.26 | 3217336.2 | 221662.56 | 32-3F201 | |
| 0.38667452 | 1.1 | 533 | 36.9 | 18.27 | 3217335.9 | 221664.99 | 32-3F202 | |
| 0.88808165 | 3 | 533 | 58.8 | 18.57 | 3217267.3 | 221697.44 | 33-2F301 | |
| 0.88808165 | 2.8 | 533 | 52.7 | 18.62 | 3217255.2 | 221700.4 | 33-2F302 | |
| 0.88808165 | 2.4 | 533 | 58.8 | 18.62 | 3217244 | 221705 | 33-2F303 | |
| 0.88808165 | 1.1 | 533 | 36.9 | 18.83 | 3217232.1 | 221701.73 | 33-3F301 | |
| 0.88808165 | 1.1 | 533 | 36.9 | 18.85 | 3217225.6 | 221703.47 | 33-3F302 | |
| 0.42332443 | 1.7 | 466 | 61 | 13.76 | 3218187.3 | 220953.03 | 41-H001 | |

## Table A5 continued

| Emission Rate | stack inside dia | gas exit temp | release height | base elevation | y coordinates | x coordinates | source ID | source type |
|---|---|---|---|---|---|---|---|---|
| g/s | m | k | m | m | m | m | | |
| 0.59537914 | 2.1 | 466 | 62.5 | 13.65 | 3218177.5 | 220949 | 41-H002 | |
| 0.14106258 | 1.2 | 466 | 54.9 | 15.76 | 3218373.1 | 220914.77 | 41-H003 | |
| 0.43112833 | 1.7 | 466 | 61 | 15.96 | 3218200.8 | 220805.27 | 42-H001 | |
| 0.62206833 | 2.1 | 466 | 62.5 | 15.68 | 3218180.4 | 220807.48 | 42-H002 | |
| 0.32436713 | 1.7 | 466 | 61 | 23.9 | 3218165.7 | 220463.01 | 81-H001 | |
| 0.56377579 | 2.1 | 466 | 62.5 | 23.72 | 3218146 | 220461.18 | 81-H002 | |
| 0.09175558 | 1.2 | 466 | 54.9 | 25.37 | 3218339 | 220432.31 | 81-H003 | |
| 0.39663183 | 1.7 | 466 | 61 | 27.43 | 3218154.5 | 220314.38 | 82-H001 | |
| 0.55721174 | 2.1 | 466 | 61 | 27.14 | 3218136.2 | 220317.45 | 82-H002 | |
| 2.857067 | 3 | 533 | 62.5 | 12.75 | 3218221 | 221685.64 | H-03-070 | |
| 0.25012793 | 2.6 | 1033 | 32 | 3.12 | 3218693.8 | 222354.96 | H-12-001 | |
| 0.30647976 | 2.4 | 489 | 61 | 4.23 | 3218739.4 | 222265.64 | H-39-001 | |
| 5.17507832 | 2.9 | 455 | 80.8 | 15.3 | 3218418.1 | 221130.29 | H-40-001 | |
| 0.00032046 | 1.2 | 672 | 45.7 | 15.08 | 3218335.6 | 221038.67 | H-43-001 | |
| 0.49152124 | 1.8 | 455 | 61 | 15.88 | 3218383 | 220963.48 | H-44-001 | |
| 3.43448921 | 3.6 | 394 | 79.3 | 16.95 | 3218372.7 | 220845.46 | H-48-001 | |
| 2.84466117 | 3.6 | 394 | 79.3 | 17.82 | 3218367.2 | 220803.63 | H-49-001 | |
| 0.70461428 | 2 | 438 | 50.6 | 18.48 | 3218389.9 | 220771.42 | H-58-001 | |
| 2.71052244 | 3 | 444 | 61 | 13 | 3218188.2 | 221259.79 | H-80-001 | |
| 2.05186243 | 2.9 | 444 | 61 | 32.69 | 3218299.5 | 220093.2 | H-83-001 | |
| 0.63720915 | 1.4 | 477 | 44.8 | 34 | 3218068.8 | 219972.24 | H-84-100 | |
| 0.63609301 | 1.4 | 477 | 44.8 | 34 | 3218069.5 | 220006.64 | H-84-200 | |
| 1.66462372 | 2.4 | 433 | 61 | 33 | 3218305.1 | 219952.01 | H-84-320 | |
| 2.92750425 | 3.6 | 394 | 79.3 | 27.25 | 3218330.7 | 220355.76 | H-88-001 | |
| 2.72972292 | 3.6 | 394 | 79.3 | 28.17 | 3218327.1 | 220311 | H-89-001 | |
| 0 | 1.2 | 600 | 79.3 | 19.14 | 3218132.9 | 220643.07 | TGTU-55 | |
| 0 | 1.5 | 593 | 79.3 | 20.27 | 3218268.3 | 220637.7 | TGTU-93 | |
| 0 | 1.83 | 588 | 79.3 | 20.19 | 3216733 | 221741 | TGTU-20-400 | |
| 0 | 1.2 | 600 | 79.3 | 19.14 | 3218132.9 | 220643.07 | TGTU-54 | |

## Table A6: The AERMOD data input for SO2 Dispersion Module

| Emission Rate | stack inside dia | gas exit temp | release height | base elevation | y coordinates | x coordinates | source ID | source type |
|---|---|---|---|---|---|---|---|---|
| | m | k | m | m | m | M | | |
| 2.2512466 | 2.97 | 675.7 | 18.3 | 12.8 | 3214937.84 | 222203.18 | B2001A | point |
| 2.2316197 | 2.97 | 648.556 | 18.3 | 12.96 | 3214928.67 | 222200.25 | B2001B | |
| 2.3612367 | 2.97 | 659.111 | 18.3 | 13.1 | 3214910.13 | 222202.51 | B2001C | |
| 1.6272991 | 2.97 | 677.444 | 18.3 | 13.16 | 3214897.74 | 222204.92 | B2001D | |
| 0.0314699 | 0.915 | 1144.111 | 73.446 | 8.18 | 3214997.87 | 222396.9 | ST2901 | |
| 0.0313685 | 0.915 | 1144.111 | 73.446 | 7.93 | 3215053.24 | 222400.95 | ST2902 | |
| 0.006059 | 0.915 | 1144.111 | 101.224 | 26.22 | 3214903.31 | 221593.02 | ST2903 | |
| 0.3235992 | 3.66 | 699.66667 | 52.2 | 20.39 | 3214815.84 | 221896.921 | H0201 | |
| 0.3380182 | 3.66 | 699.66667 | 52.2 | 21.51 | 3214811.12 | 221837.229 | H0251 | |
| 0.0204779 | 3.05 | 977.44444 | 24.7 | 14.45 | 3214796.58 | 222183.515 | H0501 | |
| 2.9673693 | 1.98 | 623.55556 | 44.2 | 19.25 | 3214910.78 | 221920.884 | H0601 | |
| 2.1192957 | 1.45 | 738 | 40.6 | 19.27 | 3214861.51 | 221919.692 | H0602 | |
| 4.166594 | 2.27 | 697.44444 | 45 | 18.77 | 3214953.96 | 221919.221 | H0603 | |
| 0.7837395 | 1.71 | 798 | 26.1 | 19.82 | 3214855.61 | 221908.717 | H0604 | |
| 0.3771817 | 1.3 | 970.22222 | 27.4 | 18.96 | 3214863.86 | 221949.538 | H0701A | |
| 0.3464731 | 1.75 | 924.66667 | 29 | 17.33 | 3214825.14 | 222021.72 | H0701B | |
| 0.049118 | 1.3 | 966.33333 | 27.4 | 19 | 3214829.92 | 221951.425 | H0702A | |
| 0.0454697 | 1.75 | 865.22222 | 29 | 16.88 | 3214858.23 | 222055.018 | H0702B | |
| 0.0005063 | 1.22 | 711.33333 | 14.7 | 17.63 | 3214927.62 | 221988.994 | H0703 | |
| 0 | 1.68 | 616.33333 | 56.4 | 16.05 | 3214888.63 | 222072.002 | H0704 | |
| 0.0208198 | 1.22 | 1009.1111 | 35.4 | 19.54 | 3214759.03 | 221952.417 | H0801 | |
| 0.3393747 | 2.44 | 926.33333 | 40.4 | 25.75 | 3213803.32 | 221904.743 | H0802 | |
| 1.2677469 | 2.44 | 960.77778 | 40.4 | 11.57 | 3214858.63 | 222293.34 | H0901 | |
| 0.0174617 | 1.52 | 1021.8889 | 30.8 | 14.17 | 3214837.07 | 222165.538 | H1001 | |
| 0.6192119 | 1.62 | 839.66667 | 32.9 | 13.63 | 3214857.71 | 222203.95 | H1102 | |
| 0.361669 | 1.37 | 875.77778 | 30.5 | 13.55 | 3214866.88 | 222206.88 | H1103 | |
| 0.6934905 | 1.68 | 1005.2222 | 33.8 | 12.73 | 3214810.4 | 222248.844 | H1104 | |
| 0.9094464 | 1.98 | 1005.2222 | 35.1 | 12.74 | 3214794.74 | 222259.298 | H1105 | |
| 0.2347601 | 1.37 | 830.77778 | 31.4 | 13.46 | 3214894.99 | 222191.311 | H1106 | |
| 0.5299421 | 1.98 | 901.33333 | 30.5 | 13.76 | 3214783.6 | 222210.283 | H1201 | |
| 0.277515 | 1.37 | 899.66667 | 28.5 | 13.22 | 3214876.12 | 222207.104 | H1203 | |
| 0.3865875 | 1.4 | 896.88889 | 27.9 | 13.54 | 3214882.54 | 222196.426 | H1204 | |
| 0.5833127 | 1.22 | 896.88889 | 30.5 | 13.03 | 3214925.53 | 222202.882 | H1301 | |
| 0.3844788 | 1.37 | 776.88889 | 30.5 | 12.96 | 3214901.09 | 222194.167 | H1303 | |
| 0.326341 | 3.66 | 699.66667 | 52.2 | 22.2 | 3214814.98 | 221804.825 | H6201 | |
| 0.0141598 | 1.75 | 505.22222 | 66.5 | 23.72 | 3214940.46 | 221713.08 | H6301 | |
| 0.0020264 | 1.52 | 741.33333 | 33.8 | 23.98 | 3214832.48 | 221718.589 | H6801 | |
| 0.0839408 | 1.75 | 644.11111 | 49.1 | 23.55 | 3214918.97 | 221709.851 | H6802 | |
| 57.175203 | 2.74 | 849.66667 | 61 | 7.12 | 3215126.89 | 222413.561 | TGTU75 | |
| 0.4913765 | 1.5243902 | 463.55556 | 18.293 | 25.3 | 3215146.53 | 221601.626 | B-06-101 | |
| 0.393010338 | 1.8292683 | 255.22222 | 18.2 | 8.34 | 3212277.81 | 222236.397 | B-31-101A | |
| 0.375456622 | 1.8292683 | 255.22222 | 18.29 | 7.4 | 3212298.45 | 222274.817 | B-31-101B | |
| 0.348076499 | 1.8292683 | 255.22222 | 18.29 | 6.47 | 3212291.77 | 222296.325 | B-31-101C | |
| 0.388498864 | 1.6996951 | 255.22222 | 30.488 | 7 | 3212206.33 | 222261.757 | B-31-102A | |
| 0.437454442 | 1.6996951 | 255.22222 | 30.488 | 6.4 | 3212209.01 | 222278.074 | B-31-102B | |
| 0.287828495 | 0.9146341 | 1644.1111 | 79.9 | 25.95 | 3212693.93 | 221848.283 | FL-01-102 | |
| 0.287828495 | 0.9146341 | 1644.1111 | 79.9 | 25.06 | 3212588.97 | 221856.578 | FL-01-103 | |

## Table A6 continued

| Emission Rate | stack inside dia | gas exit temp | release height | base elevation | y coordinates | x coordinates | source ID | source type |
|---|---|---|---|---|---|---|---|---|
| | m | k | m | m | m | M | | |
| 0.015565811 | 0.6097561 | 1644.1111 | 92.03 | 8.73 | 3211664.25 | 222124.06 | FL-23-101 | |
| 0.015565811 | 0.6097561 | 1644.1111 | 92.06 | 7.4 | 3211666.02 | 222178.28 | FL-23-102 | |
| 0.26513045 | 1.5243902 | 1644.1111 | 110.455 | 1 | 3211460.85 | 223275.837 | FL-49-101 | |
| 0.26513045 | 1.5243902 | 1644.1111 | 110.445 | 2.08 | 3211276.2 | 223265.977 | FL-49-102 | |
| 0.081602408 | 1.5243902 | 755.22222 | 20.96 | 17.36 | 3212695.45 | 222167.935 | H-01-101 | |
| 0.091424888 | 1.5243902 | 755.22222 | 20.96 | 17.16 | 3212689.23 | 222170.494 | H-01-102 | |
| 0.090659136 | 1.5243902 | 755.22222 | 20.96 | 17.05 | 3212683.07 | 222170.345 | H-01-104 | |
| 0.084091011 | 1.5243902 | 755.22222 | 20.96 | 16.89 | 3212673.83 | 222170.122 | H-01-105 | |
| 0.054146132 | 1.5243902 | 727.44444 | 20.96 | 17.7 | 3212717.01 | 222168.456 | H-01-106 | |
| 0.110523518 | 1.5243902 | 755.22222 | 20.96 | 17.7 | 3212720.09 | 222168.531 | H-01-107 | |
| 0.103295796 | 1.5243902 | 755.22222 | 20.96 | 17.8 | 3212723.17 | 222168.605 | H-01-108 | |
| 0.105023907 | 1.5243902 | 755.22222 | 20.96 | 17.99 | 3212732.41 | 222168.828 | H-01-109 | |
| 0.113813284 | 1.5243902 | 755.22222 | 20.96 | 17.8 | 3212741.45 | 222177.173 | H-01-110 | |
| 0.091322956 | 2.2865854 | 783 | 19.817 | 16.4 | 3212652.21 | 222172.308 | H-02-101A | |
| 0.081520625 | 2.2865854 | 783 | 19.817 | 16.6 | 3212643.29 | 222158.549 | H-02-101B | |
| 0.159673849 | 2.2865854 | 783 | 19.817 | 15.5 | 3212623.97 | 222193.294 | H-02-102 | |
| 0.641476314 | 2.7439024 | 560.77778 | 43.14 | 12.07 | 3212523.78 | 222258.59 | H-03-101 | |
| 0.991329297 | 2.4390244 | 449.66667 | 70.122 | 3 | 3211633.34 | 222383.363 | H-11-101 | |
| 0.05459579 | 2.1097561 | 505.22222 | 55.79 | 2 | 3211681.91 | 222668.962 | H-12-101 | |
| 0.066250907 | 2.1097561 | 505.22222 | 55.79 | 2 | 3211675.3 | 222687.765 | H-12-102 | |
| 0.050086094 | 1.0670732 | 677.44444 | 36.585 | 2 | 3211766.51 | 222738.722 | H-12-103 | |
| 0.045156549 | 2.1097561 | 505.22222 | 55.79 | 2 | 3211656.17 | 222714.392 | H-12-201 | |
| 0.070753343 | 2.1097561 | 505.22222 | 55.79 | 2 | 3211650.53 | 222692.585 | H-12-202 | |
| 0.682964228 | 1.9817073 | 449.66667 | 51.829 | 2 | 3211945.97 | 222707.834 | H-13-101 | |
| 0.729681811 | 1.9817073 | 449.66667 | 51.82 | 2 | 3211939.03 | 222740.172 | H-13-201 | |
| 0.137217226 | 1.3719512 | 527.44444 | 38.11 | 3 | 3211677.38 | 222473.817 | H-14-101 | |
| 0.121499035 | 1.3719512 | 527.44444 | 38.11 | 3 | 3211670.69 | 222495.327 | H-14-102 | |
| 0.757448977 | 1.625 | 449.66667 | 53.35 | 2.67 | 3211669.45 | 222546.764 | H-14-103 | |
| 0.062320803 | 1.2195122 | 647.44444 | 38.11 | 1.73 | 3211718.31 | 222948.848 | H-15-101 | |
| 0.069199836 | 1.1432927 | 688.55556 | 38.11 | 2 | 3211722.95 | 222883.948 | H-16-101 | |
| 0.040916545 | 0.9146341 | 455.22222 | 30.488 | 2 | 3211714.5 | 222851.239 | H-17-101 | |
| 0.577068043 | 3.0243902 | 394.11111 | 79.268 | 3 | 3211951.78 | 222466.894 | H-18-101 | |
| 0.799199445 | 3.0243902 | 394.11111 | 79.26 | 3 | 3211952.18 | 222450.651 | H-18-201 | |
| 0.706525144 | 3.0243902 | 394.11111 | 79.26 | 3 | 3211960.23 | 222372.291 | H-18-301 | |
| 0.210827197 | 1.8810976 | 449.66667 | 60.97 | 2 | 3211911.46 | 222861.402 | H-20-101 | |
| 0.204284482 | 1.8810976 | 449.66667 | 60.97 | 2 | 3211960.73 | 222862.589 | H-20-102 | |
| 0.20189781 | 1.8810976 | 449.66667 | 60.97 | 1.47 | 3211933.35 | 222975.698 | H-20-201 | |
| 0.182112026 | 1.8810976 | 449.66667 | 60.97 | 1.33 | 3211951.57 | 222986.972 | H-20-202 | |
| 16.79508674 | 2.1341463 | 538.55556 | 38.11 | 8.91 | 3211765.61 | 222137.344 | TGTU-24 | |
| 4.94504085 | 2.3 | 472 | 45.7 | 21.77 | 3217187.3 | 221364.36 | B-29-001 | |
| 3.65032251 | 2.3 | 472 | 45.7 | 20.59 | 3217250.8 | 221348.58 | B-29-011 | |
| 3.787327278 | 2.3 | 472 | 45.7 | 20.58 | 3217237.2 | 221352.04 | B-29-012 | |
| 2.71264835 | 2.3 | 472 | 45.7 | 15.84 | 3217567.3 | 221370.61 | B-29-013 | |
| 4.540299024 | 2.3 | 466 | 45.7 | 21.46 | 3217205.2 | 221359.93 | B-29-014 | |
| 4.026527327 | 2.3 | 466 | 45.7 | 21.7 | 3217224.1 | 221256.14 | B-29-101 | |
| 4.188404354 | 2.3 | 466 | 45.7 | 22.23 | 3217224.2 | 221186.29 | B-29-151 | |
| 35.5712799 | 2.3 | 547 | 79.3 | 34.21 | 3218032.3 | 219853.3 | FCC UNIT 86 | |
| 0.324454913 | 1.22 | 1033.2 | 94.03 | 25.21 | 3216986 | 221309 | 36 F 001 A | |

## Table A6 continued

| Emission Rate | stack inside dia | gas exit temp | release height | base elevation | y coordinates | x coordinates | source ID | source type |
|---|---|---|---|---|---|---|---|---|
| | m | k | m | m | m | M | | |
| **0.324454913** | **1.22** | **1033.2** | **94.03** | **26.49** | **3216886** | **221306** | 36 F 001 B | |
| **0.149580018** | **1.22** | **1033.2** | **62.82** | **2.73** | **3217332.4** | **222432.76** | 36 F 002 A | |
| **0.163179555** | **1.22** | **1033.2** | **62.82** | **3.59** | **3217502.2** | **222392.73** | 36 F 002 B | |
| **1.032786913** | **1.01** | **1033.2** | **91.44** | **25.61** | **3216656.1** | **221372.05** | S-10-301 | |
| **0.051823613** | **0.76** | **1033.2** | **73.15** | **11.54** | **3217780.4** | **221110.46** | ST-11-9800 | |
| **3.199959538** | **0.55** | **1033.2** | **85.7** | **1.69** | **3218949.4** | **222435.86** | ST-39-001 | |
| **1.424753629** | **1.01** | **1033.2** | **88.8** | **17.2** | **3217691.6** | **220694.6** | ST-62-001 | |
| **0.228850054** | **0.76** | **1033.2** | **79.7** | **29.94** | **3218442.4** | **219212.47** | ST-62-101 | |
| **0.233766517** | **0.76** | **1033.2** | **79.7** | **32.37** | **3218217.6** | **219220.51** | ST-62-102 | |
| **0.185946864** | **0.76** | **1033.2** | **80.225** | **28.23** | **3218657.1** | **219167.1** | ST-62-301 | |
| **0.34836474** | **0.71** | **1033.2** | **110.52** | **15.87** | **3217715.8** | **220737.97** | ST-62-401 | |
| **0.395928006** | **3** | **533** | **58.8** | **16.79** | **3217473.8** | **221621.22** | 31-2F101 | |
| **0.469623537** | **2.8** | **533** | **52.7** | **16.92** | **3217461** | **221624.7** | 31-2F102 | |
| **0.469623537** | **2.4** | **533** | **58.8** | **17** | **3217453.5** | **221629.4** | 31-2F103 | |
| **0.469623537** | **1.1** | **533** | **36.9** | **17.16** | **3217439.1** | **221626.07** | 31-3F101 | |
| **0.469623537** | **1.1** | **533** | **36.9** | **17.24** | **3217432** | **221627.52** | 31-3F102 | |
| **0.336286189** | **3** | **533** | **58.8** | **17.88** | **3217371.5** | **221659.08** | 32-2F201 | |
| **0.336286189** | **2.8** | **533** | **52.7** | **18.02** | **3217358.8** | **221661.21** | 32-2F202 | |
| **0.336286189** | **2.4** | **533** | **58.8** | **18.14** | **3217347.6** | **221665.81** | 32-2F203 | |
| **0.336286189** | **1.1** | **533** | **36.9** | **18.26** | **3217336.2** | **221662.56** | 32-3F201 | |
| **0.336286189** | **1.1** | **533** | **36.9** | **18.27** | **3217335.9** | **221664.99** | 32-3F202 | |
| **0.772325281** | **3** | **533** | **58.8** | **18.57** | **3217267.3** | **221697.44** | 33-2F301 | |
| **1.349722234** | **2.8** | **533** | **52.7** | **18.62** | **3217255.2** | **221700.4** | 33-2F302 | |
| **0.772325281** | **2.4** | **533** | **58.8** | **18.62** | **3217244** | **221705** | 33-2F303 | |
| **0.772325281** | **1.1** | **533** | **36.9** | **18.83** | **3217232.1** | **221701.73** | 33-3F301 | |
| **0.772325281** | **1.1** | **533** | **36.9** | **18.85** | **3217225.6** | **221703.47** | 33-3F302 | |
| **0.368124523** | **1.7** | **466** | **61** | **13.76** | **3218187.3** | **220953.03** | 41-H001 | |
| **0.517687354** | **2.1** | **466** | **62.5** | **13.65** | **3218177.5** | **220949** | 41-H002 | |
| **0.122624811** | **1.2** | **466** | **54.9** | **15.76** | **3218373.1** | **220914.77** | 41-H003 | |
| **0.374874807** | **1.7** | **466** | **61** | **15.96** | **3218200.8** | **220805.27** | 42-H001 | |
| **0.541036626** | **2.1** | **466** | **62.5** | **15.68** | **3218180.4** | **220807.48** | 42-H002 | |
| **0.28209998** | **1.7** | **466** | **61** | **23.9** | **3218165.7** | **220463.01** | 81-H001 | |
| **0.490264414** | **2.1** | **466** | **62.5** | **23.72** | **3218146** | **220461.18** | 81-H002 | |
| **0.079818294** | **1.2** | **466** | **54.9** | **25.37** | **3218339** | **220432.31** | 81-H003 | |
| **0.344956596** | **1.7** | **466** | **61** | **27.43** | **3218154.5** | **220314.38** | 82-H001 | |
| **0.484628794** | **2.1** | **466** | **61** | **27.14** | **3218136.2** | **220317.45** | 82-H002 | |
| **2.484632572** | **3** | **533** | **62.5** | **12.75** | **3218221** | **221685.64** | H-03-070 | |
| **0.217477548** | **2.6** | **1033** | **32** | **3.12** | **3218693.8** | **222354.96** | H-12-001 | |
| **0.266450608** | **2.4** | **489** | **61** | **4.23** | **3218739.4** | **222265.64** | H-39-001 | |
| **4.495477192** | **2.9** | **455** | **80.8** | **15.3** | **3218418.1** | **221130.29** | H-40-001 | |
| **0.000256165** | **1.2** | **672** | **45.7** | **15.08** | **3218335.6** | **221038.67** | H-43-001 | |
| **0.427376167** | **1.8** | **455** | **61** | **15.88** | **3218383** | **220963.48** | H-44-001 | |
| **2.986645071** | **3.6** | **394** | **79.3** | **16.95** | **3218372.7** | **220845.46** | H-48-001 | |
| **2.450486698** | **3.6** | **394** | **79.3** | **17.82** | **3218367.2** | **220803.63** | H-49-001 | |
| **0.612747438** | **2** | **438** | **50.6** | **18.48** | **3218389.9** | **220771.42** | H-58-001 | |
| **2.337831117** | **3** | **444** | **61** | **13** | **3218188.2** | **221259.79** | H-80-001 | |
| **1.784336049** | **2.9** | **444** | **61** | **32.69** | **3218299.5** | **220093.2** | H-83-001 | |
| **0.554063164** | **1.4** | **477** | **44.8** | **34** | **3218068.8** | **219972.24** | H-84-100 | |

## Table A6 continued

| Emission Rate | stack inside dia | gas exit temp | release height | base elevation | y coordinates | x coordinates | source ID | source type |
|---|---|---|---|---|---|---|---|---|
| | m | k | m | m | m | M | | |
| **0.553086805** | **1.4** | **477** | **44.8** | **34** | **3218069.5** | **220006.64** | H-84-200 | |
| **1.44757946** | **2.4** | **433** | **61** | **33** | **3218305.1** | **219952.01** | H-84-320 | |
| **2.545821525** | **3.6** | **394** | **79.3** | **27.25** | **3218330.7** | **220355.76** | H-88-001 | |
| **2.373788515** | **3.6** | **394** | **79.3** | **28.17** | **3218327.1** | **220311** | H-89-001 | |
| **2.832461722** | **1.2** | **600** | **79.3** | **19.14** | **3218132.9** | **220643.07** | TGTU-55 | |
| **28.68444035** | **1.5** | **593** | **79.3** | **20.27** | **3218268.3** | **220637.7** | TGTU-93 | |
| **111.251146** | **1.83** | **588** | **79.3** | **20.19** | **3216733** | **221741** | TGTU-20-400 | |
| **3.215566093** | **1.2** | **600** | **79.3** | **19.14** | **3218132.9** | **220643.07** | TGTU-54 | |

Table A7 Comparison Table between AERMOD results of normal refinery emissions, Fixed station results and K-EPA Ambient air quality standards for residential areas

| CO (unit - mg/m^3) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 hr | | | | | 8 hrs | | | | | 24 hrs | | | | |
| Plume Model | | Fixed Station at Umm-Alhyman | | KEPA | Plume Model | | Fixed Station at Umm-Alhyman | | KEPA | Plume Model | | Fixed Station at Umm-Alhyman | | KEPA |
| Max | Min | Max | Min | Limit | Max | Min | Max | Min | Limit | Max | Min | Max | Min | Limit |
| 3604.355 | 47.858 | 6425.37 | 0 | **34000** | 982.267 | 12.681 | - | - | **11500** | 408.853 | 5.348 | 1958.79 | 0 | **9000** |
| SO$_2$ (unit - mg/m^3) | | | | | | | | | | | | | | |
| 1 hr | | | | | 24 hrs | | | | | Annual | | | | |
| Plume Model | | Fixed Station at Umm-Alhyman | | KEPA | Plume Model | | Fixed Station at Umm-Alhyman | | KEPA | Plume Model | | Fixed Station at Umm-Alhyman | | KEPA |
| Max | Min | Max | Min | Limit | Max | Min | Max | Min | Limit | Max | Min | Max | Min | Limit |
| 809.709 | 30.942 | 330.05 | 0 | **444** | 84.42 | 3.731 | 96.36 | 0 | **157** | 20.222 | 0.261 | 330.05 | 0 | **80** |
| NOx (unit - mg/m^3) | | | | | | | | | | | | | | |
| 1 hr | | | | | 24 hrs | | | | | Annual | | | | |
| Plume Model | | Fixed Station at Umm-Alhyman | | KEPA | Plume Model | | Fixed Station at Umm-Alhyman | | KEPA | Plume Model | | Fixed Station at Umm-Alhyman | | KEPA |
| Max | Min | Max | Min | Limit | Max | Min | Max | Min | Limit | Max | Min | Max | Min | Limit |
| 5950.999 | 69.961 | 720.13 | 0 | **225** | 389.412 | 6.023 | 198.84 | 0 | **112** | 48.856 | 0.483 | 720.121 | 0 | **67** |

# Publications

Based on the work presented in this thesis the following papers have been prepared and will be submitted for the publication in relevant academic journals

1- Study of the impact of petroleum refinery emissions on the air quality in the urban areas of Kuwait. S.F.Alanezi, V.Nassehi and N.S. Hanspal

2- Computer simulation of ground level concentrations of NOx, CO and SO2 originating from multiple sources at residential district of Om-Alhyman in Kuwait. S.F.Alanezi, V.Nassehi and N.S. Hanspal

**Conferences attended:**

1- JCCP Course Program Study Tour on Practical Technology for Energy Saving. Feb. 26 - March 6, 2008. Japan.

2- AERMOD Course "Gaussian Plume Air Dispersion Model" Oct. 17-18, 2011. Barcelona-Spain.

3- Achieving Optimum Energy Efficiency. Feb. 21-23,2012. Singapore

4- Utility System Optimization using ProSteam. June 18-22, 2012. UK