

ENVIRONMENTAL EFFECTS OF MULTI-STAGE  
FLASH (MSF) DESALINATION PLANT AT  
AL-JUBAIL SAUDI ARABIA

CENTRE FOR NEWFOUNDLAND STUDIES

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FLASH (MSF) DESALINATION PLANT AT  
AL - JUBAIL SAUDI ARABIA**

**By**

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fulfillment of the requirements for the degree of  
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*Dedicated to My Parents*  
*Muhammad Hussain Khan and Amtul Hafeez*  
*For Their Love, Encouragement, and Invaluable Sacrifice,*  
*Throughout My Life*

## **Abstract**

This study presents and compares the marine and atmospheric discharges, with an attempt to assess the environmental effects resulting from Al-Jubail MSF desalination plant, the largest in the world, producing 253.5 million gallons of desalinated water per day. For the analyses of air pollution, AERMOD, an air dispersion model, is used to simulate the ambient concentrations of sulfur dioxide, oxide of nitrogen, and fine particulate matter. The emission results/pollutant levels were compared with the Meteorological and Environmental Protection Agency (MEPA) standards.

Similarly, for brine discharge, CORMIX a hydrodynamic mixing model is used for the prediction of plume dilution. Thermal effects and elevated total dissolved solids concentration in brine discharge were also simulated and the results were compared with the U.S. EPA approved Surface Water Quality Standards. It has been found in this study that the plume elevated temperature drops to ambient temperature within five minutes, traveling a distance of 101.4 meters along the downstream, and the TDS concentrations in the brine plume drops to 4700 ppm above the ambient concentration, while traveling a distance of 217 meters, downstream, which is 10 percent above the ambient concentration, which shows that both the pollutants (elevated temperature and elevated TDS) were within the limits as specified by the Surface Water Quality Standards. However, a detailed information regarding the site specific meteorological data, fuel and brine characteristics, and plant specific information should be carried out.

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## NOMENCLATURE

AGCC	Arabian Gulf Co-Operation Council
ABL	Atmospheric Boundary Layer
AERMIC	American Society/Environmental Protection Agency Regulatory Model Improvement Committee
BTG	Boiler Turbo Generator
CAA	Clean Air Act
CTDMPLUS	Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations
CO	Control
CORMIX	Cornell Mixing Expert System
CBL	Convective Boundary Layer
CO <sub>2</sub>	Carbon Dioxide
DOS	Disk Operating System
DEM	Digital Elevation Model
DC	Direct Current
ED	Electro-Dialysis
GRAMP	Gulf Regional Air Monitoring Program
HPDM	Hybrid Plume Dispersion Model
IDA	International Desalination Association
ISCST	Industrial Source Complex Short Term
ISC	Industrial Source Complex
JDP	Jubayl Desalination Plant
JIC	Jubayl Industrial City
KSA	Kingdom of Saudi Arabia
m	Meters
MSF	Multi Stage Flash
MSF-OT	Multi Stage Flash – Once Through
MSF-M	Multi Stage Flash – Brine Mixing

MED	Multiple Effect Distillation
ME	Meteorology
mb	Milli-bar
MEPA	Meteorological Environmental Protection Agency
MDCA	ministry of Defense and Civil Aviation
NWS	National Weather Services
NO <sub>x</sub>	Oxides of Nitrogen
NAAQS	National Ambient Air Quality Standards
OAQPS	Office of Air Quality Planning and Standards
OU	Out Put
pdf	Probability Distribution Function
PBL	Planetary Boundary Layer
PM	Particulate Matter
ppm	Parts Per Million
QA	Quality Assessment
RO	Reverse Osmosis
RE	Receptor
RED	Reverse Electro – Dialysis
RTD	Rough Terrain Diffusion Model
SO <sub>2</sub>	Sulfur Dioxide
SO	Source
SPM	Suspended Particulate Matter
SBL	Stable Boundary Layer
SWCC	Saline Water Conversion Cooperation
TDS	Total Dissolved Solids
U.S. EPA	United States Environmental Protection Agency
VC	Vapor Compression
VOC	Volatile Organic Compounds

# Chapter I

## INTRODUCTION

### 1.1 Background History

In March 2002, the United Nations Secretary General Kofi Annan stated that more than six billion people live on this planet earth, out of which approximately 1.1 billion people lack access to safe drinking water, and by the end of 2025, two thirds of the world's population is likely to live with moderate or severe water shortage (Annan, 2002). Water scarcity is considered to be a sleeping tiger for most of the environmental problems, and this tiger is waking up (Sandra, 1999).

Gelick in 1996 mentioned that each person consumed a minimum of 50 liters of water per day, excluding the water required for irrigation. The distribution of this 50 liters daily water consumption is as follows: 5 liters are used for drinking, 20 liters for sanitation, 15 liters for bathing, and 10 liters for food preparation.

Considering the above facts and the scarcity of renewable fresh water resources on per capita basis, Falkenmark in 1989, has distributed the water scarce countries under one of the five water competition categories:

1. **Limited water problem countries** - Countries having more than 10,000 m<sup>3</sup> per person per year renewable water resources.
2. **General water problem countries** - Countries having water availability between 1670 to 10,000 m<sup>3</sup> per person per year renewable water resources.
3. **Water Stressed Countries** - Countries having water availability between 1000 to 1670 m<sup>3</sup> per person per year renewable water resources.
4. **Chronic Water Scarcity Countries** - Countries having water availability between 500 and 1000 m<sup>3</sup> per person per year renewable water resources.

---

5. **Beyond "water barrier" countries** - Countries having less than 500 m<sup>3</sup> per person per year renewable water resources.

All of the above classification is based on the net stream flow measurement within each country in consideration, after adjusting for evaporation and other losses.

Water scarcity is a major political, economical and environmental problem in the world and in the Middle East. The shortage of natural fresh water supply for domestic purposes is very acute for the Arabian Peninsula (Saudi Arabia, Kuwait, Bahrain, Qatar, the United Arab Emirates, Oman, and Yemen). In these countries the demand for domestic water increases at the rate of 3% or more annually. These countries consume about 60% of the

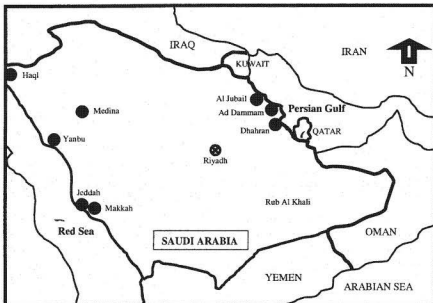
total world desalting water; therefore they are mostly dependent on brackish and seawater desalination to meet their water demands (Al-Mumtaz & Wagjalla. 1988, Al-Sahlawi M.A. 1999). The limitation of fresh ground water supply has led the Middle East countries to become increasingly dependent on desalination.

The Middle East countries are facing acute water shortage because of hot and arid climatic conditions, increase in per capita water demand due to high standard of living, and rapid population growth. Despite the shortage, countries in the region have initiated ambitious agricultural development plan with the concept of self-sufficiency in food. As a result, a significant amount of non-renewable deep groundwater resources has been mined causing water quality deterioration and significant depletion of non-renewable water resources in aquifers. To meet this increasing demand of high quality potable water, oil rich Gulf countries have heavily invested in seawater desalination. More than 40% of the world's desalination capacity is concentrated in the Gulf region of which Saudi Arabia shares more than two-third capacity. Saudi Arabia has become the world's major producer of desalinated water (Al-Sahlawi, 1999).

Saudi Arabia, with an area of about 865,000 square miles, occupies the major portion of the Arabian Peninsula. It is roughly one-third the size of the United States, and the same size as all of Western Europe. Saudi Arabia lies at the crossroads of three continents: Europe, Asia, and Africa. It extends from the Red Sea on the west to the Arabian Gulf in the east. To the north it borders on Jordan, Iraq, and Kuwait, and to the south, on Yemen

and the Sultanate of Oman. Towards the east lie the United Arab Emirates, Qatar, and the island state of Bahrain as shown in Figure 1.1.

**Figure 1.1**  
**Map of Saudi Arabia**



(Modified from Source: Saudi Arabia Map)

Saudi Arabia's terrain is varied but on the whole fairly barren and harsh, with salt flats, gravel plains, and sand dunes but few lakes or permanent streams. In the south is the Rub Al-Khali (Empty Quarter), the largest sand desert in the world. In the southwest, the mountain range of Asir Province rises to over 9,000 feet. Saudi Arabia is one of the arid countries in the world, with an average rainfall of less than 5 inches per year. The climate

is principally determined by the southerly shift in wind patterns during the winter months, which brings rain and cool weather.

Summer in Saudi Arabia is hot with temperatures in some areas reaching 49°C (120°F). Winter is mild with an average temperature of 23°C (74°F) in Jeddah and 14°C (58°F) in Riyadh. From June through August, midday temperatures in the desert can reach/soar to 50°C (122°F). In contrast to this weather in other parts of the country like in the northern and central regions the temperature may drop to below freezing.

The *shamal*, sand-laden winds from the northern deserts, is most frequent in early summer and can blow for days at 25-30 miles an hour. Rainfall ranges from none at all for up to 10 inches a years in the Rub Al-Khali, to 20 inches a year in the mountains of Asir Province. Temperature between October and May is generally pleasant with cool nights and sunny days. Night temperatures in the coastal areas may dip into the 4.4°C (40°F). From April to November, on the other hand, temperatures are considerably higher and life without air-conditioning would be very unpleasant indeed.

Due to extreme climatic and geographical conditions, there is a dearth of water resources in the kingdom. Because of the harsh climatic situations there exist a rapid increase in demand for the water in the Arabian Gulf countries. Saudi Arabia' Kuwait, the United Arab Emirates, Qatar, Bahrain, and Oman where conventional water resources such as fresh surface water and renewable groundwater are extremely limited, other alternatives



such as wastewater reclamation and desalination have been adopted since 1960s. Countries such as Saudi Arabia, Kuwait, Qatar, and Bahrain all use nonrenewable groundwater resources in large quantity, causing depletion of these valuable resources and deterioration in the quality of water. In some of the more arid parts of the Middle East, in particular the Gulf states, where good quality water is not available or is extremely limited, desalination of seawater has been commonly used to solve the problems of water supply for municipal and industrial uses (Al-Quarashi and Husain, 2001).

Saudi Arabia entered the desalinated water field in 1970. Since then it has constructed desalination plants on both the Red Sea and the Gulf coasts as shown in Figure 1.2. Realizing the need of water for the continuous growth of the country, the Saudi government constituted the Saline Water Conversion Corporation (SWCC) to meet its water needs. The SWCC has so far 23 plants, distributed at fifteen locations along the Eastern and Western Coast of Saudi Arabia. 19 of these are on the Red Sea Coast and the remaining 4 on the Persian Gulf Coast. Table 1.1 will describe the 23 plants, which are in operation in the Kingdom. The total production of desalinated water is estimated to be 2.16 million m<sup>3</sup> (572 million [US] gal.) per day including a facility at Al-Jubail producing 1 million m<sup>3</sup> per day, which is currently the world's largest distillation plant. The Al-Jubail desalination plant supplies water to the capital city Riyadh, while the Makkah and other Holy places are supplied by Al-Shoaibah plant, which has the daily production capacity of 48 million gallons of water.

**Table 1.1**  
**Desalination Plants in Operation**

PLANT		CAPACITY			BENEFICIARY CITIES
		Daily Water		Electricity	
Name	Phase	Cubic Meter	Gallons	Megawatt	
Haql	II	3,785	1,000,000	----	Haql and Adjacent Villages
Duba	III	3,785	1,000,000	----	Duba and Adjacent Villages
Alwajh	II	473	125,000	----	Al Wajh
	Exp.1	825	218,000	----	
	Exp.2	1,032	273,000	----	
Umlujj	II	3785	1000,000	----	Um Lujj
Rabigh	I	1204	318000	----	Rabigh and Surrounding Villages
Aziziah	I	3870	1000000	----	Aziziah Island
Albirk	I	1952	500,000	----	Al Birk & Adjacent Villages
Farasan	I	430	114000	----	Farasan Island and Adjacent Villages
	Exp.1	1075	284000	----	
Jeddah	II	37850	10,000,000	71	Jeddah
	III	75700	20,000,000	200	
	IV	189250	50,000,000	500	
	R.O.1	48825	13,000,000	----	
	R.O.2	48827	13,000,000	----	
Madinah/ Yanbu	I	95000	25000,000	300	Madinah/Yanbu and Adjacent Villages
Shouibah	I	181,860	48,000,000	220	Makkah/ Taif
Assir	I	75,700	20,000,000	45	Abha/Khamis Mushat/ Ahad Refida and Adjacent villages
<b>Western Coast Total</b>		<b>775,230</b>	<b>204,832,000</b>	<b>1336</b>	
Khafji	II	18624	4919902	-----	Khafji
Alkhubar	II	193536	51126405	500	Khobar, Dammam, Dharan, Khattf, Sahhat, Safwa, Rahima, Coast Guard and Airbase
Jubail	I	116035	30,653000	238	Riyadh, Jubah Marine Base & Al-Jubail Royal Commission
	II	798864	211,036,000	812	
<b>Eastern Coast Total</b>		<b>1,127,059</b>	<b>297,735,307</b>	<b>1550</b>	
<b>TOTAL</b>		<b>1,902,289</b>	<b>502,567,307</b>	<b>2,886</b>	

(Adopted From SWCC, 1995)

Figure 1.2, shows the location of main desalination plants in the kingdom of Saudi Arabia. Four new desalination and power production plants are now under construction, two of these are on Red Sea Coast, the Al-Medinah Yanbu Plant (Phase-II) and the Al-Shoaibah plant (Phase-II). The other two projects are on the Arabian Gulf Coast; these are Al-Jubail Plant (Reverse Osmosis), and the Al-Khobar Plant (Phase-III). Complete information about these four plants is provided in Table 1.2. In response to its need and care about the future consumption of sweet water, the SWCC is now studying fifteen more desalination plants in Saudi Arabia.

**Table 1.2**  
**Desalination Plants Under Construction**

PROJECT		CAPACITY			BENEFICIARY CITIES
		Daily Water		Electricity	
S.No	Name	Cubic Meter	Gallons	Megawatt	
1.	Madinah/ Yanbu PhaseII	60,000,000	227,272	35	Madinah, Yanbu, Al-Bahr, Badr, Al-Rayes, Mufrohat, Al-Hamra, Al-Frish, Mulailah, Khief, Al-Khuzami, Al-Musajjeed
2.	Al-Jubail R.O Desalinated Plant	24,015,000	90,909	-----	Interior Locations, Qassim, Sudair, Washem.
3.	Al-Khobar Phase III	60,000,000	227,272	370	Al-Khobar, Dammam, Dhahran, Qatif, Saihat, Rahima, Al-Ahsa, Buqaiq
4.	Al-Shoaibah Phase II	100,000,000	378,787	340	Jeddah, Makkah, Taif

Adopted From SWCC, 1995

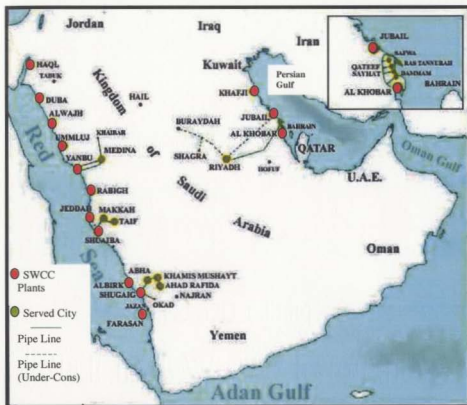


Figure 1.2 SWCC Desalination Plants Across the Kingdom (Adopted from SWCC, 1995)

Most of the above desalination plants are multistage flash (MSF) types, which use a significant amount of energy to produce high quality drinking water from seawater. Although these desalination plants are equipped with the latest technology and due consideration is given to protect the environment and coastal ecosystems, but despite all

these measures and control technologies employed, the potential coastal zone impact from these plants cannot be completely avoided (Husain, 2001<sup>a,b</sup>).

## **1.2 Desalination**

Desalting/desalination/desalinization refers to the method or water treatment process in which salt is removed from water. This process can be used in different ways but the end result will always be the same, fresh water.

The process of desalination has been practiced for more than 50 years (Wagnick, 1996, 1998) and is a well-established means of water supply in many countries. In nature, the water evaporates from the seas, giving rise to the clouds and then subsequently condenses back in as rainwater. Rainwater is almost pure and all this process of rainmaking is a true physical liquid and solid phase separation in seawater.

Desalination is also an ongoing process in the polar region of the earth where the seawater freezes; the ice crystals produced are pure water and contain none of the salt present in seawater. The basis of all desalination processes is conversion of part of the seawater into fresh water. While looking at the above natural processes one can understand that the process of distillation/desalination technique is based on evaporation and condensation (Al-Mumtaz & Wagialla, 1988; Al-Sahlawi, 1999).

Membrane separation techniques of electro dialysis and reverse osmosis also occur in nature, and its development into commercially viable processes is a recent success of understanding of physical chemistry of phase separation by membranes.

The economical production of fresh water from seawater became possible in 1957 with the advent of multistage flash process (MSF) (IDA, 1998). The MSF process brings a dramatic change in the cost of desalination water. Table 1.3 shows the statistics for the global production of desalinated water, by process and plant capacity (IDA, 1998). It shows that MSF plants have a higher total production capacity than any other process, despite the larger number of reverse osmosis plants. Table 1.3 shows that, of the larger desalination plants ( $>4000 \text{ m}^3 \text{ d}^{-1}$ ), MSF plants make up 64 per cent of the total capacity. About 67.6% of the total capacity installed in the gulf countries are of the multi-stage flash type. The capacity of the large plants installed during the eighties were as follows:

- |                                 |                               |
|---------------------------------|-------------------------------|
| ▪ Al-Jubail Plant, Saudi Arabia | 253.5 million gallons per day |
| ▪ Jeddah IV, Saudi Arabia       | 58.0 million gallons per day  |
| ▪ Al-Khobar II, Saudi Arabia    | 51.0 million gallons per day  |
| ▪ Um El-Nar Plant, Abu Dhabi    | 95.0 million gallons per day  |

**Table 1.3**  
**Summary of Worldwide Desalination capacity Split by Plant Type and Process Capacity Range**

<b>Desalting process</b>	<b>Percentage of Using Technologies</b>	<b>Capacity (10<sup>6</sup> m<sup>3</sup> d<sup>-1</sup>)</b>	<b>Capacity (10<sup>6</sup> gal d<sup>-1</sup>)</b>	<b>No. of plants</b>
<b>Unit Capacity 100-60,000 m<sup>3</sup>d<sup>-1</sup></b>				
Multistage flash	44.4	10.02	2204	1244
Reverse osmosis	39.1	8.83	1943	7851
Multiple effect	4.1	0.92	202	682
Electrodialysis	5.6	1.27	279	1470
Vapor compression	4.3	0.97	213	903
Membrane softening	2.0	0.45	99	101
Hybrid	0.2	0.05	11	62
Others	0.3	0.06	13	120
<b>Total</b>	<b>100.0</b>	<b>22.57</b>	<b>4965</b>	<b>12433</b>
<b>Unit Capacity 500-60,000 m<sup>3</sup>d<sup>-1</sup></b>				
Multistage flash	46.8	10.00	2200	1033
Reverse osmosis	37.9	8.10	1782	3835
Multiple effect	3.8	0.81	178	653
Electrodialysis	4.7	1.00	220	230
Vapor compression	4.2	0.90	198	486
Membrane softening	2.1	0.45	99	64
Hybrid	0.2	0.04	9	27
Others	0.28	0.06	13	108
<b>Total</b>	<b>100.0</b>	<b>21.36</b>	<b>4699</b>	<b>6436</b>
<b>Unit Capacity 4000-60,000 m<sup>3</sup>d<sup>-1</sup></b>				
Multistage flash	64.0	9.27	2039	496
Reverse osmosis	25.7	3.72	818	613
Multiple effect	3.6	0.52	114	48
Electrodialysis	2.1	0.31	68	60
Vapor compression	1.9	0.28	62	42
Membrane softening	2	0.36	79	50
Hybrid	0	0.02	4	2
Others	0	0.00	0	0
<b>Total</b>	<b>100.0</b>	<b>14.48</b>	<b>3186</b>	<b>1311</b>

Source: International Desalination Association, Topsfield, MA, 1998. Worldwide Desalting Plants Inventory Report No. 15

Table 1.4, as shown below, gives more information regarding the large share of the world's desalination capacity, which is in the Arab states, and particularly in the Persian Gulf.

**Table 1.4**

**Summary of Worldwide Desalination Capacity (1998), Showing Contribution Made by Arab Nations**

Desalting process	% of using Technology	Capacity (10 <sup>6</sup> m <sup>3</sup> d <sup>-1</sup> )	Capacity (10 <sup>6</sup> gal d <sup>-1</sup> )
<b>Global</b>			
Multistage Flash	44.4	10.02	2204
Reverse Osmosis	39.1	8.83	1943
Multiple Effect	4.1	0.92	202
Electrodialysis	5.6	1.27	279
Vapor Compression	4.3	0.97	213
Membrane Softening	2.0	0.45	99
Hybrid	0.2	0.05	11
Others	0.3	0.07	15
<b>Total</b>	<b>100.0</b>	<b>22.58</b>	<b>4968</b>
<b>Arab States including AGCC States</b>			
Multistage Flash	37.6	8.50	1870
Reverse Osmosis	12.0	2.70	594
Multiple Effect	0.5	0.12	26
Electrodialysis	1.6	0.35	77
Vapor Compression	1.6	0.36	79
Membrane Softening	0.0	0.00	0
Hybrid	0.0	0.01	2
Others	0.0	0.00	0
<b>Total</b>	<b>52.3</b>	<b>12.04</b>	<b>2649</b>
<b>AGCC States Only</b>			
Multistage Flash	35.0	7.90	1738
Reverse Osmosis	9.1	2.05	451
Multiple Effect	0.2	0.05	11
Electrodialysis	0.5	0.12	26
Vapor Compression	1.0	0.22	48
Membrane Softening	0.0	0.0	0.0
Hybrid	0.0	0.0	0.0
Others	0.0	0.0	0.0
<b>Total</b>	<b>45.8</b>	<b>10.34</b>	<b>2275</b>

AGCC = Arabian Gulf Co-Operation Council

Adopted from: International Desalination Association, Topsfield, MA, 1998. Worldwide Desalting Plants. Inventory Report No. 15



Therefore, it is clear from the literature search that in the arid Arabian Peninsula region the seawater desalination process is becoming increasingly important to satisfy the growing needs of domestic, agricultural, and industrial sectors (El-Nashar and Ali, 1989).

Table 1.3 and 1.4, depicts that the three main types of desalination plants are reverse osmosis (RO), electro-dialysis (ED) and multi stage flash (MSF) desalination. All of the above three desalination processes use fossil fuel as an energy driver. Burning fossil fuel produces the usual gaseous effluents along with particulate matter, because of these environmental issues the three desalination processes are evaluated and rated, as shown in Table 1.5, using the pseudo-quantitative scale where high (H=3), medium (M=2), and low (L=1). On this scale the RO seems to be close to ED and both are preferred to MSF from safety, health, and environmental point of view. However these factors are considered to be not exclusive (Sabri et al., 1980).

**Table 1.5**  
**Rating of Various Desalination Processes**

<b>EFFECTS</b>	<b>RO</b>	<b>MSF</b>	<b>ED</b>
Noise	H	M	L
Water Effluent	M	H	M
Product Water Impurities			
1. Microelements	L	H	L
2. Toxic materials	M	H	M
Air Pollution	L	H	M
Industrial Risk	M	H	M
Total	8	17	10

Source: Sabri et al., 1980

From Tables 1.3 to 1.5, it has become obvious that the multistage flash (MSF) desalination plants are among the major source of potable water in the Arab Gulf countries and also in the world and is of major concern relating the environment.

The MSF are large, complex and expensive plants, which will be explained in more detailed in chapter 2. The MSF process consists of a series of stages, in which "flash" evaporation takes place from brine flowing through the bottom of the stage, with the vapour condensing to produce water on heat transfer tubes at the top of the stage. The transfer of latent heat heats seawater or brine flowing through the tubes. The heat to operate the process is supplied by steam condensing in the brine heater (or heat input section). MSF desalination process consumes large amount of seawater, with that a large amount of concentrated brine are disposed of into the ocean. This brine discharge from the MSF desalination plants is known to impact upon the marine organism in a number of ways. For instance, elevated temperatures and increased salinity reduce the overall concentration of dissolved oxygen in water, which restricts the life forms to those, which exist at low oxygen levels. Furthermore, at the level of individual organism, extreme temperatures may result in death; at the species level, excessive temperatures may lead to changes in individual abundance and population diversity (Morton et al., 1996).

Desalination plants are usually located on or near to the ocean. The most common and least expensive brine disposal method is ocean discharge. Just like other environmental regulatory guidelines, the U.S EPA Clean Water Act in 1977, classified the brine

discharge (saline water) as conventional and non-conventional (and non toxic), and it sets the numeric limits or guidelines for conventional and non-conventional type of effluents, except for salinity. The U.S EPA Clean Water Act does not specifically identify brine total dissolved solids (TDS) as a pollutant. However, extremely low salinities (near zero) or extremely high salinities (twice the ocean ambient) can impact ocean biota if the biota is exposed for an extended period of time (Del Bene et al., 1994).

To study the concentration of TDS/salinity and temperature pattern/profile of the brine discharge from Al-Jubail desalination plant an EPA computer code will be used. Several hydrodynamic mixing models are in use for the evaluation of brine discharge in the surrounding body of water. The most popular of these are the PLUMES code from the EPA Pacific Ecosystems Branch in Newport, Oregon, and the CORMIX code from the EPA Environmental Research Laboratory in Athens, Georgia (Del Bene et al., 1994).

In this thesis in addition to detailed air pollution study, an effort will also be made while using the EPA CORMIX computer code to enable the modeling of submerge brine discharge, to suggest the mixing zone and dilution criteria in the Persian gulf.

Another feature characteristics of MSF desalination process is that it requires a large amount of energy input in order to achieve separation of fresh water from saline or seawater, this energy is mostly in the form of steam, condensing in the brine heater. In almost all instances, the energy required to run these plants is ultimately derived from the

combustion of fossil fuels. Air pollutants are emitted from the stacks while burning fossil fuel to attain the energy required for desalination plants. The principal atmospheric pollutants generated by burning the fossil fuel are:

- Sulfur dioxide (SO<sub>2</sub>)
- Oxides of nitrogen (NO<sub>x</sub>)
- Suspended particulate matter (SPM)
- Carbon dioxide (CO<sub>2</sub>), and
- Carbon Monoxide (CO)

All these pollutants are responsible for changing our atmosphere and affecting all forms of life and the environment. Studies have shown that air pollutants adversely affect human health. Mild irritation, severe asthmatic sickness and sometimes-chronic carcinogenic effects are all because of air pollutants. Children, elderly people and people with respiratory problems such as asthma, bronchitis, and people involved in vigorous outdoor activities are more susceptible to the adverse effects of air pollution. Thousands of people die prematurely each year because of air pollution (Husain, 2001<sup>b</sup>).

Besides affecting the human health the air pollution affects the environment by acidifying the water bodies creating photochemical smog, depletion of stratospheric ozone, and global warming.

Air pollutants are transported hundreds and thousands of miles away from the source by wind. These pollutants go through various physical and chemical processes before they finally are deposited. Meteorological and topographical conditions greatly influence the transportation, dispersion and deposition of air pollutants. The main factors effecting the deposition and dispersion of air pollutants are wind speed and direction, turbulence, temperature, topography, meteorological parameters, atmospheric moisture content and stability condition of the air.

In 1990, Zannetti characterized air pollution transport as:

- ***Near Field Transport:*** Where building aerodynamics causes effects of the plume
- ***Short Range Transport:*** Within 10 km from the source and in this region the primary pollutants are known to have maximum ground level impact.
- ***Intermediate Transport:*** Between 10 km and 100 km from the source, where the chemical reactions plays and important role in the transformation of pollutants
- ***Long Range Transport:*** Range more than 100 Km from the source, in this case large-scale meteorological effects and deposition and transformation rates play a significant role.

To study the detrimental affects caused by these air pollutants from an existing or proposed facility, the monitoring and controlling agencies propose two basic techniques,

which are monitoring and modeling of the site. As the cost of monitoring is very high, therefore modeling is considered to be the most viable effective and economical tool, which is also widely used and highly recommended by the USEPA for such purposes. In this thesis work an EPA air dispersion model AERMOD will be used to simulate the current physical and chemical processes and predict the future concentrations of pollutants in the atmosphere. An effort will be made to control and reduce further deterioration of the atmosphere.

### **1.3 Objectives**

Al-Mutaz and Wagialla, in 1988, stated that the desalination capacity in the Arabian Peninsula has increased from  $0.5 \times 10^6 \text{ m}^3/\text{d}$  in 1973 to  $5.8 \times 10^6 \text{ m}^3/\text{d}$  in 1984 almost a ten fold increase. Al-Sahlawi, in 1999, reported that in Arabian Peninsula which comprises of Saudi Arabia, Kuwait, Bahrain, Qatar, the United Arab Emirates, Oman, and Yemen, there is a 3% or more annual increase of water demand, which clearly shows the increasing demand for desalination plants in that area, comparing to the world desalination capacity, about 70% of large MSF plants are installed in Saudi Arabia.

A great deal of expansion is taking place in Saudi Arabia in the area of desalination. All of these desalination plants require an input of thermal or mechanical energy in order to achieve separation of fresh water from the seawater. The main consequences of such input of energy are an increase in the temperature of the brine discharge and the atmospheric emission. Therefore, this research will attempt to assess the environmental effects by MSF desalination process. Appropriate modeling techniques will be used to

estimate the air emission and water pollutants from these plants, which will help in future expansion and reduction in the emission from these plants.

## **1.4 Thesis Layout**

There are eight chapters altogether in this thesis, covering the methods, formulation and analysis of work. Chapter 1 briefly discusses the world and Middle East water shortage/crises, desalination, air and brine discharge problems from desalination plants and objectives of the study. Chapter 2 covers an extensive literature search related to desalination methods and processes. Chapter 3 represents an overview of air pollution and their effects on human health. Air pollution model selection and comparison criteria are also discussed in this chapter. Brief description of AERMOD model, formulation, data acquisition, emission inventory of Al-Jubail desalination plant, and receptor grid information about the site is discussed in chapter 4. Chapter 5 presents the background information about the study area. The results generated by AERMOD, their analysis with scientific and technical interpretation and discussions are presented in chapter 6.

Chapter 7 briefly explains the CORMIX system, the geographical description of the site, and the results and analysis of the brine discharge from Al-Jubail desalination plant.

Finally, in chapter 8, the findings and limitations were presented, and recommendations for the future work are made.

## **Chapter II**

### **LITERATURE REVIEW**

#### **2.1 Desalination Process**

In August 1999, the world population reached to six billion. As a result of rapid population growth, the need for water is rapidly increasing, and current freshwater resources will not be able to meet all the requirements. Water cannot be considered now as a low cost resource and easily accessible to all. Many years of drought at various locations, followed by desertification and movement of the population towards this essential resource calls for different considerations in terms of economic, environmental, and social effects (Semiat, 2000). The hydrological cycle provides the earth with a continuous supply of fresh water. Basically, the sun creates the cycle by providing the energy to evaporate water from ocean and from water bodies on land. This water vapor, which accumulates as clouds, condenses in the cooler upper atmosphere and falls to the



Earth's surface in the form of rain or snow. Man has distilled freshwater from seawater for many centuries. Egyptian, Persian, Hebrew, and Greek civilization all used various forms of desalination processes.

Worldwide supplies of saline water, and critical needs for fresh water have led to a substantial growth in the desalination technologies. By desalination we mean primarily the production, from saline water, of product water, which is suitable for human consumption. Even though desalted water represents only a small portion of water used, the impacts of these plants are expected to be considerable. This is especially true when it is coupled with the growth of industries and human population in the arid regions of the world.

### **2.1.1 Thermal Process**

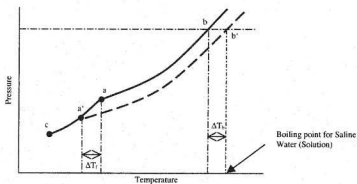
Over 60% of the world's desalted water is produced with heat to distill fresh water from seawater. In laboratory or in industrial plants, the water is heated to a boiling point to produce maximum quantity of water vapors.

Economically in the desalination plants adjusting the atmospheric pressure of the water controls the boiling point. The temperature required to boil water decreases as one moves from sea level to a higher elevation because of the reduced atmospheric pressure on the water. Thus water at a height of 6200 meters from sea level can be boiled at 16 C° less

than boiling at sea level. The reduction in boiling point is important factor in desalination process for two major reasons:

1. Multiple boiling
2. Scale control

The important condition to boiled water is the proper temperature relative to its ambient pressure and enough energy for vaporization. For example, if the water is heated to its boiling point, and then the heat is turned off the water will continue to boil for a short time, but will need additional energy (the heat of vaporization) to continue boiling, which can achieved by either providing more heat or by reducing the ambient pressure above the water. By reducing the ambient pressure above the water one can reduce the temperature at which the water boils, as shown in Figure 2.1.



**Figure 2.1** Phase Diagram for Saline Water and Pure Water  
(Adopted from Spiegler and Laird, 1980)

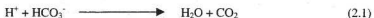
The phase diagram (Figure 2.1) shows that by reducing the pressure the boiling point of water can be reduced. The point 'a' in Figure 2.1 is called the triple point, at this point pure water under equilibrium state can exist in three phases (solid, liquid, and gases) at an absolute pressure of 4.58 mm Hg (millimeter of mercury) and a temperature of 0.01°C. Where for saline or seawater the triple point is shifted from 'a' to 'a'', the degree of shift depends upon the salinity of water. Point 'b' represents the boiling point of pure water, while 'b'' boiling point for saline water, at a pressure of 1 atmospheric or 760 mm Hg. In Figure 2.1, the points 'b' & 'b'' represents the boiling point elevation  $\Delta T_b$ .

To significantly reduce the amount of energy or heat needed for vaporization, the desalting process usually uses multiple boiling in successive stages, each operating at a lower temperature and pressure.

Scale formation is encountered in most of the desalination plants, and is basically formed from water, which contains ions (like calcium, magnesium, sulfate, and carbonate). These ions in water are capable of creating supersaturated molecules of materials, which are slightly soluble in water. These supersaturated materials tend to precipitate and produces a hard and adherent layer of the chemical, which drops out of the solution in the desalination process. This layer is referred to as "scale". In all desalination plants the scales can be formed on any heat transfer surface, and can interfere with the heat flow between the surface and the liquid, and also with the movement of liquid through these surfaces (Howe, 1974).

The major types of scale forming salts in seawater desalination are  $\text{CaCO}_3$ ,  $\text{Mg(OH)}_2$ , and  $\text{CaSO}_4$ . The solubility of  $\text{CaCO}_3$ , and  $\text{Mg(OH)}_2$ , vary widely with the alkalinity of the solution as measured by the pH value, but the solubility of the three forms of  $\text{CaSO}_4$  are nearly independent of the pH value. Therefore, in each case the scale formation control in desalination plants are treated in two parts, the first one is treating alkaline components and the other one is the control of sulfate scale components.

Sulfuric acid is the cheapest source/method of removing alkaline hardness (the bicarbonate ions), followed by aeration to remove the carbon dioxide. The action of hydrogen ion on the bicarbonate ion can be well understood from the following reaction:



In the same way the  $\text{CaSO}_4$  hardness is removed by introducing some vegetable extract, or the use of ion exchange method to replace either the calcium ions with sodium ions or sulfate ions with chloride ions. In scale control technologies the operational temperature in desalination plants are kept below the point where  $\text{CaSO}_4$  and its hydrates become soluble.

The concept of reducing pressure and temperature has made distillation a successful process around the world. The process, which accounts for most of the desalting capacity is the multi-stage flash distillation/desalination, commonly referred to as MSF process.

#### **2.1.1.1 MULTISTAGE FLASH DESALINATION (MSF) PROCESSES**

In MSF desalination process the water is heated and vapors are condensed to collect fresh water. There are four main types of MSF processes namely:

1. Multistage flash desalination process with brine circulation (MSF) system
2. Multistage flash desalination process with once through (MSF-OT) system
3. Multistage flash desalination process with brine mixing (MSF-M) system
4. Multistage flash desalination process with brine circulation and vapor compression system.

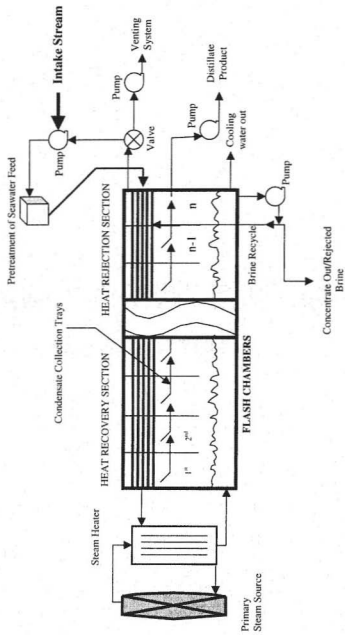
##### **2.1.1.1.1 Multistage Flash (MSF) Desalination Process with Brine Circulation**

In flash desalination process the vapors are produced by sudden release of pressure on hot water, which is at its boiling temperature. The moment when the maximum boiling temperature has reached/achieved in the system, the pressure on the liquid in different stages is reduced, and at each stage/step with the reduction of pressure the vapours are formed by flashing, which are then collected as a distillate (Howe, 1974).

Figure 2.1, shows the essential features of MSF desalination with brine circulation process. It consists of five main streams including the intake stream, the distillate product, the concentrate out, the brine recycle, and the heating system. As a whole, the system includes the flashing chambers/stages, the brine heater, the pumping units, the venting system, the pretreatment compartment, and the primary steam source.

In the system the flashing chambers are divided into two sections, the heat recovery and the heat rejection. The heat rejection section is basically limited to 3-stages, while in the heat recovery section the flashing stages vary between 21 and 40. The intake seawater is treated first at the pre-treatment compartment with water treatment chemicals (like anti-scaling etc.), after treatment the water is then introduced inside into the preheated/condenser tubes in the last flashing stage of the heat rejection section as shown in the Figure 2.1. At the same time the brine recycle stream is introduced inside into the preheater/condensor tubes of the last flashing stage of the heat rejection section (Al-Wazzan, and Al-Modaf, 2001; Semiat, 2000).

The pre-treated seawater enters into the condenser tubes at stage 'n' and is heated by condensation of the vapors rising from the flash chamber of this stage. Each stage consists of flash chambers below the condenser tube. The seawater from this stage is



**Figure: 2.2 Schematic Presentation of a Multi-Stage Flash Desalination Plant**  
 (Adopted from: Scemiati, 2000)

mixed with warm brine by the re-circulating pump to conserve heat, and pass successively through the other stages. In the heat recovery section, the heat is transferred from steam condensing on outside of the tubes while the water is flowing inside the tubes. The brine-seawater mix then enters the brine heater from the first stage of flash chambers. The brine heater is heated with the saturated steam at a temperature from 97 to 117C° (from a primary steam source). The heated steam flows outside of the brine heater tubes while the brine stream flows inside the tubes. As the heated steam condenses, the brine stream absorbs the latent heat of condensation and its temperature reaches the desired top brine temperature. The hot brine then enters the first flashing stage, where a small product of vapor is formed. The flashing process reduces the temperature of the un-evaporated brine. This temperature reduction across the stages is due to the drop in the atmospheric pressure, for pure water this pressure drop ranges from 760 mm Hg to 4.58 mm Hg, while in saline water it depends upon the percentage of salinity present in the water.

The highest pressure is found in the first stage after the brine heater and the lowest pressure is at the last stage 'n'. In each stage the flashed off vapors are condensed on the outer surface of the pre-heater/condenser tubes. The condensation process releases the latent heat of vaporization, which is used to preheat the brine recycle stream in the heat recovery section. After leaving the heat recovery section the water enters into the heat rejection section and splits into two streams. The first into the cooling seawater stream, which is rejected back to the sea, and the second to the feed seawater stream, which is



mixed back into the seawater at the last flashing stage in the heat rejection section, and part of it is rejected as a concentrate out to the ocean. The distillate is collected in the collection trays, which are provided in each stage of the desalination plant. Additional units can be introduced into the desalination plants for the pretreatment of feed and intake seawater streams. Mostly, the treatment of intake seawater is limited to simple screening and filtration.

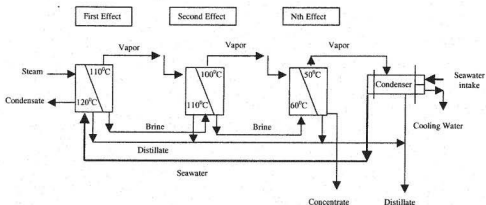
The three most important steps involved in producing distilled water in MSF desalination systems are:

1. Vapor formation by the addition of heat to a body of saline water
2. Removal of this vapor by contacting with the liquid from which it came, and
3. Condensation of vapors by removal of heat, usually it is done by contacting these vapors with cooled surface.

#### **2.1.1.1.2 Multiple-Effect Distillation/Evaporation**

From literature, it is clear that one can easily multiply the amount of vapors produced by placing several evaporators in series, while keeping the evaporating sides at low pressure values to ensure proper heat flow (Howe, 1974). The MED process has been used for a long time in the industrial sector. The MED process takes place in a series of vessels (effects), just like MSF. Similarly to MSF, in MED the ambient pressure is reduced in these vessels (effects), which basically provides the seawater intake to undergo a multiple boiling without supplying the additional heat after the first stage/effect.

As shown in Figure 2.3, the seawater enters into the condenser sector first, to gain temperature and produce vapors. Seawater from the condenser enters into the first effect of the MED system. At this section/stage the temperature of seawater is raised to its boiling point, all this heat is provided by an external steam source, as shown in Figure 2.3. The seawater is then either sprayed or distributed on the surface of evaporator tubes to achieve rapid boiling or evaporation. The condensate from the boiler steam is recycled back to the boiler for reuse. In the first effect when the seawater is heated to its boiling point, only a portion of it is evaporated and the rest of the seawater is fed to the second effect as brine (as shown in Figure 2.3). At the second stage/effect the ambient pressure is reduced, to reduce the boiling point, the seawater is again sprayed on a bundle of evaporators, which is then condensate to fresh water (distillate). In the same fashion this process can be continued for several effects, usually 8 to 16 stages/effects are used in the typical large plants.



**Figure 2.3 Schematic of Multi-Effect Distillation Plant**  
(Source: University of Waterloo, 2000)

The main differences between the MSF and MED distillation plants are:

1. The amount of water flowing in through a MSF plant is several times greater than the distillate formed in the MED process.
2. The gain output ratio (GOR), which is equal to the amount of distillate produced, divided by the amount of heating steam used in the high-pressure evaporator, is higher in MSF system than in MED system (Howe, 1974).

#### **2.1.1.1.3 Vapor Compression Method**

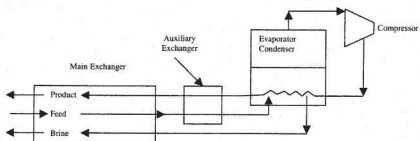
The vapor compression (VC) distillation process is generally used for small-and medium-scale seawater desalting units. The heat for evaporating the water in this system is generated from the compression of vapor rather than the direct exchange of heat from steam, produced in the boiler. The plants using this process are generally designed to take advantage of the principle of reducing the boiling point temperature by reducing the pressure.

In vapor compression system, the driving force is established by creating a higher saturated pressure through compression process. Figure 2.4 represents a conventional vapor compression system operating above the ambient temperature. In this, a mechanical compressor is used to generate the heat for evaporation. The compressor creates a vacuum in the vessel and then compresses the vapor taken from the vessel and condenses it inside of a tube bundle also in the same vessel. Seawater is sprayed on

outside of the heated tube bundle where it boils and partially evaporates, producing more water (Spielgler and Laird, 1980).

In vapor compression system, generally two primary methods are used to condense vapor to produce enough heat to evaporate incoming seawater, these are mechanical compressor or a steam jet. The mechanical compressor is usually electrically driven, allowing the sole use of electrical power to produce water by distillation. VC units have been built in a variety of configurations to promote the exchange of heat to evaporate the seawater.

VC units are usually built in the range of 20- 2000 m<sup>3</sup>/d (0.005- to 0.5-mgd). They are often used for resorts, industries, and drilling sites where fresh water is not readily available.



**Fig. 2.4 A Conventional Vapor Compression (VC) System**  
(Source: Spielgler & Laird, 1980)

## **2.1.2 MEMBRANE PROCESSES**

Membrane processes are currently the fastest growing techniques in water desalination.

The two main membrane desalination processes are:

1. Reverse osmosis (RO), and
2. Electrodialysis (ED)

Both these processes have been in use for many years. There has been faster development in the area of ED than RO, but still RO has been considered to be more sound and simple water distillation process as compared to ED (Dukhin et al., 1991).

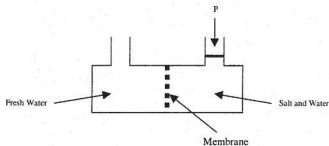
In the early 60s, the only process that was used in the industries was ED. There were no RO units at all in that era (Pilat, 2001), but with the invention/technology of organic synthesis the RO system has become dominated in the membrane processes.

Both of the above processes (i.e. reverse osmosis and electro dialysis) will be discussed briefly in the next sections.

### **2.1.2.1 Reverse Osmosis (RO)**

If a solution, for example salt water, is placed on one side of semi-permeable membrane and water is placed on the other side, then there develop a natural tendency, termed "osmosis", in which the water has to diffuse through the membrane to the solute side

until an equilibrium osmotic pressure is achieved. Now if pressure is applied to the solute side, substantially greater than the osmotic pressure, then water will diffuse from the solution through the membrane to the freshwater side. This is called reverse osmosis (RO). In this process as shown in Figure 2.5, the water flow passes through the membrane under pressure

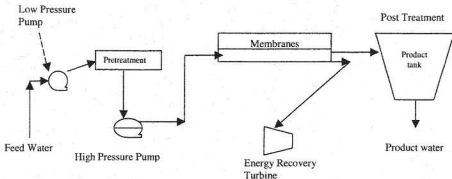


**Fig. 2.5 Principle of Water Movement in Reverse Osmosis**  
(Adopted from Pilat, 2001)

The process is continuous and the membrane separates the feed fluid into two streams: a concentrated one containing impurities, and pure water called permeate (Faller, 1999). The RO membrane technique is considered to be very effective for brackish and seawater desalination (Furukawa, 1997).

Figure 2.6, shows the schematic presentation of RO desalination plant. The process takes place in ambient temperature. The only electrical energy required is for pumping the water to a relatively high operating pressure. Some times special energy recovery

turbines are used to reclaim part of the energy. Operating pressure varies between 10-25 bars for brackish water and 50-80 bars for seawater.



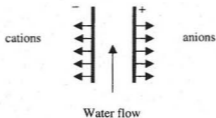
**Fig. 2.6 Schematic Presentation of a Reverse Osmosis Desalination Plant**  
(Semiat, 2000)

### 2.1.2.2 Electrodialysis (ED)

Electrodialysis (ED) or more widespread Reversible Electrodialysis (RED) system is the system in which ions are forced to pass by means of DC electrical power through semi-permeable membranes into the concentrated streams leaving behind diluted salt solutions. The main principle of water flow movement towards membranes in electro-dialysis unit is presented in Figure 2.7 (Pilat, 2001, Semiat, 2000).

Basically, the anions and cations migrate through a membrane the main water flow moves parallel with the membrane (tangentially in relation to migration ions). This

system has a nominal initial brackish water recovery, in the range of 80% to 90% (Pilat, 2001).



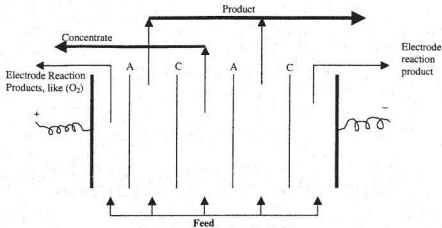
**Fig. 2.7 Principle of Water Movement in Electro-Dialysis Units**  
(Pilat, 2001)

In recent years, large variety of processes have been developed in which different types and combinations of membranes have been uniquely arranged, in an attempt to enhance the performance of, or to simplify the equipments needs for the practical application and use of electro-dialysis (Shaffer and Mintz, 1980). All of these processes use the same principle as described in Figure 2.7.

Figure 2.8, shows the conventional electro-dialysis system, in which, both the cation-permeable and anion-permeable membranes are used, these are arranged in an alternating pattern. Arrangements are made in such a way that two salts depleted boundary layers and two salt concentrated boundary layers are formed in alternate compartments. The



water flows across these compartments or membranes and the salt is removed in this process. The end result is water with an acceptable concentration of total dissolved solids/salts.



**Fig. 2.8 Conventional Electro-dialysis; A, Anion-Permeable Membrane; C, Cation-Permeable Membrane (Sahffer and Mintz, 1980)**

### 2.1.3 FREEZING PROCESS

Extensive work has been done in the late 50s and 60s to invent a freezing desalination process. During this process the dissolved salts are naturally excluded in the formation of ice crystals. Desalination can be achieved by cooling the water to form crystals under controlled conditions. Before the entire mass of water has been frozen, the mixture is

usually washed and rinsed to remove the salts in the remaining water, or adhering to the ice crystals. The ice is then melted to produce fresh water.

Theoretically, freezing has some advantages over distillation. These advantages include a lower theoretical energy requirement, minimal potential for corrosion, and little scaling or precipitation. The disadvantage is that it involves handling ice and water mixtures that are mechanically complex to move and process.

A small number of plants have been built over the past 40 years, but the process has not been a commercial success in the production of fresh water for municipal purposes. The most recent significant example of freezing desalting was an experimental solar-powered unit constructed in Saudi Arabia in the late 1980s. The experimental work has been concluded, and the plant disassembled. At this stage, freezing desalting technology probably has a better application in the treatment of industrial wastes rather than the production of municipal drinking water.

## **Chapter III**

### **AIR POLLUTION - AN OVERVIEW**

#### **3.1 Introduction**

Air pollution is a problem for all of us. It has been reported that an average adult breathes 20 m<sup>3</sup> of air every day. Children breathe even more air per pound of body weight and are more susceptible to air pollution. Many air pollutants, like urban smog and toxic compounds will remain in the environment for a longer period of time and are carried by the winds hundreds of miles from their origin.

Millions of people live in areas where urban smog, particulate matters and toxic pollutants pose serious health concerns. People exposed to high levels of air pollutants may experience burning eyes, irritated throat, or breathing difficulties. Long-term exposure to air pollution can cause cancer, and long-term damage to the immune,

neurological, reproductive, and respiratory systems. In extreme cases, it can even cause death.

The U.S Environmental Protection Agency (EPA) has set National Ambient Air Quality Standards (NAAQS) for the following five common pollutants:

1. Sulfur Dioxide ( $\text{SO}_2$ )
2. Nitrogen Dioxide ( $\text{NO}_x$ )
3. Carbon Monoxide (CO)
4. Particulate Matter (PM)
5. Ozone ( $\text{O}_3$ )

### **3.1.1 Sulfur Dioxide ( $\text{SO}_2$ )**

$\text{SO}_2$  is a colorless gas with pungent suffocating smell, which, belongs to the family of sulfur oxide gases ( $\text{SO}_x$ ). It can easily be dissolved in water vapor to form acid. When fuel-containing sulfur is burned, it will generate  $\text{SO}_2$  gas. Sulfur is basically present in raw materials like gas, crude oil, coal, and ore (containing metal like aluminum, copper, zinc, lead, and iron).

Pollutants, such as sulfate particles are formed from  $\text{SO}_2$ . These pollutants can be transported and deposited over a long distances from the point of origin. This means that pollutants created by  $\text{SO}_2$  is not confined only to the place of origin from where it is emitted. Studies show that about 65% of  $\text{SO}_2$  is released into the air (i.e. more than 13

million tons per year), has been produced by the electric generating utilities, and especially those that burn coal and crude oil as fuel (Heinsohn and Kabel, 1999).

### **3.1.1.1. Health and Environmental Impacts of SO<sub>2</sub>**

SO<sub>2</sub> causes a wide variety of health and environmental impacts, particularly with asthma among children, the elderly, and people with heart and lung diseases. Sulfur dioxide can cause temporary breathing difficulty for people with asthma who are active outdoors. Long-term exposure to high levels of SO<sub>2</sub> gas aggravates existing heart diseases. Sulfate particles, which are produced from sulfur dioxide when inhaled, deposited in the lungs causes difficulty in breathing and premature death (Amin and Husain, 1994). Sulfate particle are responsible for reducing the visibility. SO<sub>2</sub> react with other substances in the air to form acids which, falls down on the earth as acid rain, damaging forests and crops, changes the makeup of soil, and make lakes and streams acidic and unsuitable for fish. It also accelerates the decay of building materials and paints.

### **3.1.2 Nitrogen Oxide (NO<sub>x</sub>)**

Nitrogen oxide belongs to a family of highly reactive gases, which contains oxygen and nitrogen in different proportion. NO<sub>x</sub> are basically colorless and odorless in nature, but NO<sub>2</sub> along with particles in the air can be seen as a reddish-brown layer over many urban areas.

The nitrogen oxides (NO and NO<sub>2</sub>) are the principal species in tropospheric chemistry generated entirely by combustion processes. Thus the main source of nitrogen oxides is stationary and mobile combustion sources (Butler, 1979).

### **3.1.2.1 Health and Environmental Impacts of Nitrogen Oxide (NO<sub>x</sub>)**

Studies have shown that high levels of nitrogen oxides can cause lung damage and other respiratory illnesses, particularly in children and people suffering from asthma (American Lung Association, 1993). NO<sub>x</sub> is considered to be one of the main ingredients involved in the formation of ground level ozone. Nitrogen oxides are also a contributing agent in forming acid rain and deposition, which affects the plant and aquatic life and material. Also it is considered that nitric oxide and nitrogen dioxide can have an adverse human health effects (Amin and Husain, 1994). Nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) react in air to produce ozone and other pollutants that lead to the production of smog, affecting plants and causing adverse human health effects like eye irritation, shortness of breath, increased respiratory illness and decreased lung function, also reduced the resistance to infections (Gardner, D.E., 1984 and Pennington, 1988).

### **3.1.3. Carbon Monoxide (CO)**

Carbon monoxide is a colorless, odorless gas that formed when carbon in fuel is not burned completely. About 56% of all CO emission is contributed by motor vehicle exhaust. Other sources emissions are residential wood burning, gas stoves, and cigarette smoke. The highest levels of CO in the outside air typically occur in colder months of the

year when inversion conditions are more frequent. The air pollution is trapped near the ground beneath a layer of warm air. CO is considered to be a poisonous gas even to healthy people if in high levels in the air. It can also affect the heart disease and can damage the central nervous system (Butler, 1979).

### **3.1.3.1 Health and Environmental Impacts of Carbon Monoxide (CO)**

Carbon dioxide (CO) can cause harmful health effects to the heart, brain, and tissues by reducing the supply of oxygen to these organs. CO is considered to be a toxic gas because of the fact that hemoglobin absorbs CO more readily than oxygen and as a result the brain does not receive enough oxygen. It can produce adverse effects such as reduced visual acuity, psychomotor skill, and pulmonary function, and can also cause death. CO can also aggravate angina problem, a pain in the chest and left arm due to the sudden decrease in blood supply to the heart muscle (McCartney, 1990).

### **3.1.4. Particulate Matter (PM)**

Particulate matter can be described as anything that is airborne, and are microscopic in size. PM include dust, dirt, soot, and smoke. Particles might be suspended in air for long periods of time; they might be dark enough to be seen as soot or smoke, or sometimes microscopic in size. Most of these particles are directly emitted from factories, cars, and burning of fuel. Most of particles may be formed in air from the chemical change of gases, when they react with sunlight and water vapor. PM can be differentiated into Coarse and fine particulates, anything less than 10 microns and greater than 2.5 microns

in size are considered as coarse PM or  $PM_{10}$ . PM less than 2.5 microns in size are considered as fine PM or  $PM_{2.5}$ . Both  $PM_{10}$  and  $PM_{2.5}$  are of great concern to human health, and visibility. PM's can cause a serious health problem to people with sensitivity if exposed to high levels of PM for several days in a row.

#### **3.1.4.1 Health & Environmental Impacts of Particulate Matter (PM)**

Particulate matter is considered to be creating a lot of environmental and health impacts. Scientific studies and researches have shown that inhaling PM can cause a series of health problems like aggravating asthma, increase in respiratory symptoms like coughing and pain breathing, chronic bronchitis, decrease lung function, and premature death.

Particulate matter is one of the major causes of reduced visibility (haze). Particles are also carried over to a longer distances by wind which then settle down on ground and water effecting the pH of lakes and stream, changing the nutrient balance of coastal waters, large rivers basins and soil, and also affecting the diversity of ecosystems. Fine particulate in the form of soot, stains and damages the aesthetic view of the monuments and materials (Environment Canada, 1998; U.S EPA, 2001).

#### **3.1.5 Ozone ( $O_3$ )**

Ozone is a colorless, odorless gas basically composed of three oxygen atoms. Ozone can be found at two different altitudes in the atmosphere, stratospheric ozone occurs naturally in the stratosphere approximately 10 to 30 miles above the earth's surface and forms a



layer that protects the life on earth from harmful ultraviolet radiation from the sun. While the ground level ozone, which is basically generated by a chemical reaction between oxides of nitrogen ( $\text{NO}_x$ ) and volatile organic compounds (VOC) in the presence of heat and sunlight, are considered to be harmful to human health.

Ozone is a photochemical oxidant and is a major constituent of smog. The ground level ozone causes a variety of health problems, even at very low levels can cause permanent lung damage after a long-term exposure (Tilton, 1989 & Lipmann, 1991). Ozone is also responsible for damaging plants and the ecosystem.

### **3.2 Relevance to Society**

In all decision-making processes, great importance has been given to the environmental issues. Environmental Impacts due to human activities on air, water, and soil are the factors that have been quantified in many ways to identify, regulate, and control all these kinds of activities. In all these, air has been documented to have a considerable impact on the quality of human life. As mentioned before, people who are sensitive to irritation of bronchial tubes may suffer more because of air pollution. Also compounds like ozone, sulfur dioxide and nitrogen oxides in air may reduce the growth of plants and trees. Sulfur dioxide and nitrogen oxides are the major constituents of acid deposition, the sulfur dioxide emission is considered to be a factor that is too high in Europe and in the Middle East.

Mostly, on a local scale, individual sources have occasionally proven to cause large problems. The pathway of pollutants in the air on a local scale is presented in Figure 3.1 (Erbrink, 1995).

Various government organizations in the world have issued a lot of measures for the reduction of air pollution and to monitor air quality. In doing so, air quality standards have been introduced to check the hourly or daily mean maximum concentration during a year. All these standards are evaluated by means of measurements or by applying dispersion models (for future emissions). It has been considered necessary that for all rationale the dispersion model for stack emissions is an important factor. All these models are implemented on computers in which the transport and dispersion of air pollutants is described. Therefore, for these kinds of models the meteorological sciences are of importance and are frequently applied to air pollution studies.

All the processes in the atmosphere are basically started by the incoming radiation from the sun. The sun continuously disturbs the tendency of the atmosphere to keep things in balance by restoring equilibrium or at least achieving a stationary situation. Usually due to unequal heating of the earth surface, pressure gradients are developed, which force the air to move from one place to another.



The term “local” means to include distances up to several tens of kilometers. In many instances the chemical reactions determine the local concentrations, creating a third field of research to be considered: atmospheric chemistry, which describe a chain of reactions in both gas-phase and liquid phase (Erbrink, 1995).

### **3.3 Boundary Layer Meteorological Concept for Plume Dispersion**

In all air pollution studies, the basic parameters of concerned are the wind profile (wind speed and direction, determining the transport process), the degree of turbulence near the surface (responsible for the spreading and dilution of the plume) and the height of the boundary layer. The later parameter determines the extent or the height the pollutants may be carried up into the atmosphere. Turbulence and boundary layer parameters are not measured on a routine basis; therefore, indirect methods are applied to determine these parameters from heat, moisture, and fluxes at the surface of the earth.

To describe the structure of boundary layer, it is important to know the routine measurements carried out at the surface of the earth. Monin and Obukhov in 1954 presented a theory in this area, which is considered to be the most widely accepted theories in the field of plume dispersion modeling. Their theory basically claims that fluxes of heat, momentum and moisture are the functions of two scaling parameters, which are roughness length of the surface, and the length scale for instability. As their theory predicts parameter values at various heights with similar parameters measured at the surface, this theory is also sometimes called similarity theory (Erbrink, 1995).

Monin-Obukhov theory made it possible to calculate the profiles of wind speed and turbulence, which are the crucial parameters in the area of air pollution modeling. Although the Monin-Obukhov theory strictly applies to the surface layer (roughly 10% of height of the atmospheric boundary layer), it is also frequently applied to greater heights with considerable success (Barad, 1958; Businger et al., 1971; Kaimal et al., 1972 and 1976).

Deardorff in 1974 suggested that heat flux and height of the boundary layer are the only two parameters that can determine the properties of the mixed layer. He introduces the convective velocity scale, which is considered to be the most important parameter. His theory applies not only to the surface layer but also to the whole convective boundary layer.

A simple procedure is to account for the various degrees of turbulence, which consists of the use of stability classes. The concept of stability classes has played a major role in the dispersion modeling for many years. Classification of meteorological parameters in general was necessary in the early phase of dispersion modeling because of the fact that computation were not always carried out on computers but by means of nomograms (Erbrink, 1995).

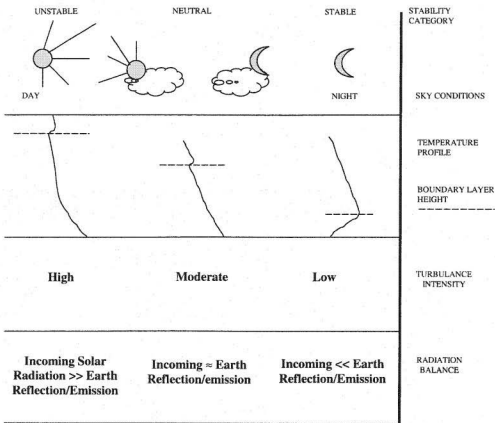
The degree and nature of atmospheric turbulence is the most important parameter. Pasquill in 1961 gave a simple method for the stability classification, modified by Turner

in 1967 and Gifford in 1976, and is known as Pasquill-Turner-Gifford method. The method is principally based on observations of the standard deviation of the wind direction on paper recorders, and was widely used in the form of a scheme derived from observations of cloud cover and wind speed.

Figure 3.2, shows the different aspects of atmospheric stability. It shows that during the day when the sky conditions are clear and the net radiation is more towards the earth surface and less reflection back to the sky (i.e. small radiation is reflected back from the earth surface), turbulence and the boundary layer will be at the maximum as shown in the Figure 3.2, and the stability class will be "unstable". While at night when the sky is clear, the net radiation of emission from the earth to the atmosphere is more, under these conditions the boundary layer height is small, the turbulence intensity is at a minimum, and the stability class is "stable". The "neutral" stability class is the time when the sky condition is overcast (day or night), and the turbulence, radiation and boundary layer is at the average.

Many methods are reported to estimate the atmospheric stability. Atmospheric stability is characterized by several physical parameters (Kretzschmar and Mertens, 1980). Most of these parameters are temperature profile near the surface, some indicators for the net radiation (cloud cover) or standard deviation of wind direction. Another and better way of stability class determination is the use of Obukhov length scale, which is considered to be

the more appropriate one (Golder, 1972) or the convective velocity scale (Weil and Brower, 1984).



**Figure 3.2 Qualitative Presentation of Atmospheric Turbulence Intensity, Temperature Profile, and Radiation during Unstable, Neutral & Stable Atmosphere**  
 (Adopted from Erbrink, 1995)

### 3.4 Plume Dispersion Modeling Concept

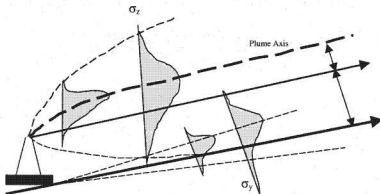
In 1921, G.I Taylor's analysis started the dispersion theory that described the behavior of particles in homogeneous turbulence state. His analysis is considered to be very important and was taken as the basis for many recommendations. Pasquill in 1976 came out with some realistic formulations, which appear to be more reliable for the value of lateral dispersion parameter  $\sigma_y$  (Irwin, 1983). The horizontal standard deviation  $\sigma_y$  and the vertical standard deviation  $\sigma_z$  of the plume shape were developed somewhat later, but most of the work was done while providing the dispersion models with stability classes.

In the eighties a more physical approach was applied to the models. At that time, classification and simple schemes were not used, but they coupled dispersion directly to physically meaningful parameters, which led to a next generation of dispersion models. Principally, most of the dispersion models use the gaussian plume concept as a starting point, considering height of the plume as axis and determining the parameters  $\sigma_y$  and  $\sigma_z$  as shown in Figure 3.3. The gaussian plume model approach is relatively simple and is frequently used in the prediction of atmospheric pollutant dispersion (Husain, 1990). In this research the air emission model selected work on the same principle as the gaussian plume concept/approach. The other non-gaussian models also became applicable because of a growing computational capacity of non-mainframe computers and later the more user-friendly workstations. The Monte Carlo models (or Lagrangian Particle Models) are one of the non-gaussian models, which are capable of handling non-homogeneous



turbulence. These models are based on the idea of describing the single motions of many particles in terms of mean and turbulent behavior.

The gaussian models can be applied to flat terrain, while Monte Carlo model is best applied to non-uniform terrain. Zannetti (1990) gives a detailed overview of all these models. It is clear from the literature search that all these different models reflect the reality that atmospheric processes are very complicated. Each model can only handle a restricted subset of processes, depending on the purpose of the model and the available input parameters, which determines the models applicability and usefulness.



**Fig. 3.3 The Gaussian Plume Concept** (Adopted from Erbrink, 1995)

### **3.5 Meteorology and Dispersion**

The earth's atmosphere can be divided into different horizontal layers, depending on the dominance of physical processes, and these are mainly determined by the vertical temperature gradient. The troposphere is the lower part of the atmosphere, where the temperature decreases with increasing height (up to 10-15 km), all weather processes like evaporation, condensation, turbulence generation and dissipation take place in this layer. From height > 15 km within the troposphere the temperature is constant for several kilometers, but then starts increasing significantly, this stage/layer is the stratosphere, which reaches up to 50 km.

The next layer of atmosphere is the mesosphere, the temperature drops until it reaches to the minimum of 180 to 200 K, but then starts increasing in the thermosphere to high values of over 1200 K. Figure 3.4 presents the detailed over view of the atmospheric layers.

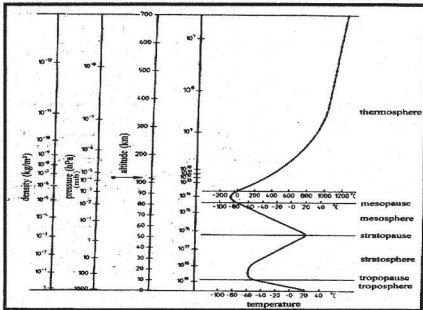


Figure 3.4 Temperature Profile in Atmospheric Layers (Williamson, 1973)

For dispersion problems the troposphere is the most important layer, since it is there that almost all air pollution processes take place like dispersion, chemical reactions, uptake in clouds and removal mechanism such as deposition.

When pollutants, able to make their way into the stratosphere (e.g. through volcanoes, or in the case of very resistant compounds by slow diffusion processes), they usually become part of a system with very low degrees of deposition and remain there for a

longer time (sometimes many years), as one can see in the case with the stratospheric ozone problem.

The troposphere layer is very different than stratosphere. In troposphere the turbulence and the clouds influence are important factors, causing pollutants mixing much faster in this layer. The troposphere layer can be divided into two parts the lower and the upper. The lower part is called *the atmospheric boundary layer* (ABL), and the upper part *the free atmosphere*. Within the atmospheric boundary layer the influence of the surface is large, that is heating and cooling of the air by the surface and friction are dominant factors. While in free atmosphere these influence are no longer important. The physical processes in the free atmosphere are determined by pressure gradients (causing the wind), density differences (causing cloud formation, convective turbulence and subsidence), and temperature effects (Erbrink, 1995). As one can observe that in most of the air emissions, air pollutants occur near the surface (except those from aircrafts and rockets), therefore the processes in the ABL are important to be understood from the viewpoint of environmental problems. In the ABL the influence of the free atmosphere and the influence of the surface interacts with each other, resulting in a large variety of wind, temperature and turbulence profiles.

To describe the pollutant pathways through air, it is important to consider two important factors. First, the description of the meteorological processes in the ABL, which is necessary in predicting the location of depositions, the concentrations occurring in the air

and the rate of changes in these concentration and deposition. Secondly, the concentration gradient, which should be described mathematically.

In the ABL, the important parameters to be considered related to meteorology are:

- mean wind field, (horizontal & vertical gradient being of greatest interest)
- turbulent components in the wind field, and
- height of the ABL

While the elements which are relevant to dispersion are:

- emission data from stack (e.g.  $\text{SO}_2$ ,  $\text{NO}_x$ , PM etc., and the heat emission)
- pollutant concentration patterns in horizontal and vertical direction: the shape (gaussian – non-gaussian), the height of the plume axis, and
- chemical reactions and deposition in the production and removal process of pollutants.

### **3.6 Model selection Criteria**

An air pollution dispersion model is a mathematical expression for predicting the air pollutants emissions. This includes mainly the effects of transport, dispersion, plume rise, and chemical and physical transformation. After the Iraq's invasion of Kuwait, more than 700 oil wells were left on fire, emitting hundreds of tons of air pollutant in the atmosphere every day after the war was over. This prompted an environmental crisis in the Gulf region, which brought in the Gulf Regional Air Monitoring Program (GRAMP)

in 1991. With the development of this program numerous models were tested and used to study the local and regional scale environmental impacts of the plumes emitted from those burning oil wells (Husain, 1995).

Many air pollution models were used in the Kuwaiti oil fire fields, to simulate the plume originated from those wells. The applications and limitations of those models used were summarized in Table 3.1 (WMO, 1992; Husain, 1995).

In this research the input is the meteorological data and total emissions from a source of pollution, while the output consists of estimated pollutant concentrations. These concentration results may be for various time periods and may be point estimates or a spatial average. Air dispersion model are usually classified in to three categories:

1. Gaussian Model,
2. Box Model, and
3. Mass conservation Model

Gaussian and box models are used for chemically non-reactive pollutants, while mass conservation models are used for chemically reactive pollutants. The above-cited models have their own limitation and assumptions. The simplest of all is the box model, which is used for area sources. The most widely used method for estimating air pollution

dispersion is the use of gaussian plume model. This model is used for point sources, area sources, and volume sources

**Table 3.1**  
**Air Pollution Models Used for Air Quality Studies During Kuwaiti Oil Fires**

Group/Model	Application	Domain (km)	Meteorology Used	Species	Diffusion Techniques Used
KNMI/RIVM (Verver, 1992)	Regional Real-Time	3500x3500 3-D	ECMWF Global Model	Soot	Multiple Puff
LLNL/ARAC (Sullivan, 1992)	Regional Real-Time Global	3000x3000 3-D	USAF Global + RWM (MATHEW)	Soot, Optical Depth	Particle in Cell
NOAA HYSPLIT (Draxler, 1992, McQueen et al., 1992, Hefter, 1991)	Regional Real-Time	2000x2000 3-D	NWS MRF	Soot, SO <sub>2</sub>	Semi-Lagrangian PIC
U.K. Met Office	Regional	3-D	ECMWF	Soot, SO <sub>2</sub>	Monte Carlo
Max Planck Inst. STEM II	Regional	4000x4000 3-D	Hydro-Mesoscale	CO <sub>2</sub> , VOC, NO <sub>2</sub> , Ozone	-----
EURAD (Hass et al., 1991)	Regional	3-D	Regional	Soot, SO <sub>2</sub> , NO <sub>x</sub>	Eulerian
CANARM (Pudykiewicz, 1991)	Regional Global	10000x10000	Regional	Soot, SO <sub>2</sub>	Semi-Lagrangian PIC
TASC (Janota and Chase, 1991)	Regional Global	Hemi-Spheric 2-d	Regional	Soot, SO <sub>2</sub>	Semi-Lagrangian PIC
Meteorological Nat. France MEDIA (Bompay, 1991)	Regional Global	Hemi-Spheric 3-d	Emeraude and Peridot	Soot	Eulerian
Sandia National Laboratory (Angi, 1991)	Regional	1000x1000 3-D	Climatology	Soot, SO <sub>2</sub> , CO, H <sub>2</sub> S	Gaussian Plume

LNLL/ARAC (Lawrence Livermore National Laboratory/Atmospheric Release Advisory Capability)

TASC (The Analytic Sciences Corporation)

NOAA (National Oceanic and Atmospheric Administration)

HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectories Model)

EURAD (European acid Deposition Model)

ECMWF (European Centre for Medium Range Weather Forecasts)

NWS (National Weather Services)

(Source: WMO, 1992; Husain, 1995)

To characterize the variations of pollutant in space and time, one has to perform either monitoring/modeling, or the combination of these two methods. Air monitoring is an expensive and time-consuming process, which requires skilled manpower and sophisticated equipment (Dop and Steyn 1991).

Pollutants emitted from the source into the atmosphere are very complex and dynamic in nature and it varies mostly with time and space and mostly depends upon meteorological and topographical conditions.

Due to these limitations and constrains in air monitoring, air quality simulation models are used with the latest and highly sophisticated and reliable techniques. These models are classified by source, pollutant, transformations and removal, distance of pollutant transport, averaging time and many other parameters. Model selection for a particular scenario, and for particular situation should be the most accurate representative of atmospheric transport, dispersion, and chemical transformation for the required study area. The extent to which a specific air quality model is suitable for evaluation of source impact depends upon several factors:

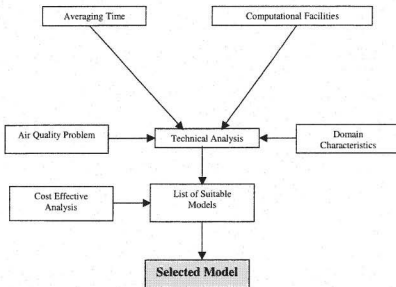
1. The availability of meteorological and topographical conditions of the area
2. The level of detail and accuracy needed for the analysis
3. The detail and accuracy of the database, i.e., emission inventory, meteorological data, air quality data



4. The type of sources the model can handle (point, line, area, combination or multiple sources)
5. The output options of the model, such as more than one averaging time period, the highest concentration tables, and
6. The validation of model under a given situation and condition.

All of the above relies heavily on experience, self-judgment and literature search. Zannetti (1990) suggested a process for selecting an air pollution model. His process of selecting a model is shown in Figure 3.5. Hunt et al. (1991), suggested some basic important points for improving the air quality modeling system, these points are:

1. That the model should be capable of optimal utilization of detailed meteorological information.
2. It should be well versed in dealing with complex effects such as buoyant gas emission or dense gas emission and dispersion from arbitrary heights in the atmosphere over irregular terrain, buildings and coastlines. It should also be able to calculate the vertical distribution of concentration, including ground level concentrations.
3. It must accommodate the complex dispersion processes associated with short time releases, deposition, and concentration fluctuations.
4. The model output should be in a form that is compatible with other calculation methodologies for various purposes such as health effect and risk assessment.



**Fig. 3.5 Model Selection Process** (Source: Zannetti, 1990)

### **3.7 Model Selection and Comparison**

Three US EPA air pollution models were examined in view of the selection criteria discussed in section 3.6. These three models ISCST3, AERMOD, and CALPUFF are compared in detail. The comparison between AERMOD and ISCST3 is given in Table 3.2. Most of the features of AERMOD and ISCST3 models are same and some of them are notably different.

After defining the study objectives and detailed analysis of the problem, the above three models were reviewed as per guidelines and criteria discussed in the previous section, to select one model. The model selected for this research is AERMOD, which is a state-of-the-art model in all the EPA's air quality models, as by superior technical formulation of AERMOD and its better evaluation performance relative to ISCST3, the American Society/Environmental Protection Agency Regulatory Model Improvement Committee (AERMIC) concluded that AERMOD could justify as a replacement for ISCST3 for Regulatory Modeling application.

In the model selection and comparison, the CALPUFF was screened out. The CALPUFF model can be defined as a multi-layer, multi-species non-steady-state puff dispersion model that simulates the effects of time- and space-varying meteorological conditions on pollutant transport, transformation and removal. The CALPUFF was not selected in this study because of the following facts:

1. It is basically a long range transport model (applicable beyond 50-100 km distances)
2. Requires large modeling domains
3. Complex winds: non-uniform wind field is a controlling feature of the analysis in CALPUFF.
4. In simplest mode, it requires the control file, and file of hourly, gridded meteorological data (which is a multi-step process with CALMET)

5. Also the land use and terrain heights are derived from programs and data provided with the CALPUFF Modeling system compact disc, or self generated software or data. Whatever method is chosen, this stage required several steps to obtain the final file of geophysical parameters. This kind of information in the present research work and for the required study area is difficult to obtain.

Because of the above facts it has been deduced that the CALPUFF is not viable for the current study area and for the available meteorological data.

The other two air dispersion models (ISCST3 and AERMOD) were compared as shown in Table 3.2. As compared to ISCST3, AERMOD contains new and improved algorithms for

1. Dispersion in both convective and stable boundary layer
2. Plume rise and buoyancy
3. Plume penetration into elevated inversion
4. Computation of vertical profiles of wind, turbulence, and temperature
5. The urban boundary layer, and
6. The treatment of receptors on all types of terrain from the surface up to and above the plume height.

AERMOD is the updated/newer version of EPA air dispersion model. Also, AERMOD duplicates most of the features available in ISCST3 model. Therefore, the AERMOD

model, which is sufficiently flexible and comprehensive in nature, was selected for the Al-Jubail desalination plant emissions study.

**Table 3.2 Comparison of Dispersion Model (AERMOD Vs ISCST3)**

<b>FEATURE</b>	<b>ISCST3</b>	<b>AERMOD</b>	<b>COMMENTS</b>
Sources types that can be modeled	Point, area, and volume sources	Point, area, and volume sources	Both models are capable of modeling the same types of sources.
Plume Rise	In any condition the ISCST3 model for plume rise use the Briggs equation with stack-top wind speed and vertical temperature gradient.	The AERMOD in stable conditions for plume rise use the Briggs equations with winds and temperature gradient at stack top, while in convective conditions, plume rise is superimposed on the displacements caused by random convective velocities.	AERMOD is better because in stable conditions it factors in wind and temperature changes above stack top, while in unstable condition it uses the convective updraft and downdrafts
Meteorological Data Input	One level of data is accepted in this case	Large number of data levels can be utilized.	AERMOD can adapt multiple levels of data to various stack and plume heights
Profiling Meteorological Data	Only wind speed profiled	AERMOD creates profile of wind, temperature, and turbulence, using all available measurement levels	AERMOD is much improved over ISCST3

<b>FEATURE</b>	<b>ISCST3</b>	<b>AERMOD</b>	<b>COMMENTS</b>
Use of Meteorological Data in Plume Dispersion	Stack-top variables for all downwind distances	Variables measured throughout the plume depth (averaged from plume centerline to 2.15 sigma-z below centerline; changes with downwind distances)	AERMOD is more advance than the ISCST3. It accounts for meteorological data throughout the plume depth.
Plume Dispersion General Treatment	For plume dispersion ISCST3 use Gaussian treatment in horizontal and vertical direction.	AERMOD in stable conditions uses Gaussian treatment in horizontal and vertical direction, while in unstable conditions it considered the non-Gaussian probability density function in vertical direction.	AERMOD in unstable conditions, gives more accurate concentration of dispersion than ISCST3
Urban Treatment	ISCST3 has only two options to model rural or urban	AERMOD can model all the sources individually as rural or urban, considering the city size and population.	AERMOD give variable urban treatment as a function of city population, and have the option of rural or urban
Characterization of the Modeling Domain Surface characteristics	Choice of rural or urban	Selection by direction and month of roughness length, albedo, and Bowen ratio, gives more flexibility	AERMODE is more comprehensive and detailed in the selection of surface characteristics.

(Adopted from U.S. EPA, 1999)

FEATURE	ISCST3	AERMOD	COMMENTS
Boundary Layer Parameters	Wind speed, mixing height, and stability class	Friction velocity, Monin-Obukhov length, Convective Velocity Scale, Mechanical and Convective mixing height, Sensible heat flux	AERMOD provides parameters, which are used with up-to-date planetary boundary layer (PBL). ISCST3 does not
Mixed Layer Height	ISCST3 uses interpolation based upon maximum afternoon mixing height	AERMOD has convective and mechanical mixing layer height, where convective height is mainly based upon hourly sensible heat flux	AERMOD uses hourly input data, which gives more realistic sequence of the diurnal mixing height changes.
Terrain Depiction	Elevation at each receptor point	Special terrain preprocessor is used to obtain hill and elevation points, by using the digital elevation model (DEM) data	AERMOD terrain processor is more advance and can use digital data to obtain receptor elevations
Plume Dispersion: Plume Growth Rates	It depends on the six discrete Pasquill-Gifford stability classes	Instead of Pasquill stability it uses the vertical and horizontal turbulence from measurements, or the PBL theory to calculate the plume growth rates.	Use of turbulence based plume growth with height dependence rather than based on stability class give AERMOD a substantial advancements over ISCST3



FEATURE	ISCST3	AERMOD	COMMENTS
Plum Interaction with Mixing Lid: Convective Conditions	If plume center line is above lid, zero ground level concentration is assumed	In this case three condition are considered: a direct plume that is directed to the ground in a downdraft, an indirect plume that is caught in an updraft that reaches the lid and eventually is brought to the ground, and a plume that penetrates the mixing lid and disperses more slowly in the stable layer aloft (can re-enter the mixed layer and disperse to the ground)	The AERMOD treatments avoid any under predictions suffered by ISCST3 due to its all or nothing treatment of the plume. AERMOD's use of convective updrafts and downdrafts in a probability density function approach is a significant advancement over ISCST3
Plume interaction with Mixing Lid, Stable Conditions	The mixing Lid id ignored in this it is assumed that its infinitely high	A mechanical mixed layer near the ground is considered. Plume reflection from an elevated lid is used to account for the effects of sharply reduced turbulence aloft	AERMOD's use of mechanically mixed layer is an advancement over the very simplistic ISCST3 approach

(Source: Adopted from U.S. EPA, 1999)

## **Chapter IV**

### **AERMOD MODEL FORMULATION**

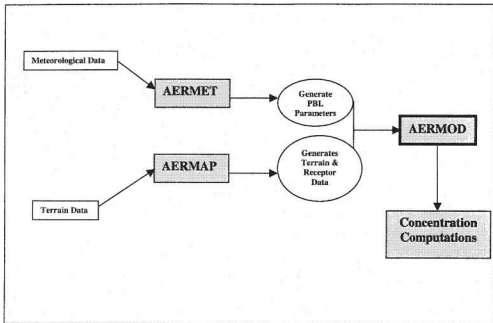
#### **4.1 MODEL OVERVIEW**

The following sections will briefly describe the AERMOD air dispersion model, based on its fundamental principles, necessary inputs and outputs, and its limitations.

##### **4.1.1 Model Description**

AERMOD is a steady state, plume, AMS/EPA Regulatory Model in a stable boundary layer (SBL). This model can be used to compute impact of various pollutants in both flat and complex terrain. AERMOD uses the Gaussian form for the distributions in both the vertical and horizontal dimensions for stable conditions, and in the horizontal for convective conditions. To calculate the vertical distribution of concentrations for convective conditions, AERMOD uses a Bi-Gaussian probability density function (pdf) this behavior of distributions in the CBL was demonstrated by Briggs in 1993.

As shown in Figure 4.1, AERMOD is designed to work in coordination with two pre-processors, AERMET and AERMAP. AERMET processes meteorological data, while the AERMAP processes the terrain elevation data and produces receptor information, both the output files from AERMET and from AERMAP are then fed into AERMOD for further processing.



**Fig. 4.1 Schematic Showing the AERMOD Air Dispersion Model with Pre-Processors**

The schematic of AERMOD (Figure 4.1) consists of two pre-processors and the dispersion model. The AERMET (Meteorological Pre-Processor) provides AERMOD with the Meteorological information needed to characterize the Planetary Boundary Layer (PBL). PBL is the turbulent air layer next to the earth's surface that is controlled by the surface heating and friction and the overlaying stratification. The PBL typically ranges from a few hundreds meters in depth at night to 1–2 km during day. Major development in understanding of the PBL began in the 1970's through numerical modeling, field observations, and laboratory simulations (Wyngaard, 1988).

Basically, the AERMET uses the meteorological data and the surface characteristics to calculate boundary layer parameters like mixing height, friction velocity, etc., which is needed by the AERMOD. This data, which is either measured off-site or on-site, must be representative of meteorology in the modeling domain. Surface characteristics like surface roughness, Bowen ratio, and albedo, plus standard meteorological observations like wind speed, wind direction, temperature, and cloud cover are inputted into AERMET. The AERMET then calculates the PBL parameters/profiles which are friction velocity ( $U_*$ ), Monin-Obukhov Length ( $L$ ), convective velocity scale ( $W_*$ ), temperature scale ( $\theta_*$ ), mixing height ( $Z_i$ ), and surface heat flux ( $H$ ). These parameters are then passed to the interface (within AERMOD) where similarity expressions (in conjunction with measurements) are used to calculate the vertical profiles of wind speed ( $U$ ), lateral and vertical turbulent fluctuations, potential temperature gradient, and potential temperature.

The AERMAP characterizes the terrain and generates receptor grids and elevations for the dispersion model. AERMOD also uses a new and simple approach about flow and dispersion in complex terrain; the plume is modeled as either impacting and/or following the terrain. This approach has been designed to be physically realistic and simple to implement, avoiding the need to distinguish among simple, intermediate and complex terrains, as is required by the other presently available air regulatory models. (Synder et al., 1985).

AERMOD has the option to construct vertical profiles of wind speed, wind direction, turbulence, and temperature. Temperature gradient is estimated using all available meteorological observations. AERMOD is designed to run with minimum observed meteorological parameters.

In 1987, Pain and Egan compared the performance of AERMOD with Rough Terrain Diffusion Model (RTDM). Hanna and Pain (1989) and Hanna and Chang (1993) compared the AERMOD with Hybrid Plume Dispersion Model (HPDM). Perry (1992) compared the Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations (CTDMPLUS). All these models were compared with AERMOD using the procedures in EPA's "Protocol for Determining the Best Performing Model". It was concluded in the 1999, at the seventh modeling conference that AERMOD is more effective, and better in performance as compare to the models listed in this section (Code of Federal Regulations, 1997).

AERMOD like most of the other air dispersion models requires an input run-stream file and meteorological data files. The run-stream file, which contains the options how to run the model, the meteorological data files, and the met data information, are explained in Appendix-A.

#### **4.1.2 Technical Description**

This section will describe the basic formulation of the AERMOD dispersion model, which includes the general form of concentration equation for terrain, and the dispersion algorithms considering the convective and stable boundary layer.

As mentioned in the previous section that AERMOD (like ISC) is a steady state plume model, this means that it is applicable to source releases and meteorological conditions that are assumed to be in steady state. AERMOD uses a simple two-layer (upper and lower layer) concept about flow and dispersion over the terrain. In very stable conditions the AERMOD assume that the lower layer of the plume remains horizontal while the upper layer tends to rise over the terrain. While in neutral and unstable conditions, the lower layer disappears and the entire flow with the plume tends to rise up and over the terrain. Basically the AERMOD assumes that the plume exists in two states and that the concentration at a receptor, located at a position  $(x,y,z)$  is the weighted sum of the two concentration estimates:

1. where the plume is horizontal (horizontal plume state)
2. where the plume travels over the terrain (terrain response plume state)

Mostly, in stable conditions, the horizontal plume dominates and is given greater weight while in neutral and unstable conditions the plume traveling over the terrain is more important or is heavily weighted, as shown in Figure 4.2 (Cimorelli et al., 1998).

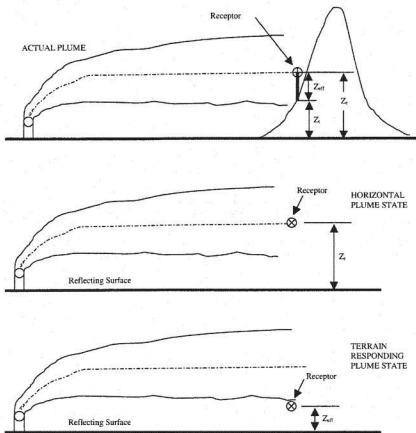


Figure 4.2 AERMOD Two State Approach. Total Concentration Predicted by AERMOD

The general form of equation applied in AERMOD for calculating the total concentration at any terrain elevation is:

$$C_T(x_r, y_r, z_r) = f \times C_{c,s}(x_r, y_r, z_r) + (1 - f) \times C_{c,s}(x_r, y_r, z_{\text{eff}}) \quad (4.1)$$

Where:

$C_T(x_r, y_r, z_r)$  = Total concentration ( $g/m^3$ ) or ( $\mu g/m^3$ )

$C_{c,s}(x_r, y_r, z_r)$  = Concentration from the horizontal plume state ( $g/m^3$ ) or ( $\mu g/m^3$ )

$C_{c,s}(x_r, y_r, z_{\text{eff}})$  = Concentration from the terrain following plume state  
( $g/m^3$ )( $\mu g/m^3$ )

$f$  = Weighting factor related to the fraction of plume material that is below the height ( $H_c$ ), of the dividing streamline.

$Z_r$  = height of receptor from the stack base elevation (meter or feet)

$Z_{\text{eff}}$  = effective receptor height (which is equal to 'z' in flat terrain) (meter or feet)

$H_c$  = is a function of wind speed, vertical potential temperature gradient and the height of the terrain influencing the flow

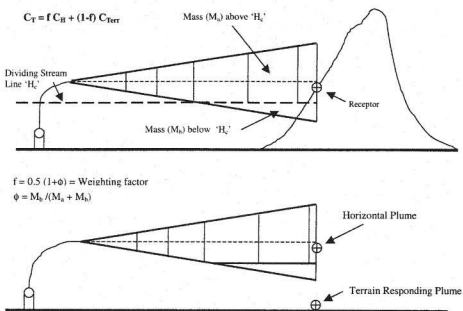
In equation (4.1) the subscripts (c,s) represent the total concentration during convective conditions 'c' and stable conditions 's'. The first term on the right hand side of equation (4.1), represents the contribution from the horizontal plume and is evaluated at a receptor height ' $Z_r$ '. The second equation on the right hand side represents the contribution from the plume adjusted by the terrain and is evaluated at an effective receptor height ' $Z_{\text{eff}}$ '.



Also in equation (4.1) the weighting factor 'f' is a function of the fraction ( $\phi$ ) of plume mass that is below 'H<sub>c</sub>' at the downwind distance of the receptor. The fraction ' $\phi$ ' of a mass below H<sub>c</sub> is calculated by the AERMOD as:

$$\phi = \frac{\int_0^{H_c} C_T(x, y, z_r) dz}{\int_0^{\infty} C_T(x, y, z_r) dz} \quad (4.2)$$

In neutral to unstable conditions (or in flat terrain for all conditions), H<sub>c</sub> = 0, and thus  $\phi = 0$ . Figure 4.3, will show the construction of the weighting factor and its relationship in calculating the total concentration.



**Figure 4.3 Construction of Weighting Factor and Calculating Total Concentration**

In the equation (4.1), the  $C_{c,s}(x_r, y_r, z_r)$  can be defined for convective and stable conditions, which are explained in the next sections.

#### 4.1.2.1 Convective Boundary Layer (CBL) Concentration Equation

In 1959, Gifford proposed a concept for the dispersion algorithms in the convective boundary layer (CBL). In this, the plume, which is randomly varying, is assumed to have Gaussian distribution about its centerline in convective conditions. The mean or average concentration in CBL is found by summing the concentrations of all the random centerline displacements. This averaging process results in a skewed distribution, which AERMOD represents as a bi-Gaussian p.d.f (i.e., one for updrafts and the other for downdrafts). Figure 4.4 shows the superposition of updraft and downdraft plumes (Cimorelli et al., 1998).

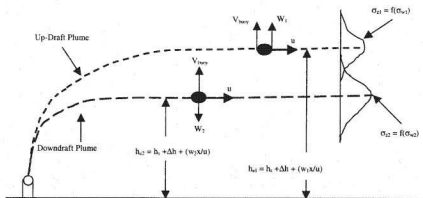


Figure 4.4 AERMOD Dispersion in CBL Using Two Gaussian distribution

In AERMOD the average concentration in the convective condition is due to three plume contributions:

- A 'direct' plume, which emanates from stacks and are sufficiently large that the downdrafts bring them down to the surface.
- An 'indirect' plume which rises to the CBL top, delayed due to buoyancy and then dispersed downwards.
- A 'penetrated' plume, which represent the plume material with sufficient buoyancy to escape the mixed layer (Venkatram, 1983).

In convective conditions when Monin-Obukhov length ( $L$ ) is less than zero ( $L < 0$ ), the general expression for the total concentration in the CBL for the horizontal plume is

$$C_c(x_r, y_r, z_r) = C_d(x_r, y_r, z_r) + C_r(x_r, y_r, z_r) + C_p(x_r, y_r, z_r) \quad (\text{g/m}^3) \text{ or } (\mu\text{g/m}^3) \quad (4.3)$$

Where:

$C_c(x_r, y_r, z_r)$  = Total Concentration in CBL

$C_d(x_r, y_r, z_r)$  = Direct Source Concentration Contribution

$C_r(x_r, y_r, z_r)$  = Indirect Source Concentration Contribution

$C_p(x_r, y_r, z_r)$  = Penetrated Source Concentration Contribution

The total concentration for the terrain responding state is almost the same as that of equation (4.3), only ' $Z_r$ ' is replaced by ' $Z_p$ '. For more detail about equation (4.3), read AERMOD description of formulation, draft document by Cimorelli et al (1998).

#### 4.1.2.2 Concentration in Stable Boundary Layer (SBL) by AERMOD

The concentration expression for stable condition ( $L > 0$ ) in AERMOD is almost the same as in ISC3. The ISC3 model uses the following equation to calculate the hourly ground level concentration at the downwind distance 'x' and crosswind distance 'y' from the source.

$$C_s(x_r, y_r, z_r) = \frac{K_s \cdot Q}{\pi \cdot u \cdot (h) \cdot \sigma_y \cdot \sigma_z} \exp \left\{ -1/2 \left[ \frac{y}{\sigma_y} \right]^2 \right\} \cdot D \quad (4.4)$$

Where:

Q = Pollutant emission rate (mass per unit time)

K = Conversion factor to calculate concentration in desired units

$\sigma_y$  = Standard deviation of lateral concentration distribution (m)

$\sigma_z$  = Standard deviation of vertical concentration distribution (m)

u = mean wind speed (m/sec)

h = stack height (m)

D = Decay term

AERMOD uses the same equation (4.4), as used by ISC3 for calculating the emission concentration in stable condition with little modification and alteration, again for more detailed information on this the author suggest to study the draft document by Cimorelli et al. (1998).

### **4.1.3 Data Acquisition**

Surface meteorological data for the year 1995, of the study site area were obtained from MEPA. The data was supplied in raw form on diskettes. The raw surface data were formatted and entered into the system. The format of data was already discussed in the previous section.

Surface meteorological data like wind speed & direction, ambient temperature, and surface heat flux for the year 1995 were obtained from the raw data provided. The rest of the upper air and surface meteorological parameters were calculated, the details of which are listed in the next section

### **4.1.4 Development of Meteorological Data for AERMOD**

The minimum meteorological input data files (Surface File with PBL Parameters & Profile File) required to perform the dispersion analysis by the AERMOD are described below:

(1) Hourly Surface Observation/Surface File with PBL Parameters

- (i) Wind speed & direction
- (ii) Ambient temperature
- (iii) Surface heat flux

The above parameters for the year 1995 were extracted from the on-site raw data collected for the study area. The rest of the parameters were calculated and are discussed below:

**(iv) Surface Roughness Height ( $Z_0$ )**

The surface roughness height ( $Z_0$ ), which is the height above the ground at which horizontal wind velocity is typically zero, is taken as 0.01 m (Rehman et al., 1990 & 1994).

**(v) Instrument Height ( $Z_{ref}$ ) for Wind Speed**

The Saudi Arabian Wind Energy Atlas (1986), has reported that all the wind sensors are located at a height of 10 m above the ground surface at most of the meteorological data acquisition stations. This height for the sensor has been recommended by the World meteorological Organization (WMO). At some stations, the sensors were installed at 7, 8, and 9 m above the ground surface. In this study the instrument height ( $Z_{ref}$ ) for wind speed were taken as 10 m above the surface (Rehman et al., 1994).

**(vi) Albedo ( $\gamma$ )**

Albedo can be defined as the fraction of total incident solar radiation reflected by the surface back to space without absorption. The values are given in Table 4.1.

**Table 4.1**  
**Albedo of Ground Covers by Land-Use and Season**

<b>Land Use</b>	<b>Spring</b>	<b>Summer</b>	<b>Autumn</b>	<b>Winter</b>
Water (Fresh and Sea)	0.12	0.10	0.14	0.20
Deciduous Forest	0.12	0.12	0.12	0.50
Coniferous Forest	0.12	0.12	0.12	0.35
Swamp	0.12	0.14	0.16	0.30
Cultivated Land	0.14	0.20	0.18	0.60
Grass Land	0.18	0.18	0.20	0.60
Urban	0.14	0.16	0.18	0.35
Desert Shrubland	0.30	0.28	0.28	0.45

Source: User's Guide for the AERMOD Meteorological Preprocessor (AERMET)

**(vii) Bowen Ratio ( $\beta_0$ )**

Bowen Ratio is an indicator for surface moisture, and can be defined as the ratio of the sensible heat flux to the latent heat flux, mainly used for determining the planetary boundary layer parameters for convective conditions.

The values used are listed in Table 4.2, adopted from the user's guide for the AERMOD meteorological pre-processor (AERMET).

**Table 4.2****Daytime Bowen Ratio by Land Use and Season Dry Conditions**

Land Use	Spring	Summer	Autumn	Winter
Water (Fresh and Sea)	0.1	0.1	0.1	2.0
Deciduous Forest	1.5	0.6	2.0	2.0
Coniferous Forest	1.5	0.6	1.5	2.0
Swamp	0.2	0.2	0.2	2.0
Cultivated Land	1.0	1.5	2.0	2.0
Grass Land	1.0	2.0	2.0	2.0
Urban	2.0	4.0	4.0	2.0
Desert Shrubland	5.0	6.0	10.0	10.0

Source: User's Guide for the AERMOD Meteorological Preprocessor (AERMET)

**(viii) Friction Velocity ( $U_*$ )**

Friction velocity is a measure of the vertical transport of horizontal moment. It is calculated via dimensional analysis that defines the velocity scale for the flow near the surface (Kagan, 1995). In this study the friction velocity parameters are calculated by using the equation (4.5), which was modified by Mackay and Yeun in 1983 (Hicks, B.B., 1973; Mackay and Yeun, 1983).

$$[U_*/U_{10}]^2 = [0.65 + 0.07 U_{10}] \times 10^{-3} \quad (4.5)$$

Where

$U_{10}$  is the wind velocity at 10 m height above the Earth's surface.

Therefore,  $[U_*]^2 = [U_{10}]^2 [0.65 + 0.07 U_{10}] \times 10^{-3}$



$$U_* = \{U_{10} [0.65 + 0.07 U_{10}^{0.5}]\}/31.6227 \quad (4.6)$$

The final values were multiplied by the factor 3 to make the data accountable to the real data as recommended by the U.S EPA AERMOD air dispersion Model.

**(ix) Turbulent Velocity Scale ( $W_*$ )**

The turbulent Velocity Scale ( $W_*$ ) parameter is calculated using the equation given in the User's Guide for the AERMOD Meteorological Preprocessor (AERMET) as shown below:

$$W_* = (g H Z_{tc} / \rho C_p T)^{1/3} \quad (4.7)$$

Where:

$$g = 9.81 \text{ m/sec}^2$$

$$H = \text{Sensible heat flux (watts/m}^2\text{)}$$

$$Z_{tc} = \text{Convective Mixing Height (m)}$$

$$C_p = \text{Specific heat Constant of air} = 1004.67 \text{ J/Kg-K}$$

$$T = \text{Temperature in (K)}$$

$$\rho = \text{Dry air density} = 1.275 \text{ kg/m}^3$$

**(x) Monin-Obukhov Length (L)**

The Obukhov length is parameter, which gives a relation between parameters characterizing dynamic, thermal and buoyancy processes. This parameter was

first described by Obukhov in 1946, and later on in 1954 was modified by Monin and is then was called as Monin-Obukhov length. The value of L has often been used to make diagnosis of the atmospheric conditions like stable, neutral, or unstable. Many researchers use a partition such as:

- Stable if  $0 < L < 1000$  (meters)
- Neutral if  $|L| > 1000$ , and
- Unstable condition if  $-1000 < L < 0$

Basically, the quantity L is a (vertical) length scale (Erbrink, 1995). 'L' reflects the height to which the friction forces are dominant over buoyant forces. In stable conditions L is positive, because of the downward (negative) sensible heat flux to the soil, where heat is converted into radiation and is sent into space in situations without clouds. In neutral conditions the L is close to zero and in unstable conditions L is negative because of a positive heat flux.

The Monin-Obukhov parameter for this research is calculated using the equation given in the User's Guide for the AERMOD Meteorological Preprocessor (AERMET), is shown below

$$L = -[\rho C_p T U_*^3] / [k g H] \quad (4.8)$$

Where

$$\rho = \text{Dry air density} = 1.275 \text{ kg/m}^3$$

$C_p$  = Specific heat Constant of air = 1004.67 J/Kg-K

$g$  = 9.81 m/sec<sup>2</sup>

$k$  = Von Kerman constant = 0.4

$H$  = Sensible heat flux (W/m<sup>2</sup>)

$U_*$  = Friction velocity (m/sec)

Placing the constant values in equation (i), it is modified to

$$L = -326.44094 \times [(T \times U_*^3) / H] \quad (4.9)$$

Equation (4.9) has been used to find the Monin-Obukhov length for the AERMOD model in this study.

#### **4.2 Run-stream File for the AERMOD Model**

The AERMOD model was used to simulate the ambient concentration of different pollutants for various averaging periods, from Al-Jubail Desalination Plant (JDP) emissions. JDP is located at 100 km north of Dammam, and to the eastern coast of Saudi Arabia. The JDP is one of the biggest water desalination plant in the world, producing approximately 253 million gallons per-day (mgd). Studies are underway to expand the desalination water capacity of JDP, which is considered to supply another 817300 m<sup>3</sup>/day (S.W.C.C., 1995).

The run-stream files/data available for AERMOD model is discussed in the following sections.

#### 4.2.1 Emission Inventory

The complete emission inventory of the primary pollutants from the Jubayl desalination plant, considering the production capacity of 253 mgd (Al Mutaz, I.S., & Wagialia, K.M, 1990), is described in detail in this section. Table 4.3 summarizes the properties of fossil fuel oil, which is mainly used in most of the MSF desalination plants in Saudi Arabia. The properties of fossil fuel used in other plants are same as used in Al-Jubail desalination plant (Abrams, et. al., 1989).

**Table 4.3**  
**Fossil Fuel Properties**

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#### Physical Properties

Specific Gravity	0.875 (source: Husain, T. 1995)
Viscosity at 50°C	184.4 (centistokes)
Appearance	Normal
Flashpoint (°C)	92
Heating Value (Btu/lb)	18492

#### Composition

Sulfur	3.5 wt. %
Nitrogen	0.24 wt. %
Ash	0.00985 wt. %
Moisture	0.0622 wt. %
Vanadium	40 ppm
Nickle	16.05 wt. %
Sodium	9.65 wt. %
Ash	0.00985 wt. %
Hydrocarbon	30.5 %

---

Source: Abrams, et al., 1989.

It has been clear from the literature search that a typical MSF desalination plant will consume about 16.62 kWh, of energy to produce 1 m<sup>3</sup> of desalinated water (Al-Marafie and Darwish, 1989). In addition to that 15% of energy will be added for using evacuating ejectors, therefore the total energy consumed by the MSF plant with a boiler efficiency of 85% to produce 1 m<sup>3</sup> of fresh water will be 19.78 kilowatts-hours (Al-Marafie and Darwish, 1989).

The total production of desalinated water from Al-Jubail MSF desalination plant in Saudi Arabia is 253 mgd. Therefore, to calculate the total amount of pollutant emission from JDP while producing 253mgd of desalinated water will be:

As we know that

$$0.003785 \text{ m}^3 = 1 \text{ gallon}$$

Therefore,  $1 \text{ m}^3 = 264.2 \text{ gallon}$

also  $1 \text{ kWh} = 3413 \text{ Btu}$

$$19.784 \text{ kWh} = 3413 \times 19.78 = 67509 \text{ Btu}$$

or  $19.784 \text{ kW} = 67509 \text{ Btu/hr}$

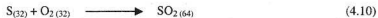
Therefore, producing  $253 \times 10^6$  gallons will required  $64647 \times 10^6$  Btu/hr. The boiler is working with an efficiency of 85 %, and the oil used in burning have a heating value of 18492 Btu/lb:

$$= 6.4 \times 10^{10} \text{ (Btu/hr)} / (0.85 \times 18492) \text{ (Btu/lb)}$$

$$= 34,95944 \text{ lb/hr}$$

The total fuel consumption by Jubayl MSF desalination plant to produce 253mgd of water is 1,585,749 kg/hr.

We know that Sulfur in fossil fuel is converted into SO<sub>2</sub>, which is shown as below



Equation (4.10) shows that, about 32 kg of sulfur produces 64 kg of SO<sub>2</sub>, or 1 kg of sulfur produces 2 kg of SO<sub>2</sub>.

From Table 4.3, it has been clear that the sulfur content in fuel is 3.5 % by wt. Therefore, the total sulfur content from the total fuel consumed in JDP will be:

$$= 0.035 \times 1585749 \text{ kg/hr}$$

$$= 55501 \text{ kg/hr}$$

The SO<sub>2</sub> generated from the plant while burning 1585749 kg/hr of fuel is

$$= 55501 \times 2$$

$$= 111002 \text{ kg/hr}$$

Therefore, the SO<sub>2</sub> produced is **30,833 g/sec**.

The other important pollutant is NO<sub>x</sub>, the formation of NO<sub>x</sub> (more precisely in this study NO<sub>2</sub>) can be attributed to two distinct chemical kinetic process. One is called the “thermal NO<sub>x</sub>” and another is “fuel NO<sub>x</sub>”. Thermal NO<sub>x</sub>/NO<sub>2</sub> are mainly generated by the oxidation of atmospheric nitrogen present in the combustion air, while the fuel NO<sub>x</sub>/NO<sub>2</sub> are formed by the oxidation of nitrogen present in the fuel.

It has been reported that the total NO<sub>x</sub> (i.e. Thermal and Fuel) emissions from an industrial boiler while burning residual oil is 60 lbs/1000 gallons (U.S. EPA, 2001). To calculate the fuel NO<sub>x</sub> emissions, it has been shown previously in Table 4.3, that the percentage of nitrogen present in the fossil fuel is 0.24 % by wt. Therefore the total Fuel NO<sub>2</sub> emitted will be:

$$\text{Fuel (NO}_2\text{)} = 22 + 400 (N)^2 \text{ (lbs/1000gallons)} \quad (4.11)$$

Where: N is the percentage, by weight, of the nitrogen present in oil

$$\begin{aligned} &= 22 + 400 (0.24)^2 \\ &= 45.04 \text{ lbs of NO}_2\text{/1000 gallons} \end{aligned}$$

Similarly, the thermal NO<sub>2</sub> emitted from the plant is 14.96 lbs of NO<sub>2</sub>/ 1000 gallons. Form equation (4.11) the amount of fuel NO<sub>2</sub> generated is 45.04 lbs/1000 gal. Also it is calculated that by burning 1000 gallons of fossil fuel in industrial or commercial boiler will generate a total of 60 lbs (27.2 kg) of NO<sub>2</sub> (U.S EPA, 2001). The residual fuel used in the Al-Jubail desalination plant has a heating value of 18492 Btu/lb, and specific density of 0.875.

Therefore,

$$\text{Density(R. Oil)} = (0.875)(1000 \text{ kg/m}^3) = 875 \text{ kg/m}^3$$

Or  $\text{Density(R. Oil)} = 1929.375 \text{ lbs/m}^3$

From the above density calculations we can conclude that 1 lb of residual oil is equal to  $5.1 \times 10^{-4} \text{ m}^3$  by volume. The heating value of residual oil is 18492 Btu/lb, so the total volume of oil burned to produced  $64647 \times 10^6 \text{ Btu/hr}$  of energy, will be  $1811.95 \text{ m}^3/\text{hr}$ .

Now we know that:

$$1 \text{ m}^3 = 264.2 \text{ gallons}$$

Therefore,  $1811.95 \text{ m}^3/\text{hr} = 4,78,718.9 \text{ gallons/hr}$

As it has been stated earlier that by burning 1000 gallons of residual oil in the boiler will generate a total (thermal and fuel) of 27.2 kg of  $\text{NO}_2$ . Therefore, by burning 4,78,718.9 gal/hr will generate total  $\text{NO}_2$  of 13021.15kg/ hr, or the total  $\text{NO}_2$  emission from Al-Jubail desalination plant is **3616.98 g/sec**.

The third important pollutant is the Particulate matter (PM), again based on previously given Table 4.3, the ash contents by wt.% is 0.00985.

Therefore, the total PM emitted from the JDP while burning 1585749 Kg/hr of fossil fuel will be:



PM in fuel =  $1585749 \times 0.0000985$

PM in emission = 156 Kg/hr, or

PM in emission = 43.3 g/sec of fine particulate

#### 4.2.2 Source Input Data

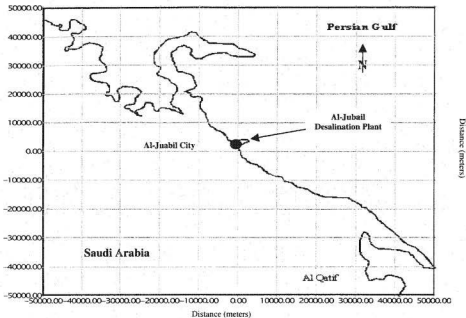
As all the stacks in JDP are placed together therefore, in this study it has been considered as a single point source and will be assumed as one single stack emission. The coordinates for the stack were entered as (0.0, 0.0). The other source parameters and their respective values, which were entered into the AERMOD model, are:

- Pollutant emission rates as been calculated in previous section
- A stack height of 65 meters (typical height)
- Stack gas exit temperature were assumed to be 440 K
- Stack gas exit velocity of 12 m/sec was assumed (Memon, 2000), and
- Stack inside diameter was taken as 1.5 meters

#### 4.2.3 Receptor Information

An option of Cartesian grid receptor network was selected to estimate the short term and annual averages concentrations at various receptor grids. The receptor grid network is extended 50 km in each direction from  $27^{\circ} 02' N$  &  $49^{\circ} 38' E$ , covering the King Abdul Aziz Naval base, Al-Ajam city, Najma, Jhaab (gas oil separator plant), Jazirat Al Batinah, Abu Ali, and Al Qatif city. The receptor network developed for this study is shown in

Figure 4.5. The vertical axis in Figure 4.5 and in all other figures (in chapter 6), which shows the AERMOD emission result are in North South direction.



**Figure 4.5 Receptor Grid for AERMOD Model Runs**

#### **4.2.4 Selected Output Options**

The AERMOD model provide user with an option to select various output options for viewing and studying the generated results. In this study the following output options were selected:

- High value summary table for different averaging times for separate receptors
- Overall maximum value summary tables
- Average annual values, and
- Daily and hourly average values table.

A sample run-stream file for AERMOD model is presented in Appendix-B

## **Chapter V**

### **STUDY AREA**

#### **5.1 Al - Jubail Desalination Plant (JDP)**

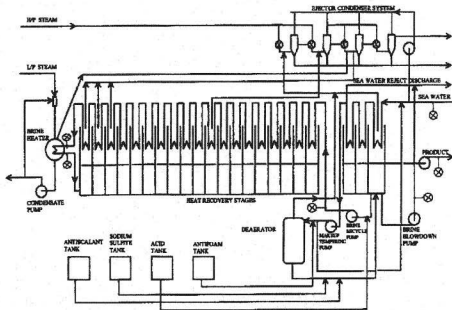
JDP is located on the shores of the Arabia/Persian Gulf and in center of Saudi Arabia's major oil producing region. Al-Jubail, the largest of the Kingdom's new cities, is a major cornerstone of the Kingdom's economic development program. The infrastructure of the industrial city of Al-Jubail is established on a site covering 1,030 km<sup>2</sup> and its population is estimated to be that by the year 2010 the city will accommodate 290,000 inhabitants.

Al-Jubail Industrial City (JIC) is considered to be one of the leading industrial cities of Saudi Arabia with a total investment of \$46 billion. This accounts for almost 60 per cent of the Kingdom's non-oil exports and has registered sustained annual production growth of 4%. JIC is also the largest converter of natural gas resources to added value petrochemicals with 6 to 7 per cent market share of world's petrochemicals.

The city of Jubail receives most of its fresh water from Al-Jubail desalination plant. The Al-Jubail power and desalination plant is one of the largest in the world. It consists of ten Boiler-Turbo-Generator (BTG) sets of about 130 MW output each. Each one of the ten-backpressure turbines feeds low-grade steam to four MSF distillers (i.e. forty distillers in total are installed). Thirty distillers have 19 stages in the recovery section and 3 stages in the rejection section each. The remaining ten distillers have 17 stages in the heat recovery and 2 stages in the heat rejection section.

The evaporators are designed for operation at a brine top temperature of 90.6°C with a production of 5.2 MGD and a top temperature of 112.8°C with a production of 6.29 MGD (Al-Sofi, et al., 1987; Al-Mudaiheem, 1991). Figure 5.1, shows the complete detail of the Al-Jubail MSF desalination plant.

Due to the projected increase in population and industries in the city of Al-Jubail an environmental assessment on air and water quality is required. This study has been conducted to observe if there is any drastic impacts/affects from Al-Jubail desalination plant on the surrounding environment.

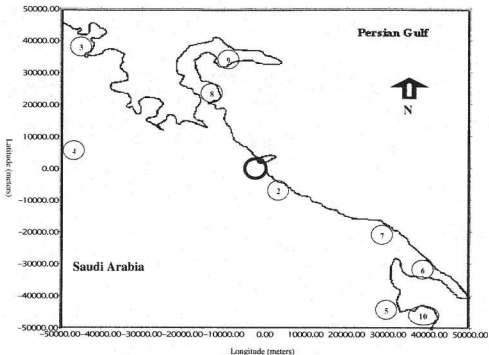


**Figure 5.1 Schematic diagram of Al-Jubail MSF Desalination Plant**  
 (Source: Al-Sofi et al., 2001)

In this research an EPA air dispersion model was used to simulate the plume and to estimate the concerned pollutants from the JDP. Also the available meteorological data for the said region was examined. Emission concentrations were predicted while using air dispersion model, and in the end the computed results were analyzed and compared with the local regulating agency's standards. This study will basically provide an estimate of different air pollutants emitted from the Al-Jubail desalination plant and its deposition at various receptor points and city. Figure 5.2 shows the Al-Jubail plant and some of the cities surrounding the plant. The coordinates and location of these cities/places in the study area are shown in Table 5.1.

**Table 5.1**  
**Coordinates and Locations of Receptor Points**

Site Number	Coordinate X (m)	Coordinate Y (m)	Location
1	0.00	0.00	Al-Jubail City
2	5000	-5000	King Abdul Aziz Naval Base
3	-45000	45,000	Cemetery Jinnah
4	-50,000	5000	Gas Oil Separator Plant
5	30,000	-50,000	Al-Ajam City
6	40,000	-35,000	Najmah
7	30,000	-20,000	Jhaab (Gas Oil separator)
8	-15,000	25,000	Jazirat Al Batimah
9	-10,000	35,000	Abu Ali (Sub Stations and Buildings)
10	35,000	-50,000	Al-Qatif City



**Figure 5.2 Al-Jubail Desalination Plant and Surrounding Cities**

## **Chapter VI**

### **DATA ANALYSIS AND RESULTS**

#### **6.1 Air Quality Standards**

Air quality has been a major environmental issue for a long time. This is because of the threat of possible global climate change and the “greenhouse effect” that are caused by anthropogenic emissions.

All types of emissions into the atmosphere must be controlled in order to maintain a clean environment for man and nature. Therefore, it is important to control all these emissions from the industries and any other sources, also it is important to determine the quality and concentration of the emissions. Environmental regulatory agencies have established ambient air quality standards, to set legal limits for all kind of emissions to protect the environment and public health.



Rapid technology advancement and industrialization has greatly increased the productivity in Saudi Arabia, but at the same time it has poses many serious environmental degradation problems (Rehman et al., 1990). In the initial period of industrialization, more importance was given to productivity than to the quality of environment. However, in the last two decades more attention has been focused on the impact of industrial pollutants. In Saudi Arabia, the Meteorological and Environmental Protection Administration (MEPA), a branch of the Ministry of Defense and Civil Aviation, is responsible since 1970s for the preparation of environmental standards for different types of environmental pollutants (Rehman et al., 1990).

The Clean Air Act (CAA), which was last amended in 1990, requires Environmental Protection Agency (EPA) to sets National Ambient Air Quality Standards (NAAQs) for pollutants considered harmful to public health and to the environment. The criteria pollutants for various averaging periods, as set by MEPA are almost the same as develop by the NAAQs. These standards are presented in Table 6.1.

The Clean Air Act (CAA) established two types of national air quality standards. *Primary Standards* are implemented to protect public health, including the health of sensitive populations such as asthmatics, children, and elderly peoples. *Secondary Standards* set limits to protect public welfare, including protection against decreased visibility, damage to animals, crops, vegetation, and buildings. These standards are set by the regulatory agencies using the best scientific evidence available relating the levels of emissions to

adverse effects to human health and to the environment (Office of Air Quality Planning and Standards, 2001)

**Table 6.1**  
**MEPA Air Quality Standards**

<b>Pollutants &amp; Averaging Time</b>	<b>Standard/Maximum Concentration</b>	<b>Standard Type</b>	<b>Exceedences</b>
<b>Sulfur Dioxide (SO<sub>2</sub>)</b>			
1 – Hour	730 $\mu\text{g m}^{-3}$ (0.28 ppm)	Secondary	Twice a Month
24 – Hour	365 $\mu\text{g m}^{-3}$ (0.14 ppm)	Primary	Once a Year
Annual	80 $\mu\text{g m}^{-3}$ (0.03 ppm)	Primary	
<b>Particulate Matter (PM)</b>			
24 – Hour	340 $\mu\text{g m}^{-3}$	Primary & Secondary	Once a Year
Annual	80 $\mu\text{g m}^{-3}$	Primary & Secondary	
<b>Nitrogen Oxide (Define as Nitrogen Dioxide, NO<sub>2</sub>)</b>			
1 – Hour	660 $\mu\text{g m}^{-3}$ (0.35 ppm)	Primary & Secondary	Twice a Month
Annual	100 $\mu\text{g m}^{-3}$ (0.05 ppm)	Primary & Secondary	
<b>Photochemical Oxidants (Define as Ozone, O<sub>3</sub>)</b>			
1 – Hour	295 $\mu\text{g m}^{-3}$ (0.15 ppm)	Primary & Secondary	Twice a Month
<b>Carbon Monoxide (CO)</b>			
1 – Hour	40.0 $\text{mg m}^{-3}$ (35.0 ppm)	Primary	Twice a Month
8 – Hour	10 $\text{mg m}^{-3}$ (9.0 ppm)	Primary	Twice a Month
<b>Hydrogen Sulfide (H<sub>2</sub>S)</b>			
1 – Hour	195 $\mu\text{g m}^{-3}$ (0.14 ppm)		Twice a Month
24 – Hour	40 $\mu\text{g m}^{-3}$ (0.03 ppm)		Once a Month
<b>Fluorides (F)</b>			
30 – Day	1 $\mu\text{g m}^{-3}$ (0.001 ppm)		
<b>Lead (Pb)</b>			
Quarterly Average	1.5 $\mu\text{g m}^{-3}$	Primary & Secondary	

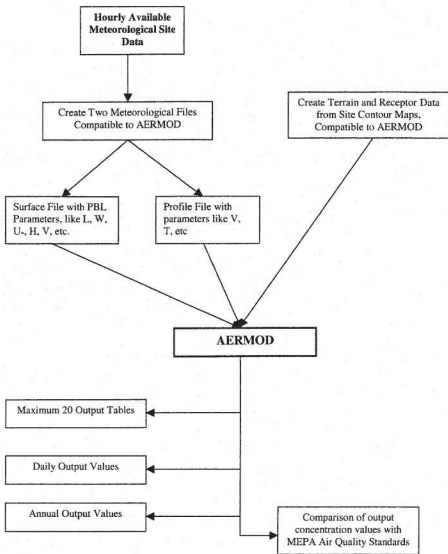
(Modified from Amin, 1994)

## 6.2 Data Analysis and Processing

The main steps, involved in this research for data analysis and processing, are shown in Figure 6.2. One year (1995) of upper air and surface meteorological data were used and processed to obtain daily maximum and minimum mixing height values.

As described previously in section 4.1, AERMOD requires two types of meteorological data files, which are provided by the AERMET meteorological preprocessor or formatting the data files manually. One file consists of surface scalar parameters, and the other consists of vertical profiles of meteorological data. These meteorological data files are described briefly in section 4.2 and 4.3, for applications involving the elevated terrain effects. The receptor and terrain data will need to be processed by the AERMAP terrain preprocessor program or can be generated manually, as done in this case. The output files generated by the preprocessors (AERMET & AERMAP) are in such a format that it is directly acceptable to the AERMOD model. The other information, like source emissions data and model control parameters, were prepared and stored in separate files.

The AERMOD model was used to print the highest concentrations, and 20 maximum concentration tables. Hourly and daily concentration values were calculated, as well as the annual average concentration values and were compared and checked against the maximum concentration allowed in the MEPA Air Quality Standards as shown in Table 6.1.



**Figure 6.1 Flow Diagram of Data Analysis and Processing System**

## 6.3 Sulfur Dioxide Results

### 6.3.1. 1-Hour Average Concentration Level

Concentration values for 1-hour average were calculated using the air emission AERMOD model. The results were then compared against the MEPA's maximum concentration standard of  $730 \mu\text{g}\cdot\text{m}^{-3}$ . The concentration values obtained for the Al-Jubail MSF desalination plants were shown in Appendix-C. A total of 441 average concentration points were calculated, out of which twenty values exceeded the standard maximum concentration. Figure 6.2 shows the concentration plot for the MSF desalination plant at Al-Jubail, Saudi Arabia.

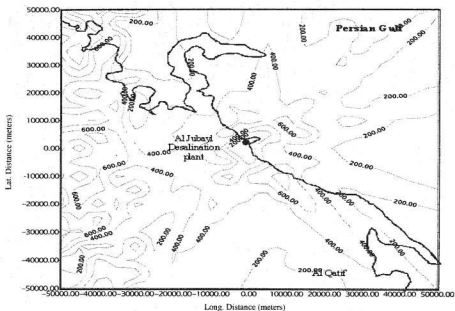


Figure 6.2 1-Hour Average Concentration ( $\mu\text{g}/\text{m}^3$ ) Plot of  $\text{SO}_2$  for the Year 1995

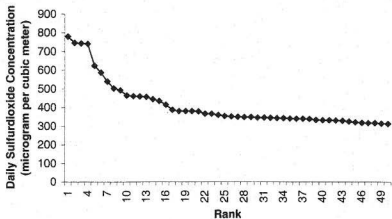
The areas where the MEPA standards have been violated are the South East part at (Figure 6.2) – 40000 meter (Long), 50000 meter (Lat) from the point of emission, the other highest concentration was calculated at –5000 meter (Long), 25000 meter (Lat) (mainly open sandy area).

It has been observed that the frequency of exceedence based on hourly average varies from a minimum of 2 in August to 3 in January, to 10 times in the month of July.

### **6.3.2 Daily Average Concentration Level**

SO<sub>2</sub> concentration values were simulated to calculate the daily average concentration levels at each grid and discrete receptor points for the year 1995. The estimated average daily concentrations were also compared against the MEPA average daily standard concentration value of 365µgm<sup>-3</sup>.

The emission result shows that only 5.2% of the total value exceeded the daily average emission concentration values. The highest concentration values based on average daily estimates for the year 1995 are given in Appendix-B. The maximum 50 daily highest concentration values for the year 1995 are shown in Figure 6.3.



**Figure. 6.3 Plot of 50 Highest Concentrations of SO<sub>2</sub> on 24-Hour (Daily) Average Basis for the Year 1995**

A total of 23 values exceeded the MEPA standard value of  $365\mu\text{g}\text{m}^{-3}$ . Analysis of SO<sub>2</sub> concentrations based on daily average data (Appendix-C) shows that values greater than the standard  $365\mu\text{g}\text{m}^{-3}$  were estimated at the King Abdul Aziz Naval Complex and towards the Persian Gulf as shown in Figure 6.4.

Values at other locations were insignificant, because of the fact that they were within the limits of maximum concentration of  $365\mu\text{g}\text{m}^{-3}$ .

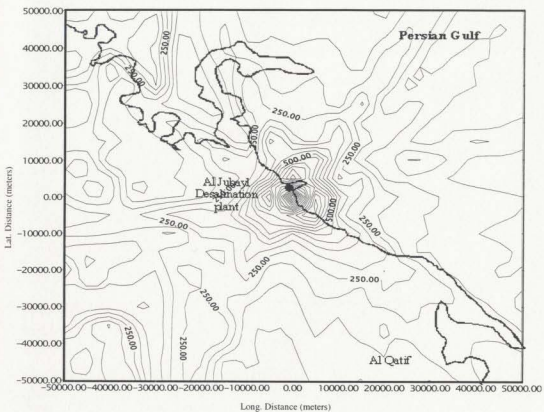


Figure. 6.4 Daily Average Concentration ( $\mu\text{g}/\text{m}^3$ ) Plot of  $\text{SO}_2$  for the Year 1995

### 6.3.3 Annual Average Concentration Level

Annual average  $\text{SO}_2$  concentration results for the year 1995 are presented in Appendix-C. The six highest annual concentrations result, along with their respective locations are also shown in Appendix-B. The annual average  $\text{SO}_2$  emissions result is plotted as shown in Figure 6.5. It has been observed from the AERMOD emission results that only 14 values



exceeded the MEPA standard of  $80\mu\text{gm}^{-3}$  for the year 1995, and the exceedance is only by  $10\mu\text{gm}^{-3}$ . AERMOD results show that over ninety percent of the annual average concentration emission from the Al-Jubail desalination plant is within the MEPA standard. Therefore we can say that the estimated annual average concentrations of  $\text{SO}_2$  are within the safe limits of specified MEPA standards.

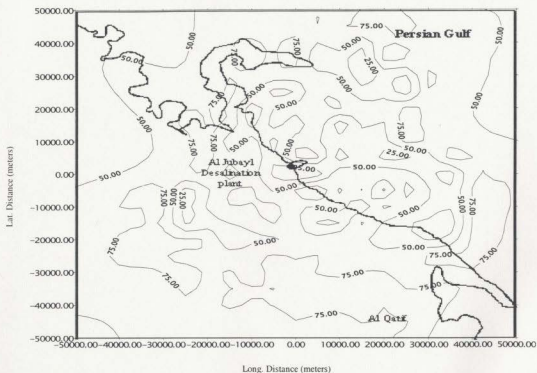


Figure. 6.5 Annual Average  $\text{SO}_2$  Concentration ( $\mu\text{g}/\text{m}^3$ ) Plot of Al-Jubail MSF Desalination Plant for the Year 1995

## 6.4 Nitrogen Oxides Results

### 6.4.1 Hourly Average Concentration Level

Hourly average ambient air concentration of  $\text{NO}_x$  contributed by Al-Jubail desalination plant for the year 1995 is shown in Appendix-D. These emission concentration results were compared against the MEPA maximum concentration standard of  $660 \mu\text{g}\cdot\text{m}^{-3}$ . It was estimated from the emission result that only eight values exceeded the specified allowable limit of MEPA. Figure 6.6 shows the concentration plot for 1-hour average concentration levels of  $\text{NO}_x$ . Maximum 20-concentration level was generated for the year 1995, and is shown in Figure 6.7.

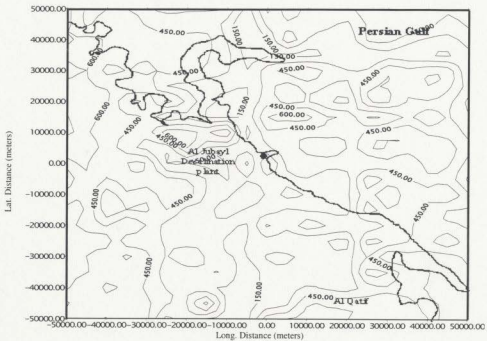
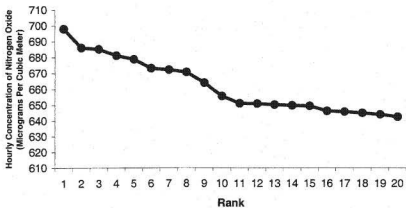


Figure 6.6 1-Hour Average Concentration ( $\mu\text{g}/\text{m}^3$ ) Plot of  $\text{NO}_x$  for Al-Jubail Desalination Plant



**Figure 6.7 Plot of 20 Highest Concentration levels of NO<sub>x</sub> on 1-Hour Average Basis for the Year 1995**

#### 6.4.2 Annual Average Concentration Level

Annual average emission concentration results of NO<sub>x</sub> from Al-Jubail desalination plants are shown in Appendix-D, all these concentration results from AERMOD were compared against the MEPA maximum standard 1 year NO<sub>x</sub> concentration of 100 µgm<sup>-3</sup>, and it was found that most of the concentration result were within the standards. The six highest concentration values were shown in Appendix-D.

The annual average concentration results for NO<sub>x</sub> were found to be more than ninety nine percent within the MEPA regulatory limits. The Annual Average concentration plot for NO<sub>x</sub> is drawn and is shown in Figure 6.8.

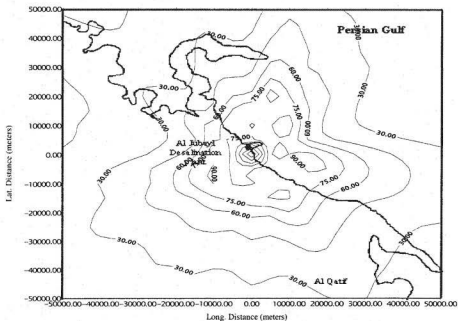
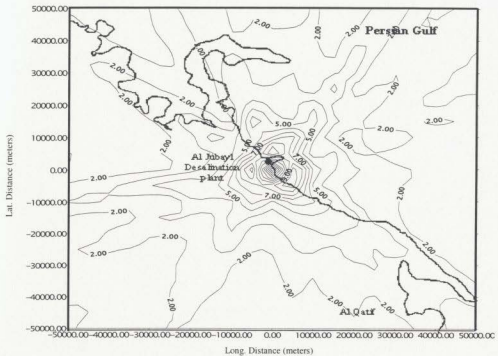


Figure 6.8 Annual Average Concentration ( $\mu\text{g}/\text{m}^3$ ) Plot of  $\text{NO}_x$  for Al-Jubail Desalination Plant

## 6.5 Particulate Matter Results

### 6.5.1 Daily Average Concentration Level

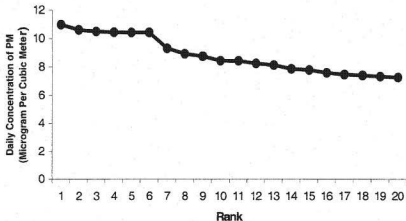
Particulate concentration values were estimated to determine the daily average concentration levels at each grid and discrete receptor point for the year 1995. Estimated average daily particulate concentrations were compared against the average daily standard value of  $340 \mu\text{g}/\text{m}^3$  as specified by MEPA. The emission results at each grid point are shown in Appendix-E. The concentration plot, as shown in Figure 6.9, and the



**Figure 6.9 Daily Average Concentration ( $\mu\text{g}/\text{m}^3$ ) Plot of Particulate Matters for the Year 1995**

AERMOD emission result shows that all the values for PM are within the standard limit and that the particulate concentration levels at all the grids are much lower than the specified MEPA standards.

The maximum 20 particulate matter concentrations were plotted as shown in Figure 6.10, the result also satisfied the MEPA standards for highest PM concentration.



**Figure 6.10 Plot of 20 Highest Concentration ( $\mu\text{g}/\text{m}^3$ ) Levels of Particulate Matters On Daily Average Basis for the Year 1995**

### 6.5.2 Annual Average Concentration Level

Annual average particulate concentration for the year 1995 are presented in Appendix-E, the result generated by AERMOD is compared with the MEPA standard of  $80 \mu\text{g}/\text{m}^3$ , it was observed that all the values were far below the MEPA standard. Figure 6.11, shows the concentration plot for PM on an annual average concentration base, which satisfied the MEPA standards for PM.

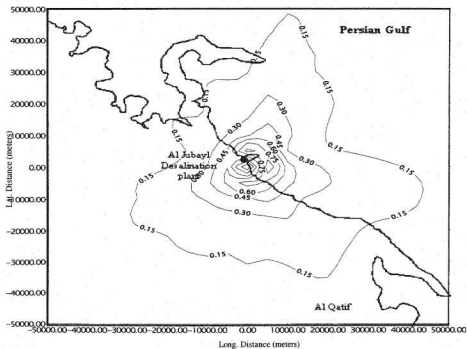


Figure 6.11 Annual Average Concentration ( $\mu\text{g}/\text{m}^3$ ) Plot of Particulate Matters for the Year 1995

## 6.6 Analysis of the Results

The analysis of the results indicates that the pollutants of concern from Al-Jubail desalination plant were  $\text{SO}_2$  and  $\text{NO}_x$ . The Sulfur dioxide results showed that some of the emission results (3 to 5%) for all the averaging period were above the standard limits.

However, the  $\text{NO}_x$  limits were within the range for annual average, and only 1.81% of the concentration level is exceeded in 24-hour averaging period. In case of particulate matter the estimated concentrations were well within the MEPA standard limits.

From the concentration plots and AERMOD results it was found that the higher concentrations were found to be towards the North East (Persian Gulf) side of Al-Jubail desalination plant.



## **Chapter VII**

### **RESULTS AND ANALYSIS OF BRINE DISCHARGE USING CORMIX-1**

#### **7.1 CORMIX System**

Brine discharge with high concentrations of total dissolved solids (TDS) and elevated temperatures to the ocean from desalination plants can cause a potential problem and may threaten the benthic environment. To deal with this the EPA CORMIX computer code model will be used to investigate the brine discharge from Al-Jubail MSF desalination plant. Suggestions will be made, regarding the high TDS (salinity) and elevated temperature in the discharge water to the ocean.

The Cornell Mixing Expert System (CORMIX) represents a robust and versatile computerized methodology for predicting both the qualitative features (e.g. flow

classification) and the quantitative features (e.g. dilution ratio, plume trajectory) of the hydrodynamic mixing processes resulting from different discharge configurations in all types of ambient water bodies, including small streams, large rivers, lakes, reservoirs, estuaries, and coastal waters (Mukhtasov et al., 2001).

The CORMIX consists of a series of software systems for analysis, prediction, and design of toxic or conventional pollutant discharges into diverse water bodies, with emphasis on the geometry and dilution characteristics of the initial mixing zone, including the evaluation of regulatory requirements. CORMIX is a U.S EPA approved system, which emphasizes on the prediction of plume boundary interaction and provides extensive documentation of input data verification, hydrodynamic model selection, and documentation of simulation results (Doneker and Jirka, 2001).

CORMIX is approved and used for environmental impact assessment of mixing zones resulting from point source discharges (Akar and Jirka, 1991; Donekar, and Jirka, 1990). The methodology contains systems to model submerged single-port (CORMIX-1), which predicts the geometry and dilution characteristics of the effluent. It has been proved that CORMIX-1 works better than 95% on submerged single-port designs, while CORMIX2 is developed for multi-port diffuser configurations. Three commonly used types of submerged multi-port diffuser discharges are accumulated in CORMIX2 under the same general effluent and ambient conditions as CORMIX1. It has been shown that CORMIX2 applies better than 80% of the multi-port designs. CORMIX3 analyzes the buoyant

surface discharges, which are originated when an effluent enters a larger water body laterally, through a canal, channel, or near-surface pipe. Also the CORMIX3, in contrast to CORMIX1 and CORMIX2, is limited to positively or neutrally buoyant effluents. In CORMIX3, different discharge geometries and orientations can be analyzed including flush or protruding channel mouths, and orientations normal, oblique, or parallel to the bank (Akar and Jirka, 1991; Donekar, and Jirka, 1990; Jones et al., 1996). The other major assumptions in CORMIX models are as follows:

- All subsystems require that, the actual cross-section of the water body be described as a rectangular straight uniform channel that may be bounded laterally or unbounded. The ambient velocity is assumed to be uniform within that cross-section.
- In addition to a uniform ambient density, CORMIX allows for three generic types of ambient stratification profiles to be used for the approximation of the actual vertical density distribution.
- All CORMIX subsystems in principle are **steady-state models**, however recent developments and with the new version of CORMIX the analysis of **unsteady mixing** in tidal environments can be performed.
- All CORMIX systems can predict mixing for both conservative and first-order decay processes, and can simulate heat transfer from thermal plumes.

As it has been observed that the Al-Jubail desalination plant is discharging the brine in a submerge fashion, the brine discharge pipe is releasing effluent from the plant into the Persian Gulf at a depth of 4 meter (Abdul Azis et al., 2000). Therefore, in this research CORMIX1 system will be used to simulate the TDS and elevated temperature results.

## 7.2 CORMIX Technical Description

This section will describe the formulation and technical description of the CORMIX computer code system. All the CORMIX sub-models assume steady-state ambient discharge conditions. All these sub-models within the CORMIX system can be used to predict the geometry and dilution characteristics of effluent flow from different discharging systems.

CORMIX system with submerge discharge/plume, the concentration profile can be calculated by using the following formula

$$C(n) = C_c e^{-(n/b)^2} \quad (7.1)$$

Where  $C(n)$  is the lateral concentration (any units), 'n' is the coordinate position measured transversely away from the centerline (meters),  $C_c$  is the centerline concentration (any units), 'e' is the natural logarithm base, and 'b' is the local plume half width (meters) (Jirka et al., 1996).

The CORMIX system is enhanced in performance by the CORJET, which contribute as a part of the CORMIX system. The model basically works on the assumption of Gaussian profile for jet velocity  $u$ , buoyancy ' $g$ ', and concentration ' $c$ ', as shown in Figure 7.1.

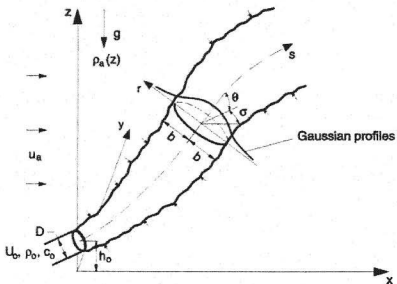


Figure 7.1 General Three-Dimensional Trajectory of Submerged Buoyant Jet in Ambient Stratified Cross flow (Adopted from Jirka et al., 1996)

Where, ' $D$ ' is the diameter of the brine discharge jet (meter), ' $h_0$ ' is the height of the jet from the surface bed (meter), ' $U_0$ ' is the discharge velocity (m/sec), ' $\rho_0$ ' is the brine density ( $\text{kg/m}^3$ ), ' $C_0$ ' is the concentration of discharge (ppb, mg/l or degrees), ' $b$ ' is the half plume width (meter), ' $s$ ' is the center of the plume, ' $g$ ' is the gravitational force

(m/sec<sup>2</sup>), 'U<sub>a</sub>' and 'ρ<sub>a</sub>' are the ambient velocity and density. From Figure 7.1, it is clear that there are three main fluid forces acting on the jet plume; the entrainment force in the x-direction, the buoyant force in the z- direction, and the drag force normal to the jet.

Where the jet velocity 'u', the Buoyancy 'g', and the concentration 'c' is calculated by the system, using the equation as shown below:

$$u = u_c e^{-r^2/b^2} + u_a \cos\sigma \cos\theta, \quad g = g_c e^{-r^2/(\lambda b)^2}, \quad c = c_c e^{-r^2/(\lambda b)^2} \quad (7.2)$$

In equation (7.2) the subscript 'c' denotes the centerline values, while the 'b' represent the jet width, and 'λ' describe the dispersion ratio which is always greater than 1 for the scalar quantities. For more information on these equations (entrainment, buoyant, and drag), the author would suggest to read Jirka (1999).

### 7.3 CORMIX Data Input

The main input data required by the CORMIX systems are the discharge configurations and discharge site information, the ambient conditions and pollutant characteristics. In all these the most important factors that can influence the mixing or dilution of the plume are the ambient depth, ambient velocity and effluent discharge velocity, all these will be discussed in detailed in the next sections.

All the CORMIX systems have the same data input features. All data is entered interactively in response to the CORMIX system prompts and is totally guided by the

system. The user is asked for a complete specification about the site/case descriptions, ambient conditions, discharge characteristics, and regulatory definitions, which will be discussed in the proceeding sections. The whole input data can be entered in an open format that is not concern for letter case or decimal placement (Jirka et al., 1996).

### **7.3.1 Site Identification Data**

The first basic input data and the information needed for the program (system) to operate/run is a two-part identifier for labeling the output and the computer file name. Site identifier data is necessary to specify the site/case labels, which help in the identification of printed output records and also aid in good record keeping. The CORMIX provide one label for SITE NAME, and another for DESIGN CASE.

### **7.3.2 Ambient Data**

All CORMIX analyses are usually carried out under the assumption of **steady-state** ambient conditions. Even though the actual water environment is never in a true steady state, this assumption is usually adequate since mixing processes are quite rapid relative to the time scale of hydrographic variations. In highly unsteady tidal reversing flows the assumption is no longer valid and significant concentration build-up can occur. CORMIX will assess this situation and compute some re-entrainment effects on plume behavior.

As this research is concerned with the desalination plant in the Persian Gulf, in the CORMIX system the water body will be taken as unbounded. Therefore, the focus of

study will be on unbounded discharge, and the ambient input data requirements for the CORMIX will be as follows:

**(1) Hydrographic Data**

If the detailed hydrographic data from field surveys or from hydraulic numerical model calculations are available, then the "*cumulative ambient discharge*" from the shore to the discharge location for the discharge cross-section is calculated. Values for the *ambient/average depth (HA)* and *ambient velocity (UA)* are calculated for input specifications. The *distance from the shore (DISTB)* for the outfall location is typically specified as the cumulative ambient discharge divided by the product UA times HA.

When detailed hydrographic data are unavailable, data or estimates of the vertically averaged velocity at the discharge location can be used to specify HA, UA, and DISTB.

**(2) Water Depth (HD)**

The actual water depth at the submerge discharge location (HD), for CORMIX1 & 2, must be specified. In CORMIX a check is used so that the HD depth should not differ more than +/- 30% of that of average depth HA. This restriction is included to prevent CORMIX misuse in several discharge/ambient combinations involving strongly non-uniform channels. In highly non-uniform conditions, HD is the variable that usually influences the near field mixing, while HA is important for far field transport and never influence the near field.



### (3) Manning (n)/ Darcy-Weisbach Friction Factor (f)

Manning's "n" or the Darcy-Weisbach Friction Factor "f" is specified for the ambient roughness characteristics. If the unbounded case represents a large lake or coastal area, it is often preferable to use the friction factor 'f'. Typical 'f' values for such open water bodies' range from 0.020 to 0.030, with larger values for rougher conditions.

### (4) Ambient Density

Ambient density specification in the water body is an important parameter for the correct prediction of effluent discharge plume behavior. In CORMIX the option is provided to describe whether the ambient water is *fresh or non-fresh* (i.e. brackish or saline). If the ambient water is fresh and above 4 °C, the system provides the option of entering ambient temperature data so that the ambient density values can be computed internally. In saline water conditions the density of water is usually specified. The CORMIX also specifies the user to input whether the ambient density (or temperature) is *uniform or non-uniform* within the water body, and most importantly within the expected plume regions. In case of uniform conditions the average ambient density or average temperature must be specified.

### (5) Wind Speed (UW)

The next important input parameter for CORMIX system is the *wind speed (UW)*. Wind speed is not an important factor in case of near-field mixing, but may critically affect the plume behavior in the far field. This is especially important for heated discharges in the

buoyant spreading region. Wind speed data from an adjacent meteorological station is usually sufficient for that purpose. Basically the wind speed categories which are measured at 10 m level are:

- Breeze (0 – 3 m/s)
- Light wind (3 – 15 m/s)
- Strong wind (15 – 30 m/s)

If the data for the wind is not available then it is recommended that a value of 2 m/s should be considered for a conservative design condition.

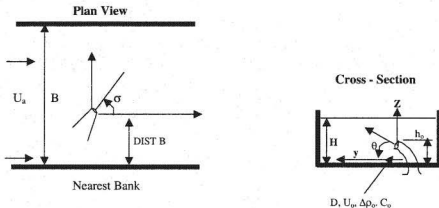
### **7.3.3 CORMIX Discharge Data**

In the discharge data, CORMIX-1 requires different parameters. Figure 7.2 defines the geometry and flow characteristics for submerge single port discharge. For the discharge geometry, CORMIX-1 requires the specification of 6 data entries, such as:

1. Location to the nearest bank (i.e. left or right), as seen by the observer looking downstream in the direction of flow
2. Distance to the nearest bank
3. Port radius (or cross sectional area for non circular shape ports)
4. Height of the port ( $H_0$ ) center above the bottom
5. Vertical angle of discharge (theta) between the port centerline and a horizontal plane. Angle theta range between  $-45^\circ$  and  $90^\circ$ . As an example the vertical angle

is  $90^\circ$  for a discharge pointing vertically upward, and it is  $0^\circ$  for a horizontal discharge.

- Horizontal angle of discharge (sigma), which is measured counterclockwise from the ambient current direction. Angle sigma ranges from  $0^\circ$  and  $360^\circ$ , as an example the horizontal angle is  $0^\circ$  (or  $360^\circ$ ) when the port points downstream in the ambient flow direction, and it is  $90^\circ$ , when the port points to the left of the ambient flow direction.



**Figure 7.2 The Geometry and Flow Characteristics for a Submerge Single Port Discharge**

In order to prevent any misuse or inappropriate system application, CORMIX-1 checks the specified geometry with the three important criteria, which are:

1. The port height ( $h_o$ ) value must not exceed one third of the local water depth (HD) value
2. The port diameter value must not exceed HD's value for near-vertical designs and one third of the HD's value for near-horizontal designs, and
3. The pycnocline (a zone or level of strong density change that separates the upper and lower levels of the water column) value must be within the 40 to 90 percent range of HD's value.

The port height restriction implies that CORMIX-1 may only be applied to submerged discharge applications. For port discharge characteristics, CORMIX-1 requires the specification of 3 parameters. These specifications include:

- The discharge flow rate ( $Q_o$ ) or discharge velocity ( $U_o$ )
- The discharge density or discharge temperature for an essentially freshwater discharge, and
- The discharge concentration of the material of interest.

The specification of the pollutants in the effluent is described in the next section.

### **7.3.4 Pollutant Data**

CORMIX can handle three types of pollutants discharges, and these are:

**1. Conservative Pollutant:**

In this case the pollutants does not undergo any type of decay or growth process

**2. Non-Conservative Pollutant**

In this case the pollutants are considered to undergo a first order decay or growth process. The coefficient of decay (positive number) or growth (negative number) should be specified in units per day.

**3. Heated Discharge**

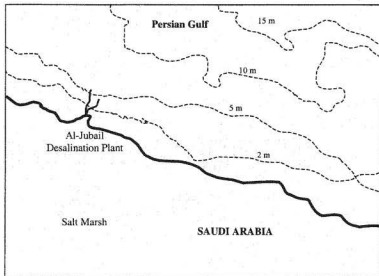
In this case the discharge will experience a heat loss to the atmosphere at a point where the plume contacts the water surface. It is therefore important to specify the discharge condition in terms of excess temperature above the ambient temperature in °C, and the surface heat exchange coefficient in  $W/(m^2 \text{ } ^\circ\text{C})$ .

## **7.4 Geographical Description of the Site**

The study was carried out for Al-Jubail desalination plant, situated at the Persian Gulf. The sea region adjacent to the Al-Jubail desalination plant, where the brine is discharged is shallow and the seabed is mainly consists of Seaweeds (Abdul Azis et al., 2000).

Figure 7.3 shows that the marine basin in the area of study is very shallow, the sea depth ranging from 3 to 8 meter over a long distance from the shore (Abdul Azis et al., 2000).

In figure 7.3, the 2-meter contour is approximately 1-2 km, 5-meter contour 2-4 km, and 10-meter contour is 4-6 km away from the shore. In the southeast of desalination plant is the Naval Base, the commercial port, and the biggest petro-chemical complex in the world.



**Figure 7.3 Persian Gulf between Lat. 26° 52' & 26° 55' N and between Long. 49° 45' & 49° 52' E. Study Site and Depth Contours**  
(Adopted from Abdul Azis et al., 2000)

The brine discharge pipe from Al-Jubail desalination plant is about 2000 meter away from the shore, and at a depth of 4 meter. While the seawater intake is at the depth of 2.5

meter, making it a typically coastal subsurface intake. The characteristics of brine discharge pipe are shown in Table 7.1.

**Table 7.1 Characteristics of Outfall**

OUTFALL	
Length (meter)	2000 m
Diameter (meter)	0.9 m (Adopted from Salibi, 2001)
Depth of Discharge (meter)	4 m

(Adopted from Abdul Azis et al., 2000)

## 7.5 Data Acquisition for CORMIX

The complete input data, which will be required to run CORMIX1, are as follows. The *Average Depth* of seawater is taken as 5 meter, while the Brine *Discharge Depth* is taken as 4 meter, both these numbers are adopted from Abdul Azis et al., (2000).

In this case the study region is the Persian Gulf, therefore the *Unbounded* option has been selected to run the CORMIX-1. Usually, in unbounded case the Darcy-Weisbach friction factor 'f' is adopted and these values ranges from 0.02 to 0.03, with larger values for rougher conditions (Jirka et al., 1996). Therefore, a value of 0.025 is selected.

Morton et al., in 1996, studied the MSF desalination plants situated at the Persian Gulf. They reported that the *Average density* of the Persian Gulf seawater is  $1027.5 \text{ kg/m}^3$ ,

while the brine from the MSF desalination plant has the *discharge density* of 1046.5 kg/m<sup>3</sup>.

Similarly, the *port diameter* of 0.9 meter was selected as reported by Salibi in 2001. The Discharge flow rate for the Al-Jubail MSF desalination plant was reported by Al-Mumtaz & Wagjalla in 1988, according to them MSF desalination plant with a production capacity of 253.5 million gallons per day has a net discharge of (Brine) about 371 million gallons per day, which is about 16.25 m<sup>3</sup>/sec. Therefore the *effluent flow rate* entered into CORMIX-1, is 16.25 m<sup>3</sup>/sec.

An *Ambient velocity* of 0.5 m/sec was selected based on Abdul Azis et al., (2001), who indicated that the Persian Gulf currents are generally of moderate nature. The average annual *wind speed* is taken as 5.0 m/sec, from the data used previously for running the AERMOD.

In the discharge analysis the first pollutant of interest is the *Temperature*. It was found by Abdul Azis et al., (2000), that the annual average ambient seawater (Persian Gulf) temperature is 26.06 °C. While Khawaji & Wie (2001), reported that for the MSF desalination plant, working with the top brine temperature (TBT) of 90 - 100 °C, has a brine discharge temperature of 33.0 °C. Therefore, a temperature rise of 6.94 degrees was simulated through CORMIX-1 to find its affects on the surrounding environment.



Elevated seawater temperature related to brine discharge of thermal effluent from MSF desalination plants has shown drastic impacts upon the marine organisms (Morton et al., 1996). From different researches it has been found that the elevated temperature and increased salinity minimizes the overall concentration of dissolved oxygen in the seawater, which might restrict the life forms of the marine organisms.

The other pollutant of interest was total dissolved solids (TDS). The average Persian Gulf seawater TDS (ambient TDS) was reported by Mumtaz and Wagialla (1988), to be 45000 ppm, while the brine discharge from Al-Jubail desalination plant have a concentration of TDS of 70,000 ppm.

All of the above parameters were plugged into the CORMIX-1 to predict the concentration profile for the brine discharge from Al-Jubail desalination plant. The results from these simulations are discussed in the next sections.

## **7.6 Results and Analysis of Elevated Thermal Discharge from Al-Jubail Plant**

The results from CORMIX-1 for the elevated thermal discharge is shown in Appendix-F, which depicts that the thermal plume first rises and then slowly falls back towards the bottom of the sea while spreading sideways in the near field mixing region (NFR). The results also show that the temperature drop in the beginning of the discharge is very sharp till the plume touches the bottom of the sea at 2.77 meters from the point of discharge.

Within this distance the plume has significant mixing, and the centerline dilution is 30 times than at the point of attachment.

As the plume (effluent stream) travels farther along the downstream, the temperature drops gradually, the plume temperature drops almost equal to the ambient seawater temperature at a distance of 101.41 meters from the point of discharge.

The thermal results from CORMIX-1 were compared with the surface water quality standards proposed by U.S. EPA, which stated that there should be no direct heat additions within 1500 feet of the shoreline and no thermal alteration, which would cause temperature to deviate from ambient temperature by more than 2.2 °C (Surface Water Quality Standards, 2002). Also the elevated temperature should not retain in the ambient atmosphere for more than 4 months. The results from CORMIX-1 showed that the brine thermal discharge is within the standards limits. The results shows that in approximately 5 minutes the plume elevated temperature drop down almost equal to the ambient temperature while covering a distance of 101.41 meters along the downstream.

In Figure 7.4, we can assume that the thermal dilution is same for the surface and the bottom of the sea, because of the fact that the discharge area is very shallow. The contour in Figure 7.4 also showed that within a radial distance of 50 meter from the point of discharge the mixing and thermal drop is very fast.

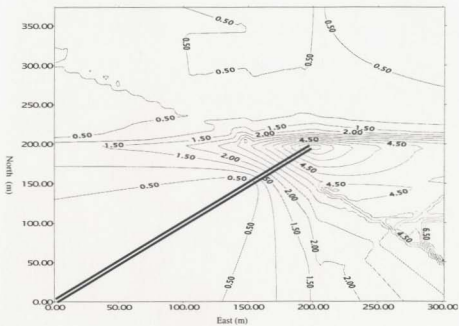
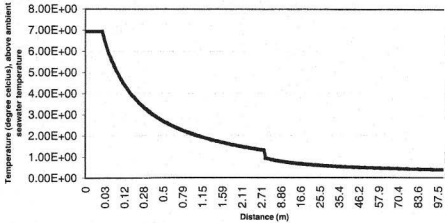


Figure 7.4 Distribution of Elevated Thermal Discharge ( $^{\circ}\text{C}$ ) in The Persian Gulf



**Figure 7.5 Temperature Drop (°C) Versus Downstream Distance**

Figure 7.5 depicts that dilution is the function of distance from the point of discharge. The Concentration plot (Figure 7.5) also showed that the effluent plume attached to the bottom of the sea at approximately 4.91 meter from the point of discharge. Within this distance, as shown in Figure 7.5, the plume has significant mixing and the dilution is rapid. While as the effluent plume travels downstream, it continues with more gradual drop in temperature and in mixing.

From the results of CORMIX-1 and from the above figures, it has been clear that the thermally elevated brine discharge from Al-Jubail desalination plant has got no drastic impacts on the marine environment in the Persian Gulf, as compared to the criteria given by the U.S EPA surface water quality standards.

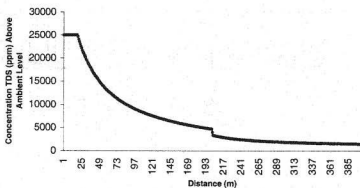
## **7.7 Results and Analysis of Elevated Total Dissolved Solids (TDS) Discharge from Al-Jubail Plant**

The CORMIX-1 results as shown in Appendix-G, were generated for the elevated TDS effluent discharges from AL-Jubail desalination plant. These results were then compared with the U.S. EPA surface water quality standards. According to U.S EPA ocean discharge regulations, lower concentration (i.e. near to zero) of TDS (Salinity) in the seawater or higher concentration (i.e. twice the ocean ambient concentration) of TDS can impact the ocean biota/marine life if exposed to these extreme concentrations for longer time (Del Bene et al., 1994).

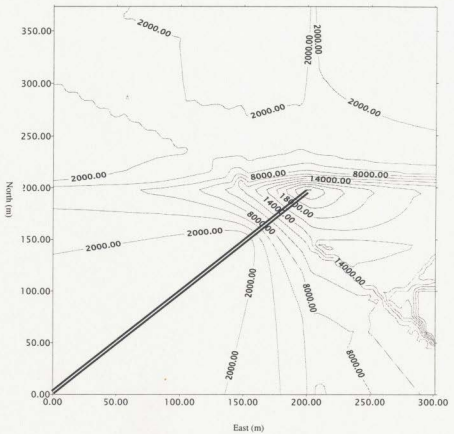
The CORMIX-1 results proved that after discharging the concentrated brine, the plume travels a distance of 3 meters downstream and 31 meters in lateral direction within 3 to 4 seconds, and dilute the higher concentration of TDS to 4700 ppm above the ambient concentration. The CORMIX-1 simulation further shows that the TDS concentration gradually decreases to a concentration of 1370 ppm as the effluent stream travels along the downstream.

Figure 7.6 shows that in the beginning of the brine discharge the mixing and dilution of TDS is fast, till the distance of 217 meter, downstream. After this, the plume travel slowly in the downstream direction and has gradual dilution/mixing in that region. Similarly Figure 7.7 shows TDS concentration distribution in the form of contour lines, it has been concluded from the result and from Figure 7.6 and 7.7, that the TDS

concentration distribution from Al-Jubail desalination plant into the Persian Gulf has got no drastic impact on the benthic/marine environment. The concentrated brine discharge from Al-Jubail desalination plant takes only 5 to 6 minutes to dilute the concentration from 25000 ppm to 1300 ppm above the ambient level. Therefore we can say that the concentrated TDS brine discharge from the Al-Jubail desalination plant is with in the limits as specified by the U.S. EPA surface water standards.



**Figure 7.6 Total Dissolved Solid Versus Downstream Distance**



**Figure 7.7 Distribution of Increased Total Dissolved Solids Concentration in the Persian Gulf as a Result of Brine Discharge from Al-Jubail Desalination Plant**

## Chapter VIII

### Conclusions and Recommendations

#### 8.1 Conclusions

The following conclusion are drawn from this study:

1. AERMOD model was found to be one of the most suitable and reliable for this research to study the short range/near source dispersion behavior of air born pollutants emitted from Al-Jubail Desalination plant.
2. In view of the nature of the fossil fuel used in generating steam for Al-Jubail desalination plant, the most important type of pollutants examined were sulfur dioxide (SO<sub>2</sub>), nitrogen oxide (NO<sub>x</sub>), and particulate matter (PM).
3. The estimated annual average concentration of SO<sub>2</sub> was found mostly within the MEPA specified standard of 80 µg/m<sup>3</sup>. However, there were some points where the concentration exceeded only by 10 µg/m<sup>3</sup> above the MEPA standards.



4. The  $\text{NO}_x$  annual average concentrations were mostly within the limits. However, the 1-hour average  $\text{NO}_x$  concentration was exceeded by less than 1 percent of the total.
5. The daily (maximum  $340 \mu\text{gm}^{-3}$ ) and annual (maximum  $80 \mu\text{gm}^{-3}$ ) average estimates for PM were well within the safe limits of MEPA standards.
6. Among all available hydrodynamic mixing models, CORMIX was found to be the most suitable and user friendly for this study.
7. The results generated by CORMIX1 for the elevated thermal discharge from Al-Jubail desalination plant, shows no exceedence whatsoever as compared to the surface water quality standards specified by the U.S EPA, which states that there should be no direct heat addition within 1500 feet of the shoreline, and no thermal deviation which would cause temperature to deviate from ambient temperature by more than  $2.2^\circ\text{C}$ .
8. The results for the elevated TDS concentration in the brine shows that the dilution in the NFR was reduced to 1300 ppm from 25000 ppm above the ambient level, which is within the criteria standards sets by the U.S. EPA for the surface water, according to which TDS (salinity) concentration in the NFR should not be twice the ocean ambient concentration.

## 8.2 Recommendations

Based on this study the following recommendations are made

1. Emission rates used in the simulation should be validated with actual measurements from Al-Jubail desalination plant.
2. Meteorological and ambient air monitoring stations at the site should be installed and operated.
3. Instead of generating the geographical file manually, DEM files should be created for the site and should be used in the AERMOD model, to get more precise readings at the grid points
4. A detailed physical oceanographic study of the region should be conducted, for effective use of any hydrodynamic mixing model. Daily measurement of brine discharge should be recorded. Also detailed characteristics of brine should be done on periodical basis.
5. Monitoring of seawater quality in the near field region (NFR) of outfall should be done on a regular basis. Such information will help in validating hydrodynamic models results.

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**APPENDIX - A**

## **AERMOD Model Inputs**

The AERMOD model basically requires the run-stream setup file, the meteorological data file, and receptor & terrain data file. The run-stream setup file consists of a variety of data, like modeling options, source location and parameter data, receptor locations, meteorological data file specifications, and output options. The meteorological data is another basic input data file required by the AERMOD. AERMOD requires two types of these meteorological data files, one includes the surface scalar parameters and the other contains the vertical profiles of meteorological data, both these data files can be developed manually or by the AERMET pre-processor. When there are elevated terrain effects involved, the receptor and terrain data are processed by AERMAP and inputted into the AERMOD model.

Basically, AERMOD provides several modeling options, which include dispersion options, source options, receptor options, meteorological options, and output options. Within dispersion options, we have the choice of using stack-tip downwash and can use a routine for processing averages when calm winds or missing meteorological data occur. Furthermore, we have the option of either specifying short-term averages, which can be calculated in a single run of the model or selecting overall period averages.

Source option makes the model capable of handling multiple sources, including point, volume, line, and area source types.

In the Receptor Options, we can specify multiple receptor networks in a single run. Elevated receptor heights can be inputted so that the effects of terrain above (or below) the stack base may be modeled. Elevations may also be specified in order to model flagpole receptors.

For Meteorological Options, AERMOD uses a file of Surface Boundary Layer (.sfc) parameters and a file of Profile (.pfl) variables. The profile variables include wind speed, wind direction, and turbulence parameters. AERMET, the meteorological-preprocessor, generates these files.

Several options are available for the output that is produced by AERMOD. The three basic types of printed output available in AERMOD are:

- (1) Summaries of high values by receptor averaging period and source group combination,
- (2) Summaries of overall maximum values for each averaging period and source group combination, and
- (3) Tables of concurrent values summarized by receptor for each averaging period and source group combination (EPA 1998a).

AERMOD requires a specific run-stream file, which is defined from a keyword/parameter approach. This run-stream has five functional pathways. A two-character ID that is placed at the beginning of each run-stream file defines each pathway.

These pathways are listed below in the order in which they are inputted to the model (EPA 1998a):

- CO – Specifies the job CONTROL options
- SO – Specifies the SOURCE information
- RE – Specifies the REceptor information
- ME – Specifies the METeological information
- OU – Specifies the OUTPUT Options

Each line in the input run-stream file consists of a pathway ID and a parameter list. Many rules should be followed while structuring the run-stream files for AERMOD. For instance, the CO pathway should always come first and is followed by the inputs for the SO pathway. Next, the beginning of each pathway is identified with a **STARTING** keyword and the end of each pathway is identified with a **FINISHED** keyword. All numeric input data are assumed to be in metric units otherwise has to be specified in the model.

If one does not specify keyword options, the AERMOD model will resort to default options. Such default options are listed below (EPA 1998a):

- Use elevated terrain algorithms requiring input of terrain height data
- Use stack-tip downwash
- Use the calms processing routines
- Use the missing data processing routines

- Use upper-bound concentration estimates for sources influenced by building downwash from super-squat buildings
- Use of a 4 hour half life for exponential decay of SO<sub>2</sub> for urban sources

The first run-stream input file for the AERMOD is the CO Pathway, which contains keywords that provide the overall control of the model run. The mandatory keywords for the CO Pathway are **STARTING**, **TITLEONE**, **MODELOPT**, **AVERTIME**, **POLLUTID**, **RUNORNOT**, and **FINISHED**. The **STARTING** keyword simply indicates the beginning of an input pathway. **TITLEONE** is a user-specified title line. **MODELOPT** keyword controls the modeling options that are selected for a model run via a series of secondary words.

In the model the secondary keyword **DFAULT** specifies that the regulatory default options will be used. **CONC** specifies that concentration values will be calculated. **FLAT** indicates the use of non-default option of assuming flat terrain. **NOSTD** indicates that the non-default option of no stack-tip downwash is used. **NOCHKD** indicates that the non-default option of suspending data checking will be used for non-sequential meteorological data files. **NOWARN** indicates that the option of suppressing the detailed list of warning messages in the main output file. Finally, the secondary keyword **SCREEN** indicates that the non-default option for running AERMOD in a screening mode will be used.

**AVERTIME** identifies the averaging periods to be calculated. **POLLUTID** identifies the type of pollutant that is to be modeled. **RUNORNOT** is a very useful keyword that instructs the model to either run the model executions or not. If the user chooses not, the run-stream setup file will be processed and the input errors are reported, but the dispersion calculations will not be carried out. **FINISHED**, the final mandatory keyword for the CO Pathway indicates that the user is finished with these inputs.

The second pathway in the input run-stream file is the **SO** Pathway, which contains keywords that define the source information for a particular model run. The **STARTING** and **FINISHED** keywords are mandatory for all five pathways. The other mandatory keywords for this pathway include **LOCATION**, **SCRPARAM**, and **SRCGROUP**. The **LOCATION** keyword identifies a particular source ID. Each individual source requires its own ID. It specifies the source type (one of the three source types point, volume, or area) and the location of that source. **SCRPARAM** specifies the source parameters for the source ID selected in the previous **LOCATION** command. **SRCGROUP** simply specifies the way in which the sources are grouped for calculation purposes. The **SO** Pathway offers some optional keywords. When a source is influenced by nearby buildings, it would be beneficial to include the optional keywords **BUILDHGT** and **BUILDWID**, as building dimensions will affect downwash effects.

The third pathway in the input run-stream file, the **RE** Pathway, contains keywords that define the receptor information. Within the **RE** Pathway, the user can specify either a

polar receptor network or a Cartesian grid receptor network. After selecting one of these we can then identify the receptor locations within the network, and the boundary around a particular source. All of the receptor data are preprocessed by AERMAP in order to obtain receptor elevations and terrain height scales. This data is included in the AERMAP.OUT file or can be entered manually by taking the elevation points of the site from the site contour maps.

For AERMOD one has to define a modeling domain, which is the area that contains the receptors that are being modeled. It is also the geographic area in which the effect of terrain is considered. The user can specify this area in either the UTM or the longitude/latitude coordinate system. The receptors are specified in AERMAP in the same way that they are specified in AERMOD. Users can identify discrete receptors and either Cartesian or polar grid networks.

The fourth pathway in the input run-stream file, the **ME** Pathway, contains the keywords that define the input meteorological data for a particular model run. The ME Pathway has several mandatory keywords including **SURFILE**, **PROFILE**, **SURFDATA**, **UAIRDATA**, and **PROFBASE**. Of course, the **STARTING** and **FINISHED** keywords are used as well.

The **SURFFILE** specifies the filename and the format for the input surface meteorological data file. This surface data file is generated by the AERMET



preprocessor. This file contains an abundance of data that is necessary for the efficient prediction of the dispersion of pollutants. The data included in the **SURFILE** are: year, month, day, Julian day, hour, sensible heat flux, surface friction velocity, convective velocity scale, vertical potential gradient, height of the convectively-generated boundary layer, height of the mechanically-generated boundary layer, Monin-Obukhov length, surface roughness length, Bowen ratio, albedo, wind speed, wind direction, height at which wind was measured, temperature used in computations, and height at which the temperature was measured.

The **PROFILE** specifies the filename and format for the meteorological data file. Like the surface file, the profile file data are generated by the AERMET preprocessor. This file consists of one or more records for each hour of data. Contents include year, month, day, hour, measurement height, top flag (=1 or =0), wind direction, wind speed, temperature at current level, standard deviation of the wind direction, and standard deviation of the vertical wind speed.

AERMET, which generates the profile and surface files, is designed to run as a 3-stage process and operate on three types of data. These three types of data are National Weather Service (NWS) hourly surface observations, NWS twice-daily upper air soundings, and data collected from an on-site measurement program (EPA 1998b). The three stages are apparent in Figure-A.

In the first stage of AERMET, the data is extracted and quality assessment (QA) of the data has been performed. The second stage merges all these data into 24-hour period and writes it to an intermediate file. The third and final stage reads the merged data file and develops the necessary boundary layer parameters for dispersion calculations by AERMOD. The last two output files from stage-3 will contain all the necessary meteorological data required by the AERMOD to perform dispersion analysis.

There will be no processing header records in these files, but there will be a single record at the beginning of the file with the boundary layer parameters that will identify the site, which is used in the processing.

The surface parameters provided by AERMET are the Monin-Obukhov Length ( $L$ ), surface friction velocity ( $u_*$ ), surface roughness length ( $z_0$ ), surface heat flux ( $H$ ), and the convective scaling velocity ( $w_*$ ). AERMET also provides estimates for the convective and mechanical mixing layer heights,  $z_{ic}$  and  $z_{im}$ . Although AERMOD is capable of estimating meteorological profiles with data from as little as one measurement height, it will use as much data as the user can provide for defining the vertical structure of the boundary layer. In addition to PBL parameters, AERMET passes all measurements of wind, temperature, and turbulence in a form compatible to AERMOD.

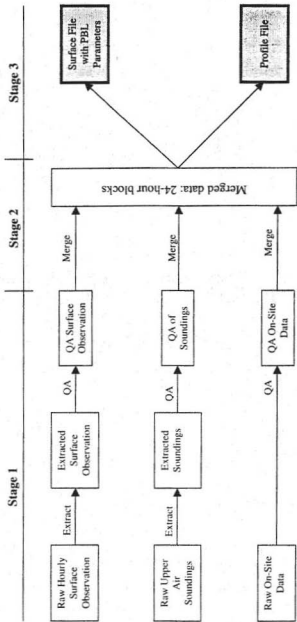


Figure-A1 Schematics Showing AERMET Three Stage Processing (EPA 1998b)

## **APPENDIX – B**

### Sample AERMOD run-stream file

- \*\* AERMOD Model is Run to Estimate The Ambient Concentrations
- \*\* of SO<sub>2</sub> as a Result of Al-Jubail Desalination Plant Emissions
- \*\* Located at Al-Jubail City in The Kingdom of Saudi Arabia

CO STARTING

TITLEONE

MODELOPT DFAULT CONC

AVERTIME 1 24 PERIOD

POLLUTID SO2

RUNORNOT RUN

CO FINISHED

SO STARTING

- \*\* As Default option is selected therefore effects of elevated terrain are
  - \*\* included, so it is important to specify the source base elevation above
  - \*\* mean sea level on the LOCATION card. Here in this example it is 24.0m (MSL)
- LOCATION STACK1 POINT 0.0 0.0 24.0
- \*\* POINT SOURCE QS(g/s) HS(m) TS(K) VS(m/s) DS(m)
  - \*\* Parameters -- -- -- -- --
- SRCPARAM STACK1 30833.0 65.0 440.0 12.0 1.5
- BUILDHGT STACK1 36\*24

BUILDWID STACK1 35.0 36.2 33.2 35.4 32.6 38.3 34.2 33.0  
 STACK1 25.6 26.3 24.3 28.9 33.5 23.6 33.9 35.6  
 STACK1 22.3 23.4 26.3 24.9 29.8 31.8 33.3 34.9  
 STACK1 15.3 16.4 18.9 16.8 29.4 28.6 33.5 34.6  
 STACK1 36.5 35.2 23.9 35.9

SRCGROUP ALL  
 SO FINISHED

RE STARTING  
 RE ELEVUNIT FEET  
 RE GRIDCART CG1 STA

XYINC -50000. 21 5000. -50000. 21 5000.  
 RE GRIDCART CG1 ELEV 1 276. 276. 318. 318. 220. 220. 220. 171. 171. 145. 112. 112. 108. 112. 112. 112. 115. 115. 115. 00. 00.  
 RE GRIDCART CG1 ELEV 2 276. 276. 318. 318. 220. 220. 220. 171. 145. 108. 112. 112. 106. 112. 112. 115. 115. 00. 00. 00. 315.  
 RE GRIDCART CG1 ELEV 3 338. 276. 220. 220. 210. 171. 171. 145. 145. 145. 145. 145. 108. 112. 108. 115. 108. 00. 00. 00. 325.  
 RE GRIDCART CG1 ELEV 4 276. 220. 220. 220. 218. 171. 171. 145. 108. 145. 145. 118. 142. 108. 108. 69. 108. 00. 235. 235. 00.  
 RE GRIDCART CG1 ELEV 5 250. 220. 220. 220. 201. 171. 171. 142. 142. 118. 145. 108. 125. 380. 115. 69. 115. 115. 00. 00. 00.  
 RE GRIDCART CG1 ELEV 6 220. 220. 203. 203. 203. 171. 165. 142. 142. 125. 125. 108. 118. 118. 115. 75. 230. 00. 00. 00. 00.  
 RE GRIDCART CG1 ELEV 7 220. 220. 215. 203. 203. 164. 164. 164. 142. 142. 118. 118. 125. 118. 69. 225. 225. 00. 00. 00. 00.  
 RE GRIDCART CG1 ELEV 8 220. 203. 203. 203. 203. 174. 164. 164. 164. 164. 110. 118. 125. 300. 220. 00. 00. 00. 00. 00. 00.  
 RE GRIDCART CG1 ELEV 9 190. 203. 203. 203. 203. 164. 164. 164. 164. 164. 306. 120. 69. 00. 00. 00. 00. 00. 00. 00. 00.  
 RE GRIDCART CG1 ELEV 10 190. 190. 135. 135. 135. 210. 164. 118. 76. 76. 76. 76. 00. 00. 00. 00. 00. 00. 00. 00. 00.  
 RE GRIDCART CG1 ELEV 11 190. 190. 135. 135. 135. 135. 135. 210. 76. 76. 76. 00. 00. 00. 00. 00. 00. 00. 00. 00. 00.  
 RE GRIDCART CG1 ELEV 12 190. 190. 135. 135. 135. 135. 118. 76. 76. 76. 00. 00. 00. 00. 00. 00. 00. 00. 00. 00.  
 RE GRIDCART CG1 ELEV 13 200. 170. 135. 76. 76. 66. 60. 79. 225. 00. 00. 00. 00. 00. 00. 00. 00. 00. 00. 00.  
 RE GRIDCART CG1 ELEV 14 200. 112. 118. 120. 66. 66. 66. 79. 00. 00. 00. 00. 00. 00. 00. 00. 00. 00. 00. 00.  
 RE GRIDCART CG1 ELEV 15 200. 112. 112. 110. 110. 66. 00. 79. 00. 00. 00. 00. 00. 00. 00. 00. 00. 00. 00. 00.



ME STARTING

SURFFILE ann1.SFC

PROFFILE ann1.PFL

SURFDATA 12345 1995 Jubail,KSA

UAIRDATA 12345 1995 Jubail,KSA

DAYRANGE 1-366

\*\*PROFBASE is used to specify the base elev. (AMSL) for potential temp.

\*\* profile generated by AERMOD for use in plume rise calculation.

\*\* this should correspond to the base elev. for main met. tower, which in this

\*\* example is 24 m and is same as the source base elevation.

PROFBASE 24 METERS

ME FINISHED

OU STARTING

OU RECTABLE ALLAVE FIRST SECOND

OU MAXTABLE ALLAVE 20

OU FINISHED



## **APPENDIX – C**

# 1-Hour Average Concentration Values of SO<sub>2</sub> for the Year 1995

\*\*\* THE 1ST HIGHEST 1-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP 1, ALL \*\*\*  
 INCLUDING SOURCE(S) STACK, RPFAULT  
 \*\*\* NETWORK ID: C01 NETWORK TYPE: ORDCANT \*\*\*  
 \*\* CONC OF SO<sub>2</sub> IN MICROGRAMS/M<sup>3</sup> \*\*

Y. COORD (METERS)	-50000.00	-45000.00	-40000.00	-35000.00	-30000.00
50000.0	329.83690 (95060301)	503.43950 (95060301)	942.56840 (95102823)	749.70410 (95068152)	168.28130 (95080322)
45000.0	352.73730 (95032115)	194.64260 (95060301)	728.99800 (95060301)	728.35550 (95102823)	730.76560 (95030903)
40000.0	20.32810 (95011705)	181.36270 (95032115)	646.36620 (95060301)	439.42770 (95060301)	376.46090 (95081522)
35000.0	851.12890 (95011705)	216.26170 (95011705)	159.84470 (95012115)	216.32810 (95060301)	721.00980 (95060301)
30000.0	726.19530 (95072723)	835.50000 (95011705)	612.22270 (95011705)	369.55470 (95011705)	221.25780 (95060301)
25000.0	942.31250 (95072723)	561.14450 (95072723)	876.55860 (95011705)	480.24610 (95011705)	385.49220 (95011705)
20000.0	72.01560 (95072924)	673.24610 (95070421)	255.50590 (95072723)	656.79100 (95072723)	163.89060 (95011705)
15000.0	250.69260 (95072521)	722.19510 (95013021)	703.02710 (95033023)	468.68750 (95072924)	726.94730 (95072723)
10000.0	726.64060 (95072521)	200.09380 (95072521)	620.95700 (95072521)	177.11910 (95072521)	291.25780 (95033023)
5000.0	411.55470 (95072521)	744.64450 (95072521)	629.34380 (95072521)	781.17970 (95072521)	444.46090 (95072521)
0.0	650.79520 (95081906)	768.94570 (981826)	827.60350 (9512521)	736.46090 (95072521)	428.00200 (95072521)
-5000.0	650.79520 (95081906)	768.94570 (981826)	827.60350 (9512521)	736.46090 (95072521)	428.00200 (95072521)
-10000.0	137.91360 (95032524)	239.57420 (95032524)	200.54490 (95032524)	510.09960 (95032524)	52.83980 (95032524)
-15000.0	639.66800 (95032524)	650.78910 (95032524)	483.26760 (95032524)	651.98050 (95112219)	38.63980 (95041418)
-20000.0	642.48440 (95112219)	239.89460 (95112219)	344.91410 (95041418)	503.79300 (95090520)	172.25980 (95090520)
-25000.0	659.67770 (95041418)	644.88610 (95090520)	637.37500 (95092520)	368.43210 (95092520)	464.73240 (95072519)
-30000.0	625.80860 (95090520)	198.68160 (95090520)	660.37500 (95092520)	269.80370 (95072519)	28.10160 (95072519)
-35000.0	313.57420 (95092520)	46.83010 (95092520)	788.89450 (95072519)	640.96290 (95032423)	52.19340 (95073020)
-40000.0	505.18550 (95090520)	310.37700 (95072519)	273.25190 (95032423)	707.82190 (95073020)	22.22160 (95120223)
-45000.0	98.57030 (95072519)	134.63870 (95032422)	724.40630 (95073020)	100.61520 (95073020)	139.75000 (95051719)
-50000.0	223.82230 (95032422)	906.68180 (95073020)	470.65920 (95073020)	864.69531 (95051719)	857.12890 (95080319)

\*\*\* THE 187 HIGHEST 1-IN AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(B) STACK1

\*\*\* NETWORK ID: C01; NETWORK TYPE: GRIDCART \*\*\*

\*\*\* CONC OF SO2 IN MICROGRAMS/M\*\*3 \*\*\*

Y-COORD (METERS)	X-COORD (METERS)									
	-25000.00	-20000.00	-15000.00	-10000.00	-5000.00	0.00	5000.00	10000.00	15000.00	20000.00
50000.0	347.86720	950803221	284.76560	950803222	225.80080	950606624	217.72270	950523241	216.19920	950626231
45000.0	328.20310	950803221	362.89840	950803222	213.33590	950101919	249.06840	950521241	226.96480	950626231
40000.0	253.66410	950803221	406.18750	950803222	300.94140	950803222	264.63280	950521241	236.93730	950626231
35000.0	150.01930	950803221	408.88750	950803222	408.88750	950803222	300.92460	950803221	265.36330	950523241
30000.0	218.01930	950803221	252.71880	950803222	499.04590	950803222	406.23050	950803221	365.39090	950523241
25000.0	302.51710	950603011	177.86720	951028231	437.49220	950803222	496.23050	950803221	365.39090	950523241
20000.0	302.51710	950117051	256.34380	950603011	241.92580	950815221	654.13280	950803221	432.38670	950523241
15000.0	312.47460	950117051	425.68750	950603011	314.73630	950603011	509.41220	950803221	581.41410	950803221
10000.0	296.14060	950130231	383.17190	950727231	549.67580	950117051	410.27340	950603011	104.91800	950803221
5000.0	519.82030	950725211	553.20310	950725211	500.39450	950725211	619.79690	950727231	682.26560	950603011
0.0	275.18550	950725211	348.01560	950725211	520.60940	950725211	654.76170	950725211	119.57800	950725211
-5000.0	375.91800	950325241	409.65630	950325241	468.71090	950325241	531.61330	950112219	708.29690	950925201
-10000.0	339.34380	951122191	287.19140	951122191	465.29690	950925201	461.19530	950725191	468.55470	950803191
-15000.0	275.98600	950925201	416.10940	950925201	323.40630	950925201	279.81540	951202231	611.10940	950323011
-20000.0	336.53910	950925201	249.81450	950725191	244.19140	951202231	259.85350	950803191	411.05470	950323011
-25000.0	204.58200	950725191	398.29100	951202231	201.42190	950521719	337.73440	950123011	297.23830	950923219
-30000.0	160.40430	951202231	163.14260	950517191	319.62890	950803191	377.21880	950323011	267.34770	950923219
-35000.0	182.02270	951202231	166.29860	950803191	218.49800	950323021	319.50310	950323011	229.07730	950923219
-40000.0	204.25940	950803191	185.14060	950803191	246.88030	950323011	318.32200	950323011	171.24190	950423001
-45000.0	204.25940	950803191	185.14060	950803191	246.88030	950323011	318.32200	950323011	171.24190	950423001
-50000.0	218.93360	950803191	187.88090	950323021	258.96680	950323011	183.56050	950923219	165.50590	950423001

\* THE 1ST HIGHEST 1-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S) ATTACH  
 \*\*\* NETWORK ID: C01 NETWORK TYPE: GRIDCONT \*\*\*  
 \*\* CONC OF SO2 IN MICROGRAMS/M\*\* \*\*

Y-COORD (METERS)	X-COORD (METERS)				
	0.00	5000.00	10000.00	15000.00	20000.00
50000.0	185.85530 (950626231)	149.10160 (950404021)	179.82030 (950681921)	157.35640 (950529011)	173.96880 (950202051)
45000.0	202.76560 (950626231)	164.69340 (950404021)	193.35940 (950681921)	192.01560 (950202051)	190.43360 (950202051)
40000.0	222.05860 (950626231)	179.47460 (950404021)	202.94140 (950681921)	215.76950 (950202051)	228.33200 (950404021)
35000.0	247.52340 (950626231)	207.95700 (950681921)	201.50590 (950681921)	221.99020 (950682821)	292.61130 (950707221)
30000.0	279.96880 (950626231)	247.36910 (950681921)	258.86670 (950202051)	281.86210 (950682821)	476.13670 (950707221)
25000.0	341.27330 (950626231)	322.52160 (950681921)	377.61930 (950202051)	408.81830 (950707221)	575.95000 (950707221)
20000.0	414.84380 (950626231)	432.42650 (950681921)	509.28130 (950707221)	707.82180 (950707221)	472.69940 (950707221)
15000.0	640.94920 (950626231)	765.52340 (950707221)	854.07030 (950707221)	607.36130 (950707221)	304.92970 (950410051)
10000.0	105.11700 (950626231)	488.96900 (950707221)	564.92580 (950413031)	266.25000 (950430051)	313.06840 (950413031)
0.0	0.00000 (000000001)	578.23440 (951210061)	351.56250 (951210061)	535.05080 (950413031)	354.56250 (950413031)
-5000.0	119.29700 (950706211)	108.04700 (950506011)	546.54690 (950681721)	262.75980 (951210061)	212.89840 (951210061)
-10000.0	750.09360 (950429031)	553.88280 (950614221)	682.48440 (950506011)	716.30470 (950681721)	322.76170 (950681721)
-15000.0	493.44530 (950429031)	435.16410 (950818221)	405.73440 (950997021)	286.90040 (950604221)	254.98440 (950681721)
-20000.0	404.63280 (950429031)	552.06250 (950818221)	323.37890 (95101721)	507.35160 (950506011)	228.72660 (950202061)
-25000.0	346.89550 (950429031)	548.26560 (950818221)	239.29100 (95051321)	319.77340 (950820201)	424.61720 (950506011)
-30000.0	305.11330 (950429031)	493.57270 (950818221)	211.31640 (950505241)	273.21480 (950614221)	239.35350 (950820201)
-35000.0	274.32230 (950429031)	424.39450 (950818221)	272.87890 (950818221)	214.44530 (95101721)	248.81050 (950907201)
-40000.0	250.83980 (950429031)	379.47660 (950706211)	318.51560 (950818221)	178.03320 (950905241)	195.71090 (950614221)
-45000.0	230.50200 (950429031)	329.00000 (950706211)	337.96880 (950818221)	158.13910 (950905241)	192.27930 (95101721)
-50000.0	214.55470 (950429031)	292.96480 (950706211)	337.28520 (950818221)	169.36050 (950313112)	141.62010 (950905241)

\*\*\* THE 1ST HIGHEST 1-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S): STACK1  
 \*\*\* NETWORK ID: COL; NETWORK TYPE: GRIDCAT \*\*\*  
 \*\* CONC OF SO2 IN MICROGRAMS/M\*\*3 \*\*

Y-COORD (METERS)	25000.00	30000.00	35000.00	40000.00	45000.00
50000.0	194.17190 (950404231)	236.80270 (950707223)	343.09380 (950707223)	362.07420 (950707223)	295.95120 (950707223)
45000.0	211.36330 (950404231)	143.11720 (950707223)	195.10940 (950707223)	332.62110 (950707223)	217.23440 (950707223)
40000.0	329.21090 (950707223)	429.59380 (950707223)	378.28130 (950707223)	244.63670 (950707223)	161.51370 (950409064)
35000.0	459.46090 (950707223)	434.42580 (950707223)	279.43950 (950707223)	175.55860 (950409064)	181.86330 (950410054)
30000.0	504.08980 (950707223)	324.15630 (950707223)	203.26950 (950410054)	180.80470 (950410054)	103.82810 (950410066)
25000.0	385.42570 (950707223)	240.44530 (950430051)	166.59140 (950430051)	98.89648 (950408222)	135.22070 (950402055)
20000.0	279.28130 (950430051)	144.79980 (950430061)	150.33400 (950402055)	186.49610 (950402055)	205.84380 (950413033)
15000.0	164.09180 (950402055)	228.76950 (950402055)	266.93950 (950413033)	271.24220 (950413033)	246.63670 (950413033)
10000.0	365.85940 (950413033)	328.53910 (950413033)	259.59770 (950413033)	192.78910 (950413033)	138.88870 (950413033)
5000.0	216.77340 (950413033)	161.21000 (950909031)	126.58980 (950909031)	102.19730 (951009055)	95.96191 (951009055)
0.0	180.61720 (951210066)	157.72070 (951210066)	140.31840 (951210066)	127.34770 (951210066)	116.88280 (951210066)
-5000.0	261.16800 (950511221)	216.45120 (950511221)	175.08400 (950511221)	147.00980 (951017233)	129.28420 (951017233)
-10000.0	480.42970 (950817221)	435.64840 (950817221)	371.23440 (950817221)	178.35160 (950511221)	172.65630 (950511221)
-15000.0	200.43750 (950604221)	352.25390 (950817221)	309.37700 (950817221)	371.30470 (950817221)	323.00590 (950817221)
-20000.0	513.84280 (950817221)	187.29380 (950604221)	151.10940 (950604221)	106.70800 (950604221)	208.68750 (950817221)
-25000.0	183.84280 (950817221)	194.36870 (950817221)	194.36870 (950817221)	141.53320 (950305056)	134.48990 (950604221)
-30000.0	180.63870 (950820201)	315.63670 (950506031)	268.47460 (950506031)	189.73050 (950817221)	132.00980 (951211201)
-35000.0	226.44920 (950907201)	166.00000 (950506031)	171.88480 (950506031)	171.88480 (950506031)	185.45500 (950817221)
-40000.0	213.79100 (951212221)	186.51950 (950820201)	167.56250 (950820201)	171.38090 (950506031)	242.10550 (950506031)
-45000.0	218.45700 (950614221)	186.07810 (950707201)	167.56250 (950707201)	171.38090 (950506031)	168.61910 (950506031)
-50000.0	165.56640 (951017231)	197.26950 (951212221)	176.72270 (950307201)	138.76950 (950820201)	168.61910 (950506031)

\*\*\* THE 1ST HIGHEST 1-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL\*\*\*  
 INCLUDING SOURCE(S): STACK1  
 \*\*\* NETWORK ID: C01; NETWORK TYPE: GRIDCAPT \*\*\*  
 \*\* CONC OF S02 IN MICROGRAMS/M\*\*3 \*\*

Y COORD (METERS)	X COORD (METERS)
50000.0	184.52730 (95070722)
45000.0	149.17580 (95040061)
40000.0	173.80470 (95043006)
35000.0	107.20310 (95043006)
30000.0	88.00391 (95040822)
25000.0	159.26460 (95040205)
20000.0	222.91990 (95041303)
15000.0	207.74020 (95041303)
10000.0	121.75980 (95009903)
5000.0	89.43945 (95100905)
0.0	107.87500 (95121006)
-5000.0	113.73240 (95101723)
-10000.0	160.34180 (95051121)
-15000.0	229.47850 (95008172)
-20000.0	287.87890 (95008172)
-25000.0	96.42578 (95060422)
-30000.0	119.45960 (95060422)
-35000.0	119.45960 (95060422)
-40000.0	133.64360 (95121101)
-45000.0	174.00200 (95008172)
-50000.0	225.10470 (95050603)

### Daily Average Concentration Values of SO<sub>2</sub> for the Year 1995

\*\*\* THIS LEFT HIGHEST 24-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S) 1  
 \*\*\* NETWORK OF POINTS IN MICROGRAMS/M\*\*3 \*\*\*  
 \*\*\* CONC OF SO<sub>2</sub> IN MICROGRAMS/M\*\*3 \*\*\*  
 \*\*\* MODELING OPTIONS USED: CONC ELEV DEFAULT  
 \*\*\* NETWORK OF POINTS IN MICROGRAMS/M\*\*3 \*\*\*  
 INCLUDING SOURCE(S) 1  
 \*\*\* CONC OF SO<sub>2</sub> IN MICROGRAMS/M\*\*3 \*\*\*

Y COORD (METERS)	-50000.00	-45000.00	-40000.00	-35000.00	-30000.00
50000.0	259.51367 (95040424)	273.37256 (95040424)	304.77692 (95040424)	341.87708 (95020124)	115.07642 (95020124)
45000.0	278.35345 (95020124)	210.54144 (95040424)	342.83203 (95040424)	269.14520 (95040424)	125.71704 (95020124)
40000.0	290.13458 (95020124)	265.75555 (95020124)	306.97021 (95040424)	271.47821 (95040424)	109.27087 (95020124)
35000.0	107.79089m(95011724)	285.91205m(95011724)	354.00293 (95020124)	210.87924 (95040424)	111.17065 (95040424)
30000.0	113.44604 (95072724)	111.30103m(95011724)	119.04814m(95011724)	103.39539 (95020124)	104.70020 (95040424)
25000.0	226.75883 (95072724)	154.68103 (95072724)	147.23349 (95072724)	140.04040m(95011724)	122.42810 (95020124)
20000.0	226.75883 (95072724)	147.23349 (95072724)	147.23349 (95072724)	140.04040m(95011724)	122.42810 (95020124)
15000.0	134.65589 (95072524)	106.33984m(95011024)	113.45106m(95011024)	119.53137 (95070424)	191.46986 (95072724)
10000.0	216.6431 (95072524)	220.46411 (95072524)	206.85962 (95072524)	187.16028 (95072524)	157.63953 (95072524)
5000.0	156.34416 (95072524)	183.71680 (95072524)	199.17572 (95072524)	235.96509 (95072524)	278.80762 (95072524)
0.0	229.74811 (95081224)	298.37909 (95081224)	282.15411 (95081224)	108.13464 (95081224)	121.91701 (95081224)
-5000.0	295.57446 (95111924)	298.14532 (95111924)	263.57184m(95032524)	104.55920m(95032524)	127.91565m(95032524)
-10000.0	283.55975 (95111924)	298.12030m(95032524)	111.51941m(95032524)	121.24536m(95032524)	122.13623m(95032524)
-15000.0	214.60590m(95032524)	200.46631m(95032524)	197.69708 (95112224)	107.62573 (95112224)	137.30957m(95041424)
-20000.0	288.42097 (95112224)	245.76678 (95112224)	106.41675m(95041424)	135.52649m(95041424)	182.45740 (95092524)
-25000.0	278.80510m(95041424)	286.86621m(95041424)	331.62671 (95092524)	177.06458 (95092524)	161.09314 (95092524)
-30000.0	244.80548m(95041424)	235.35364 (95092524)	161.23535 (95092524)	134.74011 (95072524)	351.06641 (95072524)
-35000.0	386.76270 (95092524)	318.90491 (95092524)	110.02490 (95072524)	308.43488 (95072524)	350.60350m(95042724)
-40000.0	333.92773 (95092524)	348.75159 (95072524)	302.38086 (95072524)	366.81566m(95042724)	330.79602 (95120224)
-45000.0	340.84424 (95072524)	329.03870 (95072524)	317.41223 (95073024)	332.66498m(95042724)	380.12506 (95091624)
-50000.0	360.03760 (95072524)	379.94199 (95073024)	201.51434m(95042724)	273.04715m(95042724)	340.72479 (95091624)

\*\*\* THE 1ST HIGHEST 34-IBZ AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S) STACKS  
 \*\*\* NETWORK ID, CUI / NETWORK TYPE: GRIDCART \*\*\*  
 \*\* CONC OF SO2 IN MICROGRAMS/M\*\*3 \*\*

Y COORD (METERS)	X COORD (METERS)			-5000.00
	25000.00	-20000.00	-10000.00	
50000.0	246.56234 (95080324)	277.06262 (95080324)	93.21387 (95060624)	90.19366 (95062624)
40000.0	241.79305 (95030124)	276.28210 (95080124)	239.03748 (95080324)	94.68841 (95062624)
35000.0	236.41409 (95030124)	275.35059 (95080124)	284.21619 (95080324)	101.41162 (95062624)
30000.0	228.60095 (95040424)	275.47131 (95020124)	210.46509 (95080324)	110.51514 (95052324)
25000.0	223.24573 (95040424)	250.09387 (95040424)	266.47925 (95020124)	150.30408 (95052324)
20000.0	252.52515m(95011724)	251.13428 (95040424)	206.23901 (95020124)	180.01648 (95052324)
15000.0	226.22314 (95072724)	205.52197m(95011724)	196.97656 (95040424)	276.18848 (95080324)
10000.0	151.23423m(95013024)	266.91870 (95072724)	275.64087 (95072724)	456.31982 (95020124)
5000.0	320.95288 (95072524)	346.36108 (95072524)	309.19019 (95072524)	538.87061 (95020124)
0.0	142.56628m(95032524)	182.23059m(95032524)	252.02515 (95072524)	743.10303m(95032524)
-5000.0	155.55432m(95032524)	188.71143m(95032524)	209.80664m(95032524)	444.10205 (95080324)
-10000.0	141.78430 (95112224)	190.78133m(95041424)	309.11548 (95092524)	366.71484 (95080324)
-15000.0	177.02299m(95041424)	303.56274 (95092524)	184.88147 (95072524)	267.35278 (95072524)
-20000.0	207.81421 (95092524)	141.00085 (95072524)	107.41589m(95042724)	201.14439 (95080324)
-25000.0	174.80962 (95072524)	89.41813m(95042724)	107.96279 (95080324)	277.23467 (95032324)
-30000.0	159.35368 (95120224)	101.51782 (95080124)	226.95370 (95032324)	176.34560 (95032324)
-35000.0	63.35368 (95120224)	101.51782 (95080124)	173.92619 (95032324)	176.91658m(95042924)
-40000.0	81.47882 (95091624)	128.96155 (95080124)	209.28589 (95032324)	159.15674m(95042924)
-45000.0	107.41711 (95080124)	156.46582 (95080124)	207.00220 (95032324)	145.42578m(95042924)
-50000.0	134.96130 (95080324)	155.44287 (95032324)	179.10876 (95032324)	135.31606m(95042924)



\*\*\* THE 1ST HIGHEST 24-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S): STACK1  
 \*\*\* NETWORK ID: CGL J NETWORK TYPE: GRIDCART \*\*\*  
 \*\*\* CONC OF SO2 IN MICROGRAMS/H\*\*3 \*\*\*

Y-COORD (METERS)	X-COORD (METERS)					
	0.00	5000.00	10000.00	15000.00	20000.00	
50000.0	78.72510 (95010824)	108.17690 (95081924)	118.36983 (95081924)	97.92578 (95081924)	128.36023m(95011024)	
45000.0	85.13055 (95110024)	124.20398 (95081924)	123.69263 (95081924)	116.76024m(95011024)	146.04109m(95011024)	
40000.0	96.95752 (95110024)	142.45410 (95081924)	129.51270 (95081924)	147.43718m(95011024)	155.19825m(95011024)	
35000.0	109.92286 (95110024)	163.22959 (95081924)	138.89995 (95081924)	178.60889m(95011024)	143.95459m(95011024)	
30000.0	126.32202 (95110024)	185.05164 (95081924)	168.89925m(95011024)	195.56545m(95011024)	200.49426 (95070724)	
25000.0	150.49512 (95110024)	209.42993 (95081924)	227.05448m(95011024)	291.06946 (95070724)	254.83203 (95070724)	
20000.0	185.08362 (95110024)	238.50317 (95081924)	269.44312m(95011024)	299.12769 (95070724)	249.79004 (95102924)	
15000.0	241.69043 (95110024)	310.30786m(95011024)	342.47266 (95070724)	314.37817 (95102924)	325.65214m(95043024)	
10000.0	348.87524 (95110024)	458.60986m(95011024)	434.98535 (95102924)	345.44922m(95043024)	204.51257 (95101824)	
5000.0	623.94578 (95110024)	746.37891 (95102924)	344.35669 (95101824)	244.93896m(95043024)	185.93750 (95101824)	
0.0	0.00000 (00000000)	741.30908 (95121024)	413.57764 (95121024)	291.51367 (95121024)	226.19922 (95121024)	
-5000.0	780.66899m(95042924)	491.59375 (95050624)	242.47241 (95081724)	300.34790 (95081724)	145.48840m(95013024)	
-10000.0	502.94678m(95042924)	586.95703 (95061424)	305.93431 (95050624)	159.40915 (95060624)	113.65173 (95060424)	
-15000.0	311.57129m(95042924)	282.32654 (95120824)	378.97437 (95061424)	231.14251 (95050624)	170.84216 (95123124)	
-20000.0	191.58170m(95042924)	235.45801 (95081824)	307.97664 (95120824)	308.89722 (95061424)	106.82507 (95082924)	
-25000.0	221.58170m(95042924)	235.45801 (95081824)	307.97664 (95120824)	308.89722 (95061424)	106.82507 (95082924)	
-30000.0	169.32151m(95042924)	185.10876 (95081824)	171.20313 (95050524)	208.94195 (95061424)	214.40259 (95061424)	
-35000.0	152.17744m(95042924)	161.83936 (95081824)	163.21132 (95050524)	139.58142 (95061424)	248.50072 (95061424)	
-40000.0	138.69019m(95042924)	138.96088 (95081824)	148.16248 (95050524)	118.70764 (95050524)	194.52002 (95061424)	
-45000.0	128.02075m(95042924)	123.51076 (95070624)	147.32214 (95081824)	122.95129 (95050524)	122.90759 (95061424)	
-50000.0				119.43213 (95050524)	88.18164 (95120824)	

\*\*\* THE 1ST HIGHEST 24-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S) STACKS NETWORK OPERATING AT OCCASANT \*\*\*  
 \*\*\* NETWORK ID: 001 NETWORK TYPE: OCCASANT \*\*\*  
 \*\* CONC OF SO2 IN MICROGRAMS/M\*\* \*\*

Y COORD (METERS)	25000.00	30000.00	X-COORD (METERS)	35000.00	40000.00	45000.00
50000.0	129.06999m(95011024)	98.13007 (95070724)	144.56482 (95070724)	155.28625 (95070724)	129.95032 (95070724)	
45000.0	121.48389m(95011024)	144.04895 (95070724)	168.91699 (95070724)	145.58777 (95070724)	133.64107 (95102924)	
40000.0	137.39075 (95070724)	182.20984 (95070724)	165.35803 (95070724)	148.26563 (95102924)	143.00771m(95043024)	
35000.0	194.97229 (95070724)	188.49304 (95070724)	167.78748 (95102924)	167.29814m(95043024)	179.10901m(95043024)	
30000.0	218.16187 (95070724)	187.84583 (95102924)	198.0305m(95043024)	130.37903m(95043024)	129.82227m(95043024)	
25000.0	211.81148 (95102924)	235.20923m(95043024)	195.9952m(95043024)	116.914055m(95043024)	110.62385 (95101824)	
20000.0	280.12049m(95043024)	188.98643m(95043024)	130.38936 (95101824)	125.58027 (95043024)	116.28072m(95043024)	
15000.0	168.12049m(95043024)	148.30115m(95043024)	116.26093m(95043024)	103.50098 (95043024)	91.54030 (95101824)	
10000.0	168.01782m(95043024)	148.30115m(95043024)	116.26093m(95043024)	103.50098 (95101824)	91.54030 (95101824)	
5000.0	157.08728 (95090924)	147.81458 (95080924)	133.94617 (95090924)	119.60943 (95090924)	107.66204 (95090924)	
0.0	105.71765 (95121024)	158.29297 (95121024)	137.72839 (95121024)	122.08398 (95121024)	110.00964 (95121024)	
-5000.0	140.84912m(95011024)	117.64954m(95013024)	94.13158m(95013024)	80.53595 (95100324)	76.81342 (95100324)	
-10000.0	200.65735 (95081724)	185.75452 (95081724)	133.04700 (95081724)	84.11615m(95013024)	87.07672m(95013024)	
-15000.0	104.11072 (95060424)	80.57281 (95060424)	128.80859 (95081724)	155.61096 (95081724)	139.23669 (95081724)	
-20000.0	160.71875 (95123124)	91.93842 (95060424)	79.08881 (95060424)	63.11179 (95060424)	86.13751 (95081724)	
-25000.0	163.18641 (95060624)	136.92981 (95123124)	89.50664 (95123124)	71.98712 (95060424)	63.74689 (95060424)	
-30000.0	80.60529 (95080224)	141.98230 (95050624)	116.82178 (95123124)	95.29034 (95123124)	63.10164 (95060424)	
-35000.0	143.72546 (95061424)	76.05249 (95050624)	128.87402 (95050624)	93.47168 (95123124)	87.56622 (95123124)	
-40000.0	203.49446 (95061424)	91.09204 (95061424)	79.15283 (95050624)	117.89343 (95050624)	82.40039 (95123124)	
-45000.0	205.98169 (95061424)	150.97913 (95061424)	71.31344 (95080224)	77.12817 (95050624)	107.09339 (95123124)	
-50000.0	161.44108 (95061424)	184.33838 (95061424)	108.42798 (95061424)	66.01508 (95080224)	75.79639 (95050624)	

\*\*\* THE 1ST HIGHEST 24-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S): STACK1  
 \*\*\* NETWORK ID: C01 ; NETWORK TYPE: GRIDCART \*\*\*  
 \*\* CONC OF SO2 IN MICROGRAMS/M\*\*3 \*\*

Y COORD (METERS) | X COORD (METERS)

50000.00

50000.0 | 120.742292 (951029284)  
 45000.0 | 123.26550m(95043024)  
 40000.0 | 165.43372m(95043024)  
 35000.0 | 137.98730m(95043024)  
 30000.0 | 89.91064 (95101824)  
 25000.0 | 101.97614 (95101824)  
 20000.0 | 101.97717m(95041324)  
 15000.0 | 92.46057m(95041324)  
 10000.0 | 87.09723 (95090924)  
 5000.0 | 96.77863 (95090924)  
 0.0 | 100.10297 (95121024)  
 -5000.0 | 73.84466 (95121024)  
 -10000.0 | 83.84436m(95013024)  
 -15000.0 | 81.79976 (95081724)  
 -20000.0 | 119.57654 (95081724)  
 -25000.0 | 51.02018 (95060424)  
 -30000.0 | 60.86395 (95060424)  
 -35000.0 | 56.25964 (95060424)  
 -40000.0 | 95.97198 (95121124)  
 -45000.0 | 72.41675 (95081724)  
 -50000.0 | 99.49805 (95050624)

### Annual Average Concentration Values of SO<sub>2</sub> for the Year 1995

\*\*\* AERMOD VERSION 99351 \*\*\*  
 \*\*\* MODELING OPTIONS USED: CONC ELEV DFADLT  
 INCLUDING SOURCE1S STACKS FOR SOURCE GROUP: ALL \*\*\*  
 \*\*\* NETWORK SOURCE1 NETWORK TYPE: DISCRETE \*\*\*  
 \*\* CONC OF SO2 IN MICROGRAMS/M\*\*

Y COORD (METERS)	50000.00	45000.00	40000.00	35000.00	X COORD (METERS)	30000.00	25000.00	20000.00	15000.00	-10000.00
50000.00	47.15121	49.95341	54.76144	57.70110	57.23523	60.91344	60.71569	60.91344	60.71569	57.81684
45000.00	49.47869	51.92350	56.56661	62.47505	63.81617	65.41388	68.38557	65.41388	68.38557	64.54062
40000.00	51.21001	53.85639	58.50929	65.30811	71.57571	71.84876	76.50395	71.84876	76.50395	73.52071
35000.00	59.23524	60.68187	62.46180	64.60056	68.87627	77.11064	72.06732	74.80705	75.60175	74.80705
30000.00	62.89570	67.26202	71.16849	72.55738	75.26750	80.56846	73.01653	76.01847	71.06775	71.06775
25000.00	62.05075	69.98174	78.36403	79.62525	76.36994	70.13772	70.33576	61.83300	69.08913	69.08913
20000.00	61.00000	63.32512	71.06653	73.00859	72.54039	72.54039	50.34039	43.44074	43.44074	43.44074
15000.00	57.12338	63.32512	71.06653	73.00859	73.07310	21.34639	21.34639	21.34639	21.34639	21.34639
10000.00	62.00176	68.03318	75.01471	75.17023	77.64315	18.24545	42.92404	71.28093	72.73085	72.73085
5000.00	52.95993	60.25415	68.44437	80.29718	76.02088	17.25028	46.60655	71.28093	78.80518	78.80518
0.00	40.42075	45.09927	50.37045	57.84251	67.82447	71.82774	72.86441	58.89732	59.85721	59.85721
5000.00	35.08266	38.80783	42.28630	47.96119	55.39879	67.23706	81.14172	38.82689	37.03387	37.03387
10000.00	34.21916	37.84647	41.93837	46.96885	53.59411	65.38197	90.65437	31.69188	64.04018	64.04018
15000.00	32.85141	35.61816	39.62873	46.72217	60.08915	79.87811	74.02626	71.16832	17.49834	17.49834
20000.00	31.44316	36.39905	44.64761	56.12891	70.29078	74.02657	74.46931	72.78489	11.06684	11.06684
25000.00	35.38332	42.71987	54.74224	61.79401	70.02074	68.07069	64.71356	77.78093	58.34330	58.34330
30000.00	40.63170	47.57861	54.64501	59.58032	56.64474	53.43996	60.63898	74.45787	70.81824	70.81824
35000.00	43.81429	48.71942	51.55669	48.43764	45.34657	49.82001	58.07550	74.11448	78.77422	78.77422
40000.00	40.81956	45.45808	42.30762	39.57183	42.07979	48.36021	56.01003	71.36726	77.13668	77.13668
45000.00	40.44157	37.37660	34.37698	36.13815	41.02396	46.21391	56.71255	69.81345	67.26668	67.26668
50000.00	33.35852	31.37913	32.05841	34.98003	35.64577	44.94399	57.20294	63.83154	59.37615	59.37615

\*\*\* THIS PERIOD (8760 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S): STACKS  
 \*\*\* NETWORK ID: C01 / NETWORK TYPE: GRID/CART \*\*\*  
 \*\* CONC. OF SO2 IN MICROGRAMS/M<sup>3</sup> \*\*

Y COORD (METERS)	-5000.00	0.00	5000.00	10000.00	15000.00	20000.00	25000.00	30000.00	35000.00
50000.00	62.06975	67.50315	64.75513	61.78976	66.12084	72.98638	76.79931	74.96773	67.70510
45000.00	67.97551	74.58932	71.31062	69.17136	75.83963	73.51037	74.70248	77.78236	70.01768
40000.00	75.36505	78.39425	79.48978	79.05751	78.85103	75.33951	80.95087	80.50912	74.03449
35000.00	74.92683	77.64564	80.06382	78.82421	78.39412	79.09762	74.83754	75.24290	77.65056
30000.00	77.93397	79.52672	74.39414	72.86695	75.42446	75.31070	70.45089	70.22105	71.10968
25000.00	76.84972	73.11067	75.23524	63.02614	65.37234	62.84192	67.59159	75.47674	75.88026
20000.00	46.58591	60.42636	59.12814	74.75964	58.93033	33.69749	35.94854	22.47768	34.03328
15000.00	75.73624	59.67238	23.73764	25.07990	76.80737	47.22791	28.76089	19.10631	12.47711
10000.00	81.97813	54.99405	51.11365	61.16760	33.93851	77.94328	61.07155	44.32396	28.52335
5000.00	46.52408	76.33936	98.64301	46.52563	76.01660	21.44727	81.65332	52.81534	31.52013
0.00	20.82733	0.00000	12.56049	69.27100	55.58826	66.73045	59.93254	34.66237	16.31267
-5000.00	29.70151	74.20846	78.21286	13.81329	46.07368	17.99580	22.18993	40.95721	82.17657
-10000.00	16.87956	61.83440	52.05563	37.88004	44.78278	42.34315	82.61359	70.58296	61.37997
-15000.00	65.85126	68.77583	71.92036	68.82813	63.52613	63.52613	73.29763	70.28140	57.88143
-20000.00	49.01018	65.16520	66.77583	78.11343	59.53254	65.72688	70.52076	70.28140	62.44916
-25000.00	18.11215	27.18400	73.55793	61.11343	35.19829	44.52678	12.53107	74.36787	62.44916
-30000.00	62.28884	65.11531	58.37050	48.77335	11.60876	33.05574	25.48825	76.32813	65.09727
-35000.00	72.34616	79.59291	31.35492	37.46312	11.85414	79.30131	73.91484	71.13159	65.51672
-40000.00	72.07493	77.95191	50.62591	66.05465	64.02043	71.00655	72.74236	68.68639	62.32856
-45000.00	64.14777	69.24140	74.85531	74.48383	76.00889	74.77551	78.17570	69.51360	59.54048
-50000.00	57.65431	62.08446	72.57088	63.42431	75.79710	80.47784	72.43270	68.50096	59.75109

\*\*\* THE PERIOD (8760 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL...  
 INCLUDING SOURCE(S): STACK1  
 \*\*\* NETWORK ID: COLF NETWORK TYPE: GRIDCOAT \*\*\*  
 \*\* CONC OF SO2 IN MICROGRAMS/M \*\*

Y COORD (METERS)	40000.00	45000.00	50000.00	X COORD (METERS)
50000.00	62.03587	58.56940	54.41989	
45000.00	65.50485	60.49204	55.61824	
40000.00	68.03739	62.18462	58.08739	
35000.00	70.43061	65.16817	60.37124	
30000.00	74.11207	68.06602	63.80822	
25000.00	78.54660	74.05426	71.38285	
20000.00	79.28954	76.14613	72.88829	
15000.00	79.56063	78.06093	70.67078	
10000.00	74.57037	79.67061	72.72487	
5000.00	75.32146	79.63680	72.45000	
0.00	72.41019	71.51459	72.74921	
5000.00	75.04956	69.11713	64.08850	
10000.00	57.30261	43.53999	30.06444	
15000.00	41.70629	26.18629	15.06445	
20000.00	50.11062	46.51919	40.80312	
25000.00	53.11521	45.61050	39.86174	
30000.00	55.42752	48.10581	42.24741	
35000.00	56.66788	48.90330	43.85947	
40000.00	58.43346	52.05066	43.92408	
45000.00	55.03852	52.14072	44.87943	
50000.00	51.63321	49.31878	47.08415	

GROUP ID	AVERAGE CONC	RECEPTOR	(NR, YR, ZLEV, ZPLG)	OTYPE	GRID-ID
1ST HIGHEST VALUE IS	98.64301 AT ( 5000.00,	5000.00,	0.00, 0.00)	GC	CGI
2ND HIGHEST VALUE IS	90.65437 AT (-20000.00,	-10000.00,	23.16, 0.00)	GC	CGI
3RD HIGHEST VALUE IS	83.40723 AT ( 25000.00,	-15000.00,	23.16, 0.00)	GC	CGI
4TH HIGHEST VALUE IS	82.61369 AT ( 25000.00,	-15000.00,	23.16, 0.00)	GC	CGI
5TH HIGHEST VALUE IS	81.97833 AT ( 25000.00,	-15000.00,	23.16, 0.00)	GC	CGI
6TH HIGHEST VALUE IS	81.97833 AT ( 25000.00,	10000.00,	23.16, 0.00)	GC	CGI

**APPENDIX – D**

### Hourly Average Concentration Values of NO<sub>x</sub> for the Year 1995

Y. COORD. (METERS)	MODELING OPTIONS USED:		CONC. ELEV	ELEV VALUES FOR SOURCE GROUP:	DEFAULT ALL ***					
	1ST HIGHEST	1-HR AVERAGE CONCENTRATION								
	INCLUDING SOURCE(S): STACK		CONC OF NO <sub>x</sub> IN MICROGRAMS/M**3							
	*** NETWORK ID: C01 ; NETWORK TYPE: GRIDCART ***		CONC OF NO <sub>x</sub> IN MICROGRAMS/M**3							
	50000.00	45000.00	40000.00	35000.00	30000.00					
	X. COORD. (METERS)									
50000.0	540.91113	(95060301)	509.82813	(95060301)	443.93359	(95102823)	557.15625	(95081523)	499.62500	(95080322)
45000.0	419.77246	(95032115)	575.56738	(95060301)	516.34082	(95060301)	484.70020	(95102823)	489.32422	(95030903)
40000.0	649.83643	(95011705)	453.73438	(95032115)	634.20410	(95060301)	544.34717	(95060301)	429.29004	(95061522)
35000.0	671.02832	(95011705)	617.18164	(95011705)	493.50879	(95032115)	498.78418	(95060301)	476.49707	(95060301)
30000.0	606.37695	(95072723)	600.16500	(95011705)	485.10640	(95011705)	623.86484	(95011705)	493.73242	(95060301)
25000.0	686.10254	(95072723)	642.45609	(95072723)	681.13789	(95011705)	358.86680	(95011705)	371.27539	(95011705)
20000.0	622.26953	(95072924)	566.05371	(95070421)	428.51758	(95072723)	597.70313	(95072723)	447.11720	(95011705)
15000.0	622.08789	(95072521)	588.89453	(95013023)	205.50195	(95013023)	299.53120	(95072924)	272.37700	(95072723)
10000.0	311.11330	(95072521)	588.07230	(95072521)	226.57070	(95072521)	430.58110	(95072521)	376.86230	(95013023)
5000.0	361.08496	(95081706)	465.50248	(95081706)	466.79690	(95072521)	535.73440	(95072521)	532.05080	(95072521)
-5000.0	584.21519	(95112524)	635.53865	(95112524)	462.29443	(95072521)	597.14016	(95072521)	593.17383	(95072521)
-10000.0	590.50488	(95032524)	673.37109	(95032524)	518.18366	(95032524)	450.64752	(95132524)	376.74230	(95032524)
-15000.0	590.50488	(95032524)	673.37109	(95032524)	521.86914	(95112219)	482.32330	(95112219)	425.15674	(95041418)
-20000.0	651.09766	(95112219)	628.65918	(95112219)	627.44824	(95041418)	313.76758	(95090520)	328.61120	(95090520)
-25000.0	650.29492	(95041418)	619.25110	(95090520)	579.04492	(95090520)	317.19730	(95090520)	547.20120	(95072519)
-30000.0	546.81816	(95090520)	601.00195	(95090520)	404.03180	(95092520)	457.21290	(95072519)	404.46338	(95072519)
-35000.0	642.11328	(95090520)	644.90557	(95092520)	551.26760	(95072519)	536.53906	(95032423)	497.80859	(95072519)
-40000.0	570.53564	(95090520)	646.29159	(95072519)	581.26777	(95032423)	593.28711	(95073020)	591.13086	(95120223)
-45000.0	649.45996	(95072519)	420.28857	(95032423)	574.22266	(95073020)	560.87598	(95073020)	422.36133	(95051719)
-50000.0	650.97510	(95032422)	422.46387	(95073020)	445.58691	(95073020)	444.40918	(95051719)	413.21975	(95080319)



\*\*\* THE 1ST HIGHEST 1-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S): STACK1  
 \*\*\* NETWORK ID: C03 | NETWORK TYPE: GRIDCART \*\*\*  
 CONC OF NO2 IN MICROGRAMS/M\*\*3

Y-COORD (METERS)	-25000.00	-20000.00	-15000.00	-10000.00	-5000.00
50000.0	109.65410 (95080322)	240.11820 (95080322)	129.99219 (95060624)	117.74414 (95052324)	86.71680 (95062623)
45000.0	319.92480 (95080322)	292.73830 (95080322)	641.20605 (95101919)	123.51370 (95052324)	98.17773 (95062623)
40000.0	292.02710 (95080322)	268.83400 (95080322)	168.26950 (95080322)	137.62990 (95052324)	70.39258 (95062623)
35000.0	214.22461 (95081522)	219.32810 (95080322)	288.94730 (95080322)	281.77150 (95060624)	39.96582 (95062623)
30000.0	290.24121 (95102823)	417.33960 (95080322)	280.35550 (95080322)	167.45310 (95080322)	148.46880 (95052324)
25000.0	275.76367 (95060301)	211.71777 (95102823)	255.93360 (95080322)	127.44920 (95080322)	148.70210 (95052324)
20000.0	252.44530 (95011705)	202.59180 (95060301)	292.18164 (95081522)	222.14840 (95080322)	136.12500 (95052324)
15000.0	452.21680 (95011705)	246.73440 (95011705)	257.74710 (95060301)	363.15230 (95080322)	278.32810 (95080322)
10000.0	532.11130 (95011023)	532.18160 (95072723)	277.45700 (95011705)	256.19920 (95060301)	425.34380 (95080322)
5000.0	470.41410 (95072521)	433.77730 (95072521)	288.08200 (95072521)	138.53520 (95072723)	281.45310 (95060301)
0.0	150.62700 (95072521)	150.26070 (95072521)	104.39060 (95072521)	151.19340 (95072521)	477.41410 (95072521)
-5000.0	203.43750 (95032524)	606.88670 (95032524)	293.93550 (95032524)	260.39700 (95112219)	231.64840 (95092520)
-10000.0	672.49020 (95112219)	645.71480 (95112219)	574.15430 (95092520)	698.13670 (95072519)	111.74220 (95080319)
-15000.0	269.80550 (95072520)	322.67680 (95072519)	372.67680 (95072519)	130.31500 (95160223)	205.89940 (95032301)
-20000.0	639.97950 (95092520)	588.11620 (95102823)	197.51465 (95051719)	191.65470 (95032301)	846.09180 (95092520)
-25000.0	298.67969 (95072519)	258.11620 (95102823)	117.51465 (95051719)	139.43160 (95032301)	150.39750 (95091219)
-30000.0	505.89663 (95120223)	503.33691 (95051719)	414.30859 (95080319)	312.18360 (95032301)	154.39750 (95091219)
-35000.0	568.72803 (95120223)	569.31835 (95080319)	460.63379 (95032302)	319.18360 (95032301)	90.26367 (95091219)
-40000.0	563.74756 (95051719)	541.60938 (95080319)	486.48440 (95032301)	284.29785 (95032301)	54.39307 (95091219)
-45000.0	310.29395 (95080319)	338.50488 (95080319)	394.66210 (95032301)	230.95996 (95091219)	10.27637 (95042903)
-50000.0	542.15820 (95080319)	486.38232 (95032302)	462.85450 (95032301)	434.60449 (95091219)	91.37500 (95042903)

\*\* THE 1ST HIGHEST 1-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP 1 ALL \*\*\*  
 INCLUDING SOURCE(S) STACK  
 \*\*\* NETWORK ID: C01 J NETWORK TYPE: GRIDCART \*\*\*  
 CONC OF NO2 IN MICROGRAMS/M\*\*\*

Y COORD (METERS)	X COORD (METERS)					20000.00
	0.00	5000.00	10000.00	15000.00	20000.00	
50000.0	529.20020 (950062623)	607.48438 (950410201)	629.01074 (950819211)	640.42725 (950520011)	661.13135 (950020205)	
45000.0	200.22241 (950404021)	262.61477 (950404021)	284.91329 (950404021)	278.01840 (950200505)	570.71583 (950404211)	
40000.0	213.31934 (950062623)	226.54199 (950404021)	320.70117 (950819211)	274.48343 (950200505)	227.78983 (950404211)	
35000.0	222.32610 (950062623)	240.49805 (950819211)	218.46680 (950819211)	299.17969 (950828211)	184.35160 (950707221)	
30000.0	313.44100 (950062623)	333.89060 (950819211)	247.04000 (95020205)	241.43460 (950404211)	210.35160 (950707221)	
25000.0	235.32130 (950062623)	186.82120 (950819211)	164.22660 (95020205)	157.10160 (950707221)	101.10940 (950707221)	
20000.0	468.56450 (95062623)	348.09570 (950819211)	526.67380 (950404211)	262.48830 (950707221)	236.29880 (95043005)	
15000.0	225.11330 (95062623)	320.91020 (95020205)	284.93750 (950707221)	180.75590 (95043005)	272.79490 (95041303)	
10000.0	277.11320 (95062623)	104.18950 (950707221)	164.40630 (950707221)	172.32420 (95041303)	238.25200 (95041303)	
5000.0	208.99610 (95062623)	235.45310 (950707221)	289.04100 (95043003)	364.36820 (95121006)	362.40430 (95121006)	
0.0	0.00000 (000000000)	344.25980 (95121006)	427.31250 (95121006)	206.00590 (950817221)	305.40230 (950817221)	
-5000.0	264.17190 (95070621)	411.87500 (95050601)	215.89450 (950817221)	360.18360 (950604221)	331.91800 (950817221)	
-10000.0	413.87890 (9502903)	343.80860 (950614221)	368.78170 (95050601)	459.01170 (95050601)	426.63379 (95020206)	
-15000.0	593.75780 (95042903)	664.24020 (950818221)	643.94140 (95090720)	188.43160 (950802020)	122.43360 (95050601)	
-20000.0	392.78520 (95042903)	229.82420 (950818221)	311.88090 (95101721)	295.02330 (950614221)	270.71875 (950802020)	
-25000.0	348.01560 (95042903)	222.22660 (950818221)	372.39941 (95051423)	408.83400 (95081104)	307.61520 (950907220)	
-30000.0	467.87260 (95062603)	322.99220 (950818221)	156.53374 (95050584)	299.02330 (950614221)	409.83400 (95081104)	
-35000.0	127.87260 (95062603)	322.99220 (950818221)	156.53374 (95050584)	203.52012 (95050524)	192.75000 (95101721)	
-40000.0	141.69430 (95042903)	539.09380 (95070621)	289.62880 (95081822)	342.52012 (95050524)	278.68652 (95101721)	
-45000.0	346.42773 (95042903)	336.79490 (95070621)	369.43160 (95081822)	387.58984 (95090524)	383.40967 (95101721)	
-50000.0	487.11328 (95042903)	187.58200 (95070621)	368.64800 (95081822)	387.58984 (95090524)	383.40967 (95101721)	

\*\*\* THE 1ST HIGHEST 1-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S): STACK 1  
 \*\*\* NETWORK ID: C01 / NETWORK TYPE: GRIDCART \*\*\*  
 CONC OF NO2 IN MICROGRAMS/M\*\*3

Y COORD (METERS)	25000.00	30000.00	X COORD (METERS)	35000.00	40000.00	45000.00				
50000.0	590.20020	(95040421)	580.47461	(95070723)	528.09180	(95070723)	471.46090	(95070723)	397.91800	(95070723)
45000.0	563.36719	(95040421)	564.72560	(95070723)	555.62300	(95070723)	348.74120	(95070723)	280.13867	(95070723)
40000.0	363.31250	(95070723)	423.08010	(95070723)	423.08010	(95070723)	327.05470	(95070723)	291.14155	(95070723)
35000.0	639.85550	(95070723)	603.44920	(95070723)	603.44920	(95070723)	347.38570	(95070723)	311.06250	(95040904)
30000.0	452.98830	(95070723)	176.77140	(95070723)	242.19141	(95043005)	233.71338	(95043005)	218.55033	(95043005)
25000.0	636.98840	(95070723)	561.98242	(95043005)	451.43359	(95043005)	399.63940	(95040822)	548.18896	(95040205)
20000.0	348.53710	(95043005)	475.65186	(95043006)	482.66016	(95040205)	356.16895	(95040205)	333.52246	(95041303)
15000.0	679.01563	(95040205)	469.46289	(95040205)	507.90210	(95041303)	399.78710	(95041303)	297.58398	(95041303)
10000.0	528.15040	(95041303)	315.59960	(95041303)	535.69040	(95041303)	482.11523	(95041303)	562.88867	(95041303)
5000.0	685.32813	(95041303)	539.98535	(95090903)	447.73926	(95090903)	417.38623	(95100905)	388.21484	(95100905)
0.0	319.06738	(95121006)	395.03223	(95121006)	301.50781	(95121006)	515.99512	(95121006)	472.29883	(95121006)
-5000.0	587.01070	(95051121)	592.90039	(95051121)	535.57715	(95051121)	596.99609	(95101723)	523.76563	(95101723)
-10000.0	481.00210	(95001722)	598.81450	(95081722)	586.59200	(95081722)	421.59082	(95051121)	400.83984	(95051121)
-15000.0	139.27051	(95060422)	190.48438	(95081722)	330.12990	(95081722)	205.80180	(95081723)	311.53910	(95081723)
-20000.0	576.22852	(95101320)	643.02637	(95060422)	434.06449	(95060422)	430.36201	(95060422)	345.28387	(95081722)
-25000.0	576.22852	(95101320)	586.90040	(95050601)	495.15410	(95081723)	578.92188	(95020306)	545.18164	(95060422)
-30000.0	329.61865	(95020200)	586.90040	(95050601)	495.15410	(95081723)	166.44336	(95081723)	138.32910	(95121120)
-35000.0	174.04688	(95090720)	234.12207	(95050601)	205.03910	(95050601)	267.84280	(95050601)	250.49434	(95081721)
-40000.0	470.75391	(95112122)	549.20763	(95082020)	355.21191	(95050601)	496.37012	(95050601)	383.01953	(95050601)
-45000.0	476.26172	(95061422)	549.15869	(95090720)	579.35938	(95082020)	561.94629	(95082020)	481.84668	(95050601)
-50000.0	592.58789	(95101721)	517.15332	(95112122)	571.51758	(95090720)				

\*\*\* THE 1ST HIGHEST 1-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING ADDITIONAL SPACE  
 \*\*\* NETWORK ID: CCL1 NETWORK TYPE: GRIDCART \*\*\*  
 CONC OF NO2 IN MICROGRAMS/M\*\*

X-COORD (METERS)

Y-COORD (METERS) 50000.00

50000.0	278.42480 (95070722)
45000.0	260.62061 (95040904)
40000.0	170.30859 (95043005)
35000.0	241.14844 (95043006)
30000.0	333.45239 (95040822)
25000.0	248.01633 (95041103)
20000.0	290.21004 (95041105)
15000.0	284.01633 (95041103)
10000.0	349.98633 (95090903)
5000.0	136.33545 (95100905)
0.0	243.61230 (95121006)
-5000.0	345.21533 (95101723)
-10000.0	265.41211 (95051121)
-15000.0	193.21680 (95081722)
-20000.0	116.92850 (95081722)
-25000.0	234.55322 (95060422)
-30000.0	149.15479 (95060422)
-35000.0	248.17676 (95060422)
-40000.0	354.48438 (95123120)
-45000.0	470.77734 (95081721)
-50000.0	591.73228 (95050601)

\*\*\* APPROX - VERSION 99351 \*\*\*  
 MODELING OPTIONS USED: CONC ELEV DEFAULT  
 \*\*\* THE MAXIMUM 20 1-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE(S): STACK1  
 CONC OF NO2 IN MICROGRAMS/M\*\*3

BANK	CONC	(YRMDHRH) AT	RECEPTOR (XR,YR) OF TYPE	BANK	CONC	(YRMDHRH) AT	RECEPTOR (XR,YR) OF TYPE
1.	698.11670	(95072519) AT (-	10000.00,	11.	651.09766	(95112219) AT (-	50000.00,
2.	686.10254	(95072723) AT (-	50000.00,	12.	650.97510	(95032422) AT (-	50000.00,
3.	685.32813	(95041303) AT (-	25000.00,	13.	650.29432	(95041418) AT (-	50000.00,
4.	681.31689	(95011705) AT (-	25000.00,	14.	649.45996	(95072519) AT (-	50000.00,
5.	673.37109	(95031924) AT (-	15000.00,	15.	646.23199	(95072519) AT (-	45000.00,
6.	672.49020	(95112219) AT (-	25000.00,	16.	645.71480	(95112219) AT (-	20000.00,
7.	671.02832	(95011705) AT (-	35000.00,	17.	644.90527	(95092520) AT (-	45000.00,
8.	664.24020	(95081822) AT (-	5000.00,	18.	643.94140	(95090720) AT (-	10000.00,
9.	655.71826	(95111922) AT (-	45000.00,	19.	642.49609	(95072723) AT (-	45000.00,
10.				20.			

# Annual Average Concentration Values of NO<sub>x</sub> for the Year 1995

\*\*\* THE PERIOD (8760 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 MODPLING OPTIONS USED: CONC ELEV DEFAULT  
 INCLUDING SOURCE(S): STACK1  
 NETWORK ID: C01; NETWORK TYPE: GRIDCART \*\*\*  
 CONC OF NO2 IN MICROGRAMS/H\*\*\*

Y-COORD (METERS)	-50000.00	-45000.00	-40000.00	-35000.00	-30000.00	-25000.00	-20000.00	-15000.00	-10000.00
50000.00	18.29823	19.11889	20.25482	22.20416	23.39641	23.20906	24.69886	24.61869	23.44326
45000.00	19.42996	20.06210	21.05167	22.91631	25.33205	25.87583	26.52366	27.72863	26.16958
40000.00	21.61587	21.83740	22.91110	24.19514	26.48077	29.02216	29.13287	31.02041	29.81082
35000.00	24.02003	24.60495	25.26665	26.19190	27.92756	31.26640	33.27620	34.38709	34.70935
30000.00	25.50301	27.27305	28.85701	29.42018	30.51910	33.07393	37.71584	38.93303	40.98042
25000.00	25.16000	28.35961	31.77464	33.91489	35.02082	36.54856	40.68359	46.15640	48.27954
20000.00	23.15582	26.75980	31.24287	36.16261	40.27807	43.17361	45.67511	52.80677	58.16451
15000.00	23.16210	25.67671	28.90504	34.02079	41.79360	50.01303	56.15866	60.96148	73.64257
10000.00	25.14016	27.58570	30.41657	34.53439	39.59181	47.94554	62.00674	78.76754	90.31169
5000.00	16.38958	18.28662	20.42353	23.55847	38.93407	47.54200	59.44522	78.57554	91.13800
0.00	14.27933	15.79560	17.14062	19.44704	27.50109	33.17907	41.70852	56.11940	65.09176
10000.00	13.32943	14.44846	15.66846	17.92185	22.62280	27.26292	32.75092	44.12659	49.81017
15000.00	11.32943	12.44226	13.66846	15.94464	24.36469	28.38554	31.79092	41.07698	45.07598
20000.00	12.72940	14.75889	18.10145	22.75884	34.50111	34.07666	42.18002	45.07598	47.64260
25000.00	14.34704	17.32195	20.98018	25.01940	38.19166	37.60093	42.20173	31.56715	45.03473
30000.00	16.47131	19.29192	22.15718	24.15810	22.96800	21.66855	24.58757	31.53818	43.91084
35000.00	17.76558	19.75448	20.90494	19.64025	18.38688	20.20075	23.54815	30.05152	40.87956
40000.00	16.55130	18.43210	17.05467	16.04539	17.06228	19.60884	22.71064	29.74857	31.27652
45000.00	16.39802	15.15166	13.93900	14.66131	16.63418	18.73857	22.99551	28.30757	27.27493
50000.00	13.60713	12.72343	12.99888	14.18351	16.07536	18.22364	23.19433	25.88207	24.07553

\*\*\* THE PERIOD (8760 HRS) MODELING OPTIONS USED: CONC BELY EMPAINT  
 NETWORK ID: C01 IN MICROGRAMS/M\*\*3 INCLUDING SOURCE(S), STACKS  
 \*\*\* NETWORK ID: C01 IN MICROGRAMS/M\*\*3 INCLUDING SOURCE(S), STACKS  
 \*\*\* NETWORK ID: C01 IN MICROGRAMS/M\*\*3 INCLUDING SOURCE(S), STACKS  
 CONC OF NO2 IN MICROGRAMS/M\*\*3

Y COORD (METERS)	-5000.00	0.00	5000.00	10000.00	15000.00	20000.00	25000.00	30000.00	35000.00
	X-COORD (METERS)								
50000.00	25.15999	27.27085	26.25657	25.05120	26.81401	29.59415	31.14017	30.35696	27.45271
45000.00	37.56234	30.24366	28.91466	28.04224	30.75104	33.86946	34.34472	31.53875	28.39042
40000.00	30.55863	31.81422	32.21108	32.05381	35.94577	38.67578	36.87826	32.64443	30.01911
35000.00	34.47868	38.37642	36.51893	41.95266	42.45469	43.76540	38.45417	34.56394	31.48534
30000.00	48.38555	57.77975	57.89349	57.99349	58.94513	49.80933	47.62569	38.71338	32.82225
25000.00	47.37943	58.38555	50.77975	54.31530	64.44221	54.21096	47.01415	41.55208	38.12608
20000.00	59.43691	65.04881	64.52244	74.31530	71.69089	59.67915	52.20925	48.29459	45.60564
15000.00	79.36615	85.01679	90.71996	91.26811	82.65193	72.15147	65.31645	58.51974	52.11298
10000.00	74.33501	73.66731	82.36776	85.89520	82.65193	72.15147	73.55569	61.96278	53.32803
5000.00	71.04009	73.69347	82.18726	80.50754	91.91776	89.79122	73.55569	61.96278	53.32803
0.00	70.63484	0.00000	88.92490	89.72987	93.63466	79.76917	64.84859	54.60214	47.16183
-5000.00	73.68558	73.37463	86.06787	86.65931	59.22910	47.84422	41.43507	36.88084	33.32051
-10000.00	87.90161	73.19441	88.96891	96.45428	58.70572	41.49757	33.49781	28.78180	25.69893
-15000.00	77.03827	87.23467	80.39492	85.88728	61.57893	44.04484	33.81957	27.86660	23.47190
-20000.00	60.41992	64.90092	96.81753	75.45906	56.57736	46.92437	35.80060	28.41612	23.93724
-25000.00	47.89155	51.56989	78.48259	66.13795	54.81957	42.38303	37.52104	30.15430	25.32161
-30000.00	39.44817	42.62007	64.23545	60.12385	44.84890	41.96895	34.66088	28.94922	26.39532
-35000.00	33.50601	36.32770	53.25102	55.73789	45.35408	40.26414	34.02535	28.84211	26.97080
-40000.00	29.24856	31.60751	44.85683	41.11132	42.50205	36.30086	33.25802	27.85057	25.27265
-45000.00	28.96367	28.96367	46.46530	46.46530	40.50205	33.25802	31.55814	27.85057	24.15216
-50000.00	23.37737	23.37734	33.48043	41.93594	38.83327	32.63179	25.36960	27.79542	24.22759

MODELING OPTIONS USED: CONC, ELEV, DEFAULT  
 \*\*\* THIS PERIOD (8760 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL  
 INCLUDING SOURCE(S): STACK1  
 \*\*\* NETWORK ID: CGL; NETWORK TYPE: GRIDCART \*\*\*  
 CONC OF NO2 IN MICROGRAMS/M\*\*3

Y-COORD (METERS)	40000.00	50000.00	X-COORD (METERS)
50000.00	25.15397	23.74841	22.07400
45000.00	26.52000	24.52799	24.55288
40000.00	27.38744	25.21425	23.55297
35000.00	28.52053	26.47901	24.47901
30000.00	29.84199	27.84199	25.84199
25000.00	31.64866	30.02714	28.04199
20000.00	36.20461	34.93007	33.60909
15000.00	42.80215	39.76126	36.76469
10000.00	46.45596	41.63033	37.59757
5000.00	46.75996	41.61664	37.48613
0.00	41.52470	37.10682	33.55274
-5000.00	30.43071	28.02522	25.98628
-10000.00	23.47801	21.70909	20.29974
-15000.00	20.97510	19.02927	17.57101
-20000.00	20.33037	18.05138	16.54461
-25000.00	21.53698	18.49389	16.16295
-30000.00	22.47442	19.50570	17.13024
-35000.00	22.97738	19.82903	17.78387
-40000.00	23.69240	21.10540	17.81008
-45000.00	24.31654	23.18176	18.19750
-50000.00	26.95395	19.97971	19.09146

GROUP ID	AVERAGE CONC	RECEPTOR	(X, YR, Z,ELEV, ZFLAG)	OF TYPE	GRID ID
ALL	96.81753 AT (-5000.00,	-20000.00,	35.97,	0.00)	GC CGL
1ST HIGHEST VALUE IS	96.45428 AT (-10000.00,	10000.00,	49.99,	0.00)	GC CGL
2ND HIGHEST VALUE IS	93.63466 AT (-15000.00,	0.00,	0.00,	0.00)	GC CGL
3RD HIGHEST VALUE IS	91.91776 AT (-15000.00,	5000.00,	0.00,	0.00)	GC CGL
4TH HIGHEST VALUE IS	91.26411 AT (-10000.00,	15000.00,	0.00,	0.00)	GC CGL
5TH HIGHEST VALUE IS	91.15800 AT (-10000.00,	5000.00,	36.58,	0.00)	GC CGL
6TH HIGHEST VALUE IS					



**APPENDIX – E**

### Daily Average Concentration Values of PM for the Year 1995

\*\*\* THE 1ST HIGHEST 24-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 MODELING OPTIONS USED: CONC ELEV DEFALT  
 INCLUDING SOURCE(S) STACK  
 NETWORK ID: COJ NETWORK TYPE: GRIDCART  
 CONC OF PM IN MICROGRAMS/M\*\*3

Y COORD (METERS)	-50000.00	-45000.00	-40000.00	-35000.00	-30000.00
50000.0	0.92618 (95040424)	1.08608 (95040424)	1.13018 (95040424)	1.46315 (95020124)	1.62631 (95020124)
45000.0	0.95264 (95020124)	0.99784 (95040424)	1.18362 (95040424)	1.22057 (95040424)	1.76006 (95020124)
40000.0	1.00000 (95020124)	1.05478 (95011724)	1.15548 (95011724)	1.39429 (95040424)	1.45634 (95020124)
35000.0	1.13158 (95011724)	1.16486 (95011724)	1.68247 (95011724)	1.45926 (95020124)	1.47133 (95040424)
30000.0	1.87993 (95072724)	2.16164 (95072724)	2.07454 (95072724)	1.96756 (95011724)	1.72173 (95020124)
25000.0	1.77499 (95072724)	1.42904 (95070424)	1.12542 (95072724)	2.57148 (95072724)	2.12115 (95072724)
20000.0	1.21647 (95013024)	1.49891 (95013024)	1.59176 (95013024)	1.67612 (95070424)	2.71384 (95072724)
15000.0	1.88275 (95072524)	3.10284 (95072524)	2.89696 (95072524)	2.63196 (95072524)	2.20852 (95072524)
10000.0	3.03571 (95072524)	2.57797 (95072524)	2.79848 (95072524)	3.14149 (95072524)	3.90801 (95072524)
5000.0	1.16525 (95081224)	1.26163 (95081224)	1.17928 (95081224)	1.52530 (95081224)	1.71321 (95081224)
0.0	0.97682 (95111924)	1.12087 (95111924)	1.21275 (95012524)	1.46130 (95012524)	1.78480 (95032524)
-5000.0	1.24082 (95111924)	1.40170 (95032524)	1.57213 (95032524)	1.70240 (95032524)	1.72612 (95032524)
-10000.0	1.28442 (95032524)	1.26456 (95032524)	1.37442 (95112224)	1.51335 (95112224)	1.92438 (95041424)
-15000.0	1.23966 (95032524)	1.18774 (95112224)	1.49920 (95041424)	1.90222 (95041424)	2.56191 (9502524)
-20000.0	1.23144 (95041424)	1.56336 (95041424)	1.70996 (95092524)	2.49420 (95092524)	2.27095 (9502524)
-25000.0	1.36938 (95041424)	1.87529 (95092524)	2.26693 (95092524)	1.88566 (95072524)	0.33562 (95072524)
-30000.0	1.36938 (95041424)	1.47280 (95072524)	1.79202 (95042724)	1.79202 (95042724)	0.31367 (95042724)
-35000.0	1.17132 (95092524)	1.47280 (95072524)	0.94638 (95072524)	0.79202 (95042724)	0.31367 (95042724)
-40000.0	1.13126 (95072524)	0.89318 (95072524)	0.72671 (95071024)	0.74800 (95042724)	0.95151 (95091624)
-45000.0	0.78648 (95072524)	0.67400 (95073024)	0.67662 (95042724)	0.65432 (95042724)	1.04023 (95091624)

\*\*\* THE 1ST HIGHWAY 24 IN MICHIGAN CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 MODELING OPTIONS USED: CONC BLV FRATEP  
 INCLUDING SOURCE(S) STACKS  
 \*\*\* NETWORK ID: 001 NETWORK TYPE: GRIDCART \*\*\*  
 CONC OF PM IN MICROGRAMS/M\*\*3

Y COORD (METERS)	25000.00	20000.00	-15000.00	-10000.00	-5000.00
50000.0	2.0556	1.7948	1.3187	1.2749	1.2689
45000.0	1.9299	1.7983	1.3594	1.4609	1.3283
40000.0	2.0692	2.4165	1.8216	1.5495	1.3840
35000.0	1.8652	2.4307	2.9598	2.0573	1.8511
30000.0	1.7361	2.1178	2.9063	1.1457	1.1139
25000.0	2.1451	2.1549	2.9030	1.5284	2.5364
20000.0	3.1769	2.8796	2.9030	1.5284	2.8888
15000.0	2.1332	3.7435	2.7538	1.8507	6.4107
10000.0	4.5078	4.8695	3.8628	3.8401	7.5640
5000.0	2.0619	2.5622	3.5474	6.4732	10.4442
0.0	2.1812	2.6467	2.9432	3.8908	6.2351
-5000.0	1.9896	2.6721	4.3494	3.7571	5.1553
-10000.0	2.4913	1.9802	2.5964	1.9150	6.5183
-15000.0	2.9179	1.8012	1.5106	2.8295	4.4618
-20000.0	1.6105	1.2617	1.5052	3.8205	3.1918
-25000.0	1.0665	1.1384	2.0584	3.9019	2.7795
-30000.0	0.9720	1.4212	2.4363	3.1879	2.4813
-35000.0	1.5343	1.8074	2.9030	2.8191	2.9077
-40000.0	1.5343	2.1899	2.5167	1.6979	1.9075
-45000.0	1.8878	2.1899	2.5167	1.6979	1.9075
-50000.0	1.8878	2.1899	2.5167	1.6979	1.9075

\*\*\* THE LEFT HIGHEST 24-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 MODELING OPTIONS USED: CONC ELVEY DEFAULT  
 INCLUDING SOURCE(S): STACKS  
 \*\*\* NETWORK ID: C01 / NETWORK TYPE: GRIDCART \*\*\*  
 CONC OF PM IN MICROGRAMS/M\*\*3

Y-COORD (METERS)	0.00	5000.00	10000.00	15000.00	20000.00
50000.0	1.09781 (95010024)	1.52396 (95081924)	1.66045 (95081924)	1.17194 (95081924)	1.80649m(95011024)
45000.0	1.26651 (95103024)	1.75099 (95081924)	1.71112 (95081924)	1.63172m(95011024)	2.05320m(95011024)
40000.0	1.35232 (95103024)	2.03744 (95081924)	1.82074 (95081924)	2.07142m(95011024)	2.17998m(95011024)
35000.0	1.53764 (95103024)	2.29160 (95081924)	1.91925 (95081924)	2.50196m(95011024)	2.01797m(95011024)
30000.0	1.78115 (95103024)	2.60372 (95081924)	2.16196m(95011024)	2.74542m(95011024)	2.81218 (95070724)
25000.0	2.11563 (95103024)	2.94129 (95081924)	3.20057m(95011024)	2.69222 (95070724)	3.58083 (95070724)
20000.0	2.60517 (95103024)	3.34444 (95081924)	3.77970m(95011024)	4.20056 (95070724)	3.50634 (95102924)
15000.0	3.39907 (95103024)	4.36512m(95011024)	4.80151 (95070724)	4.41297 (95102924)	4.57625m(95043024)
10000.0	4.89957 (95103024)	6.44537m(95011024)	6.09903 (95102924)	4.85262m(95043024)	2.86818 (95101824)
5000.0	8.75739 (95103024)	10.48252 (95102924)	4.83985 (95101824)	3.43914m(95041324)	2.60777 (95121024)
0.0	0.00000 (00000000)	10.41923 (95121024)	5.80495 (95121024)	4.08875 (95121024)	3.17830 (95121024)
-5000.0	10.95479m(95042924)	6.89895 (95050624)	3.40338 (95081724)	4.22615 (95081724)	2.04540m(95033024)
-10000.0	4.66180m(95042924)	8.23358 (95061424)	4.28452 (95050624)	2.23347 (95060424)	1.59624 (95123124)
-15000.0	3.71610m(95042924)	4.11461 (95120824)	5.30837 (95061424)	3.24563 (95050624)	2.39558 (95123124)
-20000.0	2.41929m(95042924)	3.54673 (95050524)	4.76957 (95061424)	2.70027 (95061424)	1.50699 (95020204)
-25000.0	2.16929m(95042924)	2.33087 (95081824)	2.33087 (95081824)	4.32184 (95061424)	1.80699 (95061424)
-30000.0	2.14929m(95042924)	2.40189 (95050524)	2.40189 (95050524)	1.96549 (95061424)	1.49416 (95061424)
-35000.0	2.38699m(95042924)	2.69530 (95081824)	2.90800 (95050524)	1.66935 (95050524)	2.71638 (95061424)
-40000.0	2.14777m(95042924)	2.26497 (95081824)	2.08005 (95050524)	1.71744 (95050524)	1.72159 (95061424)
-45000.0	1.95019m(95042924)	1.94909 (95081824)	2.05774 (95081824)	1.71744 (95050524)	1.72159 (95061424)
-50000.0	1.80882m(95042924)	1.72808 (95070624)	2.06994 (95081824)	1.67598 (95050524)	1.24450 (95120824)

\*\*\* THE 1ST HIGHEST 24-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 MODELING OPTIONS USED: CONC ELVY DPFAULT  
 INCLUDING SOURCE(S): STACK1  
 \*\*\* NETWORK ID: C01 / NETWORK TYPE: GRIDCART \*\*\*  
 CONC OF PM IN MICROGRAMS/M\*\*3

Y COORD (METERS)	25000.00	30000.00	X COORD (METERS)	35000.00	40000.00	45000.00
50000.0	1.81872m(95011024)	1.38486 (95070724)	2.02866 (95070724)	2.19415 (95070724)	1.82557 (95070724)	1.82557 (95070724)
45000.0	1.72802m(95011024)	2.02513 (95070724)	2.17122 (95070724)	2.04815 (95070724)	1.87008 (95102924)	1.87008 (95102924)
40000.0	1.9573 (95070724)	2.56321 (95070724)	2.31907 (95070724)	2.08863 (95102924)	2.01088m(95041024)	2.01088m(95041024)
35000.0	2.72859 (95070724)	2.65209 (95070724)	2.34635 (95102924)	2.35409m(95041024)	2.52094m(95041024)	2.52094m(95041024)
30000.0	3.06590 (95070724)	2.63152 (95102924)	2.78064m(95041024)	2.67720m(95041024)	1.81977m(95041024)	1.81977m(95041024)
25000.0	2.96992 (95102924)	3.30751m(95041024)	2.74254m(95041024)	1.63313m(95041024)	1.56929 (95101824)	1.56929 (95101824)
20000.0	3.91377m(95041024)	2.64154m(95041024)	1.81600 (95101824)	1.68886 (95101824)	1.35279m(95041124)	1.35279m(95041124)
15000.0	2.29275m(95041024)	2.10615 (95101824)	1.74123m(95041124)	1.73267m(95041124)	1.55199m(95041124)	1.55199m(95041124)
10000.0	2.37055m(95041124)	2.08587m(95041124)	1.63221m(95041124)	1.42470 (95121024)	1.28592 (95121024)	1.28592 (95121024)
5000.0	2.21757 (95090924)	2.06693 (95090924)	1.86910 (95090924)	1.67635 (95090924)	1.50498 (95090924)	1.50498 (95090924)
0.0	2.61027 (95121024)	2.22067 (95121024)	1.31620 (95121024)	1.71903 (95121024)	1.54760 (95121024)	1.54760 (95121024)
-5000.0	1.96667m(95011024)	1.65663m(95011024)	1.32756m(95011024)	1.12563 (95100124)	1.07546 (95100124)	1.07546 (95100124)
-10000.0	2.81382 (95081724)	2.60611 (95081724)	1.87486 (95081724)	1.18543m(95013024)	1.22890m(95013024)	1.22890m(95013024)
-15000.0	1.46769 (95060424)	1.13692 (95060424)	1.80852 (95081724)	2.18039 (95081724)	1.95798 (95081724)	1.95798 (95081724)
-20000.0	2.27778 (95050624)	1.93195 (95121124)	1.26040 (95121124)	0.89589 (95060424)	0.89206 (95060424)	0.89206 (95060424)
-25000.0	1.11696 (95082024)	1.98180 (95050624)	1.63159 (95121124)	1.39913 (95121124)	0.89331 (95060424)	0.89331 (95060424)
-30000.0	2.09922 (95061424)	1.07841 (95050624)	1.80721 (95050624)	1.31512 (95123124)	1.37564 (95123124)	1.37564 (95123124)
-35000.0	2.85432 (95061424)	1.27948 (95061424)	1.11105 (95050624)	1.64433 (95050624)	1.15914 (95123124)	1.15914 (95123124)
-40000.0	2.89151 (95061424)	2.11912 (95061424)	1.02986 (95082024)	1.08714 (95050624)	1.51261 (95050624)	1.51261 (95050624)
-45000.0	2.27003 (95061424)	2.59008 (95061424)	1.51869 (95061424)	0.85526 (95082024)	1.05718 (95050624)	1.05718 (95050624)

MODELING OPTIONS USED: CONC ELLEV DEFNMT  
 1ST HIGHEST 24 HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 EXCLUDING SOURCE(S): STACK  
 \*\*\* NETWORK ID: CO1 ; NETWORK TYPE: GRILLCART \*\*\*  
 CONC OF PM IN MICROGRAMS/M\*\*3

\*\*\* THE

X-COORD (METERS)

50000.00

Y-COORD  
(METERS)

50000.0 | 1.65187 (95102924)  
 40000.0 | 1.3333m(95043024)  
 35000.0 | 2.2279m(95043024)  
 30000.0 | 1.92677(95043024)  
 25000.0 | 1.25957 (95101824)  
 20000.0 | 1.42116 (95101824)  
 15000.0 | 1.42959m(95041324)  
 10000.0 | 1.29966m(95041324)  
 5000.0 | 1.22753 (95090924)  
 0.0 | 1.35769 (95090924)  
 -5000.0 | 1.40870 (95121024)  
 -10000.0 | 1.03617 (95121024)  
 -15000.0 | 1.17943m(95013024)  
 -20000.0 | 1.58519 (95081724)  
 -25000.0 | 1.68040 (95081724)  
 -30000.0 | 0.72885 (95060424)  
 -35000.0 | 0.84522 (95060424)  
 -40000.0 | 0.78820 (95060424)  
 -50000.0 | 1.34251 (95121124)  
 50000.0 | 1.02154 (95081724)  
 50000.0 | 1.40363 (95050624)

MODELING OPTIONS USED: CONC ELEV DEFAULT  
**\*\*\* THE MATHEM 20, 24-HR AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\***  
 INCLUDING SOURCE(S) STACK(S)  
 CONC OF PM 10 MICROGRAMS/M\*\*3

RANK	CONC	(YYSRDDHH) AT	RECEPTOR (XR, YR) OF TYPE	RANK	CONC	(YYSRDDHH) AT	RECEPTOR (XR, YR) OF TYPE		
1.	10.95479m	(95042924) AT (	0.00,	-5000.00) GC	11.	8.42960	(95091724) AT (	0.00,	5000.00) GC
2.	10.60131	(95032324) AT (	0.00,	-5000.00) GC	12.	8.23358	(95061424) AT (	5000.00,	-10000.00) GC
3.	10.48252	(95102924) AT (	5000.00,	5000.00) GC	13.	8.11813	(95090924) AT (	5000.00,	0.00) GC
4.	10.44228m	(95032524) AT (	0.00,	0.00) GC	14.	7.85833m	(95040924) AT (	5000.00,	5000.00) GC
5.	10.42048m	(95043024) AT (	5000.00,	5000.00) GC	15.	7.77990	(95120824) AT (	0.00,	-5000.00) GC
6.	10.41323	(95221024) AT (	5000.00,	0.00) GC	16.	7.56680	(95203124) AT (	-5000.00,	5000.00) GC
7.	8.91219	(95070724) AT (	5000.00,	0.00) GC	17.	7.44870	(95220224) AT (	0.00,	-5000.00) GC
8.	8.91219	(95070724) AT (	5000.00,	5000.00) GC	18.	7.31534m	(95031624) AT (	-5000.00,	5000.00) GC
9.	8.75719	(95103024) AT (	0.00,	5000.00) GC	19.	7.23981	(95040424) AT (	5000.00,	-5000.00) GC
10.	8.43232	(95081824) AT (	0.00,	-5000.00) GC	20.	7.23981	(95040424) AT (	-5000.00,	5000.00) GC

RECEPTOR TYPES: GC = GRIDCART  
 GP = GRIDPOLR  
 DC = DISCCART  
 DP = DISCPOLR

### Annual Average Concentration Values of PM for the Year 1995

MODELING OPTIONS USED: CONC ELEV DEFAULT  
 INCLUDING SOURCE(S) FACTOR FROM SOURCE GROUP: ALL \*\*\*  
 \*\*\* NETWORK MODEL (CONC IN MICROGRAMS/M<sup>3</sup>) \*\*\*  
 CONC OF PM IN MICROGRAMS/M<sup>3</sup>

Y COORD (METERS)	50000.00	45000.00	40000.00	35000.00	X COORD (METERS)	-30000.00	-25000.00	-20000.00	-15000.00	-10000.00
50000.00	0.06337	0.06622	0.07015	0.07650	0.08103	0.08608	0.09038	0.08554	0.08527	0.08819
45000.00	0.06726	0.06948	0.07292	0.07944	0.08774	0.09786	0.08962	0.09186	0.09604	0.09064
40000.00	0.07487	0.07563	0.07336	0.08180	0.09171	0.10052	0.10952	0.10900	0.10744	0.10325
35000.00	0.08319	0.08522	0.08772	0.09072	0.09673	0.10229	0.10829	0.11529	0.11910	0.12021
30000.00	0.08633	0.08446	0.08994	0.10190	0.11455	0.12853	0.14455	0.13083	0.13468	0.14733
25000.00	0.08020	0.08268	0.08255	0.09225	0.10129	0.11129	0.11953	0.12829	0.13729	0.14733
20000.00	0.08022	0.08893	0.10021	0.11783	0.14475	0.17322	0.19450	0.19859	0.18200	0.20145
15000.00	0.08707	0.09554	0.10535	0.11961	0.13712	0.16606	0.21476	0.21114	0.20506	0.21506
10000.00	0.07437	0.08462	0.09612	0.11276	0.13485	0.16466	0.20589	0.27214	0.27280	0.41962
5000.00	0.05676	0.06333	0.07074	0.08123	0.09525	0.11491	0.14446	0.19506	0.29471	0.29471
0.00	0.04927	0.05450	0.05938	0.06735	0.07780	0.09442	0.11395	0.15283	0.25564	0.25564
-5000.00	0.04806	0.05315	0.05890	0.06596	0.07526	0.09182	0.12731	0.18775	0.23037	0.23037
10000.00	0.04613	0.05002	0.05565	0.06561	0.08439	0.11218	0.14609	0.15612	0.16501	0.16501
15000.00	0.04416	0.05112	0.06269	0.07862	0.09871	0.11800	0.11862	0.11626	0.12558	0.12558
20000.00	0.04969	0.05999	0.07266	0.08665	0.09833	0.09559	0.09088	0.10223	0.10223	0.10223
25000.00	0.05706	0.06682	0.07674	0.08367	0.07955	0.07505	0.08156	0.08456	0.08456	0.08456
30000.00	0.06153	0.06884	0.07240	0.08002	0.08368	0.06996	0.06996	0.10408	0.10408	0.10408
35000.00	0.05732	0.06384	0.06941	0.07557	0.07909	0.06791	0.07866	0.10103	0.10103	0.10103
40000.00	0.05479	0.06245	0.06858	0.07481	0.07870	0.07470	0.07894	0.09804	0.09804	0.09804
45000.00	0.04711	0.04407	0.04302	0.04912	0.05568	0.06312	0.06033	0.08033	0.08033	0.08033



MODELING OPTIONS USED: CONC ELEV DEFAULT  
 \*\*\* THE PERIOD (8760 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL \*\*\*  
 INCLUDING SOURCE (S): STACK 1  
 \*\*\* NETWORK ID: CQ1; NETWORK TYPE: GRIDCAST \*\*\*  
 CONC OF PM IN MICROGRAMS/M\*\*3

Y-COORD (METERS)	X-COORD (METERS)									
	-5000.00	0.00	5000.00	10000.00	15000.00	20000.00	25000.00	30000.00	35000.00	
50000.00	0.26714	0.09480	0.09094	0.08677	0.07287	0.10250	0.10785	0.10514	0.09508	
45000.00	0.09586	0.10475	0.10014	0.09107	0.10650	0.11131	0.11895	0.10523	0.09833	
40000.00	0.11927	0.12591	0.12648	0.13036	0.14801	0.15840	0.13318	0.11976	0.10905	
35000.00	0.13753	0.15381	0.14660	0.15848	0.17614	0.16194	0.14107	0.12670	0.11391	
30000.00	0.16410	0.18272	0.17587	0.20086	0.20415	0.17251	0.15110	0.13408	0.12060	
25000.00	0.20586	0.22529	0.22347	0.25947	0.23319	0.18776	0.16283	0.14391	0.13205	
20000.00	0.27488	0.29445	0.31420	0.31609	0.24810	0.20676	0.18082	0.16727	0.15796	
15000.00	0.39459	0.42831	0.49108	0.36676	0.28640	0.24989	0.22620	0.20268	0.18049	
10000.00	0.62707	0.80938	0.70026	0.48664	0.38762	0.31099	0.25510	0.21460	0.18470	
5000.00	0.59098	0.00000	1.00068	0.51858	0.35893	0.27628	0.22460	0.18511	0.16334	
0.00	0.46301	0.94682	0.71370	0.30027	0.20514	0.16571	0.14351	0.12773	0.11540	
-5000.00	0.30444	0.42668	0.50508	0.33406	0.20332	0.14372	0.11602	0.09968	0.08901	
-10000.00	0.26682	0.30213	0.41698	0.29747	0.21328	0.15251	0.11713	0.09451	0.08129	
-15000.00	0.20226	0.22478	0.33532	0.26135	0.19595	0.16252	0.12399	0.09444	0.08291	
-20000.00	0.16267	0.17861	0.27182	0.22907	0.18986	0.16679	0.12395	0.09444	0.08770	
-25000.00	0.13663	0.14761	0.22441	0.20893	0.15513	0.14636	0.11205	0.10719	0.09452	
-30000.00	0.11023	0.11867	0.17478	0.17007	0.12785	0.12785	0.11285	0.09869	0.09341	
-35000.00	0.10275	0.10947	0.15830	0.17702	0.14720	0.13785	0.11825	0.09825	0.09423	
-40000.00	0.09072	0.09734	0.13321	0.16077	0.14045	0.11905	0.10979	0.09525	0.09142	
-45000.00	0.08097	0.08719	0.11396	0.14524	0.13453	0.11302	0.10172	0.09620	0.09391	
-50000.00										

MODELING OPTIONS USED: CONC ELEV      DEFAULT  
 THE PERIOD (8760 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ALL  
 INCLUDING SOURCE (S): STACK 1  
 \*\*\* NETWORK ID: C01; NETWORK TYPE: GRIDCART \*\*\*  
 CONC OF PM IN MICROGRAMS/M\*\*3

Y-COORD (METERS)	40000.00	45000.00	50000.00	X-COORD (METERS)
50000.00	0.08712	0.08225	0.07645	0.07645
45000.00	0.09185	0.08495	0.07813	0.07813
40000.00	0.09555	0.08733	0.08157	0.08157
35000.00	0.09891	0.09152	0.08478	0.08478
30000.00	0.10408	0.09559	0.08961	0.08961
25000.00	0.11031	0.10400	0.10025	0.10025
20000.00	0.12539	0.12098	0.11640	0.11640
15000.00	0.14824	0.13771	0.12733	0.12733
10000.00	0.16090	0.14418	0.13022	0.13022
5000.00	0.16195	0.14414	0.12983	0.12983
0.00	0.14302	0.12852	0.11621	0.11621
-500.00	0.10940	0.09706	0.09000	0.09000
-1000.00	0.08241	0.07581	0.07031	0.07031
-15000.00	0.07261	0.07243	0.07106	0.07106
-20000.00	0.07641	0.06252	0.05731	0.05731
-25000.00	0.07459	0.06405	0.05598	0.05598
-30000.00	0.07784	0.06756	0.05931	0.05931
-35000.00	0.07958	0.06868	0.06159	0.06159
-40000.00	0.08206	0.07310	0.06310	0.06310
-45000.00	0.07729	0.07322	0.06303	0.06303
-50000.00	0.07251	0.06926	0.06612	0.06612

MODELING OPTIONS USED: CONC ELEV DEFAULT  
 \*\*\* THE SUMMARY OF MAXIMUM PERIOD (8760 HRS) RESULTS \*\*\*  
 CONC OF PM IN MICROGRAMS/M\*\*3

GROUP ID	AVERAGE CONC	RECEPTOR (XR, YR, Z/ELEV, ZFLAG)	OF TYPE	NETWORK GRID-ID			
ALL	1.00068 AT (	5000.00,	0.00,	0.00,	OC	CC1	
	2ND HIGHEST VALUE IS	0.94682 AT (	0.00,	23.16,	0.00)	OC	CC1
	3RD HIGHEST VALUE IS	0.80938 AT (	5000.00,	23.16,	0.00)	OC	CC1
	4TH HIGHEST VALUE IS	0.71370 AT (	5000.00,	23.16,	0.00)	OC	CC1
	5TH HIGHEST VALUE IS	0.70026 AT (	5000.00,	0.00,	0.00)	OC	CC1
	6TH HIGHEST VALUE IS	0.62707 AT (	-5000.00,	23.16,	0.00)	OC	CC1

\*\*\* RECEPTOR TYPES: OC = GRIDCART  
 GP = GRIDPOLAR  
 DC = DISCONT  
 DP = DISCPOLAR  
 \*\*\* AERMOD - VERSION 99351 \*\*\*

**APPENDIX – F**

## CORMIX SESSION REPORT FOR ELEVATED TEMPERATURE:

CORMIX: CORNELL MIXING ZONE EXPERT SYSTEM

CORMIX-GJ Version 4.1GT

SITE NAME/LABEL: Al-Jubail Saudi Arabia

DESIGN CASE: MSF Desalination Plant

FILE NAME: E:\cormix\Mansoor.prd

Using subsystem CORMIX1: Submerged Single Port Discharges

Start of session: 07/16/2002--14:27:14

\*\*\*\*\*  
**SUMMARY OF INPUT DATA:**

-----  
**AMBIENT PARAMETERS:**

Cross-section = unbounded  
Average depth HA = 5 m  
Depth at discharge HD = 4 m  
Ambient velocity UA = 0.5 m/s  
Darcy-Weisbach friction factor F = 0.025  
Wind velocity UW = 5 m/s  
Stratification Type STRCND = U  
Surface density RHOAS = 1027.5 kg/m<sup>3</sup>  
Bottom density RHOAB = 1027.5 kg/m<sup>3</sup>

-----  
**DISCHARGE PARAMETERS:** Submerged Single Port Discharge

Nearest bank = left  
Distance to bank DISTB = 2000 m  
Port diameter DO = 0.9 m  
Port cross-sectional area AO = 0.6362 m<sup>2</sup>  
Discharge velocity UO = 25.54 m/s  
Discharge flowrate QO = 16.25 m<sup>3</sup>/s  
Discharge port height HO = 0.2 m  
Vertical discharge angle THETA = 45 deg  
Horizontal discharge angle SIGMA = 90 deg  
Discharge density RHO0 = 1046.5 kg/m<sup>3</sup>  
Density difference DRHO = -19 kg/m<sup>3</sup>  
Buoyant acceleration GPO = -0.1813 m/s<sup>2</sup>  
Discharge concentration CO = 6.94 deg. C  
Surface heat exchange coeff. KS = 0.000007 m/s  
Coefficient of decay KD = 0 /s

-----  
**DISCHARGE/ENVIRONMENT LENGTH SCALES:**

LQ = 0.80 m Lm = 40.75 m Lb = 23.57 m  
LM = 53.57 m Lm' = 99999 m Lb' = 99999 m

-----  
**NON-DIMENSIONAL PARAMETERS:**

Port densimetric Froude number FR0 = 63.23  
Velocity ratio R = 51.09

---

**MIXING ZONE / TOXIC DILUTION ZONE / AREA OF INTEREST  
PARAMETERS:**

Toxic discharge = no  
Water quality standard specified = no  
Regulatory mixing zone = no  
Region of interest = 2000 m downstream

\*\*\*\*\*  
**HYDRODYNAMIC CLASSIFICATION:**

\*-----\*  
| FLOW CLASS = NH5 |  
\*-----\*

This flow configuration applies to a layer corresponding to the full water depth at the discharge site.

Applicable layer depth = water depth = 4 m

\*\*\*\*\*  
**MIXING ZONE EVALUATION (hydrodynamic and regulatory summary):**

-----  
X-Y-Z Coordinate system:

Origin is located at the bottom below the port center:

2000 m from the left bank/shore.

Number of display steps NSTEP = 200 per module.

-----  
**NEAR-FIELD REGION (NFR) CONDITIONS :**

Note: The NFR is the zone of strong initial mixing. It has no regulatory implication. However, this information may be useful for the discharge designer because the mixing in the NFR is usually sensitive to the discharge design conditions.

Pollutant concentration at edge of NFR = 0.38 deg. C

Dilution at edge of NFR = 18.3

NFR Location: x = 101.41 m

(centerline coordinates) y = 173.25 m

z = 0 m

NFR plume dimensions: half-width = 14.91 m

thickness = 4 m

-----  
**Buoyancy assessment:**

The effluent density is greater than the surrounding ambient water density at the discharge level.

Therefore, the effluent is **NEGATIVELY BUOYANT** and will tend to sink towards the bottom.

-----  
Near-field instability behavior:

The discharge flow will experience instabilities with full vertical mixing in the near-field.

There may be benthic impact of high pollutant concentrations.

-----  
**FAR-FIELD MIXING SUMMARY:**

Plume becomes vertically fully mixed **ALREADY IN NEAR-FIELD** at 0 m

downstream and continues as vertically mixed into the far-field.

---

**PLUME BANK CONTACT SUMMARY:**

Plume in unbounded section does not contact bank in this simulation.

\*\*\*\*\*

**TOXIC DILUTION ZONE SUMMARY**

No TDZ was specified for this simulation.

\*\*\*\*\*

**REGULATORY MIXING ZONE SUMMARY**

No RMZ and no ambient water quality standard have been specified.

\*\*\*\*\*

**FINAL DESIGN ADVICE AND COMMENTS**

The discharge port or nozzle points towards the nearest bank.

Since this is an UNUSUAL DESIGN, check whether you have specified correctly the port horizontal angle (SIGMA).

---

REMINDER: The user must take note that HYDRODYNAMIC MODELING by any known technique is NOT AN EXACT SCIENCE.

Extensive comparison with field and laboratory data has shown that the CORMIX predictions on dilutions and concentrations (with associated plume geometries) are reliable for the majority of cases and are accurate to within about +50% (standard deviation).

As a further safeguard, CORMIX will not give predictions whenever it judges the design configuration as highly complex and uncertain for prediction.

## CORMIX1 PREDICTION FILE FOR ELEVATED TEMPERATURE:

CORNELL MIXING ZONE EXPERT SYSTEM  
Subsystem CORMIX1: Submerged Single Port Discharges  
CORMIX-GI Version 4.1GT

---

### CASE DESCRIPTION

Site name/label: Al-Jubail Saudi Arabia  
Design case: MSF Desalination Plant  
FILE NAME: E:\cormix\Mansoor.prd  
Time stamp: Tue Jul 16 14:27:15 2002

### ENVIRONMENT PARAMETERS (metric units)

Unbounded section  
HA = 5.00 HD = 4.00  
UA = 0.500 F = 0.025 USTAR=0.2795E-01  
UW = 5.000 UWSTAR=0.5890E-02  
Uniform density environment  
STRCND= U RHOAM = 1027.5000

### DISCHARGE PARAMETERS (metric units)

BANK = LEFT DISTB = 2000.00  
D0 = 0.900 A0 = 0.636 H0 = 0.20  
THETA = 45.00 SIGMA = 90.00  
U0 = 25.543 Q0 = 16.250 =0.1625E+02  
RHO0 = 1046.5000 DRHO0=-.1900E+02 GPO =-.1813E+00  
C0 = 0.6940E+01 CUNITS= deg. C  
IPOLL = 3 KS =0.7165E-05 KD =0.0000E+00

### FLUX VARIABLES (metric units)

Q0 =0.1625E+02 M0 =0.4151E+03 J0 =-.2947E+01 SIGNJ0= -1.0  
Associated length scales (meters)  
LQ = 0.80 LM = 53.57 Lm = 40.75 Lb = 23.57  
Lmp = 99999.00 Lbp = 99999.00

### NON-DIMENSIONAL PARAMETERS

FR0 = 63.23 R = 51.09

### FLOW CLASSIFICATION

1 Flow class (CORMIX1) = NH5 1  
1 Applicable layer depth HS = 4.00 1

### MIXING ZONE / TOXIC DILUTION / REGION OF INTEREST PARAMETERS

C0 = 0.6940E+01 CUNITS= deg. C  
NTOX = 0  
NSTD = 0  
REGMZ = 0  
XINT = 2000.00 XMAX = 2000.00



**X-Y-Z COORDINATE SYSTEM:**

ORIGIN is located at the bottom and below the center of the port:

2000.00 m from the LEFT bank/shore.

X-axis points downstream, Y-axis points to left, Z-axis points upward.

NSTEP =200 display intervals per module

NOTE on dilution/concentration values for this HEATED DISCHARGE (IPOLL=3):

S = hydrodynamic dilutions, include buoyancy (heat) loss effects, but provided plume has surface contact

C = corresponding temperature values (always in "degC"), include heat loss, if any

**BEGIN MOD101: DISCHARGE MODULE**

COANDA ATTACHMENT immediately following the discharge.

X	Y	Z	S	C	B
0.00	0.00	0.00	1.0	0.694E+01	0.64

END OF MOD101: DISCHARGE MODULE

**BEGIN CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION**

Bottom-attached jet motion.

Profile definitions:

B = Gaussian 1/e (37%) half-width, normal to trajectory

Half wall jet, attached to bottom.

S = hydrodynamic centerline dilution

C = centerline concentration (includes reaction effects, if any)

X	Y	Z	S	C	B
0.00	0.00	0.00	1.0	0.694E+01	0.45
0.00	0.12	0.00	1.0	0.694E+01	0.47
0.00	0.28	0.00	1.0	0.694E+01	0.49
0.00	0.44	0.00	1.0	0.694E+01	0.50
0.00	0.60	0.00	1.0	0.694E+01	0.52
0.00	0.76	0.00	1.0	0.694E+01	0.54
0.00	0.92	0.00	1.0	0.694E+01	0.56
0.00	1.08	0.00	1.0	0.694E+01	0.57
0.00	1.24	0.00	1.0	0.694E+01	0.59
0.00	1.36	0.00	1.0	0.694E+01	0.60
0.01	1.52	0.00	1.0	0.694E+01	0.62
0.01	1.68	0.00	1.0	0.694E+01	0.64
0.01	1.84	0.00	1.0	0.694E+01	0.66
0.01	2.00	0.00	1.0	0.694E+01	0.67
0.01	2.16	0.00	1.0	0.694E+01	0.69
0.01	2.32	0.00	1.0	0.694E+01	0.71
0.02	2.48	0.00	1.0	0.694E+01	0.73
0.02	2.64	0.00	1.0	0.694E+01	0.75
0.02	2.76	0.00	1.0	0.694E+01	0.76
0.02	2.92	0.00	1.0	0.682E+01	0.78
0.02	3.08	0.00	1.0	0.667E+01	0.79
0.03	3.24	0.00	1.1	0.652E+01	0.81
0.03	3.40	0.00	1.1	0.638E+01	0.83

0.03	3.56	0.00	1.1	0.625E+01	0.85
0.04	3.72	0.00	1.1	0.612E+01	0.86
0.04	3.88	0.00	1.2	0.600E+01	0.88
0.04	4.04	0.00	1.2	0.588E+01	0.90
0.04	4.16	0.00	1.2	0.580E+01	0.91
0.05	4.32	0.00	1.2	0.569E+01	0.93
0.05	4.48	0.00	1.2	0.558E+01	0.95
0.06	4.64	0.00	1.3	0.548E+01	0.97
0.06	4.80	0.00	1.3	0.538E+01	0.98
0.06	4.96	0.00	1.3	0.528E+01	1.00
0.07	5.12	0.00	1.3	0.519E+01	1.02
0.07	5.28	0.00	1.4	0.510E+01	1.04
0.08	5.44	0.00	1.4	0.502E+01	1.05
0.08	5.56	0.00	1.4	0.496E+01	1.07
0.08	5.72	0.00	1.4	0.488E+01	1.08
0.09	5.88	0.00	1.4	0.480E+01	1.10
0.09	6.04	0.00	1.5	0.465E+01	1.14
0.10	6.36	0.00	1.5	0.458E+01	1.16
0.11	6.52	0.00	1.5	0.451E+01	1.17
0.12	6.68	0.00	1.6	0.444E+01	1.19
0.12	6.84	0.00	1.6	0.437E+01	1.21
0.13	6.96	0.00	1.6	0.433E+01	1.22
0.13	7.12	0.00	1.6	0.426E+01	1.24
0.14	7.28	0.00	1.7	0.420E+01	1.26
0.14	7.44	0.00	1.7	0.415E+01	1.28
0.15	7.60	0.00	1.7	0.409E+01	1.29
0.16	7.76	0.00	1.7	0.403E+01	1.31
0.16	7.92	0.00	1.7	0.398E+01	1.33
0.17	8.08	0.00	1.8	0.393E+01	1.35
0.18	8.24	0.00	1.8	0.388E+01	1.36
0.18	8.36	0.00	1.8	0.384E+01	1.38
0.19	8.52	0.00	1.8	0.379E+01	1.40
0.20	8.68	0.00	1.9	0.374E+01	1.41
0.20	8.84	0.00	1.9	0.369E+01	1.43
0.21	9.00	0.00	1.9	0.365E+01	1.45
0.22	9.16	0.00	1.9	0.360E+01	1.47
0.23	9.32	0.00	1.9	0.356E+01	1.48
0.24	9.48	0.00	2.0	0.352E+01	1.50
0.24	9.64	0.00	2.0	0.348E+01	1.52
0.25	9.76	0.00	2.0	0.345E+01	1.53
0.26	9.92	0.00	2.0	0.341E+01	1.55
0.27	10.08	0.00	2.1	0.337E+01	1.57
0.28	10.24	0.00	2.1	0.333E+01	1.59
0.28	10.39	0.00	2.1	0.329E+01	1.60
0.29	10.55	0.00	2.1	0.326E+01	1.62
0.30	10.71	0.00	2.2	0.322E+01	1.64
0.31	10.87	0.00	2.2	0.319E+01	1.66
0.32	11.03	0.00	2.2	0.315E+01	1.68
0.33	11.15	0.00	2.2	0.313E+01	1.69
0.34	11.31	0.00	2.2	0.309E+01	1.71
0.35	11.47	0.00	2.3	0.306E+01	1.72
0.36	11.63	0.00	2.3	0.303E+01	1.74
0.37	11.79	0.00	2.3	0.300E+01	1.76

0.38	11.95	0.00	2.3	0.297E+01	1.78
0.39	12.11	0.00	2.4	0.294E+01	1.80
0.40	12.27	0.00	2.4	0.291E+01	1.81
0.41	12.43	0.00	2.4	0.288E+01	1.83
0.42	12.55	0.00	2.4	0.286E+01	1.85
0.43	12.71	0.00	2.4	0.283E+01	1.86
0.44	12.87	0.00	2.5	0.281E+01	1.88
0.45	13.03	0.00	2.5	0.278E+01	1.90
0.46	13.19	0.00	2.5	0.275E+01	1.92
0.48	13.35	0.00	2.5	0.273E+01	1.94
0.49	13.51	0.00	2.6	0.270E+01	1.95
0.50	13.67	0.00	2.6	0.268E+01	1.97
0.51	13.83	0.00	2.6	0.265E+01	1.99
0.52	13.95	0.00	2.6	0.263E+01	2.00
0.53	14.11	0.00	2.7	0.261E+01	2.02
0.54	14.27	0.00	2.7	0.259E+01	2.04
0.56	14.43	0.00	2.7	0.256E+01	2.06
0.57	14.58	0.00	2.7	0.254E+01	2.08
0.58	14.74	0.00	2.8	0.252E+01	2.09
0.60	14.90	0.00	2.8	0.250E+01	2.11
0.61	15.06	0.00	2.8	0.248E+01	2.13
0.62	15.22	0.00	2.8	0.246E+01	2.15
0.63	15.34	0.00	2.8	0.244E+01	2.16
0.65	15.50	0.00	2.9	0.242E+01	2.18
0.66	15.66	0.00	2.9	0.240E+01	2.20
0.67	15.82	0.00	2.9	0.238E+01	2.22
0.69	15.98	0.00	2.9	0.236E+01	2.23
0.70	16.14	0.00	3.0	0.234E+01	2.25
0.72	16.30	0.00	3.0	0.232E+01	2.27
0.73	16.46	0.00	3.0	0.230E+01	2.29
0.75	16.62	0.00	3.0	0.229E+01	2.31
0.76	16.74	0.00	3.1	0.227E+01	2.32
0.77	16.90	0.00	3.1	0.225E+01	2.34
0.79	17.06	0.00	3.1	0.224E+01	2.36
0.80	17.21	0.00	3.1	0.222E+01	2.37
0.82	17.37	0.00	3.2	0.220E+01	2.39
0.84	17.53	0.00	3.2	0.219E+01	2.41
0.85	17.69	0.00	3.2	0.217E+01	2.43
0.87	17.85	0.00	3.2	0.215E+01	2.45
0.88	18.01	0.00	3.2	0.214E+01	2.47
0.90	18.13	0.00	3.3	0.212E+01	2.48
0.91	18.29	0.00	3.3	0.211E+01	2.50
0.93	18.45	0.00	3.3	0.209E+01	2.52
0.95	18.61	0.00	3.3	0.208E+01	2.53
0.96	18.77	0.00	3.4	0.206E+01	2.55
0.98	18.93	0.00	3.4	0.205E+01	2.57
1.00	19.08	0.00	3.4	0.203E+01	2.59
1.01	19.24	0.00	3.4	0.202E+01	2.61
1.03	19.40	0.00	3.5	0.200E+01	2.63
1.05	19.52	0.00	3.5	0.199E+01	2.64
1.06	19.68	0.00	3.5	0.198E+01	2.66
1.08	19.84	0.00	3.5	0.197E+01	2.68
1.10	20.00	0.00	3.6	0.195E+01	2.69

1.12	20.16	0.00	3.6	0.194E+01	2.71
1.14	20.32	0.00	3.6	0.193E+01	2.73
1.15	20.48	0.00	3.6	0.191E+01	2.75
1.17	20.63	0.00	3.7	0.190E+01	2.77
1.19	20.79	0.00	3.7	0.189E+01	2.79
1.21	20.91	0.00	3.7	0.188E+01	2.80
1.23	21.07	0.00	3.7	0.187E+01	2.82
1.25	21.23	0.00	3.7	0.185E+01	2.84
1.27	21.39	0.00	3.8	0.184E+01	2.86
1.29	21.55	0.00	3.8	0.183E+01	2.87
1.31	21.71	0.00	3.8	0.182E+01	2.89
1.33	21.87	0.00	3.8	0.180E+01	2.91
1.35	22.02	0.00	3.9	0.179E+01	2.93
1.37	22.18	0.00	3.9	0.178E+01	2.95
1.38	22.30	0.00	3.9	0.177E+01	2.96
1.40	22.46	0.00	3.9	0.176E+01	2.98
1.42	22.62	0.00	4.0	0.175E+01	3.00
1.44	22.78	0.00	4.0	0.174E+01	3.02
1.47	22.94	0.00	4.0	0.173E+01	3.04
1.49	23.09	0.00	4.0	0.172E+01	3.06
1.51	23.25	0.00	4.1	0.171E+01	3.08
1.53	23.41	0.00	4.1	0.170E+01	3.09
1.55	23.57	0.00	4.1	0.169E+01	3.11
1.57	23.69	0.00	4.1	0.168E+01	3.13
1.59	23.85	0.00	4.2	0.167E+01	3.15
1.61	24.01	0.00	4.2	0.166E+01	3.16
1.64	24.16	0.00	4.2	0.165E+01	3.18
1.66	24.32	0.00	4.2	0.164E+01	3.20
1.68	24.48	0.00	4.3	0.163E+01	3.22
1.71	24.64	0.00	4.3	0.162E+01	3.24
1.73	24.80	0.00	4.3	0.161E+01	3.26
1.75	24.96	0.00	4.3	0.160E+01	3.28
1.77	25.07	0.00	4.4	0.159E+01	3.29
1.79	25.23	0.00	4.4	0.158E+01	3.31
1.82	25.39	0.00	4.4	0.157E+01	3.33
1.84	25.55	0.00	4.4	0.157E+01	3.35
1.87	25.71	0.00	4.5	0.156E+01	3.37
1.89	25.87	0.00	4.5	0.155E+01	3.39
1.92	26.02	0.00	4.5	0.154E+01	3.40
1.94	26.18	0.00	4.5	0.153E+01	3.42
1.97	26.34	0.00	4.6	0.152E+01	3.44
1.98	26.46	0.00	4.6	0.152E+01	3.46
2.01	26.62	0.00	4.6	0.151E+01	3.48
2.04	26.77	0.00	4.6	0.150E+01	3.49
2.06	26.93	0.00	4.7	0.149E+01	3.51
2.09	27.09	0.00	4.7	0.148E+01	3.53
2.11	27.25	0.00	4.7	0.147E+01	3.55
2.14	27.41	0.00	4.7	0.147E+01	3.57
2.17	27.56	0.00	4.8	0.146E+01	3.59
2.19	27.72	0.00	4.8	0.145E+01	3.61
2.21	27.84	0.00	4.8	0.144E+01	3.62
2.24	28.00	0.00	4.8	0.144E+01	3.64
2.27	28.15	0.00	4.9	0.143E+01	3.66

**APPENDIX – G**

## CORMIX SESSION REPORT FOR TOTAL DISSOLVED SOLIDS:

CORMIX: CORNELL MIXING ZONE EXPERT SYSTEM

CORMIX-GI Version 4.1GT

SITE NAME/LABEL: Al-Jubail Saudi Arabia

DESIGN CASE: MSF Desalination Plant

FILE NAME: E:\cormix\MansoorTDS.prd

Using subsystem CORMIX1: Submerged Single Port Discharges

Start of session: 07/16/2002--14:55:32

\*\*\*\*\*

### SUMMARY OF INPUT DATA:

#### AMBIENT PARAMETERS:

Cross-section = unbounded  
Average depth HA = 5 m  
Depth at discharge HD = 4 m  
Ambient velocity UA = 0.5 m/s  
Darcy-Weisbach friction factor F = 0.025  
Wind velocity UW = 5 m/s  
Stratification Type STRCND = U  
Surface density RHOAS = 1027.5 kg/m<sup>3</sup>  
Bottom density RHOAB = 1027.5 kg/m<sup>3</sup>

#### DISCHARGE PARAMETERS:

Submerged Single Port Discharge

Nearest bank = left  
Distance to bank DISTB = 2000 m  
Port diameter DO = 0.9 m  
Port cross-sectional area AO = 0.6362 m<sup>2</sup>  
Discharge velocity UO = 25.54 m/s  
Discharge flowrate QO = 16.25 m<sup>3</sup>/s  
Discharge port height HO = 0.2 m  
Vertical discharge angle THETA = 45 deg  
Horizontal discharge angle SIGMA = 90 deg  
Discharge density RHOO = 1046.5 kg/m<sup>3</sup>  
Density difference DRHO = -19 kg/m<sup>3</sup>  
Buoyant acceleration GPO = -0.1813 m/s<sup>2</sup>  
Discharge concentration CO = 25000 ppm  
Surface heat exchange coeff. KS = 0 m/s  
Coefficient of decay KD = 0 /s

#### DISCHARGE/ENVIRONMENT LENGTH SCALES:

LQ = 0.80 m Lm = 40.75 m Lb = 23.57 m  
LM = 53.57 m Lm' = 99999 m Lb' = 99999 m

#### NON-DIMENSIONAL PARAMETERS:

Port densimetric Froude number FR0 = 63.23  
Velocity ratio R = 51.09

**MIXING ZONE / TOXIC DILUTION ZONE / AREA OF INTEREST  
PARAMETERS:**

Toxic discharge = no  
Water quality standard specified = no  
Regulatory mixing zone = no  
Region of interest = 2000 m downstream  
\*\*\*\*\*

**HYDRODYNAMIC CLASSIFICATION:**

\*-----\*  
| FLOW CLASS = NH5 |  
\*-----\*

This flow configuration applies to a layer corresponding to the full water depth at the discharge site.

Applicable layer depth = water depth = 4 m  
\*\*\*\*\*

**MIXING ZONE EVALUATION (hydrodynamic and regulatory summary):**

X-Y-Z Coordinate system:

Origin is located at the bottom below the port center:

2000 m from the left bank/shore.

Number of display steps NSTEP = 200 per module.

**NEAR-FIELD REGION (NFR) CONDITIONS :**

Note: The NFR is the zone of strong initial mixing. It has no regulatory implication. However, this information may be useful for the discharge designer because the mixing in the NFR is usually sensitive to the discharge design conditions.

Pollutant concentration at edge of NFR = 1368.7229 ppm

Dilution at edge of NFR = 18.3

NFR Location: x = 101.41 m

(centerline coordinates) y = 173.25 m

z = 0 m

NFR plume dimensions: half-width = 14.91 m

thickness = 4 m  
-----

**Buoyancy assessment:**

The effluent density is greater than the surrounding ambient water density at the discharge level.

Therefore, the effluent is **NEGATIVELY BUOYANT** and will tend to sink towards the bottom.

**Near-field instability behavior:**

The discharge flow will experience instabilities with full vertical mixing in the near-field.

There may be benthic impact of high pollutant concentrations.  
-----

**FAR-FIELD MIXING SUMMARY:**

Plume becomes vertically fully mixed **ALREADY IN NEAR-FIELD** at 0 m downstream and continues as vertically mixed into the far-field.

**PLUME BANK CONTACT SUMMARY:**

Plume in unbounded section does not contact bank in this simulation.

\*\*\*\*\*

**TOXIC DILUTION ZONE SUMMARY**

No TDZ was specified for this simulation.

\*\*\*\*\*

**REGULATORY MIXING ZONE SUMMARY**

No RMZ and no ambient water quality standard have been specified.

\*\*\*\*\*

**FINAL DESIGN ADVICE AND COMMENTS**

The discharge port or nozzle points towards the nearest bank.

Since this is an UNUSUAL DESIGN, check whether you have specified correctly the port horizontal angle (SIGMA).

-----  
REMINDER: The user must take note that HYDRODYNAMIC MODELING by any known technique is NOT AN EXACT SCIENCE.

Extensive comparison with field and laboratory data has shown that the CORMIX predictions on dilutions and concentrations (with associated plume geometries) are reliable for the majority of cases and are accurate to within about  $\pm 50\%$  (standard deviation).

As a further safeguard, CORMIX will not give predictions whenever it judges the design configuration as highly complex and uncertain for prediction.



## CORMIX1 PREDICTION FILE FOR TOTAL DISSOLVED SOLIDS:

### CORNELL MIXING ZONE EXPERT SYSTEM

Subsystem CORMIX1: Submerged Single Port Discharges

CORMIX-GI Version 4.1GT

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### CASE DESCRIPTION

Site name/label: Al-Jubail Saudi Arabia

Design case: MSF Desalination Plant

FILE NAME: E:\cormix\MansoorTDS.prd

Time stamp: Tue Jul 16 14:55:33 2002

### ENVIRONMENT PARAMETERS (metric units)

Unbounded section

HA = 5.00 HD = 4.00

UA = 0.500 F = 0.025 USTAR = 0.2795E-01

UW = 5.000 UWSTAR = 0.5890E-02

Uniform density environment

STRCND= U RHOAM = 1027.5000

### DISCHARGE PARAMETERS (metric units)

BANK = LEFT DISTB = 2000.00

DO = 0.900 A0 = 0.636 H0 = 0.20

THETA = 45.00 SIGMA = 90.00

U0 = 25.543 Q0 = 16.250 = 0.1625E+02

RHO0 = 1046.5000 DRHO0 = -.1900E+02 GP0 = -.1813E+00

C0 = 0.2500E+05 CUNITS= ppm

IPOLL = 1 KS = 0.0000E+00 KD = 0.0000E+00

### FLUX VARIABLES (metric units)

Q0 = 0.1625E+02 M0 = 0.4151E+03 J0 = -.2947E+01 SIGNJ0 = -1.0

Associated length scales (meters)

LQ = 0.80 LM = 53.57 Lm = 40.75 Lb = 23.57

Lmp = 99999.00 Lbp = 99999.00

### NON-DIMENSIONAL PARAMETERS

FR0 = 63.23 R = 51.09

### FLOW CLASSIFICATION

1 Flow class (CORMIX1) = NH5 1

1 Applicable layer depth HS = 4.00 1

### MIXING ZONE / TOXIC DILUTION / REGION OF INTEREST PARAMETERS

C0 = 0.2500E+05 CUNITS= ppm

NTOX = 0

NSTD = 0

REGMZ = 0

XINT = 2000.00 XMAX = 2000.00

**X-Y-Z COORDINATE SYSTEM:**

ORIGIN is located at the bottom and below the center of the port:

2000.00 m from the LEFT bank/shore.

X-axis points downstream, Y-axis points to left, Z-axis points upward.

NSTEP =200 display intervals per module

**BEGIN MOD101: DISCHARGE MODULE**

COANDA ATTACHMENT immediately following the discharge.

X	Y	Z	S	C	B
0.00	0.00	0.00	1.0	0.250E+05	0.64

**END OF MOD101: DISCHARGE MODULE**

---

**BEGIN CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION**

Bottom-attached jet motion.

Profile definitions:

B = Gaussian 1/e (37%) half-width, normal to trajectory

Half wall jet, attached to bottom.

S = hydrodynamic centerline dilution

C = centerline concentration (includes reaction effects, if any)

X	Y	Z	S	C	B
0.00	0.00	0.00	1.0	0.250E+05	0.45
0.00	0.12	0.00	1.0	0.250E+05	0.47
0.00	0.28	0.00	1.0	0.250E+05	0.49
0.00	0.44	0.00	1.0	0.250E+05	0.50
0.00	0.60	0.00	1.0	0.250E+05	0.52
0.00	0.76	0.00	1.0	0.250E+05	0.54
0.00	0.92	0.00	1.0	0.250E+05	0.56
0.00	1.08	0.00	1.0	0.250E+05	0.57
0.00	1.24	0.00	1.0	0.250E+05	0.59
0.00	1.36	0.00	1.0	0.250E+05	0.60
0.01	1.52	0.00	1.0	0.250E+05	0.62
0.01	1.68	0.00	1.0	0.250E+05	0.64
0.01	1.84	0.00	1.0	0.250E+05	0.66
0.01	2.00	0.00	1.0	0.250E+05	0.67
0.01	2.16	0.00	1.0	0.250E+05	0.69
0.01	2.32	0.00	1.0	0.250E+05	0.71
0.02	2.48	0.00	1.0	0.250E+05	0.73
0.02	2.64	0.00	1.0	0.250E+05	0.75
0.02	2.76	0.00	1.0	0.250E+05	0.76
0.02	2.92	0.00	1.0	0.246E+05	0.78
0.02	3.08	0.00	1.0	0.240E+05	0.79
0.03	3.24	0.00	1.1	0.235E+05	0.81
0.03	3.40	0.00	1.1	0.230E+05	0.83
0.03	3.56	0.00	1.1	0.225E+05	0.85
0.04	3.72	0.00	1.1	0.221E+05	0.86
0.04	3.88	0.00	1.2	0.216E+05	0.88
0.04	4.04	0.00	1.2	0.212E+05	0.90

0.04	4.16	0.00	1.2	0.209E+05	0.91
0.05	4.32	0.00	1.2	0.205E+05	0.93
0.05	4.48	0.00	1.2	0.201E+05	0.95
0.06	4.64	0.00	1.3	0.197E+05	0.97
0.06	4.80	0.00	1.3	0.194E+05	0.98
0.06	4.96	0.00	1.3	0.190E+05	1.00
0.07	5.12	0.00	1.3	0.187E+05	1.02
0.07	5.28	0.00	1.4	0.184E+05	1.04
0.08	5.44	0.00	1.4	0.181E+05	1.05
0.08	5.56	0.00	1.4	0.179E+05	1.07
0.08	5.72	0.00	1.4	0.176E+05	1.08
0.09	5.88	0.00	1.4	0.173E+05	1.10
0.09	6.04	0.00	1.5	0.170E+05	1.12
0.10	6.20	0.00	1.5	0.167E+05	1.14
0.10	6.36	0.00	1.5	0.165E+05	1.16
0.11	6.52	0.00	1.5	0.162E+05	1.17
0.12	6.68	0.00	1.6	0.160E+05	1.19
0.12	6.84	0.00	1.6	0.158E+05	1.21
0.13	6.96	0.00	1.6	0.156E+05	1.22
0.13	7.12	0.00	1.6	0.154E+05	1.24
0.14	7.28	0.00	1.7	0.151E+05	1.26
0.14	7.44	0.00	1.7	0.149E+05	1.28
0.15	7.60	0.00	1.7	0.147E+05	1.29
0.16	7.76	0.00	1.7	0.145E+05	1.31
0.16	7.92	0.00	1.7	0.143E+05	1.33
0.17	8.08	0.00	1.8	0.141E+05	1.35
0.18	8.24	0.00	1.8	0.140E+05	1.36
0.18	8.36	0.00	1.8	0.138E+05	1.38
0.19	8.52	0.00	1.8	0.136E+05	1.40
0.20	8.68	0.00	1.9	0.135E+05	1.41
0.20	8.84	0.00	1.9	0.133E+05	1.43
0.21	9.00	0.00	1.9	0.131E+05	1.45
0.22	9.16	0.00	1.9	0.130E+05	1.47
0.23	9.32	0.00	1.9	0.128E+05	1.48
0.24	9.48	0.00	2.0	0.127E+05	1.50
0.24	9.64	0.00	2.0	0.125E+05	1.52
0.25	9.76	0.00	2.0	0.124E+05	1.53
0.26	9.92	0.00	2.0	0.123E+05	1.55
0.27	10.08	0.00	2.1	0.121E+05	1.57
0.28	10.24	0.00	2.1	0.120E+05	1.59
0.28	10.39	0.00	2.1	0.119E+05	1.60
0.29	10.55	0.00	2.1	0.117E+05	1.62
0.30	10.71	0.00	2.2	0.116E+05	1.64
0.31	10.87	0.00	2.2	0.115E+05	1.66
0.32	11.03	0.00	2.2	0.114E+05	1.68
0.33	11.15	0.00	2.2	0.113E+05	1.69
0.34	11.31	0.00	2.2	0.111E+05	1.71
0.35	11.47	0.00	2.3	0.110E+05	1.72
0.36	11.63	0.00	2.3	0.109E+05	1.74
0.37	11.79	0.00	2.3	0.108E+05	1.76
0.38	11.95	0.00	2.3	0.107E+05	1.78
0.39	12.11	0.00	2.4	0.106E+05	1.80
0.40	12.27	0.00	2.4	0.105E+05	1.81

0.41	12.43	0.00	2.4	0.104E+05	1.83
0.42	12.55	0.00	2.4	0.103E+05	1.85
0.43	12.71	0.00	2.4	0.102E+05	1.86
0.44	12.87	0.00	2.5	0.101E+05	1.88
0.45	13.03	0.00	2.5	0.100E+05	1.90
0.46	13.19	0.00	2.5	0.992E+04	1.92
0.48	13.35	0.00	2.5	0.982E+04	1.94
0.49	13.51	0.00	2.6	0.973E+04	1.95
0.50	13.67	0.00	2.6	0.964E+04	1.97
0.51	13.83	0.00	2.6	0.956E+04	1.99
0.52	13.95	0.00	2.6	0.949E+04	2.00
0.53	14.11	0.00	2.7	0.941E+04	2.02
0.54	14.27	0.00	2.7	0.932E+04	2.04
0.56	14.43	0.00	2.7	0.924E+04	2.06
0.57	14.58	0.00	2.7	0.916E+04	2.08
0.58	14.74	0.00	2.8	0.908E+04	2.09
0.60	14.90	0.00	2.8	0.900E+04	2.11
0.61	15.06	0.00	2.8	0.892E+04	2.13
0.62	15.22	0.00	2.8	0.885E+04	2.15
0.63	15.34	0.00	2.8	0.879E+04	2.16
0.65	15.50	0.00	2.9	0.872E+04	2.18
0.66	15.66	0.00	2.9	0.865E+04	2.20
0.67	15.82	0.00	2.9	0.857E+04	2.22
0.69	15.98	0.00	2.9	0.850E+04	2.23
0.70	16.14	0.00	3.0	0.844E+04	2.25
0.72	16.30	0.00	3.0	0.837E+04	2.27
0.73	16.46	0.00	3.0	0.830E+04	2.29
0.75	16.62	0.00	3.0	0.823E+04	2.31
0.76	16.74	0.00	3.1	0.819E+04	2.32
0.77	16.90	0.00	3.1	0.812E+04	2.34
0.79	17.06	0.00	3.1	0.806E+04	2.36
0.80	17.21	0.00	3.1	0.800E+04	2.37
0.82	17.37	0.00	3.2	0.793E+04	2.39
0.84	17.53	0.00	3.2	0.787E+04	2.41
0.85	17.69	0.00	3.2	0.781E+04	2.43
0.87	17.85	0.00	3.2	0.775E+04	2.45
0.88	18.01	0.00	3.2	0.770E+04	2.47
0.90	18.13	0.00	3.3	0.765E+04	2.48
0.91	18.29	0.00	3.3	0.760E+04	2.50
0.93	18.45	0.00	3.3	0.754E+04	2.52
0.95	18.61	0.00	3.3	0.749E+04	2.53
0.96	18.77	0.00	3.4	0.743E+04	2.55
0.98	18.93	0.00	3.4	0.738E+04	2.57
1.00	19.08	0.00	3.4	0.732E+04	2.59
1.01	19.24	0.00	3.4	0.727E+04	2.61
1.03	19.40	0.00	3.5	0.722E+04	2.63
1.05	19.52	0.00	3.5	0.718E+04	2.64
1.06	19.68	0.00	3.5	0.713E+04	2.66
1.08	19.84	0.00	3.5	0.708E+04	2.68
1.10	20.00	0.00	3.6	0.703E+04	2.69
1.12	20.16	0.00	3.6	0.699E+04	2.71
1.14	20.32	0.00	3.6	0.694E+04	2.73
1.15	20.48	0.00	3.6	0.689E+04	2.75

1.17	20.63	0.00	3.7	0.684E+04	2.77
1.19	20.79	0.00	3.7	0.680E+04	2.79
1.21	20.91	0.00	3.7	0.676E+04	2.80
1.23	21.07	0.00	3.7	0.672E+04	2.82
1.25	21.23	0.00	3.7	0.667E+04	2.84
1.27	21.39	0.00	3.8	0.663E+04	2.86
1.29	21.55	0.00	3.8	0.659E+04	2.87
1.31	21.71	0.00	3.8	0.654E+04	2.89
1.33	21.87	0.00	3.8	0.650E+04	2.91
1.35	22.02	0.00	3.9	0.646E+04	2.93
1.37	22.18	0.00	3.9	0.642E+04	2.95
1.38	22.30	0.00	3.9	0.639E+04	2.96
1.40	22.46	0.00	3.9	0.635E+04	2.98
1.42	22.62	0.00	4.0	0.631E+04	3.00
1.44	22.78	0.00	4.0	0.627E+04	3.02
1.47	22.94	0.00	4.0	0.623E+04	3.04
1.49	23.09	0.00	4.0	0.619E+04	3.06
1.51	23.25	0.00	4.1	0.615E+04	3.08
1.53	23.41	0.00	4.1	0.611E+04	3.09
1.55	23.57	0.00	4.1	0.608E+04	3.11
1.57	23.69	0.00	4.1	0.605E+04	3.13
1.59	23.85	0.00	4.2	0.601E+04	3.15
1.61	24.01	0.00	4.2	0.598E+04	3.16
1.64	24.16	0.00	4.2	0.594E+04	3.18
1.66	24.32	0.00	4.2	0.590E+04	3.20
1.68	24.48	0.00	4.3	0.587E+04	3.22
1.71	24.64	0.00	4.3	0.583E+04	3.24
1.73	24.80	0.00	4.3	0.580E+04	3.26
1.75	24.96	0.00	4.3	0.577E+04	3.28
1.77	25.07	0.00	4.4	0.574E+04	3.29
1.79	25.23	0.00	4.4	0.571E+04	3.31
1.82	25.39	0.00	4.4	0.567E+04	3.33
1.84	25.55	0.00	4.4	0.564E+04	3.35
1.87	25.71	0.00	4.5	0.561E+04	3.37
1.89	25.87	0.00	4.5	0.558E+04	3.39
1.92	26.02	0.00	4.5	0.554E+04	3.40
1.94	26.18	0.00	4.5	0.551E+04	3.42
1.97	26.34	0.00	4.6	0.548E+04	3.44
1.98	26.46	0.00	4.6	0.546E+04	3.46
2.01	26.62	0.00	4.6	0.543E+04	3.48
2.04	26.77	0.00	4.6	0.540E+04	3.49
2.06	26.93	0.00	4.7	0.537E+04	3.51
2.09	27.09	0.00	4.7	0.534E+04	3.53
2.11	27.25	0.00	4.7	0.531E+04	3.55
2.14	27.41	0.00	4.7	0.528E+04	3.57
2.17	27.56	0.00	4.8	0.525E+04	3.59
2.19	27.72	0.00	4.8	0.522E+04	3.61
2.21	27.84	0.00	4.8	0.520E+04	3.62
2.24	28.00	0.00	4.8	0.517E+04	3.64
2.27	28.15	0.00	4.9	0.514E+04	3.66
2.29	28.31	0.00	4.9	0.512E+04	3.68
2.32	28.47	0.00	4.9	0.509E+04	3.70
2.35	28.63	0.00	4.9	0.506E+04	3.72

2.38	28.79	0.00	5.0	0.504E+04	3.74
2.40	28.94	0.00	5.0	0.501E+04	3.76
2.43	29.10	0.00	5.0	0.498E+04	3.78
2.45	29.22	0.00	5.0	0.496E+04	3.79
2.48	29.38	0.00	5.1	0.494E+04	3.81
2.51	29.53	0.00	5.1	0.491E+04	3.83
2.54	29.69	0.00	5.1	0.489E+04	3.85
2.57	29.85	0.00	5.1	0.486E+04	3.87
2.60	30.01	0.00	5.2	0.484E+04	3.89
2.63	30.16	0.00	5.2	0.481E+04	3.91
2.66	30.32	0.00	5.2	0.479E+04	3.93
2.69	30.48	0.00	5.2	0.476E+04	3.95
2.71	30.59	0.00	5.3	0.474E+04	3.96
2.74	30.75	0.00	5.3	0.472E+04	3.98
2.77	30.91	0.00	5.3	0.470E+04	4.00

Cumulative travel time = 3. sec

END OF CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION

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 BEGIN MOD133: LAYER BOUNDARY IMPINGEMENT/FULL VERTICAL MIXING

Control volume inflow:

X	Y	Z	S	C	B
2.77	30.91	0.00	5.3	0.470E+04	4.00

Profile definitions:

BV = layer depth (vertically mixed)

BH = top-hat half-width, in horizontal plane normal to trajectory

ZU = upper plume boundary (Z-coordinate)

ZL = lower plume boundary (Z-coordinate)

S = hydrodynamic average (bulk) dilution

C = average (bulk) concentration (includes reaction effects, if any)

X	Y	Z	S	C	BV	BH	ZU	ZL
-1.23	34.84	0.00	5.3	0.470E+04	0.00	0.00	0.00	0.00
-0.76	34.84	0.00	5.3	0.470E+04	4.00	1.08	4.00	0.00
-0.28	34.84	0.00	5.3	0.470E+04	4.00	1.52	4.00	0.00
0.20	34.84	0.00	5.3	0.470E+04	4.00	2.15	4.00	0.00
1.15	34.84	0.00	5.3	0.470E+04	4.00	2.41	4.00	0.00
1.62	34.84	0.00	5.3	0.470E+04	4.00	2.64	4.00	0.00
2.10	34.84	0.00	5.3	0.470E+04	4.00	2.85	4.00	0.00
2.58	34.84	0.00	5.3	0.470E+04	4.00	3.04	4.00	0.00
3.05	34.84	0.00	6.2	0.401E+04	4.00	3.23	4.00	0.00
3.53	34.84	0.00	7.4	0.336E+04	4.00	3.40	4.00	0.00

Cumulative travel time = 5. sec

END OF MOD133: LAYER BOUNDARY IMPINGEMENT/FULL VERTICAL MIXING

**Phase 1: The plume is VERTICALLY FULLY MIXED over the entire layer depth.**

Profile definitions:

BV = layer depth (vertically mixed)

BH = Gaussian 1/e (37%) half-width in horizontal plane normal to trajectory

ZU = upper plume boundary (Z-coordinate)

ZL = lower plume boundary (Z-coordinate)

S = hydrodynamic centerline dilution

C = centerline concentration (includes reaction effects, if any)

X	Y	Z	S	C	BV	BH	ZU	ZL
3.53	34.84	0.00	7.4	0.336E+04	4.00	2.77	4.00	0.00
3.80	35.53	0.00	7.5	0.331E+04	4.00	2.84	4.00	0.00
4.07	36.22	0.00	7.6	0.327E+04	4.00	2.90	4.00	0.00
4.35	36.91	0.00	7.7	0.324E+04	4.00	2.97	4.00	0.00
4.62	37.60	0.00	7.8	0.320E+04	4.00	3.04	4.00	0.00
4.91	38.30	0.00	7.9	0.316E+04	4.00	3.10	4.00	0.00
5.19	38.99	0.00	8.0	0.313E+04	4.00	3.17	4.00	0.00
5.48	39.68	0.00	8.1	0.310E+04	4.00	3.24	4.00	0.00
5.77	40.37	0.00	8.2	0.306E+04	4.00	3.30	4.00	0.00
6.07	41.07	0.00	8.2	0.303E+04	4.00	3.37	4.00	0.00
6.37	41.76	0.00	8.3	0.300E+04	4.00	3.43	4.00	0.00
6.67	42.45	0.00	8.4	0.297E+04	4.00	3.50	4.00	0.00
6.97	43.14	0.00	8.5	0.294E+04	4.00	3.56	4.00	0.00
7.28	43.83	0.00	8.6	0.291E+04	4.00	3.63	4.00	0.00
7.59	44.53	0.00	8.7	0.289E+04	4.00	3.70	4.00	0.00
7.90	45.22	0.00	8.7	0.286E+04	4.00	3.76	4.00	0.00
8.22	45.91	0.00	8.8	0.284E+04	4.00	3.83	4.00	0.00
8.53	46.60	0.00	8.9	0.281E+04	4.00	3.89	4.00	0.00
8.86	47.29	0.00	9.0	0.279E+04	4.00	3.96	4.00	0.00
9.18	47.99	0.00	9.1	0.276E+04	4.00	4.02	4.00	0.00
9.51	48.68	0.00	9.1	0.274E+04	4.00	4.09	4.00	0.00
9.84	49.37	0.00	9.2	0.272E+04	4.00	4.15	4.00	0.00
10.17	50.06	0.00	9.3	0.269E+04	4.00	4.22	4.00	0.00
10.50	50.75	0.00	9.4	0.267E+04	4.00	4.28	4.00	0.00
10.84	51.45	0.00	9.4	0.265E+04	4.00	4.35	4.00	0.00
11.18	52.14	0.00	9.5	0.263E+04	4.00	4.41	4.00	0.00
11.52	52.83	0.00	9.6	0.261E+04	4.00	4.47	4.00	0.00
11.87	53.52	0.00	9.6	0.259E+04	4.00	4.54	4.00	0.00
12.22	54.21	0.00	9.7	0.257E+04	4.00	4.60	4.00	0.00
12.57	54.91	0.00	9.8	0.255E+04	4.00	4.67	4.00	0.00
12.92	55.60	0.00	9.9	0.254E+04	4.00	4.73	4.00	0.00
13.28	56.29	0.00	9.9	0.252E+04	4.00	4.80	4.00	0.00
13.63	56.98	0.00	10.0	0.250E+04	4.00	4.86	4.00	0.00
13.99	57.67	0.00	10.1	0.248E+04	4.00	4.92	4.00	0.00
14.36	58.37	0.00	10.1	0.247E+04	4.00	4.99	4.00	0.00
14.72	59.06	0.00	10.2	0.245E+04	4.00	5.05	4.00	0.00
15.09	59.75	0.00	10.3	0.243E+04	4.00	5.11	4.00	0.00
15.46	60.44	0.00	10.3	0.242E+04	4.00	5.18	4.00	0.00
15.84	61.14	0.00	10.4	0.240E+04	4.00	5.24	4.00	0.00
16.21	61.83	0.00	10.5	0.239E+04	4.00	5.31	4.00	0.00
16.59	62.52	0.00	10.5	0.237E+04	4.00	5.37	4.00	0.00
16.97	63.21	0.00	10.6	0.236E+04	4.00	5.43	4.00	0.00
17.35	63.90	0.00	10.7	0.234E+04	4.00	5.50	4.00	0.00

17.74	64.60	0.00	10.7	0.233E+04	4.00	5.56	4.00	0.00
18.12	65.29	0.00	10.8	0.231E+04	4.00	5.62	4.00	0.00
18.51	65.98	0.00	10.9	0.230E+04	4.00	5.69	4.00	0.00
18.90	66.67	0.00	10.9	0.229E+04	4.00	5.75	4.00	0.00
19.30	67.36	0.00	11.0	0.227E+04	4.00	5.81	4.00	0.00
19.69	68.06	0.00	11.1	0.226E+04	4.00	5.87	4.00	0.00
20.09	68.75	0.00	11.1	0.225E+04	4.00	5.94	4.00	0.00
20.49	69.44	0.00	11.2	0.224E+04	4.00	6.00	4.00	0.00
20.90	70.13	0.00	11.2	0.222E+04	4.00	6.06	4.00	0.00
21.30	70.82	0.00	11.3	0.221E+04	4.00	6.13	4.00	0.00
21.71	71.52	0.00	11.4	0.220E+04	4.00	6.19	4.00	0.00
22.12	72.21	0.00	11.4	0.219E+04	4.00	6.25	4.00	0.00
22.53	72.90	0.00	11.5	0.218E+04	4.00	6.31	4.00	0.00
22.94	73.59	0.00	11.5	0.216E+04	4.00	6.38	4.00	0.00
23.36	74.28	0.00	11.6	0.215E+04	4.00	6.44	4.00	0.00
23.78	74.98	0.00	11.7	0.214E+04	4.00	6.50	4.00	0.00
24.20	75.67	0.00	11.7	0.213E+04	4.00	6.56	4.00	0.00
24.62	76.36	0.00	11.8	0.212E+04	4.00	6.63	4.00	0.00
25.05	77.05	0.00	11.8	0.211E+04	4.00	6.69	4.00	0.00
25.47	77.74	0.00	11.9	0.210E+04	4.00	6.75	4.00	0.00
25.90	78.44	0.00	12.0	0.209E+04	4.00	6.81	4.00	0.00
26.33	79.13	0.00	12.0	0.208E+04	4.00	6.87	4.00	0.00
26.77	79.82	0.00	12.1	0.207E+04	4.00	6.94	4.00	0.00
27.20	80.51	0.00	12.1	0.206E+04	4.00	7.00	4.00	0.00
27.64	81.21	0.00	12.2	0.205E+04	4.00	7.06	4.00	0.00
28.08	81.90	0.00	12.2	0.204E+04	4.00	7.12	4.00	0.00
28.52	82.59	0.00	12.3	0.203E+04	4.00	7.18	4.00	0.00
28.96	83.28	0.00	12.4	0.202E+04	4.00	7.25	4.00	0.00
29.41	83.97	0.00	12.4	0.201E+04	4.00	7.31	4.00	0.00
29.86	84.67	0.00	12.5	0.200E+04	4.00	7.37	4.00	0.00
30.31	85.36	0.00	12.5	0.200E+04	4.00	7.43	4.00	0.00
30.76	86.05	0.00	12.6	0.199E+04	4.00	7.49	4.00	0.00
31.21	86.74	0.00	12.6	0.198E+04	4.00	7.55	4.00	0.00
31.67	87.43	0.00	12.7	0.197E+04	4.00	7.62	4.00	0.00
32.12	88.13	0.00	12.8	0.196E+04	4.00	7.68	4.00	0.00
32.58	88.82	0.00	12.8	0.195E+04	4.00	7.74	4.00	0.00
33.04	89.51	0.00	12.9	0.194E+04	4.00	7.80	4.00	0.00
33.51	90.20	0.00	12.9	0.194E+04	4.00	7.86	4.00	0.00
33.97	90.89	0.00	13.0	0.193E+04	4.00	7.92	4.00	0.00
34.44	91.59	0.00	13.0	0.192E+04	4.00	7.98	4.00	0.00
34.91	92.28	0.00	13.1	0.191E+04	4.00	8.04	4.00	0.00
35.38	92.97	0.00	13.1	0.190E+04	4.00	8.10	4.00	0.00
35.85	93.66	0.00	13.2	0.190E+04	4.00	8.17	4.00	0.00
36.33	94.35	0.00	13.2	0.189E+04	4.00	8.23	4.00	0.00
36.80	95.05	0.00	13.3	0.188E+04	4.00	8.29	4.00	0.00
37.28	95.74	0.00	13.3	0.187E+04	4.00	8.35	4.00	0.00
37.76	96.43	0.00	13.4	0.187E+04	4.00	8.41	4.00	0.00
38.24	97.12	0.00	13.4	0.186E+04	4.00	8.47	4.00	0.00
38.73	97.81	0.00	13.5	0.185E+04	4.00	8.53	4.00	0.00
39.21	98.51	0.00	13.5	0.185E+04	4.00	8.59	4.00	0.00
39.70	99.20	0.00	13.6	0.184E+04	4.00	8.65	4.00	0.00
40.19	99.89	0.00	13.6	0.183E+04	4.00	8.71	4.00	0.00
40.68	100.58	0.00	13.7	0.183E+04	4.00	8.77	4.00	0.00



41.18	101.27	0.00	13.7	0.182E+04	4.00	8.83	4.00	0.00
41.67	101.97	0.00	13.8	0.181E+04	4.00	8.89	4.00	0.00
42.17	102.66	0.00	13.8	0.181E+04	4.00	8.95	4.00	0.00
42.67	103.35	0.00	13.9	0.180E+04	4.00	9.01	4.00	0.00
43.17	104.04	0.00	13.9	0.179E+04	4.00	9.07	4.00	0.00
43.67	104.74	0.00	14.0	0.179E+04	4.00	9.14	4.00	0.00
44.17	105.43	0.00	14.0	0.178E+04	4.00	9.20	4.00	0.00
44.68	106.12	0.00	14.1	0.177E+04	4.00	9.26	4.00	0.00
45.19	106.81	0.00	14.1	0.177E+04	4.00	9.32	4.00	0.00
45.70	107.50	0.00	14.2	0.176E+04	4.00	9.38	4.00	0.00
46.21	108.20	0.00	14.2	0.176E+04	4.00	9.44	4.00	0.00
46.72	108.89	0.00	14.3	0.175E+04	4.00	9.50	4.00	0.00
47.24	109.58	0.00	14.3	0.174E+04	4.00	9.56	4.00	0.00
47.75	110.27	0.00	14.4	0.174E+04	4.00	9.62	4.00	0.00
48.27	110.96	0.00	14.4	0.173E+04	4.00	9.68	4.00	0.00
48.79	111.66	0.00	14.5	0.173E+04	4.00	9.74	4.00	0.00
49.31	112.35	0.00	14.5	0.172E+04	4.00	9.79	4.00	0.00
49.83	113.04	0.00	14.6	0.171E+04	4.00	9.85	4.00	0.00
50.36	113.73	0.00	14.6	0.171E+04	4.00	9.91	4.00	0.00
50.89	114.42	0.00	14.7	0.170E+04	4.00	9.97	4.00	0.00
51.41	115.12	0.00	14.7	0.170E+04	4.00	10.03	4.00	0.00
51.94	115.81	0.00	14.8	0.169E+04	4.00	10.09	4.00	0.00
52.48	116.50	0.00	14.8	0.169E+04	4.00	10.15	4.00	0.00
53.01	117.19	0.00	14.9	0.168E+04	4.00	10.21	4.00	0.00
53.55	117.88	0.00	14.9	0.168E+04	4.00	10.27	4.00	0.00
54.08	118.58	0.00	15.0	0.167E+04	4.00	10.33	4.00	0.00
54.62	119.27	0.00	15.0	0.167E+04	4.00	10.39	4.00	0.00
55.16	119.96	0.00	15.1	0.166E+04	4.00	10.45	4.00	0.00
55.70	120.65	0.00	15.1	0.166E+04	4.00	10.51	4.00	0.00
56.25	121.34	0.00	15.1	0.165E+04	4.00	10.57	4.00	0.00
56.79	122.04	0.00	15.2	0.165E+04	4.00	10.63	4.00	0.00
57.34	122.73	0.00	15.2	0.164E+04	4.00	10.69	4.00	0.00
57.89	123.42	0.00	15.3	0.164E+04	4.00	10.75	4.00	0.00
58.44	124.11	0.00	15.3	0.163E+04	4.00	10.80	4.00	0.00
58.99	124.81	0.00	15.4	0.163E+04	4.00	10.86	4.00	0.00
59.54	125.50	0.00	15.4	0.162E+04	4.00	10.92	4.00	0.00
60.10	126.19	0.00	15.5	0.162E+04	4.00	10.98	4.00	0.00
60.65	126.88	0.00	15.5	0.161E+04	4.00	11.04	4.00	0.00
61.21	127.57	0.00	15.6	0.161E+04	4.00	11.10	4.00	0.00
61.77	128.27	0.00	15.6	0.160E+04	4.00	11.16	4.00	0.00
62.33	128.96	0.00	15.6	0.160E+04	4.00	11.22	4.00	0.00
62.90	129.65	0.00	15.7	0.159E+04	4.00	11.28	4.00	0.00
63.46	130.34	0.00	15.7	0.159E+04	4.00	11.33	4.00	0.00
64.03	131.03	0.00	15.8	0.158E+04	4.00	11.39	4.00	0.00
64.59	131.73	0.00	15.8	0.158E+04	4.00	11.45	4.00	0.00
65.16	132.42	0.00	15.9	0.158E+04	4.00	11.51	4.00	0.00
65.73	133.11	0.00	15.9	0.157E+04	4.00	11.57	4.00	0.00
66.31	133.80	0.00	15.9	0.157E+04	4.00	11.63	4.00	0.00
66.88	134.49	0.00	16.0	0.156E+04	4.00	11.69	4.00	0.00
67.46	135.19	0.00	16.0	0.156E+04	4.00	11.74	4.00	0.00
68.03	135.88	0.00	16.1	0.155E+04	4.00	11.80	4.00	0.00
68.61	136.57	0.00	16.1	0.155E+04	4.00	11.86	4.00	0.00
69.19	137.26	0.00	16.2	0.155E+04	4.00	11.92	4.00	0.00

69.77	137.95	0.00	16.2	0.154E+04	4.00	11.98	4.00	0.00
70.36	138.65	0.00	16.3	0.154E+04	4.00	12.04	4.00	0.00
70.94	139.34	0.00	16.3	0.153E+04	4.00	12.09	4.00	0.00
71.53	140.03	0.00	16.3	0.153E+04	4.00	12.15	4.00	0.00
72.12	140.72	0.00	16.4	0.153E+04	4.00	12.21	4.00	0.00
72.71	141.41	0.00	16.4	0.152E+04	4.00	12.27	4.00	0.00
73.30	142.11	0.00	16.5	0.152E+04	4.00	12.33	4.00	0.00
73.89	142.80	0.00	16.5	0.151E+04	4.00	12.39	4.00	0.00
74.48	143.49	0.00	16.5	0.151E+04	4.00	12.44	4.00	0.00
75.08	144.18	0.00	16.6	0.151E+04	4.00	12.50	4.00	0.00
75.68	144.87	0.00	16.6	0.150E+04	4.00	12.56	4.00	0.00
76.28	145.57	0.00	16.7	0.150E+04	4.00	12.62	4.00	0.00
76.88	146.26	0.00	16.7	0.150E+04	4.00	12.67	4.00	0.00
77.48	146.95	0.00	16.8	0.149E+04	4.00	12.73	4.00	0.00
78.08	147.64	0.00	16.8	0.149E+04	4.00	12.79	4.00	0.00
78.68	148.34	0.00	16.8	0.148E+04	4.00	12.85	4.00	0.00
79.29	149.03	0.00	16.9	0.148E+04	4.00	12.91	4.00	0.00
79.90	149.72	0.00	16.9	0.148E+04	4.00	12.96	4.00	0.00
80.51	150.41	0.00	17.0	0.147E+04	4.00	13.02	4.00	0.00
81.12	151.10	0.00	17.0	0.147E+04	4.00	13.08	4.00	0.00
81.73	151.80	0.00	17.0	0.147E+04	4.00	13.14	4.00	0.00
82.34	152.49	0.00	17.1	0.146E+04	4.00	13.19	4.00	0.00
82.96	153.18	0.00	17.1	0.146E+04	4.00	13.25	4.00	0.00
83.57	153.87	0.00	17.2	0.146E+04	4.00	13.31	4.00	0.00
84.19	154.56	0.00	17.2	0.145E+04	4.00	13.37	4.00	0.00
84.81	155.26	0.00	17.2	0.145E+04	4.00	13.42	4.00	0.00
85.43	155.95	0.00	17.3	0.145E+04	4.00	13.48	4.00	0.00
86.05	156.64	0.00	17.3	0.144E+04	4.00	13.54	4.00	0.00
86.68	157.33	0.00	17.4	0.144E+04	4.00	13.60	4.00	0.00
87.30	158.02	0.00	17.4	0.144E+04	4.00	13.65	4.00	0.00
87.93	158.72	0.00	17.4	0.143E+04	4.00	13.71	4.00	0.00
88.56	159.41	0.00	17.5	0.143E+04	4.00	13.77	4.00	0.00
89.19	160.10	0.00	17.5	0.143E+04	4.00	13.83	4.00	0.00
89.82	160.79	0.00	17.6	0.142E+04	4.00	13.88	4.00	0.00
90.45	161.48	0.00	17.6	0.142E+04	4.00	13.94	4.00	0.00
91.08	162.18	0.00	17.6	0.142E+04	4.00	14.00	4.00	0.00
91.72	162.87	0.00	17.7	0.141E+04	4.00	14.05	4.00	0.00
92.35	163.56	0.00	17.7	0.141E+04	4.00	14.11	4.00	0.00
92.99	164.25	0.00	17.8	0.141E+04	4.00	14.17	4.00	0.00
93.63	164.94	0.00	17.8	0.140E+04	4.00	14.23	4.00	0.00
94.27	165.64	0.00	17.8	0.140E+04	4.00	14.28	4.00	0.00
94.91	166.33	0.00	17.9	0.140E+04	4.00	14.34	4.00	0.00
95.56	167.02	0.00	17.9	0.140E+04	4.00	14.40	4.00	0.00
96.20	167.71	0.00	18.0	0.139E+04	4.00	14.45	4.00	0.00
96.85	168.40	0.00	18.0	0.139E+04	4.00	14.51	4.00	0.00
97.50	169.10	0.00	18.0	0.139E+04	4.00	14.57	4.00	0.00
98.14	169.79	0.00	18.1	0.138E+04	4.00	14.62	4.00	0.00
98.79	170.48	0.00	18.1	0.138E+04	4.00	14.68	4.00	0.09
99.45	171.17	0.00	18.2	0.138E+04	4.00	14.74	4.00	0.00
100.10	171.87	0.00	18.2	0.137E+04	4.00	14.79	4.00	0.00
100.75	172.56	0.00	18.2	0.137E+04	4.00	14.85	4.00	0.00
101.41	173.25	0.00	18.3	0.137E+04	4.00	14.91	4.00	0.00

Cumulative travel time = 240. sec

Entire region is occupied by Phase 1.  
Plume does not re-stratify in this flow region.

END OF MOD154: VERTICALLY MIXED PLUME IN WEAK CROSS-FLOW

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\*\* End of NEAR-FIELD REGION (NFR) \*\*

CORMIX1: Submerged Single Port Discharges

End of Prediction File







