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Minimization of SO_2 Emissions at ADGAS (Das Island, UAE): II- Impact on Air Quality

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Abstract

In Part I of this work, two SO_2 minimization schemes, namely, Fuel Gas Sweetening (FGS) and Seawater-Flue Gas Desulfurization (SW-FGD) schemes have been proposed to be implemented at the ADGAS plant (Das Island, UAE). The implementation of such schemes is expected to reduce the SO_2 emissions by 77%. The FGS scheme is expected to reduce the H_2S content in the fuel gas system by 94% and results in decreasing the total SO_2 emissions due to fuel gas usage by 98%. The SW-FGD scheme is expected to reduce the SO_2 emissions due to incomplete sulfur recovery by 99.5%.

This work is based on on-site measurements and data collected from specific locations at the ADGAS plant and over the Das Island, UAE. These data were loaded into air dispersion model software (AERMOD 7, 2008) and simulated to predict future air quality on the Island. The SO_2 Ground Level Concentrations (GLCs) were predicted for the current conditions and for the proposed SO_2 minimization schemes (presented in Part I of this work) using the BREEZE AERMOD Pro software model. Upon implementing the proposed SO_2 minimization schemes, the predicted GLCs were found to comply with the United Arab Emirates Federal Environment Agency (UAE-FEA) standard limits at all sites in the ADGAS plant and over the Island. Also the remaining SO_2 emissions have the potential to challenge any future stringent limits set by the UAE-FEA with a high level of confidence since the emission rates after implementing the proposed SO_2 minimization schemes will be reduced to about 5% of the current standard emission limit (25 mg/Nm^3).

Lastly, the general approach presented in this work may be of value in application to other similar systems worldwide.

Keywords: SO_2 emission; Ground level concentration (GLC); Air quality; Modeling and simulation

Acronyms

ADGAS: Abu Dhabi Gas Liquefaction Company; ADMA-OPCO: Abu Dhabi Marine Operating Company; BFW: Boiler Feed Water; DEA: Diethanol Amine; FEA: Federal Environmental Agency; FGD: Flue Gas Desulfurization; GLC: Ground Level Concentration; MW: Molecular Weight; ppm: parts per million; SD: Standard Deviation; SRU: Sulfur Recovery Unit; UAE: United Arab Emirates; UGA: Utility Gas Absorber; US EPA: United States Environmental Protection Agency; WHB: Waste Heat Boiler; WHO: World Health Organization

Introduction

Das Island is an Emirati island in the Arabian Gulf. It is part of the emirate of Abu Dhabi, United Arab Emirates (UAE) but lies well offshore, about 160 km north-west of the mainland. It covers approximately 1.21 km by 2.4 km, and is almost rectangular in shape. It is characterized as a rocky-low island with about 10 m (highest point is 50 m) above sea level. The island is inhabited by oil and gas industry personnel. It exports crude oil and liquefied natural gas by tankers as far as Japan and Europe. The island was formerly a noted breeding site for turtles and seabirds. Despite the oil and gas production, turtles still feed safely in the area and the island is still remained an important landfall for migrant birds.

Throughout its history, the ADGAS Plant at Das Island suffers high rates of SO_2 emissions. The source of SO_2 emissions is mainly coming from the H_2S containment in the feed natural gas. The SO_2 is the dominant air pollutant to the high pollution levels in the Western Region of the UAE. The high levels of SO_2 emissions there necessitate the need to research all possible means to combat the SO_2 impacts. Lewis et al. [1] described a Model Predictive Control (MPC) that can dramatically result in the minimization of flaring from fuel gas supply networks at the LNG facility at ADGAS. In our opinion, this will also contribute to the reduction of sulfur-containing gases emitted into the atmosphere.

Globally, the SO_2 emitted has the potential to travel in any direction for hundreds of kilometers depending on the meteorological conditions. SO_2 is relatively stable in the atmosphere and has the ability to travel as far as 1000 km [2]. The health and environmental impacts of SO_2 can be found elsewhere [3]. Jie [4] constructed a model to study the impact of SO_2 pollution on health over 78 Chinese counties and found that, after attaining the threshold (8 μg/m^2), continuous increase in industrial SO_2 emission density will raise the ratio of population suffering chronicle diseases, among which respiratory diseases occupy a significant proportion.

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Source	Current	Proposed	% Reduction
Fuel Gas Usage	10,092	168	98.34
Incomplete Sulfur Recovery	11,299	57	99.50
Continuous Flaring of Flash Gas	6,140	6,140	0.00
Total	27,532	6,364	76.88

Table 1: Total SO_2 Emissions (ton/yr) at Current vs. Proposed SO_2 Minimization Schemes from Various Sources at ADGAS.

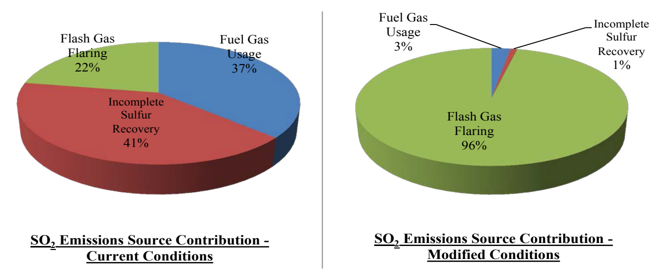

Figure 1: Contribution of ADGAS sources toward total SO_2 emission rates under current and proposed SO_2 minimization schemes.

In general, the workers of ADGAS (and other inhabitants) are subject to be exposed to the outdoor air at all locations within the Das Island during their stay time. There is a lack of long-term studies on the effect of exposure on the health of the workers there. Such studies will help in determining the highest continuous exposure time an employee can withstand during his stay at the Island. In fact, the average exposure duration for the Das Island inhabitants to the various SO_2 GLCs for the various time averages cannot yet be easily determined.

The aim of Part I of this work was to explore feasible technologies that can be implemented at the ADGAS plant at Das Island (UAE) that will result in minimizing SO_2 emissions [5]. Two modifications on the SO_2 minimization schemes have been proposed and suggested to be applied on the current Fuel Gas Sweetening (FGS) and Flue Gas Desulfurization (FGD) systems. It is worth noting that the effect of implementing the SO_2 minimization schemes on plant operations through the FGS and FGD schemes aspects has been discussed elsewhere [5]. The total SO_2 emission rates from ADGAS three LNG trains under current and proposed SO_2 minimization schemes are presented in Table 1. The contribution of the various sources at the ADGAS plant toward total SO_2 emission rates at current and proposed conditions is shown in Figure 1.

Based on the results of part I of this work [5], the current contribution of fuel gas usage of Trains 1 & 2 is 37% of the total SO_2 emissions (Figure 1). Upon implementation of the proposed FGS scheme, the total SO_2 emissions due to fuel gas usage will be reduced by 98.34% (Table 1) and result in reducing the contribution of fuel gas usage to only 3% of the total SO_2 emissions. On the other hand, the current contribution of the Sulfur Recovery Units (SRUs) to the total SO_2 emissions is 41% (Figure 1) and upon implementation of the proposed FGD scheme the SO_2 emissions due to incomplete sulfur recovery in the SRUs will be reduced by 99.50% (Table 1) and it will become only 1% of the total SO_2 emissions upon the implementation of the proposed SO_2 minimization schemes.

Furthermore, the implementation of the proposed schemes is expected to result in reducing the total SO_2 emissions from the ADGAS plant by 76.88% (Table 1) and it will result in minimizing the SO_2 emissions from the fuel gas usage and incomplete sulfur recovery but leaves the SO_2 emissions from the Continuous Flaring of Flash Gas (CFFG) as the main contributor to the total SO_2 emissions. If the contribution of the flash gas flaring is excluded, the SO_2 minimization schemes will reduce the SO_2 emissions by 98.96% (from 21,391 to 224 ton/yr), which can be considered as the optimum minimization level [5].

The ultimate goal of this work was to investigate the impact of our proposed minimization schemes of SO_2 emissions [5] on the ambient air quality of the Das Island. The "BREEZE AERMOD GIS Pro" has been used in this work as the air quality model to establish and predict the baseline of the SO_2 GLC at the Das Island post the implementation of the proposed SO_2 minimization schemes. More about the steady-state air dispersion model used in this work can be found elsewhere [6-9].

Al-Nuaimi [10] studied the effect of upgrading of the SRUs at the ADGAS plant from conventional Claus® to SuperClaus® technology and used the Industrial Source Complex (ISC) model to only estimate the highest SO_2 GLCs at the Das Island. The study resulted in a maximum reduction of 33.9%, 0% and 11.4% for the 1-h, 24-h and 1-yr base, respectively. Deligiorgi et al. [11] have used AERMOD steady-state dispersion model to model air pollutant emission from a power plant and identified the dispersion patterns in complex topography in the Chania plain on the Crete Island (Greece). The meteorological assessment is based on a two year dataset (August 2004 – July 2006) from six automated surface meteorological stations. Case studies of the predicted GLCs of SO_2 are presented for days with commonly observed meteorological phenomena. Saqer et al. [12] used AERMOD to estimate the total emissions of SO_2, non-methanated hydrocarbons (VOCs) and NO_x from flares in two petroleum refineries and assessed the impact of these pollutants on air quality in industrial and suburban areas in Kuwait.

Currently the Das Island is lacking continuous monitoring of SO_2 GLCs, which is the indicator of effectiveness of any minimization scheme. However, starting from 2003, ADGAS hired a private company to carry out air quality monitoring at Das Island twice a year. Various pollutants, including SO_2, were measured at specific locations for a period of 24-h. The used methodology in this work includes the following:

- Establishing the design basis for the AERMOD GIS Pro software in order to predict the SO_2 ground-level concentrations under current conditions and predict the 1-h, 24-h and 1-year SO_2 levels on the Das Island. This will acquire site meteorological and air quality data, selection of receptors locations for SO_2 GLCs, and characteristics and rates of all SO_2 emission sources from the ADGAS plant.
- Using the AERMOD GIS Pro software to predict the SO_2 GLCs upon implementing the proposed fuel gas sweetening and flue gas desulfurization schemes by simulating the 1-h, 24-h and 1-year SO_2 levels over the Das Island.
- Exploring the compliance of the predicted SO_2 emission levels upon implementation of the proposed SO_2 minimization schemes to the United Arab Emirates Federal Environment Agency (UAE-FEA) standards.

Design Basis for the Modelling of the SO_2 Ground-Level Concentrations

The design basis for running the BREEZE AERMOD Pro software includes (1) physical characteristics of all SO_2 emission sources, (2)

Figure 2: Arial View of the Das Island and the location of the receptors.

Receptor	Location E(m) : N(m)	Latitude	Longitude
Al-Jimi Camp (Contractors housing area)	1457 : 3148	25.148737	52.878168
Al-Sahil Accommodation (Housing area for ADGAS and ADMA-OPCO employees)	1803 : 3075	25.144231	52.872718
Sailing Club (Popular outdoor recreation area at Das Island)	1772 : 3075	25.142212	52.880448

Table 2: Receptors' Locations for SO_2 GLCs Measurement and Prediction.

locations of the selected receptor within the Das Island where the SO_2 GLCs are to be predicted, and (3) SO_2 emission rates from the various sources at the ADGAS plant under current conditions. These data, along with site meteorological data (obtained from AERMOD GIS Pro), are required to run the AERMOD air dispersion model to simulate the background SO_2 GLCs (measured by ADGAS) and predict them once the proposed SO_2 minimization schemes are implemented. More about simulation theory can be found in the literature [13-16].

Site meteorological data

The meteorological data of the site at hand has to be possessed, and if not available, well established meteorological data at the nearest station has to be used. Meteorological data of the Das Island are not available and the nearest meteorological station (i.e., Abu Dhabi International Airport) is about 160 km away from the Island. However, meteorological data for numerous locations around the world are available through "AERMOD GIS Pro". Acquisition of such data from the "AERMOD GIS Pro" supplier is considered the best choice because these data are reliable and accurate and the supplier provides the necessary data in a format that suits the software itself. Thus the meteorological data provided by AERMOD GIS Pro have been used in this work.

Receptors' locations for prediction of SO_2 ground level concentrations

An aerial view map of the Das Island along with the location of the receptors is shown in Figure 2. The rationale for the receptors' distribution is mainly to monitor the air quality in the residential and recreation areas on the Island. Three locations on the Island had been selected by ADGAS Company for monitoring of air quality and they were selected here as receptors prediction of the SO_2 GLCs over the Island. The physical characteristics of these receptors are given in Table 2.

Physical characteristics of the SO_2 emission sources

The physical characteristics of the SO_2 emission sources include the physical parameters and SO_2 emission rates from each emission source. The locations of the SO_2 emission sources have been obtained from the ADGAS plant records and placed on the Das Island Map. Each location was oriented through the determination of its longitude and latitude ordinates. The diameter and height of each emission source were also obtained. The available physical data were then collected from the data sheets of each stack at the ADGAS plant. See Table 3. It is worth mentioning here that each SO_2 emission source has been individually considered in this study and all the data from the various sources were fed into the AERMOD software. It is also assumed that the plant emissions are evenly distributed over the time.

Estimation of SO_2 emission rates from various sources at ADGAS

All the data necessary to estimate the SO_2 emission rates from all sources were collected. The SO_2 emission rate (kg/h) from each source was determined using the data available from the fuel gas usages (that are emitted from all non-flare sources such as boilers and gas turbines) and the data from flared gases in the continuous flaring of flashed gas sources. The data acquired are the flow rates (mol/h) and the H_2S concentration (mol %) of the fuel gas usage and flare gas systems. The SO_2 emission rates were then calculated based on the following equations (1 and 2):

$$2H_2S(g) + 3O_2(g) \rightarrow 2SO_2(g) + 2H_2O(g) \quad (1)$$

$$SO_2\ Emission\ Rate(\text{kg/ h}) = \left(\frac{mol\%H_2S}{100}\right)\left(\frac{1molSO_2}{1molH_2S}\right)\left(MW_{SO_2}\frac{kg}{kmol}\right)\left(Gas\ Flow\frac{kmol}{h}\right) \quad (2)$$

Table 4 presents a summary of the estimated H_2S and SO_2 emission rates under current conditions from the various sources at ADGAS. Table 5 summarizes the SO_2 emission rates at the current and proposed

Emission Source (Stacks)	No.	Latitude	Longitude	Height range (m)	Diam. range (m)
Boilers	6	25.16252	52.87633	30.9 - 43.3 (37)	3.5 - 3.8 (3.6)
Regeneration Gas Heater	4	25.16077	52.87480	26.4 (26.4)	1.32 (1.32)
Gas Turbines	5	25.15777	52.87206	13 - 20 (18.6)	3.25 - 3.84 (3.49)
SRU Incinerators	3	25.16023	52.87661	46 - 70.3 (54.1)	2 - 4.23 (2.73)
Flares	9	25.16410	52.87780	10 - 75 (58.9)	0.6 - 1.8 (0.96)

* Numbers in parenthesis are average values.

Table 3: SO_2 Emission Sources, Location: Average Latitude and Longitude, and Stack Height and Diameter*.

Emission Sources	No	H_2S (mol %)	Flow rate (each) (kmol/h)	Total SO_2 emission rate (ton/day)
Boilers 1, 2, 3, & 4	4	0.08	1,159.99	2081.08
Boilers 5 & 6	2	0.0004	1,522.27	6.82
Fired Heaters of Plant 3 & 9 - Trains 1 & 2	2	0.12	32.48	87.41
Combined Flares - Trains 1 & 2 (Pilot)	2	0.12	0.45	1.21
Sweet & Sour Flares (Purge & Pilot) - Trains 1 & 2	2	0.0004	9.42	0.09
Sour Flare (Carbonate Flash Gas) - Trains 1 & 2	2	7.67	29.87	4636.71
Sour Flare (DEA Flash Gas) - Trains 1 & 2	2	0.06	9.96	13.40
Continuous Sweet & Sour Flare (Purge & Pilot) - Train 3	1	0.0004	9.42	0.02
Sour Flares (Carbonate Flash Gas) -Train 3	1	4.95	14.94	1503.36
Sour Flares (DEA Flash Gas) - Train 3	1	0.11	4.98	3.07
Sour Flares (Excess Fuel Gas) - Train 3	1	0.0004	149.37	0.33
Gas Turbines (GT-1, GT-2 & GT-3)	3	2.22	198.98	7429.64
LG Turbines (LG-5 & LG-6)	2	0.12	348.44	468.84
Purge & Pilot Flares of LNG/LPG & LPG Tankage	2	0.0004	37.68	0.17
Purge & Pilot Burners of Sour (Warm) Liquid & LNG	2	0.0004	37.68	0.17
SRU Incinerators - Trains 1 & 2	2	0.17	4,735.90	9027.44
SRU Incinerator - Train 3	1	0.13	3,117.40	2271.96
Total				**27531.71**

Table 4: Estimated H2S and SO_2 Emission Rates from Various Sources at ADGAS under Current Conditions.

Emission Source	Current Total (ton/year)	Modified Total (ton/year)	% Reduction
Combined Sweet & H_2S Flare - Trains 1 & 2	1.60	0.08	94.75
Sour Gas High Level Flare - Trains 1 & 2	4,636.71	4,636.71	0.00
Sour Gas High Level Flare - Train 3	1,503.36	1,503.36	0.00
LNG / LPG Flare, LPG Tankage Flare, Sour (Warm) Liquid Burner	12.69	0.66	94.75
LNG Burner	12.68	0.67	94.75
Power Generation Gas Turbine	468.84	28.18	93.99
ADMA Power Generation Gas Turbine	7,429.77	23.07	99.69
Plant 3 Regeneration Gas Heater	43.70	2.64	93.97
Plant 9 Regeneration Gas Heater	41.78	2.52	93.95
Plant 31 Boilers 1, 2, 3, & 4	2,081.08	109.88	94.72
SRU Incinerator - Trains 1 & 2	9,027.44	45.14	99.50
SRU Incinerator - Train 3	2,271.96	11.36	99.50
Total	**27,531.61**	**6,364.27**	**76.88**

Table 5: SO_2 Emission Rates from ADGAS Plant under Current and Modified SO_2 Minimization Schemes.

SO_2 minimization conditions as well as percent reduction in SO_2 emission upon implementation of the proposed minimization schemes.

Prediction of SO_2 Ground Level Concentrations

The main objective of air quality models is, in general, to simulate and/or predict the ambient level concentrations of any pollutant given the necessary emissions' source data (i.e., stack size, location and emission rate), and terrain description and meteorological data of the site of interest. Typical outputs of any air quality model include location and magnitude of the pollutant highest GLC and the magnitude of the pollutant GLC at specified receptor locations. Air quality models are also used to verify air quality standards' compliance of existing or proposed industrial facilities, and to assist in the design of effective control strategies to reduce emissions of harmful air pollutants [17].

In fact, the absence of continuous SO_2 GLC monitoring on the Das Island necessitates the use of air quality models in order to simulate the SO_2 GLCs under current conditions and reveal the effectiveness of the proposed SO_2 minimization schemes on the SO_2 GLCs, in particular, and air quality over the Island, in general.

Assessment of the SO_2 GLCs at the selected receptors

Table 6 shows a summary of the 1-h, 24-h and 1-year SO_2 GLC averages at the selected receptors for the years 2003 to 2007 under current conditions and proposed SO_2 minimization schemes. It also shows the corresponding SO_2 GLC standards for ambient air quality set by the UAE-FEA [18]. It is clear from Table 6 that the 1-h SO_2 GLC highest averages under the current conditions always exceed the UAE-FEA at the three receptors. However, the 24-h and the 1-yr SO_2 GLCs highest averages do not exceed the standards except for the 24-h SO_2 level at Al-Jimi receptor. The Al-Sahil and Al-Jimi receptors show SO_2 levels of almost 500 μg/m^3 or more for the 1-h average periods; this imposes serious health effects as per the WHO Air Quality Guidelines [19]. The 24-h SO_2 levels at the receptors frequently comply with UAE-FEA standards but are far exceeding the WHO 24-h set standards (20 μg/m^3). Exposure to such levels may exert serious health effects as indicated by the recorded WHO studies [19]. The 1-yr SO_2 levels at the three receptors always comply with UAE-FEA at the three selected receptors. In general, the ambient air quality at Das Island under the current conditions with respect to SO_2 GLCs is considered deteriorated and has the potential to impact the health of the residents of the Island as high SO_2 levels are experienced in the residential areas.

Measured vs. predicted SO_2 GLCs at the selected receptors

A comparison between the measured and AERMOD predicted 24-h highest SO_2 GLCs at the three receptors for the years 2003 to 2007 are shown in Table 7. In fact, AERMOD only predicts the highest

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pollutant GLC for a given average. So for various receptors, AERMOD predicts the 24-h highest SO_2 GLCs for a given year. As seen in Table 7, the predicted SO_2 GLC is not occurring in the period when the actual SO_2 GLC measurements were made. Thus, the AERMOD model cannot be verified for the ADGAS SO_2 GLC database because the available data are not sufficient for validation purposes. In addition, the measured SO_2 GLCs are not indicative because there is a possibility that the meteorological conditions during the test period allow for the SO_2 GLCs to be lower than should be.

Temporal variations of highest SO_2 GLC distribution

The predicted temporal variations in the SO_2 highest GLC averages over the Das Island for the years 2003 to 2007 show similar trends for the 1-h, 24-h and 1-yr toward the distribution of the SO_2 GLC highest averages. This can be observed through examining the location of the highest SO_2 GLC averages, and the comparison of SO_2 GLCs at the selected receptors.

(1) Location of the Highest Averages of the SO_2 GLCs

Currently, the 1-h highest SO_2 levels are centered in the mid-west part of the Island; more specifically at the end of the Das Island Airport runway. This runway is used by individuals for exercise and run around in the evening (the last flight leaves Das Island at 2 pm). Thus this might lead to increasing the potential of exposure to high SO_2 concentrations. The 24-h highest SO_2 levels occur in either the middle of the Island (for 2003, 2004 and 2006) or in the north-west part of the Island (for 2005 and 2007). The middle area of the Island is an empty area where almost no activities take place while the north-west area is an industrial area. The 1-yr highest SO_2 levels take place either in the middle of the Island (for 2005, 2006 and 2007) or in the north-east part of the Island (for 2003 and 2004) toward the LNG/LPG storage tanks area. It has been noticed under the current conditions that the locations of the highest predicted SO_2 GLCs at the Das Island are not much affected over the 5-years test period.

(2) Comparison of the SO_2 GLCs at the Selected Receptors

The average 1-h, 24-h and 1-yr, the mean and the Standard Deviation (SD) of the SO_2 levels at the selected receptors are presented in Table 8. The standard deviations for the 1-h, 24-h and 1-yr averages of the highest SO_2 level are considered low; hence this indicates that the predicted SO_2 levels at each receptor for the specified duration are close to each other. This in turn implies that the variations in SO_2 levels over the 5-years period is small, and, therefore, the effect of yearly-temporal variations does not impact the SO_2 levels at the specified receptors.

1-h SO_2 GLC (μg/m³)				
Location	UAE-FEA Standard [18]	Current	Proposed	% Reduction
Al-Sahil	350	585.42	232.56	60.3
Sailing Club	350	376.29	253.93	32.5
Al-Jimi	350	488.48	278.42	43.0
24-h SO_2 GLC (μg/m³)				
Location	UAE-FEA Standard [18]	Current	Proposed	% Reduction
Al-Sahil	150	136.71	32.56	76.2
Sailing Club	150	127.34	41.28	67.6
Al-Jimi	150	207.07	50.84	75.4
1-yr SO_2 GLC (μg/m³)				
Location	UAE-FEA Standard [18]	Current	Proposed	% Reduction
Al-Sahil	60	26.21	4.56	82.6
Sailing Club	60	35.69	7.73	78.3
Al-Jimi	60	51.24	9.23	82.0

Table 6: Average SO_2 GLCs under Current and Proposed SO_2 Minimization Schemes for the Selected Receptors over the 2003-2007 period.

Simulation of the SO_2 ground level concentrations

Upon acquisition of the necessary data, the SO_2 GLCs on the Das Island have been predicted using the BREEZE AERMOD GIS Pro software. The 1-h, 24-h and 1-yr highest averages of SO_2 GLCs were predicted at the selected receptors' locations under current and modified SO_2 minimization schemes for the years 2003 to 2007. Upon these results, the impact of process modifications on the air quality has been predicted. Figure 3 shows a sample of the results for the 1-yr highest SO_2 GLCs at the three receptors under current and proposed conditions for the year 2007. Table 9 shows the predicted 1-h, 24-h and 1-yr highest SO_2 GLC averages at the same receptors under current and proposed conditions.

Location	Date	Measured GLC (μg/m³)	Predicted GLC (μg/m³) (Date)
Al Sahil	18-05-2004	18	124.94 (26-09-2004)
	20-05-2004	21	
	21-05-2004	4	
	5/12/2004	10	
	6/12/2004	10	
	7/12/2004	6	
	16-03-2005	86	203.26 (19-03-2005)
	17-03-2005	78	
	18-03-2005	42	
	17-11-2005	69	
	18-11-2005	36	
	19-11-2005	51	
	13-06-2006	60	94.28 (17-08-2006)
	14-06-2006	49	
	15-06-2006	71	
	11/11/2006	34	
	12/11/2006	40	
	13-11-2006	37	
	6/9/2007	13	142.11 (15-04-2007)
	7/9/2007	12	
	8/9/2007	18	
Sailing Club	18-05-2004	87	136.90 (08-02-2004)
	21-05-2004	21	
	23-05-2004	8	
	5/12/2004	10	
	6/12/2004	14	
	6/12/2004	17	
	16-03-2005	67	118.82 (24-03-2005)
	17-03-2005	172	
	18-03-2005	81	
	17-11-2005	44	
	18-11-2005	12	
	19-11-2005	30	
	13-06-2006	44	111.06 (30-01-2006)
	14-06-2006	63	
	15-06-2006	40	
	11/11/2006	63	
	12/11/2006	116	
	13-11-2006	83	
	6/9/2007	88	150.13 (19-03-2007)
	7/9/2007	109	
	8/9/2007	97	

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Al Jimi Camp	18-05-2004	9	187.57 (16-03-2004)
	20-05-2004	85	
	21-05-2004	46	
	22-05-2004	66	
	23-05-2004	79	
	24-05-2004	67	
	5/12/2004	38	
	6/12/2004	79	
	7/12/2004	64	
	8/12/2004	98	
	16-03-2005	103	221.21 (30-12-2005)
	17-03-2005	136	
	18-03-2005	105	
	17-11-2005	129	
	18-11-2005	51	
	19-11-2005	65	
	14-06-2006	89	194.92 (10-07-2006)
	15-06-2006	76	
	16-06-2006	69	
	4/11/2006	134	
	12/11/2006	109	
	13-11-2006	125	
	6/9/2007	82	192.17 (11-03-2007)
	7/9/2007	96	
	8/9/2007	68	

Table 7: Measured vs. AERMOD-Predicted 24-h Highest SO_2 GLCs for the years 2004 to 2007.

1-h (µg/m³)							
Location	2003	2004	2005	2006	2007	Mean	SD, %
Al-Sahil	587.32	587.37	579.69	586.75	585.96	585.42	2.91
Sailing Club	373.56	377.45	362.67	383.68	384.11	376.29	7.87
Al-Jimi	484.64	490.41	493.99	486.70	486.64	488.48	3.33
24-h (µg/m³)							
Location	2003	2004	2005	2006	2007	Mean	SD, %
Al-Sahil	118.97	124.94	203.26	94.28	142.11	136.71	36.64
Sailing Club	119.79	136.90	118.82	111.06	150.13	127.34	14.18
Al-Jimi	239.47	187.57	221.21	194.92	192.17	207.07	20.00
1-yr (µg/m³)							
Location	2003	2004	2005	2006	2007	Mean	SD, %
Al-Sahil	22.27	20.62	32.29	28.45	27.43	26.21	4.25
Sailing Club	32.39	34.24	39.84	35.21	36.76	35.69	2.51
Al-Jimi	45.57	47.43	61.26	49.49	52.46	51.24	5.51

Table 8: Highest Average SO_2 GLCs at the Selected Receptors for the years 2003 to 2007.

Table 9 also shows the AERMOD predictions using the proposed SO_2 minimization schemes once the CFFG is eliminated. The elimination of the CFFG under the proposed SO_2 minimization schemes will result in reducing the SO_2 GLCs at the selected receptors by about 97%. In this case, the highest SO_2 GLC averages at the selected receptors will be about 4.6 µg/m³ for the 1-hr basis and less than 1 µg/m³ for the 24-h and 1-yr bases, which represent the minimum that can be achieved at the ADGAS plant.

Spatial distribution of highest SO_2 ground level concentrations

The BREEZE AERMOD GIS Pro software has been used in this work to generate the contour plots of the predicted SO_2 GLCs over the Das Island. The generated contour plots for the 1-yr highest average under current and proposed SO_2 minimization schemes for the year 2007 are shown in Figures 4 and 5, respectively, for comparison purposes. The complete set of the contour plots of the SO_2 GLC distribution over the Das Island is available elsewhere [20].

Based on these contour plots, the highest 1-h highest averages under current conditions occur in the central-west part of the Das Island (residential area). The 24-h highest averages occur in the middle and north-west parts of the Island while the 1-yr highest averages occur in the middle and north-east parts of the Island. . Table 10 shows the SO_2 highest GLCs under current and proposed SO_2 minimization schemes for the years 2003 to 2007.

As seen in Table 10, the current conditions highest SO_2 levels within Das Island, over the years 2003-2007, frequently exceed the standard limits set by the UAE-FEA. The 1-h highest SO_2 level is 1869 µg/m³ (0.65 ppm). However, exposure to 0.15-0.25 ppm SO_2 (which is less than the current highest 1-h level at Das Island) has the potential to cause cardio respiratory effects to human body. The WHO limit is not to exceed 500 µg/m³ SO_2 in 10-minutes periods as this imposes health risks on humans in the form of changes in pulmonary functions and respiratory symptoms [19]. On the other hand, the 24-h highest average SO_2 level is 507 µg/m³ (or 0.18 ppm); the WHO 24-h average limit is 20 µg/m³. The effect of this is similar to that of the 1-h highest level. Moreover, the 1-yr highest average SO_2 level is 74 µg/m³ (or 0.02 ppm); long time exposure to such concentration may have serious effects. Thus, the 1-h, 24-h and 1-yr highest SO_2 levels under the current conditions represent threat to the health of the Das Island residents.

Table 10 also shows the highest SO_2 levels at Das Island, over the years 2003 to 2007, upon implementation of the proposed SO_2 minimization schemes. The 1-h highest SO_2 level is 636 µg/m³ (or 0.22 ppm); the exposure to such level is associated with cardio respiratory response effect on human health. The 24-h and 1-yr highest SO_2 levels are 158 and 37 µg/ m³, respectively; the exposure to such levels has the potential to affect the health of the Island residents. However, none of these highest GLC levels exceed the UAE-FEA standards.

Lastly, it should be kept in mind that upon implementation of the proposed SO_2 minimization schemes, the highest 1-h, 24-h and 1-yr SO_2 levels will be shifted to the north and north-east parts of the Island. The north-east part of the Island is no more than an industrial area. See Figures 4 and 5. This shift in SO_2 levels to non-residential areas is justified by the elimination of the SO_2 emissions from the ADMA Gas Turbines (GTs) and the SRU incinerators of Trains 1, 2 and 3. In this case the only remaining contributor to the SO_2 emissions at the Island is the CFFG from the fuel gas sweetening units of Trains 1, 2 and 3, which

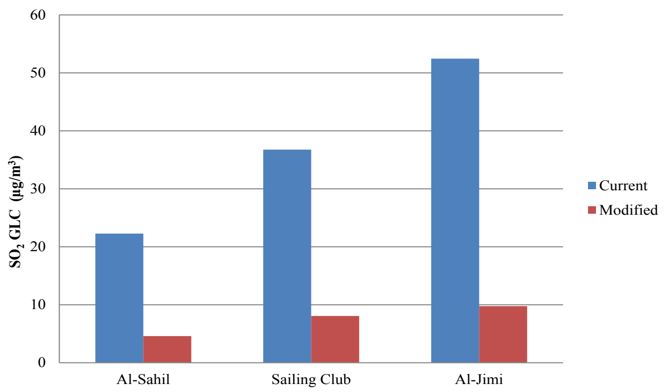

Figure 3: Comparison of 1-yr SO_2 GLC under current and proposed conditions – Year 2007.

Year	Receptor Location	Condition	1-h Highest (Standard = 350)	24-h Highest (Standard = 150)	1-yr Highest (Standard = 60)
2003	Al-Sahil	Current	587.32	118.97	22.27
		Proposed	230.57	36.02	4.59
		Proposed + CFFG	4.78	0.68	0.12
	Sailing Club	Current	373.56	119.79	32.39
		Proposed	253.41	31.61	7.06
		Proposed + CFFG	4.02	0.73	0.21
	Al-Jimi	Current	484.64	239.47	45.57
		Proposed	218.89	40.07	8.03
		Proposed + CFFG	5.11	0.97	0.28
2004	Al-Sahil	Current	587.37	124.94	20.62
		Proposed	203.70	30.25	3.90
		Proposed + CFFG	4.74	0.82	0.12
	Sailing Club	Current	377.45	136.90	34.24
		Proposed	216.02	38.18	7.49
		Proposed + CFFG	4.05	0.76	0.21
	Al-Jimi	Current	490.41	187.57	47.43
		Proposed	255.77	41.34	8.01
		Proposed + CFFG	4.91	1.03	0.29
2005	Al-Sahil	Current	579.69	203.26	32.29
		Proposed	317.44	31.03	4.35
		Proposed + CFFG	4.64	1.16	0.18
	Sailing Club	Current	362.67	118.82	39.84
		Proposed	333.13	46.75	7.12
		Proposed + CFFG	3.93	0.92	0.25
	Al-Jimi	Current	493.99	221.21	61.26
		Proposed	376.00	65.48	9.69
		Proposed + CFFG	5.18	1.19	0.38
2006	Al-Sahil	Current	586.75	94.28	28.45
		Proposed	200.22	30.60	5.19
		Proposed + CFFG	4.73	0.69	0.16
	Sailing Club	Current	383.68	111.06	35.21
		Proposed	227.14	42.16	8.91
		Proposed + CFFG	4.07	0.86	0.23
	Al-Jimi	Current	486.70	194.92	49.49
		Proposed	258.21	54.31	10.66
		Proposed + CFFG	5.09	1.08	0.32
2007	Al-Sahil	Current	585.96	142.11	27.43
		Proposed	210.88	34.92	4.76
		Proposed + CFFG	4.72	0.72	0.15
	Sailing Club	Current	384.11	150.13	36.76
		Proposed	240.25	47.68	8.06
		Proposed + CFFG	5.22	1.14	0.23
	Al-Jimi	Current	486.64	192.17	52.46
		Proposed	283.25	53.00	9.76
		Proposed + CFFG	4.05	1.52	0.32

Table 9: Predicted SO_2 GLCs (μg/m³) under Current and Proposed SO_2 minimization schemes and post Elimination of Continuous Flaring of Flash Gas (CFFG) at the Three Selected Receptors' Locations for the years 2003 to 2007.

as mentioned above, can be routed back to the ADGAS plant gas feed inlet and will result in the reduction of the SO_2 levels to much less than the UAE-FEA standard limits.

Compliance of the Predicted SO_2 Emission Levels with the UAE-FEA Standards Upon Implementation of the Proposed SO_2 Minimization Schemes

Currently, the SO_2 emission from the ADMA-GTs and the SRU incinerators of Trains 1, 2 and 3 are not complying with the UAE-FEA standard limits. Also, the current SO_2 emission rates from the Fuel Gas Users of Trains 1 & 2 are 89.54% of the UAE-FEA standard limits. This makes these sources susceptible to exceeding these limits in case of malfunction (sudden decrease in the UGAs removal efficiency as a result of process parameters changes). However, upon implementation of the proposed FGS scheme, the SO_2 emission rates (from the Fuel Gas Users of Trains 1 & 2) will be only 5.37% of the UAE-FEA limits (i.e., it will decrease the current SO_2 emission rates by 94%). Furthermore, Table 11 shows that the implementation of the proposed SO_2 minimization schemes has resulted in all SO_2 emission sources at the ADGAS plant to comply with the UAE-FEA limits and have the potential to challenge any future stringent limits imposed by the UAE-FEA with high level of confidence.

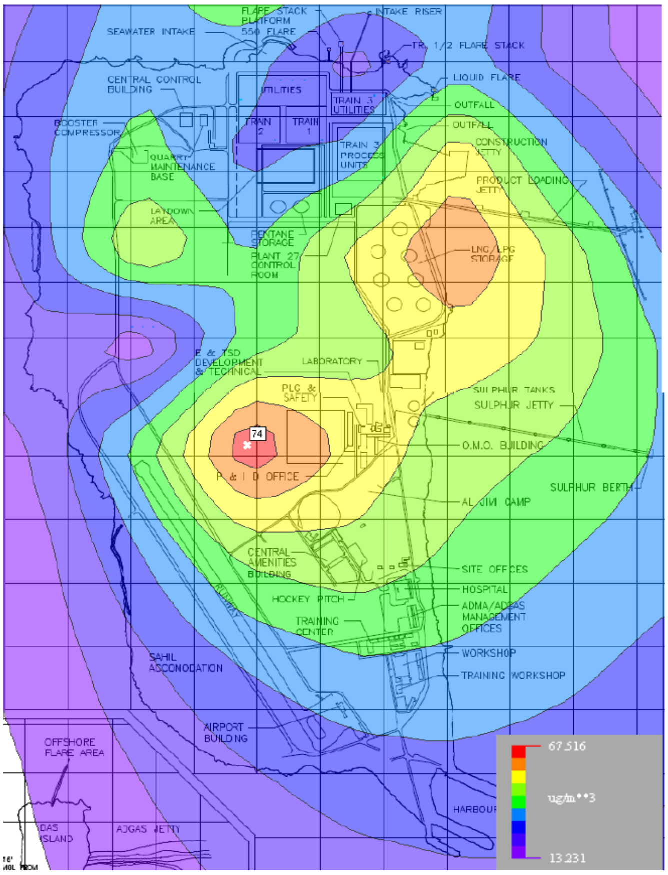

Figure 4: Contour plot of the 1-yr highest average SO_2 GLCs under current conditions for the year 2007. Each square on the diagram is 200 m x 200 m.

The compliance of the SO_2 levels with the UAE-FEA standards for the 1-h, 24-h and 1-yr at the Das Island have been plotted using the BREEZE AERMOD GIS Pro software. Figures 6(a) and 6(b) respectively represent the 1-yr compliance plot under current and under proposed SO_2 minimization schemes for the year 2007. The red color on these plots means the SO_2 GLC exceeds the limit set by the UAE-FEA. The complete set of the compliance plots is available elsewhere [20]. Table 11 shows the compliance results for the ADGAS plant SO_2 emission sources under current conditions and after implementation of the proposed SO_2 minimization schemes.

On the other hand, Table 12 summarizes the main observations of the spatial distribution compliances at the current and proposed SO_2 minimization schemes.

On the other hand, the contour plots indicate that the implementation of the proposed SO_2 minimization schemes will result in a greater area of the Das Island and most of the Island residential areas comply with the UAE-FEA air quality standards. Another aspect is that even though the northern part of the Island does not totally comply with the 1-h standard, its air quality will be improved. Also the highest predicted SO_2 level around the northern part of the Island will be about 650 μg/m^3 compared to the current 2000 μg/m^3 highest level. This means that under the proposed SO_2 minimization schemes all the Das Island area will comply with the 24-h and the 1-yr limits of the UAE-FEA.

Lastly, the present study is expected to be of importance to modeling experts and managers of ADGAS plant at the Das Island. Also, the outcome of this study could further assist managers of ADGAS, and similar gas processing plants, on the methodology to reduce SO_2 emissions to meet air quality standards. Meanwhile, the general approach presented here may be of value in application to other similar plants and systems around the world.

Conclusions

Currently the SO_2 emission rates from the ADGAS plant at Das Island are as follows:

- The SO_2 emission rates from the SRU incinerators of Trains 1, 2 & 3 and ADMA-GTs do not comply with the UAE-FEA standards. The SO_2 emission rates from Fuel Gas Users of Trains 1 and 2 are 89.54% of the UAE-FEA limits. This makes these sources susceptible to exceeding the standards' limits in case of malfunctions.

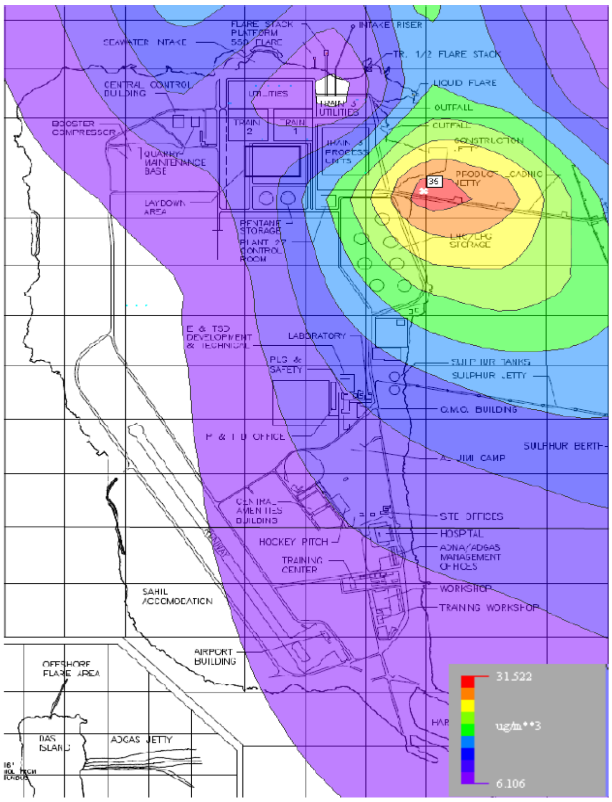

Figure 5: Contour plot of the 1-yr highest average SO_2 GLC under proposed SO2 minimization schemes for the year 2007. Each square on the diagram is 200 m x 200 m.

Basis	Condition	2003	2004	2005	2006	2007	Average
1-h	Current	1988	1674	1708	2024	1953	1869
	Proposed	659	642	630	603	647	636
24-h	Current	496	373	425	485	758	507
	Proposed	157	134	159	168	170	158
1-yr	Current	66	69	92	70	74	74
	Proposed	35	37	46	33	35	37

Table 10: Highest SO_2 GLCs (μg/m3) at Das Island under Current and Proposed SO_2 Minimization Schemes.

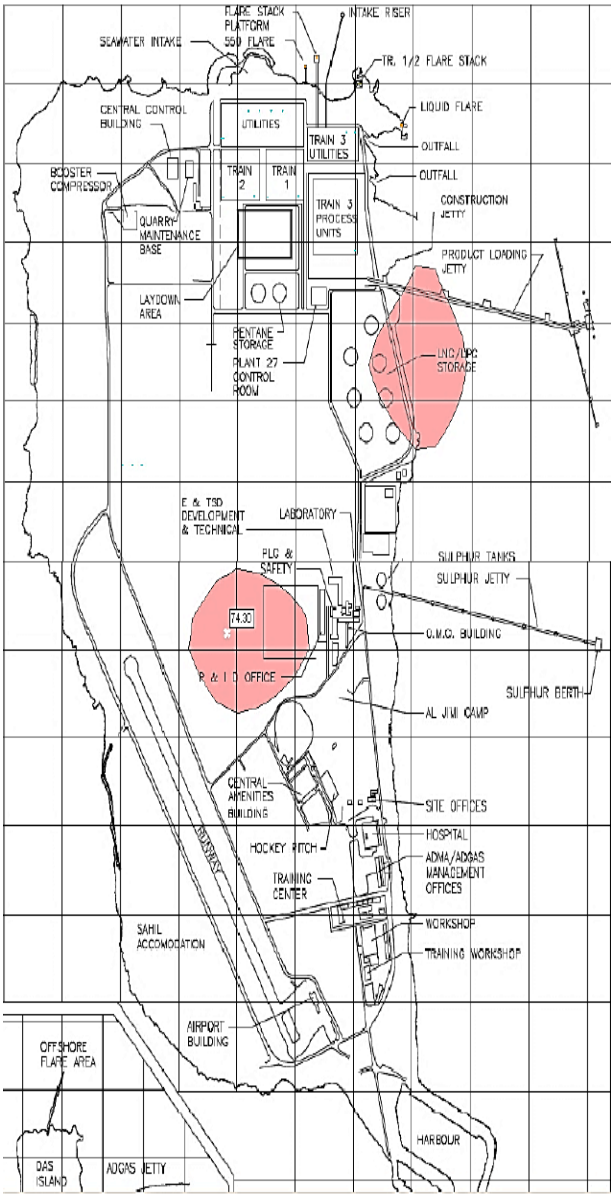

Figure 6a: Compliance plot of the 1-yr SO_2 GLC under current conditions for the year 2007. Each square on the diagram is 200 m x 200 m.

- All locations in the Das Island do not comply with the 1-h SO_2 GLC of the UAE-FEA air quality standard (350 μg/m^3), most of the Island does not comply with the 24-h regulatory limit (150 μg/m^3), while most of the Island complies with the 1-yr limit (60 μg/m^3).
- The highest 1-h, 24-h and 1-yr SO_2 levels are 1869, 507 and 74 μg/m^3, respectively.
- The locations of the highest SO_2 levels are more of Residential Areas which represent a threat to the health of the Das Island residents.

Upon implementation of the proposed SO_2 minimization schemes, the situation at the Das Island will be as follows:

- The 1-h, 24-h and 1-yr SO_2 GLC highest averages at the specified receptors will comply with the UAE-FEA air quality standard. In addition, SO_2 levels > 500 μg/m^3 will not be experienced for short periods.
- The average of the 1-h highest SO_2 levels is 636.2 μg/m^3. The averages of the 24-h and 1-yr highest SO_2 levels are 157.6 and 37.2 μg/m^3, respectively. The highest SO_2 GLC will shift to the north-east part of the Island (i.e., the Industrial Area).
- The temporal variations in the SO_2 highest averages in the Das Island through years 2003 to 2007 show similar trends toward the distribution of SO_2 GLC levels for the 1-h, 24-h and 1-yr highest averages.
- Generally, the SO_2 GLC in the north part of the Island exceeds the 1-h limits of the UAE-FEA air quality standard. However, the residential areas comply with these standards. The highest 1-h SO_2 GLCs are 650 μg/m^3, which is 32.5% of the highest current averages of 2000 μg/m^3). Moreover, all the Das Island area complies with the UAE-FEA 24-h (150 μg/m^3) and 1-yr (60 μg/m^3) limits.
- A greater area of the Das Island will comply with the UAE-FEA air quality standard. Also all the Island area will comply with the 24-h and 1-yr UAE-FEA standard.
- The implementation of the proposed SO_2 minimization schemes along with the elimination of the continuous flaring of flash gases will result in 99.2% reduction in the total SO_2 emissions at ADGAS. Once the flash gas flaring is eliminated, the SO_2 GLC 1-h highest averages at the selected receptors will be about 4 - 5 μg/m^3 while the 24-h and 1-yr highest averages will be < 1 μg/m^3.

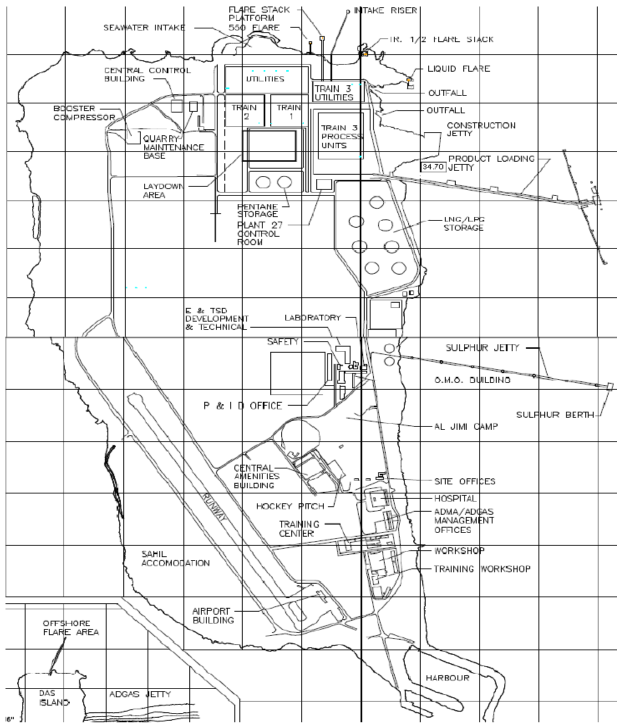

Figure 6b: Compliance plot of the 1-yr SO_2 GLC under proposed SO_2 minimization schemes for the year 2007. Each square on the diagram is 200 m x 200 m.

Equipment	UAE-FEA Emission Standard (mg/Nm³)	Current (mg/Nm³)	Proposed (mg/Nm³)	Reduction (%)	Proposed / UAE-FEA (%)
Boilers 1, 2, 3 and 4	500	290	15.40	97.7	1.95
ADMA-GTs	500	8554	26.84	99.7	5.37
Trains 1 & 2 Fuel Gas Users	500	448	26.84	94.0	5.37
Trains 1 & 2 SRU Incinerators	500	4854	24.28	99.5	4.86
Train 3 SRU Incinerator	500	3712	18.55	99.5	1.99

On the other hand, Table 12 summarizes the main observations of the spatial distribution compliances at the current and proposed SO_2 minimization schemes.

Table 11: Compliance of the Various SO_2 Emission Sources at ADGAS with the UAE-FEA Emission Standards.

Basis	Current Conditions	Proposed Conditions
1-h	All of the Das Island areas do not comply with the UAE-FEA limit (350 µg/m³)	Generally, the GLC in the northern part of the Das Island exceeds the limits. Residential areas comply with the standards. The highest concentration is about 650 µg/m³, which is 32.5% of the highest current average (2000 µg/m³)
24-h	Most of the Das Island areas do not comply with the UAE-FEA limit (150 µg/m³)	All of the Das Island areas comply with the UAE-FEA limit (150 µg/m³)
1-yr	Most of the Das Island areas comply with the UAE-FEA limit (60 µg/m³) except the Middle and Jetty areas.	All of the Das Island area complies with the UAE-FEA limit (60 µg/m³)

Table 12: Compliances of SO_2 GLCs Spatial Distribution under Current and Proposed SO_2 Minimization Schemes.

- The routing of the Continuous Flaring of the Flash Gas (CFFG) back to the inlet feed gas of the plant trains will result in 99.19% reduction in the total SO_2 emissions at the ADGAS plant.

Lastly, based on the results of this work, it is recommended

- To implement the proposed SO_2 minimization schemes presented in Part I of this work (i.e., fuel gas sweetening and flue gas desulfurization) in order maintain good air quality at ADGAS and in the Das Island. This also requires the replacement of the HYPAK packing of the UGAs of Trains 1 and 2 by IMTP packing.
- To have continuous monitoring of the air quality on the Island that should be easily accessed by the Island workers through brochures and/or broadcasting. This will help to worn the workers on occasions of high levels of SO_2 emissions.
- To carry out comprehensive studies on the occupational health of the workers and residence of the Island.

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