GOVERNMENT OF
WESTERN AUSTRALIA

Browse LNG Precinct




Browse Liquefied Natural Gas Precinct
Strategic Assessment Report

(Draft for Public Review)
December 2010

Appendix C-25

Browse LNG Development –
Air Quality Assessment

BROWSE LNG DEVELOPMENT

Air Quality Assessment

Prepared for

Woodside Energy Ltd

Prepared by

Air Assessments

October 2010
Final

WEL Doc No. JA0006RH0075

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Prepared	**Date**	**Checked**	**Date**	**Approved**	**Date**
Owen Pitts	28 April 2010	Mark Hibberd CSIRO	15 February 2010	Owen Pitts	28 April 2010
Owen Pitts	4 August 2010	Mark Hibberd CSIRO	28 July 2010	Owen Pitts	4 August 2010
Owen Pitts	14 October 2010			Owen Pitts	14 October 2010

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Glossary

Term	***Definition***
%	percent
$\mu g/m^3$	micrograms per cubic metre
µm	micro metre
<	less than
>	greater than
C	degrees Celsius
AGT	Aero-derivitive Gas Turbines. As per the Pluto LNG project
BoM	Bureau of Meteorology
BLNG	Browse Liquefied Natural Gas
BTEX	Benzene, toluene, ethyl- benzene and xylenes
CO	Carbon monoxide
CO_2	Carbon dioxide
e.g.	for example
DLN	Dry Low NO_X as per a design for a gas turbine burner that reduces NO_X emissions
DWT	Dead Weight Tonnage. A measure of how much weight a ship can safely carry
EPA	Environmental Protection Authority
EPP	Environmental Protection Policy
MW	Megawatt
GJ	Gigajoules
GJ/s	Gigajoules per second
i.e.	that is,
IS	Integrated Steam. As per the Tangguh (Indonesia) LNG project
km	kilometre
H_2S	Hydrogen Sulphide
IOA	Index of Agreement as used in determining the skill of a model prediction
LIGT	Large Industrial Gas Turbines. As per the Gorgon LNG project
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
m	metre
M	million
m/s	metres per second
m^2	square metres
m^3	cubic metres
m^3/s	cubic metres per second
mg	milligram
MEG	Mono-ethylene glycol
MIGT	Medium Industrial Gas Turbine. As per the Pluto LNG project
Mtpa	million tonnes per annum
NMVOC	Non Methane Volatile Organic Compounds
No.	Number
NO_X	Oxides of nitrogen
NO	Nitric oxide
NO_2	Nitrogen dioxide
NPI	National Pollution Inventory
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter (fine dust)
$PM_{2.5}$ and PM_{10}	Particulate matter less than 2.5 or 10 microns, respectively
ppmv	Parts by million by volume

T	tonnes
TAPM	The Air Pollution Model
TAPM-CTM	The Air Pollution Model with Chemical Transport Model
TCU	Thermal Combustion Unit
tpa	tonnes per annum
tph	tonnes per hour
SO_2	Sulphur dioxide
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compounds

Executive Summary

Woodside Energy Ltd (Woodside) proposes to construct a 15 Mtpa LNG plant as the foundation industry at the proposed Browse LNG (BLNG) Precinct. This Precinct approximately 55 km north of Broome near James Price Point has been selected as the processing hub for natural gas from the offshore Browse gas fields. It is planned that the BLNG Precinct will be able to accommodate LNG plants with a production capacity of up to 50 Mtpa of LNG. As part of environmental assessment of this project, this report presents an assessment of the likely local and regional impacts from atmospheric emissions.

The air quality assessment was undertaken using two models; TAPM for the local area (up to 14 to 18 km from the sources) to investigate peak concentrations close to the plants and TAPM-CTM to assess the broader regional impacts due to photochemistry, particularly the formation of ozone where the peaks may occur up to one hundred kilometres from the Precinct.

To gauge the suitability of the models, both models were validated where possible against observations; TAPM against the available meteorological observations where it performance was fair and TAPM-CTM for gaseous pollutants at Dampier where it was shown to perform credibly for predictions of gaseous pollutants from industry and fires. Dampier was used as the nearest site with good quality monitoring data.

To assess the 50 Mtpa LNG Precinct as the LNG technologies may vary from plant to plant, four typical LNG technology cases were assessed. Emissions for these whenever possible were based on conservative estimates. NO_X and PM for the most significant source (the gas turbines and compressors), were estimated based on the guaranteed maximum emission concentrations and will therefore overstate the emissions. Likewise emissions of H_2S and SO_2 are conservatively based on a maximum H_2S content in the feed gas. BTEX emissions were conservatively estimated based on an upper content in the feed gas, a high removal efficiency from the feed gas by the CO_2 Removal Unit and a worst case availability of 90% for the Thermal Combustion Units (TCUs) which normally destroy these compounds. The results from the regional TAPM-CTM modelling showed the following:

- The contribution from the BLNG precinct at sensitive receptors will be below the NEPM standards, with the pollutant closest to its respective standard being ozone at 64% of the 1-hour standard. At other locations (non sensitive receptors) the maximum 1-hour ozone level is predicted to be 84 ppb or 84% of the standard. This peak is due in main to the high VOC emission estimated for condensate loading which are considered conservative. Note, that about 25 ppb of this ozone is from the clean background air. For the extremely unlikely case that full emergency shutdown / flaring occurs (once in 10 year event) at the time of the worst case meteorology, the maximum ozone levels anywhere are predicted to be 92% of the NEPM standard;
- In comparison, fires are the existing dominant source of pollutant in the region leading to high particulate, ozone and NO_2 concentrations. These high levels are due not only to the very large extent of land burned but, also to a build up of pollutants in the atmosphere as the fires typically last for days. The predicted existing levels of ozone are typically in the range of 60 to 85 % of

the NEPM standards, with peak concentration anywhere of 91% and 111% of the respective 1 and 4-hour standards. The predicted particulate levels from fires for most of the Dampier Peninsula are below the NEPM PM_{10} standard with more than 5 exceedances, but do exceed it for a small area. Note, for both ozone and particulate matter there are no measurements within the Kimberley to confirm the predictions;

- Considering the BLNG and existing sources, there is negligible cumulative impact to the maximum ozone, particulate and NO_2 concentrations as the predicted concentrations are dominated by the concentrations from fires; and
- Impacts on vegetation, as assessed through deposition rates of nitrogen and sulphur were predicted to be low, both under the WHO guidelines.

The local modelling conducted using TAPM showed that:

- All pollutants from the LNG Precinct are predicted to be well within the adopted criteria except for benzene, H_2S and to a lesser degree toluene. The primary source of benzene and toluene emissions is from venting from ships holds during condensate loading. Predictions indicate that benzene concentrations would be well in exceedance of the NSW modelling guidelines. This criteria however is intended more as a screening level to flag possible issues. A more appropriate measure as directly related to benzene's health endpoint is the annual average benzene concentration. Annual benzene concentrations were predicted to be just exceed the annual criteria (5.5 $\mu g/m^3$ or 110% of the European standard) outside the south west corner of the Precinct buffer. Model sensitivity tests without condensate ship-loading emissions predicted that BTEX concentrations are greatly reduced, with the annual average benzene level outside the buffer being less than 10% of the WHO annual guideline of 5 $\mu g/m^3$;
- Hydrogen sulphide levels were predicted to exceed the adopted NSW single residence criteria (1-second 99^{th} percentile of 4.8 $\mu g/m^3$) out to 9 km to the east of the buffer zone. For the more stringent criteria applicable for an urban area with >2000 people (or very sensitive land uses such as hospitals), the 1-second 99^{th} percentile criteria of 1.38 $\mu g/m^3$ would be exceeded to 20 to 30 km to the east of the buffer. In these areas the maximum 1-second H_2S concentration is predicted to be around 50 $\mu g/ m^3$ and therefore H_2S levels would at times be above the odour threshold of about 1.2 $\mu g/m^3$ and would be recognizable by its characteristic rotten egg gas smell. Though detectable by its odour, the concentrations are well below the level of concern for health, with the WA Health Department recently recommending a limit of 2 ppm (approximately 3000 $\mu g/m^3$ for a 30-minute average). Therefore, in the area to the east of the Precinct it is predicted that the H_2S odour will at times be recognizable, though the concentrations are 60 times lower than levels that can cause health effects.

Comparison between the four LNG technology cases showed that there were small differences in the predicted concentrations of pollutants. For most pollutants these are not significant as the concentrations are well below the criteria. Also though a LNG technology may lead to lower concentrations of one pollutant for one averaging time, it may lead to higher concentrations for another pollutant at another averaging time. For the pollutants which are relatively high to the criteria, benzene and H_2S the differing LNG technologies do result in some small variation, For benzene, considering the more relevant annual average concentration all predicted concentrations are well below the criteria such that there is no one preferred technology. For H_2S it is considered that the high levels are primarily a result

of the conservative nature of the emissions used and not that one LNG technology is favoured over the others.

1 Introduction

1.1 Background and Scope of Work

Woodside Energy Ltd (Woodside) proposes to construct a 15 Mtpa LNG plant as the foundation industry at the proposed Browse LNG (BLNG) Precinct. This Precinct approximately 55 km north of Broome near James Price Point has been selected as the processing hub for natural gas from the offshore Browse gas fields. See **Figure 2-1** for the location of the Project and nearby communities. It is planned that the BLNG Precinct will be able to accommodate LNG plants with a production capacity of up to 50 Mtpa of LNG. To assess the air quality impacts of this development, Woodside have contracted Air Assessments to assess the 15 Mtpa Browse development and also the precinct at its capacity of 50 Mtpa.

The scope of the assessment to be undertaken by Air Assessments is to:

- Determine baseline atmospheric conditions and air quality in the James Price Point area;
- Undertake modelling for a range of scenarios, which will be used to assess how the environmental objectives for air quality (atmospheric conditions) are achievable; and
- Identify any significant considerations for the Precinct layout and design.

Note, this study addresses all atmospheric emissions that may be of concern with regards to health and vegetation impacts, excepting emissions from CO_2 and other greenhouse gases in regards to their effect via the potential enhanced greenhouse warming of the earths atmosphere. These emissions do not have any direct impact on health issues in the area but are considered under the greenhouse assessment as detailed in Woodside (2010). Note, also the scope of the report is to predict the likely air quality from the Precinct at capacity and makes no recommendation on the management of issues that may result.

1.2 Overview of report

To determine the impacts of a proposed facility a modelling approach must be used to predict the concentrations from the proposed sources, combine these with existing levels from other sources in the area and compare the resultant concentrations to relevant criteria. For this approach the key requirements are:

1. Identify and estimate emissions for all future sources and the potential variability of the emissions;
2. Determine existing concentrations and background levels for the pollutants of concern;
3. Predict the ground level concentrations in a model that can account for the important dispersion processes which are dependent on the region of interest (topography, land use, meteorology) and also the source type (e.g. tall buoyant or surface releases). The model must also account for chemical reaction, deposition or wash-out that may occur;
4. Estimate the cumulative concentrations incorporating existing levels if the cumulative impact is important; and
5. Compare the results against some accepted criteria.

Figure 2-1 Location of the Browse LNG Development at James Price Point

These steps are addressed in this report with:

- **Section 2** summarising the processes involved in a LNG plant and the sources of atmospheric emissions for both routine and non-routine operations;
- **Section 3** provides estimates of the emissions from the LNG plant, the associated sources and the existing sources in the region;
- **Section 4** describes the applicable criteria for the pollutants of concern;
- **Section 5** provides a summary of the existing concentrations in the region and also the meteorological measurements that are available;
- **Section 6** describes the important dispersion processes that are required to be modelled, the selection of the models and the model parameters used;
- **Section 7** provides an evaluation of the modelling system for this area for both the meteorology and for prediction of gaseous concentrations from both fires and industry for the nearby Pilbara where there good quality monitoring data;
- **Section 8** presents the results from the regional modelling assessment using TAPM-CTM for pollutants such as ozone, NO_2 and CO. This involves predictions for the existing sources, predominantly bushfires and also sources at Broome, for the LNG Precinct by itself and for cumulative impacts and compares these predictions against the criteria listed in **Section 4**;
- **Section 9** presents the results from local modelling within 14 to 18 km of the plant using the model TAPM and a finer grid. Pollutants addressed includes NO_2 on the finer scale grid as well as pollutants such as benzene and H_2S;
- **Section 10** provides an assessment of vegetation impacts using nitrogen and sulphur deposition as the measure; and
- **Section 11** summarises the conclusions of the study.

2 LNG Process Description

2.1 Overview

LNG plants consist of the following units/processes:

- Gas reception (slug catcher, separation and MEG treatment);
- Gas purification (CO_2 removal and gas dehydration);
- Condensate and if required LPG removal (fractionation, stabilisation and LPG removal);
- Liquefaction;
- Product storage;
- Offloading - in this case ship-loading; and
- Associated utilities – Power generation, flares and water treatment;

The process flow of gas and liquid streams is shown in **Figure 2-1** with a description of the various units described further in the following section. This description follows that detailed in Woodside (2010) but with the emphasis on atmospheric emissions.

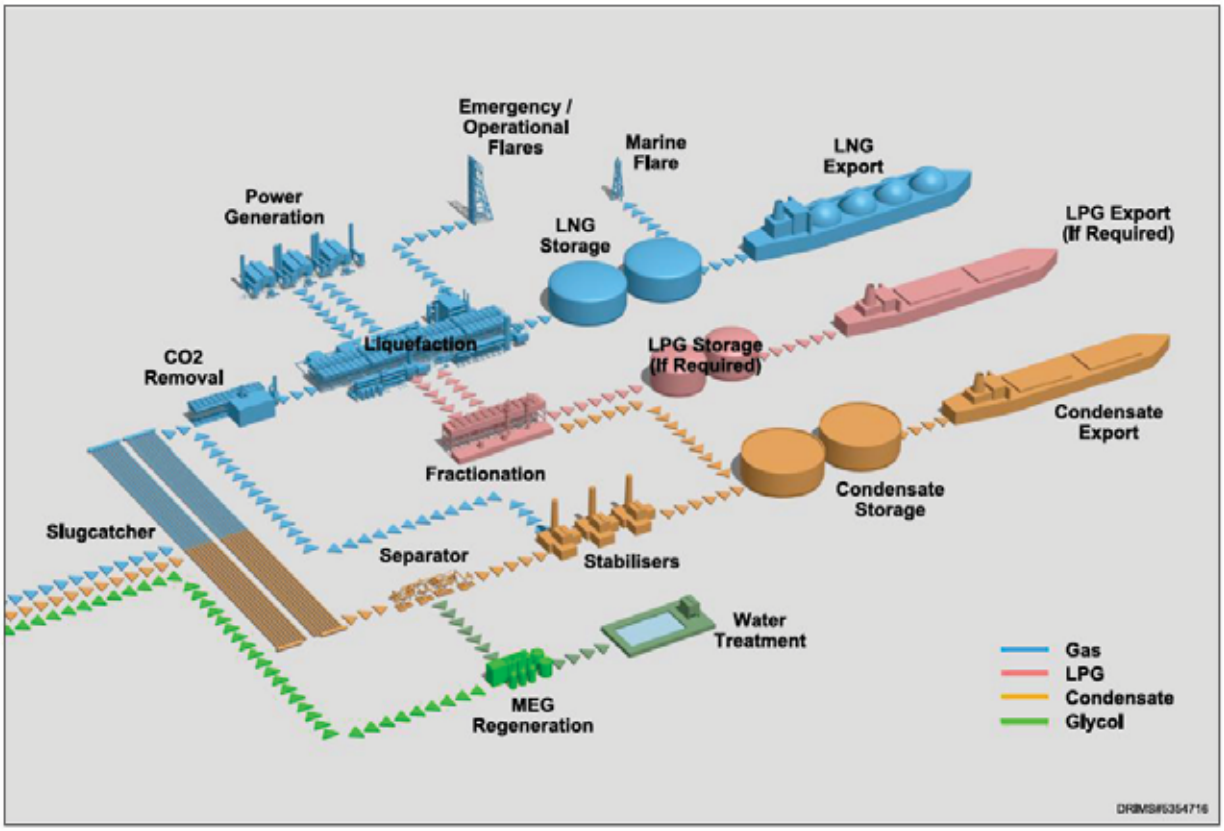

Figure 2-1 Schematic of General LNG Plant

2.2 LNG Plant Process Units

2.2.1 Gas and Liquid Receipt

Hydrocarbons can be received either in separate liquid and gas pipelines or together in a multi-phase pipeline, depending on the design of the upstream facilities. In any case, gas, condensate and potentially water separation facilities will be required. The separators may be in the form of a finger-type slug catcher or process vessels. Gas liberated from the separator is compressed and returned to the gas stream. Condensate will be separated from the water phase and directed to a stabilisation unit where the liquids will be stabilised to drive off the associated gas, which is cooled. Water separated from gas and condensate will be directed to the onshore waste water treatment plant for appropriate treatment and disposal. The inlet facilities may also incorporate MEG regeneration facilities. Mono-ethylene glycol (MEG) is used in pipelines to manage hydrate formation. A hydrate is a compound that contains water molecules. MEG works by dissolving water into the MEG and therefore inhibiting the formation of hydrates. MEG is regenerated by heating which drives the water out of it. This water is then condensed and sent to the waste water treatment facilities.

As the gas and liquid receival system is fully enclosed no gaseous emissions occur from this area.

2.2.2 Gas Purification – CO_2 Removal Unit

Gas flow from the inlet facilities will be rich in CO_2 with residual traces of hydrogen sulphide (H_2S). Typical CO_2 levels from the Browse Basin hydrocarbon reservoir range from 6 to 12 %. The CO_2 Removal Unit is designed to remove carbon dioxide from the feed gas that would solidify when cooled to the temperatures required to liquefy natural gas. This is achieved using a solvent to absorb the "contaminants", which are released when the solvent is regenerated (by heating). Whilst the solvents used to remove carbon dioxide are highly selective, some hydrocarbons, including BTEX (benzene, toluene, ethyl benzene, and xylenes) and hydrogen sulphide (H_2S) are also co-absorbed. These co-absorbed species are released into the acid gas stream as the solvent is regenerated. In CO_2 Removal Units initially installed in the Northwest the solvent used was Sulfinol which removed a proportionally high amount of BTEX. This solvent is no longer favoured, with activated methyl-di-ethanol-amine (aMDEA) or similar solvents designed to remove approximately 0 to 15% of CO_2 now used which absorbs less BTEX and therefore results in less BTEX in the CO_2 gas stream.

The CO_2 gas stream can be:

- Released directly to atmosphere as a "cold" plume, the temperatures are around 50 deg Celsius but with nearly 100% CO_2 in the emissions results in a heavier than air release. If this gas stream is not dispersed quickly the plume may tend to slump to ground level;
- Injected into or adjacent to the exhaust from a much larger buoyant plume where the CO_2 removal emissions will therefore be mixed into and rise to much greater heights than would otherwise occur. This therefore can reduce the ground level concentrations substantially; or
- Pass the gas to a thermal oxidizer where the BTEX and H_2S are oxidised and destroyed forming SO_2, CO_2 and H_2O. Though SO_2 may be created it is generally of less concern than H_2S due to the H_2S air quality criteria being much lower than that of SO_2. A potential disadvantage of a thermal oxidiser for a gas stream with nearly 100% CO_2 is that an appreciable amount of natural gas is required for combustion. The amount of fuel gas required is strongly dependent on the

destruction technology selected, but can potentially result in a significant increase in CO_2 emissions.

To minimise emissions to the environment from the Browse LNG development, some form of BTEX disposal is anticipated (by e.g. thermal oxidation or geo-sequestration of the entire acid gas stream). For this air quality assessment a Thermal Combustion Unit (TCU) has been selected as the thermal oxidation process for modelling purposes.

In the event that TCUs (or alternative selected mitigation measures) are temporarily unavailable, the CO_2 gas stream will be vented adjacent to the exhausts from the compressors on the LNG trains. Emissions of concern from this gas stream from a local air quality viewpoint are primarily BTEX (benzene, toluene, ethyl benzene, and xylenes) and H_2S (hydrogen sulphide). With the exhaust volume from the LNG compressors being up to 10 times higher than that from the CO_2 gas vent, the merged plume will have characteristics similar to the original compressor emissions and therefore a high level of dispersion will occur.

2.2.3 Gas Purification - Dehydration and Mercury Removal

Treated gas from the CO_2 Removal Unit is next passed to a dehydration system. The may occur through chilling of the gas to a temperature slightly above the hydrate point to remove as much water as possible and then passed to a molecular sieve system to remove the final traces of water. Following this the dry gas passes through a mercury guard bed to remove any trace-level mercury that may be present in the gas.

2.2.4 Separator

Liquids from the liquid inlet facilities are separated into condensate and water (potentially containing MEG and other water soluble chemicals). Gas that is liberated from the separator is directed to the feed gas stream to be treated at the CO_2 Removal Unit.

2.2.5 Condensate Stabilizers

Condensate liquids from the separator are “live” and contain high vapour pressure components (i.e. shorter chain hydrocarbons). To remove the very light, high vapour pressure components the condensate is treated by heating the condensate in a stabilisation column. This light gaseous fraction is then sent to the CO_2 Removal Unit with the main gas feed. The heat required for this process will be obtained from heat recovered from the exhausts of gas turbines used within the facility. No atmospheric emissions will therefore occur from this process unit.

2.2.6 MEG Recovery System

Water containing MEG is treated in the MEG recovery system where the liquids are heated to vaporise the water, therefore concentrating the MEG so that it is suitable for reuse. The MEG is cooled for storage. The very small amount of hydrocarbon gases that are liberated from the MEG regeneration process (containing some BTEX) are captured, with this gas stream passed to the operational flare. The water from MEG regeneration is passed to the water treatment plant.

2.2.7 Water Treatment

An onshore waste water treatment plant and associated marine outfalls will be developed to treat and manage waste water generated from the LNG facilities and associated supporting infrastructure. Potential waste water streams that will require treatment prior to discharge to an approved location include:

- Produced water and associated liquid effluent from LNG processing;
- Condensed waste water from ancillary equipment;
- Oily contaminated water from process areas;
- Surface run-off (e.g. stormwater) from process areas;
- Sanitary waste water (sewage and grey water); and
- Other waste water associated with provision and supply of water (such as brine water) for the LNG facilities at the Precinct.

It is highly unlikely that the installed level of pre-treatment would allow more than negligible emissions of VOCs from the discharged water streams.

2.2.8 LNG Production - Liquefaction

The dry, mercury free feed gas is fed to each of the LNG units or trains where it is cooled in a number of steps by heat exchange with different refrigerants. These reduce the temperature of the gas to minus 161º C (the boiling point for methane) liquefying the natural gas.

The refrigerant compressors are driven by gas turbines, with additional power added by electric helper motors or steam turbines. (This is described further in **Section 2.3).** Therefore atmospheric emissions under normal operation from a LNG train consists of the combustion products from the gas turbine refrigerant compressors with the emissions of concern primarily being NO_X and to a lesser extent CO, PM and VOCs. The gas turbines used in the past generally have been open cycle, but now there is the tendency to utilise waste heat recovery on the hot exhaust gas to improve the efficiency of the LNG plant. Additionally CO_2 Removal Unit vents are sometimes also vented alongside the compressor exhausts to increase the dispersion of the CO_2 plumes.

The other source of atmospheric emissions from the LNG trains can be fugitive gas from leaks on the seals on the compressors. Older style trains have oil seals whilst new plant tend to have dry gas seals with emissions routed to the flares. For this modelling assessment the emissions from seals are considered to be dry seals with the small emissions captured in the operational flare emissions (see **Section 2.2.10**).

With the large amount of refrigeration occurring on LNG trains there must be a corresponding large amount of heat rejected or released from the refrigeration circuit. For LNG trains this occurs through the use of fin fan coolers or condensers that are located on top of the trains. These give off a large amount of low grade heat. The resultant thermal plumes contain no pollutants but are important as they tend to interact with the plumes from the compressors and increase their overall plume rise (see **Section 6.5**).

A nitrogen rejection unit or an end flash gas system may be included as part of the liquefaction process to reduce the nitrogen content of the LNG product. The end flash gas system rejects nitrogen as part of a hydrocarbon-rich stream, which is subsequently used as fuel gas for the LNG plant. A nitrogen rejection unit produces a high purity nitrogen stream that may be emitted to atmosphere.

2.2.9 Utilities - Power-Plant

In broad terms electrical power for the LNG plant could be provided via:

- Gas turbine and generators (with heat recovered to meet process heating demands if required);
- Combined cycle power station based on gas turbines. However this is only typically considered where a large power demand is required due to operability requirements and constraints imposed by small "island" grids (e.g. when utilising electrically driven liquefaction compressors); or
- A fully integrated combined Heat and Power system which is integrated with the liquefaction compressors. The ability to implement this type of concept efficiently and effectively is highly dependent on the power and heat balance of the facility which is driven by factors such as inlet gas composition, LNG technology and size of the LNG trains.

Emissions of pollutants addressed in the study from gas turbines when gas fired with low sulphur gas are primarily NO_X, with smaller amounts of CO, VOC, PM and SO_2.

2.2.10 Flares

For the LNG plants four flares are generally used. These are the Wet and Dry gas flares for "emergency" releases, the operational/ Start-up Flare and the Marine flare. For the BLNG, elevated stack flares are proposed which will be designed in accordance with safety requirements to minimise radiant heat at the surface. Smokeless flares will be installed resulting in near zero particulate emissions. As an alternative to the stack flares ground flares can be used but have not been modelled in this study.

Wet and Dry Gas Flares

Wet and dry gas flare systems are provided to support the emergency depressurisation of the process. The wet gas flare system is connected to the front end of the LNG train and processes the blowdown of wet, warm condensate gases. The dry gas flare system is connected to the rear end of the LNG train and processes the blowdown of dry, cold gases. The systems need to be segregated as the cold gas from the dry gas flare system could cause freezing of the water in the warm wet flare, potentially causing a catastrophic failure in this system due to an ice blockage.

The flare systems are designed to be able to handle the gas flow from the largest possible event. These peak flows are very unlikely events, caused by the failure of typically very reliable systems (e.g. a failure of a pressure reduction valve in the gas inlet facilities). There are a range of much smaller non-routine operations that also are required to be flared. Overall the Wet and Dry gas flares are infrequently used, primarily for major upsets where large volumes of gas are released for short periods of time.

Operational and Start-Up Flare

For the small amount of gas flared under normal operation and for the small non-routine flare events, the gas will be typically directed to the operational flare. Additionally when starting up an LNG train, the gas vented will likely be vented to the operational flare (see **Section 3.3** for a fuller description).

Marine Flare

A separate service flare associated with LNG storage and loading operations is utilised. Under normal loading of LNG tankers clean LNG vapour is produced, which is recompressed and reused. On average the marine flare has a low flaring rate of approximately 10 tpd.

Higher flaring events occur when the LNG vapour evolution is at a greater rate than the boil-off gas compressors can process and/or the vapour from the LNG tanker has been inerted, which may occur at certain times during LNG carrier loading. High flaring events are associated with the cool down of LNG carriers following dry-dock, where the ship's LNG tanks are both warm and inerted (with e.g. CO_2). The inert gas is purged with LNG vapour, and as the resulting purge gas can not be accepted by the fuel gas system it is necessary to send the gas stream to the flare for safe destruction. Following this further cooling down the ship's tanks takes place, which can generate high flows of vaporised LNG that also need to be directed to the flare. In such circumstances flaring of up to approximately 400 tonnes of LNG over 32 hours can occur. For a 15 Mtpa precinct development, 3 such events are expected per year, rising to 10 for a 50 Mtpa development. Flaring may also be caused by a fault with a boil off gas compressor.

2.2.11 Storage (LNG and Condensate)

The LNG storage tanks are a totally enclosed system. In normal operation any boil off gas is compressed and used as fuel gas on the site. Condensate storage tanks will have floating roof tanks with no headspace. Therefore, there are minimal emissions from these tanks.

2.2.12 Ship Loading

VOCs are emitted during the loading of condensate ships. Whilst the condensate ships arrive at the loading terminal notionally empty, there is a small residual amount of condensate left in the ship's tanks after unloading at its previous destination. This condensate reaches a vapour-liquid equilibrium with the atmosphere inside the tank, creating a VOC-rich vapour space. This VOC-rich vapour is displaced by the condensate liquid being loaded into the ship's tanks, causing VOCs to be discharged to atmosphere.

VOCs that may be released during LNG ship-loading have been described in **Section 2.2.10**.

2.2.13 Fugitive Releases from Seals

With older LNG plants there can be appreciable VOCs released from seals around compressors etc. In particular for plants with oil seals. Current practice is to use dry seals which have negligible VOC release with the small emissions captured and sent to the operational flare.

2.3 Possible Variations in LNG Plant Design

With LNG plants there are a number of different LNG liquefaction technologies available and therefore some variation to the atmospheric emissions that may occur. This variation for the facilities at the

BLNG precinct is primarily likely to occur in the level of heat integration/recovery applied by different proponents. A case map of technology options that may potentially be used has been developed to determine the potential ranges in emissions levels from the LNG precinct. These cases are described below:

Conventional Industrial Turbine LNG Facility - Large Industrial[1] GTG's (LIGT)
In this LNG facility design, each LNG train uses two large industrial gas turbines (e.g. GE Frame 7 turbines) with electrical helper motors to drive propane-mixed refrigerant circuits. Heat is recovered from the refrigerant compressor gas turbines to provide process heat to the plant, but heat is not recovered at sufficient quality to be used to generate power. Large industrial gas turbines are used to generate the electricity required for the electrical helper motors and the site-wide power demand.

Conventional Industrial Turbine LNG Facility - Medium Industrial GTG's (MIGT)
The technology and level of heat integration is the same as the case "Conventional Industrial Turbine LNG Facility (LIGT)", with the exception that smaller power generation gas turbines are used for power generation. Such a configuration may be implemented where the construction of LNG trains is staged in such a way as to encourage smaller power generation facilities in the foundation phase(s) for each proponent.

Integrated Steam (IS) LNG Facility
Each LNG train uses two large industrial gas turbines (e.g. GE Frame 7 turbines) with steam helper motors to drive propane-mixed refrigerant circuits. High pressure steam is generated using the heat available from the refrigerant compressor gas turbine exhausts. This high pressure steam is used to drive steam turbine helper motors and steam turbine-driven electrical generators, meeting the site-wide power demand. Gas fired boilers are used to balance the site's steam generation to the overall demand. Low pressure steam is used to provide process heat to the plant. The increased heat integration introduces complexity, but allows for a significant reduction in fuel gas consumption.

Aero-derivative LNG Facility - Medium Aero-derivative GTG's (AGT)
Each train uses a number of aero-derivative gas turbines to drive a three-stage liquefaction process. Here an indicative train configuration consisting of eight GE LM2500+ aero-derivative turbines has been used. Heat is recovered from the refrigerant compressor gas turbines to provide process heat to the plant but heat is not recovered at sufficient quality to be used to generate power. Gas fired boilers are used to balance the site's steam generation to the overall demand. Medium industrial gas turbines are used to generate the electricity required for the site-wide power demand.

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[1] **Industrial or Frame Gas Turbines** are exclusively for stationary power generation and are available in the 1 to 350 MW capacity range. They are generally less expensive, more rugged, can operate longer between overhauls, and are more suited for continuous base-load operation with longer inspection and maintenance intervals than aero-derivative turbines. However, they are less efficient and much heavier.

Aero-derivative Gas Turbines are adapted from their jet and turbo-shaft aircraft engine counterparts. While these turbines are lightweight and thermally efficient, they are usually more expensive than products designed and built exclusively for stationary applications. The largest aero-derivative generation turbines are also smaller than that available from industrial turbines with the largest size being up to 40 to 50 MW in capacity.

Other LNG configurations are possible, but those presented above are representative of the broad range of possible options. These four cases are also summarised in **Table 2.1**.

Table 2.1 LNG Plant Configurations Modelled in this Study

LNG Plant Refrigeration Compressors Drivers	Train Size (Mtpa)	Example	Refrigeration Compressor Drivers for Smallest Configuration of Plant	Power Generation	Acronym Used in Report
Industrial Gas Turbines with electrical helper motors	5	Gorgon	Two Frame 7 compressors per train with heat recovery on each.	One Frame 9 per train plus one reserve	LIGT
Industrial Gas Turbines with electrical helper motors	5	Pluto	Two Frame 7 compressors per train.	Three Frame 6 per train	MIGT
Industrial Gas Turbines with steam turbine helper motors	4.17	Tangguh Indonesia	Two Frame 7 compressors per train with heat recovery on each	One 100 tph boiler per train	IS
Aero-derivative Gas Turbines	5	Darwin	Eight LM2500+ compressors per train	Five Frame 6 per 3 trains and one 100 tph boiler per train	AGT

To compare the size of the gas turbines, the electrical power generated by those in **Table 2.1**.at standard conditions are:

- LM2500+ (30 MW);
- Frame 6 (42MW);
- Frame 7 (87 MW); and
- Frame 9 (126 MW).

2.4 Other Emissions

2.4.1 Ship and Tug Emissions

The BLNG precinct will have a purpose built port facilities within the Precinct with a capacity of up to 6 ships at any one time. For a 50 Mtpa facility it is expected that there will be approximately 660 LNG shipments from on average 165,000m^3 carriers annually, with a peak of about 168 shipments of condensate from 100,000 dead weight tonne (DWT) carriers. To berth these ships there will a fleet of tugs moored at special pens within the port. These will assist in guiding down the approximately 3 km long shipping channel and in berthing operations. LNG carriers primarily use boil off gas (BOG) from their tanks for fuel and only use small amounts of fuel oil. The majority of the existing LNG carrier fleet utilises boilers to generate power to drive propeller shafts and for generating electricity for ship needs. There is now a shift to more fuel efficient dual fired engines (DFE) which have higher efficiencies using BOG as the primary fuel source. In both cases using LNG as the fuel source results in much lower emissions than from conventional ships that use slow or medium speed reciprocating engines using heavy fuel oil (HFO). HFO can have up to 4% sulphur with the emissions of NO_X, PM and SO_2 being much higher than from typical LNG carriers utilising BOG as the fuel source.

Tug boats that operate at the BLNG port will most likely use marine fuel oil. Emissions of concern from ships and tugs will be NO_X, SO_2, PM and CO.

2.4.2 Vehicle Emissions

Motor vehicle emissions at LNG plants in comparison to the other sources are relatively small and therefore are neglected in air quality assessments. Emissions from vehicles at the Karratha Gas plant for example contribute less than 1% for all substances.

3 Atmospheric Emissions

3.1 Emissions of Concern for Air Quality

Atmospheric emissions of most concern for local and regional air quality from LNG plants are:

- Oxides of Nitrogen (NO_X) consisting of nitric oxide (NO) and nitrogen dioxide (NO_2). These arise from combustion, both from the high temperature combustion where nitrogen in the air is oxidised and from nitrogen in the fuel. Emissions can be reduced by adoption of dry low NO_X burners;
- Oxides of Sulphur (SO_X) primarily being sulphur dioxide (SO_2). These arise from sulphur in the natural gas, generally in the form of hydrogen sulphide which is oxidised in combustion processes;
- Hydrogen sulphide (H_2S). This is emitted wherever un-combusted gas is released with the largest potential source being the direct venting of CO_2 Removal Unit emissions to air;
- Benzene, toluene, ethyl benzene and xylenes (BTEX). These arise primarily from the CO_2 Removal Unit gas stream when it is vented directly to air;
- Volatile Organic Compounds (VOC) from un-combusted gas;
- Formaldehyde which may arise from combustion of gas;
- Particulates as PM_{10} and $PM_{2.5}$. Small quantities are emitted from incomplete combustion of methane and VOCs; and
- Ozone. Though not a pollutant that is emitted directly, ozone is formed through photochemical reactions from the primary pollutants emitted, NO_X, CO and VOCs.

3.2 LNG Plants and Utilities – Routine Operations

Emissions from the four LNG plant types considered are presented in **Table 3.1** and **Table 3.2**. These have been estimated based on the following:

- The configurations of the LNG cases have been scaled where necessary to a 5 Mtpa train from the typical case they have been based on. This may entail an increase in the size of the compressors or power gas turbines or the number of units required;
- The LNG technology cases emissions are for LNG production only. If LPG is also produced there will however only be a small change in atmospheric emissions and as such this has been neglected in the modelling to simply the assessment;
- All gas turbines and boilers have been assumed to have low NO_X burners. For the gas turbines dry low NO_X burners are specified with a maximum NO_X concentration of 25 ppmv (0 deg C, dry and 15% O_2). For the boilers NO_X control is estimated with NO_X based on NPI emission factors (DEWHA, 2008). Boiler emissions are based on the emission factor for a wall fired low NO_X burner from the NPI emission manual (DEWHA, 2008);
- Particulate emissions for Frame 6 and smaller turbines are based on the guaranteed level for a Frame 6 turbine of 3.2 kg/hr with the emissions scaled by the power generated by the turbine to that of the Frame 6. Emissions for a Frame 7 turbine are based on the guaranteed level of 2 kg/hr for this turbine, with the Frame 9 emissions scaled from the Frame 7 turbine data;

Table 3.1 Emissions Parameters for BLNG Sources (LIGT and AGT) – Routine Operations

Source	Number Modelled for 15 and 50 Mtpa	Stack Height (m)	Exit Temp. (Deg C)	Stack Tip Diam. (m)			Velocity (m/s)	PM (g/s)	NO_X (g/s)	SO_2 (g/s)	CO (g/s)	VOC (g/s)	Benzene (g/s)	Toluene (g/s)	Ethyl-Benzene (g/s)	Xylene (g/s)	H_2S (g/s)
LIGT (5 Mtpa train)				Actual	15 Mtpa[1]	50 Mtpa[1]											
Power Generation - Frame 9	4 (11)	40	450	8.61	13.8	14.3	15.0	0.79	19.8	0.59	7.89	0.75	0.0043	Negl	0.0115	Negl	Negl
LNG Refrig. Compressor - Frame 7	5 (18)	40	220	6.0	7.17	7.17	15.1	0.56	14.2	0.41	5.57	0.53	0.0030	Negl	0.0081	Negl	Negl
LNG Refrig. Compressor - Frame 7 plus CO_2 RU vent gas when TCU offline	1 (2)	40	191	6.0	7.17	7.17	15.9	0.56	14.2	0.41	5.57	Negl	37.48	15.1	0.26	1.56	8.3
Thermal Combustion Unit	2 (8)	30	930	6.66	6.66	6.66	16.0	0.62	10.4	15.7	0.37	0.5	0.19	0.076	0.001	0.008	0.0
Operational Flare inc Marine Flare	1 (3)	35	1000[2]	1.14[2]	1.14[2]	1.14[2]	20.0[2]	0	2.43	0.043	6.17	20.1	0.044	0.016	0.0003	0.0018	0.0
Wet and Dry Flare	1	150	NA	NA	NA	NA	NA	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Condensate Tank Losses	3 (10)											0.51	0.007	0.04	0.01	0.046	0
Total 15 Mtpa (3 Trains)								**7.7**	**187.7**	**32.3**	**71.9**	**28.3**	**38.0**	**15.4**	**0.38**	**1.72**	**8.3**
Total 50 Mtpa (10 Trains)								**24.7**	**592.5**	**140.4**	**219.7**	**82.6**	**76.7**	**30.9**	**0.81**	**3.23**	**16.6**
AGT (5 Mtpa train)																	
Power Generation – Boilers	3 (10)	35	400	3.43	4.29	4.35	8.6	0.59	5.61	0.13	3.37	0.22	0.0013	Negl	0.0034	Negl	Negl
Power Generation- Frame 6s	5 (15)	40	450	4.97	8.84	9.61	15.0	0.88	6.58	0.21	2.78	0.26	0.0015	Negl	0.004	Negl	Negl
LNG Refrig. Compressor – LM2500+	22 (76)	40	400	3.72	7.81	7.81	15.0	0.51	3.96	0.12	1.60	0.15	0.0009	Negl	0.0023	Negl	Negl
LNG Refrig. Compressor – LM2500 plus CO_2 RU vent gas when TCU offline	2 (4)	40	307	3.72	7.81	7.81	15.9	0.51	3.96	0.12	1.60	Negl	18.74	7.56	0.13	1.78	4.16
Thermal Combustion Unit	2 (8)	30	930	6.66	6.66	6.66	16.0	0.62	10.4	15.7	0.37	0.5	0.19	0.076	0.001	0.008	0.0
Operational Flare inc Marine Flare	1	35	1000[2]	1.14[2]	1.14[2]	1.14[2]	NA	0	2.43	0.043	6.17	20.1	0.044	0.016	0.0003	0.0018	0.0
Wet and Dry Flare	1	150	NA	NA	NA	NA	NA	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Condensate Tank Losses	3 (10)											0.51	0.007	0.04	0.01	0.046	0
Total 15 Mtpa (3 Train)								**19.6**	**168.0**	**35.8**	**69.3**	**27.9**	**38.0**	**15.4**	**0.37**	**3.7**	**8.3**
Total 50 Mtpa (10 Trains)								**64.9**	**557.2**	**139.7**	**212.5**	**46.7**	**76.7**	**31.3**	**0.90**	**7.6**	**16.6**

Notes:

1) Stack diameters at 15Mtpa and 50 Mtpa are estimated accounting for plume merging (see **Section 6.5**). That is, they are an equivalent diameter.
2) The flare exit parameters were calculated using the Screen3 methodology (see **Section 6.6**) using the heat content of the gas being flared. That is, the temperature, diameter and velocity are pseudo parameters.

Table 3.2 Emissions Parameters for BLNG Sources (MIGT and IS) – Routine Operations

Source	Number Modelled for 15 and 50 Mtpa	Stack Height (m)	Exit Temp. (Deg C)	Stack Tip Diam. (m)			Velocity (m/s)	PM (g/s)	NO_X (g/s)	SO_2 (g/s)	CO (g/s)	VOC (g/s)	Benzene (g/s)	Toluene (g/s)	Ethyl-Benzene (g/s)	Xylene (g/s)	H_2S (g/s)
MIGT (5 Mtpa train)				Actual	15 Mtpa[1]	50 Mtpa[1]											
Power Generation - Frame 6	10 (31)	40	450	4.97	8.84	9.4	15.0	0.89	6.58	0.21	2.78	0.26	0.0015	-	0.004	-	-
LNG Refrig. Compressor - Frame 7	5 (18)	40	220	6.0	7.17	7.17	15.1	0.56	14.2	0.41	5.57	0.53	0.0030	-	0.0081	-	-
Compressor - Frame 7 plus CO_2 RU vent gas	1 (2)	40	191	6.0	7.17	7.17	15.9	0.56	14.2	0.41	5.57	-	37.48	15.1	0.26	1.56	8.3
Thermal Combustion Unit	2 (8)	30	930	6.66	6.66	6.66	16.0	0.62	10.4	15.7	0.37	0.5	0.19	0.076	0.001	0.008	0.0
Operational Flare	1 (3)	35	1000[2]	1.14[2]	1.14[2]	1.14[2]	1000[2]	0	2.43	0.043	6.17	20.1	0.044	0.016	0.0003	0.0018	0.0
Wet and Dry Flare	1	150	NA	NA	NA	NA	NA	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Condensate Tank Losses	3 (10)											0.51	0.007	0.04	0.01	0.046	0
Total 15 Mtpa (3 Trains)							**(g/s)**	**13.5**	**174.2**	**36.0**	**68.1**	**27.9**	**38.0**	**15.4**	**0.37**	**1.72**	**8.3**
Total 50 Mtpa (10 Trains)							**(g/s)**	**43.6**	**578.5**	**140.4**	**219.1**	**87.0**	**76.8**	**31.3**	**0.89**	**3.65**	**16.6**
IS 4.17 Mtpa train																	
Power Generation – Boilers	4 (12)	35	400	3.43	4.33	4.36	8.6	0.59	5.61	0.13	3.37	0.22	0.0013	-	0.0034	-	-
LNG Refrig. Compressor - Frame 7	7 (22)	40	220	6.0	7.17	7.17	15.1	0.56	14.2	0.41	5.57	0.53	0.0030	-	0.0081	-	-
LNG Refrig. Compressor - Frame 7 plus CO_2 RU vent gas	1 (2)	40	191	6.0	7.17	7.17	15.9	0.56	14.2	0.41	5.57	-	31.2	12.6	0.22	1.30	6.9
Thermal Combustion Unit	3 (10)	30	930	6.08	6.08	6.08	16.0	0.52	8.7	13.1	0.31	0.42	0.16	0.063	0.0008	0.007	0.0
Operational Flares	1 (3)	35	1000[2]	1.14[2]	1.14[2]	1.14[2]	20.0[6]	0	2.43	0.043	6.17	20.1	0.044	0.016	0.0003	0.0018	0.0
Wet and Dry Flare	1	150	NA	NA	NA	NA	NA	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Condensate Tank Losses	3 (10)											0.51	0.007	0.04	0.01	0.046	0
Total 16.7 Mtpa (4 Trains)								**8.4**	**164.6**	**43.14**	**65.1**	**27.5**	**31.8**	**12.9**	**0.33**	**1.346**	**6.9**
Total 50 Mtpa (12 Trains)								**25.6**	**502.4**	**142.5**	**195.7**	**83.9**	**64.2**	**26.3**	**0.77**	**3.13**	**13.8**

Notes:

1) Stack diameters at 15Mtpa and 50 Mtpa are estimated accounting for plume merging (see **Section 6.5**). That is, they are an equivalent diameter.
2) The flare exit parameters were calculated using the Screen3 methodology (see **Section 6.6**) using the heat content of the gas being flared. That is, the temperature, diameter and velocity are pseudo parameters.

- Exit temperatures and exhaust flow volumes for the gas turbines, boilers and TCUs are based on typical data for these units;
- Stack tip diameters are based on typical units and sized to generally achieve an exit velocity of at least 15 m/s;
- Exhaust parameters for the merged compressor plus CO_2 Removal Unit exhaust have been estimated from combining the exhaust flows from the compressor and the CO_2 Removal Unit. This results in a cooler exhaust than the exhaust from the compressor alone;
- Speciation of VOC for gas turbines is based on Table 3.12.a and 3.1.3 of USEPA, (Stationary Gas Turbine Emission Factors, AP42);
- Stack diameters are provided for the actual diameter and the equivalent diameter assuming that adjacent plumes merge as estimated in **Section 6.5**. The equivalent diameters are listed for the 15 and 50 Mtpa Precinct cases to account for plume merging;
- The maximum H_2S content in the feed gas is assumed to be 20.5 ppm. Measurements of H_2S in the field drilling indicated H_2S concentrations range from 4 to 7 ppm. These measured concentrations have been increased to take into account temperature variation in the fields and to allow for uncertainty to arrive at the maximum concentration of 20.5 ppm. In practise it is expected that a more realistic, but still very conservative (high) estimate of the H_2S concentration would be 13ppm and that even at 10ppm the concentrations would still be above the average for the gas fields;
- BTEX emissions are conservative estimates based on both the high end of expected CO_2 and BTEX concentrations from the Browse gas field and high BTEX co-absorption rate within the CO_2 Removal Unit based on design expectations for the likely solvent employed;
- Flare emissions of NO_X, CO, and VOC are estimated based on NPI Oil and Gas manual emission factors with VOCs estimated using the composition of gas being flared and a destruction efficiency of 98%;
- Operational flare gas flows were based on the 80^{th} percentile flow-rate from a similar facility. This will be slightly conservative. The minor emissions from the marine flare have been included in the operational flare and not presented separately;
- The operational flare emissions have been grouped into one flare per 3 trains. Therefore one operational flare is modelled for 15 Mtpa facility and three for a 50 Mtpa Precinct;
- Flare exit parameters were calculated using the USEPA Screen3 methodology (see **Section 6.6**) using the heat content of the gas being flared. This method estimates equivalent exit temperature, velocity and diameter such that they approximate the buoyancy that would occur from the flaring. That is, the diameter, exit temperature and exit temperature are pseudo parameters and are not actual physical measurements;
- Emissions from storage tanks condensate losses have been estimated using the USEPA model Tanks based on the throughput of condensate;
- Emissions on a g/s basis were estimated assuming all LNG trains are online continually. On average the availability for each train will be around 93% such that it is likely that in a 50 Mtpa precinct one train will not be operational at any time;
- 1 and 2 TCUs are conservatively assumed offline for the 15 and 50 Mtpa cases respectively, with the emissions from the CO_2 Removal Unit vented at a LNG refrigeration compressor instead of being passed to the TCU. The number of TCUs offline is based on an expected worst

case availability of 90% for the TCUs. In practise the TCUs are expected to be available for greater than 95 to 97% of the time. With a TCU offline, emissions of BTEX and H_2S from a train will be much higher as they are not being destroyed, though emissions of NO_X are lower as there is less combustion with nearly negligible SO_2 produced as the TCU is the primary source of SO_2. The probability that one, two or three etc TCUs are offline at a time is provided in **Table 3.3** for the 15 Mtpa and 50 Mtpa precinct scenarios.

Table 3.3 Probability of TCUs Being Offline Based on a TCU Availability of 90%

Number of TCUs Offline	Probability for 3 Trains (15 Mtpa)	Probability for 10 Trains (50 Mtpa)
0	0.729	0.349
1	0.243	0.387
2	0.027	0.194
3	0.001	0.057
4	NA	0.011
5	NA	0.0015
6	NA	0.00014

Note: NA is not applicable

Table 3.3 indicates that the assumption of one and two TCUs being offline is an above average estimate. This will be conservative for estimating impacts of VOC, BTEX and H_2S emissions, but slightly less conservative for estimating impacts from NO_X and SO_2.

3.2.1 Annual Emissions

Annual emissions of key pollutants for a 50 Mtpa Precinct are summarised in **Table 3.4** based on a 93% availability of the LNG trains and 90% availability of the TCUs (i.e. 1 TCU offline out of the 10 TCUs).

Table 3.4 indicates that in terms of emissions per tonne of LNG there are differences of up to 20% between the configurations for most pollutants with an Integrated Steam facility having the lowest emissions of the four. This occurs as it makes the most efficient use of waste heat in the gas turbine exhausts. It is noted that though this is the most efficient LNG plant, the lower temperatures of the exhausts may offset or even result in relatively higher ground level concentrations. For the particulate emissions there are a much greater emissions with the AGT technology case having the highest emissions. This is due to the emission factors used for gas turbines up to the Frame 6 turbine size being pro-rated from the Frame 6 guaranteed emissions, whilst the Frame 7 and (turbines were based on a Frame 7 guaranteed figure. The Frame 6 figure is considered to overstate the emissions as it is also larger than the generic NPI factor for gas turbines. Gas turbines are typically considered to emit negligible particulate and in many assessments are not modelled.

Table 3.4 Summary of Annual Emissions from 50 Mtpa LNG Precincts

Species	Units	LIGT	IS	AGT	MIGT
NOx	(tpa)	17,700	15,000	16,800	17,300
SO_2	(tpa)	4,570	4,560	4,550	4,570
CO	(tpa)	6,460	5,750	6,610	6,440
PM	(tpa)	740	770	1,930	1,300
Benzene	(tpa)	1,160	973	1,160	1,160
Toluene	(tpa)	465	391	465	465
Ethyl-Benzene	(tpa)	16	14	16	16
Xylenes	(tpa)	48	40	48	48
NOx	(kg/ tonne LNG)	0.354	0.300	0.336	0.346
SO_2	(kg/ tonne LNG)	0.091	0.091	0.091	0.091
CO	(kg/ tonne LNG)	0.130	0.115	0.132	0.129
PM	(kg/ tonne LNG)	0.015	0.015	0.039	0.026
Benzene	(kg/ tonne LNG)	0.023	0.019	0.023	0.023
Toluene	(kg/ tonne LNG)	0.0093	0.0078	0.0093	0.0093
Ethyl-Benzene	(kg/ tonne LNG)	0.00033	0.00027	0.00033	0.00033
Xylenes	(kg/ tonne LNG)	0.00096	0.00081	0.00096	0.00096

Notes:

1) LIGT (Large Industrial Gas Turbines), IS (Integrated Steam), AGT (Aero-derivative Gas Turbines) and MIGT (Medium Industrial Gas Turbines)
2) Excludes emissions from storage tanks and loading and shipping.
3) Based on 1 TCU offline on average and plant availability of 93%

3.3 LNG Plants and Utilities – Non Routine Operations

Non routine operations occur for a number of conditions. In this assessment the following three scenarios have been modelled as representative, worst case, non routine events:

- Start-Up. The process of starting up an LNG train is done by ramping up and achieving steady state conditions for each unit in succession. This sequential process means that the products from each unit during its own start-up phase are not fed forward into the next unit, but rather are routed to the flare until the unit achieves the desired operating state, with the products achieving the required quality specification. The level of flaring is reduced by maintaining low process flows during the start-up sequence and by flare gas recovery. In this case one train is brought on line where for up to 15-hours, gas (conservatively assumed to be stabiliser overheads) is routed to the flare with a flare rate of up to 150 tph. At the same time the compressor driver gas turbines are assumed to be loaded to 50% of their capacity. In this mode the NO_X emissions are higher as the turbine burner sets are operating outside their dry low NO_X (DLN) mode, with exhaust NO_X concentrations assumed to be 100 ppm (although the overall exhaust flow rate is lower). The occurrence of start-up per train is estimated at 5 per year per train. For a 15 Mtpa facility this is up to 225 hours and for a 50 Mtpa precinct up to 750 hours per year. For modelling given the low probability of start-up occurring in any given hour (2.6% and 8.6%

respectively for the 15 and 50 Mtpa cases), one train only is assumed to undergo start-up at any one time for a 15 Mtpa facility, whilst a maximum of 2 trains was assumed for a 50 Mtpa precinct;

- "Emergency flaring" is flaring associated with safe-guarding the facility, allowing the controlled destruction of hydrocarbons to prevent e.g. the over-pressure of processing vessels or pipe work. The need for emergency flaring can be caused by a number of reasons (fire, emergency shutdown, failure of a pressure reduction valve etc), with the maximum flare rate set by the largest credible flow requirement to the flare. For Browse the emergency flare flow rate is assumed to be set by the blocked propane compressor discharge case, with an estimated flow of 1850 tph. This figure is not scaleable across the facility, as the emergency flare capacity would be shared by the LNG trains within a single proponent's facility (i.e. sequential blow-down of trains if more than a single train is required to be depressurised). The probability of individual proponents within the precinct simultaneously utilising their independent emergency flare systems at capacity is seen to be negligible. The worst case ”Emergency flaring” scenario considered will be short term with 50% of the inventory flared in the first 15 minutes with the amount of gas tapering down over the next few hours. The probability such an event is estimated at less than one in 10 years for the full 50 Mtpa precinct (10 trains); and
- Turn Down. This situation may occur if gas supplies are likely to be low for a number of days and instead of shutting down the LNG train, it is decided to turn down the production of one or more trains to minimise the gas usage, thus hopefully averting a shutdown and later start-up. In this case it is assumed that only one of the 15 Mtpa plants at any time has a turn down due to issues with its gas supply. For such a turn down case all three trains are assumed at ½ load. This situation is similar to the non-routine start-up case in that 3 trains are assumed at half load compared to two trains for the start-up case, though there is no flaring for a turn down.

Emissions from these three non-routine events are provided in **Table 3.5** and **Table 3.6**. Other non routine events include flaring from a warm ship with flare rates of up to 400 tonnes of LNG over 32 hrs (average of 12.5 tph) occurring. This is much smaller than the other cases non routine cases considered and therefore has not been modelled.

Table 3.5 Emissions Parameters for a 15 and 50 Mtpa LIGT Precinct– Non Routine Operations

Source	Number Modelled for 15 and 50 Mtpa	Stack Height (m)	Exit Temp. (Deg C)	Stack Tip Diam. (m)			Velocity (m/s)	PM (g/s)	NO_X (g/s)	SO_2 (g/s)	CO (g/s)	VOC (g/s)	Benzene (g/s)	Toluene (g/s)	Ethyl-Benzene (g/s)	Xylene (g/s)	H_2S (g/s)
Start-Up				Actual	15 Mtpa[1]	50 Mtpa[1]											
Power Generation - Frame 9	4 (11)	40	450	8.61	13.8	14.3	15.0	0.79	19.8	0.59	7.89	0.75	0.0043	-	0.0115	-	-
Compressor - Frame 7 (100% load)	3 (14)	40	220	6.0	7.17	7.17	15.1	0.56	14.2	0.41	5.57	0.53	0.0030	-	0.0081	-	-
Compressor - Frame 7 plus CO_2 RU when TCU Offline (100% load)	1 (2)	40	191	6.0	7.17	7.17	15.9	0.56	14.2	0.41	5.57	-	37.48	15.1	0.26	1.56	8.3
Compressor - Frame 7 (50% load)	2 (4)	40	170	6.0	7.04	7.04	12.8	0.56	48.3	0.27	5.8	0.55	0.0032	-	0.0083	-	-
Thermal Combustion Unit	2 (8)	30	930	6.66	6.66	6.66	16.0	0.62	10.4	15.7	0.37	0.5	0.19	0.076	0.001	0.008	0.0
Operational Flare – Normal	1 (3)	35	1000[2]	1.14[2]	1.14[2]	1.14[2]	20.0[2]	0	2.43	0.043	6.17	20.1	0.044	0.016	0.0003	0.0018	0.0
Operational flare – Start Up	1 (2)	35	1000[2]	8.53[2]	8.53[2]	8.53[2]	20.0[2]	Negl	101	1.8	256	833	1.8	0.63	0.014	0.075	Negl
Condensate Tank Losses	3 (10)											0.51	0.007	0.04	0.01	0.046	0
Total 15 Mtpa (3 Trains)							**(g/s)**	**7.7**	**356.8**	**37.9**	**328**	**861**	**39.8**	**16.0**	**0.39**	**1.8**	**8.3**
Total 50 Mtpa (10 Trains)							**(g/s)**	**24.7**	**930.7**	**143.4**	**733**	**1753**	**80.4**	**32.5**	**0.93**	**3.8**	**16.6**
Turn-Down																	
Power Generation - Frame 9	4 (11)	40	450	8.61	13.8	14.3	15.0	0.79	19.8	0.59	7.89	0.75	0.0043	-	0.0115	-	-
Compressor - Frame 7 (100% Load)	3 (12)	40	220	6.0	7.17	7.17	15.1	0.56	14.2	0.41	5.57	0.53	0.0030	-	0.0081	-	-
Compressor - Frame 7 plus CO_2 RU when TCU Offline (100% load)	1 (2)	40	191	6.0	7.17	7.17	15.9	0.56	14.2	0.41	5.57	-	31.2	12.6	0.22	1.30	6.9
Compressor - Frame 7 (50% load)	2 (6)	40	170	6.0	7.04	7.04	12.8	0.56	48.3	0.27	5.8	0.55	0.0032	-	0.0083	-	-
Thermal Combustion Unit	2 (8)	30	930	6.66	6.66	6.66	16.0	0.62	10.4	15.7	0.37	0.5	0.19	0.076	0.001	0.008	0.0
Operational Flare	1 (3)	35	1000[2]	1.14[2]	1.14[2]	1.14[2]	20.0[2]	0	2.43	0.043	6.17	20.1	0.044	0.016	0.0003	0.0018	0.0
Condensate Tank Losses	3 (10)											0.51	0.007	0.04	0.01	0.046	0
Total 15 Mtpa (3 Trains)								**7.7**	**256**	**36.0**	**72.4**	**28.3**	**31.7**	**12.9**	**0.34**	**1.46**	**6.9**
Total 50 Mtpa (12 Trains)								**24.7**	**797**	**140**	**221**	**87.3**	**64.2**	**26.3**	**0.82**	**3.13**	**13.8**

Notes:

1) Stack diameters at 15Mtpa and 50 Mtpa are given accounting for plume merging (see **Section 6.5**).
2) Flare exit parameters were calculated using the Screen3 methodology (see **Section 6.6**) using the heat content of the gas being flared. That is, the temperature, diameter and velocity are pseudo parameters.
3) Note relatively high BTEX in Star-tup flaring compared to Emergency due to differences in gas composition flared.

Table 3.6 Emissions Parameters for 15 and 50 Mtpa LIGT Precinct– Non Routine Operations

Source	Number Modelled for 15 and 50 Mtpa	Stack Height (m)	Exit Temp. (Deg C)	Stack Tip Diam. (m)			Velocity (m/s)	PM (g/s)	NO_X (g/s)	SO_2 (g/s)	CO (g/s)	VOC (g/s)	Benzene (g/s)	Toluene (g/s)	Ethyl-Benzene (g/s)	Xylene (g/s)	H_2S (g/s)
"Emergency Flaring"				Actual	15 Mtpa[1]	50 Mtpa[1]											
Power Generation - Frame 9	4 (11)	40	450	8.61	13.8	14.3	15.0	0.79	19.8	0.59	7.89	0.75	0.0043	-	0.0115	-	-
Compressor - Frame 7	5 (18)	40	220	6.0	7.17	7.17	15.1	0.56	14.2	0.41	5.57	0.53	0.0030	-	0.0081	-	-
Compressor - Frame 7 plus CO_2 RU vent gas when TCU Offline	1 (2)	40	191	6.0	7.17	7.17	15.9	0.56	14.2	0.41	5.57	-	37.48	15.1	0.26	1.56	8.3
Thermal Combustion Unit	2 (8)	30	930	6.66	6.66	6.66	16.0	0.62	10.4	15.7	0.37	0.5	0.19	0.076	0.001	0.008	0.0
Operational flare	1 (3)	35	1000[2]	1.14[2]	1.14[2]	1.14[2]	20.0[2]	0	2.43	0.043	6.17	20.1	0.044	0.016	0.0003	0.0018	0.0
Wet and Dry Flare	1 (1)	150	1000[2]	21.6[2]	21.6[2]	21.6[2]	20.0[2]	Negl	1310	32.2	3324	10,300	2.1	0.70	0.011	0.063	Negl
Condensate Tank Losses	3 (10)											0.51	0.007	0.04	0.01	0.046	0
Total 15 Mtpa (3 Trains)								**7.7**	**1,497**	**68.5**	**3,396**	**10,330**	**40.1**	**16.1**	**0.39**	**1.78**	**8.3**
Total 50 Mtpa (10 Trains)								**24.7**	**1,902**	**173**	**3,544**	**10,400**	**78.9**	**32.0**	**0.91**	**3.71**	**16.6**

Notes:

1) Stack diameters at 15Mtpa and 50 Mtpa are given accounting for plume merging (see **Section 6.5**).
2) Flare exit parameters were calculated using the Screen3 methodology (see **Section 6.6**) using the heat content of the gas being flared. That is, the temperature, diameter and velocity are pseudo parameters.

3.4 Ship and Tug Emissions

Ship emissions were estimated using the following information and assumptions:

- For a 50 Mtpa facility, approximately 660 150,000 tonne LNG carriers and at peak production, 168 100,000 deadweight (DWT) condensate ships. Therefore on average approximately two LNG ships will arrive and leave daily with one condensate ship arriving and leaving every second day;
- The berthing time for both ships is approximately 24 hours with 18 hours of actual loading. Therefore for modelling the 50 Mtpa case two LNG ships were assumed berthed at any time with one condensate ship berthed every second day for a period of 24 hours;
- LNG carriers were assumed to have a main "engine" size of approximately 30 to 40 MW with this power produced using gas fired boilers to drive steam turbines using 100% BOG as the fuel. This is the standard propulsion method for current LNG ships, though in the future more ships are expected to use duel fuel electric engines (DFE) using BOG as they are more fuel efficient. Note, the choice of steam boilers instead of DFE is not significant as emissions from both are similar. Emissions from the steam boilers were estimated based on the NPI emission factor for gas fired boiler with the gas consumption based on a boiler efficiency of 29% (Wartsila, 2006). At berth the electricity demand was taken as 3 MW which is considerably more than the default NPI Emission Estimation Technique (EET) (Environment Australia, 1999) value of 600kW for auxiliary engines in port as LNG carriers have a much larger power demand than many other ship types. For travelling in the shipping channel, as this is short (only 3 km from the end to the berths), the ship speed will be low with an average ship speed of 15 km/hr assumed with propulsion power from the LNG carriers taken as 15 MW;
- Emissions from the condensate carriers were based on the NPI EET methodology (Environment Australia, 1999) assuming low speed reciprocating engines using heavy fuel oil (HFO). Main engines totalling 12MW, with 1 to 1.5MW of auxiliary engines were assumed for the carriers based on a 100,000 DWT tankers of gross tonnages of 60,000 tonne as obtained from data in the Pilbara Airshed study (SKM, 2003) (Appendix B) for the Karratha Gas Plant. Power generated by the engines was assumed to be a total of 7 MW from the main engines in the shipping channel and at berth as per the NPI defaults at 600kW. The sulphur content of HFO was taken as 3.5% by mass which is the maximum sulphur content stipulated for the years 2012 to 2021 by IMO (2008). Note that in 2021 this decreases substantially to 0.5% sulphur by mass;
- Emissions for the ships "steaming" were estimated only for hours in which this occurred. With a 3km long shipping channel, including turning circle, at an average speed of 15 km/hr a passage time of 12 minutes is derived. Therefore, for each hour in which a ship passage occurred average emissions equivalent to 12 minutes of steaming and 48 minutes of zero emissions were assumed. For modelling, the ship arrival and departure times were spread uniformly across the day at 2am, 8am, 2pm and 8pm for the LNG ships and 11am for the condensate ship;
- Negligible or no anchorage was assumed;
- Tugs are to be penned close to the berths with a small transit time to the berth area. For each ship arrival and departure three tugs were assumed to operate with 1 hour spent guiding the ship in and out of the shipping channel and 1-hour in the berthing operations. In the steaming and

berthing hour when "working" the power output was assumed at 2500 kW for 24 minutes in the hour such that average hourly power output was 1000 kW. At 1000 kW and a brake specific fuel consumption of 250 g/kWhr, a fuel consumption of 250 kg/hr or about 295 litres per hour is obtained. For the 50 Mtpa precinct each of the three tugs per ship were assumed to operate for a total of 5 hours steaming to the ships and 5 hours berthing per day. Emissions from the tugs were estimated based on the NPI manual for maritime operations for auxiliary engines (i.e. smaller medium speed engines) using marine diesel oil usage. The sulphur content of this fuel is approximately 1%;

- The speciation of VOC for all shipping and tug exhausts was taken from heavy vehicle exhaust (DECC, NSW, 2008);
- Emissions of VOC from loading condensate to ships were estimated by Woodside using the expected condensate composition for the Browse project and the model Hysys. Inputs and assumptions used were:
    - A calculated true vapour pressure of 0.7638 bar;
    - The condensate tanker is assumed to be inert gas filled, with the tanks at atmospheric pressure;
    - Condensate rundown temperature is assumed to be 40 deg C.
    - Tanker loading rate is 6000m^3/hr with loading for 18 hours per ship. This would also be the rate at which the vapour is emitted from the tanker;
    - The hydrocarbon vapour portion in the tank is 0.7638 (determined from the true vapour pressure of the condensate and the pressure in the tank); and
    - A ratio of hydrocarbon vapour to inert gas of 3.2 to 1.

The resultant VOC emissions are presented in **Table 3-7** along with that estimated using the NPI method (DEWHA, 2010) and using the method of the American Petroleum Institute (API, 2006).

Table 3-7 Estimates of VOC Emissions from Condensate Tanker Loading

	Units	Woodside Calculated using Hysys	NPI (2010)	API (2006)
VOC Emission Factor	(kg VOC / tonne product)	Hysys (2.49 kg/tonne)	NPI (0.1 kg/tonne)	Estimated here (0.265 kg/tonne)
Speciation of VOC by		Hysys	Default NPI (light oil)	-
Composition of VOC				
Benzene	(%)	1.1	0.12	Not provided
Ethyl benzene	(%)	0.018	0.016	Not provided
Toluene	(%)	0.506	0.11	Not provided
Xylenes	(%)	0.092	0.033	Not provided
Emissions				
VOC	(g/s)	2990	120	318
Benzene	(g/s)	55.7	0.144	Not provided
Ethyl benzene	(g/s)	1.26	0.019	Not provided
Toluene	(g/s)	30.2	0.132	Not provided
Xylenes	(g/s)	0.25	0.040	Not provided

Notes:

1) Based on a typical tanker condensate loading rate of 6000 m^3/hr or 4320 tph.
2) API Based on the true vapour pressure and temperature of 40 deg C.

3) Vent assumed as 0.4m diameter vent, 6m above ships deck with exit velocity of 13.73 m/s at 40 degrees C.
4) Emissions from ship-loading have an molecular weight of 52 g/mol and as such at temperatures near ambient will be heavier than air.

Table 3-7 indicates that the Woodside estimated BTEX emissions are significantly higher than that estimated from the NPI EET manual (DEWHA, 2010) or from API (2006). This is due to the much higher VOC emission factor, approximately 2.5 kg/tonne compared to 0.1 and 0.26 kg/tonne respectively and secondly due to the higher BTEX percentages in the VOC than used in the NPI. It is considered that the NPI default VOC emissions are not applicable as these are for much cooler climates and the NPI composition is also for a "typical" light oil with the condensate considered here being more volatile. Nevertheless the very large difference in the benzene emissions (a factor of 390) indicates that the Woodside emissions may be on the conservative side and further work is needed to verify these; and

- Exhaust volumes from the condensate ship and tug engines were estimated from the power generated in MW multiplied by 5.7 to convert to exhaust flow wet at 0 deg C and 1 atmosphere (Cooper, 2000), with the temperature assumed from typical engines. Exhaust volume for the LNG ships were taken as 1.25 times the power generated as derived for the LNG boilers (Woodside, 20010). For modelling within TAPM the ship's bridge superstructure area was taken to extend to 32m above with building downwash estimated. The tug's "bridge" structure was assumed 8m tall by 4 by 4m. Emissions from shipping and tug boats are summarised in **Table 3.8**.

Table 3.8 Estimated Emissions from Ships and Tug boat operations associated with the LNG Facilities

	Units	LNG Carrier		Condensate Carrier		Tug Working	
		In Channel	At Berth	In Channel	At Berth	Steaming to Ships	Berthing Ships
Number of ships per year for LNG production of	50 Mtpa	660	660	168	168	NA	NA
	15 Mtpa	200	200	50	50	NA	NA
Number of Arrivals/ Departures per day or at berth Modelled	50 Mtpa	Four transits a day	Two at berth always	One transit per day	One at berth every second day	5 hours per day	5 hours per day
	15 Mtpa	One transit a day	One at berth every second day	One transit per third day	1 at berth every 6th day	1 hour per day with 2 hours every 3rd day	1 hour per day with 2 hours every 3rd day
Power whilst operating in that hour and as used for stack parameters	(kW)	15,000	3,000	7,000	600	2,500	2,500
Exhaust Height	(m)	35	35	35	35	10	10
Exhaust Tip Diameter	(m)	1.8	0.6	1.5	0.5	0.7	0.7
Exit Volume (wet, 0 deg C, 1 atm)	(m^3/s)	18.5	0.74	11.1	0.95	3.96	3.96
Exit Temperature	(deg C)	400	400	400	400	400	400
Exit Velocity	(m/s)	17.9	9.3	15.5	11.9	25.4	25.4
Time Assumed operating within that hour	(minutes)	12	60	12	60	24	24
NO_X (ave for hour)	(g/s)	1.17	1.17	6.80	1.85	3.86	3.86
SO_2 (ave for hour)	(g/s)	0.007	0.007	4.4	1.97	1.71	1.71
CO (ave for hour)	(g/s)	0.44	0.44	0.51	0.33	0.31	0.31
PM (ave for hour)	(g/s)	0.03	0.03	0.58	0.25	0.21	0.21
VOC (ave for hour)	(g/s)	0.02	0.02	0.11	0.12	0.10	0.10
VOC Loading Loss		-	-	-	92.0	-	-

Note: LNG carrier and condensate tanker whilst in the shipping channel and tug boat exit velocity based on when operating. The emission in g/s is the hourly average emissions.

Overall maximum emissions from shipping occur for an hour with a condensate carrier being brought down the shipping channel with NO_X and SO_2 emissions of 19.6 g/s and 9.5 g/s respectively.

3.5 Other Emission in the Region

Besides the proposed LNG precinct other significant existing sources of atmospheric emissions in the area are:

- Emissions from bushfires;
- Emissions from vegetation (terpenes etc) and soils (NO_X);
- Existing industrial sources within the area. These are generally listed in the National Pollutant Inventory (NPI). See www.npi.gov.au;
- Emissions from combustion from vehicles, aircraft and shipping;
- Emissions from domestic activities (cooking, lawn-mowing, painting etc); and

- Emissions from small commercial facilities such as from service stations, dry cleaning, evaporative losses from tanks etc.

Emission estimates for these sources have been sourced from publicly available data where available, excepting from fires where a methodology based on fuel loadings and area burned on a daily basis was used. Where the emissions were relatively small compared to other sources modelled, approximate estimates were used as this is sufficient for the purpose of this modelling assessment. Where emissions were too small and or too distant from the area of concern to affect model outcomes (such as existing shipping at Broome and aircraft) the sources have been omitted. Likewise emissions from the Light Industrial Area that will develop next to the Precinct have been omitted as atmospheric emissions will be much smaller than from the LNG facility and can be neglected.

The derivation of the emission estimates is detailed further below.

3.5.1 Sources within the Town of Broome

Emissions from facilities that are required to report to the NPI for the Broome are summarised in **Table 3.9**.

Table 3.9 Annual Emissions (tpa) from Anthropogenic Sources in Broome for 2007/2008

Substance	Fuel Storage [1] (Airport)	Fuel Storage [1] (Port)	Broome Power Station [1,3]	Motor Vehicles (Estimated) [2]	Other Area Sources (Estimated) [2]	Total
Carbon Monoxide	-	-	200 (110)	2,860	120	3,290
NO_X	-	-	790 (1,300)	510	25	2,625
PM_{10}	-	-	25 (0.025)	46	0.15	71
SO_2	-	-	12 (0.19)	8.5	4.3	25
VOC	2.7	85	48 (12)	540	360	1,048
Toluene	0.03	0.916	0.072 (-)	36		1
Xylenes	0.081	0.372	0.056 (-)	44	10	54.5

Notes:

1) Source. NPI Emission Inventory http://www.npi.gov.au/
2) Scaled from the Karratha-Dampier and Burrup Peninsula Emissions Inventory 1999 (DEP, 2002)
3) Broome Power Station operated with older diesel fired engines up to December 2007 and then with new gas (LNG) fired reciprocating engines. Values without brackets are from the diesel fired power station and in brackets from LNG fired power station.
4) The year 2007/2008 is used as it is the latest period of reported data available.

The list of facilities summarised in **Table 3.9** is small compared to other towns of comparable size indicating the lack of reporting industry. The only significant reporting sources are the Broome Power Station and fuel storage facilities.

Apart from reporting sources, other sources in Broome are small industry that are sub threshold facilities, small commercial sources and domestic sources. For the town of Broome these have been estimated from a study done for the Karratha/Dampier region by the Department of Environmental Protection (DEP, 2002) by scaling by the relative populations. The Karratha/Dampier emission

inventory included motor vehicles, auto refinishing, cutback bitumen, domestic gas consumption, aircraft, garden maintenance, service station emissions, amongst other sources.

Source not included in this study are from the existing shipping, boating and aircraft. These are considered small for Broome, except for the occasional large cruise ships. For the purposes of modelling these have been neglected as will have little impact on the air quality.

3.5.2 Future Emissions from the Broome Power Station

Table 3.9 presents the annual emissions from the Broome Power Station for the 12 month period from July 2007 to June 2008, the year in which the station switched from diesel fired generators to gas fired engines. For future modelling an assessment of the impacts from the new power station is required at its approved capacity. The current power station has 17 natural gas fired gas engines installed (maximum electrical output of 33.4 MW) though with approval for a further 8 units to be installed by 2025 to increase the capacity to 46.3 MW (DEC, 2009 BPS Licence 8155/1). Emission parameters per generator for the new power station are listed in **Table 3.10** as derived from the licence data and from equipment specifications.

Table 3.10 Estimated Emissions from the New Broome Power Station

Parameter	Units	Value per Unit
Stack Height	(m)	12
Exit Temperature	(deg C)	488
Exit Velocity	(m/s)	35
Stack Diameter	(m)	0.36
NO_X	(g/s)	0.62
CO	(g/s)	1.55
Total Hydrocarbon (THC)	(g/s)	3.45
Non Methane Hydrocarbon (NMHC) or VOC	(g/s)	0.52
PM_{10}	(g/s)	0.00016

Sources:

1) (DEC, 2009 BPS Licence 8155/1).
2) Caterpillar specification sheet from Caterpillar G3520C gas generator set from http://www.cat.com/cda/components/
3) PM_{10} from NPI emission factors for combustion engines, 4-stroke uncontrolled gas fired, table 54 based on engine efficiency of 40%

Therefore maximum NO_X emissions from the power station are at most 10.5 g/s at present and with the full 25 generators installed will be a maximum of 15.5 g/s.

3.5.3 Vegetation and Soil Emissions

Estimates of VOCs emissions from vegetation and NO_X from soils were determined by the model TAPM-CTM. These are required as inputs into the regional smog assessment (see **Section 6**).

The vegetation VOC emissions were derived from estimates of VOCs per leaf surface area for grasses and trees multiplied by the leaf area index (LAI), which is the density of vegetation matter per square

meter. The VOC emissions for vegetation were parameterised as described in Cope et al, (2009a) with temperature dependence with increasing emissions at higher temperatures. Estimates of the LAI were provided by a database developed from MODIS satellite data (Hurley, 2008) which provides LAIs on a 4km grid over Australia for each month of the year. The estimated LAIs for the central Dampier Peninsula ranged from 0.6 in April to 1.6 in November which along with the seasonal temperature variation provides a strong seasonal variation in plant VOCs. For comparison the LAIs for the central Pilbara region which was also modelled in this study are much lower ranging from 0.3 to 0.4 in December to 0.3 to 0.8 in April.

3.5.4 Emissions from Fires

Estimates of particulate and gaseous emissions from fires were estimated by the Centre for Australian Weather & Climate Research using the methods and tools developed by Meyer et al. (2008a). This methodology provides estimates on an hourly basis and on a spatial resolution of 1 km square for Australia. This method utilises satellite data (fire-scar and hotspot data) to estimate the area burned daily, with the hourly variation estimated from a fire danger meter using the meteorological output from TAPM. Fuel loads are estimated by the model VAST that uses rainfall, radiation, temperature, soil moisture and vegetation class to determine the biomass or fuel load available. The fire emissions are then estimated from the fuel consumed by using emission factors that relate the emission of a substance such as carbon monoxide to the amount of carbon burned.

3.5.5 Further Fire Emission Detail

Fire scar data used in the study were determined by:

- Fire scars (or burned areas) at a grid resolution of 1 km x 1 km as reported by the Department of Land Information (DLI) of Western Australia, based on NOAA AVHRR (Advanced Very High Resolution Radiometer) satellite images;
- Hotspot data at 1 km x 1 km resolution, also from AVHRR images processed by the DLI; and
- Hotspot data at 1 km x 1 km resolution from Sentinel—a national bushfire monitoring system managed by Geoscience Australia—based on MODIS (Moderate Resolution Imaging Spectra Radiometer) on the Terra/Aqua satellite.

The data were processed as detailed in Meyer et al (2008a).

The daily variation in the area burned and therefore emissions was based on weighting by McArthur's Mark 5 grassland fire danger meter for the Top End. In practice the emissions during the day vary by about a factor of 3 to 4 with peak emissions occurring during periods with low humidity and high winds such as in the early afternoon, with low emissions occurring for periods with higher humidity and low winds such as in early hours of the morning.

Estimates of the fuel consumed are made for both the fine fuel component (i.e., grass, leaf litter and twigs up to 6mm in diameter) and coarse fuel woody debris component averaging 46mm in diameter. These were estimated at a grid resolution of 1 km by 1 km using a semi-empirical model, VAST1.2 (Vegetation and Soil Carbon Transfer developed by Barrett, 2002). VAST is a biogeochemical production model relating the main drivers of production, namely intercepted radiation, temperature, soil moisture, rainfall, and vegetation class to biomass and soil pools of carbon.

The area within a fire-scar area that has actually been burnt (estimated at 20% and 92% respectively for the coarse and fine fuel) is used to estimate the total fuel biomass within a grid cell F_b (kg ha^{-1}) subject to combustion in the event of fire as:

$$F_b = 0.17\ F_{coarse} + 0.76\ F_{fine} \qquad \textbf{Equation 3.1}$$

As the carbon content of the above fuels typically ranges between 45% and 53% of dry weight (Barrett, 2002) a value of 46% has been adopted, which is also the value used in the ANGGI methodology (AGO, 2007). Therefore the fuel carbon that can potentially be emitted ($kgCha^{-1}$) is FC = 0.46 F_b.

Emission factors of the various VOCs were estimated based on the factors provided in Andreae and Merlet (2001).

This method has been validated by Luhar et al. (2008) for particulate concentrations for the Northern Territory where good agreement was found with measured concentrations.

3.5.6 Representativeness of the Study Year - 2006

For this study, emission estimates for the year 2006 were available and used. Reasons for the usage of 2006 data was that the data were readily available as it had been processed to derive emissions for a separate study for Australia (Cope et al, 2009a) and an analysis indicated it was a year with above average fires (Cope, pers comm. 2009).

To determine the representativeness of the year for the study area, the annual variation in the area burned (Kimberley and Pilbara) is presented in **Figure 3-1**. Additionally for the more local areas, the monthly variation in land area burned is presented in **Figure 3-2** and **Figure 3-3** for the Kimberley region and for the Shire of Broome respectively.

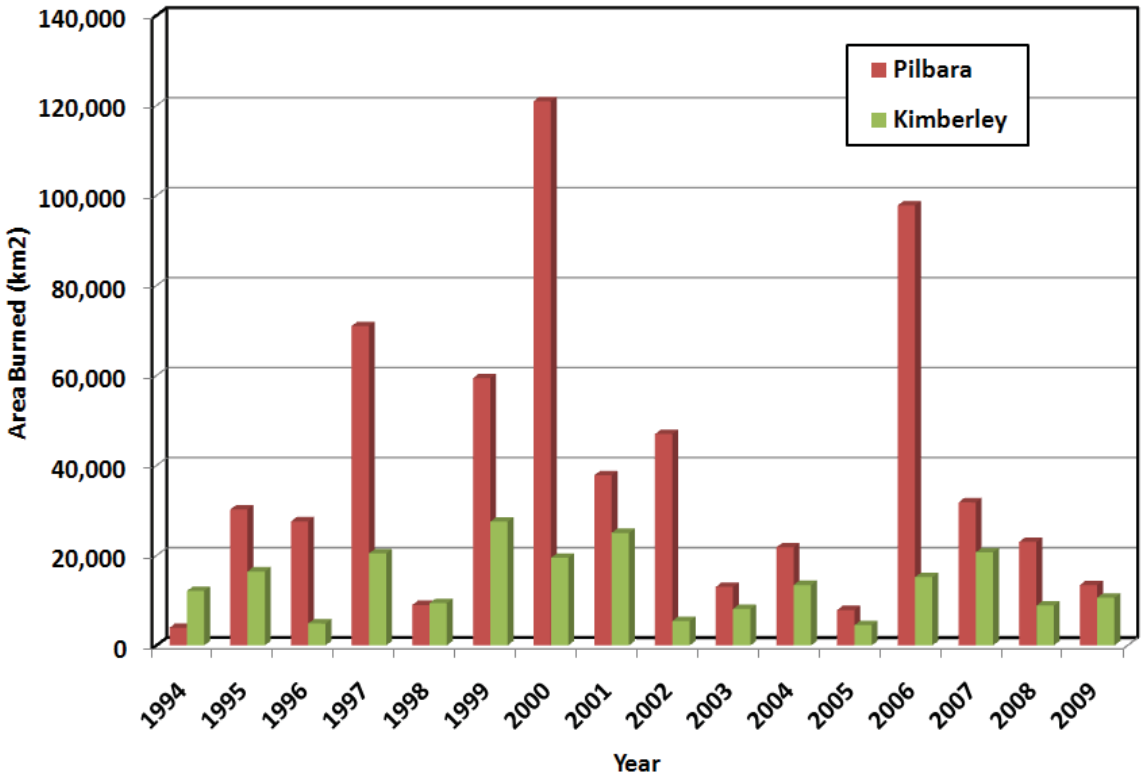


Figure 3-1 Land Area Burned by Year in the Pilbara and Kimberley

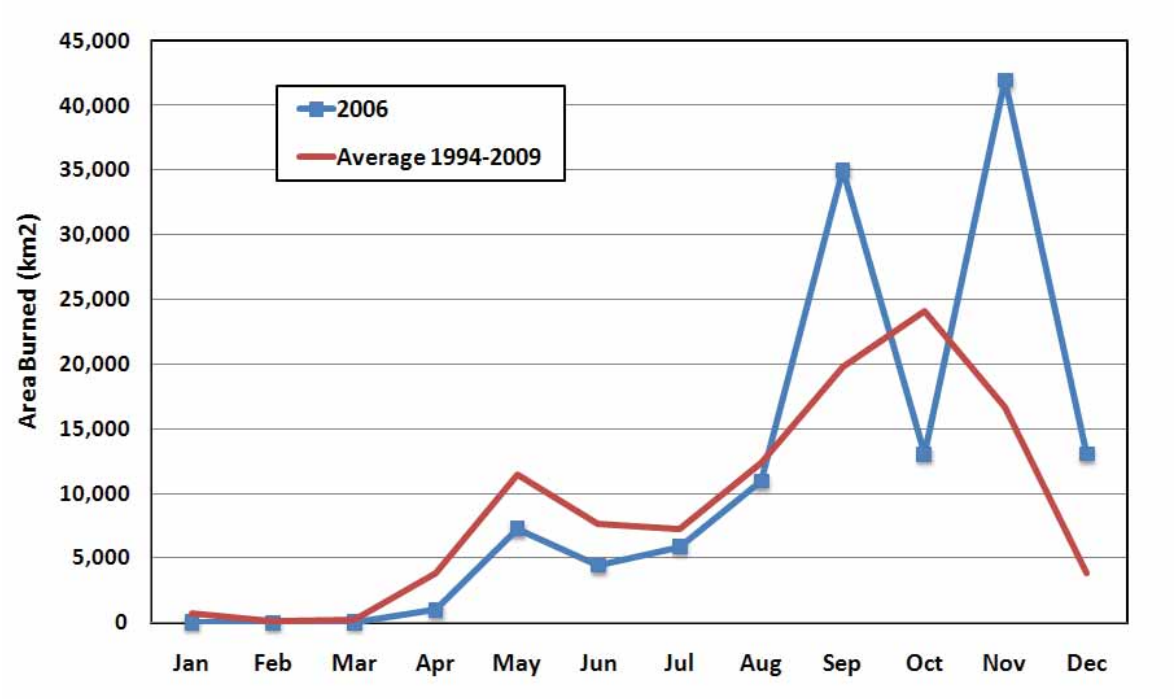


Figure 3-2 Land Area Burned by Month in the Kimberley

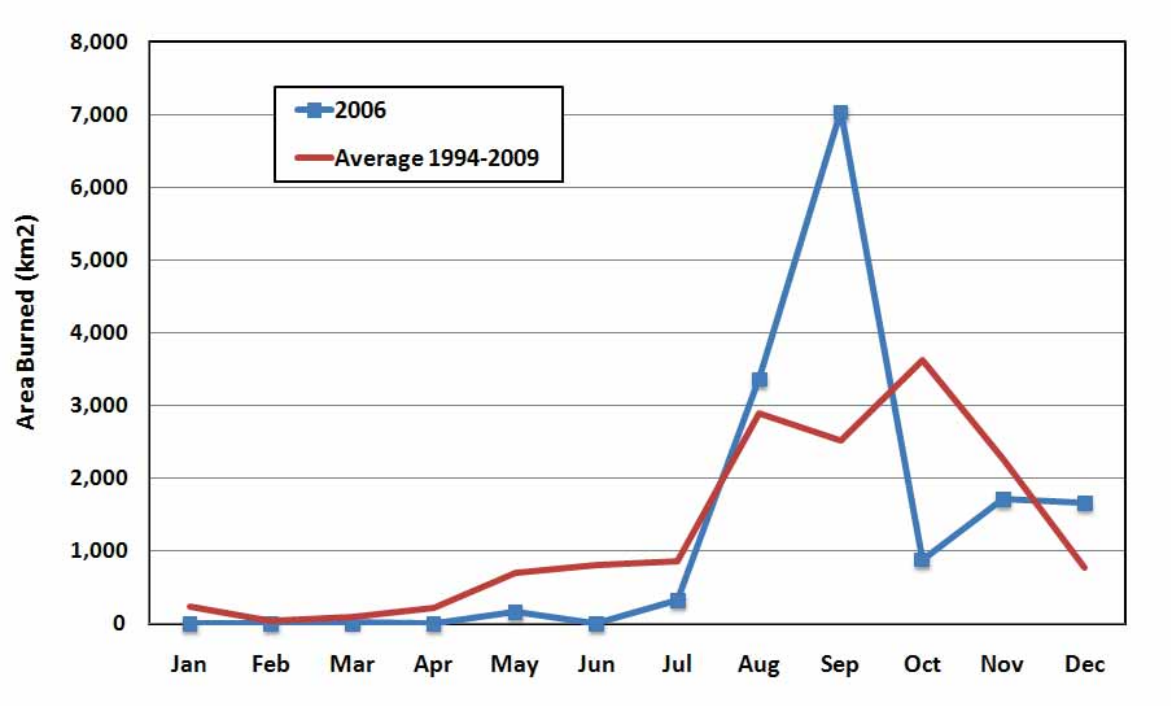


Figure 3-3 Land Area Burned by Month in the Shire of Broome

Figure 3-1 indicates that there is significant yearly variation (particularly for the Pilbara) in the land area burned. This variation occurs due to the yearly variation of rainfall, with a year with above average rainfall in the wet season resulting in good growth, which results invariably in large fires once the vegetation has dried out in the September to November period.

The monthly variation in land area burned for the Kimberley and Shire of Broome (**Figure 3-2** and **Figure 3-3**) clearly indicates the seasonal peak in fires in the September to November period with much lower areas burned in the wet season (December to March). In terms of the representativeness of 2006 **Figure 3-1** to **Figure 3-3** indicate that:

- For the Pilbara 2006 was an above year in terms of land area burned area with 97,800 km^2 burned compared to the long term average of 47,770 km^2. 2006 was the second highest year on record;
- For the Kimberly region 2006 was slightly an above average year with 15,170 km^2 burned compared to the long term average of 13,990 km^2; and
- On a monthly basis 2006 had above average area burned for the for the peak periods (September to November) for the Kimberley region, whilst for the Shire of Broome, September 2006 had a much greater area burned than for other years (7,040 km^2 compared to 2,360 km^2).

Therefore in terms of the land area burned, 2006 was a year with well above average land area burned for the Pilbara and was slightly above an average year for the Kimberley.

3.6 Summary of Future Annual Emissions

Annual emissions for the region around Broome as estimated for this study are presented in **Table 3.11**. The Broome area is taken here to cover the inner pollution grid of the model as defined in **Figure 6-2**.

Table 3.11 Estimated Annual Emissions (tpa) for the Inner Model Grid

Substance	Broome Power Station (07/08)	Other Broome Sources	Biogenic (Inner Grid Area)	Fires (Inner Grid Area)	LIGT LNG (50 Mtpa)	Condensate Ship Loading (50 Mtpa)	Ship, Tug and Fugitive (50 Mtpa)
CO	310	2,860	0	202,000	6,460	0	44
NO_X	2,090	510	570	12,100	17,700	0	245
PM_{10}	25	46	0	NK	740	0	14
SO_2	12.2	8.5	0	33	4,570	0	96
VOC	58	540	11,700	18,350	2,380	32,660	7.1
Benzene			-	Not est.	1,160	606	
Toluene	0.072	36	-	167	465	360	-
Xylenes	0.056	44	-	840	48	70	-

Table 3.11 indicates that on an annual basis:

- The proposed 50 Mtpa LNG precinct will make a large contribution to emissions, being the largest source of NO_X, SO_2 and toluene;
- Ship exhaust emissions for the berth and shipping channel are relatively small;
- Ship-loading condensate emissions are the largest source of VOCS and a sizeable source of benzene, toluene and xylenes; and
- Fires are the largest source for CO and VOCs. It is noted that fires unlike the other sources occur over short durations and therefore when they do occur are the dominant source for most pollutants such as NO_X and PM.

4 Air Pollutants and Relevant Air Quality Criteria

4.1 Summary of Air Pollutants

The common sources and effects of the principal air pollutants discussed in this study are summarised below as sourced from DEFRA (2007) and DEH (2009).

Oxides of Nitrogen and Nitrogen Dioxide
All combustion processes in air produce oxides of nitrogen (NO_X). Nitrogen dioxide (NO_2) and nitric oxide (NO) are both oxides of nitrogen and together are referred to as NO_X.

NO_2 is associated with adverse effects on human health. At high levels NO_2 causes inflammation of the airways. Long term exposure may affect lung function and respiratory symptoms. NO_2 also enhances the response to allergens in sensitive individuals. High levels of NO_X can have an adverse effect on vegetation, including leaf or needle damage and reduced growth. Deposition of pollutants derived from NO_X emissions contribute to acidification and/or eutrophication of sensitive habitats leading to loss of biodiversity, often at locations far removed from the original emissions. NO_X also contributes to the formation of secondary particles and ground level ozone, both of which are associated with ill-health effects.

Ozone
Ozone is not emitted directly from any human-made source, though small amounts are produced through arcing of power lines and photocopiers etc. Its primary anthropogenic source arises from chemical reactions between various air pollutants, primarily NO_X and Volatile Organic Compounds (VOCs), initiated by strong sunlight. Formation can take place over several hours or days and may have arisen from emissions many hundreds, or even thousands of kilometres away.

Exposure to high concentrations may cause irritation to eyes and nose. Very high levels can damage airways leading to inflammatory reactions. Ozone reduces lung function and increases incidence of respiratory symptoms, respiratory hospital admissions and mortality. Ground level ozone can also cause damage to many plant species leading to loss of yield and quality of crops, damage to forests and impacts on biodiversity.

Particulate Matter (PM_{10} and $PM_{2.5}$)
Particulate Matter is generally categorised on the basis of the size of the particles (for example $PM_{2.5}$ is particles with a diameter of less than 2.5μm). PM is made up of a wide range of materials and arise from a variety of sources. Concentrations of PM comprise **primary** particles emitted directly into the atmosphere from combustion sources and dust from wind erosion and **secondary** particles formed by chemical reactions in the air. Primary PM derives from both human-made and natural sources (such as sea spray and dust from motor vehicles on unpaved roads). Secondary PM is formed from emissions of ammonia, sulphur dioxide and oxides of nitrogen as well as from emissions of organic compounds from both combustion sources and vegetation.

Both short-term and long-term exposure to ambient levels of PM are consistently associated with respiratory and cardiovascular illness and mortality as well as other ill-health effects. The associations are believed to be causal. It is not currently possible to discern a threshold concentration below which there are no effects on the whole population's health. PM_{10} equates to the mass of particles less than 10 μm in diameter that are likely to be inhaled into the thoracic region of the respiratory tract. Recent reviews by WHO and the Committee on the Medical Effects of Air Pollutants (COMEAP) have suggested exposure to a finer fraction of particles ($PM_{2.5}$, which typically make up around two thirds of PM_{10} emissions and concentrations in urban environments) give a stronger association with the observed ill‑health effects, but also warn that there is evidence that the coarse fraction between ($PM_{10} – PM_{2.5}$) also has some effects on health.

Sulphur Dioxide (SO_2)

SO_2 arise from combustion of fuels containing sulphur. These can be both man made or anthropogenic such as from the small amounts in bushfires. SO_2 causes constriction of the airways of the lung. This effect is particularly likely to occur in people suffering from asthma and chronic lung disease. SO_2 is a precursor to secondary particulate matter and therefore contributes to the ill-health effects caused by PM_{10} and $PM_{2.5}$. Potential damage to ecosystems occur at high levels, including the degradation of chlorophyll, reduced photosynthesis, raised respiration rates and changes in protein metabolism. Deposition of pollution derived from SO_2 emissions contribute to acidification of soils and waters and subsequent loss of biodiversity, often at locations far removed from the original emissions.

Benzene

Benzene is formed from a variety of sources, but primarily arises directly from fuels, domestic and industrial combustion and road transport. Benzene is a recognised human carcinogen which attacks the genetic material and, as such, no absolutely safe level can be specified in ambient air. Studies in workers exposed to high levels have shown an excessive risk of leukaemia.

Carbon Monoxide (CO)

CO is formed from the incomplete combustion of carbon containing fuels. The largest source in the Kimberley is from bushfires, with residential and industrial combustion making small contributions in Broome. At high levels CO substantially reduces the capacity of the blood to carry oxygen to the body's tissues and blocks important biochemical reactions in cells. People with existing diseases which affect delivery of oxygen to the heart or brain, such as angina, are at particular risk.

Ammonia (NH_3)

Though not assessed in this study as there are negligible emissions from the BLNG, ammonia is important in its role with reacting with emissions from the BLNG. Ammonia is mainly derived from agriculture, primarily livestock manure/ slurry management and fertilisers. Ammonia is an important source of nitrogen deposition and can lead to damage of terrestrial and aquatic ecosystems through deposition of eutrophying pollutants and through acidifying pollutants. Ammonia is also a precursor to secondary PM and therefore contributes to the ill-health effects caused by PM_{10} and $PM_{2.5}$.

Hydrogen Sulphide (H_2S)

Hydrogen sulphide (H_2S) is a colourless gas with a characteristic odour of rotten eggs with an odour threshold of around 0.8 ppb (1.2 $\mu g/m^3$). Hydrogen sulphide occurs naturally in some environments

such as swamps and salt marshes, and is often associated with the decomposition of organic material. Human activities and industries that may produce hydrogen sulphide include sewage treatment plants, manure handling operations and oil and gas operations. In Western Australia some coastal communities, especially near Busselton have been exposed to hydrogen sulphide generated by the breakdown of seaweed that has accumulated on the shore line. Hydrogen sulphide is also present in some contaminated bore water for example in many suburbs in Perth.

Human health impacts from hydrogen sulphide (as distinct from odour nuisance) are not likely until air concentrations reach at least 2 ppm for 30 minutes (DEH, 2009). At this point sensitive groups such as some asthmatics may respond with some minor irritative changes in their bronchial capacity. The lowest level for adverse health effects is at least 500 times the odour detection limit. At this level, irritation of the mucous membranes of the eye can occur (DEH, 2009).

Volatile Organic Compounds (VOCS)
VOCs are organic chemical compounds that have high enough vapour pressures under normal conditions to significantly vaporize and enter the earth's atmosphere. There is a myriad of VOCs whose health effects vary substantially between compounds. As such, no generic health standard can be specified. VOCs referred to in this report include BTEX, formaldehyde and acetaldehyde. The most common VOC is methane, though this is commonly not included in analysis of other VOCs as it is less reactive. This leads to use of the term non-methane VOCs, or NMVOCs.

BTEX
BTEX is an acronym for benzene, toluene, ethyl-benzene, and xylenes. BTEX is primarily emitted to air from petroleum hydrocarbons, such as gasoline and from oil and gas products. Of the four substances, benzene exhibits adverse health effects on humans at the lowest levels, with benzene as described earlier a recognized human carcinogen. Adverse affects of toluene and xylenes occur at higher levels with toluene acting to irritate the respiratory system and depressing the central nervous system at high concentrations. Xylenes act as an irritant of the nose, throat and eyes at high concentrations. The health effects of exposure to ethyl-benzene are not as well understood, although adverse outcomes associated with airborne ethyl-benzene have been demonstrated in animal studies. High concentrations of ethyl-benzene have been shown to cause liver and lung cancer in mice and kidney cancer in rats.

4.2 Air Quality Criteria

4.2.1 Human Health Criteria

For assessing ambient ground level concentrations the WA EPA does not have state wide standards, but are in the process of implementing a Statewide Environmental Policy(SEP) with a draft policy released for public comment in June 2009 (EPA, 2009a). The policy objective is to meet environmental quality criteria with these being the:

- Approved National Environmental Protection Measure (NEPM) standards; and
- Standards or guidelines for Local Pollutants that are not part of an approved air related NEPM and are published as guidelines by the Chief Executive Officer of the Department. At present there are no Local Pollutants defined.

These criteria are to apply to the whole of Western Australia, excepting for the following:

- Where an Ambient Air SEP pollutant is covered by an Environmental Protection Policy (EPP). There are currently two existing EPPs; the Kwinana EPP which cover SO_2 and total suspended particulate and the Goldfields Residential Areas EPP which covers SO_2;
- Within the boundary of industrial premises;
- Within defined industrial buffer areas. These are to be recognised resident free buffer area which are secured by the planning system. Examples of residence free buffers are the Kemerton, Oakajee and Boodarie Resource Processing estates;
- Within the boundary of a road; and
- In an area where there are no sensitive receptors as determined by the Chief Executive Officer of the Department.

"If an industrial premises exists in a remote area where there is a reasonable likelihood that no sensitive receptors will be present, other than on a temporary basis, it may be determined that there is no need for the environmental quality criteria to be achieved at the premises boundary. There is an expectation however, that the environmental quality criteria will be achieved at the nearest sensitive receptor.

It is important to remember the term 'sensitive receptor' extends beyond a location where humans are likely to reside and includes areas of cultural or environmental significance, including environmentally sensitive areas declared under the act.

It is also expected that industry adopt and achieve best practice management of its operation and emissions control, which may require emission limits to be set and monitoring at the source." (EPA, 2009a),

The NEPM standards are listed in **Table 4.1** and **Table 4.2** these being for:

- Ambient Air Quality NEPM Standards (1998) covering 6 criteria pollutants with the goal to achieve these standards by 8 July 2008;
- Ambient Air Quality NEPM Advisory Reporting standard (2005) for $PM_{2.5}$ with goal to gather sufficient data nationally to facilitate a review; and
- Air Toxics NEPM (2004) with goal to gather sufficient data nationally to facilitate development of standards for air toxics.

For gaseous pollutants these criteria are given in parts per million (ppm) or parts per billion (ppb) as the in this form the concentrations are invariant with temperature and pressure. **Table 4.1** and **Table 4.2** also provide these in terms of mass per volume of air. These have been converted as per the NSW guidelines for the criteria pollutants at standard conditions of 0 deg C and 101.3 kPa and for the air toxics at 25 deg C and 101.3 kPa.

Table 4.1 National Environmental Protection Measure - Air Quality Standards and Goals

Pollutant	Averaging Period	Maximum Concentration		Goal
		(ppm)	($\mu g/m^3$)	
				Maximum allowable exceedances within 10 years
Carbon Monoxide	8-hour	9.0	*11,240*	1 day a year
Nitrogen Dioxide	1-hour 1-year	0.12 0.03	*246* *62*	1 day a year none
Photochemical Oxidants (as ozone)	1-hour 4-hours	0.10 0.08	*214* *171*	1 day a year 1 day a year
Sulphur Dioxide	1-hour 1-day 1-year	0.20 0.08 0.02	*570* *228* *60*	1 day a year 1 day a year none
Lead	1-year	-	0.5	none
Particles as PM_{10}	1-day	-	50	5 days a year
Advisory Reporting Standards and Goal				
Particles as $PM_{2.5}$	1-day 1-year	- -	25 $\mu g/m^3$ 8 $\mu g/m^3$	Goal is to gather sufficient data nationally to facilitate a review of the advisory Reporting standard as part of the review of this Measure scheduled to commence in 2005

Notes:

1) Concentrations of gaseous pollutants in italics have been converted from the NEPM standard quoted at 0 deg C and 101.3kPa as per the NSW Guidelines (NSW DEC, 2005)

Table 4.2 National Environmental Protection Measure (Air Toxic) Monitoring Investigation Levels

Pollutant	Averaging Period	Monitoring Investigation Level (ppb)	Equivalent Concentration at 101.3 kPa and 25 deg C ($\mu g/m^3$)
Benzene	Annual Average	3 ppb	9.6
Benzo (a)pyrene as a marker for Polycyclic Aromatic Hydrocarbons	Annual Average	0.3 ng/m^3	NA
Formaldehyde	24 hours	40 ppb	49
Toluene	24 hours Annual Average	1000 ppb 100 ppb	3,770 377
Xylenes (as total of ortho, meta and para isomers)	24 hours Annual Average	250 ppb 200 ppb	1,085 868

Notes:

1) The 8-year goal (date 2012) of the air toxics NEPM is to gather sufficient data nationally to facilitate development of a standard.

Of note is that for benzene lower guidelines than set in the Air Toxic NEPM have subsequently been introduced, with the new European Union regulation (commenced 1st January 2010) specifying an annual mean of 5 $\mu g/m^3$. This is being adopted for England from 31st December 2010 whilst a lower value of 3.25 $\mu g/m^3$ is to apply for Scotland, Northern Island and Wales based also on a stricter rolling annual average (DEFRA, 2007). This value of 3.25 $\mu g/m^3$ (approximately 1ppb) is about 3 times lower than the Air Toxic NEPM investigation level. For this study the new European Union value or English value of 5 $\mu g/m^3$ has been adopted.

In modelling assessments the DEC requires that the NEPM criteria be compared to the predicted maximum for that averaging period. That is, the predicted maximum 1-hour ozone level is to be compared to the standard and not the predicted 2nd highest hour. The DEC modelling guidance (DoE, 2006) also requires that modelling be presented for existing concentrations, the proposed facility alone and cumulative (existing and proposed facility). This is similar to the NSW guidelines (DEC NSW, 2005) which require the assessment of the predicted 100th percentile concentration at the nearest existing or likely future offsite sensitive receptor, with both the incremental impact (source alone) and total impact (source and background concentrations predicted).

For assessing the NEPM air toxics pollutants for shorter averaging periods (as the NEPM criteria are investigation levels) and for pollutants not covered (Local Pollutants under the draft SEP) the DEC look at applying other Australian guidelines and where these do not exist World Health Organisation (WHO) guidelines. Of these the Victorian and NSW Guidelines (Victoria Govt Gazette 2001, DEC NSW, 2005) are generally the most stringent and are adopted as per used for the recent Pluto LNG assessment. These modelling criteria are listed in **Table 4.3**.

Table 4.3 Air impacts Assessment Criteria for non NEPM Pollutants from DEC NSW (2005) (1hour 99.9th Percentile Criteria)

Pollutant	Maximum Concentration (µg/m^3)	Equivalent Concentration (ppb)	Reason for Criteria Value
Benzene	29	9	Air Toxic
Ethyl benzene	8000	1800	Air Toxic
Toluene	360	90	Odour
Xylenes (as total of ortho, meta and para isomers)	190	40	Odour
Formaldehyde	20	18	Air Toxic
Acetaldehyde	42	23	Odour

Notes:

1) Gas volumes are expressed at 25 deg C and an absolute pressure of 1 atmosphere (101.325 kPa).

In modelling assessments the 2005 NSW guidelines state that pollutants listed in **Table 4.3** are to be assessed:

- As the incremental concentration from the facility alone;
- For dispersion modelling that uses real data and emissions, that the concentrations are to be assessed as the 99.9th percentile1-hour predictions. (Note, the 99.9th is approximately the 9th highest hour in a year with 8760 hours); and
- Air toxic listed pollutants are to be assessed at or beyond the boundary of the facility, whilst the odorous listed pollutants are to be assessed at the nearest existing or likely future off-site sensitive receptor.

In applying these guidelines DEC NSW (2005) also state that:

"Principal air toxics must be minimised to the maximum extent achievable through the application of best-practice process design and/or emission controls. Decisions with respect to achievability will have regard to technical, logistical and financial considerations. Technical and logistical considerations

include a wide range of issues that will influence the feasibility of an option: for example, whether a particular technology is compatible with an enterprise's production processes.

Financial considerations relate to the financial viability of an option. It is not expected that reductions in emissions should be pursued 'at any cost'. Nor does it mean that the preferred option will always be the lowest cost option. However it is important that the preferred option is cost effective. The costs need to be affordable in the context of the relevant industry sector within which the enterprise operates. This will need to be considered on a case by case basis through discussions with the EPA."

With the NSW modelling guidelines in **Table 4.3** it is noted that these may be overly conservative as are based on occupational health criteria which have been adjusted by the application of large uncertainty or safety correction factors. For example the benzene guideline was derived from the Australian occupational health standard at the time of 5 ppm (16 mg/m^3) for a time weighted average 5 day 8 hour per day working week by dividing by a factor of 300. This factor consisted of a factor of 30 intended to account for differences in exposure regimes (working week versus lifetime exposure) and sensitivities (adult healthy workers versus the general population including sensitive sub groups). Additionally for IARC 2A or higher carcinogens (as per benzene) an additional factor of 10 was applied. The resultant concentration of 0.0167ppm (53 $\mu g/m^3$) was applied as a 3 minute design ground level concentration initially, but was later converted to a 1-hour level by dividing by 1.82 (the ratio of 60 minutes to 3 minutes to the power of 0.2) to result in a 1-hour level of 29 $\mu g/m^3$.

For comparison to the NSW value, the Californian Office of Environmental Health Hazard Assessments (OEHHA) acute reference exposure level is a 6-hour average 1300 $\mu g/m^3$. This acute value is based on the no observed effect level for reproductive/developmental toxicity in rats and reduced for application for humans using an uncertainty factor of 100. The Californian acute criteria has been used in many studies within Australia including the Worsley Alumina refinery expansion (Toxikos, 2005) and Manjimup biomass power station assessment (Toxikos, 2008). As such there are large differences in derived acute levels.

For hydrogen sulphide the NSW modelling guideline has been adopted. This has been developed from studies within NSW and specifies a 99th percentile (88th highest hour in the year) predicted peak concentration with criteria that varies from 4.83 $\mu g/m^3$ for "single rural residence with less than approximately 2 people" to 1.38 $\mu g/m^3$ for "Urban - greater than approximately 2000 and/or schools and hospitals" (NCW DEC 2005). The peak concentration is specified as the peak 1-second average within that hour. For tall wake free stacks in the far field (e.g. greater than 5 km as per outside the buffer area) and for the unstable conditions where the BLNG plumes containing H_2S are brought to ground, a peak to mean factor of 3 is recommended. For neutral and stable conditions a peak to mean ratio of 6 is recommended. For assessing peak concentrations the model predicted 1-hour concentrations have been converted using these factors dependent on the stability class at that time.

The NSW criteria is to protect the public from annoyance at sensitive receptors. Health effects as discussed in **Section 4.1** occur at much higher concentrations with health effects not likely until above 500 times the odour threshold of around1.2 $\mu g/m^3$.

4.3 Vegetation Criteria

Effects on vegetation and ecosystems can occur from the elevated pollutant concentrations directly affecting plant physiology, growth and vitality. Examples are sulphur dioxide and ozone damage to vegetation at high levels and damage due to fine particulate deposition on vegetation. These effects can be observed over days to years on the plant species. The direct effects can be described by Critical Levels - *the concentration of pollutant in the atmosphere above which adverse effects on receptors such as plants, ecosystems or materials may occur* (WHO, 2000).

Air pollutants can also affect ecosystems by adding to nutrients in the soil or acidifying the soil through dry and wet deposition. This can affect the ecosystem structure and functioning by favouring the conditions for one species over other species, with the effects normally observed after many years. These effects can be described by Critical Loads - deposition levels below which harmful effects on specified sensitive elements in the environment do not occur.

WHO (2000) summarises these two as"
"Critical levels provide effect thresholds for relatively short term exposures, and are not aimed at providing complete protection of all plants in all situations from adverse effects, critical loads provide the long term deposition below which we are sure that adverse affects will not occur."

Criteria for critical levels and loads have been determined for plant species and ecosystems for Europe and North America, but there is no data available for the north west of Australia. The vegetation in the north west and soil types are very different to that from which the European studies were based. As such, for the similar Gorgon LNG project on Barrow Island in the Pilbara, the WA EPA in their assessment report (1323) stated or concluded that:

"there are no data available on the effects of these pollutants on the fauna and flora of Barrow Island. In the absence of such standards, the EPA considers that the limit for humans is the only available surrogate for mammals and the WHO deposition limits are the only available surrogate for vegetation" (EPA, 2009b).

Therefore, for this study to assess the likely impact on vegetation the WHO deposition limits have been adopted. WHO (2000) report that critical loads range between less than 250 to greater than 1,500 eq/ha/year (eq - acid equivalents), depending on the type of soil and ecosystem. Less than 250 eq/ha/year is stated for sands, granites and gravel base material of coarse texture (<18% clay content) to >1500 eq/ha/year for base material from dolomite, basalt and volcanic deposits with fine soil texture (clay content > 35%). For the sandy soils of the Barrow region and as for the Dampier Peninsula a critical load at the low end of around 200 to 500 eq/ha/year is considered appropriate. According to SKM (2008) this equates to a sulphur load of 4 to 8 kg/ha/year.

For nitrogen, WHO (2000) estimate that critical loads for various ecosystems range between 5 to 35 kg N/ha/year, depending on the type of soil and ecosystem. The low critical loads of 5 -10 kg N/ha occur for the most sensitive species (artic bogs, softwater lakes, forest in humid climates) with "an average value for natural and semi natural ecosystems of 15 to 20 kg N/ha per year". For areas not covered for the categories, (such as the Kimberley) the WHO (2000) document offers guidance that the values

should be increased for the following factors; hot climates, wet soils, no frosts and high base cation availability. For this study critical loads toward the middle to high end would be expected and the average value "for natural and semi natural ecosystems of 15 to 20 kg N/ha per year" is considered appropriate.

4.4 Emission Criteria

Within WA, the EPA "require that all reasonable and practicable means should be used to prevent and minimise the discharge of waste" (EPA, 2003). For the definition of what is reasonable and practicable the EPA have released one guidance statement for large open cycle gas turbines burning natural gas. This guidance statement (EPA, 2000) considered that:

"In relation to large gas turbines burning natural gas, the EPA notes that most new industries are now, as a matter of course, adopting dry low NO_X burner technology as best practice. Alternatively, where gas turbines are installed as part of combined cycle or cogeneration plant, injection of steam into the gas turbine combustion chambers does represent, in certain circumstance, best practice. These technologies can achieve NO_X emissions at base load of 25 parts per million volume dry at 15% oxygen reference level" (EPA, 2000).

Besides gas turbines the WA EPA do not have any specific guidance. As such for this assessment the 2005 NSW regulations have been used. Though these regulations are only applicable in NSW under state legislation, they are considered to be a benchmark on what is considered best practice within Australia. These regulations, introduced in late 2005, in many instances adopted much lower limits than previously regulated in NSW or in other states such as Victoria or in the old 1985 National Health and Medical Research Council guidelines.

The three major combustion processes or sources of emissions, gas turbines for electricity generation and driving compressors, boilers for generating steam and thermal combustion units w ill all meet the respective emission guidelines under normal operation. The gas turbines will be specified with Dry Low NO_X burners with guaranteed emission limit during normal operations of 25 ppmv, dry (51 mg/m^3 at 0 deg C). This meets the NSW criteria of 70 mg/m^3 and meets the requirements of the WA guidance notes. For boilers, use of low NO_X burners will result in emission concentrations of about 175 mg/m^3, which meets the NSW regulations of 350 mg/m^3. Afterburners will likewise have low NO_X burners with emission concentration of about 75 mg/m^3 and therefore easily meet the NSW criteria of 350 mg/m^3.

5 Existing Environment

5.1 Introduction

This section provides details with regards to the existing air quality of the region and the important air quality meteorology for existing and proposed sources. This section does not provide a review of the climatology of the region in terms of the annual winds, temperatures and rainfall as this broader description is provided in Woodside (2010).

5.2 Meteorological Data Available

Good quality meteorological measurements in the region that are available are listed in **Table 5.1**.

Table 5.1 Meteorological Data Available in the Region

Site	Data	Latitude (South)	Longitude (East)	Measurements	Distance from James Price Point
Bureau of Meteorology (BoM) Sites					
Broome Airport	Continuous	17° 56' 52"	122° 14' 06"	WS10, WD10, GU10, AT1.2, RH1.2, BP, RN	48 km South
West Roebuck	Continuous	17° 53' 47"	122° 18' 45"	WS10, WD10,	43km SSE
Derby	Continuous	17° 22' 09"	123° 39' 46"	WS10, WD10, GU10, AT1.2, RH1.2, BP, RN	160 km East
Cygnet Bay	4 observations per day	16° 27' 10"	123° 00' 32"	WS10, WD10, GU10, AT1.2, RH1.2, BP, RN	150km NE
Department of State Development Sites					
Lacepede Island	Continuous 1- minute	16° 54' 08"	122° 11' 52"	WS17, WD17, GU17, AT , RH, SR, BP, RN	70 km North
North Head	Continuous 1- minute	16° 49' 55"	122° 32' 15"	WS10, WD10, GU10, AT , RH, SR, BP, RN	88 km NNE
Gourdon Bay	Continuous 1- minute	18° 27' 08"	121° 55' 23"	WS10, WD10, GU10, AT , RH, SR, BP, RN	100 km SSW

Notes:

1) Measurements numbers refer to the measurement height above ground level. Abbreviations are, wind speed (WS), wind direction (WD), dry bulb air temperature (AT), relative humidity (RH), barometric pressure (BP), rainfall (RN) and short wave solar radiation (SR).
2) There was an additional site at Cape Leveque which undertook manual observations until 1985.

Of these sites:

- The Bureau of Meteorology (BoM) Broome airport site contains a robust wind sensor (Synchrotac 706) which has a relatively high stalling speed of 0.7 m/s. Therefore this sensor, though suitable for routine weather measurements as used by the BoM, tends to record low wind speeds as calms. As such, it does not provide as much information on the very light winds which may be important in modelling surface sources, such as odours from a waste water treatment plant. For this study the anemometer is not used as input into the modelling, but only

for a comparison against the model wind predictions as it is the closest good quality data to the south of the site. Other measurements obtained from the site are all of good quality;

- The BoM West Roebuck site is in a small 30 by 30m clearing surrounded by small trees and therefore does not meet the requirements for siting air quality wind sensors according to AS 2923. With these small trees within 30m it will tend to record below average wind speeds and as such has not been used in this report;
- The Lacepede Island east site is located 70 km north of James Price Point situated on a small approximately 50m wide by 300m long NW-SE orientated island. Two sensors are mounted 17m above ground level on either side of an approximately 20m high tower, with the tower base approximately 8m above mean sea level. Depending on the wind direction, the wind sensor which is upwind of the tower is used to measure the wind. Being 17m above ground level and on a narrow island the wind speed is considered to be representative of a height of about 20 to 25m above mean sea level. This site is considered to be the best site north of James Price Point and has been used in model validation (see **Section 7.2**);
- The North Head and Gourdon Bay sites are located within 50 to 100m of the coast and are both well sited with no obstructions. North Head is located 88km north of James Price Point and is on the coast with the site meeting the requirements for AS 2923. However, being only 50m from the coast, it will measure wind representative of the ocean for onshore winds whilst for offshore winds will measure winds representative of the land. Therefore the data will be difficult to incorporate or use in a model as the different roughness needs to be accounted for. The Gourdon Bay data likewise has the same issue as the North Head data. As the Gourdon Bay data is located 100 km SSW of James Price Point, the Broome data is preferred because of its much closer proximity; and
- The BoM Cygnet Bay site only records 4 observations per day and as 150km to the NE of the site is not preferred. The Derby data likewise because of its distance is not used within the air quality study.

5.3 Meteorology in Terms of Pollution Dispersion

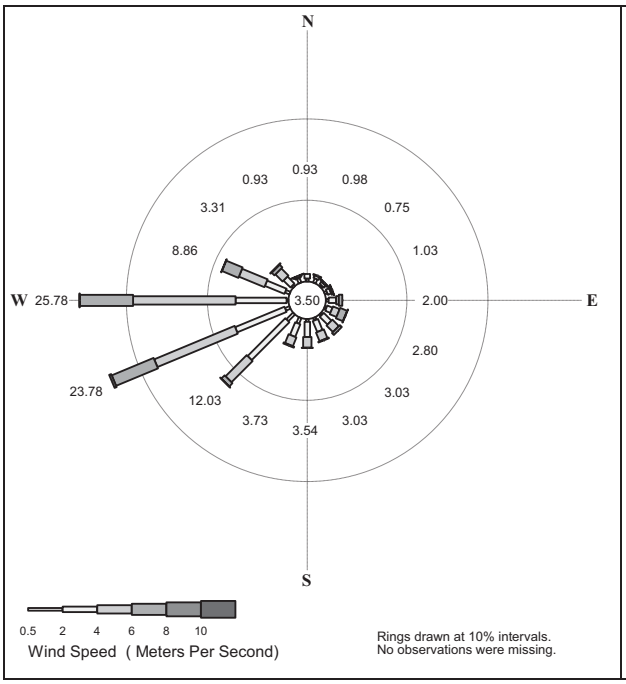
The Kimberley region has a tropical monsoon climate with two dominant seasons separated by short transitional periods. Hot and humid conditions characterize a 'tropical summer' season that extends from November to April. During this period low pressure systems and unstable air characterize much of the weather pattern with the region receiving about 90% of its annual rainfall. From May to October the Kimberley is influenced by high pressure systems and a predominantly south easterly airflow from the continent's interior.

The seasonal pattern of winds as recorded at Broome are presented in **Figure 5-1**. The winds have been classified in periods of:

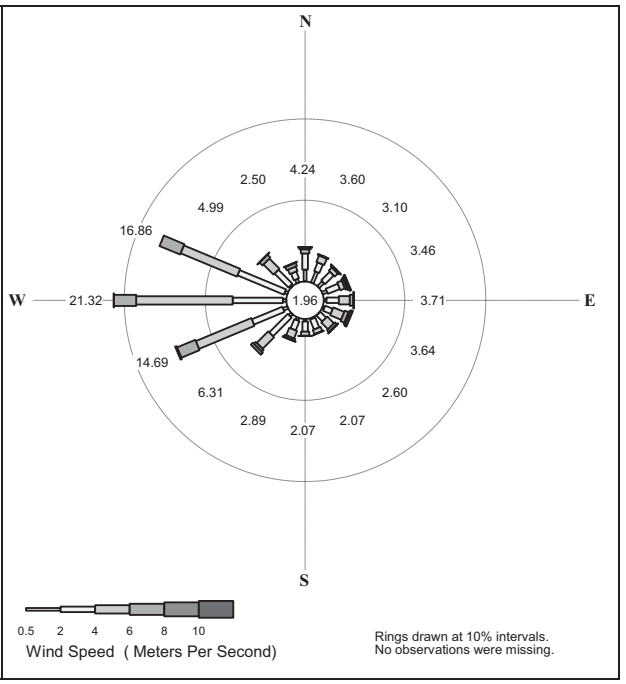
- September to November with predominant westerly winds and dry conditions, though the rain can start in November in some years. In this period winds are sometimes from the SE quadrant though with very infrequent winds from the north and NE quadrant;
- December to March (the peak of the wet season) with dominant westerly winds, though with a small percentage of winds from the North and NE quadrant;
- May to July where the winds are predominantly south easterlies; and

- April and August where the winds tend to transition between the westerlies and the south westerlies with the wind speeds lighter than for the other periods.

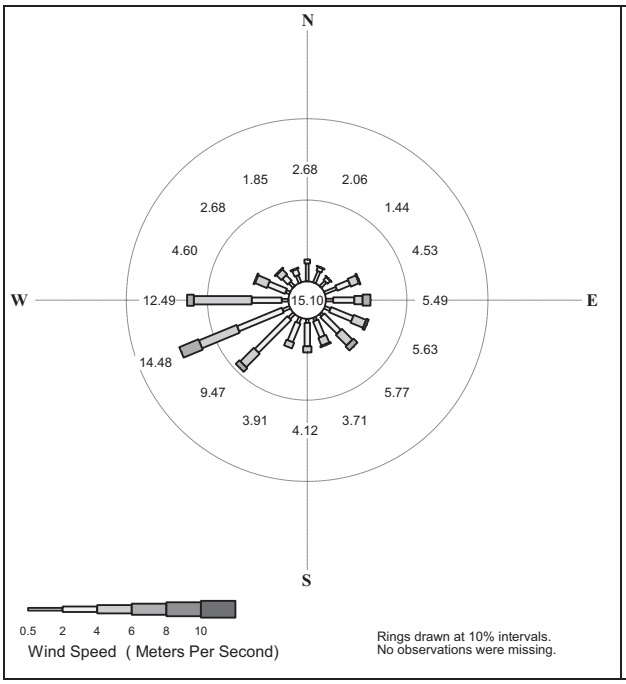
September to November



Peak of the Wet (Dec – March)



Transitional Months (April and August)



Early Dry Season (May to July)

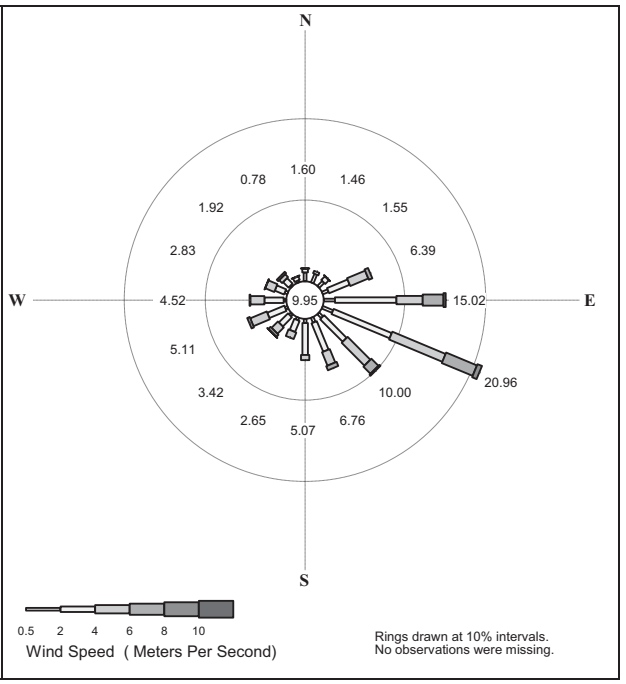


Figure 5-1 Observed "Seasonal" Wind Roses at Broome Airport (Data from 1 Oct 2008 to 30 Sep 2009)

The variation in wind speed for these periods is summarised in **Table 5.2** which shows that the lowest wind speeds and highest number of calms occur in the transitional months followed by the period May to July, with highest winds occurring in the period September to March.

Table 5.2 Wind Speed Statistics for Broome Airport

Statistic	September to November	December to March	Transitional Months April and August	May to July
Average wind speed (m/s)	4.3	4.2	3.0	3.5
Percentage of winds < 2m/s	10.7	10.3	29.6	20.6
Percentage of calm winds	3.5	2.0	15.1	10.0

In terms of implications on the air quality from a LNG plant with their associated buoyant emission sources:

- Areas to the due east of the plant will have the highest overall concentrations due to the very frequent and persistent westerlies,
- The consistent westerly winds in these periods with the winds varying little throughout a day will result in relatively higher 24-hour concentrations than would otherwise occur;
- For these steady westerly winds, high concentrations for a period of hours could occur due to processes such as sea breeze fumigation to the areas to the east (see **Section 6.1.2**); and
- Areas to the south of plant such as Broome will have relatively low concentrations due to the low frequency of northerly winds.

5.4 Existing Air Quality in the Region

5.4.1 Background

There has been little monitoring of air pollutants in the Kimberley region to date with what monitoring that has been undertaken being conducted using methods that do not allow direct comparison to current air quality criteria. As such, no assessment of the compliance of measurements with air quality standards can be made.

It is known that the Kimberley like much of northern Australia is affected by the large fires that burn for up to weeks in the region which create persistent plumes of smoke and associated pollutants. This has been of concern to the EPA who recommended that monitoring for particulate be conducted in the area to determine pollutant levels (EPA, 2006) *Fire Management in the Kimberley and other Rangeland regions of Western Australia. Advice of the Environmental Protection Authority to the minister for the Environment under Section 16(e) of the Environmental Protection Act 1986.*

An example of the smoke and the extent of the areas burned is provided in **Figure 5-2**. This shows a series of satellite images from the 8th to 21st August 2006 showing the large area (indicated by the burnt darker areas) and the large plumes of smoke that at times covered Broome. To gauge the area burned compare the size of the dark burned area on the 21st August to that at the beginning of the fires on the 8th August and note the progression of the fires throughout the period.

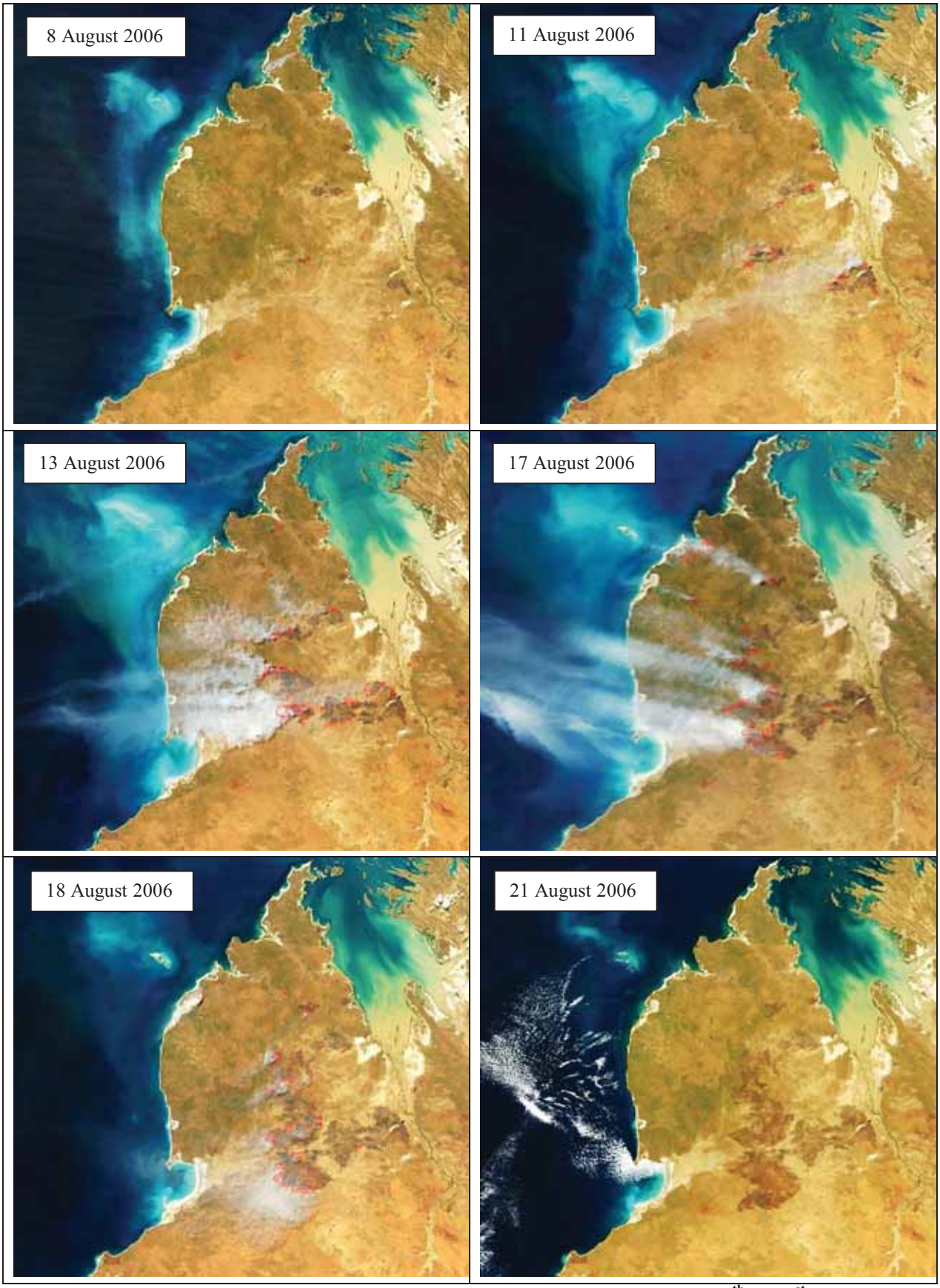


Figure 5-2 MODIS satellite images of the Dampier Peninsula from the 8th to 21st August 2006 showing smoke from fires and development of fire scars (dark land areas). Red shapes are the estimated fire scar for the last 24 hours.

Besides fires contributing to high particulate there is occasional dust from distant dust storms that can create high dust/haze levels in the region. A satellite image of a dust storm on the 29th September 1999 showing the large clouds of dust that originate well to the SE of the region and which is transported by strong south easterly winds is presented in **Figure 5-3**. Apart from this particular distant dust storm, local dust storms are infrequent in the region with only two dust storms reported since 1990 (Kowald, 2009). The 2001 State of the Environment report (Hamblin, 2002) also reports that Broome as in the higher rainfall area is a region with low frequency of dust storms. This for instance differs from the coastal area on the Pilbara where dust storms are more frequent.

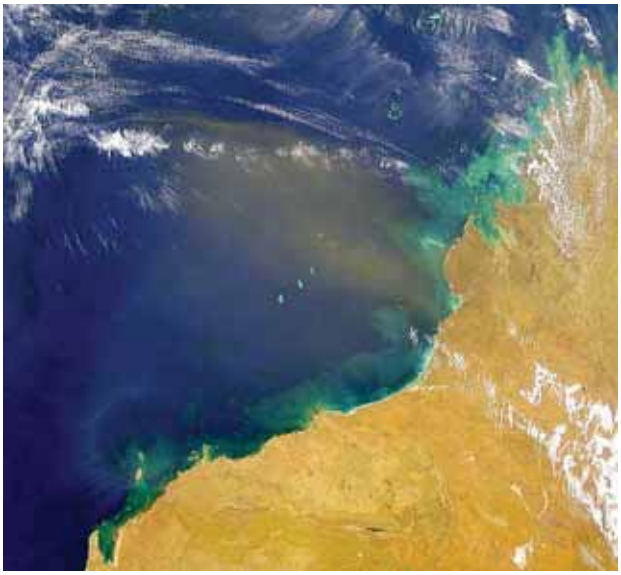


Figure 5-3 Satellite Image (SeaWiFS) of North Western Australia showing large dust storm passing to the west of Broome in 1999 (Source http://www.aims.gov.au/)

5.4.2 Ambient Concentration Measurements Available

A summary of ambient air quality measurements undertaken in the past and currently in the Kimberley region is presented in **Table 5.3** with gaseous measurements from nearby regions also included.

Table 5.3 Ambient Measurements in the Region and Nearby Regions

Site	Year	Measurements	Reference
Dampier Peninsula			
North Head Lacepede Island Gourdon Bay	Nov 2008 Ongoing	PM_{10} from Dustrak monitors	Monitoring conducted for the Department of State Development - Ongoing
Broome Airport	1979-1983	TSP concentrations with chemical analysis	Savoie (1984)
Broome Airport	Ongoing	Aerosol Optical depth	Reported in Scott et al (1992) and Mitchell and Forgan (2002)
Northern Territory (Gaseous)			
Casuarina	2007	Ozone	Meyer et al (2008b)
Middle Arm	2008	Ozone, VOCs passive samplers	Sowden et al (2009)
Pilbara (Gaseous)			
Dampier - Karratha	1998-2000	NO_X, CO and Ozone	DEP (2002)
Dampier - Karratha	2004/2005 and 2007/2008	Burrup Rock Art	Gillett (2008)
Port Hedland	1998-2002	Particulate, H_2S, NO_X	BHP for the DRI Plant

Table 5.3 indicates the following:

Particulate Measurements

At present there are no standard compliant particulate measurements undertaken in the Kimberley region to assess against particulate criteria. The DEC have committed to undertaking measurements for Kununurra to understand the air quality primarily due to concerns with high levels of smoke as recommended by the EPA (EPA, 2006). The Department of State Development have commissioned monitoring of PM_{10} measurements using DustTrak monitors. These are not a recognised standard method and utilise a photometer that measures the reflectance of light off aerosol that is drawn though the instrument. The measurements commenced in October 2008, but at the time of writing this report there were no data suitable for analysis due to issues with the instrumentation.

In the past particulate measurements were undertaken at Broome (1979 to 1983) as part of global aerosol program with total suspended particulate (TSP) and speciation of the aerosol conducted by the University of Miami (Savoie, 1984). The data was collected using a high volume TSP sampler, sampling 7 day averages with an average flow rate of 45 to 52 m^3/hr. This is lower than that required by AS 3580.9.3:2003 which specifies a flow rate of between 60 and 90 m^3/hr and as such is slightly non standard. Additionally, as 7 day averages were measured it is not possible to compare the data to the 24-hour criterion that is used within Australia.

The data as summarised in Savoie (1984) showed pronounced seasonal trend in sodium, sulphates and mineral dust with:

- Monthly sodium levels highest in the summer months with a peak of 3.7 µg/m^3 in January and minimum of 0.5 µg/m^3 in May. This is as expected with the westerly onshore winds in January

and ESE continental winds in winter. Using a standard sea salt to sodium ratio for clean air of 3.27 (based on sea salt to sodium ratio) an average sea salt concentration in the summer months of 12 $\mu g/m^3$ is derived; and

- Monthly mineral dust levels peak from June to August with an average concentration of 10 $\mu g/m^3$ and a minimum concentration of 2 $\mu g/m^3$ in the months January and February. The peaks are associated with dry months with south easterly winds. Savoie (1984) reported maximum 7 day average mineral dust concentrations of 54 $\mu g/m^3$ with four seven day periods over 30 $\mu g/m^3$. These are probably associated with dust storms to the south east which occasionally bring dust into the region in these months. In these periods dust levels over 100 $\mu g/m^3$ for a 24-hour average are expected.

The other aerosol measurements that have been conducted are radiometer measurements at Broome Airport (Scott et al, 1992 and Mitchell and Forgan, 2002). These are not direct aerosol measurements but use sun photometer measurements to determine the aerosol optical depth (AOD), which is a measure of the aerosol load in the atmosphere. Scott et al (1992) reported that the measurements at Broome show a distinct seasonal trend with the lowest AOD in April to June and the highest levels in September to December. This is in agreement with the occurrence of smoke from fires as detailed in **Section 3.5.4.**

Gaseous Monitoring

No gaseous monitoring data has been undertaken to date for the Kimberley region primarily because of its small population and lack of industry. The closest monitoring sites able to provide some indication of levels are in the Dampier and Karratha region with some measurements undertaken at Port Hedland as part of monitoring from the Direct Reduced Iron Plant. There are also measurements taken further afield near Darwin in the Northern Territory.

The Dampier measurements were undertaken by the DEC in 1998 to 2000 and consist of ozone, NO_X and CO. The data showed that ozone levels were below the NEPM standard with the maximum 1-hour concentration recorded of 63 ppb (63% of standard) and the peak 4-hour level of 61 ppb (76% of the standard). These peaks were due to distant fires with about ten 1-hour events around 60 ppb. Other pollutant levels such as CO and NO_2 were much lower relative to air quality criteria. Therefore of the gaseous pollutants, ozone is closest to its respective standard, this occurring for the 4-hour standard. That this occurs for the 4-hour standard is due to the broad nature of the ozone plumes from distant fires which results in the 4-hour averages being very close to the 1-hour average.

The closest VOC measurements available include the measurements conducted in the Dampier region as part of the Burrup Rock art study (Gillett, 2008). This study used passive samplers and found that away from the immediate sources that the VOC levels were very low indicating that average background levels in the region are low.

The Northern Territory measurements (Meyer et al, 2008b) indicate that ozone levels there are slightly lower than in the Pilbara.

5.4.3 Expected Concentrations for the Dampier Peninsula

Based on available measurements at the site, measurements from nearby regions and modelling (as detailed in **Section 8.2.2**) the expected maximum existing pollutant levels on the Dampier Peninsula are listed in **Table 5.4**.

Table 5.4 Expected Existing Concentrations for the Dampier Peninsula

Pollutant	Ave. Period	Criteria (ppb)	Goal	Anticipated Concentration (ppb)	Percent of Standard (%)	Reference
Nitrogen Dioxide	1-hour 1-year	120 30	1 day a year None	60 - 80 4	50 - 67 13	Modelling Fires (Section 8) Dampier Measurements
Sulphur Dioxide	1 hour 24-hour Annual	200 80 20	1 day a year 1 day a year None	Negligible Negligible Negligible	Negligible Negligible Negligible	Dampier Measurements
Ozone	1-hour 4-hour	100 80	1 day a year 1 day a year	60 - 80 60 - 80	60 - 80 75 - 100	Measurements Pilbara and Modelling Fires (Section 8)
Carbon Monoxide	8-hour Annual	9000 -	1 day a year -	1000 - 2000 65	11 - 22 NA	Modelling Fires (Section 8) Dampier Measurements
Benzene	Annual	3	Reporting Standard	0.02	0.7	Dampier Measurements
Toluene	24-hour Annual	1000 100	Reporting Standard	Low 0.03	Low 0.03	- Dampier Measurements
Xylenes	24-hours Annual	250 200	Reporting Standard	0.015 -	0.06 -	Dampier Measurements
		(µg/m^3)				
PM_{10}	24-hour	50	Max 5th Highest	200 50 - 100	NA 100 – 200	Level recorded in the Pilbara and Modelling Fires (Section 8)
$PM_{2.5}$	24-hour Annual	25 8	Reporting Standard	100 – 150 5 – 6	NA NA	Levels recorded in the Pilbara and Modelling Fires (Section 8)

Table **5.4** indicates that:

- The pollutants of most concern will be particulate ($PM_{2.5}$ and PM_{10}) due to smoke during the fire season September to November with levels likely to be above the NEPM goal. There is also some potential for exceedances of the standard due to dust from dust storms principally in the months June to August;
- Ozone is the pollutant of next most concern with levels at or just below the 4-hour NEPM standard due to plumes from fires;
- NO_2 is below the NEPM standard at around 50 to 67% of the standard due to fires; and
- Other pollutant levels such as CO, BTEX are well below the criteria.

6 Atmospheric Dispersion Modelling

6.1 Overview and Requirements of Models

As detailed in **Section 1.2** to predict concentrations from the proposed plant, model(s) are required that can model:

- The various sources at the site. Sources may range from surface area sources to releases from tall stacks;
- The important dispersion processes. This will depend on the location, proximity to coast, topography, and vegetation in the region which may lead to complex wind flows (meteorology); and
- Chemical transformation or deposition. This depends on the type of emissions – for some pollutants complex reactions may occur.

For this project these details are discussed in the following sections with the rationale for the selection of the models for this study given in **Section 6.3** and the details of model set up and other modelling issues given in **Sections 6.3** to **6.9**.

6.1.1 Sources to be Modelled

As listed in **Section 3** the sources and pollutants that need to be modelled are:

- Gas turbines with stack heights of about 30 to 40m with very buoyant plumes that will typically rise to 200 to 400m above ground level with emissions of most concern being NO_X and CO;
- CO_2 Removal Unit vents with emissions of BTEX and H_2S. These will be released either from the thermal oxidiser or with gas turbine exhaust and as such will have good dispersion;
- Boilers with stack heights of about 35m with reasonably buoyant plumes;
- Flares which can be variable in emission properties with emissions of NO_X, PM and VOCs. For the large venting releases these will be a very buoyant plume that will rise hundreds of metres above ground; and
- Ships engine emissions. These are less buoyant emissions and under stronger winds will be subject to plume downwash due to the superstructure of the ships.

6.1.2 Important Dispersion Processes to be Modelled

For the site, which is 1 to 3km from the coast, situated in a tropical region, with flat terrain that gradually increases with height inland and with the predominantly very buoyant plumes, the following meteorology and dispersion processes are important:

1) Effects that result from the large plume rise of the plumes:
    - Plume trapping by the nocturnal inversion before it breaks up. Generally, buoyant plumes will penetrate any low inversion and remain above the inversion. As such, at night when there are low winds the ground level concentrations should be negligible;

- Fumigation of the plumes in the morning when the morning mixed layer grows to the plume height and the plumes can be mixed rapidly to the ground; and
- Plume trapping or fumigation of the plume due to the onshore winds. For onshore winds when the temperature of the sea is cooler than the land the onshore airflow can be relatively stable with plumes in this air dispersing relatively slowly. When this air passes over the hotter land surface a growing region of thermal dispersion occurs (termed the Thermal Internal Boundary Layer, TIBL). The TIBL is important for tall stacks and/or very buoyant plumes as it can lead to a process of fumigation of the plume at distances of several to ten kilometres downwind, leading to higher concentrations that would otherwise occur (see **Figure 6-1**).

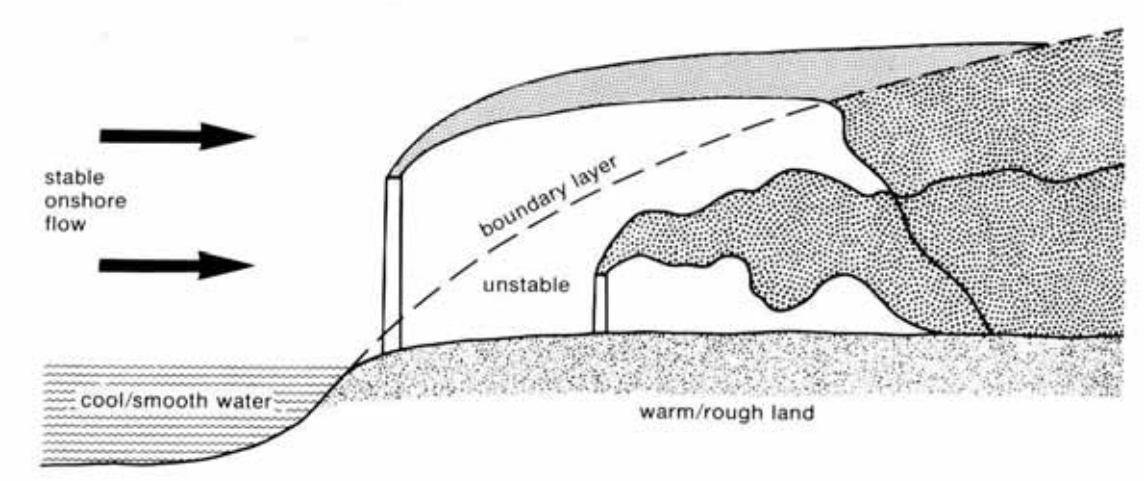


Figure 6-1 The fumigation process due to the presence of a thermal internal boundary layer (From DCE, 1982). Note the plume from the tall stack on the coast is undergoing fumigation, whilst the shorter stack inland is just trapped.

2) Plume merging with nearby plumes. Plumes that are sufficiently close together may in the process of rising start to merge, resulting in overall greater plume rise for each plume. This is especially important when there are many closely spaced plumes such as at power stations;
3) Downwash of the plume by the turbulent eddies that develop when air flows over and around buildings. If the plume is emitted into or is caught in such an eddy, it can be brought to ground much sooner than would otherwise occur, resulting in higher ground level concentrations. This is especially important for the emissions from the ships with stacks just above superstructures of the ships;
4) Convective dispersion. During the day time, the heated earth's surface will generate convective cells of rising and descending air which can bring any plume to the ground within several hundred metres of the source; and
5) Terrain effects on the airflow. The topography of the sites consists of gradually sloping terrain towards the centre of the Dampier Peninsula where the terrain is around 200m high. A surface drainage flow can develop on this slope under low wind speed cloudless nights (katabatic flow). This flow will be relatively slow, much less than 100m deep and will not affect the elevated plumes

6.1.3 Photochemistry and Deposition to be Modelled

Of the pollutants NO_X will react with VOCs in the presence of sunlight and can create ozone and other secondary pollutants. Therefore modelling of chemical transformation will be important. Maximum ozone levels may occur a number of hours after release such that modelling the transformation and long transport of the plumes is important. For the winds on the Dampier peninsula with the development of sea breezes, land breezes and katabatic flows, plumes which are blown out to sea in the morning can be blown back across land when the sea breeze develops. Therefore predicting the 3-dimensional structure of the wind is also critical. Such wind fields could in principle be determined using observational data if there were a adequate number of observations from the ground up to several hundred metres to resolve the winds. However, for this region with sparse data, deriving an accurate wind field from observations is not feasible. Therefore, the winds and turbulence have to be generated with a mesoscale model such as TAPM.

6.1.4 Inclusion of Existing Concentrations – Cumulative Assessment

For pollutants where there is a significant cumulative impact (i.e. background levels are significant) the impact assessment needs to include existing or background concentrations. For crustal particulate, as in the case of mining studies the background particulate is simply added to the predicted particulate levels. This approach is acceptable whenever the new industrial emissions do not interact with the background concentrations. However, for pollutants such as NO_X, ozone and CO the chemical reactions are dependent on the background concentrations in a complex manner. Therefore the cumulative concentrations are not the simple addition of the background and predicted concentrations but instead a photochemistry model is needed to resolve the complex interactions.

In the past, smog assessments have assumed that the background pollutant levels are constant and specified a typical "low" constant background level therefore neglecting days when there may be high background levels due to fires. For the Kimberley region however with frequent smoky haze events, this standard approach may understate the actual cumulative impact. What is required is that realistic levels of background pollutants levels are incorporated in the modelling such that a realistic cumulative assessment can be made.

6.2 Model Selection – TAPM and TAPM-CTM

For the important processes described in **Section 6.1** the models TAPM and TAPM-CTM have been selected. TAPM (The Air Pollution Model) is a prognostic meteorological and dispersion model that can predict the meteorology in the region of interest without recourse to observational data, though local observational data can be assimilated within the model. TAPM-CTM utilises the meteorology predicted by TAPM but instead of the normal dispersion options available within TAPM predicts the photochemistry using the Chemical Transport Model. TAPM has been selected to model the local effects within 15 km of the plant on a fine 500m grid such that the peak concentrations, neglecting any chemical reactions can be determined. To model the long range transport and photochemistry TAPM-CTM has been selected.

6.2.1 Local Scale Modelling - TAPM

To determine the local impacts TAPM v4.03 has been used. TAPM is supplied with databases of terrain, vegetation and soil types to assist in model setup for any region within Australia and uses the Limited Area Prediction Systems (LAPS) analyses to initialise the model. For the important processes identified in **Section 6.1**, TAPM can model all the processes and is especially suited for modelling effects from tall and very buoyant sources such as fumigation (both morning fumigation and sea breeze fumigation), generating three dimensional wind fields and convective processes. TAPM incorporates building downwash using the USEPA PRIME algorithm. It is noted that past versions of TAPM under-predicted the frequency of occurrence of low winds speeds, although this has been improved considerably in version 4. Based on earlier versions of TAPM the DoE (2006) in their modelling guidance state that:

"*the DoE will not accept the use of TAPM to model dispersion of low sources with zero or low buoyancy, either directly (TAPM calculating concentrations) or indirectly (TAPM) producing a meteorological file for another model) unless performance of the model(s) is demonstrated to be reliable, or there is a margin of safety in results which is demonstrably larger than model error".*

In this study however, as the sources to be modelled are not low sources with low buoyancy, this issue does not apply. Additionally besides the issue of low winds, TAPM tends to under predict the high winds (see **Section 7.2**) which is important particularly for fugitive dust assessments involving wind erosion. In this study however as wind erosion is not being modelled nor releases from surface sources with little buoyancy TAPM is considered to be the most appropriate model of those available.

6.2.2 Regional Scale Photochemical Modelling

As the maximum concentrations of ozone can develop 2 to 5 hours after release of the precursors from the source, an assessment on a regional scale (order of 100km) is needed for modelling the production and dispersion of ozone. This model not only needs to predict the photochemistry but also must accurately model the wind fields as over 5 hours the winds will likely move the plume in one direction and then another. With regards to modelling the photochemistry, in the past in the Northwest, TAPM modelling has employed the Generic Reaction Set (GRS) mechanism. For example, it has been used for all photochemistry modelling in the Burrup Peninsula area, the Gorgon project on Barrow Island and the Cape Preston Iron ore project. The GRS mechanism has been used as it was the only photochemistry option available within TAPM until a few years ago. It is a simplified set of the reactions which results in quick model run times. The downside of the GRS equations as it is an approximation and is intended primarily for a screening approach with there being some uncertainty in model predictions.

For the BLNG project, with the high background levels to be modelled and the relatively large scale of the project, the more advanced TAPM-CTM model with the Carbon Bond 2005 (CB05) reaction mechanism has been used. CB05 is a state of the art chemical transformation mechanism which has recently been released by the U.S.E.P.A. (Yarwood et al, 2005). The mechanism has 511 chemical species and 155 reactions. Organic species are lumped according to their carbon-carbon bonding type. Organic species treated in CB05 include alkanes, ethene, terminal and internal-bonded alkenes, toluene, xylene, formaldehyde, higher aldehydes, isoprene and terpenes.

TAPM-CTM has been validated for a number of studies including:

- A comprehensive validation study for Sydney using ozone and NO_x data. The study was designed to identify areas of uncertainty in the emission inventory and the modelling tools (CSIRO, 2008);
- Modelling of fine particulate $PM_{2.5}$, CO, NO_2, ozone and validation against monitoring data for Sydney (Cope et al, 2009b). The model was then used to predict estimates of the future changes with different ethanol blends in petrol and various uptake scenarios as input into a health study and for use in policy making;
- Prediction and validation of formaldehyde for Melbourne from other anthropogenic VOCs (Gillett, and Cope 2009); and
- Modelling particulate across northern Australia (Luhar et al, 2008). This study used the same methodology for emissions as used in this project with the results providing good agreement with $PM_{2.5}$ measurements.

TAPM-CTM has also been applied in a number of recent studies throughout Australia such as:

- The South East Queensland modelling study where ozone levels where predicted for current and future growth scenarios (Killip et al, 2007);
- The 1000 MW open cycle Westlink Fords Road Power Station in Queensland (Katestone, 2009); and
- Modelling mercury concentrations for Australia including the emissions from fires (Cope et al, 2009a). This again used the same methodology for fire emissions as used in this study.

6.3 TAPM and TAPM–CTM Modelling Methodology

To investigate the contributions from the proposed LNG Precinct, the following set up options within TAPM and TAPM-CTM were used:

- Use of TAPM v4.03 with new surface schemes;
- Default options for turbulence and land use schemes for version 4;
- Modelling of pollutants was undertaken for the year 2006 to be consistent with the fire emission database. A model comparison with meteorology for the Dampier Peninsula was additionally conducted for October 2008 to September 2009;
- Sea surface temperatures were obtained from the TAPM data bases;
- 25 vertical levels;
- Deep soil moisture specified as 0.11 for January to March, 0.10 for April and 0.08 for rest of months. Higher values were specified at the beginning of the year to correspond to periods of higher rainfall with a drier value for the rest of the year;
- Two spin up days for each model run. TAPM-CTM as it is configured must be run in monthly periods whilst TAPM was run in quarterly periods;
- Soils as per the soil database except that sandy soils were reclassified as sandy loam as it is found that the sandy soil classification within TAPM results in excessive latent heat flux even with dry soils with soil moisture of 0.08;

- No data assimilation of surface observations to nudge the model predictions. Data assimilation is considered to lead to sharp wind shears in the vertical at night when the winds above the number of layers used to define surface layer return to that derived by TAPM;
- Emissions as from **Section 3;**
- Plant layouts of the BLNG from Woodside with a southern and northern industrial area. In each area the LNG trains were orientated in an E/W direction with the LNG trains spaced about 235m apart in a N/S direction. For the 50 Mtpa Precinct, 5 trains were assumed in each area, whilst for the 15 Mtpa Precinct, 3 (or 4) trains were assumed in the southern precinct only.

Specific set up for TAPM-CTM were:

- A meteorological grid with 30, 10 and 3 km nested grids with 49 by 49 grid points;

  The pollution grids were predicted on a subset of the meteorological grid at each of the 30, 10 and 3km grids. The outer pollution grid (and meteorological grid) was selected to capture the major distant sources of fires, especially the Pilbara area with the large fires in and around the Karijini National Park in 2006 (see **Figure 6-2**). The outer pollution grid was selected to be also in from the boundary of the meteorological grid boundary to minimise boundary effects on the pollution. The 3 km grid was selected to cover the areas with peak ozone from the new plant and include the nearest residential areas such as Broome, the Coconut Wells area and the Beagle Bay settlement;
- Emissions from fires were entered separately for each pollution grid. For the outer 30 km pollution grid, a 10km emission grid was used, whilst for the 10km pollution grid emissions were entered on a 3 km grid, whilst for the inner 3km pollution grid emissions were specified on a1 km grid such that the emission database would be smaller than the pollution grid resolution;
- For modelling the long range pollution with TAPM-CTM a Eulerian dispersion scheme is used;
- 12 vertical levels for modelling pollution; and
- Use of the Carbon Bond 5 mechanism.

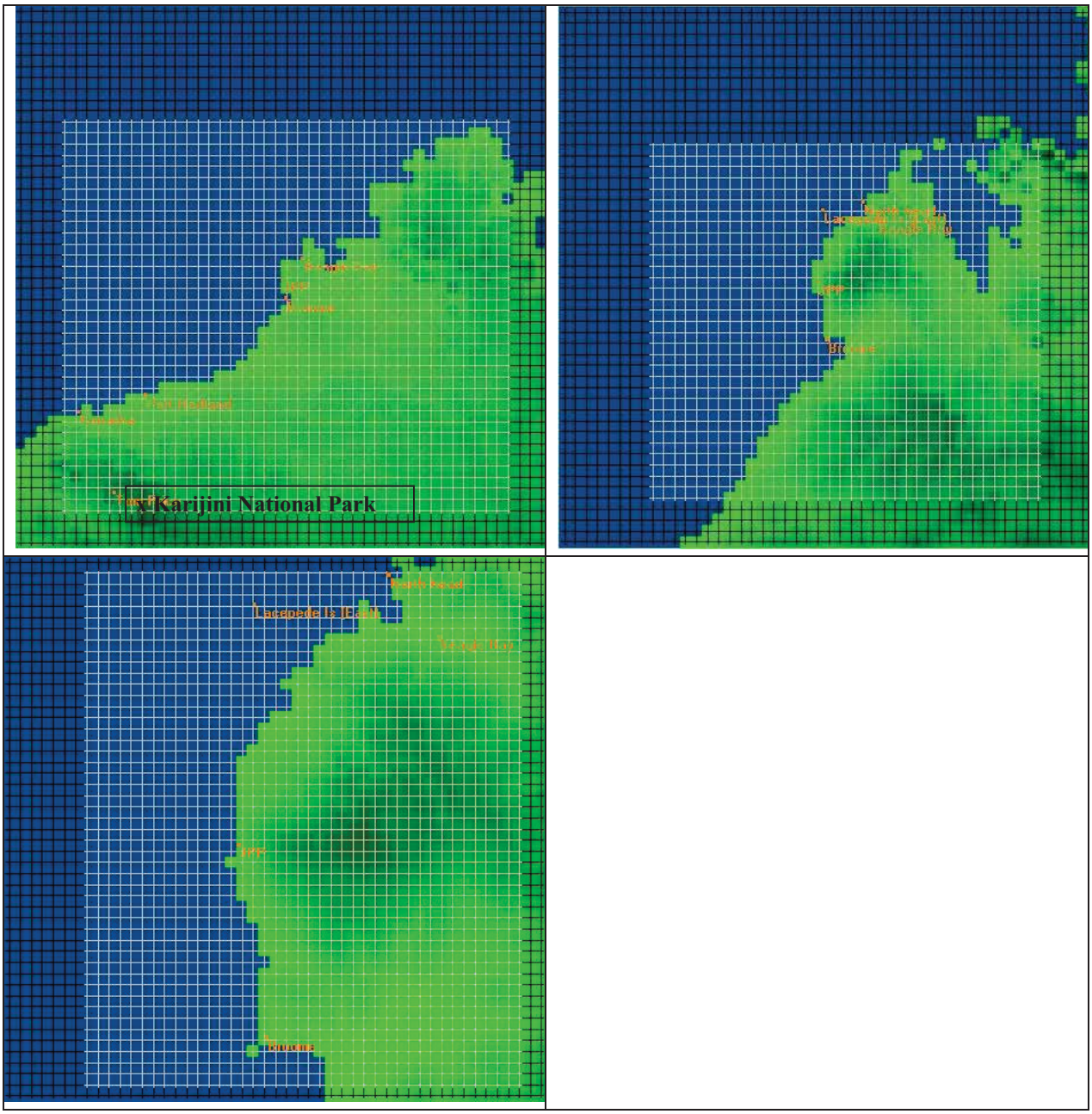


Figure 6-2 TAPM-CTM model Grids for 30km (top left), 10km (top right) and 3km (bottom left) grids. Overall area is meteorological model domain and white squares the pollution model domain.

- Emissions from biogenic and soils and fires are as described in **Sections 3.5.3** and **3.5.4**; and
- Initial and Boundary VOC levels developed through a literature review of available measurements including those from the Burrup rock art study and background aerosol measurements for Australia sites (Galbally et al., 2009 and references therein; Gillett and Cope 2009, Cainey et al, 2007). These levels are summarised in **Table 6.1**.

Table 6.1 Initial and Boundary Concentrations used in TAPM-CTM Modelling

Substance	Average Concentration (ppb)	Substance	Average Concentration (ppb)
Ozone	20	Ethane	0.03
NO	0.1	Olefins	0.02
NO_2	1.0	Toluene	0.02
CO	65	Xylenes	0.01
SO_2	0.1	MEK	0.001
Formaldehyde	0.3	PAN	0.0
Aldehyde	0.0	Methane	1700
Paraffins	0.6	-	-

Specific set ups for TAPM local modelling were:

- Meteorological grid predicted on 30, 10 and 3 km and 1 km nested grids with 33 by 33 grid points;
- Pollution modelled for the inner grid using Lagrangian/Eulerian scheme with a change to Eulerian after 3600 seconds. A larger than usual change over time was specified to ensure that sea breeze fumigation for the very buoyant plumes was predicted using the Lagrangian scheme before switching to the Eulerian scheme; and
- Pollution modelled was conducted over an area 25 by 26 km grid with a fine 500 m resolution. For buoyant plumes a 500 m grid should be fine enough to resolve maximums as the peaks typically occur from 5 to 10 km down wind of the sources where the plumes are well spread.

6.4 Modelling Emissions from Condensate Loading of Ships

Emissions from the loading of condensate to ships will be emitted at a small "stack" or vent about 6m above the ships deck. The emissions have a molecular weight of about 52 g/mol and at an emission temperature of about 40 deg Celsius will be heavier than air. As such, the plume will be negatively buoyant with this negative buoyancy tending to counteract the plume rise that will occur due to its momentum. Within standard dispersion models, negatively buoyant plumes can not be modelled. Therefore in this modelling study the following has been undertaken:

- For the TAPM local modelling, the plume has been modelled with no plume rise with an exit velocity set to zero such that the final plume height is the release height. The TAPM local modelling also included the ship wake effects to simulate the airflow around the ship and increase the dispersion of the plume. Sensitivity tests were conducted modelling the plume as above and assuming the plume density was as air at a temperature of 40 degrees, with the exit velocity of 13.6 m/s. This indicated that at 5 km down wind (edge of the buffer), modelling with no plume rise resulted in 10% higher concentrations, whilst at 15 km down wind there was negligible difference between the two methods. As such, the plume negative buoyancy is most important in the first few kilometres from the source, whilst at the areas of interest for this

assessment (more than 5 km kilometres from the ship loading) the assumption used should be adequate; and

- For the TAPM-CTM modelling as modelling is on a regional scale with a much larger, 3 km grid, and can not include building or ship downwash, the condensate ship emissions were modelled approximately as a stack of height 15 m, diameter of 0.25 m and exit velocity of 5 m/s. This choice results in little plume rise and should provide a reasonable approximation to the regional pollutant concentrations. To confirm this sensitivity studies would be required.

6.5 Plume Merging and Building Downwash

Combined plume rise or plume rise enhancement is often used to account for the effect that nearby plumes will tend to merge and increase the overall plume rise of each individual plume. For the LNG facilities this will occur for:

- The power station with the number of very large exhausts in close proximity; and
- LNG trains with a number of compressor exhausts and also with the large bank of fin fan coolers on top of the LNG train.

An aerial photo of train 4 of the Karratha Gas Plant at Dampier indicates the magnitude of the cooling with 180 fin fan coolers on top of the LNG train covering an area of 180 by 30m.

Figure 6-3 Karratha Gas Plant - Train 4 (Source DOLA Landgate)

This large number of fans for a LNG train actually release greater heat than the nearby refrigeration compressors. For the LIGT style LNG train with two Frame 7 refrigeration compressors, the relevant parameters and heat released in megawatts (MW) and the buoyancy flux are listed in **Table 6.2**.

Table 6.2 Estimates of the Heat Released and Plume Rise Parameters for a LIGT LNG Train

Source	Number Per Train	Stack Diam. (m)	Temp. above Ambient (deg C)	Exit Velocity (m/s)	Total Heat Released (MW)	Buoyancy Flux (m^4/s^3)	Momentum Flux (m^4/s^2)	Equivalent Diameter (Assumes no separation of sources)
Frame 7 Compressors	2	6	200	15	60	535	1,207	8.48
Fin Fan Coolers	180	3	20	12	340	3,024	54,617	40.2
Total						**3,559**	**55,824**	

Table 6.2 indicates that the majority of the buoyancy and momentum from a LNG train are from the fin fan coolers and if considered as a single exhaust they would be equivalent to 40.2m diameter. Therefore the greatest plume rise will potentially be from the coolers and with their close proximity to the compressor exhausts will tend to increase the plume rise from the LNG refrigeration compressors.

For treating stacks that are in a line and not significantly separated the plume merging method of Briggs (1974) is generally used within Australia. This defines the effective stacks (*Ne*) as:

$$Ne = \left[\frac{n+S}{1+S}\right] \qquad \textbf{Equation 6.1}$$

where n is the number of stacks, and S is a dimensionless separation factor:

$$S = 6 \cdot \left[\frac{(n-1)\cdot \Delta s}{n^{1/3}\cdot \Delta z}\right]^{3/2} \qquad \textbf{Equation 6.2}$$

where Δs is the stack separation and Δz is the plume rise for an individual plume. The rise enhancement factor E_N is then:

$$E_N = Ne^{1/3} \qquad \textbf{Equation 6.3}$$

with the enhanced plume rise Δz_E

$$\Delta z_E = E_N \,.\, \Delta z \qquad \textbf{Equation 6.4}$$

This method has been used in the past for LNG assessments (e.g. Hurley et al, 2004) for the Karratha Gas Plant. They calculated enhancement factors of 2.7 and 2.1 for example for the power generators and compressors for Trains 1 to 3. The results of the modelling showed that the model over-predicted concentrations close to the nearest monitor 4.5 km away whilst performing better at more distant monitors. At the time it was considered that some mechanism was occurring such that for the majority of the time the plumes were passing over this monitor. This interpretation is consistent with plume merging and enhancement from the condenser plumes that can occur as outlined above. Not only would

plume rise enhancement be occurring for the condenser and plume on train 1 only, but for winds across the three trains (i.e. a northerly) there would be some enhancement from the plumes between trains.

For this study, as the plume merging equations are not developed for the configuration of sources of different buoyancies it was considered that the fin fan coolers could not be incorporated in the calculations in a rigorously defensible way. To incorporate these further testing possibly using computational fluid dynamic models would be required to estimate the degree of plume merging. Preliminary work has been conducted for a similar facility indicating that considerable plume merging does occur but this could not be extrapolated to these configurations.

Therefore estimates of the plume enhancement factors were only conducted for the gas turbines and compressors and boilers. These are estimated using **Equations 6.1** to **6.3** and are presented in **Table 6.3**.

Table 6.3 Estimates of Plume Enhancement

Source	Number in Row	Stack Separation (m)	Diameter (m)	Average Plume Rise (m)	S Factor	Ne	En	Diam. Increase	Equiv. Diam (m)
LM2500	8	15	3.72	167	1.1	4.4	1.639	2.098	7.81
LM2500 with CO_2 RU	8	15	3.72	167	1.1	4.4	1.639	2.098	7.81
Frame 6	4	25	4.97	216	0.6	2.86	1.419	1.691	8.40
Frame 6	5	25	4.97	216	0.8	3.17	1.469	1.78	8.84
Frame 6	7	25	4.97	216	1.3	3.59	1.552	1.896	9.42
Frame 6	8	25	4.97	216	1.5	3.75	1.553	1.936	9.61
Frame 7	2	100	6.0	215	1.3	1.43	1.126	1.194	7.17
Frame7 with CO_2 RU	2	100	6.0	211	1.4	1.42	1.124	1.191	7.15
Frame 9 (15 Mtpa case)	4	50	8.61	327	0.9	2.55	1.367	1.598	13.8
Frame 9 (50 Mtpa case)	5	50	8.61	327	1.3	2.75	1.401	1.659	14.3
Boiler (16 Mtpa case)	4	50	3.43	123	4.0	1.60	1.168	1.263	4.33
Boiler (50 Mtpa case)	5	50	3.43	123	5.6	1.61	1.172	1.269	4.35
Boiler (50 Mtpa case)	6	50	3.43	123	7.1	1.62	1.174	1.272	4.36

Note: Average plume rise derived from one month of TAPM modelling (July 2006).

In modelling the equivalent diameter was used for those stacks that the plume enhancement was calculated, with the exit temperature and velocity unchanged.

The model validation study by Physick and Blockley (2001) also has implications in that building downwash was not of importance for the LNG trains and was not considered. According to modelling guidance "rules of thumb" downwash should be considered when nearby structures are more than 40% of the stack height. With the height of the main structure of the LNG train about 25m and stack height of 40m, this would suggest this should be considered. However the LNG structures, particularly near the top is reasonably open and not a bluff body upon which the empirical down wash formula was based. Note, that building downwash for ships was included.

6.6 Modelling Flares

Plume rise from flares were modelled using the USEPA Screen3 method which approximates the plume rise by considering it as a pseudo stack of exit velocity 20 m/s and exit temperature 1000 deg C with

55% of the heat released contributing to buoyancy. The other heat is lost as radiant heat. For the three flare cases considered the equivalent diameters were estimated as listed in **Table 6.4**.

Table 6.4 Estimates of Pseudo Stack parameters for Flare Releases

Flare Case	Frequency	Gas Flow (kg/s)	Heat Released (Btu/s)	Equiv Diam. (m)
Operational Flare	80th percentile of Continuous Release	0.75	2.9 x 10^4	1.14
Start Up Flaring	5 times per year per train for up to 15 hours	41.7	1.61 x 10^6	8.5
Emergency Case	1 in 10 years for < 1 hour	514 (ave for hour)	1.03 x 10^7	21.6

6.7 Estimating the NO_2 Fraction within NO_X for Local Modelling

To estimate the proportion of NO_X in the form of NO_2 for the local model (TAPM modelling), the ozone limiting method (OLM) as developed by Cole and Sumerhays (1979) and as specified by the USEPA and the NSW modelling regulations (DEC NSW, 2005) was used. Note in TAPM-CTM the NO2 is explicitly calculated. This method estimates the NO_2 concentrations as:

$$[NO_2]_{total} = 0.1 \times [NO_2]_{pred} + \min\{(0.9 \times [NO_X]_{pred} \text{ or } (46/48) \times [O_3]_{bkgd}\} + [NO_2]_{bkgd} \quad \textbf{Equation 6.5}$$

Where:

- $[NO_X]$ is the predicted NO_X concentration in µg/m^3;
- $[O_3]$ is the measured ozone concentration in µg/m^3;
- NO_2 is the NO_2 concentrations in µg/m^3; and
- "*pred*" refers to predictions and "*bkgd*" refers to measured background concentrations.

A coefficient of 0.1 has been used in equation 2 because NO_X emissions from gas fired boilers and gas turbines are typically less than 10%. For the background ozone and NO_2 values, concentrations of 25 ppb (53.5 µg/m^3) and 1.5 ppb (3.1 µg/m^3) have been used respectively from their 70th percentile values (see **Table 9.3**).

6.8 Modelling Sources from Broome

The following provides further details on modelling the Broome sources listed in **Section 3.5.1.**

VOC emissions as estimated from the DEP Karratha and Dampier study (DEP, 2002) were speciated to individual substances such as formaldehyde according to (DECC, NSW, 2008). VOC emissions from vehicles were speciated with the evaporative emissions taken from the petrol evaporation profile, with the exhaust VOCs speciated based on 70% petrol usage for Karratha (DEP, 2002) and that there are approximately 3 times the amount of VOC emissions from petrol exhausts as diesel exhausts

(Environment Australia, 2000, Table 11). Therefore approximately 87% of VOC exhaust emissions were assumed from petrol engines. NO_X emissions were taken as 90% NO and 10% NO_2 which is typical if not conservative (high) for the fraction of NO_2 in combustion sources. Emissions were spatially distributed approximately by population density in the town of Broome and assigned as a point source at height of 10m. With TAPM - CTM these are then spread uniformly throughout the grid cell in which they are located and up to the height of the first grid cell.

As required for photochemistry modelling the emissions were varied by the hour of day according to the motor vehicle variation determined for Karratha (DEP, 2002). This results in hourly emissions for the period 9am to 3pm being 8.5% of the daily emissions, whilst for the hour ending at 2am the emissions were only 0.2% of the daily emissions. The use of the motor vehicle profile to scale all area sources is considered acceptable given that motor vehicle are the dominant source and that many of the other sources follow a similar pattern.

For the Broome power station, the generator stacks are grouped by three with stacks less than 1m apart. As such for modelling 100% plume enhancement from each group of three was assumed (they behaved as one stack) with the power station modelled as one stack, with an effective diameter of 0.55m, velocity of 35 m/s but with all emissions from the plant. Emission from the power station were assumed at the maximum licence condition (as per for the LNG plant) with emissions constant. This will overstate the ground level concentrations from the plant on the majority of days.

6.9 Sensitive Receptors

Sensitive receptors defined here as residential areas or areas where people may congregate outside the BLNG buffer are listed in **Table 6.5**.

Table 6.5 Sensitive Receptors used for Comparison against Ambient Criteria

Location Description	Easting GDA94 (m)	Northing GDA94 (m)	Approximate Distance to BLNG (km)
Broome (Broome Airport)	418,650	8,015,400	48 km to South
Coconut Wells	416,530	8,030,570	34 km to South
12 Mile	433,100	8,025,150	44 km to SSE
Kilto Station	469,760	8,044,000	61 km to ESE
Beagle Bay Settlement	464,500	8,122,400	76 km to ENE
Country Downs	454,380	8,089,850	48 km to NE
Willie Creek Pearl Farm	416,730	8,030,630	27 km to South
BLNG Workers Accommodation (Approximate)	416,000	8,059,000	6 km to SE

6.10 Modelling Exceedances of Intermittent Sources

To model accurately the number of exceedances of a given criteria for emission sources that vary intermittently, a probabilistic approach was undertaken as recommended and used for the Kwinana EPP by the DEC.

In this approach the total number of exceedances (N_T) of a criteria is determined from:

$$N_T = P_1N_1 + P_2N_2 + P_3N_3 \text{ etc} \qquad \textbf{Equation 6.6}$$

Where:

P_1 is the probability of the 1st emission scenario occurring, P_2 the second etc, with all probabilities adding to 1; and

N_1 is the number of exceedances predicted for the 1st scenario when running the model for a year with that emissions occurring continuously.

For a 50 Mtpa Precinct using the probabilities of TCUs not operating (see **Table 3.3**) the total number of exceedances equates to:

N_T = 0.349 x (Exceedances with zero TCUs offline) +
0.387 x (Exceedances with 1 TCUs offline +
0.194 x (Exceedances with 2 TCUs offline) +
0.057 x (Exceedances with 3 TCUs offline) +
0.011 x (Exceedances with 4 TCUs offline) +
0.0015 x (Exceedances with 5 TCUs offline) +
0.00014 x (Exceedances with 6 TCUs offline)

7 Model Verification

7.1 Overview

TAPM and TAPM-CTM have been verified in numerous sites around the world (Hurley et al, 2004 and 2008) and (Cope et al, 2009b and Gillett, and Cope, 2009). In particular TAPM has been validated extensively for the Dampier and Karratha area as described in (Physick and Blockley 2001, Hurley, et al, 2003 and Hurley et al, 2004).

For this study to confirm the suitability of TAPM and TAPM-CTM to predict concentrations in the area, the models were verified in two stages. The first stage was to verify the meteorological parameters predicted by TAPM, comparing model predictions against available meteorological observations to confirm that it predicts the correct winds and other parameters in the region. The second stage was to verify the predicted concentrations from TAPM-CTM against monitored ozone and NO_2 data to confirm that the combination of meteorology, emission estimates, dispersion and chemical reactions is realistic. That is, it verifies the overall scheme which importantly for this case includes emission estimates from fires.

7.2 Validation against Meteorology

As discussed in **Section 5.2**, good quality meteorological data within the region are available at Broome Airport (BoM) and the Department of State Development sites at Gourdon Bay, Lacepede Island and North Head. Of these the Broome Airport and Lacepede Island data are considered to be the best for model validation due to their siting of the wind sensors and also as they are the closest sites to the area of interest, excluding the West Roebuck site which is considered unsuitable due to the proximity of trees.

Data from the Lacepede Islands (and Gourdon bay and North Head) sites is only available from October 2008 onwards, so the 12 month meteorological validation has been conducted from October 2008 to September 2009.

Observed and predicted wind roses for Broome Airport and the Lacepede Islands are presented in **Figure 7-1** and **Figure 7-2**.

Observed **Predicted (TAPM)**

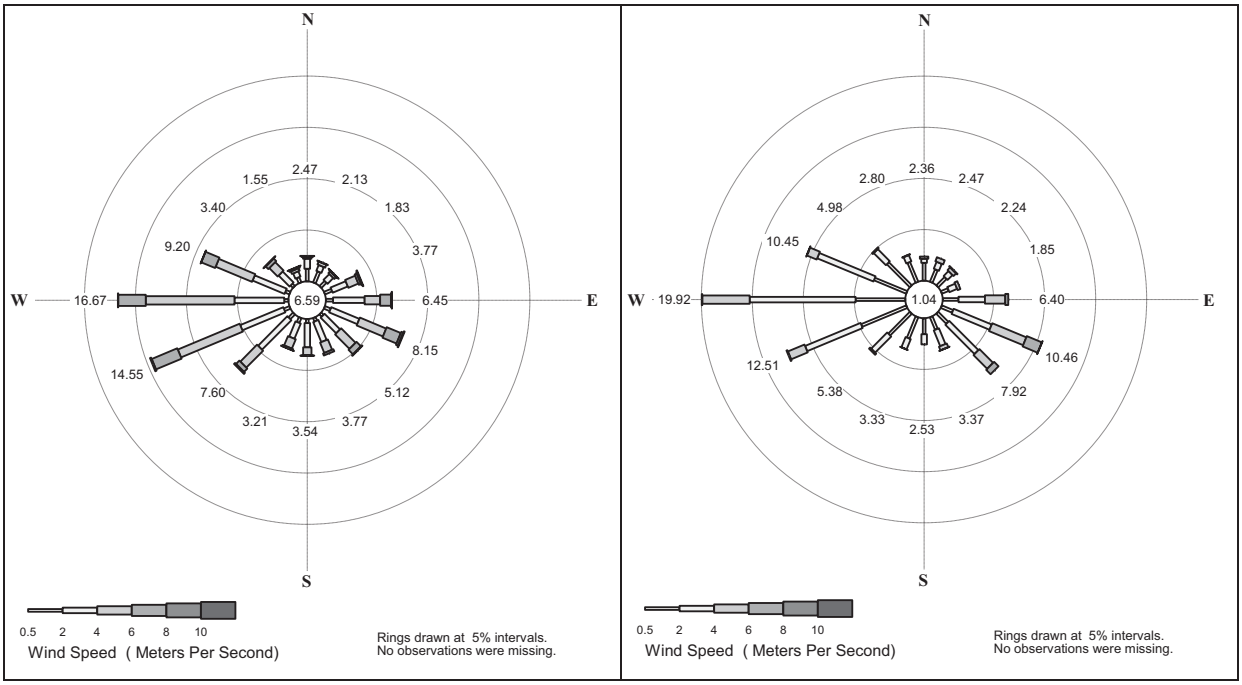


Figure 7-1 Observed and Predicted Annual Wind Roses at Broome Airport (1 Oct 2008 to 30 Sep 2009)

Observed **Predicted (TAPM)**

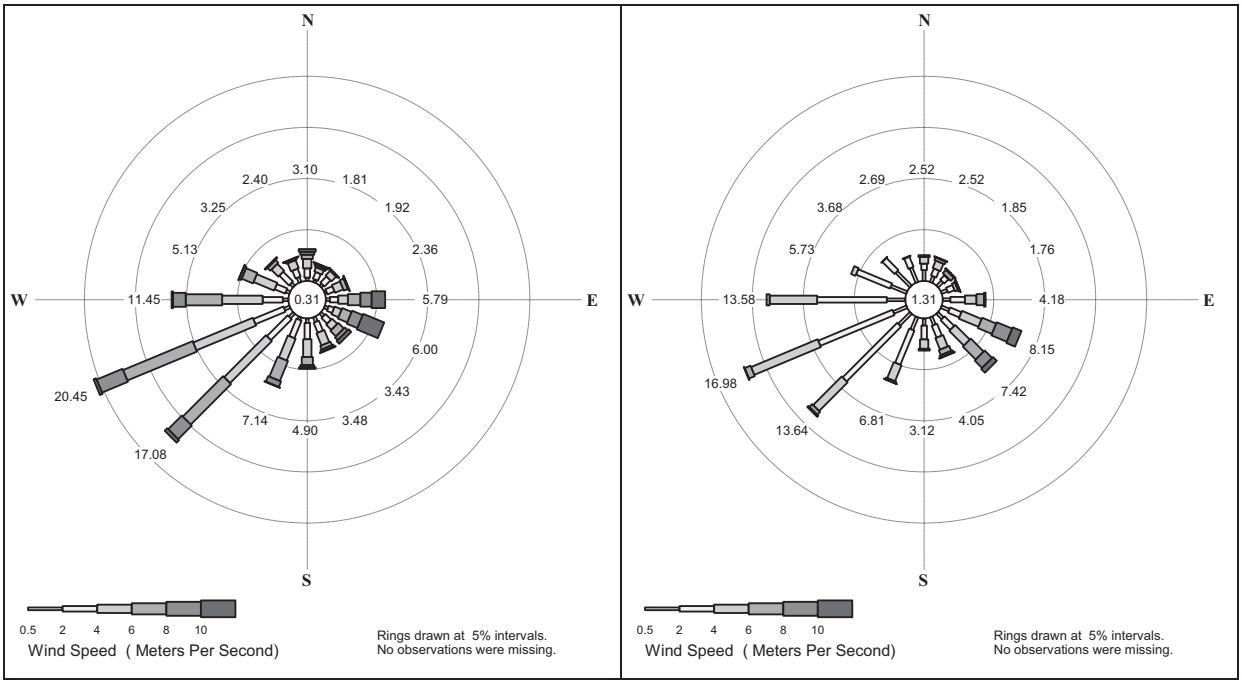


Figure 7-2 Observed and Predicted Annual Wind Roses at Lacepede Island (10 Oct 2008 to 30 Sep 2009)

Figure 7-1 and **Figure 7-2** demonstrate good agreement between the observed and predicted wind directions with the model also reproducing the wind variation between sites with more westerly winds at Broome and more south westerly winds at the Lacepede Islands. The wind speeds at both sites are

however not as well predicted with TAPM generally predicting lighter winds. This is better illustrated in the wind speed distribution plots presented in **Figure 7-3** and **Figure 7-4**.

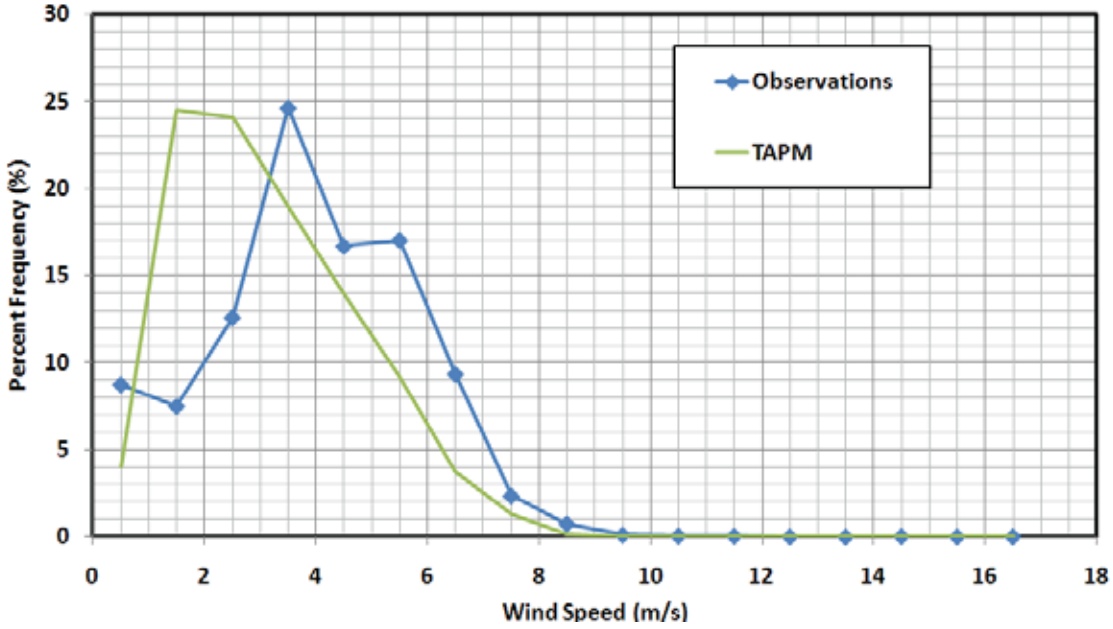


Figure 7-3 Observed and Predicted Annual Wind Speeds At Broome airport (1 October 2008 to 30 Sep 2009)

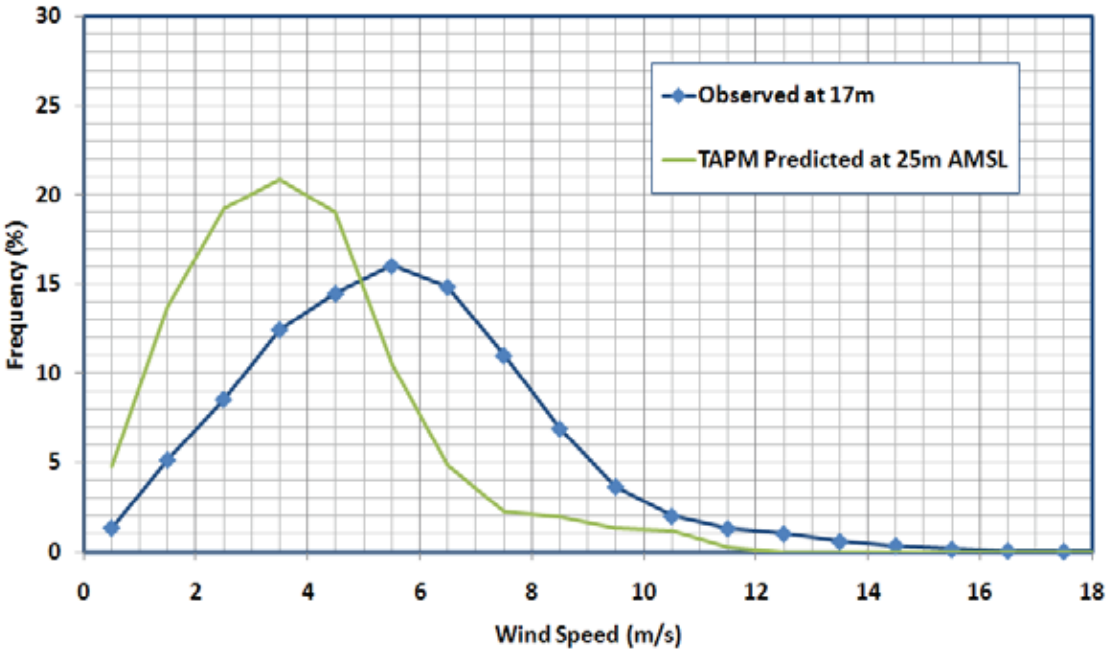


Figure 7-4 Observed and Predicted Annual Wind Speeds at Lacepede Island (10 Oct 2008 to 30 Sep 2009)

This under-prediction of the wind speeds near the surface is generally observed by TAPM for sites now, though TAPM is found to better predict the wind speeds aloft at 100 to 200m (Hurley et al, 2008). As such, for the plumes here which are generally over100m above ground level the winds should be reasonable. With lower wind speeds there may be a tendency for the model to over-predict the concentrations.

Ambient air temperatures which are less important in terms of dispersion from the very buoyant plumes are reasonably well predicted by TAPM as indicated by the temperature cross plots in **Figure 7-5** and **Figure 7-6**.

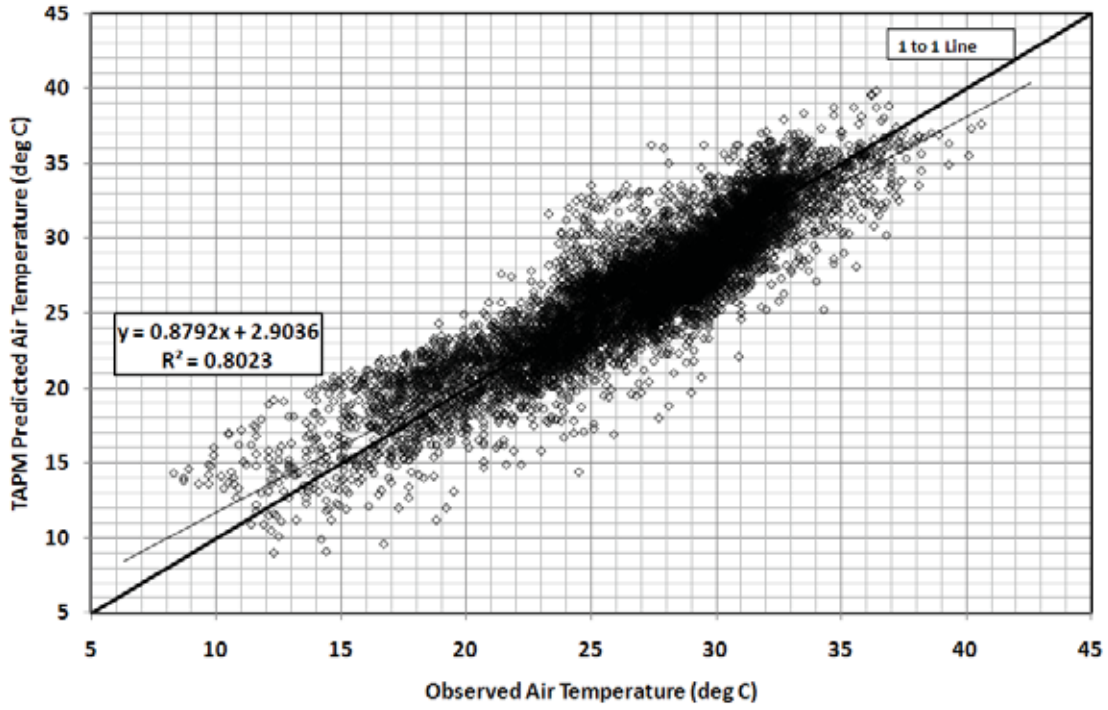


Figure 7-5 Observed and Predicted Air temperatures at 1.2m at Broome airport (1 October 2008 to 30 September 2009)

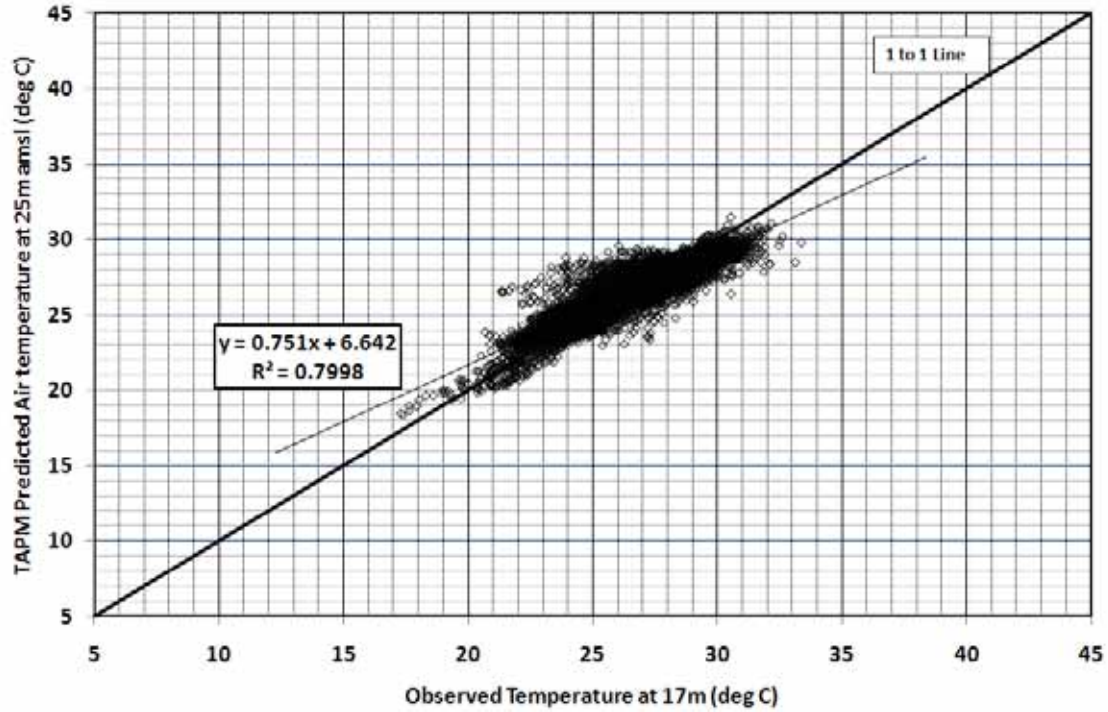


Figure 7-6 Observed and Predicted Air temperatures at Lacepede Islands (10 October 2008 to 30 September 2009)

A summary of the observed and predicted winds and temperatures is also presented in **Table 7.1**. This indicates (using the IOA and Correlation coefficient) that both the temperatures and winds are not as well predicted by TAPM for this region as for other TAPM modelling studies within Australia.

Table 7.1 Summary Statistics of Model Agreement with Observations

	Mean Observations	Mean Modelled	Standard Deviation Observations	Standard Deviation Modelled	CORR	RMSE	IOA
Lacepede Islands							
Wind Speed	5.66	3.9	2.6	2.1	0.66	2.64	0.71
East West - Component	-1.65	-1.06	4.8	3.5	0.81	2.92	0.87
North South Component	-1.56	-1.11	3.2	2.2	0.69	2.36	0.80
Temperature	26.7	26.7	2.3	1.9	0.87	1.12	0.93
Broome Airport							
Wind Speed	3.85	3.1	1.9	1.6	0.59	1.79	0.73
East West - Component	-1.18	-0.63	3.6	3.0	0.85	1.98	0.91
North South Component	-0.63	-0.35	2.0	1.5	0.56	1.75	0.73
Temperature	26.9	26.6	4.6	4.5	0.89	2.13	0.94
Perfect Agreement	NA	NA	NA	NA	1.0	0.0	1.0
Range reported in Hurley et al (2008) – Wind Speed	2.0 – 4.0	2.2 – 3.7	1.5 – 1.9	1.2 – 1.6	0.65 - 0.77	1.3 – 1.4	0.77 - 0.84
Range reported in Hurley et al (2008) – Air Temperature	14.6 – 21.3	14.9 – 21.4	5.0 - 6.0	4.7 – 5.8	0.90 – 0.94	1.7 – 2.8	0.94 - 0.97

See Hurley et al (2008) for a full description of the various statistics. CORR Pearson correlation coefficient, RMSE is the root mean square error, IOA is the index of agreement.

7.3 Validation against Observed Pollution Levels

For the model validation there are no suitable ambient air monitoring data available within the study region. Particulate monitoring data was undertaken from October 2008 but due to issues with the data was not available or of suitable quality for this study. Additionally this monitoring was undertaken with DustTraks which are not an air quality grade instrument and therefore there are some uncertainties with the data. It is noted that particulate and some VOC measurements are to be conducted at James Price Point from January 2010.

7.3.1 Verification of Pollutant Levels from Fires

As the method used to predict pollutant levels from fires for use as background levels is new, some form of model verification was deemed necessary. With no monitoring data within the Kimberley region it was considered that verification for a nearby area with similar fire regime would provide similar assurance. For this verification study the comparison was undertaken for the Karratha Dampier area within the Pilbara (650 km to the SW) as this was the closest region with ozone monitoring sites and the impact from fires is similar with extensive area burnt within the Pilbara for the September to November period.

For this validation TAPM-CTM was run using the same methodology as for the Dampier Peninsula modelling, with the same background ambient air concentrations and the same methodology used to derive fire emissions. As the fire emissions were readily available for 2006, this year was used with the 2006 meteorology used to derive 2006 pollution statistics. These 2006 statistics were then compared to the 1999 monitoring data as this is the only complete year of ozone levels available their and this year has already been already extensively studied (Physick and Blockley, 2001, Hurley et al, 2004). It is noted that comparing two separate years does introduce some difficulties in that the frequency of fires and therefore resultant pollutant levels can vary significantly from year to year in the Pilbara. The yearly variation in area burned is presented in **Figure 3-1** where it is seen that 1999 was an above average for fires whilst 2006 had the second highest area burned in a year after 2000. Considering the area burned on a monthly basis (**Figure 7-7**), 1999 had one of the worst months on record (October 1999) with this only being slightly lower than the peaks months recorded in 1997, 2000 and 2006. Therefore 2006 is an extreme fire year with two months of large area burned, whilst 1999 is an above average year, with one month of fires that is slightly less than an extreme worst case month. Therefore peak pollutants levels may be similar from both years though 2006 will probably have more high pollutant levels from smoke.

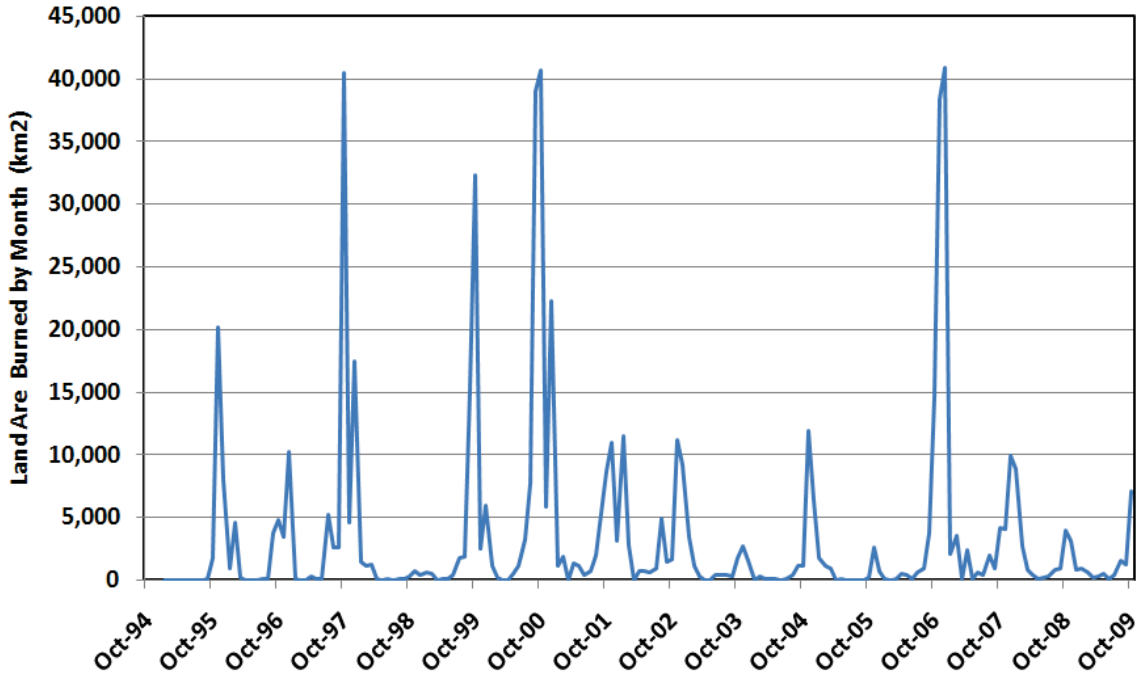


Figure 7-7 Land Area Burned by Month in the Pilbara

Observed ozone, NO_2 and CO concentrations for the years 1999 and model predicted TAPM-CTM predictions for the year 2006 respectively are presented in **Figure 7-8** to **Figure 7-10**. Industrial impacts were removed from the observations by:

- As the Dampier ozone (also CO) observations have significant impacts from Burrup industry all hours with wind from the north (15 to 80 degrees) were removed with all hours with north westerly wind (270 to 360 degrees) removed when the wind was from the east (15 to 120 degrees in any of the previous 5 hours. This was to remove times when a sea breeze developed after an easterly and the Karratha Gas Plant plumes were blown back across the region as

commonly happens. Additionally the 18 days that were ascribed to fires by Physick and Blockley (2001) were retained in the data base. Physick and Blockley, determined these days by their high 24-hour PM_{10} concentrations as well as high ozone levels. The results is that all hours with ozone levels greater than 50 ppb were attributable to fires.; and

- The observed NO_2 data was more clearly impacted from local sources than the ozone or CO data with high concentrations from winds from 30 degrees (Karratha Gas Plant) and SE from what was considered to be locomotives working on the Parker Point car dumper railway line. As such, to remove industry plumes only data from 15 degrees through north to 185 degrees (essentially winds with a westerly component) was considered to be from background sources.

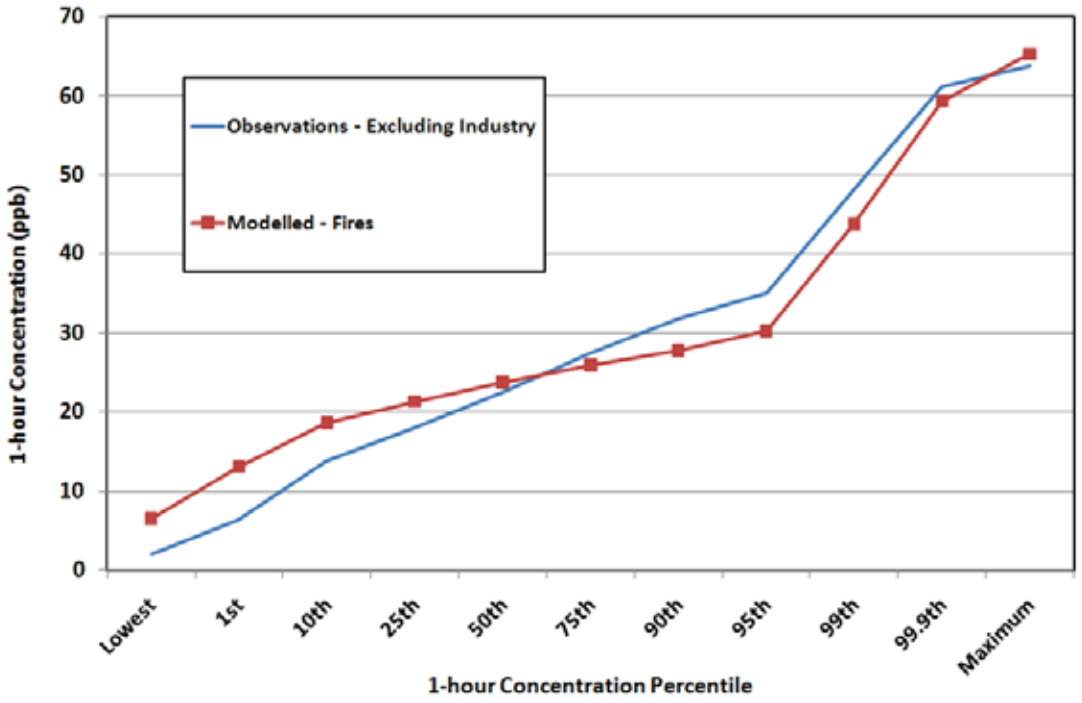


Figure 7-8 Observed 1-hour Ozone levels at Dampier for 1999 and predicted levels for 2006 from TAPM-CTM and inclusion of Pilbara Fires.

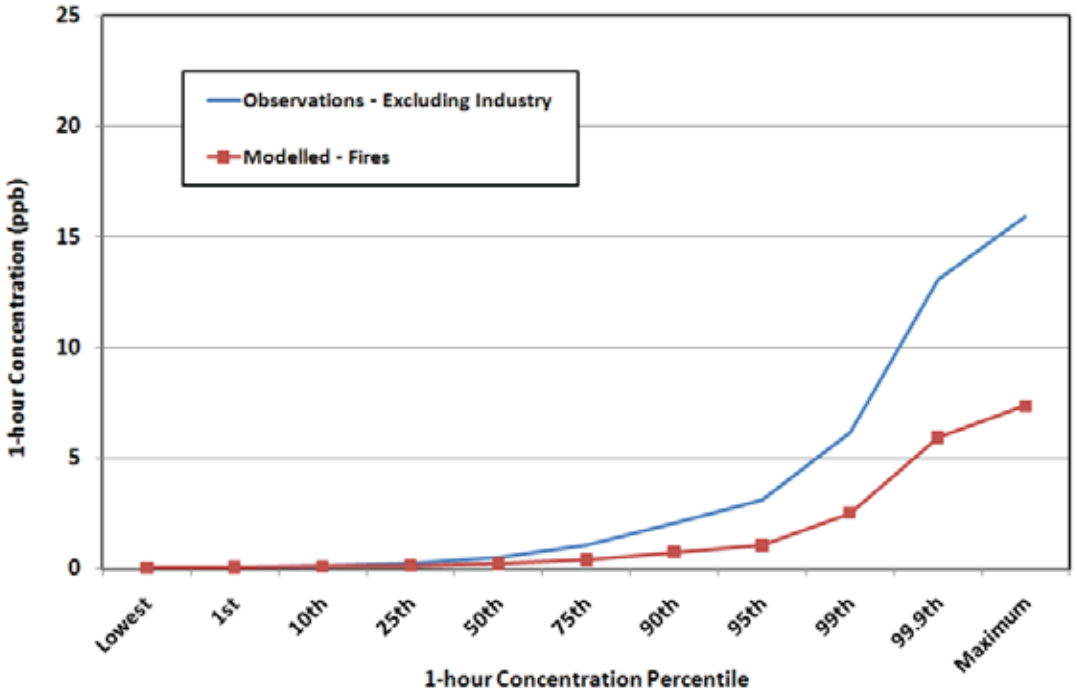


Figure 7-9 Observed 1-hour NO_2 levels at Dampier for 1999 and predicted levels for 2006 from TAPM-CTM and inclusion of Pilbara Fires.

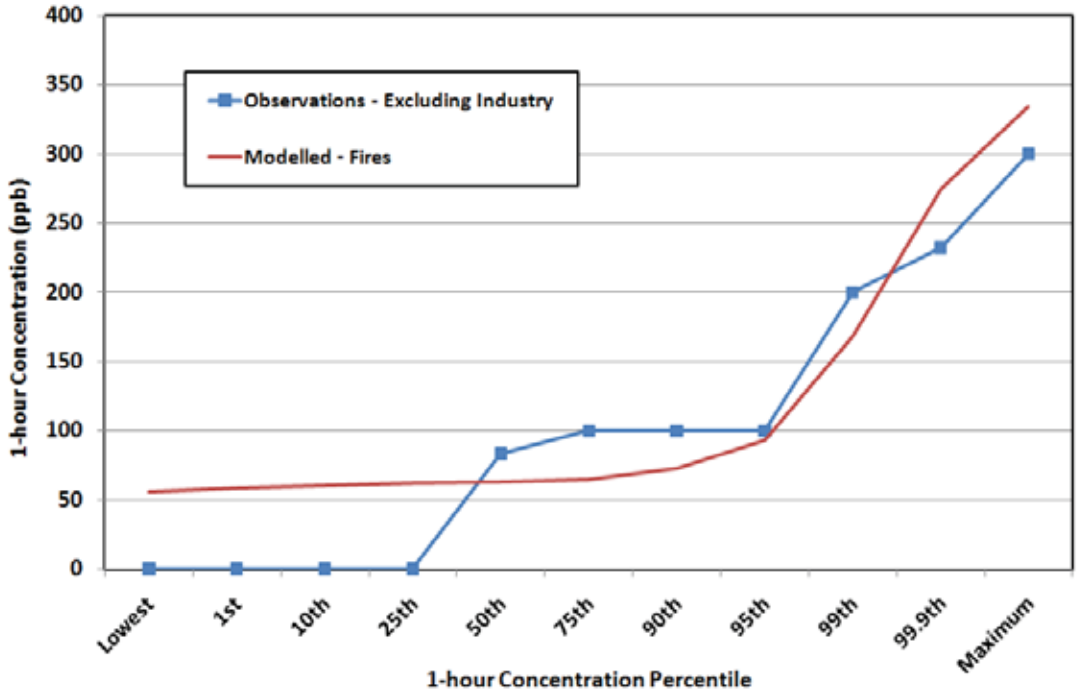


Figure 7-10 Observed 1-hour CO levels at Dampier for 1999 and predicted levels for 2006 from TAPM-CTM and inclusion of Pilbara Fires.

The comparisons noting that the model and observations are for different years and the difficulty in removing industry impacts, show the model within 10% for ozone, over-predicting slightly for CO, whilst under-predicting by a factor of 2 for nitrogen dioxide. The slight over-prediction is consistent with higher areas burnt in 2006 where higher and certainly more frequent high ozone impacts would

occur. The under-prediction in NO_2 may be due to local sources contributing more to concentrations as these are more difficult to remove from the data base as relatively fires make a smaller contribution than industry, unlike for ozone. Therefore overall the comparison gives some confidence that the modelling system for fires (meteorology, emissions and chemistry) are providing reasonable predicted concentrations.

7.3.2 Verification of Pollutants Levels from Industry in 1999

Apart from verifying the model against pollutant levels from fires, the model was also verified for industry impacts. Sources from industry impacts sources were modelled assuming constant emission rates as specified in Hurley et al (2004). Plume rise enhancement as used by Hurley et al (2004) was however not incorporated due to an oversight (see below for a discussion of the likely effects). The results are presented in **Figure 7-11** to **Figure 7-12** for ozone and NO_2. CO was excluded as the industry sources make a relatively small contribution and are "swamped" by other sources making it extremely difficult to derive an industry only observational data base.

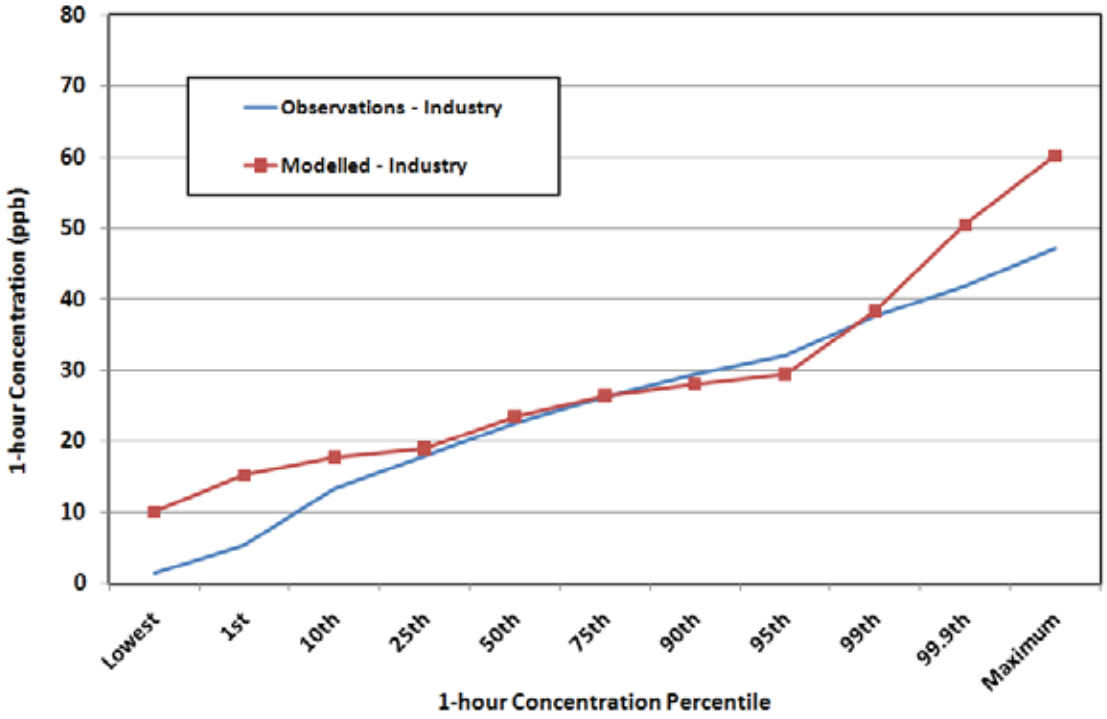


Figure 7-11 Observed 1-hour Ozone levels at Dampier for 1999 and predicted from TAPM-CTM from Industry

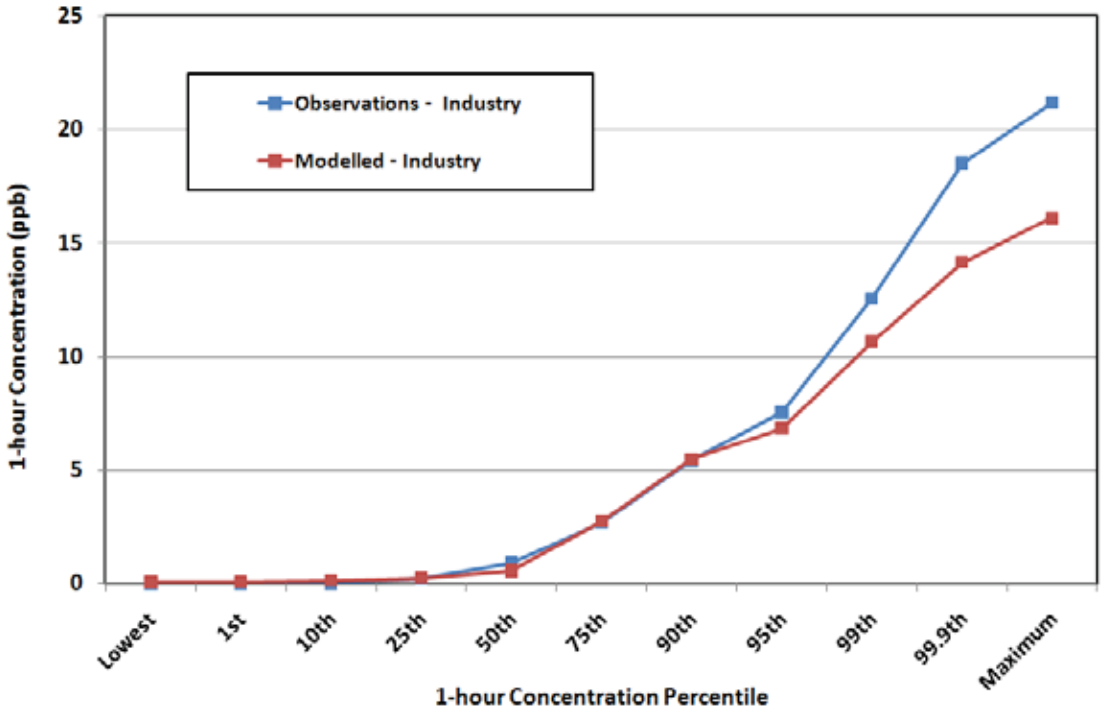


Figure 7-12 Observed 1-hour NO_2 levels at Dampier for 1999 and predicted from TAPM-CTM from Industry.

Figure 7-11 to **Figure 7-12** indicate that the model over-predicts the higher percentile ozone concentrations by about 25% and under-predicts the NO_2 concentrations by about 25%. The over-prediction in ozone is to be expected as plume rise enhancement was not included and the model assumed continuous emissions. The under-prediction in NO_2 is expected as pollution modelling was only on a 3 km grid. The highest concentrations of NO_2 occur when the plume comes directly from the Karratha Gas Plant with a smaller grid resolution required to predict the narrower plumes that occur with travel time of less than an hour. Maximum ozone levels on the other hand generally occur for winds from the NW when the plume has been advected in a morning easterly and is brought back to Dampier in the afternoon in a north-westerly sea breeze and as a result is a broader plume. When the wind is directly from the Karratha Gas Plant to Dampier, ozone levels are usually low. Therefore for regional ozone a 3km grid resolution is often used for resolving the majority of the peak ozone levels. For assessing the peak NO_2 levels a finer grid resolution is required as these occurs within1 to 2 hours travel time from the sources.

8 Predicted Regional Concentrations

This section presents results from the regional modelling using the model TAPM-CTM. Concentrations were predicted for ozone, NO_2, CO, formaldehyde and acetaldehyde and in some cases particulate. These concentrations are then compared to the criteria adopted and conclusions drawn as to the impacts of the proposed BLNG.

8.1 Introduction

An assessment of the predicted concentrations for the proposal has been carried out in accordance with the WA DEC modelling guidance (DoE, 2006). This requires predicted concentrations from:

1. Existing sources;
2. The proposed precinct alone; and
3. Cumulative concentrations from the proposed precinct and existing sources.

For most regional smog assessments, the predictions of existing sources have neglected the contribution from fires such that the total cumulative impact from all sources is not modelled. This may be acceptable if the contribution from fires is small. However, for the Kimberly region fires are by far the greatest cause of high air pollutant days and therefore it is considered that they need to be included to adequately determine both existing and cumulative concentrations.

8.2 Predicted Concentrations from Existing Sources

Existing sources that have been included in the modelling include those from:

- The town of Broome including, vehicles, Broome power station and other small sources, see **Section 3.5**);
- Biogenic emissions from vegetation and soils; and
- Emissions from fires.

The predicted concentrations from these sources are presented in the following sections, with **Section 8.2.1** providing snapshots of plumes from these sources to illustrate typical plume dispersions from various sources, and **Section 8.2.2** providing annual concentration statistics.

8.2.1 Case Studies

To indicate typical plume dispersal from existing sources and the resultant concentrations, two periods are presented showing the plume from the town of Broome and that from large fires.

Figure 8-1 presents a plot of the predicted ozone levels at 1100 WST 2nd August 2006 showing an ozone plume originating from Broome emissions that is being blown by a southerly wind to the west of James Price Point and then further north. The predicted maximum ozone levels is 33 pbb which is about 5 to 7 ppb higher than the background ozone levels indicating the small, but not negligible contribution that the Broome emissions make. Note the Broome emissions includes an expanded Broome Power Station.

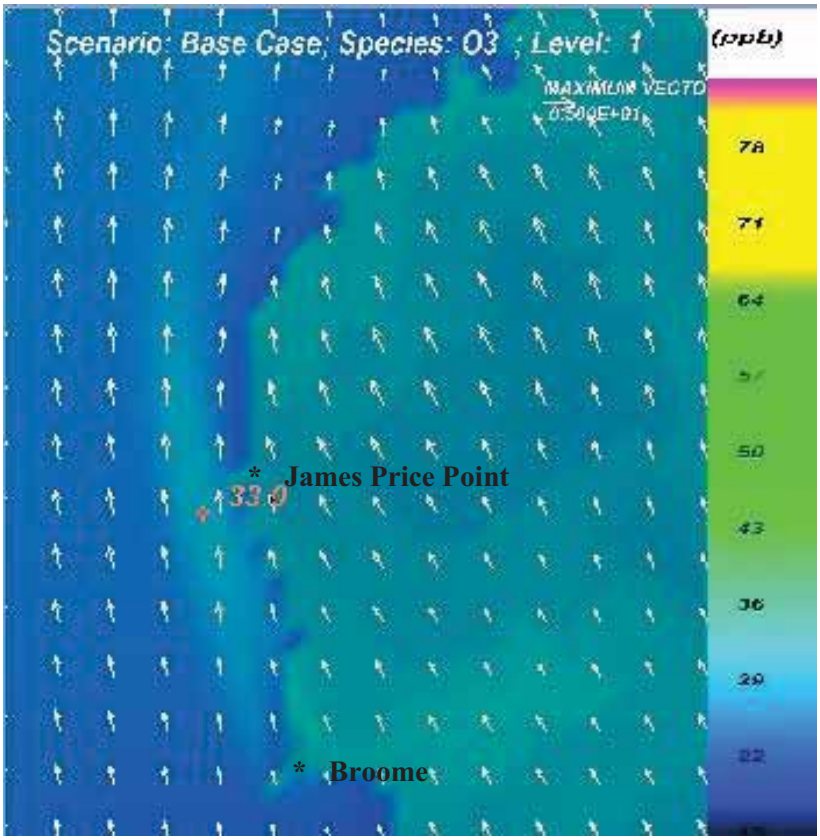


Figure 8-1 Predicted O_3 levels (ppb) at 1100 WST 2 August 2006 from Existing and approved Sources. Inner Grid.

The influence of fires on air quality in the Kimberley is much greater. **Figure 8-2** presents a snapshot of predicted pollutant levels at 1300 WST on the 13th August 2006, which is in a period with extensive fires that lasted for many days on the peninsula. **Figure 8-2** present snapshots of NO_2, ozone, elemental carbon (a component of the particulate) and the NO emissions from fires for that hour. The emissions show the large extent of fires on the Dampier peninsula to the east and north east of Broome, with the plumes being blown by easterly winds across Broome and out to sea. The maximum predicted NO_2 and ozone levels are estimated at 32 and 44.5 ppb respectively. The maximum elemental carbon concentration (which is only one of the components of $PM_{2.5}$) is predicted to be 10.9 $\mu g/m^3$.

The satellite image for the fire event is also presented in **Figure 8-3** showing the large extent of the fires and smoke plumes at this time, which is in good agreement with the plume positions estimated by TAPM-CTM.

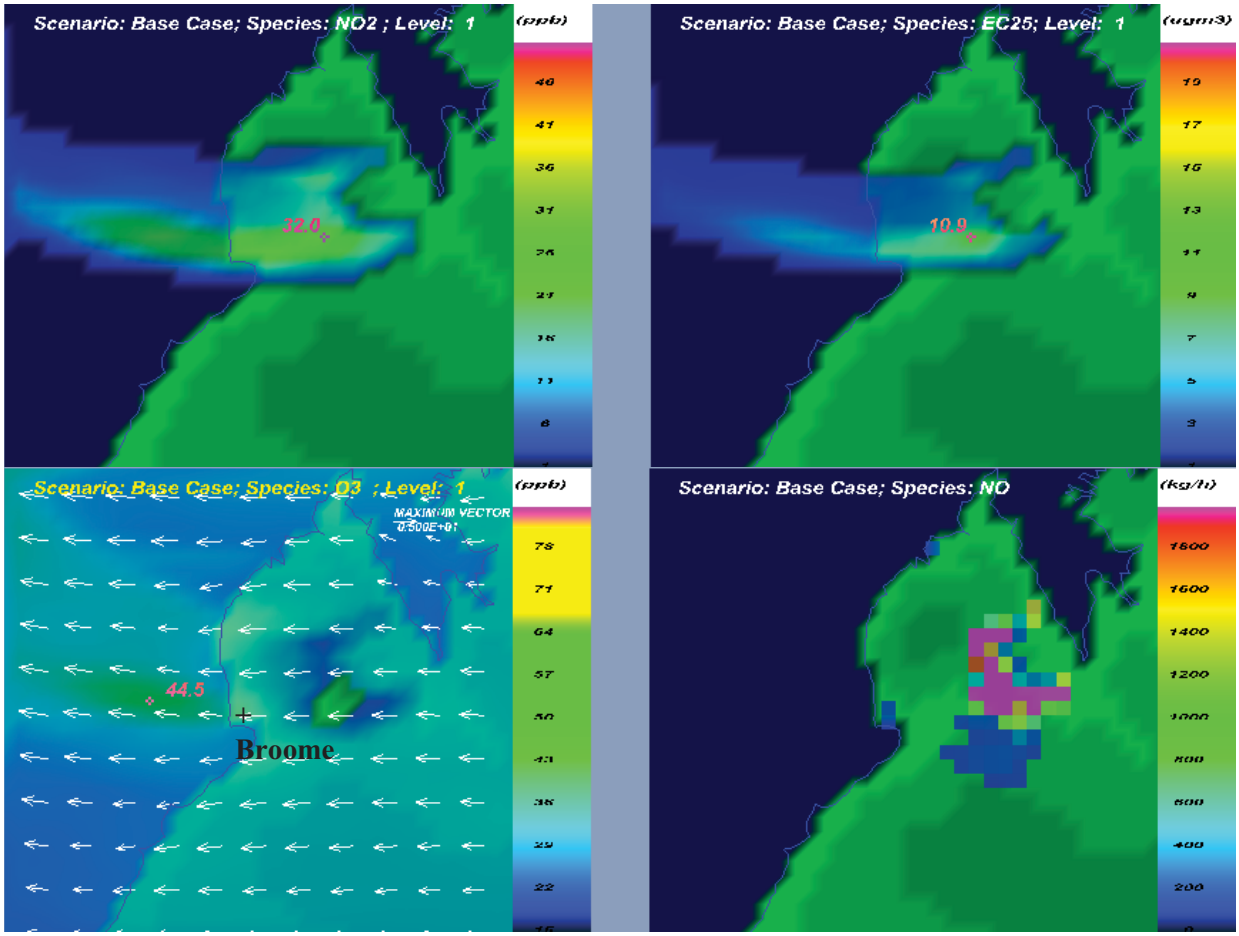


Figure 8-2 TAPM-CTM Predicted NO_2 (ppb, top left), Elemental Carbon (µg/m^3, top right), ozone (ppb, bottom left) and emissions of NO (kg/hr, bottom right) for 1300 WST 13th August 2006. 10km grid.

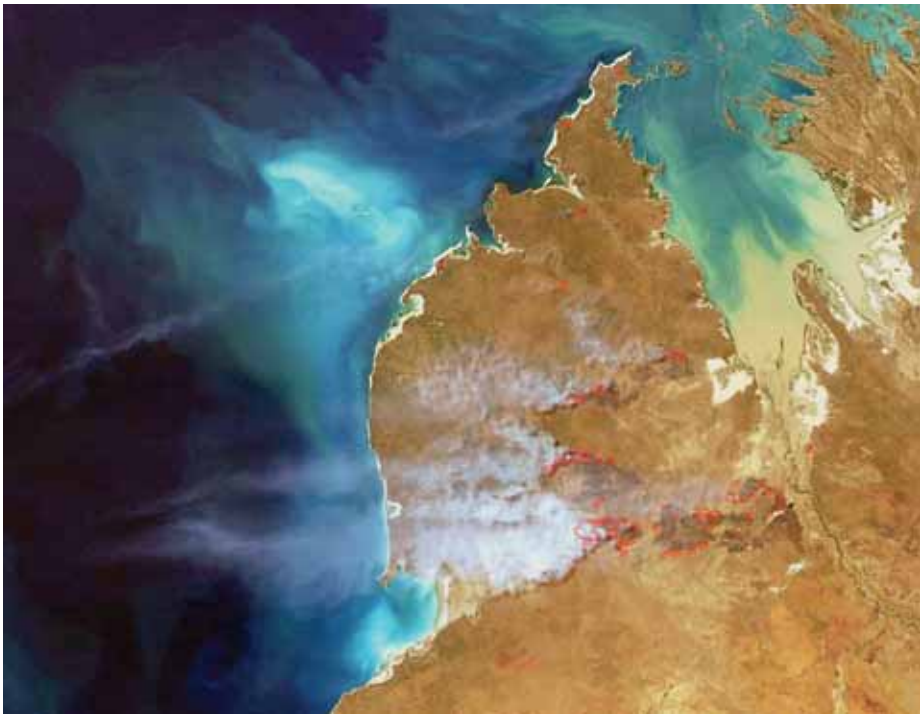


Figure 8-3 MODIS satellite Image at around 1230 WST 13th August 2006. Red shapes are new fire scars for that day

8.2.2 Annual Concentration Statistics

Predicted annual concentration statistics from TAPM-CTM for the existing sources are summarised in **Table 8.1** with contour plots of species that are close to or exceed the criteria presented in **Figure 8-4** to **Figure 8-12**.

Table 8.1 TAPM-CTM Predicted Regional Concentrations from Existing Sources

Pollutant	Averaging Period	Maximum Concentration Statistic	Criteria	Max at Sensitive[1] receptor	Percent of Criteria (%)	Receptor	Max Predicted Anywhere
Carbon Monoxide	8-hour	Max	9000 ppb	1520	17	Kilto	2444
Nitrogen Dioxide	1-hour	Max	120 ppb	73	61	12 Mile	91
	1-hour	3rd		36	-	12 Mile	47
	1-year	Ave	30 ppb	4.4	15	Broome	4.4
Ozone	1-hour	Max	100 ppb	78	78	BLNGV	91
	4-hours	Max	80 ppb	74	92	BLNGV	89
Particles as PM_{10}	1-day	Max	-	86	-	Kilto	155
	1-day	5th	50 µg/m^3	38	76	Kilto	67
Particles as $PM_{2.5}$	1-day	Max	25 µg/m^3	75	-	Kilto	131
	1-day	5th	-	33	-	Kilto	59
	1-year	Ave	8 µg/m^3	3.6	-	Kilto	3.8
Formaldehyde	1-hour	99.9th percentile	18 ppb	6.0	33	Kilto	8.3
Acetaldehyde	1-hour	99.9th percentile	23 ppb	4.8	21	Kilto	6.5

Notes:

1) Sensitive receptors include Broome, Coconut Wells, Country Downs station, Kilto station, Beagle Bay settlement, 12 Mile and BLNGV, the proposed site of the BLNG workers accommodation village.
2) The third highest NO_2 and 5th highest $PM_{2.5}$ concentrations are presented to show concentrations just below the maximum to illustrate how representative the maximum concentrations are.
3) $PM_{2.5}$ concentrations are not provided as a percent of the criteria as the NEPM goal is to gather sufficient data nationally to facilitate a review and does not set a number of allowable exceedances.

Noting that these are model predictions for an above average fire year, the results in **Table 8.1** indicate that:

- Concentrations of ozone, PM_{10} and NO_2 are predicted to be relatively high with the concentrations at the sensitive receptors listed in **Table 6.5** predicted to be 92, 76 and 61% of their respective standards. Elsewhere on the Dampier Peninsula predicted concentrations of ozone and PM_{10} exceed their criteria with the maximum 4-hour concentration of ozone (89 ppb) exceeding the criteria of 80 ppb and the 5th highest 24-hour PM_{10} concentration of 67 µg/m^3 exceeding the NEPM of 50 µg/m^3;
- Predicted $PM_{2.5}$ concentrations exceed the 24-hour NEPM investigation level but are well below the annual investigation level;
- These high pollutant levels are due to the impacts of fires in the Kimberley. That the predictions did not exceed the criteria at sensitive receptors can be considered fortuitous being dependent on the locality of the fires in this year; and
- Pollutants such as carbon monoxide, formaldehyde and acetaldehyde are predicted to be relatively low at 17 to 33% of their respective criteria.

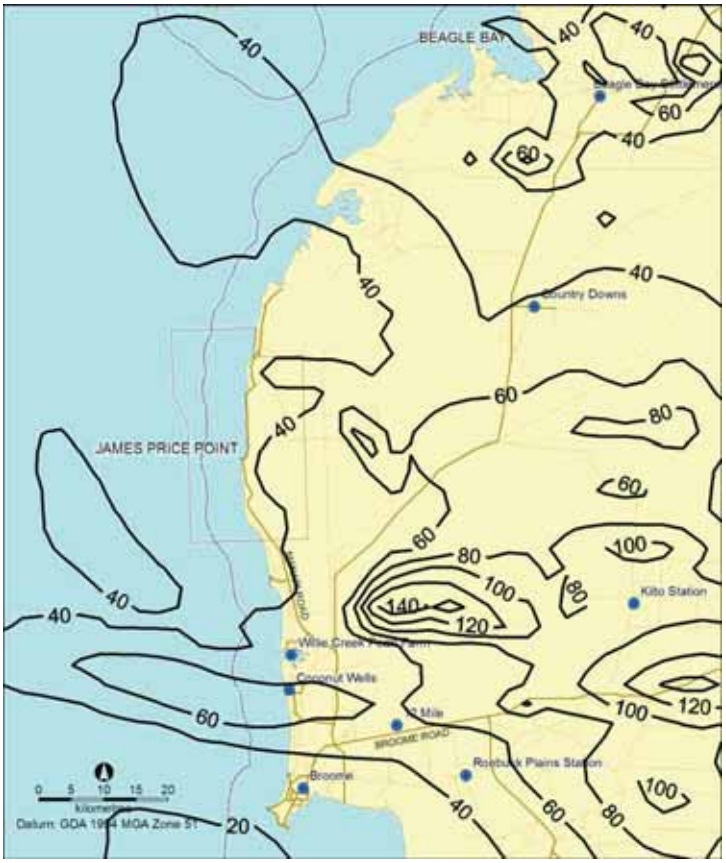


Figure 8-4 Predicted Maximum 24-hour PM_{10} Concentrations (µg/m^3) for Existing Sources for 2006

Figure 8-5 Predicted 5th Highest 24-hour PM_{10} Concentrations (µg/m^3) for Existing Sources for 2006

Figure 8-6 Predicted 5th Highest 24-hour $PM_{2.5}$ Concentrations (µg/m^3) for Existing Sources for 2006

Figure 8-7 Predicted Maximum 1-hour O_3 levels (ppb) for Existing Sources for 2006

Figure 8-8 Predicted Maximum 4-hour O_3 levels (ppb) for Existing Sources for 2006

Figure 8-9 Predicted Maximum 1-hour NO_2 levels (ppb) for Existing Sources for 2006

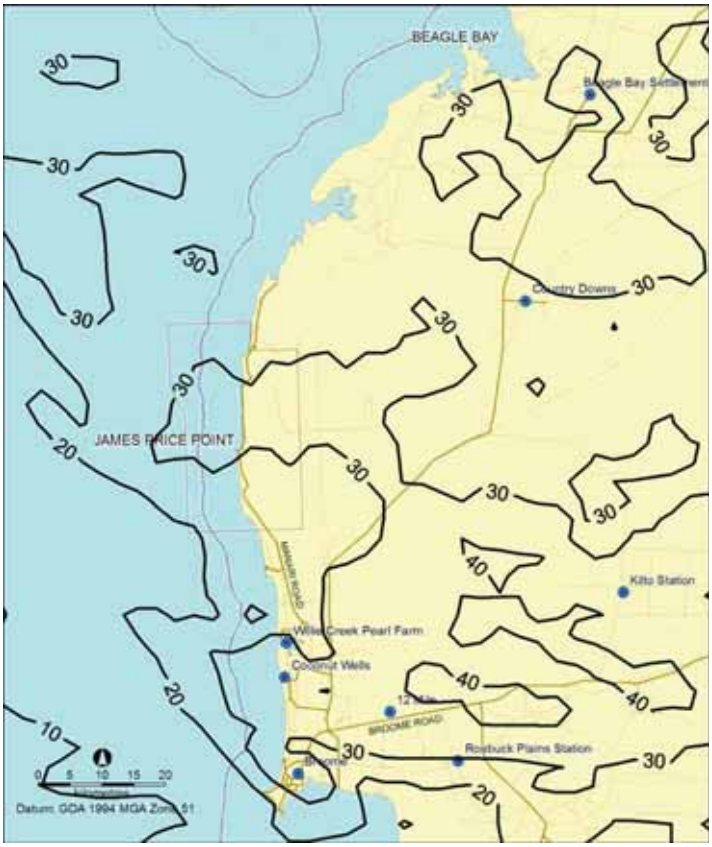


Figure 8-10 Predicted 3rd highest 1-hour NO_2 levels (ppb) for Existing Sources for 2006

Figure 8-11 Predicted Annual Average NO_2 levels (ppb) for Existing Sources for 2006

Figure 8-12 Predicted maximum 8-hour CO levels (ppb) for Existing Sources for 2006

8.3 Predicted Concentrations from the BLNG Precinct Alone

8.3.1 Introduction

There are potentially 32 possible combinations of LNG plant scenarios to be assessed as summarised in **Table 8.2**, consisting of four 15 Mtpa cases and four 50 Mtpa cases along with the four modes of operation (normal operation and three non routine operations).

Table 8.2 BLNG Modelling Scenarios

Operation Scenario	LNG Production (Mtpa)	LIGT	MIGT	AGT	IS
Normal	15	O	O	O	O
	50	O / X	O	O	O
Start Up	15	-	-	-	-
	50	O /X	-	-	-
Emergency	15	-	-	-	-
	50	O	-	-	-
Turn Down	15	-	-	-	-
	50	O	-	-	-

Notes:

1) LIGT (Large Industrial GTs), MIGT (Medium Industrial GTs), IS (Integrated Steam), AGT (Aero-derivative GT).
2) O is an one month run and X is a 12 month run

Further to this for each case, model predictions with and without existing sources can be modelled. For ascertaining annual impacts using TAPM-CTM this is far too many cases to model and present. As such, to simplify the process the following model runs were conducted:

Monthly Sensitivity Modelling

- Monthly runs for each LNG case for normal operations for both a nominal 15Mtpa facility and for a 50 Mtpa Precinct. This will determine the variability in the resultant concentrations to the LNG case;
- Monthly runs for a LNG case for the normal and 3 non routine scenarios to show the impact of the non routine operations; and

Annual Modelling

- For a representative LNG case, annual predictions for the normal operation and for the highest non routine operations.

8.3.2 Sensitivity Studies for All BLNG Cases – Monthly Results

For the sensitivity analysis, modelling was conducted for a 1-month period to identify the variation in concentrations between the cases. The month used, September 2006, was selected as it was a month with winds from most quadrants which should ensure that the full range of dispersive conditions are covered. Months such as November through to March tend to have consistent westerlies, whilst months such as June and July tended to have easterly winds only (see **Figure 5-1**). A summary of the model cases is presented in **Table 8.2**.

To model the TCUs, which have been specified with 90% availability, it is assumed for the 50 Mtpa case that two of the ten TCUs do not operate at any time. For the 15 Mtpa case, one TCU has been assumed to not operate. Assuming that two TCUs do not operate is conservative as it results in higher ozone concentrations due to the much higher VOC emissions that occur. The option to model 1 TCU for the 50 Mtpa case may understate their impact as seen by the percentage times that 2 TCUs are down (see **Table 3.3**). Another alternative would be to model the TCUs using some random emissions of TCUs but this would be too complex for the "smog" modelling required here.

The results of the sensitivity modelling are presented in **Table 8.3** along with selected plots of ozone and NO_2 for various cases in **Figure 8-13** to **Figure 8-15**. Note that all eight normal operation cases have been modelled, though for the non routine operation only the LIGT case has been modelled as the emissions from the non routine operations are reasonably consistent between LNG scenarios.

Table 8.3 TAPM-CTM Predicted Regional Concentrations for Various LNG Scenarios - September 2006 with Typical Background Air

Scenario	Ozone Maximum 1-hour (ppb)	Ozone 3rd Highest 1-hour (ppb)	Ozone Maximum 4-hour (ppb)	NO_2 Maximum 1-hour (ppb)	NO_2 Monthly Average (ppb)
Criteria	100	NA	80	120	NA
15 Mtpa Cases (run with 1 TCU down)					
LIGT 15 Mtpa	45.8	36.6	38.8	8.2	1.00
MIGT 15 Mtpa	47.8	36.8	39.2	8.8	1.08
AGT 50 Mtpa	47.4	37.2	39.5	9.2	1.10
IS 16.7 Mtpa	48.4	37.9	43.2	10.4	1.34
50 Mtpa Cases (run with 2 TCU down)					
LIGT 50 Mtpa	65.1 (84)	46.0 (55)	50.7 (61)	26.7 (34)	2.59 (1.8)
MIGT 50 Mtpa	65.9	47.1	52.4	31.6	2.83
AGT 50 Mtpa	65.8	47.2	52.5	31.9	2.85
IS 50 Mtpa	65.1	47.5	53.6	33.4	3.36
Non Routine 50 Mtpa Cases (2 TCU down)					
LIGT 50 Mtpa Emergency Shut Down / Flaring	65.8 (95)	51.1 (66)	51.5 (70)	26.9 (34)	2.62 (1.9)
LIGT 50 Mtpa – Start Up	65.8	50.8	54.0	37.6	3.44
LIGT 50 Mtpa – Turn Down	64.1	48.7	53.3	36.8	3.51
Sensitivity Run 50 Mtpa Case (2 TCU down)					
LIGT 50 Mtpa (no plume enhancement)	64.7	47.3	53.2	34.5	3.30
Including Fires in Background Emissions					
Existing Sources – No LNG	91.1	72.2	88.8	82.0	5.49
Existing plus LIGT (50 Mtpa) – 2 TCU down	91.7	74.7	89.9	89.1	4.51

Notes:

1) All concentrations predicted on a 3km grid. Therefore the NO_2 concentrations will understate the true maximum value which requires using a finer grid as per **Section 9**.
2) LIGT (Large Industrial GTs), MIGT (Medium Industrial GTs), IS (Integrated Steam), AGT (Aero-derivative GT).
3) Values in brackets are annual statistics predicted from the same 3 km grid (see **Section 8.4.1**).

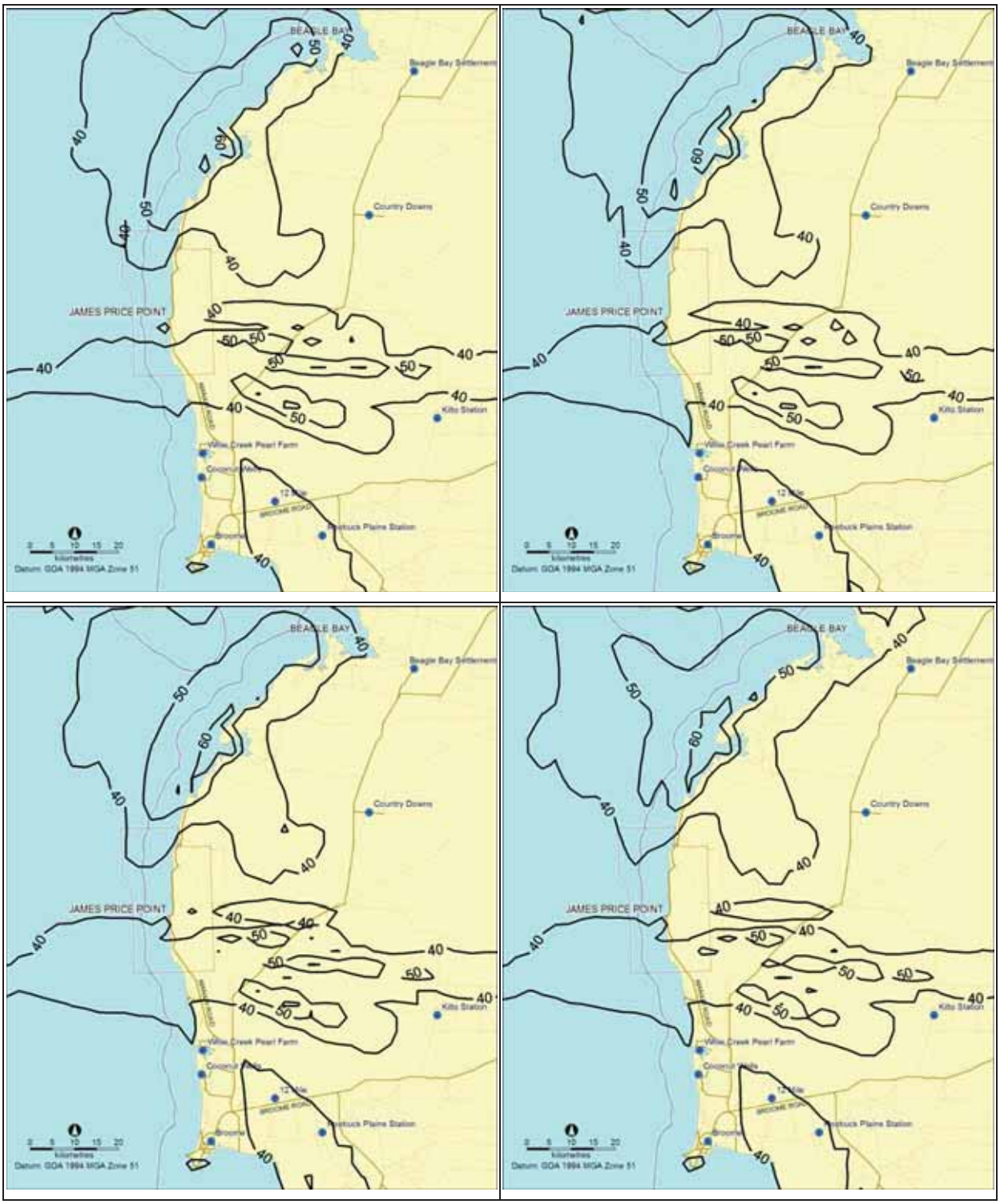


Figure 8-13 Predicted Maximum 1-hour O_3 levels (ppb) for 50 Mtpa LIGT (top left), MIGT (top right), AGT (bottom left) and IS (bottom right) Precincts for September 2006 – No Existing Sources

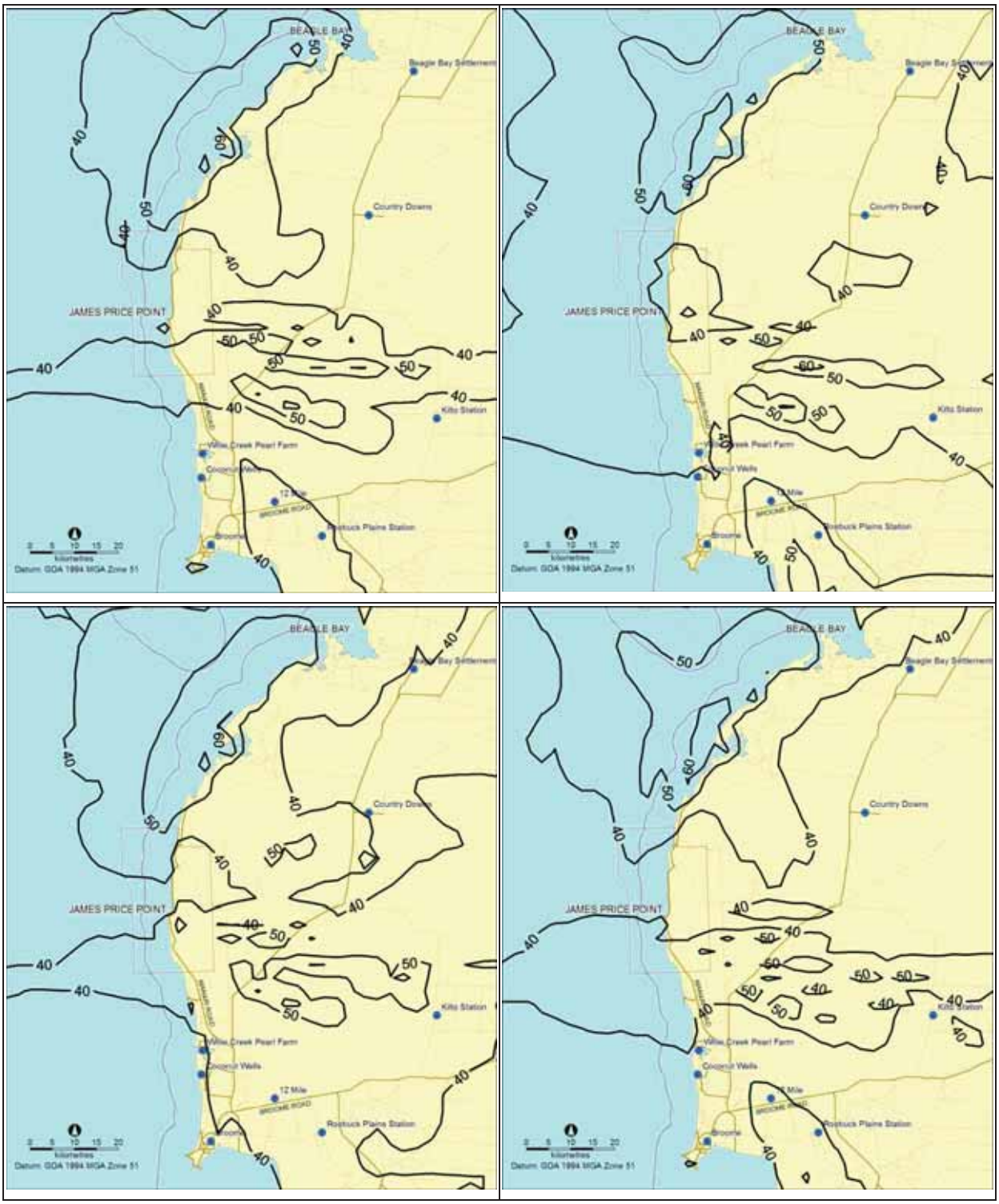


Figure 8-14 Predicted Maximum 1-hour O_3 levels (ppb) for 50 Mtpa LIGT, Routine Operations (top left), Start up (top right), Emergency Flaring (bottom left) and Turn Down (bottom right) for September 2006 – No Existing Sources

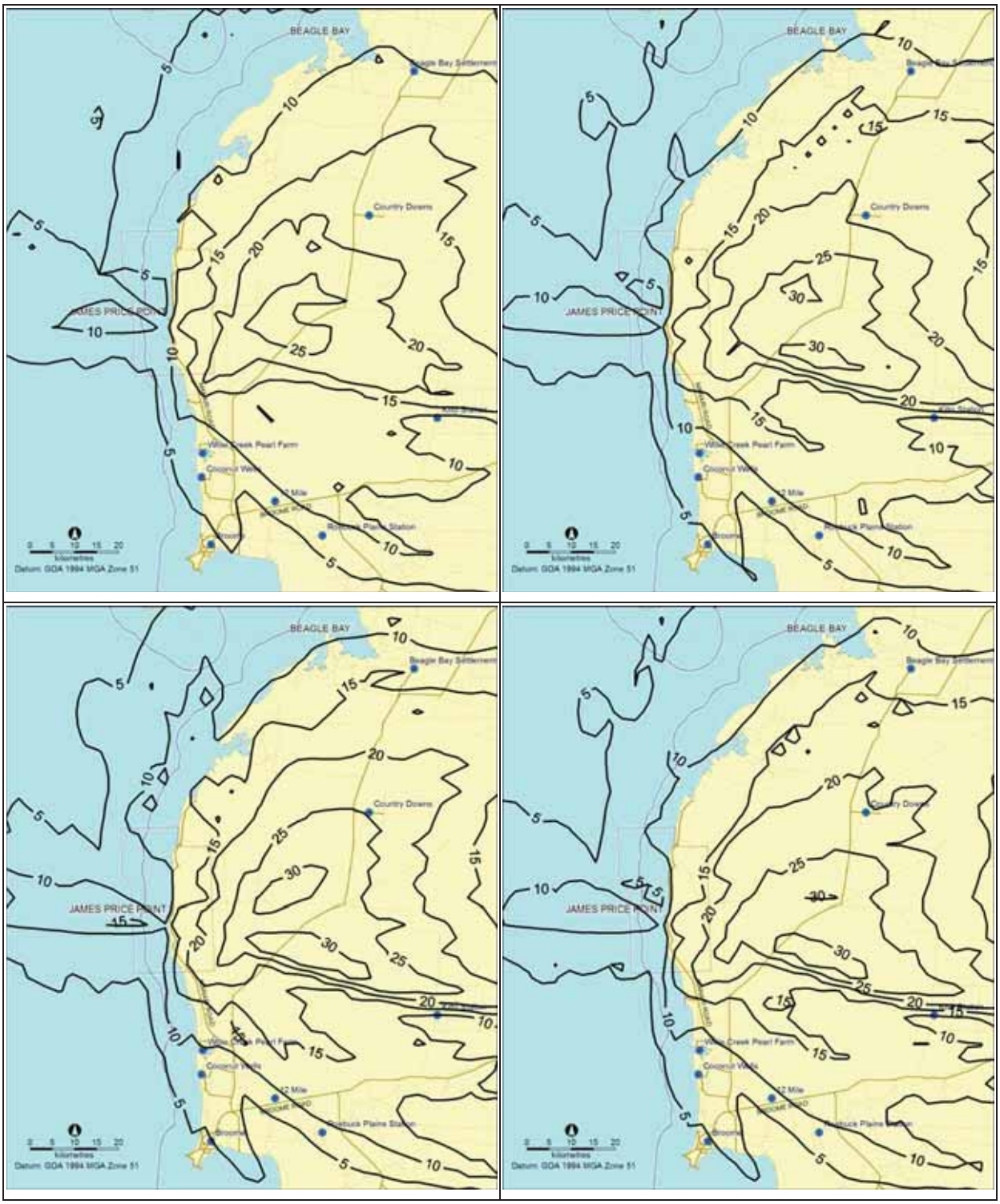


Figure 8-15 Predicted Maximum 1-hour NO_2 levels (ppb) for 50 Mtpa LIGT (top left), MIGT (top right), AGT (bottom left) and IS (bottom right) Precincts for September 2006 – No Existing Sources

The results indicate:

1) Predicted ozone concentrations due to the BLNG for the month of September 2006 are well below the NEPM 1-hour and 4-hour ozone standards. For 50 Mtpa facilities these are around 65% of the standards and 47 to 50% for a 15 Mtpa facility;
2) The levels from the BLNG are much less than that predicted from fires (see **Section 8.2.2**), which showed maximum predicted 1-hour concentrations of 70 to 90 ppb for much of the peninsula;
3) There is little variation in the predicted ozone concentrations between the 4 LNG cases. There is however some variation in the predicted maximum NO_2 concentrations with the IS case predicted to result in the highest NO_2 concentrations;
4) Predicted ozone concentrations from non routine operations also show little variation from the routine predictions, though showing slightly higher concentrations of NO_2 than the n routine operations;
5) The predicted concentrations from emergency shutdown / flaring with very high NO_X emissions are not significantly higher as the plumes from this flaring will typically rise above 500m and therefore typically not be mixed to ground. When the plume is mixed to ground the large mixing involved results in the plume being diluted substantially; and
6) The inclusion of plume rise enhancement for the gas turbine emissions only makes a small decrease in the predicted concentrations.

8.3.3 Predicted Annual Concentrations from the LIGT LNG Case for Routine and Non-Routine Operations – Excluding Existing Sources

As determined in **Section 8.3.2** maximum ozone concentrations (the pollutant of most concern from the LNG plant) from normal operations are similar for the four LNG plant types considered. Maximum ozone concentrations occurred for the case of Emergency Shutdown / Flaring and for the Start Up case. Therefore for prediction of annual concentration statistics without existing sources for the 50 Mtpa BLNG, two cases were modelled: the LIGT case under normal operation and the LIGT plant design assuming that Emergency Flaring occurred continuously. This run with Emergency Flaring was undertaken as an extreme worst case scenario to see what the maximum concentrations could be in very improbable event of the 1 in 10 year flaring event occurring at the same time as the worst case meteorological conditions. Note that the Start Up case has been modelled including existing sources in **Section 8.4.2.**

The results for the normal and Emergency Flaring cases are presented in **Table 8.4** with contour plots of pollutants closest to the criteria presented in **Figure 8-16** to **Figure 8-22**.

Table 8.4 TAPM-CTM Predicted Regional Concentrations for a 50 Mtpa LIGT Precinct – Background Levels Included and Existing Sources Omitted

Pollutant	Averaging Period	Maximum Concentration Statistic	Criteria	Max at Sensitive[1] Receptor	Percent of Criteria	Receptor	Max predicted Anywhere
Carbon Monoxide	8-hour	Max	9000 ppb	78 (94)	0.9 (1.0)	BLNGV	84 (103)
Nitrogen Dioxide	1-hour 1-year	Max Ave	120 ppb 30 ppb	23 (24) 1.3 (1.4)	19 (20) 4 (5)	BLNGV BLNGV	34 (34) 1.8 (1.9)
Ozone	1-hour 4-hours	Max Max	100 ppb 80 ppb	64 (72) 50 (60)	64 (72) 62 (75)	BLNGV BLNGV	84 (95) 61 (70)
Particles as PM_{10}	1-day	Max	50 $\mu g/m^3$	NA	NA	NA	NA
Particles as $PM_{2.5}$	1-day 1-year	Max	25 $\mu g/m^3$ 8 $\mu g/m^3$	NA	NA	NA	NA
Formaldehyde	1-hour	99.9	18 ppb	1.4 (1.7)	8 (9)	Country Downs	1.6 (1.9)
Acetaldehyde	1-hour	99.9	23 ppb	2.7 (3)	12 (13)	BLNGV	3.2 (3.6)

Notes:

1) Concentrations from normal operations without brackets and from Emergency Shutdown / Flaring with brackets.
2) The modelling omits other sources such as Fires and Broome sources but includes background concentrations.
3) Sensitive receptors include Broome, Coconut Wells, Country Downs station, Kilto station, Beagle Bay settlement, 12 Mile and BLNGV, the proposed site of the BLNG workers accommodation village.
4) Particulate sources not estimated in this section. See the cumulative particulate in **Section 8.4**.

Table 8.4 and **Figure 8-16** to **Figure 8-22** indicate that for normal operation:

- The contribution from the LNG plant at sensitive receptors will be below the NEPM standards, with the pollutant closest to its respective standard being ozone at 64% of the 1-hour standard. Of this, background ozone concentrations are around 20 to 25 ppb such that the actual contribution is about 40 to 45% of the NEPM standard;
- Of the other pollutants, the next highest at sensitive receptors relative to its criteria is NO_2, with predicted levels only 19% of the NEPM standard. This estimate it is noted is based on use of a 3 km grid as used in TAPM-CTM. A more accurate assessment of the NO_2 concentrations is provided in **Section 9** using a finer 500m grid;
- At other locations (non sensitive receptors) the maximum 1-hour ozone level is predicted to be 84 ppb or 84% of the standard. This peak is predicted to occur approximately 15 km to the SE of the Precinct. Sensitivity tests indicate that a major contributor to this and the other ozone peaks is the VOC emission from condensate loading. As discussed in **Section 3.4** these emissions are probably over stated. Therefore, in reality lower VOC emissions and lower ozone concentrations are expected; and
- Considering the extreme case of Emergency Shutdown / Flaring occurring for the whole year the predicted maximum 1-hour concentrations at sensitive receptor increases from 64 to 72% of the standard. At any location (non sensitive receptors) the maximum increases from 84 to 92% of the standard. These peaks as stated earlier are considered to be overstated due to the conservative nature of the condensate emissions and, secondly would only occur if the short period of flaring (for less than 1-hour in 10 years) occurred at the "worst" dispersive conditions. Therefore, these concentrations are considered extremely unlikely to occur.

Figure 8-16 Predicted Maximum 1-hour O_3 Concentrations (ppb) for a 50 Mtpa LIGT Precinct without Existing Sources

Figure 8-17 Predicted Maximum 4-hour O_3 Concentrations (ppb) for a 50 Mtpa LIGT Precinct without Existing Sources

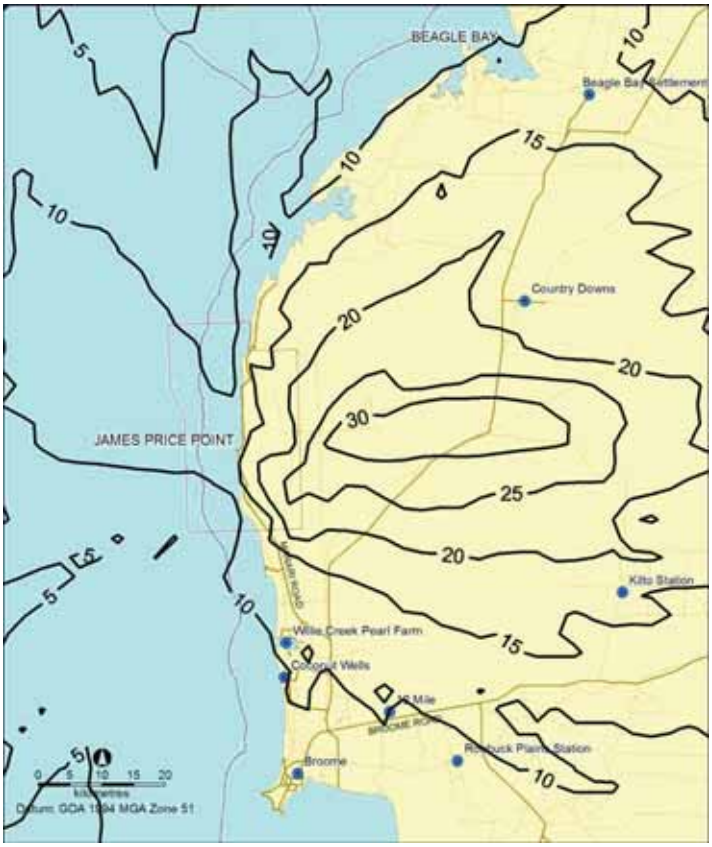


Figure 8-18 Predicted Maximum 1-hour NO_2 Concentrations (ppb) for a 50 Mtpa LIGT Precinct without Existing Sources

Figure 8-19 Predicted Annual Average NO_2 Concentrations (ppb) for a 50 Mtpa LIGT Precinct without Existing Sources

Figure 8-20 Predicted Maximum 1-hour O_3 Concentrations (ppb) for a 50 Mtpa LIGT Precinct with 1 Train with Continuous "Emergency Flaring. No Existing Sources.

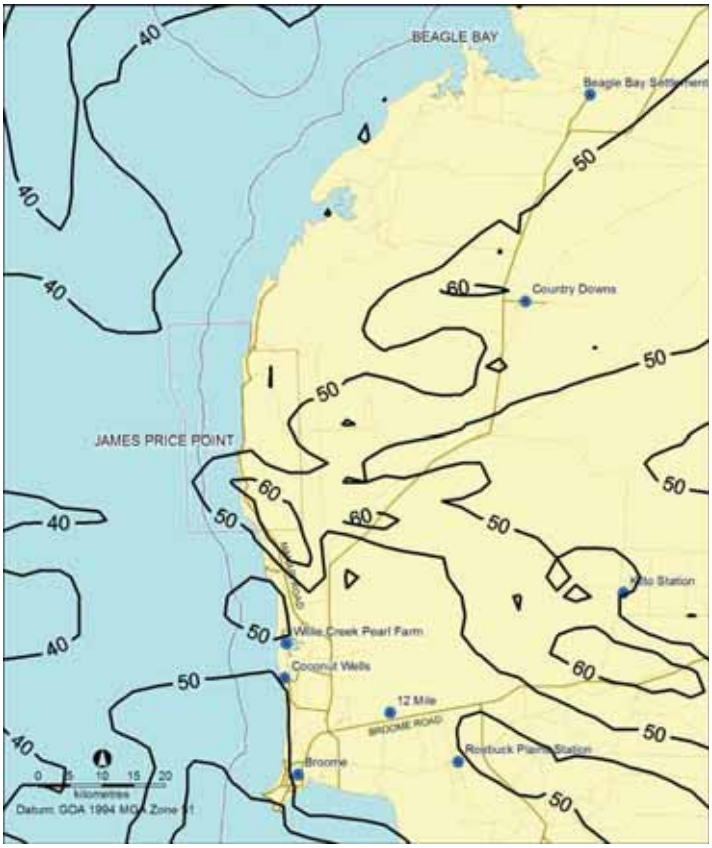


Figure 8-21 Predicted Maximum 4-hour O_3 Concentrations (ppb) for a 50 Mtpa LIGT Precinct with 1 Train with Continuous Emergency Flaring. No Existing Sources.

Figure 8-22 Predicted Maximum 1-hour NO_2 Concentrations (ppb) for a 50 Mtpa LIGT Precinct with 1 Train with Continuous Emergency Flaring. No Existing Sources

Figure 8-23 Predicted Annual Average NO_2 Concentrations (ppb) for a 50 Mtpa LIGT Precinct with 1 Train with Continuous Emergency Flaring. No Existing Sources

8.4 Cumulative Impacts – Annual Predictions at 50 Mtpa

8.4.1 Normal Operation

Predicted ground level concentrations from existing sources (fires and Broome sources) with the addition of a 50 Mtpa LIGT Precinct (in normal operation) are presented in **Table 8.5** and in **Figure 8-24** to **Figure 8-29**.

Table 8.5 TAPM-CTM Predicted Regional Concentrations from Existing Sources with the addition of a 50 Mtpa LIGT Precinct under Normal Operation

Pollutant	Averaging Period	Maximum Concentration Statistic	Criteria	Max at Sensitive Receptor	Receptor	Percent of Criteria (%)	Max Predicted Anywhere
Carbon Monoxide	8-hour	Max	9000 ppb	1550 (30)	Kilto	17	2448 (4)
Nitrogen Dioxide	1-hour	Max	120 ppb	73 (0)	12 Mile	61	89 (-2)
	1-hour	3rd		36 (0)	12 Mile	-	54 (7)
	1-year	Ave	30 ppb	4.5 (0.07)	Broome	15	4.5 (0.07)
Ozone	1-hour	Max	100 ppb	82 (4)	BLNGV	82	92 (1)
	4-hours	Max	80 ppb	79 (5)	BLNGV	99	90 (1)
Particles as PM_{10}	1-day	Max	-	88 (2)	Kilto	-	158 (3)
	1-day	5th	50 µg/m^3	40 (2)	Kilto	80	69 (2)
Particles as $PM_{2.5}$	1-day	Max	25 µg/m^3	77 (2)	Kilto	-	134 (3)
	1-day	5th		35 (2)	Kilto	-	61(2)
	1-year	Ave	8 µg/m^3	3.6 (0.2)	Kilto	45	4.0 (0.2)
Formaldehyde	1-hour	99.9th percentile	18 ppb	6.1 (0.1)	Kilto	34	8.4 (-0.05)
Acetaldehyde	1-hour	99.9th percentile	23 ppb	5.0 (0.2)	Kilto	17	6.6 (-0.1)

Notes:

1) Values in brackets are the Precinct addition to the existing levels in **Table 8.1**.
2) Sensitive receptors include Broome, Coconut Wells, Country Downs station, Kilto station, Beagle Bay settlement, 12 Mile and BLNGV, the proposed site of the BLNG workers accommodation village.
3) $PM_{2.5}$ 24-hour concentrations are not provided as a percent of the criteria as the NEPMs goal is to gather sufficient data nationally to facilitate a review and does not set a number of allowable exceedances.

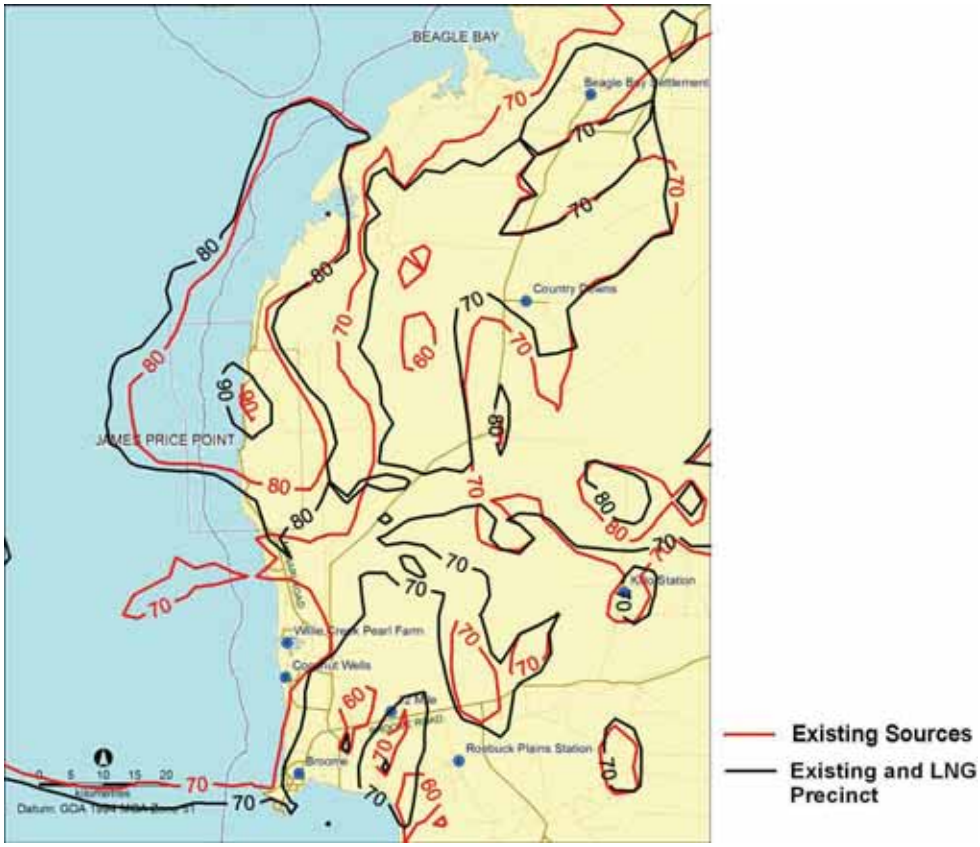


Figure 8-24 Predicted Maximum 1-hour O_3 Concentrations (ppb) for a 50 Mtpa LIGT Precinct – Including Existing Sources

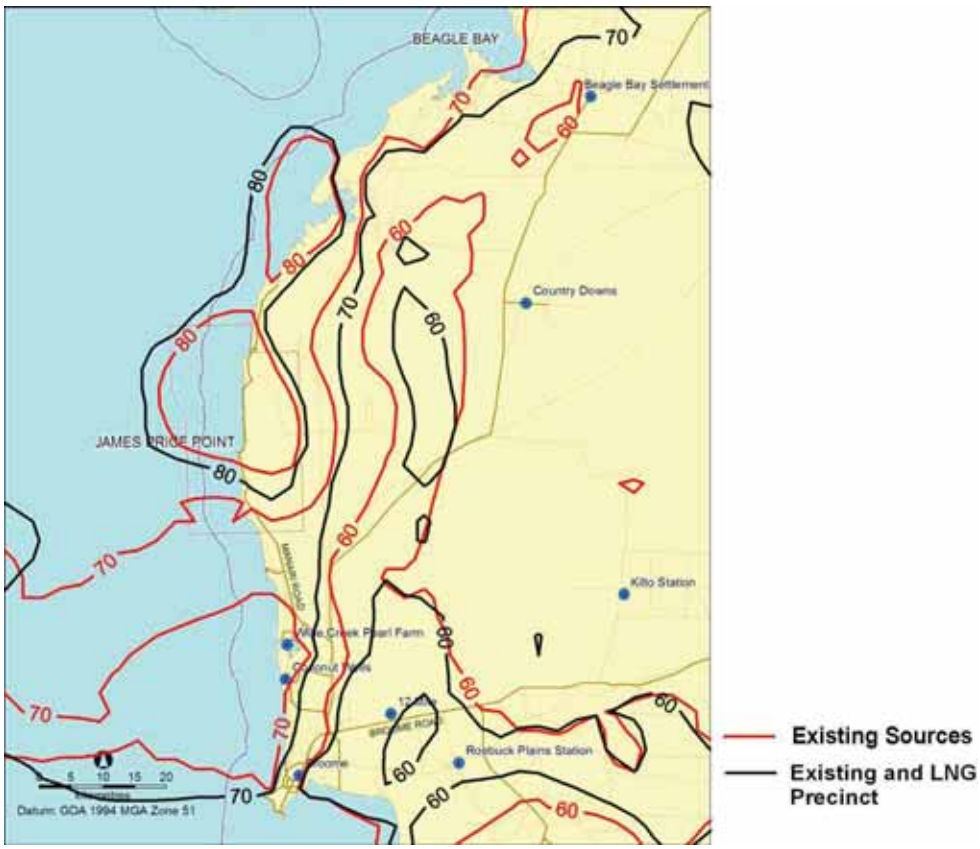


Figure 8-25 Predicted Maximum 4-hour O_3 Concentrations (ppb) for a 50 Mtpa LIGT Precinct – Including Existing Sources

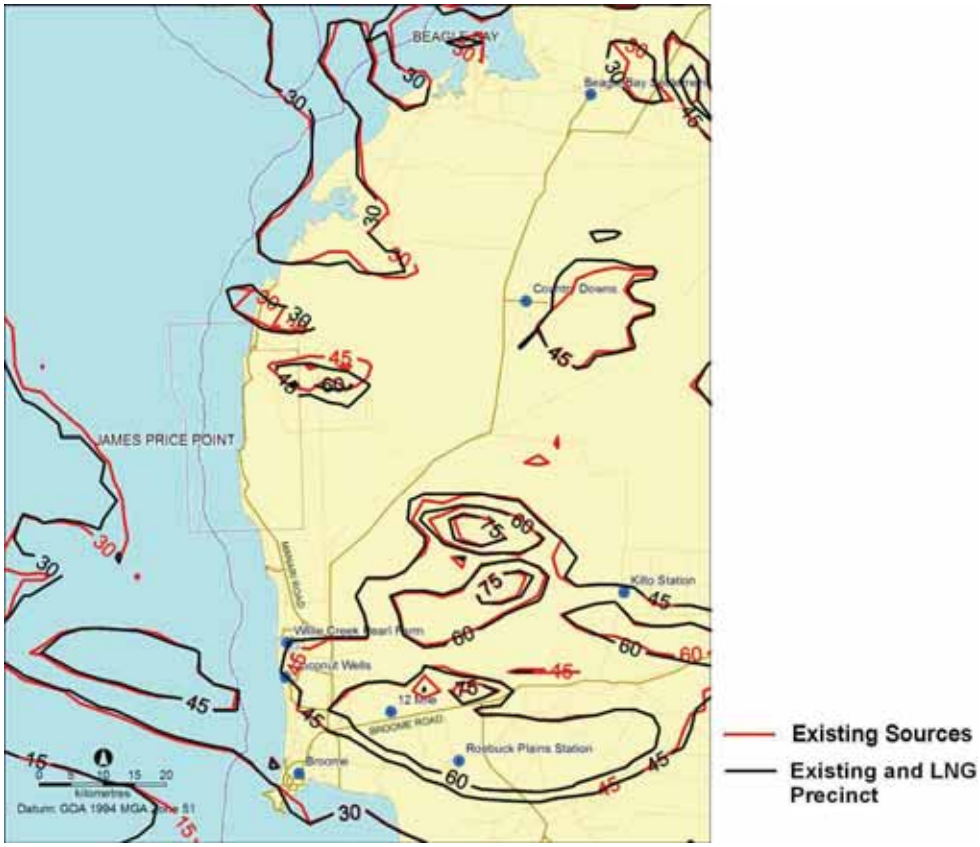


Figure 8-26 Predicted Maximum 1-hour NO_2 Concentrations (ppb) for a 50 Mtpa LIGT Precinct – Including Existing Sources

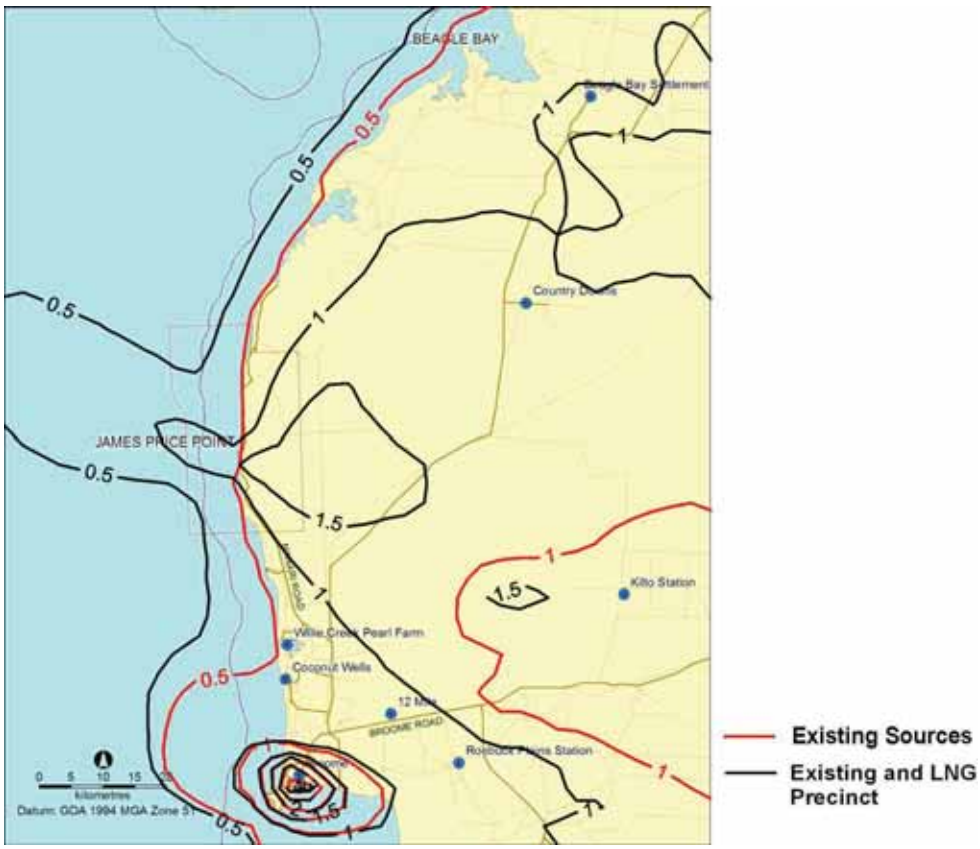


Figure 8-27 Predicted Annual Average NO_2 Concentrations (ppb) for a 50 Mtpa LIGT Precinct – Including Existing Sources

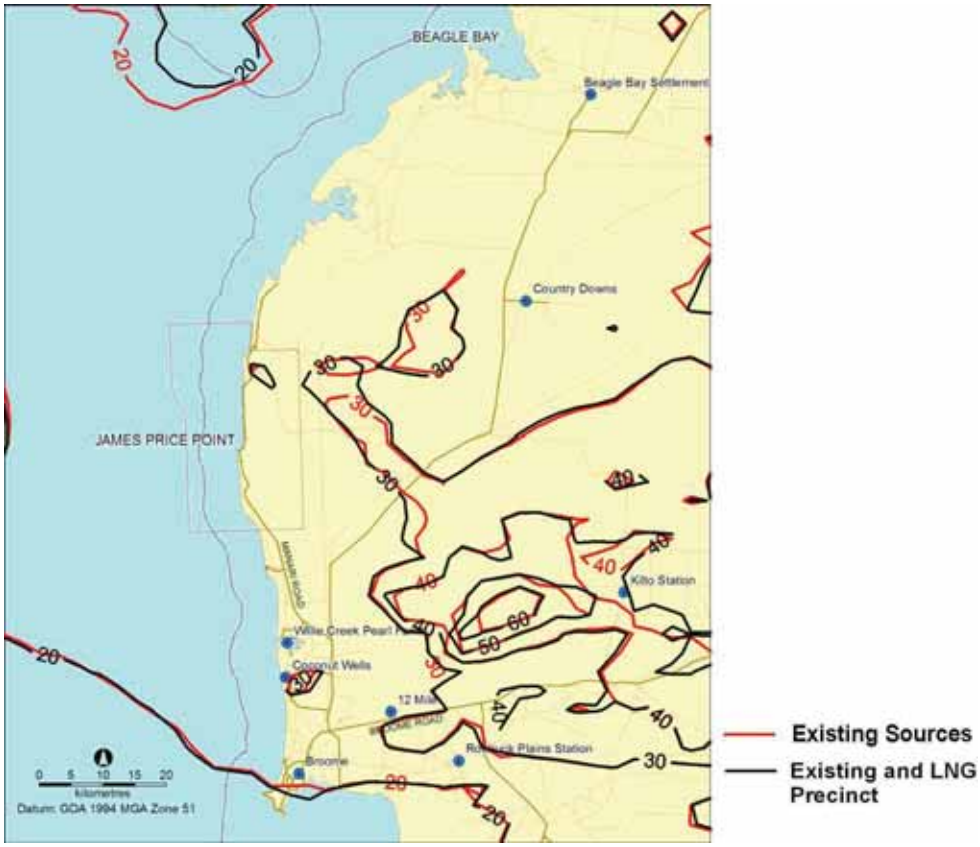


Figure 8-28 Predicted 5th Highest 24-hour PM_{10} Concentrations (µg/m^3) for a 50 Mtpa LIGT Precinct – Including Existing Sources

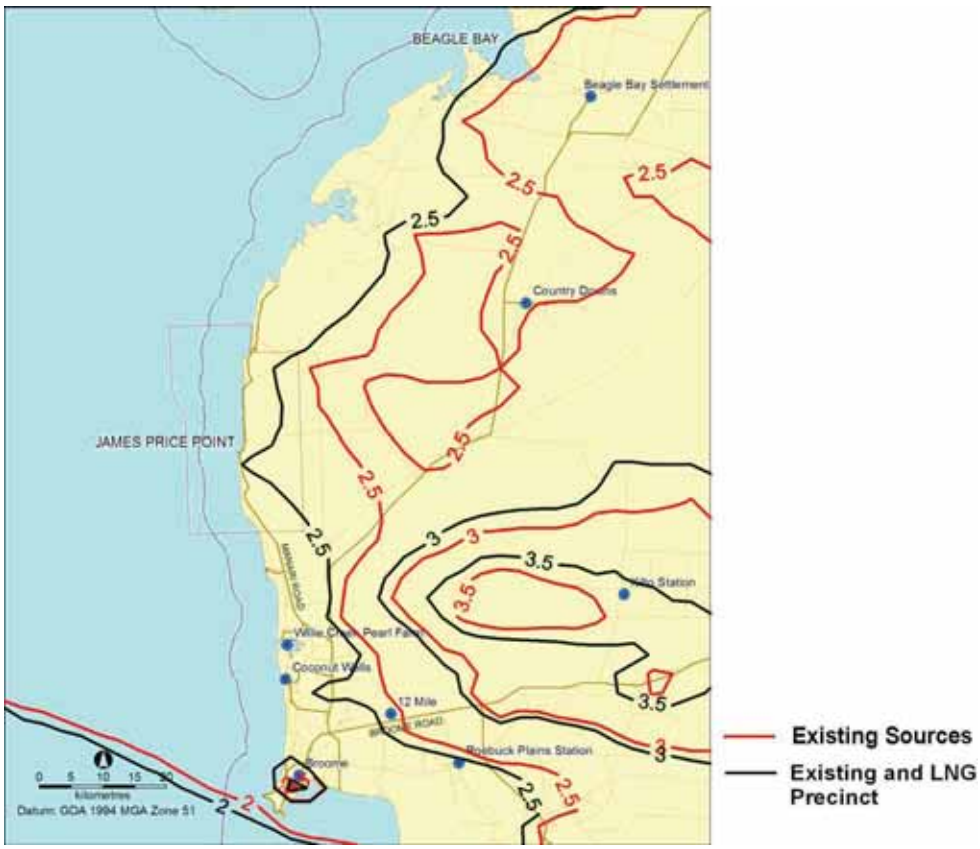


Figure 8-29 Predicted Annual Average $PM_{2.5}$ Concentrations (µg/m^3) for a 50 Mtpa LIGT Precinct – Including Existing Sources

Table 8.5 and **Figure 8-24** to **Figure 8-29** indicate that there will be small changes to the various concentration statistics used for the air quality criteria. Maximum concentrations do not increase by more than 6.3% for any of the criteria, though for some criteria there is no change whilst for the maximum 1-hour NO_2 levels there is a small decrease.

This small change in the concentrations is further illustrated in **Figure 8-30** to **Figure 8-32** for various statistics from the minimum to maximum concentrations for ozone and NO_2 for selected locations.

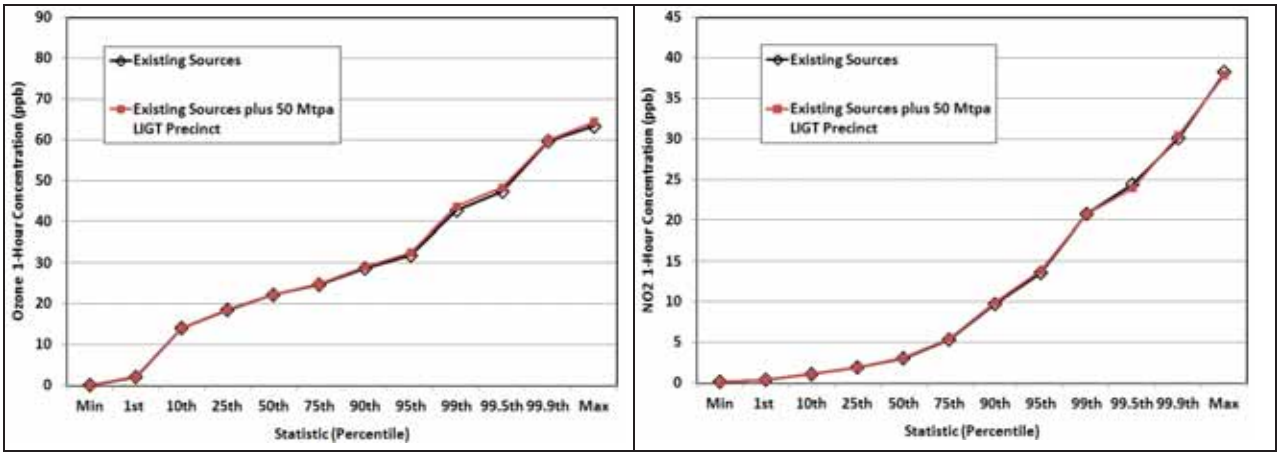


Figure 8-30 Predicted 1-hour Ozone and NO_2 Concentration Statistics at Broome for the Existing Sources and with a 50 Mtpa LIGT Precinct

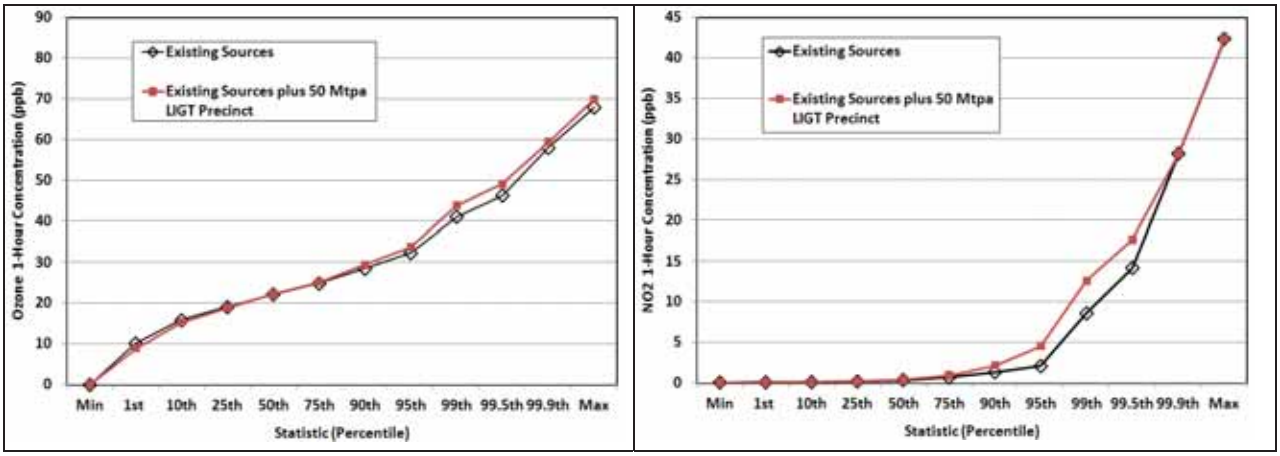


Figure 8-31 Predicted 1-hour Ozone and NO_2 Concentration Statistics at Country Downs Station for the Existing Sources and with a 50 Mtpa LIGT Precinct

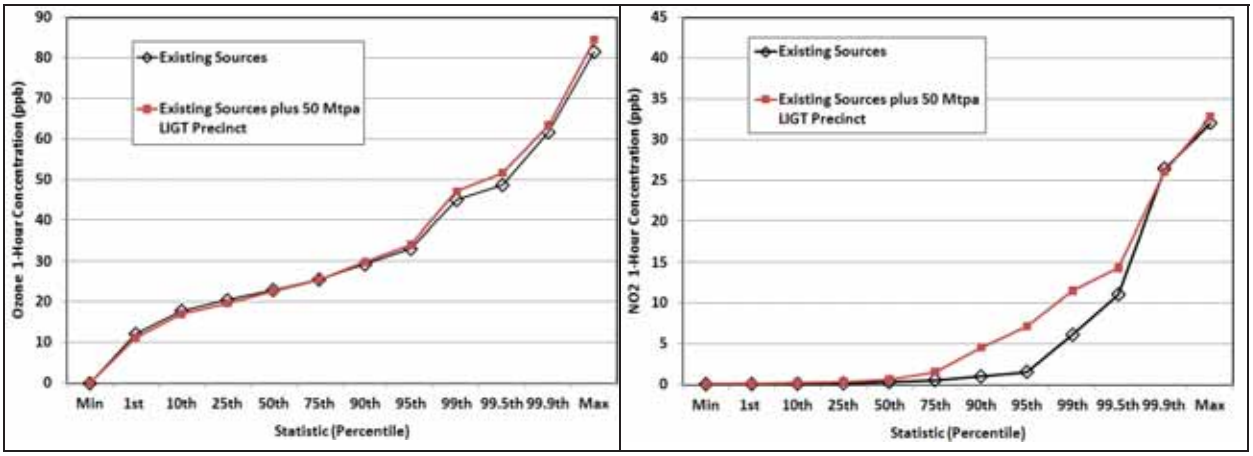


Figure 8-32 Predicted 1-hour Ozone and NO_2 Concentration Statistics at the Proposed BLNG Workers Accommodation for Existing Sources and with a 50 Mtpa LIGT Precinct

Figure 8-30 to **Figure 8-32** indicate for the full range of statistics that there is generally only a small change in ozone concentrations. For NO_2 there is predicted to be a greater change with the largest change occurring for concentrations in the range of 10 to 20 ppb range with this being largest at the BLNG accommodation location. That there is only minor change in the ozone levels is that fires lead to larger impacts and that dependent on the time and down wind distance, the emissions from the BLNG may decrease the ozone levels or increase ozone levels. During the daytime there is generally a region of ozone depletion for the first several tens of kilometres from the plant followed by a region where elevated ozone levels occur. During the late afternoon/early evening this "ozone hole" then extends for the full length of the plume with no areas of ozone formation. This effect is illustrated in **Figure 8-33** and **Figure 8-34**.

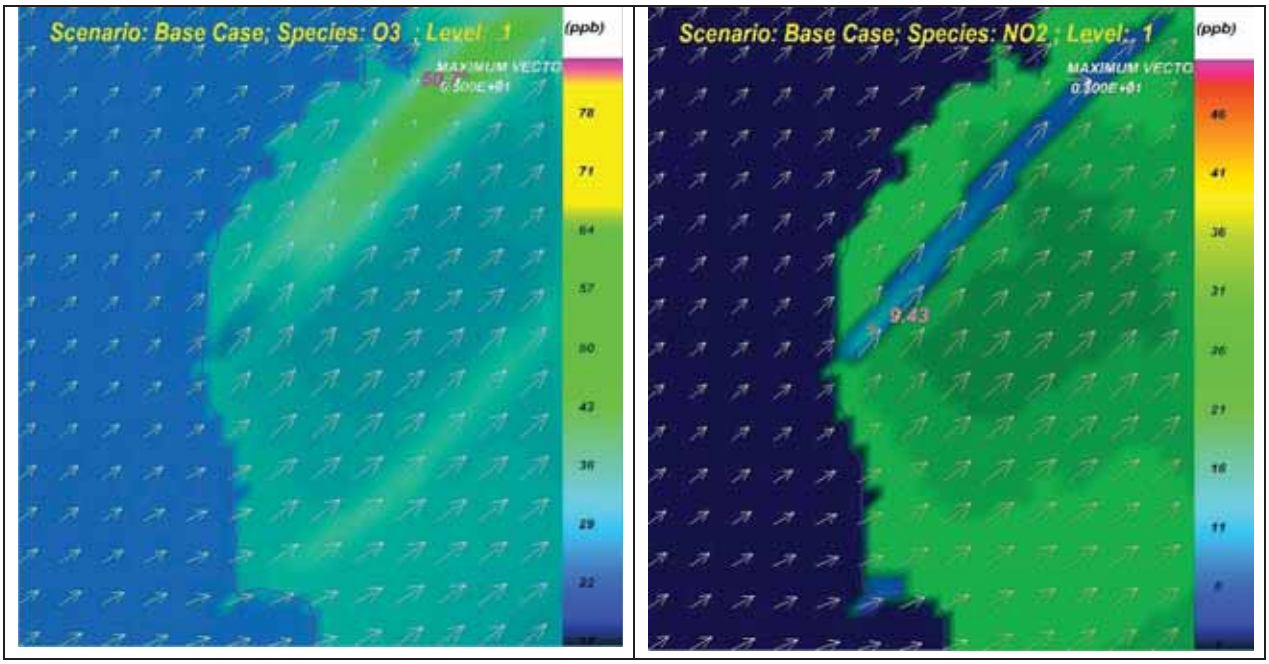


Figure 8-33 Predicted 1-hour Ozone (left) and NO_2 (right) concentrations (ppb) for a 50 Mtpa LIGT LNG Facility for 1200WST on the 11th Jan 2006

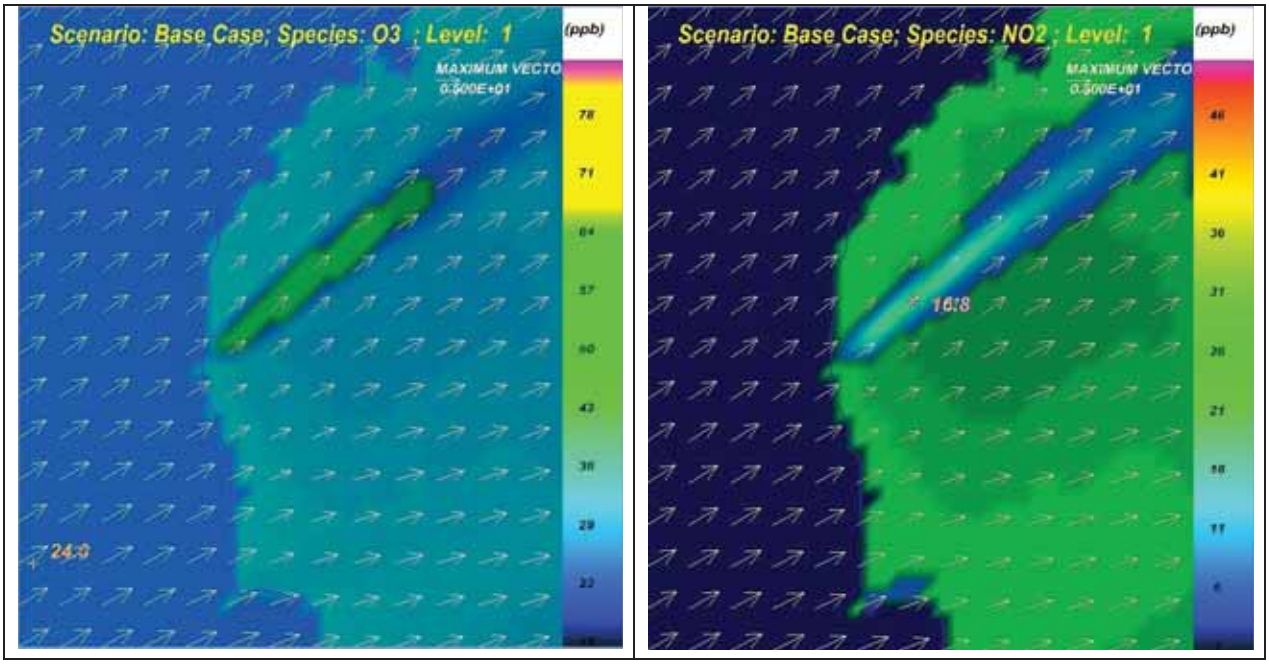


Figure 8-34 Predicted 1-hour Ozone (left) and NO_2 (right) concentrations (ppb) for a 50 Mtpa LIGT LNG Facility 2100WST on the 11th Jan 2006

The increase of NO_2 in the 2 to 20 ppb range as seen at the BLNG camp site occur as the highest NO_2 concentrations occur within 20 km of the plant with predicted concentrations generally up to 20 ppb. Therefore, there is an increase in the number concentration events in this range at this site whilst further away this increase is smaller.

8.4.2 Non-Routine Operation – Start-Up

Annual predictions from start up of the plant are presented in **Table 8.6** with predicted concentrations in **Figure 8-35** to **Figure 8-38**. This assumes 2 trains in start up continually with associated turn down of compressors to 50% load and associated flaring. The assumption of continual start up for the year is very conservative as the maximum concentrations would occur only if the start up occurred at the worst case meteorological conditions. This is very unlikely.

Table 8.6 TAPM-CTM Predicted Regional Concentrations from the BLNG with Continuous Start-Up Occurring - Including Existing Sources

Pollutant	Averaging Period	Maximum Concentration Statistic	Criteria	Max at Sensitive Receptor	Receptor	Percent of Criteria (%)	Max Predicted Anywhere
Carbon Monoxide	8-hour	Max	9000 ppb	1520 (-30)	Kilto	17	2480 (32)
Nitrogen Dioxide	1-hour 1-year	Max Ave	120 ppb 30 ppb	73 (0) 4.5 (0.0)	12 Mile Broome	61 15	93 (4) 4.5 (0.0)
Ozone	1-hour 4-hours	Max Max	100 ppb 80 ppb	84 (2) 81 (2)	BLNG BLNG	84 101	92 (0.7) 91 (1)
Formaldehyde	1-hour	99.9	18 ppb	5.8 (-0.3)	Kilto	32	8.4 (0.0)
Acetaldehyde	1-hour	99.9	23 ppb	4.8 (-0.2)	Kilto	21	6.4 (-0.2)

Notes:

1) Values in brackets are the Start Up addition to the LNG Precinct mode in normal operation in **Table 8.1**.

2) Sensitive receptors include Broome, Coconut Wells, Country Downs station, Kilto station, Beagle Bay settlement, 12 Mile and BLNGV, the proposed site of the BLNG workers accommodation village.
3) Particulate concentrations were not modelled for the LNG start up option. It would be expected to show the same small increase as per the gaseous concentrations.

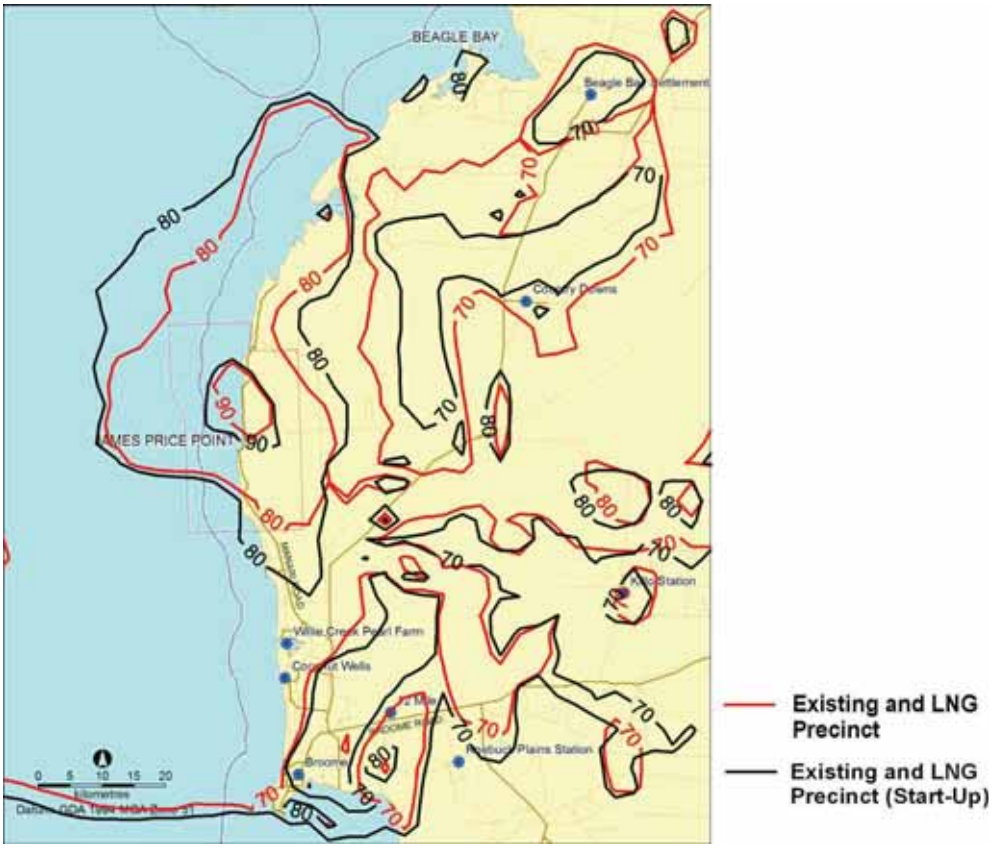


Figure 8-35 Predicted Maximum 1-hour O_3 levels (ppb) for a LIGT 50 Mtpa plant with Continuous Start-Up Occurring– Including Existing Sources

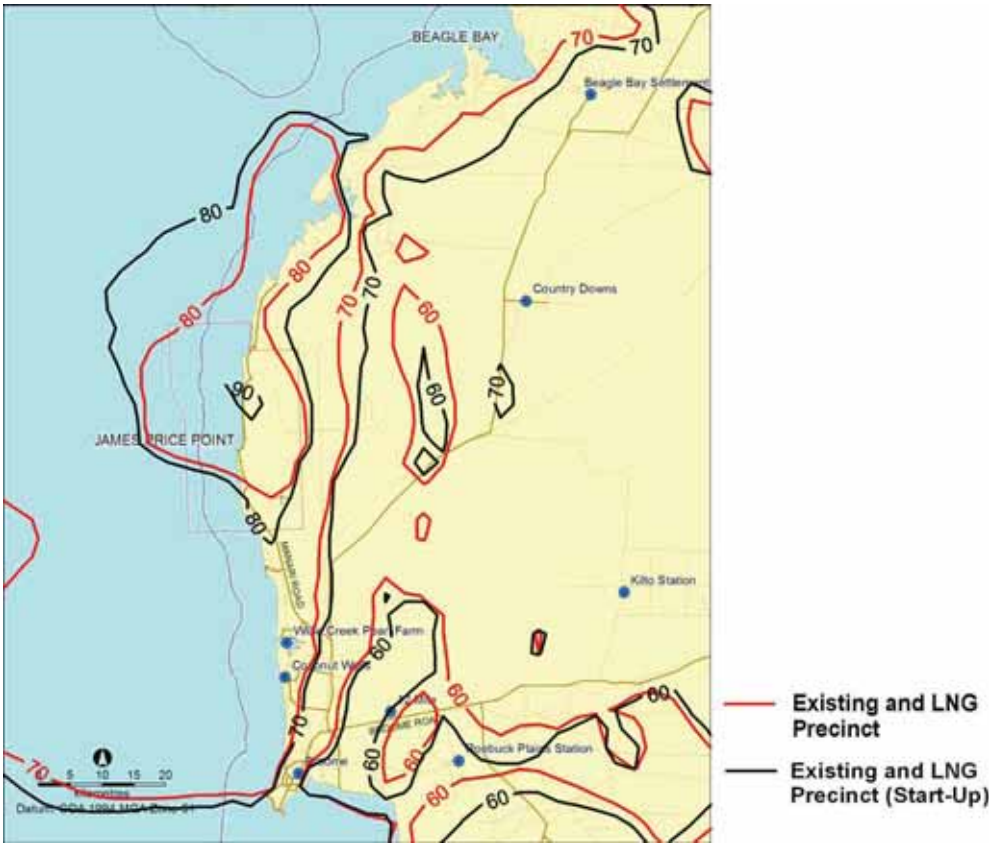


Figure 8-36 Predicted Maximum 4-hour O_3 levels (ppb) for the LIGT 50 Mtpa plant with Continuous Start-Up Occurring – Including Existing Sources

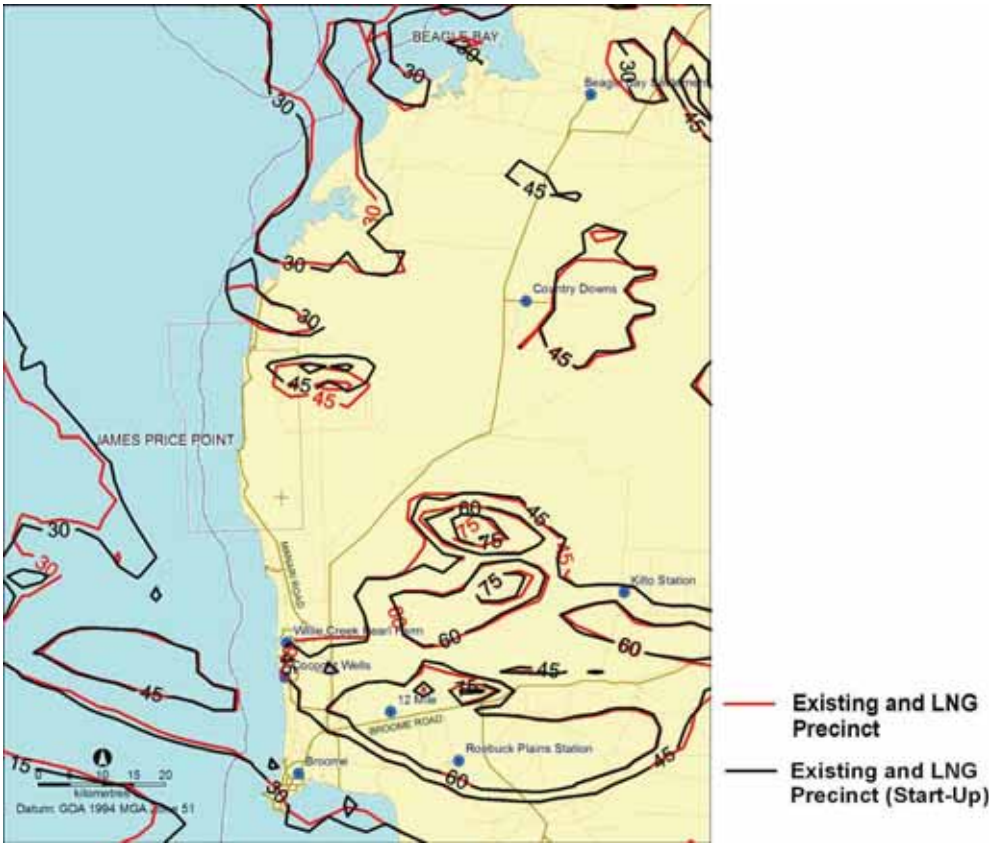


Figure 8-37 Predicted Maximum 1-hour NO_2 levels (ppb) for the LIGT 50 Mtpa plant with Continuous Start-Up Occurring – Including Existing Sources

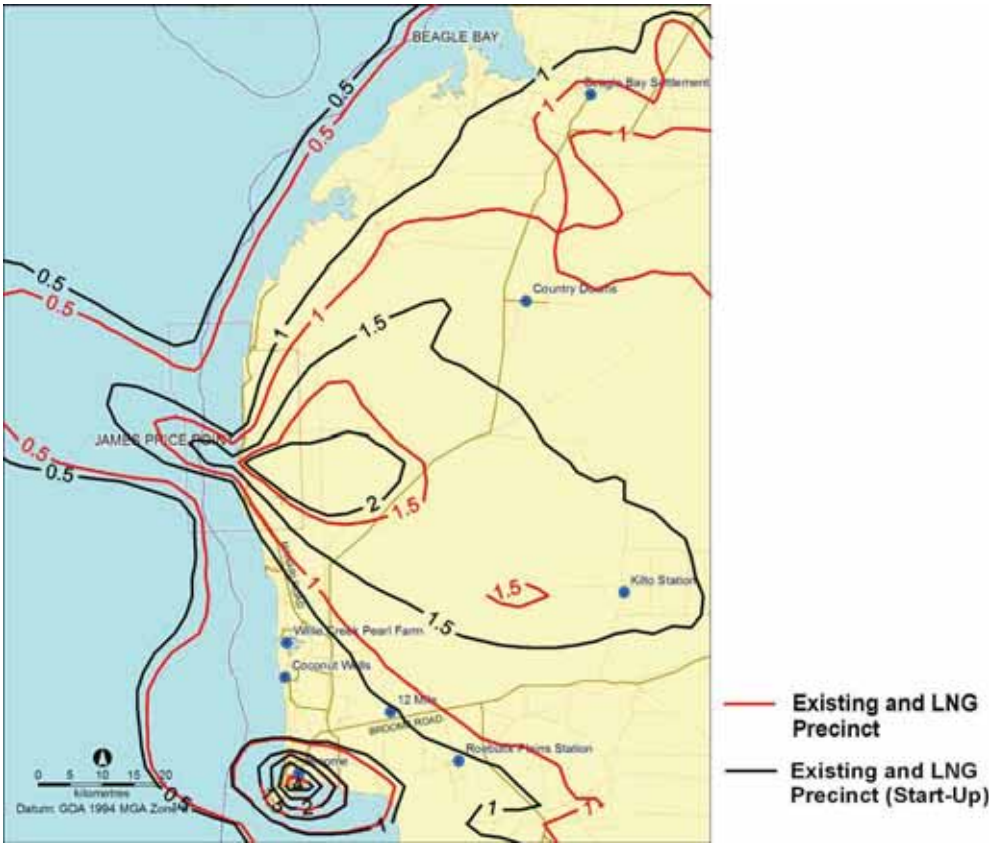


Figure 8-38 Predicted Annual Average NO_2 levels (ppb) for the LIGT 50 Mtpa plant with Continuous Start-Up Occurring – Including Existing Sources

The results from **Table 8.6** and **Figure 8-35** to **Figure 8-38** indicates that start up of 2 LNG trains makes little additional contribution at the sensitive receptors to that predicted with the LNG trains operating normally.

8.5 Sensitivity Test to Condensate VOC emissions

As the VOC emissions from condensate ship loading are considered to be conservative, a sensitivity test was undertaken to compare the predicted ozone concentrations with these emissions and with these emissions at a much smaller rate. To assess the impacts modelling for the LNG precinct in isolation without other existing sources was conducted as this more clearly enables the effects of the changes to be seen. This was conducted for only two months (due to time constraints) which lead to the highest concentrations (March and April) with modelling conducted with condensate emissions as per **Table 3-7** and with condensate emissions only 10% of those. The results are presented in **Figure 8-39** and **Figure 8-40** for the maximum 1-hour ozone concentration in the period.

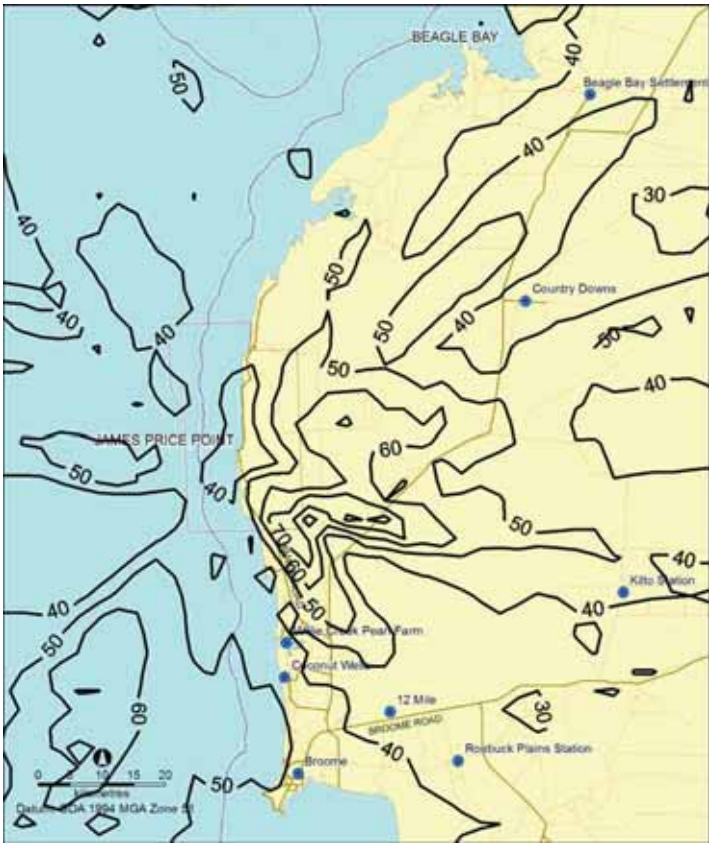


Figure 8-39 Predicted Maximum 1-hour ozone concentrations (ppb) for the LIGT 50 Mtpa plant for March and April 2009. Condensate Ship loading emissions as per Table 3-7.

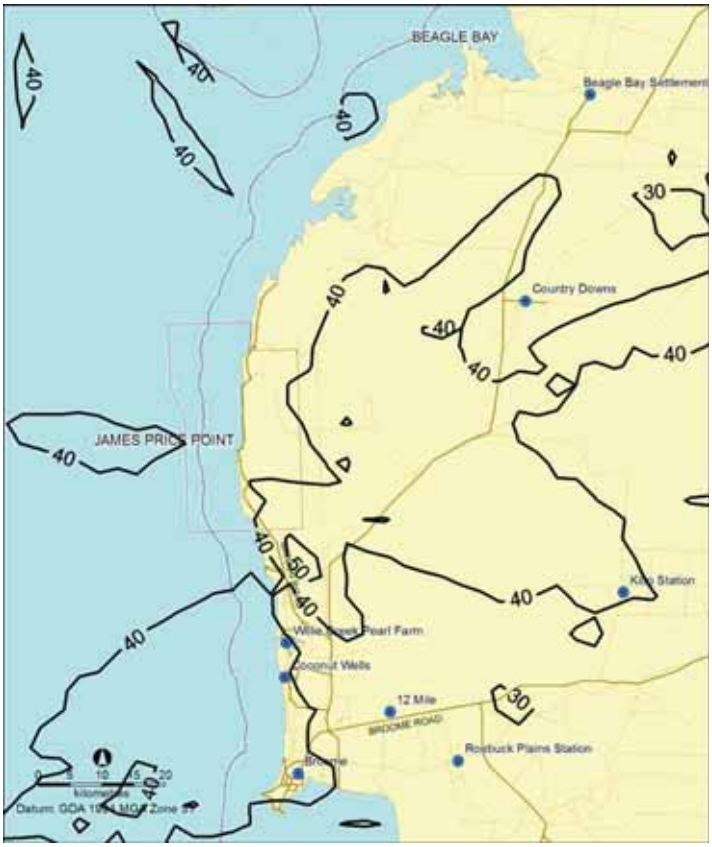


Figure 8-40 Predicted Maximum 1-hour ozone concentrations (ppb) for the LIGT 50 Mtpa plant for March and April 2009. Condensate Ship loading emissions 1/10th of Table 3-7.

Figure 8-39 and **Figure 8-40** indicate that the maximum concentrations decrease substantially indicating that the VOCs for the condensate loading as estimated by Woodside are a significant contributor to the Precincts contribution to ozone levels.

8.6 Conclusions from Regional Modelling

The regional modelling conducted using TAPM-CTM has shown the following:

- Fires are the existing dominant source of pollutant in the region leading to high particulate, ozone and NO_2 concentrations. These high levels are due not only to the very large extent of land burned but, also to a build up of pollutants in the atmosphere as the fires typically last for days;
- The predicted existing levels of ozone are typically in the range of 60 to 85 % of the NEPM standards with peak concentration anywhere of 91% and 111% of the respective 1 and 4-hour standards;
- The predicted particulate levels are below the NEPM PM_{10} standard with more than 5 exceedances for most of the Dampier Peninsula, but do exceed it for a small area. Note, for both ozone and particulate matter there are no measurements within the Kimberley to confirm the predictions;
- The contribution from the BLNG precinct at sensitive receptors will be below the NEPM standards, with the pollutant closest to its respective standard being ozone at 64% of the 1-hour standard. At other locations (non sensitive receptors) the maximum 1-hour ozone level is predicted to be 84 ppb or 84% of the standard. This peak is due in main to the high VOC emission estimated for condensate loading which are considered conservative;
- For the extremely unlikely case that full emergency shutdown / flaring occurs (once in 10 year event) at the time of the worst case meteorology, the maximum ozone levels anywhere are predicted to be 92% of the NEPM standard; and
- Considering the BLNG and existing sources, there is negligible cumulative impact to the maximum ozone, particulate and NO_2 concentrations as the predicted concentrations are dominated by the concentrations from fires.

9 Predicted Local Concentrations

This section presents results from the local modelling using the model TAPM with predictions undertaken on a 500 m grid. Concentrations were predicted for NO_2, CO, SO_2, PM_{10} and $PM_{2.5}$, benzene, toluene, xylenes and H_2S. Predicted PM_{10} concentrations have been taken to be equal to $PM_{2.5}$ as the emissions from gas turbines, boilers and engines are predominantly less than 2.5 μm and can be assumed equivalent. These concentrations are then compared to the criteria adopted and conclusions drawn as to the impacts of the proposed BLNG.

9.1 Predicted Concentrations from the BLNG Precinct Alone

The predicted maximum concentrations from the BLNG Precinct for the various criteria are presented in **Table 9.1** and as a percentage of their criteria in **Table 9.2**. These have been presented for:

- Excluding existing sources;
- All four cases for the 50 Mtpa Precinct as this will be the ultimate capacity and therefore result in the highest concentrations; and
- The two 15 Mtpa cases that result in the highest concentrations; the LIGT and IS cases; and
- Three non routine scenarios for the LIGT LNG option as this option resulted in the highest concentrations for the pollutants closest to or that most exceeded the criteria.

These concentrations are the maximum concentrations predicted on the model grid, excepting for BTEX and H_2S which are presented for locations on land outside the buffer where the ambient health criteria could be taken to apply. This distinction has been made as the highest concentrations of BTEX occur right at the ship-loader where occupational health criteria apply (note, the comparison to occupational health criteria is not presented in this report). Presenting predictions at the ship-loader is considered not appropriate for comparison to the ambient health criteria.

9.1.1 Normal Operation - 50 Mtpa Precinct

Predicted concentrations from a 50 Mtpa Precinct under normal operation are presented in **Table 9.1**.

Table 9.1 Predicted Maximum Concentrations from BLNG (Excluding Background Levels)

Pollutant	Ave. Period	Conc. Statistic	Criteria Value	Units	Criteria Source	LIGT 15 Mtpa	IS 15 Mtpa	LIGT 50 Mtpa	MIGT 50 Mtpa	AGT 50 Mtpa	IS 50Mtpa	LIGT 50 Mtpa Start Up	LIGT 50 Mtpa Turn Down	LIGT 50 Mtpa Emergency
Carbon Monoxide	8-hour	Max	9000	ppb	NEPM	23.5	37.8	48.3	48.4	48.4	60.2	197	206	157
Nitrogen Dioxide	1-hour	Max	120	ppb	NEPM	33.6	33.6	35.8	36.7	37.0	38.2	42.6	37.0	35.8
	1-year	Ave	30	ppb	NEPM	0.83	1.41	2.05	2.34	1.79	3.07	3.30	3.69	2.09
Sulphur Dioxide	1-hour	Max	200	ppb	NEPM	40.7	40.7	44.2	44.5	44.5	44.5	44.5	44.5	44.2
	1-day	Max	80	ppb	NEPM	9.6	9.5	9.0	9.1	9.1	9.0	9.0	9.0	9.0
	1-year	Ave	20	ppb	NEPM	0.20	0.21	0.64	0.67	0.64	0.65	0.65	0.64	0.64
Particles as PM_{10}	1-day	Max	50	$\mu g/m^3$	NEPM	3.5	3.5	3.6	3.6	4.1	4.2	3.6	3.6	3.6
Particles as $PM_{2.5}$	1-day	Max	25	$\mu g/m^3$	NEPM	3.5	3.5	3.6	3.6	4.1	4.2	3.6	3.6	3.6
	1-year	Ave	8	$\mu g/m^3$		0.08	0.18	0.25	0.28	0.38	0.38	0.25	0.25	0.25
H_2S	Peak	99^{th}	1.38 to 4.8	$\mu g/m^3$	NSW	9.6	7.8	12.6	12.6	10.5	11.4	12.6	12.6	12.6
Including Ship-loading Emissions of BTEX														
Benzene	1-hour	99.9^{th}	29	$\mu g/m^3$	NSW	670	670	840	840	840	840	840	840	840
	Annual	Ave	5	$\mu g/m^3$	EU	1.9	1.9	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Ethyl benzene	1-hour	99.9^{th}	800	$\mu g/m^3$	NSW	13	13	19	19	19	19	19	19	19
Toluene	1-hour	99.9^{th}	360	$\mu g/m^3$	NSW	350	350	470	470	470	470	470	470	470
Xylenes	1-hour	99.9^{th}	190	$\mu g/m^3$	NSW	2.7	2.7	8	8	8	8	8	8	8
Excluding Ship-loading Emissions of BTEX														
Benzene	1-hour	99.9^{th}	29	$\mu g/m^3$	NSW	25.3	21.1	36.3	36.3	28.3	30.4	37.6	36.3	36.3
	Annual	Ave	5	$\mu g/m^3$	EU	0.53	0.45	0.85 (0.44)	0.85	0.89	0.93 (0.48)	0.85	0.85	0.85
Ethyl benzene	1-hour	99.9^{th}	800	$\mu g/m^3$	NSW	0.09	0.09	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Toluene	1-hour	99.9^{th}	360	$\mu g/m^3$	NSW	10.25	8.51	14.73	14.7	13.27	12.20	14.7	14.7	14.7
Xylenes	1-hour	99.9^{th}	190	$\mu g/m^3$	NSW	2.4	2.4	8.0	8.0	8.0	8.0	8.0	8.0	8.0

Notes:

1) The benzene annual average and maximum 1-hour concentrations for the 50 Mtpa case were predicted assuming 2 TCUs offline. This is conservative for predicting the annual average concentrations. The value in brackets is a more accurate estimate of the annual average concentration based on the probability of each TCU being offline for 10% of the year.
2) Highest concentration for H_2S and BTEX concentrations evaluated on land outside the buffer. Higher concentrations occur over-water.

Table 9.2 Predicted Maximum Concentrations from BLNG (Excluding Background Levels). Percentage (%) of Criteria

Pollutant	Ave. Period	Conc. Statistic	Criteria Value	Units	Criteria Source	LIGT 15 Mtpa	IS 15 Mtpa	LIGT 50 Mtpa	MIGT 50 Mtpa	AGT 50 Mtpa	IS 50Mtpa	LIGT 50 Mtpa Start Up	LIGT 50 Mtpa Turn Down	LIGT 50 Mtpa Emergency
Carbon Monoxide	8-hour	Max	9000	ppb	NEPM	0.3	0.4	0.5	0.5	0.5	0.7	2.2	2.3	1.7
Nitrogen Dioxide	1-hour	Max	120	ppb	NEPM	28	28	30	31	31	32	36	31	30
	1-year	Ave	30	ppb	NEPM	2.8	4.7	6.8	7.8	6.0	10	11	12	7.0
Sulphur Dioxide	1-hour	Max	200	ppb	NEPM	20	20	22	22	22	22	22	22	22
	1-day	Max	80	ppb	NEPM	12	12	11	11	11	11	11	11	11
	1-year	Ave	20	ppb	NEPM	1.0	1.0	3.2	3.3	3.2	3.2	3.2	3.2	3.2
Particles as PM_{10}	1-day	Max	50	$\mu g/m^3$	NEPM	6.9	6.9	7.2	7.1	8.1	8.3	7.2	7.2	7.2
Particles as $PM_{2.5}$	1-year	Ave	8	$\mu g/m^3$	NEPM	1.0	2.2	3.1	3.5	4.8	4.8	3.1	3.1	3.1
H_2S	Peak	99^{th}	1.38 to 4.8	$\mu g/m^3$	NSW	200	162	263	263	219	240	263	263	263
Including Ship-loading Emissions of BTEX														
Benzene	1-hour	99.9^{th}	29	$\mu g/m^3$	NSW	2320	2320	2900	2900	2900	2900	2900	2900	2900
	Annual	Ave	5	$\mu g/m^3$	EU	38.5	38.5	110	110	110	110	110	110	110
Ethyl benzene	1-hour	99.9^{th}	800	$\mu g/m^3$	NSW	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Toluene	1-hour	99.9^{th}	360	$\mu g/m^3$	NSW	98	98	131	131	131	131	131	131	131
Xylenes	1-hour	99.9^{th}	190	$\mu g/m^3$	NSW	1.4	1.4	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Excluding Ship-loading Emissions of BTEX														
Benzene	1-hour	99.9^{th}	29	$\mu g/m^3$	NSW	87	73	125	125	98	105	130	125	125
	Annual	Ave	5	$\mu g/m^3$	EU	11	9	17 (9)	17	18	19 (9.6)	17	17	17
Ethyl benzene	1-hour	99.9^{th}	800	$\mu g/m^3$	NSW	0.001	0.011	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Toluene	1-hour	99.9^{th}	360	$\mu g/m^3$	NSW	2.8	2.4	4.1	4.1	3.7	3.4	4.1	4.1	4.1
Xylenes	1-hour	99.9^{th}	190	$\mu g/m^3$	NSW	1.3	1.3	4.2	4.2	4.2	4.2	4.2	4.2	4.2

Notes:

1) The benzene annual average and maximum 1-hour concentrations for the 50 Mtpa case were predicted assuming 2 TCUs offline. This is conservative for predicting the annual average concentrations. The value in brackets is a more accurate estimate of the annual average concentration based on the probability of each TCU being offline for 10% of the year.
2) $PM_{2.5}$ 24-hour concentrations are not provided as a percent of the criteria as the NEPM goal is to gather sufficient data nationally to facilitate a review and does not set a number of allowable exceedances.
3) Highest concentration for H_2S and BTEX concentrations evaluated on land outside the buffer. Higher concentrations occur over-water.

9.1.1.1 NO_2, SO_2, PM_{10}, $PM_{2.5}$ and CO

Table 9.1 indicates that For NO_2, SO_2, PM_{10} and CO the predicted concentrations are well below the criteria; at most 32% of the 1-hour NO_2 NEPM standard, 22% of the 1-hour SO_2 standard, 8.3% of the NEPM PM_{10} standard and 0.7% of the CO 8-hour standard. Plots of those concentrations for the LIGT LNG case are presented in **Figure 9-1** to **Figure 9-7**;

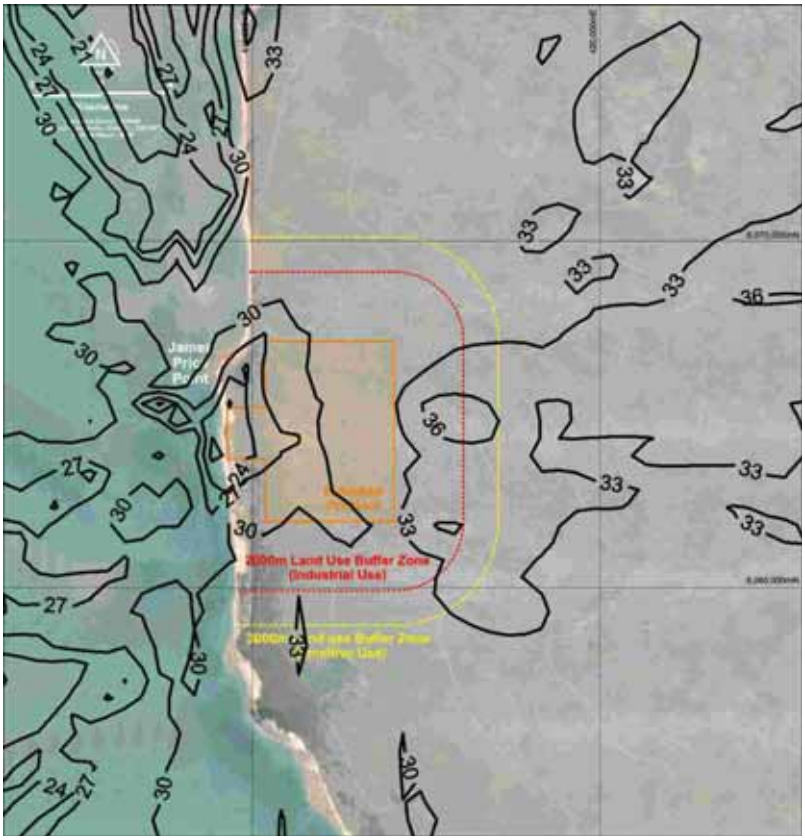


Figure 9-1 Predicted Maximum 1-hour NO_2 Concentrations (ppb) for a LIGT 50 Mtpa Precinct- Excluding Existing Sources

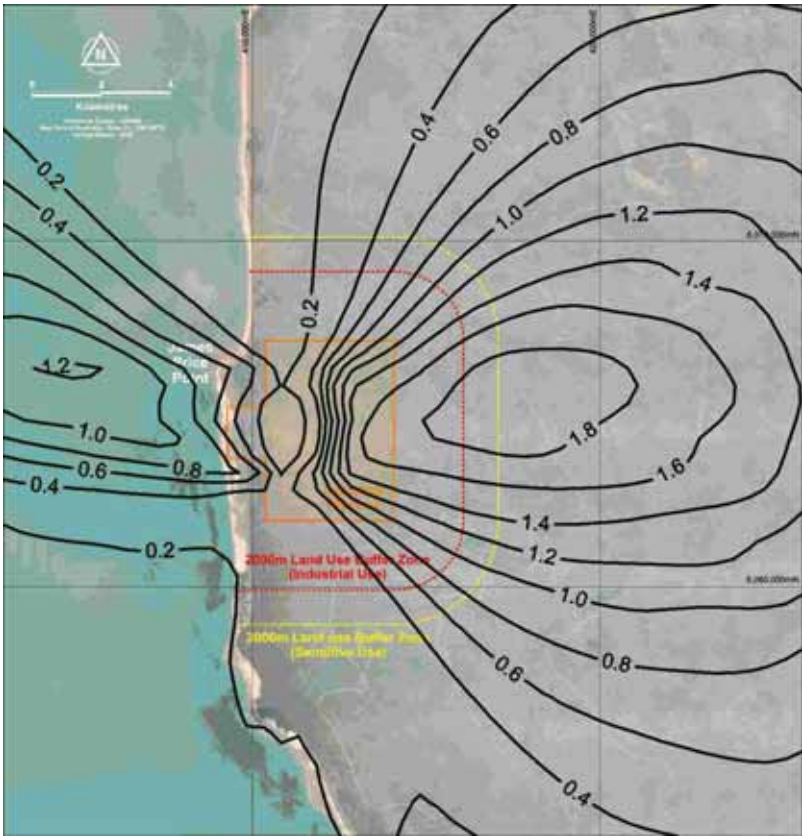


Figure 9-2 Predicted Annual Average NO_2 Concentrations (ppb) for a LIGT 50 Mtpa Precinct - Excluding Existing Sources

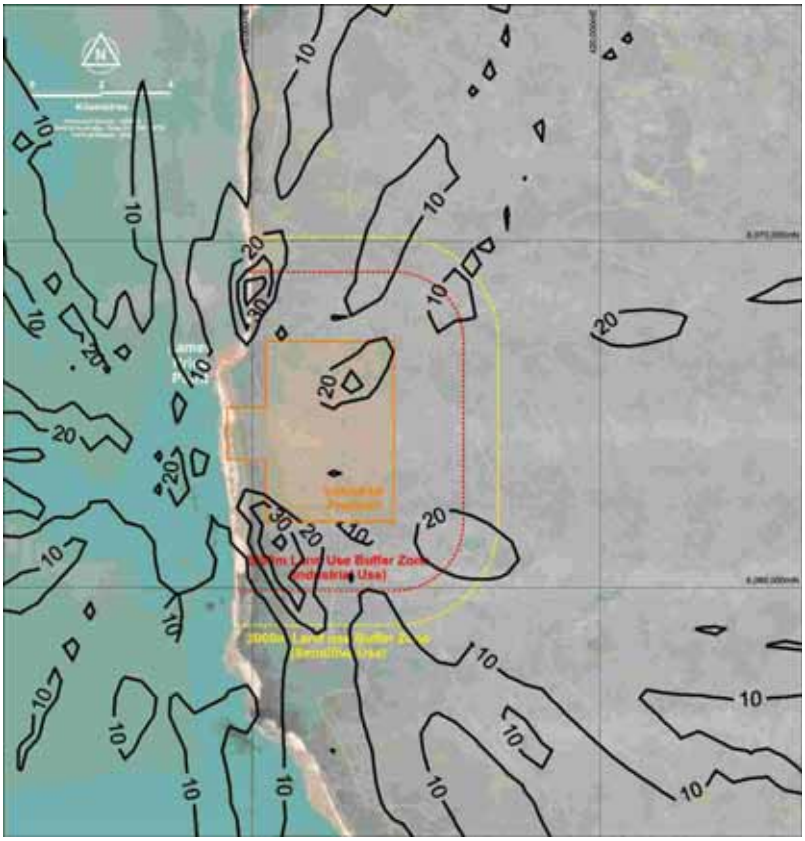


Figure 9-3 Predicted Maximum 1-hour SO_2 Concentrations (ppb) for a LIGT 50 Mtpa Precinct - Excluding Existing Sources

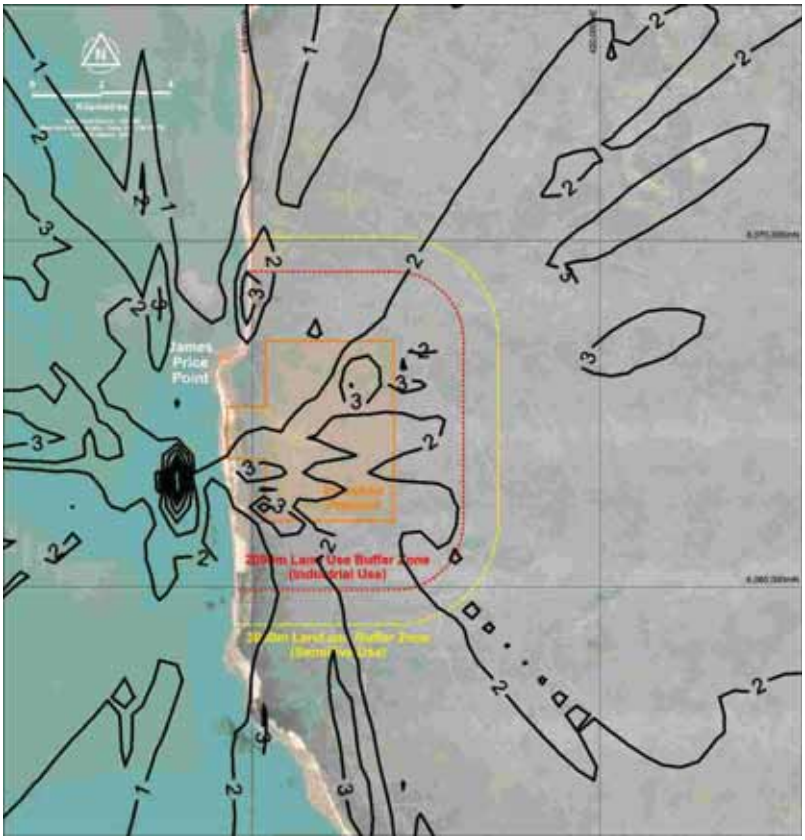


Figure 9-4 Predicted Maximum 24-hour SO_2 Concentrations (ppb) for a LIGT 50 Mtpa Precinct - Excluding Existing Sources

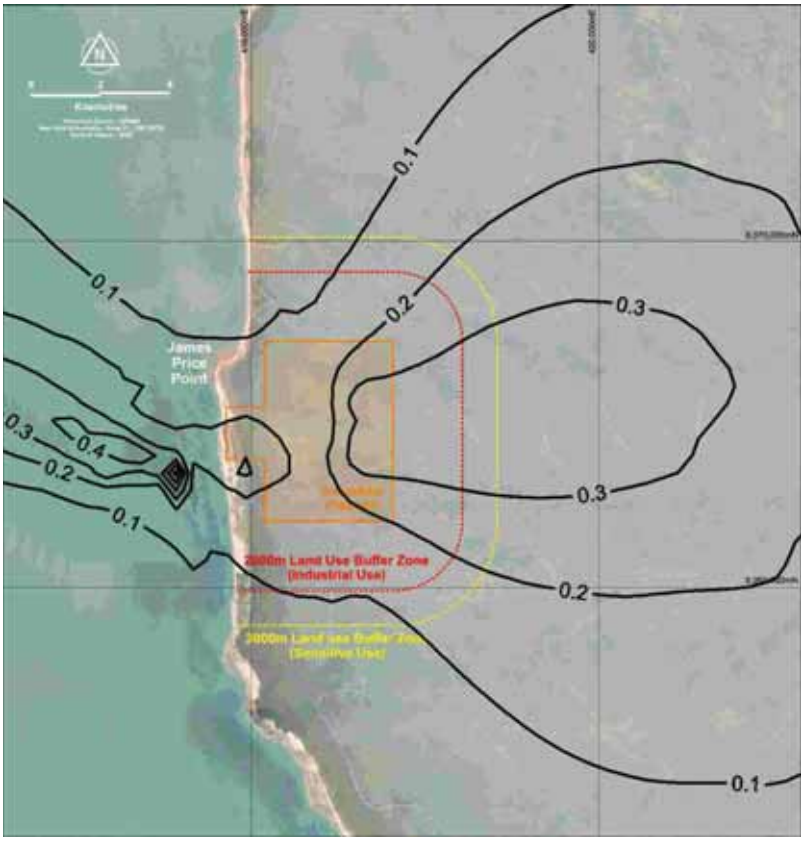


Figure 9-5 Predicted Annual Average SO_2 Concentrations (ppb) for a LIGT 50 Mtpa Precinct- Excluding Existing Sources

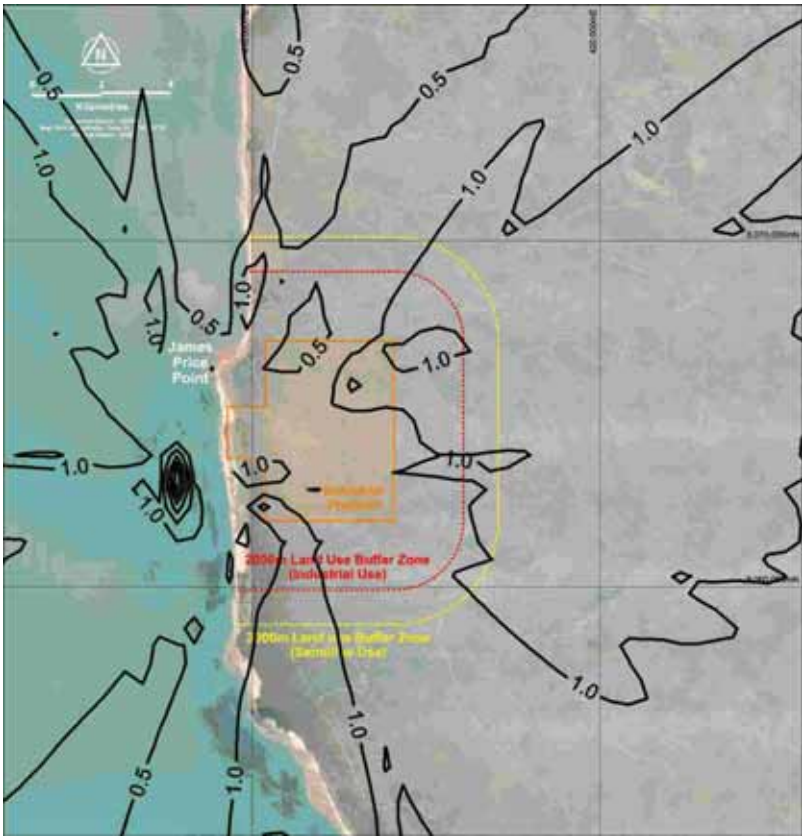


Figure 9-6 Predicted Maximum 24-hour PM_{10} (or $PM_{2.5}$) Concentrations (µg/m^3) for a LIGT 50 Mtpa Precinct - Excluding Existing Sources

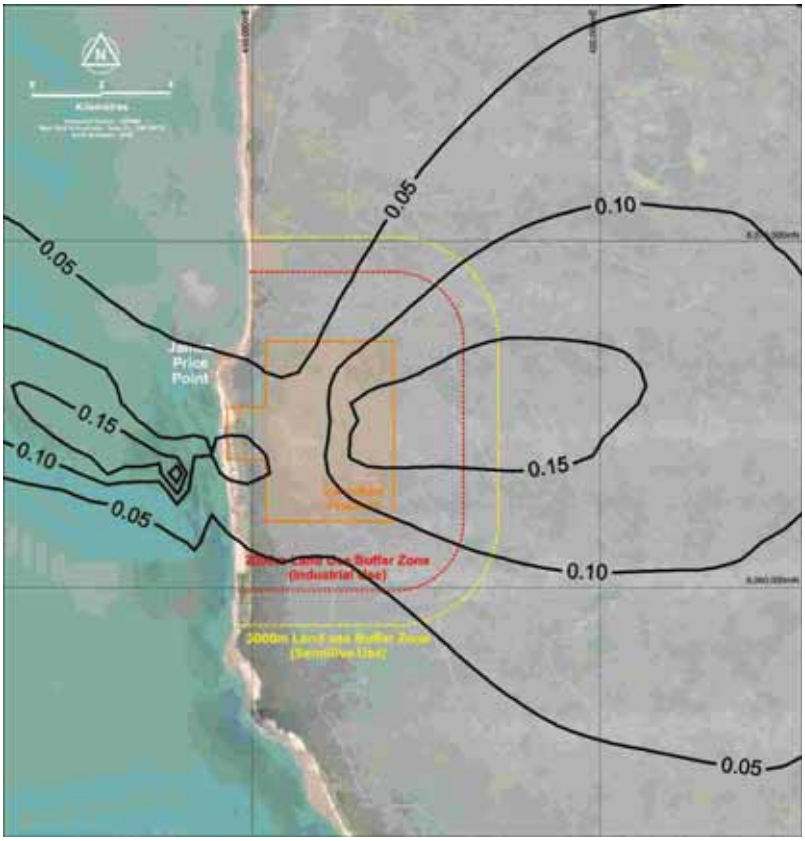


Figure 9-7 Predicted Annual Average PM_{10} (or $PM_{2.5}$) Concentrations (µg/m^3) for a LIGT 50 Mtpa Precinct - Excluding Existing Sources

Comparison between the four technologies for these substances indicates that the IS case results in the highest concentrations with the LIGT, MIGT and AGT technologies resulting in similar, but lower concentrations. The IS technology result in higher concentrations as though it has lower emissions, the lower exhaust temperatures, due to the higher recovery of waste heat, results in less plume rise and therefore higher ground level concentrations.

9.1.1.2 BTEX

The pollutants of most concern (closest to or exceed their criteria) are benzene and H_2S and to a lesser extent toluene. For comparison to the benzene NSW modelling guidance criteria, the concentrations were predicted assuming that 2 TCUs are always offline to approximate the assumed 90% availability of the TCUs. This assumption is necessary in that it simplifies the estimation of the 99.9th percentile prediction from a random process, whilst still being slightly conservative. Other options to predict the concentrations such as assuming that 1 and 3 TCUs are offline continuously would result in either underestimating or overestimating the emissions and are not presented. Modelling 1 TCU not operating continuously understates the emissions as 2 or more TCUs may be down with higher emissions for 26% of the time. Modelling 3 TCUs offline continually overstates the emissions as 3 or more TCUs are offline for only 7% of the time (see **Section 3.2**). Note that the modelled concentrations are conservative being based on:

- 90% availability of each TCU. In practice an availability of at least 95 to 97% is expected;
- The Precinct absolute maximum size of 50 Mtpa;
- High BTEX feed gas, with it being very likely that some proponents will have lower BTEX in the feed gas; and
- Possibility that the condensate containing BTEX will be removed offshore for some proponents, therefore resulting in lower emissions.

The results for 2 TCU offline are presented in **Figure 9-8** indicating that the NSW modelling guidance is exceeded throughout the model domain with peak 9th highest concentrations of several thousand µg/m^3 near the ship-loader, decreasing to 750 µg/m^3 at the south west corner of the buffer and to about 25 µg/m^3 at the SE corner of the model grid.

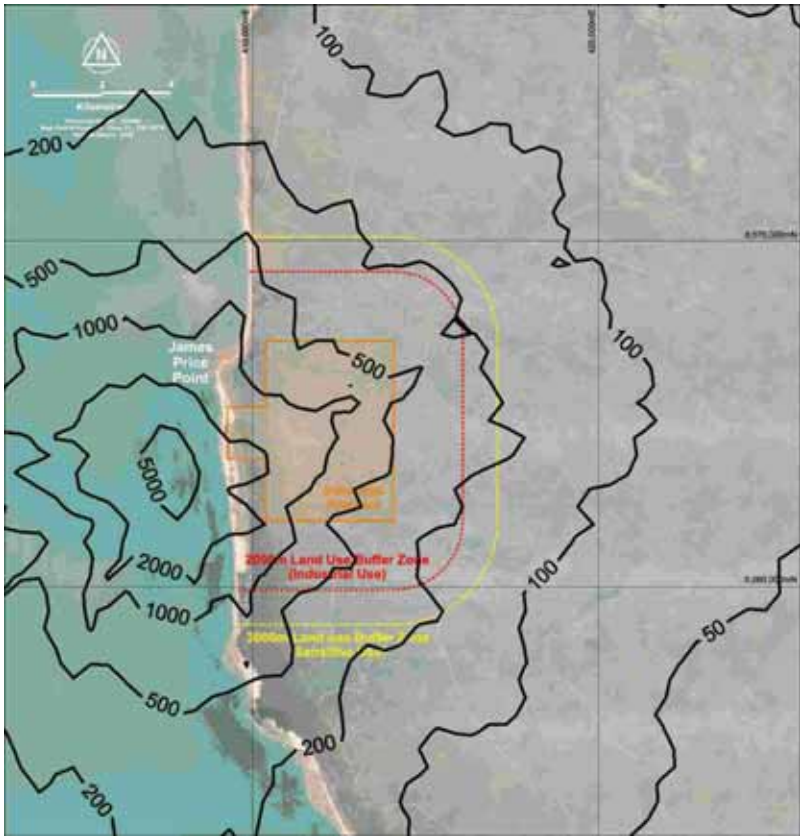


Figure 9-8 Predicted 99.9th Percentile 1-hour Benzene Concentrations (µg/m^3) for a LIGT 50 Mtpa Precinct Including Condensate Ship-loading. Modelling Conducted Assuming 2 TCUs are Offline Continuously.

The modelling clearly indicates that emissions from condensate loading to ships is the dominant source, with other sources such as the AGRU emissions when a TCU is offline not showing up in the contours.

A more realistic estimate of the area exceeding the NSW benzene guidance level can be undertaken by estimating the number of exceedances using the probability that the TCUs are offline using the methodology described in **Section 6.10**. The results are presented in **Figure 9-9** indicating that the number of exceedances of the NSW modelling guideline range from 10 in the SE corner (and therefore just exceeding the NSW criteria of 9) to over 1000 at the ship.

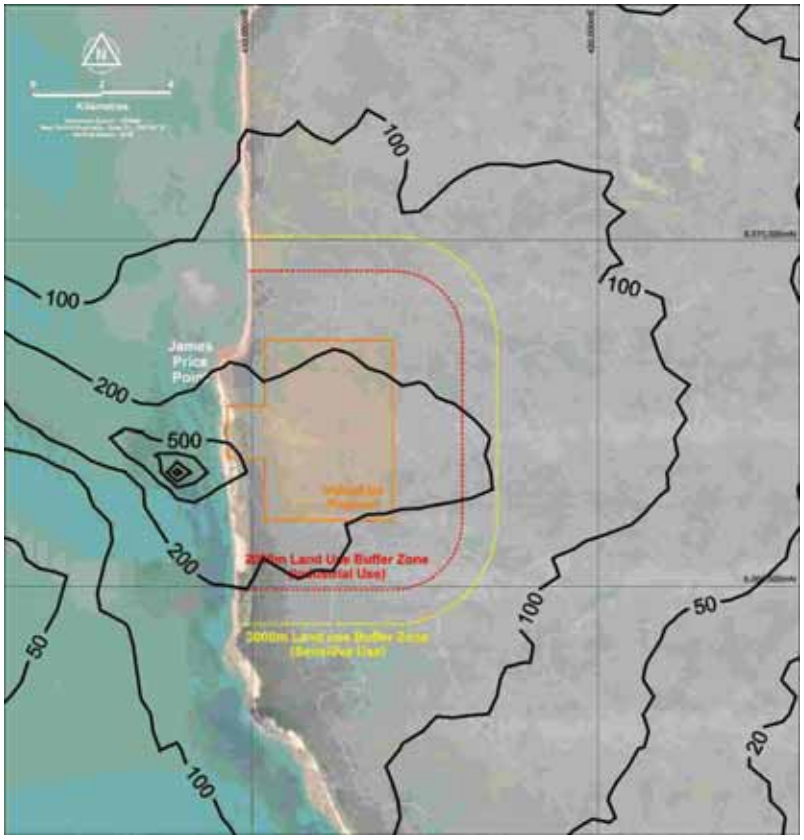


Figure 9-9 Predicted Annual Number of Exceedances of Benzene 1-hour Concentration of 29 µg/m^3 for a LIGT 50 Mtpa Precinct including Condensate Ship-Loading. Modelling Conducted using the Probabilities of the TCUs being Offline According to Section 6.10.

The NSW modelling guidelines as discussed in **Section 4.2** are not limits but guidelines and have been developed using large conservative uncertainty or safety factors. Therefore that the values are exceeded do not necessarily indicate that adverse impacts will occur. For comparison the Californian OEHHA have developed what is argued to be a more applicable acute criteria, of a 6-hour 1300 µg/m^3 level, which is well above the concentrations predicted here. This criteria as discussed in **Section 4.2.1** has been used in many assessments in Australia, including the Worsley Alumina refinery expansion.

Of more relevance for assessing benzene is the annual average criteria which is based on the studies of carcinogenicity of benzene and does not require the uncertainty correction factors as used in the NSW guidelines. **Table 9.1** and **Table 9.2** and **Figure 9-10** present the predicted concentrations assuming the probabilities of the TCUs being offline. This indicates that the concentrations will be at most 5.5 µg/m^3 (110% of the European standard) just at the south western edge of the buffer, near the coast and decrease rapidly with distance away from this area.

Therefore, though the short term benzene levels exceed the NSW modelling guidance (or investigation level) investigation to over 10 km from the buffer, using what is considered the more appropriate annual average criteria indicate that benzene levels will just exceed European standard for a small area outside the buffer.

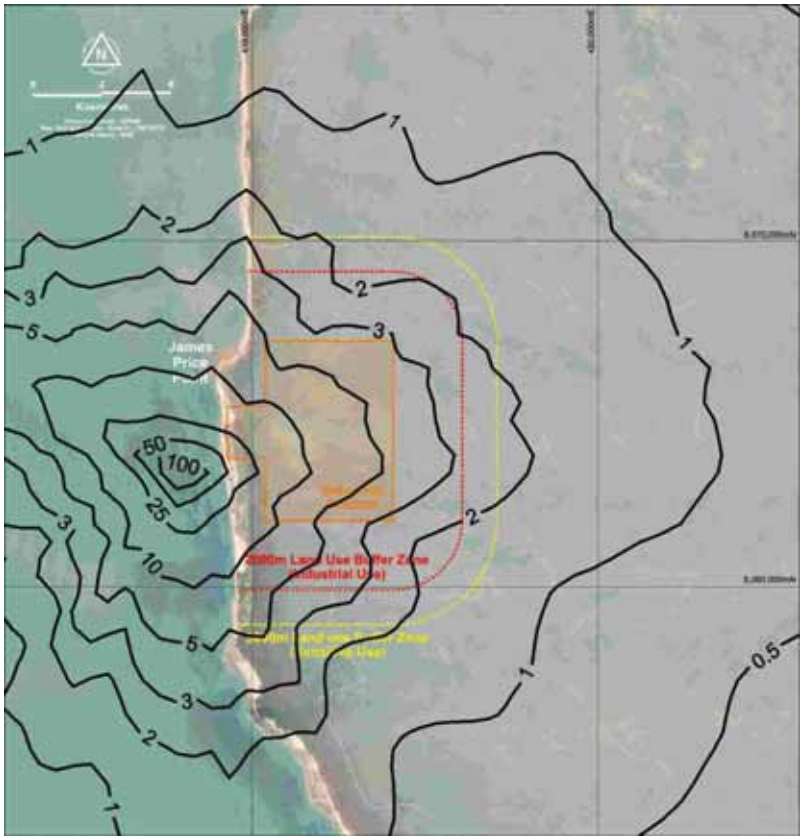


Figure 9-10 Predicted Annual Average Benzene Concentrations (µg/m^3) for a LIGT 50 Mtpa plant - Excluding Existing Sources. Modelling Conducted using the Probabilities of the TCUs being Offline According to Section 6.10.

9.1.1.3 Predicted Benzene Concentrations without Condensate Ship Loading Emissions

Given the concentrations predicted of benzene, as a sensitivity test a model run was conducted without emissions from condensate ship loading. In this situation the major source of benzene will be when the TCUs do not operate and the AGRU emissions are vented with the gas turbine exhausts. Note, this prediction is in fact very similar to that which would occur if the NPI emission factors were used for estimating ship-loading emissions, as the NPI emissions are around 380 times less than that estimated here by Woodside (see **Section 3.4**).

The results from this modelling are presented in **Figure 9-11** to **Figure 9-13** which can be compared to the results including condensate ship-loading emissions in **Figure 9-8** to **Figure 9-10**.

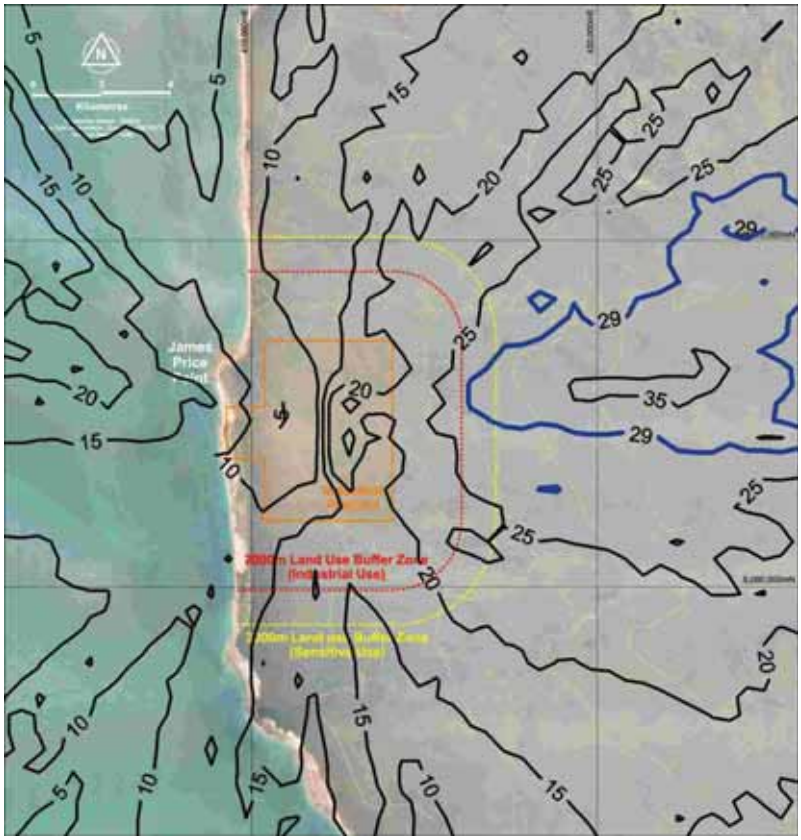


Figure 9-11 Predicted 99.9th Percentile1-hour Benzene Concentrations (µg/m^3) for a LIGT 50 Mtpa Precinct excluding Condensate Ship loading – Blue Line NSW Modelling Guideline. Modelling Conducted Assuming 2 TCUs Offline Continuously.

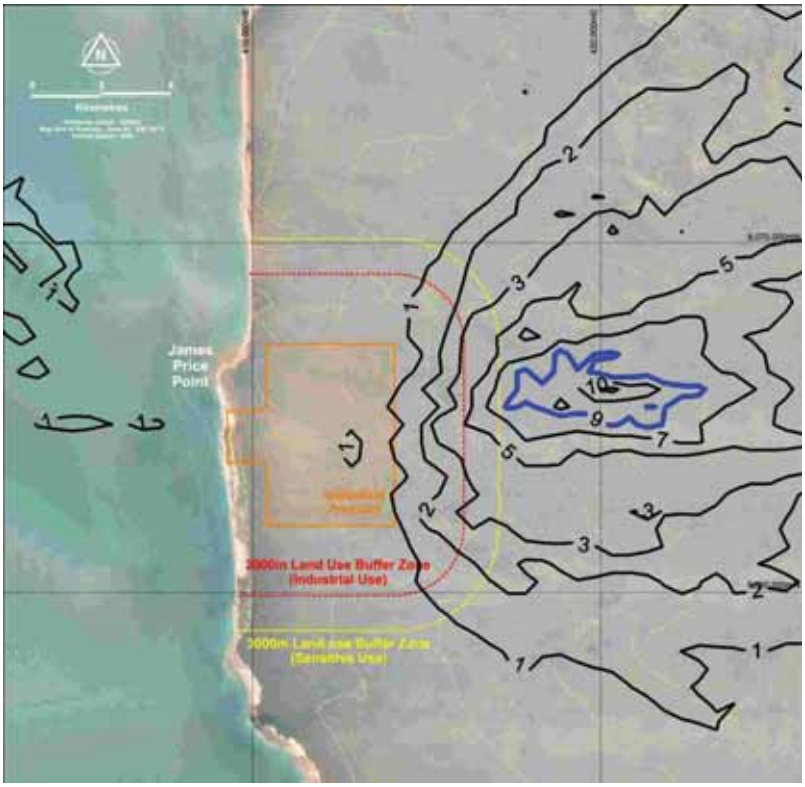


Figure 9-12 Predicted Annual Number of Exceedances of Benzene 1-hour Concentration of 29 µg/m^3 for a LIGT 50 Mtpa Precinct excluding Condensate Ship Loading - Blue Line NSW Modelling Guideline. Modelling Conducted using the Probabilities of the TCUs being Offline According to Section 6.10.

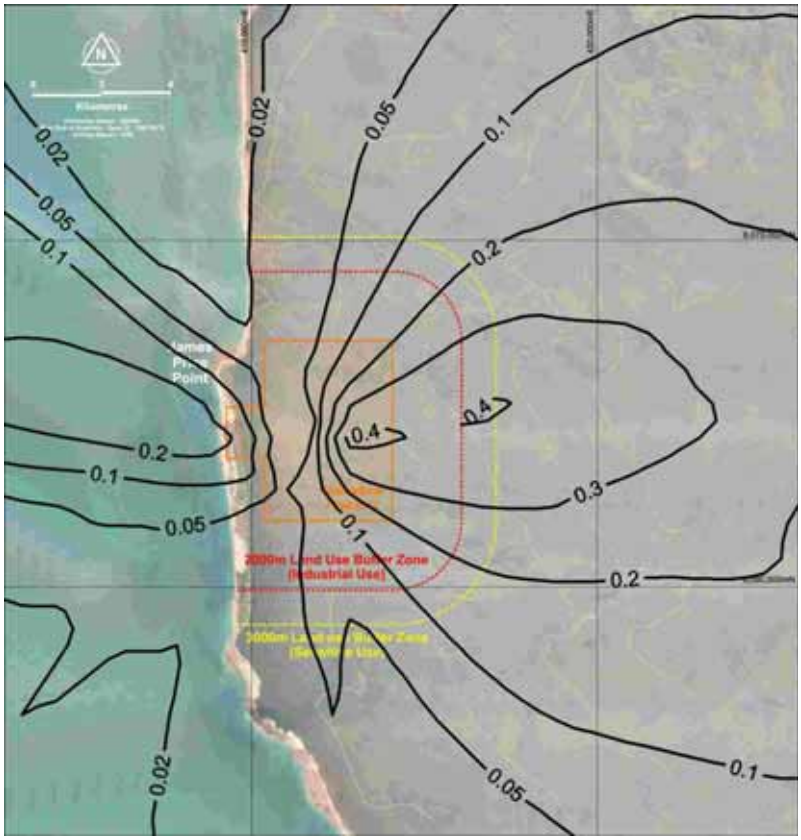


Figure 9-13 Predicted Annual Average Benzene Concentrations (µg/m^3) for a LIGT 50 Mtpa plant excluding Ship loading emissions - Excluding Existing Sources. Modelling Conducted using the Probabilities of the TCUs being Offline According to Section 6.10.

Figure 9-11 to **Figure 9-13** indicate significantly lower benzene concentrations with concentrations of toluene, xylenes and ethyl benzene being well below the NSW modelling guidelines. **Figure 9-11** presents predicted concentrations assuming conservatively that 2 TCU are not operating for the entire year indicating there will be an area to the west of the Precinct that exceeds the NSW modelling guidelines. Modelling the operations more realistically taking into account the probabilities that the TCUS operate (see **Figure 9-12**) indicate that this area will be reduced with only a small are just exceeding the guidelines.

Figure 9-13 presenting the annual averages indicate using the probability approach for TCU emissions for the LIGT case indicates that the highest concentrations are 0.44 µg/m^3 or 9.0% of the annual European criteria. For the other LNG scenarios considered the maximum annual concentration is 0.48 µg/m^3 which is only 9.6% of the criteria.

Therefore, without emissions from condensate loading, though the short term benzene levels just exceed the NSW modelling guidance (or investigation level), considering the more appropriate annual average criteria indicate that benzene levels will be acceptable.

9.1.1.4 Hydrogen Sulphide

For H_2S, if two TCUs are offline continuously H_2S is predicted to exceed the equivalent NSW modelling guidance for a single residence (peak 1-second 99th percentile value of 4.8 µg/m^3) to past the edge of the

model domain (probably to 30km from the buffer) for the LIGT case (see **Figure 9-14**). This will be slightly less for the AGT and IS case. Using the actual probabilities that the TCUs may be offline, the number of hours with an exceedance of the 1-second criteria is presented in **Figure 9-15**. This shows a reduced area with a region up to 9 km to the east exceeding the criteria.

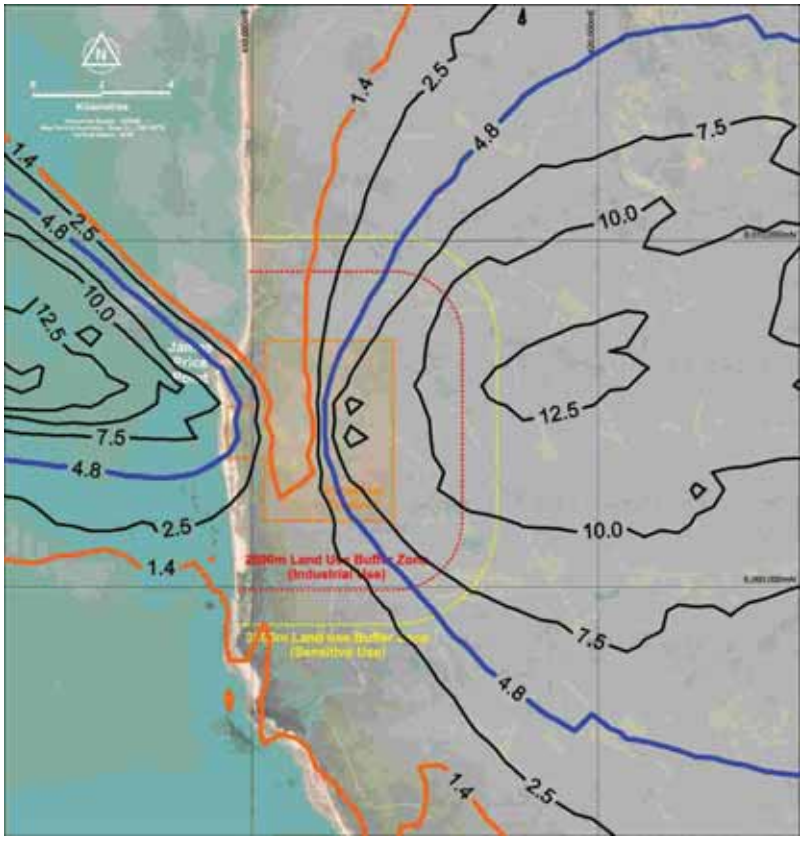


Figure 9-14 Predicted 99th Percentile 1-second H_2S Concentrations (µg/m^3) for a LIGT 50 Mtpa Precinct with H_2S Concentration in the feed gas of 20.5 ppm. Orange and blue contours – NSW Criteria. Modelling Conducted Assuming 2 TCUs Offline Continuously.

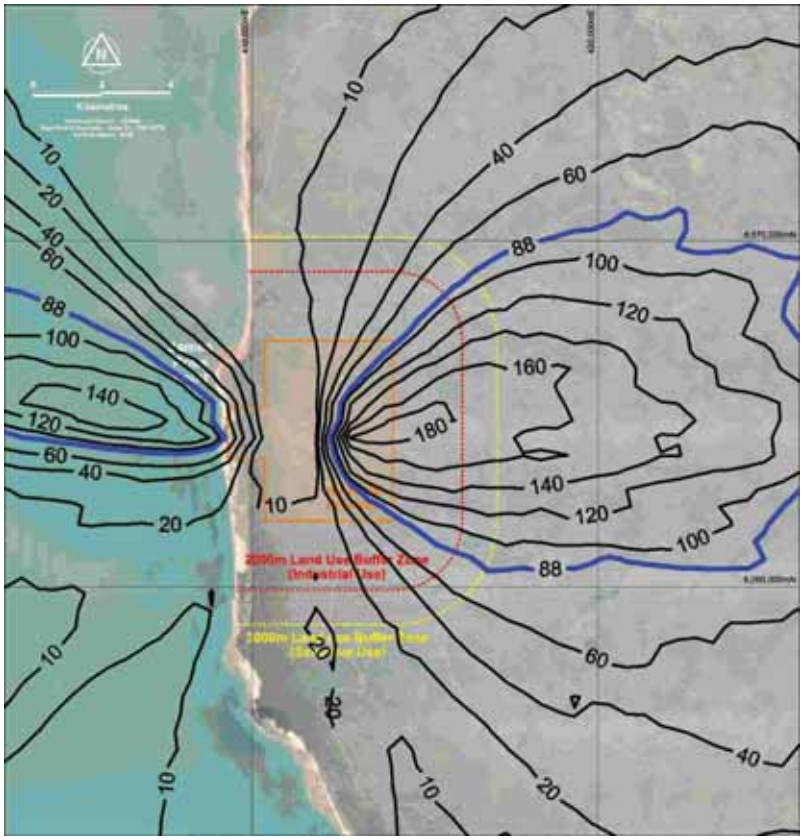


Figure 9-15 Predicted Annual number of hours in which an exceedance of a 1-second H_2S concentration of 4.8 µg/m^3 occurs for a LIGT 50 Mtpa Precinct with H_2S Concentration in the feed gas of 20.5 ppm. Blue Contour is the 99th Percentile or 88th highest hour in a year. Modelling Conducted using the Probabilities of the TCUs being Offline.

Figure 9-16 presents the number of hours with 1-second concentration within that hour greater than 1.38 µg/m^3. The area inside the 88th highest hour value (the 99th percentile) corresponds to the region where the NSW criteria for urban areas and very sensitive receptors (e.g. hospitals) is exceeded. This area extends past the model domain and probably extends to 20 to 30km to the east of the proposed buffer.

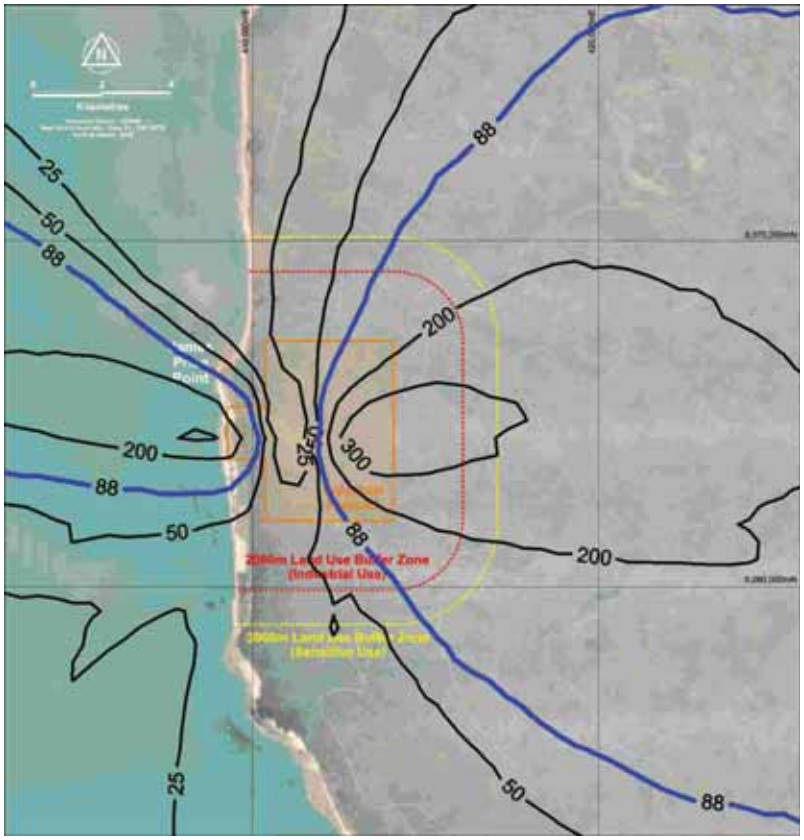


Figure 9-16 Predicted Annual number of hours in which an Exceedances of a 1-second H_2S concentration of 1.38 µg/m^3 occurs for a LIGT 50 Mtpa Precinct. Blue Contour is the 99th Percentile or 88th highest hour in a year. Modelling Conducted using the Probabilities of the TCUs being Offline According to Section 6.10.

In the area exceeding the NSW criteria the H_2S levels will be above the odour threshold of about 1.2 µg/m^3 for short periods of time and would be recognizable by its characteristic rotten egg gas smell. In this area the maximum 1-second concentration is predicted to be about 50 µg/m^3. At this level, though odorous, the H_2S will not pose any health risk.

The Western Australian Health Department have recently set exposure limits for health effects in response to hydrogen sulphide issues at Port Geographe, Busselton. For the shortest averaging period this is 2 ppm (3,030 µg/m^3 at 0 deg C) for a 30 minute averaging time (DEH, 2009) which is 60 times higher than the maximum concentration predicted here.

Also to place the predicted levels in context the concentrations predicted will be similar to that experienced in Perth suburbs due to bore water usage.

9.1.1.5 Sensitivity Tests for H_2S Feed Gas Concentrations

The predictions of H_2S in **Section 9.1.1.5** are based on conservative assumptions of a maximum expected H_2S in the feed gas (the worst case expected in the worst gas field), absolute maximum Precinct size of 50 Mtpa and a probability of the TCUs being online of 90%. Measurements of H_2S in the drilling program found H_2S concentrations ranging from 4 to 7 ppm. These have been increased for modelling purposes to take into account the temperature variation in the fields and to allow for

uncertainty to arrive at the maximum concentration of 20.5 ppm. In practise it is expected that a more realistic, but still very conservative estimate of the H_2S concentration would be 13 ppm and that even at 10 ppm the concentrations would still be above the average for the gas fields.

To assess the impacts of the lower expected H_2S concentrations **Figure 9-17** to **Figure 9-18** present the predicted number of hours of exceedance of the 1-second 4.8 µg/m^3 level for H_2S feed gas concentrations of 13 and 10 ppm. These figures indicate a marked reduction in the area exceeding the single residence criteria from the 20.5 ppm case (see **Figure 9-15**) with all areas meeting this criteria for 10 ppm feed gas.

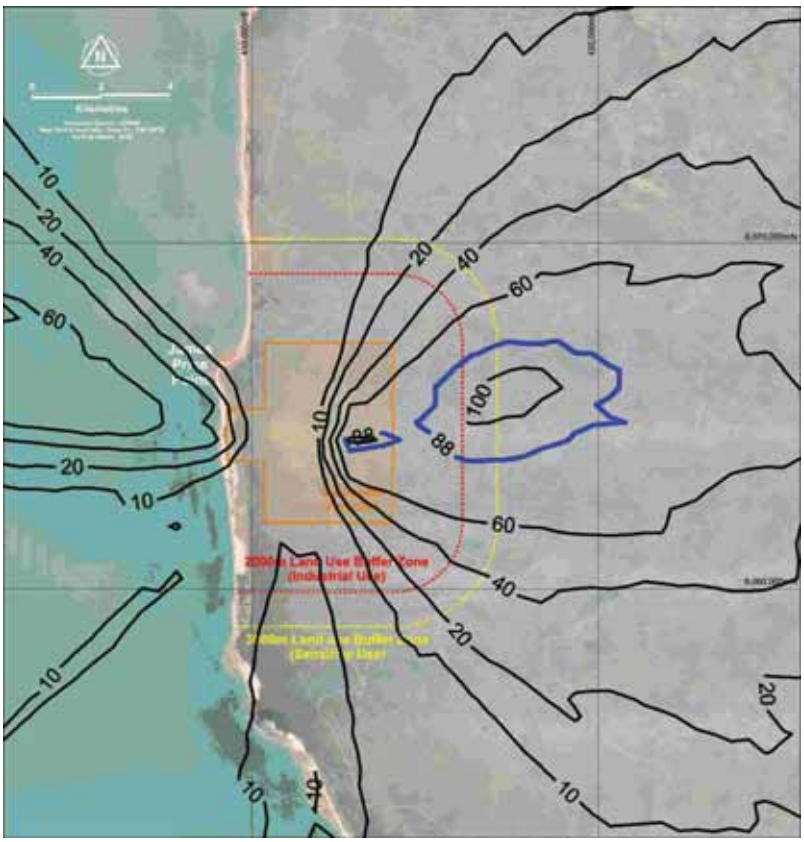


Figure 9-17 Predicted Annual number of hours in which an exceedance of a 1-second H_2S concentration of 4.8 µg/m^3 occurs for a LIGT 50 Mtpa Precinct with H_2S Concentration in the feed gas of 13 ppm. Blue Contour is the 99th Percentile or 88th highest hour in a year. Modelling Conducted using the Probabilities of the TCUs being Offline According to Section 6.10.

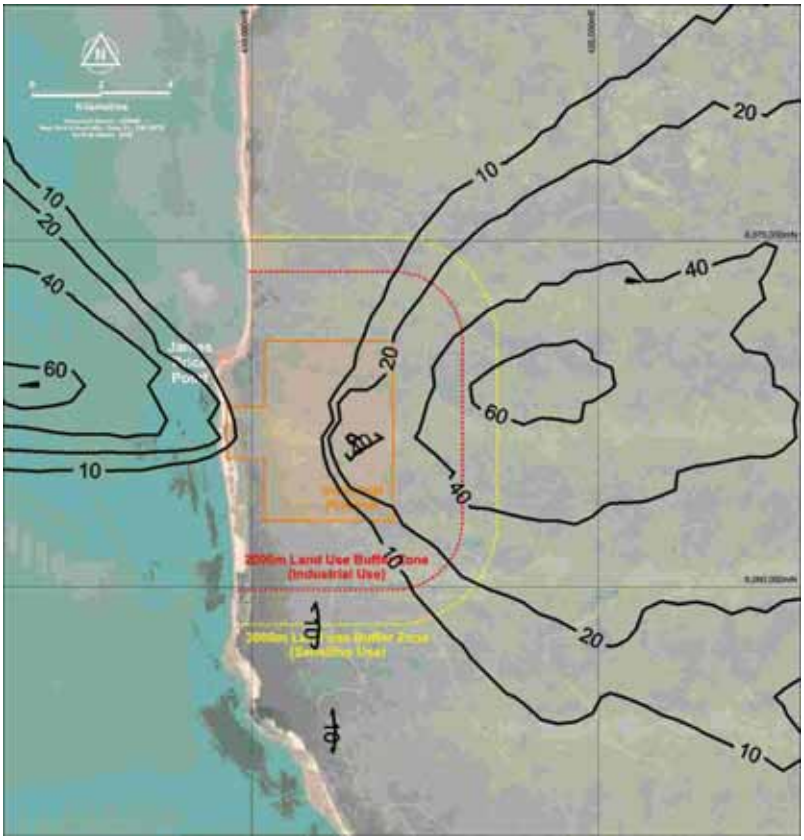


Figure 9-18 Predicted Annual number of hours in which an exceedance of a 1-second H_2S concentration of 4.8 µg/m^3 occurs for a LIGT 50 Mtpa Precinct with H_2S Concentration in the feed gas of 10 ppm. Blue Contour is the 99th Percentile or 88th highest hour in a year. Modelling Conducted using the Probabilities of the TCUs being Offline According to Section 6.10.

The number of hours of exceedances of a 1 second level of 1.38 µg/m^3 is presented in **Figure 9-19** and **Figure 9-20** for H_2S feed gas concentrations of 13 and 10 ppm. These show a smaller reduction in the number of hours from the 20.5 ppm case (see **Figure 9-16**) with the area exceeding the criteria occurring to an estimated 20 km from the sources.

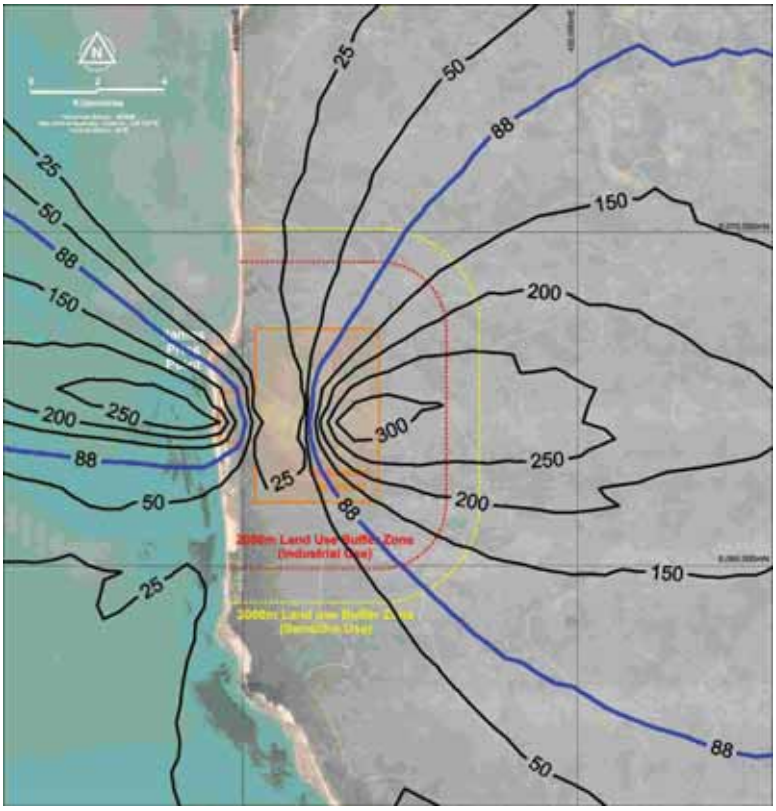


Figure 9-19 Predicted annual number of hours in which an exceedance of a 1-second H_2S concentration of 1.38 µg/m^3 occurs for a LIGT 50 Mtpa Precinct with H_2S Concentration in the feed gas of 13 ppm). Blue Contour is the 99th Percentile or 88th highest hour in a year. Modelling Conducted using the Probabilities of the TCUs being Offline.

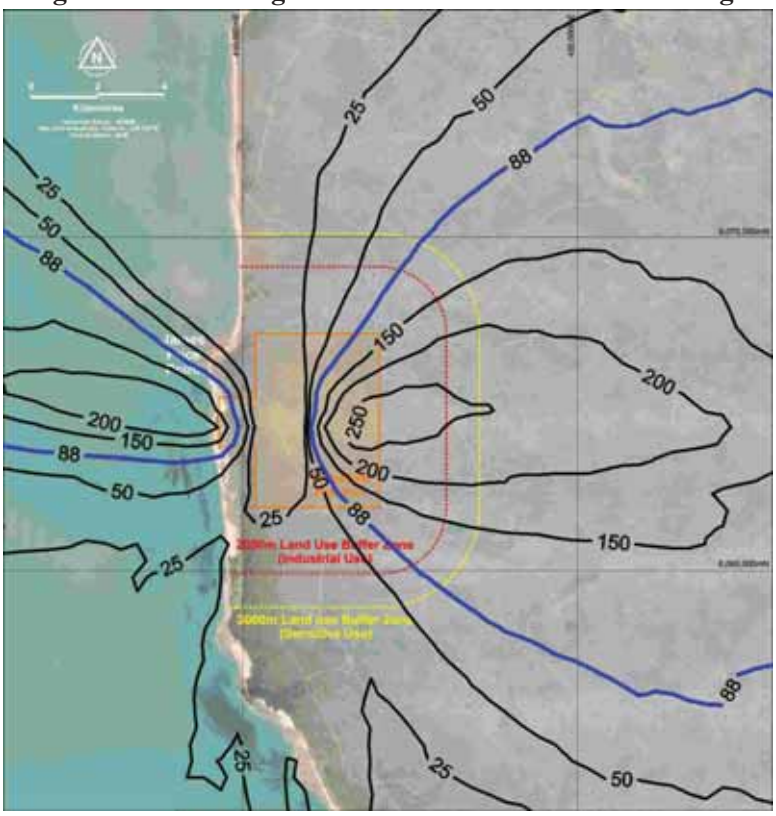


Figure 9-20 Predicted Annual number of hours in which an exceedance of a 1-second H_2S concentration of 1.38 µg/m^3 occurs for a LIGT 50 Mtpa Precinct with H_2S Concentration in the feed gas of 10 ppm). Blue Contour is the 99th Percentile or 88th highest hour in a year. Modelling Conducted using the Probabilities of the TCUs being Offline.

9.2 Non Routine Operations – 50 Mtpa

Predicted concentrations form non routine operations are also presented in **Table 9.1** and **Table 9.2**. These assume that the operations occur for the entire year, which is a very conservative assumption given the small number of hours that these events will occur.

The results in **Table 9.1** and **Table 9.2** show generally little or no change in the concentrations from the normal operations. The exceptions to this are for CO with concentrations that are three times the normal operations, but are still relatively low at about 2% of the NEPM standard, and nitrogen dioxide and particulate matter which increase slightly. These increases are due to the higher emissions and lower exhaust temperature and velocity and therefore lower plume rise from the LNG train compressors when in turn down mode. The 9th highest (99.9th percentile) 1-hour benzene concentration (excluding ship loading emissions) increases slightly for the start up case as there is a small amount of BTEX estimated in the flare emissions.

9.3 Cumulative Concentrations - BLNG Plant and Existing Sources

9.3.1 Existing Concentrations

Existing maximum concentrations of the pollutants of concern have been listed in **Table 5.4**. These have been derived from monitoring data in nearby regions and estimated by the CTM modelling. The background maximum concentrations are not used in a cumulative modelling approach as it would be extremely unlikely that the maximum background concentrations would occur at the same time as concentrations from a new plant. This occurs as conditions that lead to maximum concentrations from a fire at Broome such as under strong winds from the east would be unlikely to be the conditions that lead to highest concentrations from the BLNG, which would be lighter winds from the north. As such in modelling assessments the following methodology is adopted. If monitored and modelled data for the same period exists then the data are added together on a hourly basis. This is the process used in CTM where CTM was explicitly modelling the background sources. If no data exists then some percentile of the background data is added to the modelled maximums to recognise that the maximums from both do not occur at the same time. For this cumulative assessment the WA modelling guidance does not provide a percentile. The Victorian modelling guidance recommends that the 70th percentile 1-hour levels are used whilst the NSW modelling guidance has a tiered approach. For this assessment the estimated 70th percentile concentrations have been used as estimated or modelled by CTM for background levels. These are listed in **Table 9.3**.

Table 9.3 Estimated Existing Background Concentrations for Modelling

Pollutant	Ave. Period	Statistic	Concentration		Source of Estimate
			ppb	($\mu g/m^3$)	
Nitrogen Dioxide	1-hour	70th Percentile	1.5	3.1	Modelling from Kimberley Fires and Dampier Measurements
	1-year	Average	0.5	1.0	
Sulphur Dioxide	1 hour	70th Percentile	0	0	Dampier Measurements
	24-hour		0	0	
	Annual	Average	0	0	
Ozone	1-hour	70th Percentile	25	53.5	Dampier measurements and modelling from Kimberley Fires
Carbon Monoxide	8-hour	70th Percentile	100	125	Dampier Measurements
	Annual	Average	65	81	
Benzene	1-hour	70th Percentile	0.02	0.07	Dampier Measurements
	Annual	Average	0.02	0.07	
Toluene	1-hour	70th Percentile	0.05	0.2	Dampier Measurements
	24-hour	70th Percentile	0.05	0.2	
	Annual	Average	0.05	0.2	
Xylenes	24-hours	70th Percentile	0.015	0.07	Dampier Measurements
	Annual	Average	0.015	0.07	
H_2S	Peak	70th Percentile	0	0	Expected to be negligible
PM_{10}	24-hour	70th Percentile	-	20 – 25	Level recorded in the Pilbara from fires
$PM_{2.5}$	24-hour	70th Percentile	-	7	Levels recorded in the Pilbara
	Annual	Average		5	

Note: Conversion between $\mu g/m^3$ and ppb at 101.3 kPa and 0 deg C

9.3.2 Predicted Cumulative Concentrations

Predicted concentrations from the BLNG with existing background concentrations as defined in **Table 9.3** are presented in **Table 9.4** and **Table 9.5**. For most substances there is little or no change from that predicted from the BLNG in isolation as existing background levels are low. The exception to this is PM_{10} and $PM_{2.5}$ where the concentrations increase to 54% and 71% if the criteria. This increase is due to the relatively high background particulate levels with the BLNG emissions adding little to these. For benzene and H_2S the existing concentrations are negligible and therefore no cumulative increase occurs.

Table 9.4 Predicted Maximum Concentrations from BLNG (Including Background Levels)

Pollutant	Ave. Period	Conc. Statistic	Value of Criteria	Units	Criteria Source	LIGT 15 Mtpa	IS 15 Mtpa	LIGT 50 Mtpa	MIGT 50 Mtpa	AGT 50 Mtpa	IS 50Mtpa	LIGT 50 Mtpa Start Up	LIGT 50 Mtpa Turn Down	LIGT 50 Mtpa Emergency
Carbon Monoxide	8-hour	Max	9000	ppb	NEPM	124	138	148	148	148	160	297	306	257
Nitrogen Dioxide	1-hour 1-year	Max Ave	120 30	ppb ppb	NEPM NEPM	35.1 1.3	35.1 1.9	37.3 2.6	38.2 2.8	38.5 2.3	39.7 3.6	44.1 3.8	38.5 4.2	37.3 2.6
Sulphur Dioxide	1-hour 1-day 1-year	Max Max Ave	200 80 20	ppb ppb ppb	NEPM NEPM NEPM	40.7 9.6 0.20	40.7 9.5 0.21	44.2 9.0 0.64	44.5 9.1 0.67	44.5 9.1 0.64	44.5 9.0 0.65	44.5 9.0 0.65	44.5 9.0 0.64	44.2 9.0 0.64
Particles as PM_{10}	1-day	Max	50	µg/m^3	NEPM	25.5	25.5	25.6	25.6	26.1	26.2	25.6	25.6	25.6
Particles as $PM_{2.5}$	1-day 1-year	Max Ave	25 8	µg/m^3 µg/m^3	NEPM	10.5 5.1	10.5 5.2	10.6 5.3	10.6 5.3	11.1 5.4	11.2 5.4	10.6 5.2	10.6 5.2	10.6 5.3
H_2S	1-hour	99th	0.47 to 1.6	µg/m^3	NSW	3.2	2.6	4.53	4.53	3.5	3.8	4.53	4.53	4.53
Including Ship-loading Emissions of BTEX														
Benzene	1-hour Annual	99.9th Ave	295	µg/m^3 µg/m^3	NSW EU	672 2.0	672 2.0	840 5.6	840 5.6	840 5.6	840 5.6	840 5.6	840 5.6	840 5.6
Ethyl benzene	1-hour	99.9th	800	µg/m^3	NSW	14.3	14.3	19	19	19	19	19	19	19
Toluene	1-hour	99.9th	360	µg/m^3	NSW	352	352	470	470	470	470	470	470	470
Xylenes	1-hour	99.9th	190	µg/m^3	NSW	2.8	2.8	8.1	8.1	8.1	8.1	8.1	8.1	8.1
Excluding Ship-loading Emissions of BTEX														
Benzene	1-hour Annual	99.9th Ave	29 5	µg/m^3 µg/m^3	NSW EU	25.4 0.6	21.2 0.5	36.4 0.9	36.4 0.9	28.4 1.0	30.5 1.0	37.6 0.9	36.4 0.9	36.4 0.9
Ethyl benzene	1-hour	99.9th	800	µg/m^3	NSW	0.2	0.2	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Toluene	1-hour	99.9th	360	µg/m^3	NSW	10.5	8.7	14.9	14.9	13.5	12.4	14.9	14.9	14.9
Xylenes	1-hour	99.9th	190	µg/m^3	NSW	2.5	2.5	8.1	8.1	8.1	8.1	8.1	8.1	8.1

Notes:

1) The benzene annual average and maximum 1-hour concentrations were predicted assuming 2 TCUs offline. This is conservative for predicting the annual average concentrations. The value in brackets is a more accurate estimate of the annual average concentration based on the probability of each TCU being offline for 10% of the year.

Table 9.5 Predicted Maximum Concentrations from BLNG (Including Background Levels). Percentage (%) of Criteria

Pollutant	Ave. Period	Conc. Statistic	Value of Criteria	Units	Criteria Source	LIGT 15 Mtpa	IS 15 Mtpa	LIGT 50 Mtpa	MIGT 50 Mtpa	AGT 50 Mtpa	IS 50Mtpa	LIGT 50 Mtpa Start Up	LIGT 50 Mtpa Turn Down	LIGT 50 Mtpa Emergency
Carbon Monoxide	8-hour	Max	9000	ppb	NEPM	1.4	1.5	1.6	1.6	1.6	1.8	3.3	3.4	2.9
Nitrogen Dioxide	1-hour 1-year	Max Ave	120 30	ppb ppb	NEPM NEPM	29 4.4	29 6.4	31 8.5	32 9.5	32 7.6	33 12	37 13	32 14	31 8.6
Sulphur Dioxide	1-hour 1-day 1-year	Max Max Ave	200 80 20	ppb ppb ppb	NEPM NEPM NEPM	20 12 1.0	20 12 1.0	22 11 3.2	22 11 3.3	22 11 3.2	22 11 3.2	22 11 3.2	22 11 3.2	22 11 3.2
Particles as PM_{10}	1-day	Max	50	$\mu g/m^3$	NEPM	51	51	52	51	52	52	51	51	51
Particles as $PM_{2.5}$	1-year	Ave	25 8	$\mu g/m^3$ $\mu g/m^3$	NEPM	64	65	66	66	67	67	65	65	66
H_2S	1-hour	99th	0.47 to 1.6	$\mu g/m^3$	NSW	200	162	283	283	219	238	283	283	283
Including Ship-loading Emissions of BTEX														
Benzene	1-hour Annual	99.9th Ave	29 5	$\mu g/m^3$ $\mu g/m^3$	NSW EU	2320 40	2320 40	2900 111	2900 111	2900 111	2900 111	2900 111	2900 111	2900 111
Ethyl benzene	1-hour	99.9th	800	$\mu g/m^3$	NSW	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Toluene	1-hour	99.9th	360	$\mu g/m^3$	NSW	98	98	131	131	131	131	131	131	131
Xylenes	1-hour	99.9th	190	$\mu g/m^3$	NSW	1.5	1.5	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Excluding Ship-loading Emissions of BTEX														
Benzene	1-hour Annual	99.9th Ave	29 5	$\mu g/m^3$ $\mu g/m^3$	NSW EU	87 12	73 10	125 18	125 18	98 19	105 20	130 18	125 18	125 18
Ethyl benzene	1-hour	99.9th	800	$\mu g/m^3$	NSW	0.002	0.002	0.005	0.005	0.03	0.03	0.005	0.005	0.005
Toluene	1-hour	99.9th	360	$\mu g/m^3$	NSW	2.9	2.4	4.1	4.1	3.7	3.4	4.1	4.1	4.1
Xylenes	1-hour	99.9th	190	$\mu g/m^3$	NSW	1.3	1.3	4.2	4.2	4.2	4.2	4.2	4.2	4.2

Notes:

1) The benzene annual average and maximum 1-hour concentrations were predicted assuming 2 TCUs offline. This is conservative for predicting the annual average concentrations. The value in brackets is a more accurate estimate of the annual average concentration based on the probability of each TCU being offline for 10% of the year.
2) $PM_{2.5}$ 24-hour concentrations are not provided as a percent of the criteria as the NEPM goal is to gather sufficient data nationally to facilitate a review and does not set a number of allowable exceedances.

10 Deposition Predictions

To assess the likely impacts on vegetation and ecosystems predictions of the deposition of nitrogen and sulphur were modelled using TAPM-CTM. These were made for the existing sources alone (fires and sources at Broome) and for the case of the existing and the proposed precinct. The Precinct contribution was then determined by the difference between the two model runs. This approach was undertaken as modelling the industry by itself may not determine the true deposition due to the reactions that occur between the LNG Precinct gases and aerosols and the existing ambient gases and aerosols. Therefore it is considered that existing levels needed to be included.

Using TAPM-CTM dry nitrogen deposition was predicted for the gaseous species, NO, NO_2, HONO, HNO_3, NH_3, NH_4 and nitrate aerosols. Dry sulphur deposition was predicted for the gaseous species SO_2, SO_3 and sulphate aerosol. Wet deposition was not predicted from TAPM as TAPM performed poorly in predicting rainfall for the region, predicting far too many light rainfall hours. Instead an estimate of the total deposition (dry and wet) was made based on the Burrup rock art study which found that for the background sites near Dampier that wet deposition contributed between 15 to 40% of total deposition for a dry and a wet year respectively Gillett (2008). As such, wet deposition was estimated to contribute around 50% of the total deposition for the wetter Dampier Peninsula.

The results for nitrogen deposition are presented in **Figure 10-1** to **Figure 10-2**.

Figure 10-1 Predicted Annual Nitrogen Dry Deposition (kg/ha/yr)

Figure 10-2 Predicted Annual Nitrogen Dry Deposition (kg/ha/yr) from the LNG Precinct Alone

Figure 10-1 to **Figure 10-2** show that the predicted existing dry nitrogen deposition on the peninsula is in the range of 1.5 to 1.9 kg/ha/yr of nitrogen. Note, this excludes locally at Broome where nitrogen deposition is predicted to be slightly higher at 2.4 kg/ha/year. With the 50 Mtpa LNG Precinct this increases slightly to 2.2 kg/ha/yr with an industry contribution of up to 0.42 kg/ha/yr. Assuming wet deposition of up to 50 % indicates that the total nitrogen deposition may currently be up to 3.8 kg/ha/year and with industry will increase to 4.4 kg/ha/year (i.e. double the dry deposition estimate). These are below the WHO guidelines, below the 5 to 10 kg N/ha for the most sensitive species (artic bogs, softwater lakes, forest in humid climates) and well below the considered applicable average value for this area of 15 to 20 kg N/ha per year based on the WHO natural and semi natural ecosystems value.

Of the deposition TAPM-CTM predicts that overall about 77% of the contribution is from HNO_3 with 17 % from NH_3 with only a minor contribution from NO_2. For comparison for background sites near Dampier and Karratha, Gillett (2008) "measured" (by a combination of measurements and using estimates of deposition velocities) dry deposition rates of about 5, 2 and 2 meq/m^2/yr of NH_3, NO_2 and HNO_3. This equates to 0.7, 0.28 and 0.28 kg/ha/yr of nitrogen respectively or a total of 1.26 kg/ha/yr of nitrogen. This estimate is similar to though slightly lower than the background predicted dry deposition of nitrogen for the Dampier Peninsula of 1.5 to 1.9 kg/ha/yr.

For sulphur the predicted existing and future level and contribution from the LNG precinct are presented in **Figure 10-3** and **Figure 10-4**.

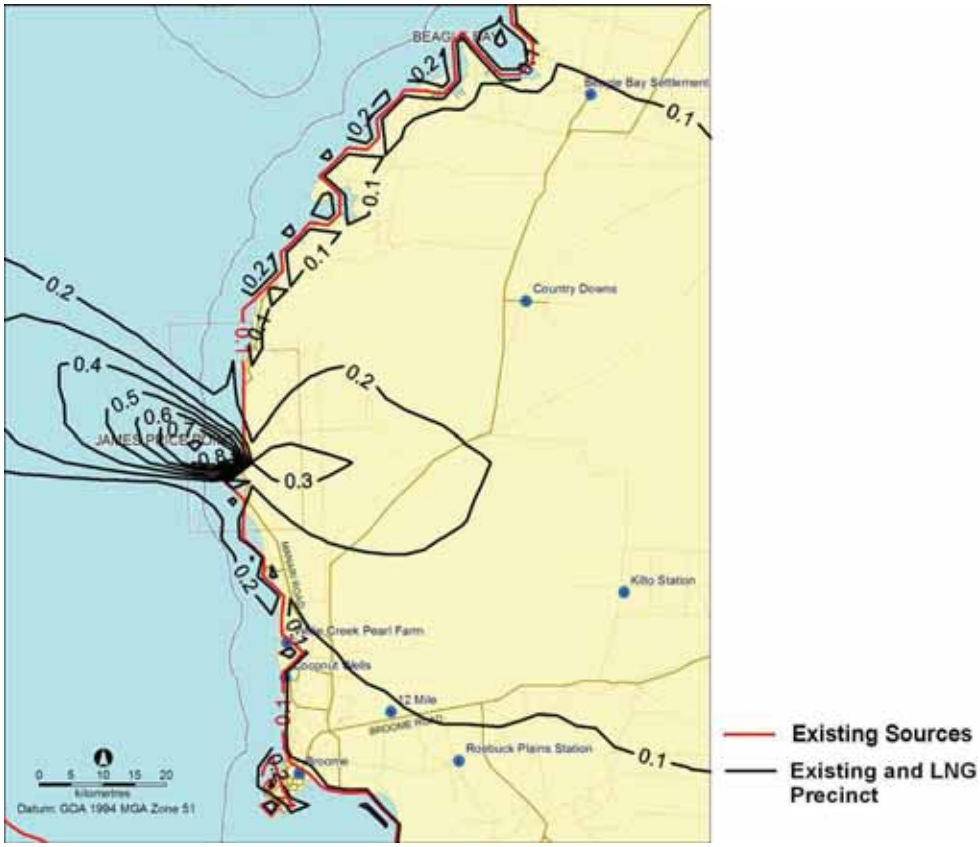


Figure 10-3 Predicted Annual Sulphur Dry Deposition (kg/ha/yr)

Figure 10-4 Predicted Annual Sulphur Dry Deposition (kg/ha/yr) from the LNG Precinct Alone

Figure 10-3 and **Figure 10-4** indicate that existing deposition rates of sulphur over the land are very low at around 0.07 kg/ha/yr. With the Precinct it is predicted that Precinct contribution will be up to 1 kg/ha/year over water in the berth area, with a maximum over land outside the buffer of about 0.2 kg/ha/yr. This is much smaller than the sulphur critical loads of 4 to 8 kg/ha/year provided by WHO (2000) and indicates that sulphur deposition is not an issue for the project. The contribution from the Precinct is greatest over water due to the greater emissions from near surface sources over water (the ships and tugs) and also to the greater deposition rate over sea than land due to the high solubility of SO_2.

11 Conclusions

This report presents an assessment of the likely local and regional impacts from atmospheric emissions from a 50 Mtpa LNG Precinct at James Price Point. The major sources of atmospheric emissions include the LNG trains (refrigeration compressors), associated power stations, emissions from the CO_2 Removal Unit vent, thermal oxidisers, flares and the associated shipping. Existing sources in the region include bushfires, biogenic emissions and emission from the town of Broome.

The air quality assessment was undertaken using two models; TAPM for the local area (up to 14 to 18 km from the sources) to investigate peak concentrations close to the plants and TAPM-CTM to assess the broader regional impacts due to photochemistry, particularly the formation of ozone where the peaks may occur up to one hundred kilometres from the Precinct.

To gauge the suitability of the models, both models were validated where possible against observations; TAPM against the available meteorological observations where its performance was shown to be fair and TAPM-CTM for gaseous pollutants at Dampier where it was shown to perform credibly for predictions of gaseous pollutants from industry and fires. Dampier was used as the nearest site with good quality monitoring data.

To assess the 50 Mtpa LNG Precinct as the LNG technologies may vary from plant to plant, four typical LNG technology cases were assessed. Emissions for these whenever possible were based on conservative estimates. NO_X and PM for the most significant source (the gas turbines and compressors), were estimated based on the guaranteed maximum emission concentrations and will therefore overstate the emissions. Likewise emissions of H_2S and SO_2 are conservatively based on a maximum H_2S content in the feed gas. BTEX emissions were conservatively estimated based on an upper content in the feed gas, a high removal efficiency from the feed gas by the CO_2 Removal Unit and a worst case availability of 90% for the Thermal Combustion Units (TCUs) which normally destroy these compounds.

The results from the regional TAPM-CTM modelling showed the following:

- The contribution from the BLNG precinct at sensitive receptors will be below the NEPM standards, with the pollutant closest to its respective standard being ozone at 64% of the 1-hour standard. At other locations (non sensitive receptors) the maximum 1-hour ozone level is predicted to be 84 ppb or 84% of the standard. This peak is due in main to the high VOC emission estimated for condensate loading which are considered conservative. Note, that about 25 ppb of this ozone is from the clean background air. For the extremely unlikely case that full emergency shutdown / flaring occurs (once in 10 year event) at the time of the worst case meteorology, the maximum ozone levels anywhere are predicted to be 92% of the NEPM standard;
- In comparison, fires are the existing dominant source of pollutant in the region leading to high particulate, ozone and NO_2 concentrations. These high levels are due not only to the very large extent of land burned but, also to a build up of pollutants in the atmosphere as the fires typically last for days. The predicted existing levels of ozone are typically in the range of 60 to 85 % of the NEPM standards, with peak concentration anywhere of 91% and 111% of the respective 1 and 4-hour standards. The predicted particulate levels from fires for most of the Dampier

Peninsula are below the NEPM PM_{10} standard with more than 5 exceedances, but do exceed it for a small area. Note, for both ozone and particulate matter there are no measurements within the Kimberley to confirm the predictions;

- Considering the BLNG and existing sources, there is negligible cumulative impact to the maximum ozone, particulate and NO_2 concentrations as the predicted concentrations are dominated by the concentrations from fires; and
- Impacts on vegetation, as assessed through deposition rates of nitrogen and sulphur were predicted to be low, both under the WHO guidelines.

The local modelling conducted using TAPM showed that:

- All pollutants from the LNG Precinct are predicted to be well within the adopted criteria except for benzene, H_2S and to a lesser degree toluene. The primary source of benzene and toluene emissions is from venting from ships holds during condensate loading. Predictions indicate that benzene concentrations would be well in exceedance of the NSW modelling guidelines. This criteria however is intended more as a screening level to flag possible issues. A more appropriate measure as directly related to benzene's health endpoint is the annual average benzene concentration. Annual benzene concentrations were predicted to be just exceed the annual criteria (5.5 $\mu g/m^3$ or 110% of the European standard) outside the south west corner of the Precinct buffer. Model sensitivity tests without condensate ship-loading emissions predicted that BTEX concentrations are greatly reduced, with the annual average benzene level outside the buffer being less than 10% of the WHO annual guideline of 5 $\mu g/m^3$;
- Hydrogen sulphide levels were predicted to exceed the adopted NSW single residence criteria (1-second 99^{th} percentile of 4.8 $\mu g/m^3$) out to 9 km to the east of the buffer zone. For the more stringent criteria applicable for an urban area with >2000 people (or very sensitive land uses such as hospitals), the 1-second 99^{th} percentile criteria of 1.38 $\mu g/m^3$ would be exceeded to 20 to 30 km to the east of the buffer. In these areas the maximum 1-second H_2S concentration is predicted to be around 50 $\mu g/ m^3$ and therefore H_2S levels would at times be above the odour threshold of about 1.2 $\mu g/m^3$ and would be recognizable by its characteristic rotten egg gas smell. Though detectable by its odour, the concentrations are well below the level of concern for health, with the WA Health Department recently recommending a limit of 2 ppm (approximately 3000 $\mu g/m^3$ for a 30-minute average). Therefore, in the area to the east of the Precinct it is predicted that the H_2S odour will at times be recognizable, though the concentrations are 60 times lower than levels that can cause health effects.

Comparison between the four LNG technology cases showed that there were small differences in the predicted concentrations of pollutants. For most pollutants these are not significant as the concentrations are well below the criteria. Also though a LNG technology may lead to lower concentrations of one pollutant for one averaging time, it may lead to higher concentrations for another pollutant at another averaging time. For the pollutants which are relatively high to the criteria, benzene and H_2S the differing LNG technologies do result in some small variation, For benzene, considering the more relevant annual average concentration all predicted concentrations are well below the criteria such that there is no one preferred technology. For H_2S it is considered that the high levels are primarily a result of the conservative nature of the emissions used and not that one LNG technology is favoured over the others.

12 References

AGO (Australian Greenhouse Office), 2007. *National Inventory Report 2005. Volume 1*. Australian Government Department of the Environment and Water Resources. 198pp.

Andreae, M. O. And Merlet, P., 2001. *Emission of trace gases and aerosols from biomass burning*. Global Biogeochemical Cycles, Vol 15, 14, 955-966.

API (American Petroleum Institute). 2006. *Atmospheric Hydrocarbon Emissions from Marine vessel Transfer Operations.* API Publication 2514A. Second Edition 1981. Reaffirmed, July 2006.

Barrett, D. J., 2002. *Steady State Turn Over time of carbon in the Australian terrestrial biosphere*. Global Biochemical Cycles. Vol 16, 1108.

Briggs, G.A. 1974. Plume rise from multiple sources. *In Cooling Tower Environment – 1974*, S.R Hanna and J. Pells (Eds), University of Maryland Education Center, 4-6 March 1974, NTIS CONF – 740302, pp161-179.

Cainey J., Derek N. Krummel P., 2007. *Baseline Atmospheric Program Australia 2005-2006.* ISBN 978 1 921424 10 6 http://www.cmar.csiro.au:8000/e-print/open/baseline_2005-2006.pdf, Melbourne, Australia.

Cole, H.S. and Summerhays, J.E., 1979. *A review of techniques available for estimating short-term NO_2 concentrations*. J. Air Pollution Control Association. 29, 812-817.

Cooper. D.A. 2003. *Exhaust Emissions from Ships at Berth*. Atmos. Environ. 37, 3817-3830.

Cope, M. 2010. Personal communication with Dr Martin Cope of CSIRO Marine and Atmospheric Sciences.

Cope, M, Lee, S, Hibberd, M, Meyer, M. McGregor, J, Nelson, P Morrison, A and Malfroy, H., 2009a. Modelling the emission and transport of mercury in Australia, *19th International Clean Air and Environment Conference, Perth 6th-9th September 2009*.

Cope, M., Lee, S., Azzi, M, Xu, C. 2009b. *The Ethanol and Health Study. An airshed modelling assessment of ethanol usage by passenger motor vehicles.*

CSIRO (Commonwealth Industrial Scientific Research Organisation), 2008. *Sources of Ozone Precursors and Atmospheric Chemistry in a Typical Australian City A report to Air Quality Section, Environment Standards Branch, Department of the Environment, Water, Heritage and the Arts. Commonwealth of Australia. 6 Dec 2008*. CSIRO Marine and Atmospheric Research. Available at http://www.environment.gov.au/atmosphere/airquality/publications/ozone-precursors.html

DECC NSW (Department of Environment and Climate Change NSW), 2008. Air emissions Inventory for the Greater Metropolitan Region in New South Wales. Technical Reports. Available at www.environment.nsw.gov.au/resources/air/

DEC NSW (Department of Environment and Conservation NSW), 2005. *Approved Methods for the Modelling and Assessment of Air Pollutants in New South Wales*. August 2005. Available at http://www.environment.nsw.gov.au/air/appmethods.htm

DEFRA (Department for Environment, Food and Rural Affairs), 2007. *The Air Quality Strategy for England, Scotland, Wales and Northern Ireland. Volume 1*. July 2007

DoE (Department of Environment), 2005. *2004 Western Australia Air Monitoring Report. Written to comply with the National Environment Protection Measure (Ambient Air Quality). Technical Series 122. April 2005.*

DoE (Department of Environment), 2006. *Air Quality Modelling Guidance Notes.* March 2006.

DEH (Department of Environment and Heritage), 2005. *National Pollutant Inventory. Emission Estimation Technique Manual for Oil & Gas production. Version 1.1 1 June 2005.*

DEH (Department of Health, Western Australia), 2009. Environmental Health Guide. Hydrogen Sulphide and Public Health. Available at http://www.public.health.wa.gov.au/

DEP (Department of Environmental Protection), 2002. *Monitoring of Ambient Air Quality and Meteorology during the Pilbara Air Quality Study. Technical Series 113,* Department of Environmental Protection, Perth, Western Australia, September 2002.

DEWHA (Department of the Environment, Water, Heritage and the Arts). 2008. *National Pollutant Inventory. Emission Estimation Technique Manual for Combustion in Boilers. Version 3.1. June 2008.*

DEWHA (Department of the Environment, Water, Heritage and the Arts). 2010. *NPi. Emission Estimation Technique Manual for Oil and Gas Exploration & production. Version 1.2. February 2010.*

Environment Australia, 1999. *NPi. Emission Estimation Technique Manual for Aggregated Emissions from Commercial Ships/Boats and Recreational Boats – Version 1.0 1November 2009.*

Environment Australia. 2000. *Emission Estimation Technique Manual for Aggregated Emissions from Motor Vehicles. 2 November 2000 – Version 1.0*

EPA (Environmental Protection Authority), 2000. *Emissions of Oxides of Nitrogen from gas turbines. Guidance for the assessment of environmental factors. No. 15.* May 2000. Environmental Protection Authority, Western Australia.

EPA (Environmental Protection Authority), 2003. *Implementing Best Practice in proposals submitted to the Environmental Impact assessment process. Guidance for the Assessment of Environmental Factors. No. 55 December 2003*, Western Australia.

EPA (Environmental Protection Authority), 2006. *Fire Management in the Kimberley and other Rangeland regions of Western Australia. Advice of the Environmental Protection Authority to the minister for the Environment under Section 16(e) of the Environmental Protection Act 1986.* Environmental Protection Authority Perth, Western Australia. Bulletin 1243. December 2006.

EPA (Environmental Protection Authority), 2009a. *State Environmental (Ambient Air) Policy 2009. Draft Policy for public and stakeholder comment*. June 2009.

EPA (Environmental Protection Authority), 2009b. *Gorgon Gas Development. Revised and Expanded Proposal: Barrow Island Nature Reserve. Report and Recommendations of the Environmental protection Authority*. Report 1323. April 2009.

Galbally I, Lawson, L., Cheng, M., Bentley, S., Gillett, R., Selleck, P., Cope, M., Hibberd, M, Dunne, E., Weeks, I., Quigley, S., 2009. *A new look at VOCs in the Lower Atmosphere over Australia.* International Clean Air and Environment Conference, 6th-9th September 2009. Perth, Western Australia.

Gillett, R. 2008. *Burrup Peninsula Air Pollution Study: Report for 2004/2005 and 2007/2008*. Report of 10th September by Rob Gillett, CSIRO Marine and Atmospheric Research.

Gillett, R., and Cope M., 2009. *The relationship between the atmospheric concentrations of formaldehyde, hydrogen peroxide and methyl hydroperoxide.* International Clean Air and Environment Conference, 6th-9th September 2009. Perth, Western Australia.

Hamblin, A. 2002. *Australia State of the Environment, 2001 Land Theme Report.* Available at http://www.environment.gov.au/soe/2001/

Hurley, P. 1998. *Air Pollution Modelling for the proposed Extension to the Woodside Offshore petroleum Liquid Natural Gas Plant,* CSIRO, May. 1998.

Hurley, P. 2008. TAPM V4. User Manual. CSIRO Marine and Atmospheric Research Internal Report No. 5. October 2008.

Hurley, P, Physick, W and Cope, M. 2003. *Woodside LNG Expansion Project – Modelling Existing and Proposed Emissions on the Burrup Peninsula.* October 2003

Hurley, P, Physick, W, and Cope, M. 2004. *Summary of TAPM Verification for the Pilbara Region.* CSIRO, March 2004.

Hurley, P, Edwards, M, and Luhar, A. 2008. *TAPM V4. Part 2: Summary of Some Verification Studies.* CSIRO Marine and Atmospheric Research paper No, 26. October 2006.

Hurley, P, Edwards, M Luhar, A and Thatcher, M. 2009. *Evaluating the Meteorological performance of TAPM.* 19th Internal Clean Air Conference Perth.

International Maritime Organization (IMO). 2008. *MEPC.176(58) Amendments to the Annex of the Protocol of the 1997 to amend the International Convention for the Prevention of Pollution to ships, 1973.as modified by the protocol of 1978 relating thereto (Revised MARPOL Annex VI).* Available at http://www.imo.org/

Katestone Environmental Pty Ltd. 2009. *Air Quality Assessment for the proposed Power station, Fords Road, Adare,* September 2009. Prepared for Westlink Pty Ltd.

Killip, C, Leishman, N Heuff, D, Schloss, A and Welchman, S. 2007. *Is the clean air of Brisbane Threatened by Future Population Growth?* Conference Proceedings of 14th IUAPPA World Congress, Brisbane 2007, 9-13 September 2007.

Kowald, B 2009. Email from Brian Kowald of the Bureau of Meteorology. December 2009.

Luhar, A. K., Mitchell, R. M., Meyer, C. P. (Mick), Qin, Y., Campbell, S., Gras, J. L., Parry, D., 2008: *Biomass burning emissions over Northern Australia constrained by aerosol measurements: II-Model validation, and impacts on air quality and radiative forcing*. Atmos. Environ., 42, 1647–1664.

Meyer, C.P. (Mick), Luhar, A.K., Mitchell, R.M., 2008a: *Biomass burning emissions over northern Australia constrained by aerosol measurements: I-Modelling the distribution of hourly emissions.* Atmos. Environ., 42, 1629–1646.

Meyer . C.P. (Mick)., Reisen, F., Luhar, A., Powell, J., Lee, S., Keywood, M., Galbally, I., Linfoot, S., Parry, D., McCaw, L. and Tolhurst, K., 2008b. *Particles, Ozone and Air Toxic Levels in Rural Communities during prescribed burning seasons.* Final report, CSIRO.

Mitchell, R.M. and Forgan, B.W. 2002. Aerosol measurement in the Australian Outback: Intercomparison of Sun Photometers. J. Atmos. And Oceanic tech. 20, 54-66.

Physick, W, and Blockley, A. 2001. An Evaluation *of Air Quality Models for the Pilbara Region.* June 2001.

Savoie, D.L., 1984. *Nitrate and Non-Sea-Salt Sulfate Aerosols Over Major Regions of the World Ocean: Concentrations, Sources and Fluxes.* Ph.D. Thesis. University of Miami.

Scott, W.D. Forgan, B.W. and Prospero, J.M. 1992. *Atmospheric Turbidity Measurements at Broome in Western Australia.* J. Roy. Soc. West. Aust. 75, 111-118.

SKM (Sinclair Knight Merz) 2003. Aggregated Emissions Inventory for the Pilbara Airshed 1999/2000. Emissions Inventory report. Revision 2. 2003. Available at http://www.npi.gov.au/publications/pubs/pilbara-airshed.pdf

SKM (Sinclair Knight Merz) (2008) Gorgon Gas development, Revised Proposal. Air Quality Assessment. Final 20 June 2008. Appendix G in Chevron Australia 2008. Gorgon Gas Development Revised and Expanded Proposal Public Environmental review. Chevron Australia, Perth.

Sowden, M and Harper, J., 2009. Improving Local BVOC Emission Factors from Vegetation Surrounding Darwin. Proceedings of the 19th International Clean Air and Environment Conference, 6th to 9th September 2009, Perth, Western Australia.

Toxikos. 2005. *Health Risk & Toxicological Assessments – Worsley Expansion Emissions (Volume 1 of 2).* Prepared for : Worsley Alumina Pty Ltd. April 2005. Available at http://www.epa.wa.gov.au/docs/2028_ERMP/ERMP_WorsleyAlumina_A10_V1.pdf

Toxikos. 2008. Preliminary health risk assessment of air emissions from proposed Biomass Power Station, Manjimup, 11th April 2008. Available at http://www.epa.wa.gov.au/docs/B1294/AppendixH_a.pdf

Victoria Government Gazette. 2001. State Environment protection Policy (Air Quality Management). No S 240 Friday 21 December 2001. Available at http://www.epa.vic.gov.au/Air/EPA/default.asp

Wartsila, 2006. *Duel Fuel Electric LNG Carriers*. LNG Shipping Operations, Hamburg, September 27, 2006.

World Health Organisation (WHO). 2000. Guidelines for Air Quality. World Health Organization, Geneva.

Woodside. 2009. Emails from David Lazarus. Woodside.

Woodside (Woodside Energy Limited). 2010. BLNG Strategic Assessment Impact Assessment Modules. January 2010

Yarwood G, Rao, S, Yocke M. Whitten G., 2005. Updates to the Carbon Bond Chemical Mechanism. Final report RT-04-00675 to U.S. Environmental Protection Agency, Research Triangle Park, NC 27703.