**Plume Rise Assessment**

# 1 Introduction

Heggies Pty Ltd (Heggies) has been commissioned by GHD Pty Ltd (GHD) on behalf of Delta Electricity (DE) to conduct a Plume Rise Assessment (PRA) as part of the Environmental Impact Statement (EIS) for a proposed gas turbine power facility at Bamarang, NSW.

The Royal Australian Navy Naval Air Station (NAS Nowra) is located approximately 4 km to the southwest of the site of the proposed gas turbine power facility at Bamarang.

The proposed power station will have two exhaust stacks, both of which are anticipated to have a height of 40 m Above Ground Level (AGL). Additionally, the power station will have an air cooled condenser (ACC) system, consisting of 36 release points at 30 m AGL. The Defence (Areas Control) Regulations (DACR) controls the height of structures, and the purpose for which they may be used, within a 15 km radius of an aerodrome. Although the exhaust stacks and ACC system proposed for the Bamarang site are located within this 15 km radius, the structures will not infringe on the Obstruction Clearance Surface (OCS) for NAS Nowra.

However, the exhaust plumes of the stacks have the potential to affect aircraft operations in terms of damage caused to airframes and the handling of aircraft during flight. The Civil Aviation Safety Authority (CASA) has identified that there is a need to assess the potential hazards that the vertical velocity from gas efflux present to the aviation activities in the surrounding region.

According to CASA's Advisory Circular entitled *Guidelines for Conducting Plume Rise Assessments*, June 2004, exhaust plumes with a vertical velocity in excess of 4.3 m/s may cause damage to an aircraft airframe, or disturb aircraft handling when flying at low levels.

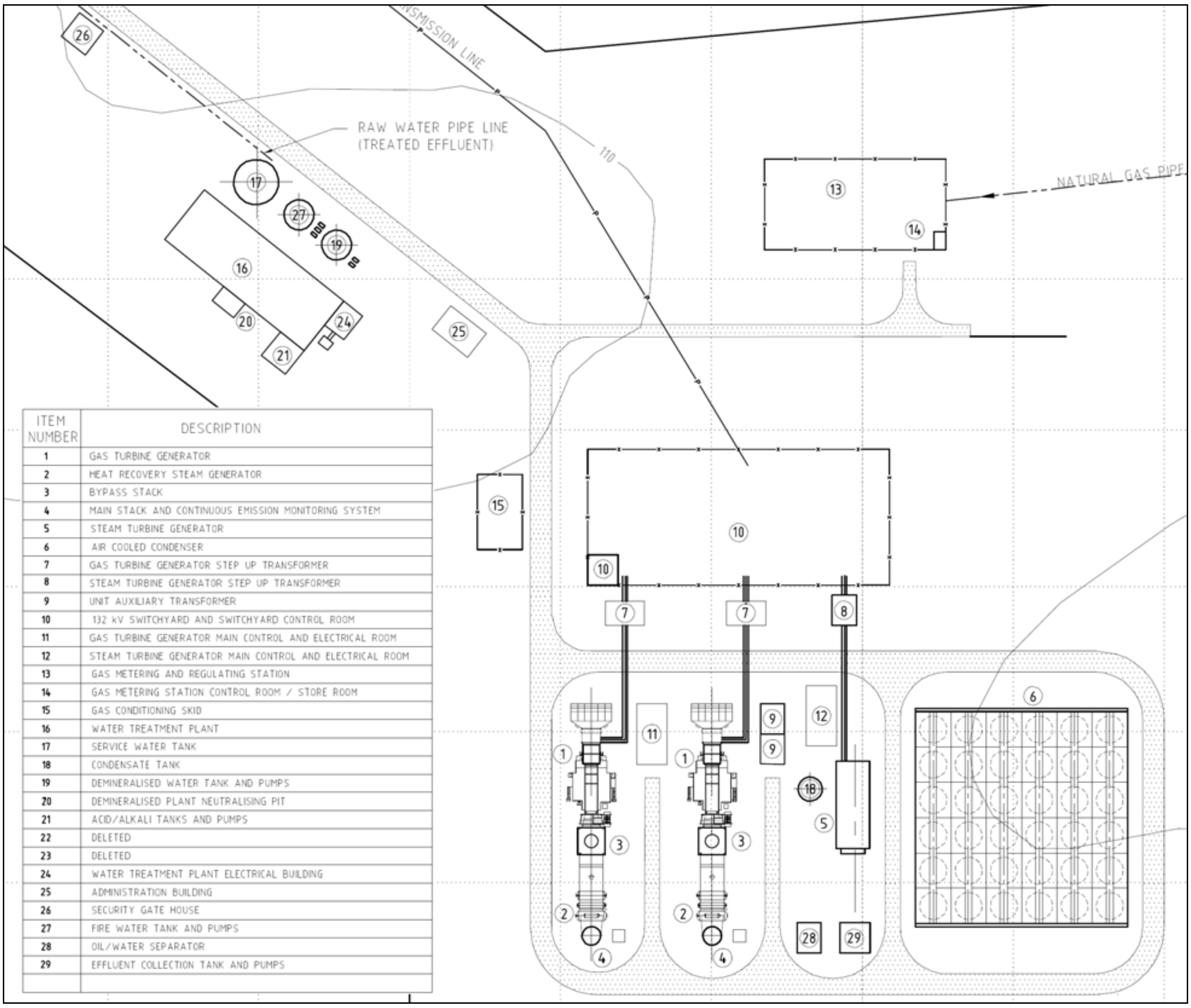
The proposed gas turbine power facility at Bamarang is located within the Conical Surface OCS for NAS Nowra. Through correspondence with the Department of Defence it is understood that the exhaust plume velocity from the power station should not exceed 4.3 m/s at the height of the Conical Surface OCS. The Conical Surface OCS at the site of the Bamarang stacks has been determined as 167 m AHD.

Topographical data for the site indicates that the Bamarang site lies at an elevation of approximately 107 m AHD. Accordingly, the critical OCS used for this assessment is 60 m AGL directly above the stacks.

**Figure 1** shows the location of the NAS Nowra in relation to the gas turbine power facility at Bamarang, including a scaled illustration of the 15 km radius. **Figure 2** illustrates the site layout.

Figure 1 NAS Nowra, Location of proposed Bamarang Site and 15km

Figure 2 Layout of Project Site – with Air Cooled Condenser System




## 2 Assessment Methodology

This assessment has been conducted for Stage 2 Operations, to account for the plume rise from both turbine exhaust stacks and the ACC system

In accordance with CASA requirements, The Air Pollution Model (TAPM) was used in plume rise mode to analyse plume behaviour from the stacks for meteorological conditions predicted for the site over a modelling period of 5 years (2002-2006).

TAPM software, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), is a prognostic model which may be used to predict three-dimensional meteorological data, with no local data inputs required. The model predicts wind speed and direction, temperature, pressure, water vapour, cloud, rain water and turbulence. The program allows the user to generate synthetic observations by referencing databases (covering terrain, vegetation and soil type, sea surface temperature and synoptic scale meteorological analyses) which are subsequently used in the model input to generate site-specific hourly meteorological observations.

The TAPM plume rise estimation uses commonly referenced plume rise algorithms for the determination of vertical plume rise velocity. For multiple sources TAPM allows a buoyancy enhancement factor to be input to account for overlapping plumes from multiple stacks. The buoyancy enhancement factor used is based on the Briggs (1984) equations discussed in Manins et al. (1992).

The proposed gas turbine power facility at Bamarang will have two units operating online with corresponding identical stacks situated 40 m apart. Additionally, the ACC system comprises of 36 identical release points equally spaced within a 70 m x 70 m area. **Table 1** and **Table 2** details the other parameters of the exhaust stacks and ACC system respectively. The plumes from each source group (i.e. exhaust stacks and ACC system) may merge for some wind conditions and accordingly the combined plume may rise higher than the plumes would have in isolation.

CASA have determined that TAPM is not suitable for the determination of plume dynamics for plumes that merge significantly.

To conservatively account for the possibility that plume merging may occur between the two stacks resulting in enhanced plume rise, an hourly-varying plume rise enhancement factor for each source group has been applied to the TAPM exit velocity input. The buoyancy enhancement factor used is based on the Briggs (1984) equations discussed in Manins et al. (1992).

Manins et al. (1992) identifies that for a number of stacks with the same emission geometries and exit conditions, as is the case with this Project for the two exhaust stacks and the 36 ACC system release points, then the buoyancy enhancement factor ( $N_E$ ) is defined as:

$$N_E = \left[\frac{n+S}{1+S}\right]$$

Where $n$ is the number of stacks and $S$ is the dimensionless separation factor, defined as:

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

Where $\Delta s$ is the stack separation and $\Delta z$ is the rise of an individual plume.

The plume rise enhancement factor is then determined by the following:

$$E_N = N_E^{1/3} < N^{1/3}$$

To determine the individual plume rise value, single stack scenarios representing the exhaust stacks and ACC system were modelled with TAPM using the stack parameters detailed in **Table 1** and **Table 2**. An hourly-varying plume rise enhancement factor for each source group was derived based on the single stack final plume rise for each hour of the modelling period, accounting for varying ambient conditions.

The hourly varying plume rise enhancement factors have been applied to the exit velocities for each source (16 m/s for the exhaust stacks; 6.14 m/s for the ACC system release points) to account for varying ambient conditions.

Table 1 Exhaust Stack Exit Parameters

| Stack Parameter | East and West HRSG Exhaust Stacks |
|---|---|
| Project Stage | Stage 2 |
| Description | Exhaust stack servicing the Eastern Gas Turbine, operating in Combined Cycle mode. Combustion gases passed through the Heat Recovery Steam Generator prior to exhaust |

| **Stack Parameter** | **East and West HRSG Exhaust Stacks** | | | |
|---|---|---|---|---|
| Location (Easting, Northing) | 273812<br>6134875 | | 273851<br>6134869 | |
| Height (m) | 40 | | 40 | |
| Diameter (m) | 6.7 | | 6.7 | |
| Area ($m^2$) | 35.3 | | 35.3 | |
| Exit Temperature (K) | 398 | | 398 | |
| | **Ambient Temperature** | | | |
| | **273** | **288** | **298** | **313** |
| Exit Temperature (K) | 398 | 422 | 416 | 406 |
| Flow Rate (Nm3/s) | 392 | 372 | 360 | 339 |
| Flow Rate (Am3/s) | 572 | 575 | 548 | 503 |
| Exit Velocity (m/s) | 16.0 | 16.2 | 15.5 | 14.2 |

Table 2 ACC System Parameters

| **Parameter** | **Value** |
|---|---|
| Number of Release Points | 36 |
| Exit Velocity (m/s) | 6.14 |
| Exit Diameter (m) | 9.14 |
| Exit Temperature (°K) | 315.15 |
| Exit Flow Density ($kg/m^3$) | 1.16 |
| Total Area of Structure ($m^2$) | 4900 |
| Centre of Structure (m AMG) | 273958 E, 6134892 N |

It is noted that the two source groups (exhaust stacks and ACC system) have been modelled as two separate plumes. This approach differs from that adopted in **Section 6.6** of the air quality impact assessment, where a combined buoyancy enhancement factor, accounting for the interaction between the exhaust stacks and the ACC system, was applied to the exit velocity of the exhaust stacks.

This approach does not model the interaction between the plumes from the exhaust stacks and the ACC system, but rather allows for the calculation of the maximum plume rise height from each individual source group while calculating the maximum horizontal area of influence. A discussion on plume merging and enhancement and the limitations of this assessment will be conducted in this report (**Section 4**) following the analysis of the individual plume rise associated with each source group.

The modelling period was 1 January 2002 to 31 December 2006. TAPM was used in a nested mode, consisting of 25 × 25 × 25 grid points, and 30-km, 10-km, 3-km spaced horizontal grids for meteorology. The number of vertical levels was set to 25 and the grid centre coordinates were extracted over the plume source. No observational meteorology data was assimilated into the model.

# 3 Results and Discussion

### 3.1.1 Upper Level Wind Analysis

As per CASA requirements, analysis of the upper level TAPM generated meteorology was carried out for the Bamarang site at 35 m, 50 m, 80 m, 100 m, 150 m, 200 m, 250 m, 300 m and 350 m, corresponding to the maximum height over at which the peak vertical velocity reduces to the critical vertical velocity, (approximately 289 m).

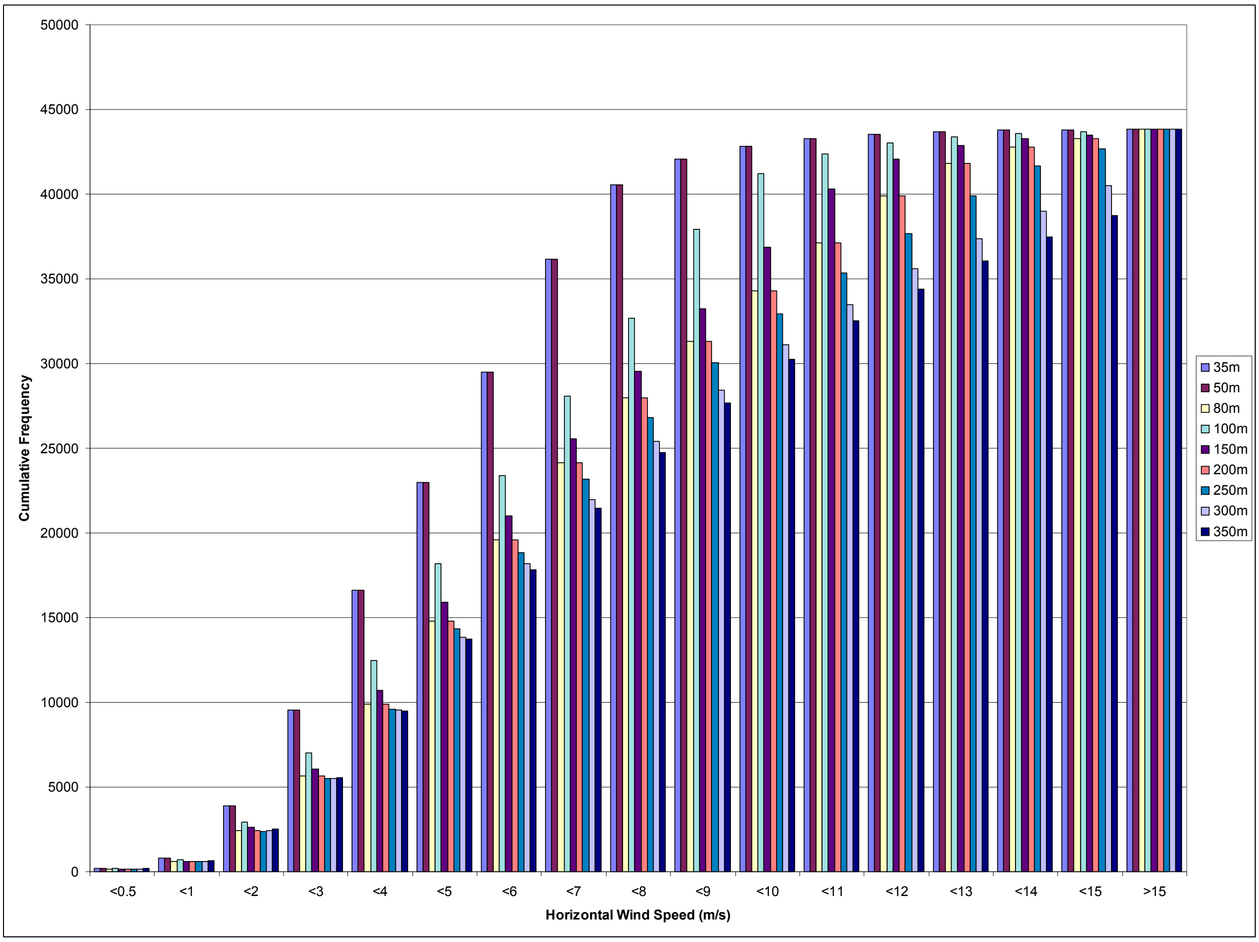
**Table 3** shows the percentage occurrences of wind speeds less than 0.5 m/s predicted by the TAPM model for various heights above the Bamarang site. The results indicate that calm conditions are experienced less than 1% of the time at Bamarang at all heights.

**Table 3 Percentage of Low Horizontal Wind Velocities with Height – 2002 - 2006**

| Height AGL (m) | <0.1 m/s | <0.2 m/s | <0.3 m/s | <0.4 m/s | <0.5 m/s |
|---|---|---|---|---|---|
| 35 | 0.01 | 0.09 | 0.17 | 0.30 | 0.45 |
| 50 | 0.01 | 0.09 | 0.17 | 0.30 | 0.45 |
| 80 | 0.03 | 0.07 | 0.13 | 0.23 | 0.35 |
| 100 | 0.01 | 0.06 | 0.16 | 0.28 | 0.42 |
| 150 | 0.02 | 0.06 | 0.13 | 0.21 | 0.37 |
| 200 | 0.03 | 0.07 | 0.13 | 0.23 | 0.35 |
| 250 | 0.01 | 0.06 | 0.13 | 0.24 | 0.38 |
| 300 | 0.02 | 0.08 | 0.17 | 0.29 | 0.44 |
| 350 | 0.02 | 0.09 | 0.20 | 0.32 | 0.45 |

**Figure 3** illustrates the cumulative frequency of the horizontal wind speeds predicted by TAPM at the heights of 35 m, 50 m, 80 m, 100 m, 150 m, 200 m, 250 m, 300 m and 350 m for the modelled period. The frequency bars are grouped in bins of 1 m/s, covering a range of occurrences of wind speeds less than 0.5 m/s to those greater than 15 m/s. The plots displayed in **Figure 3** show that as height above ground level increases, the frequency of occurrence of low wind speeds decreases.

**Figure 3 Horizontal Wind Speeds by Height – Cumulative Frequency Plots**




## 3.2 Plume Development

### 3.2.1 Horizontal Plume Radius

The predicted horizontal plume radius values for each hour of the modelled period have been calculated for a range of heights to illustrate the plume growth from each source. In order to determine the likely horizontal plume radii that occur when the critical vertical velocity is exceeded; the corresponding minimum, average and maximum horizontal plume radii with height are listed in **Table 4**.

Table 4 Minimum, Average and Maximum Horizontal Plume Radii with Height – Stage 2 Operations

| Height (m AGL) | Horizontal Plume Radii (m) | | | | | |
|---|---|---|---|---|---|---|
| | Minimum | | Average | | Maximum | |
| | Exhaust Stacks | ACC system | Exhaust Stacks | ACC system | Exhaust Stacks | ACC system |
| 50 | 6.00 | 7.00 | 8.52 | 9.98 | 9.00 | 11.00 |
| 100 | 12.58 | 16.50 | 17.62 | 20.72 | 21.30 | 23.60 |
| 150 | 19.00 | 24.78 | 23.74 | 25.48 | 27.00 | 26.09 |
| 200 | 26.00 | - | 28.76 | - | 31.36 | - |
| 250 | 32.26 | - | 33.36 | - | 35.77 | - |
| 300 | 39.50 | - | 39.50 | - | 39.50 | - |

### 3.2.2 Horizontal Plume Extent

In addition to determining the minimum, average and maximum vertical plume extent, the horizontal movement and extent of the generated plume from the Project Site has also been assessed. This analysis assists in determining the affected area from plume rise.

Horizontal plume extent has been generated by summing the distance travelled by the plume centerline, calculated by horizontal wind speed and modelled timesteps, until the height where the critical vertical velocity is no longer exceeded. The relevant plume radius is then added to this distance. **Table 5** details the minimum, average and maximum horizontal plume extent predicted for the revised Stage 2 operations at the Project Site.

Table 5 Minimum, Average and Maximum Horizontal Plume Extent – Stage 2 Operations

| | **Exhaust Stacks** | **ACC system** |
|---|---|---|
| Minimum (m) | 44.2 | 25.8 |
| Average (m) | 69.0 | 40.9 |
| Maximum (m) | 119.3 | 72.9 |

## 3.3 Frequency of Exceedance of Critical Vertical Velocity

As per CASA requirements, the frequency with which the average vertical plume velocity exceeds the critical vertical velocity has been calculated. **Table 6** details the percentage of time and height (AGL) that the average vertical velocity exceeds the critical vertical velocity for both the exhaust stacks and ACC system, as a function of height. Furthermore, **Table 7** details the maximum, minimum and average heights (AGL) that the average vertical plume velocity exceeds the critical vertical velocity for each source type.

**Table 6 Frequency of Exceedance of Critical Vertical Velocity with Height**

| Frequency of Exceedance of Critical Velocity | Height AGL (m) | |
|---|---|---|
| | **Exhaust Stacks** | **ACC system** |
| 100% | 48 | 29 |
| 90% | 49 | 41 |
| 80% | 50 | 41 |
| 70% | 51 | 42 |
| 60% | 51 | 46 |
| 50% | 55 | 47 |
| 40% | 57 | 49 |
| 30% | 59 | 52 |
| 20% | 63 | 55 |
| 10% | 70 | 61 |
| 9% | 71 | 62 |
| 8% | 72 | 63 |
| 7% | 74 | 63 |
| 6% | 75 | 65 |
| 5% | 76 | 66 |
| 4% | 77 | 68 |
| 3% | 79 | 69 |
| 2% | 82 | 70 |
| 1% | 109 | 73 |
| 0.5% | 133 | 76 |
| 0.3% | 143 | 96 |
| 0.2% | 162 | 101 |
| 0.1% | 187 | 104 |
| 0.05% | 208 | 106 |

**Table 7 Minimum, Average and Maximum Heights AGL of Average Plume Vertical Velocity Exceedances of Critical Vertical Velocity**

| | Height AGL (m) | |
|---|---|---|
| | **Exhaust Stacks** | **ACC system** |
| Minimum | 48 | 29 |
| Average | 57.8 | 49 |
| Maximum | 289 | 156 |

The results presented in **Table 6** suggest that at 100 m (60 m above stack height) the probability of exceedance of the critical velocity is between approximately 2% and 1% for the exhaust stacks and between approximately 0.3% and 0.2% for the ACC system.

# 4 Plume Merging Buoyancy Enhancement

As discussed in **Section 2** of this report, the modelling of plume rise from the exhaust stacks and the ACC system has been conducted without accounting for the interaction between the two different source groups. By modelling the plume rise from the exhaust stacks and ACC system in isolation, enhanced by the Briggs 1984 approach, from release points representative of the maximum extent of plume merging for each source type (i.e. at the centre point between exhaust stacks and the centre of the ACC structure), the maximum plume rise and horizontal plume extent from the two source types was modelled in accordance with CASA requirements.

The complex nature of the cooling tower system, particularly in relation to the varying separation distances between each individual ACC system release point and each individual exhaust stack caused by the "square" alignment of the ACC system (see **Figure 2**), meant the conventional plume rise enhancement equations used in the standard approach for plume rise assessments, as specified by CASA, were not readily applicable to account for plume merging within the modelling.

However the results in **Section 3** show that plume interaction between the two source groups has the potential to occur. In order to analyse the extent of plume merging and resultant buoyancy enhancement, the approach of Anfossi et al in 1978 (as discussed by Zanetti et al, 2003) has been applied.

Anfossi et al (Zanetti et al, 2003) developed a methodology in 1978 that allows for the calculation of final plume rise from multiple sources of differing buoyancy and stack heights ($\Delta H^N$), as is the case with the exhaust stacks and ACC system, by first deriving the point of plume merging ($H_i$), as follows:

$$\Delta H^N = H_i + C\sum_{j=1}^{N}\left\{F_j^{1/3} - \left[\left(H_i - H_j\right)/C\right]^3\right\}^{1/3}$$

in which

$$H_i = H_{MAX} + \frac{\Delta H_{MIN} - (H_{MAX} - H_{MIN})}{1 + \left[\Delta H_{MIN} - (H_{MAX} - H_{MIN})\right]/D}$$

is the merging point, $\Delta H_{MIN}$ is the maximum single plume rise from the lowest stack $H_{MIN}$, $C = \Delta H_{MIN} / F_{MIN}^{1/3}$ and $D = (n-1)\Delta s$. $F_{MIN}$ is the buoyancy flux parameter, $F_B$, for the lowest stack defined by Anfossi et al (Zanetti et al, 2003):

$$F_b = U_{SC} R^2 g \left[\frac{(\rho_a - \rho_s)}{\rho_a}\right]$$

where $U_{SC}$ is the plume centreline velocity, $R$ is the plume radius, $g$ is the acceleration due to gravity and $\rho_a$ and $\rho_s$ are the density of the air and plume respectively. Ambient air density is assumed to be 1.2 kg/m$^3$ while the plume density for the exhaust stacks and ACC system are 0.87 kg/m$^3$ and 1.16 kg/m$^3$ respectively (personal correspondence, GHD, 2007).

The Anfossi et al approach was applied in the atmospheric dispersion modelling conducted for this Project, and is detailed in **Section 6.6** of the main body of report 10-4044R3. Plume modelling for the purpose of pollution dispersion was conducted for each exhaust stack. Each stack had an hourly-varying exit velocity, enhanced by the interaction between the two exhaust stacks (utilising the Briggs 1984 method for identical stacks) and interaction with the nearest release point of the ACC system (utilising the Anfossi et al. approach).

This approach is based on the assumption that the plume enhancement potential of the closest ACC system release point (lower left opening of the ACC system in **Figure 2**) is equal to that across the entire ACC system. In reality, the point of maximum plume merging, and subsequently the point of maximum buoyancy enhancement, could be expected to occur at the centre of the ACC structure (see **Figure 2**). Due to the square alignment of the ACC resulting in varying degrees of plume overlapping across the system, the level of buoyancy enhancement is not likely to be consistent across the domain, indeed at a minimum at the outer corners.

Subsequently, the exhaust stack plume enhancement generated by merging with the ACC plume can be viewed as conservatively high. While this approach does not meet the predefined requirements of CASA in assessing plume rise, it is adequate in conservatively quantifying the extent plume interaction between the exhaust stacks and the ACC system. The results of this approach have been analysed and compared with the modelling results previously listed in **Section 3.3**.

It is noted that the predicted plume rise for the eastern exhaust stack, accounting for interaction with the closest release point of the ACC system (and therefore the lowest potential point for plume merging), has been used in this comparison, further emphasising the conservative nature of this approach. Additionally, as the atmospheric dispersion modelling was conducted for the 2006 calendar year only, comparison against the results obtained from both year 2006 and the full five year modelling period (2002-2006) of the CASA assessment, has been completed.

**Table 8** details the percentage of time and height (AGL) that the average vertical velocity for the exhaust stack, enhanced by the ACC system, exceeds the critical vertical velocity for the modeling period (2006). In addition, the corresponding results from the CASA assessment for 2006 and the five year modeling period, and the percentage increase due to plume enhancement by the ACC system, are also listed.

Furthermore, **Table 9** details the maximum, minimum and average heights (AGL) that the average vertical plume velocity exceeds the critical vertical velocity for the CASA modeling (2006 and five year period) and the enhanced 2006 plume rise. Percentage increase values are also listed.

The results presented in **Table 8** suggest that at 100 m (60 m above stack height) the probability of exceedance of the critical velocity is between approximately 3% and 2% for the exhaust stacks (an increase from between 2% and 1% as stated in **Section 3.3**), accounting conservatively for the influence of the ACC system.

**Table 9** indicates that when the plume interaction between the ACC system and the exhaust stack is conservatively represented, the average height of exceedance of critical vertical velocity is increased by approximately 16%. Furthermore, **Table 9** shows that the maximum height of exceedance can be expected to increase by approximately 8%.

From analysis of these results, and on the basis that the assumptions underpinning the modelling were conservative, it can be considered that the extent of plume rise enhancement of the exhaust stack plumes due to interaction with the ACC system plume will be relatively minimal.

**Table 8 Frequency of Exceedance of Critical Vertical Velocity with Height – Exhaust Stack Plume Enhancement**

| Frequency of Exceedance of Critical Velocity | Height AGL (m) | | |
|---|---|---|---|
| | Enhanced Exhaust Stack | 2006 CASA Modelling (% Increase) | 2002-2006 CASA Modelling (% Increase) |
| 100% | 50 | 48 (4%) | 48 (4%) |
| 90% | 53 | 50 (6%) | 50 (8%) |
| 80% | 54 | 50 (8%) | 50 (8%) |
| 70% | 58 | 51 (14%) | 51 (14%) |
| 60% | 61 | 52 (17%) | 52 (20%) |
| 50% | 63 | 55 (16%) | 55 (16%) |
| 40% | 66 | 56 (18%) | 56 (16%) |
| 30% | 70 | 60 (18%) | 60 (20%) |
| 20% | 74 | 64 (16%) | 64 (17%) |
| 10% | 80 | 71 (12%) | 71 (14%) |
| 9% | 80 | 71 (14%) | 71 (14%) |
| 8% | 81 | 72 (13%) | 72 (13%) |
| 7% | 82 | 74 (11%) | 74 (11%) |
| 6% | 83 | 75 (11%) | 75 (11%) |
| 5% | 84 | 76 (12%) | 76 (12%) |
| 4% | 86 | 77 (13%) | 77 (13%) |
| 3% | 90 | 79 (16%) | 79 (16%) |
| 2% | 113 | 82 (38%) | 82 (38%) |
| 1% | 135 | 109 (26%) | 109 (26%) |
| 0.5% | 152 | 135 (16%) | 135 (17%) |
| 0.3% | 170 | 149 (17%) | 149 (22%) |
| 0.2% | 186 | 164 (15%) | 164 (17%) |
| 0.1% | 212 | 189 (13%) | 189 (14%) |
| 0.05% | 237 | 209 (14%) | 209 (15%) |

**Table 9 Minimum, Average and Maximum Heights AGL of Average Plume Vertical Velocity Exceedances of Critical Vertical Velocity – Exhaust Stack Plume Enhancement**

| | Height AGL (m) | | |
|---|---|---|---|
| | Enhanced Exhaust Stack | 2006 CASA Modelling (% Increase) | 2002-2006 CASA Modelling (% Increase) |
| Minimum | 50 | 48 (4%) | 48 (4%) |
| Average | 67 | 58.2 (15%) | 57.8 (16%) |
| Maximum | 308 | 285 (8%) | 289 (7%) |

# 5 CONCLUSIONS

An assessment has been conducted of the potential hazard that exhaust plumes from the proposed gas turbine power facility at Bamarang present to aviation activities in the surrounding region.

The Air Pollution Model (TAPM) was used in plume rise mode to analyse plume behaviour from the exhaust stacks and ACC system for meteorological conditions predicted for the site over a modelling period of 5 years (2002-2006).

The plume rise from a single stack from each source type was modelled, and an hourly-varying plume rise enhancement factor was applied to the vertical velocity inputs to conservatively account for the impact of enhanced buoyancy as a result of plume merging.

Results of the assessment indicate that the probability of an exceedance of the critical vertical velocity (4.3 m/s) decreases significantly with altitude. Approximately 98% and 99.7% of all predicted exceedances of the critical vertical velocity occur beneath 100 m AGL, (60 m above stack height) for the exhaust stacks and ACC system respectively.

The maximum height at which the average vertical plume velocity is predicted to exceed the critical vertical velocity is 289 m and 156 m AGL for the exhaust stacks and ACC system respectively. The frequency with which this was predicted to occur was less than 0.05% for both sources.

Conservative modelling accounting for the enhancement of the exhaust stacks plume rise by the ACC system was conducted and compared with the modelling of the two soure types in isolation. Following comparison between the modelling approaches, the interaction between the ACC system and the exhaust stacks is unlikely to significantly increase plume rise.

Finally, it is noted that the original plans for the power station comprised of a water cooling tower system. The original assessment did not account for plume rise from this system due to the fact that the number of release points (6 compared with 36 for the ACC system) and proximity to the exhaust stacks (a minimum of approximately 190 m compared with a minimum of approximately 75 m for the ACC system) negated the need for closer inspection.

# 6 REFERENCES

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