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REVISED AIR DISPERSION MODELLING OF EMISSIONS TO ATMOSPHERE FROM THE ABBVIE FACILITY, BALLYTIVNAN, CO. SLIGO

Technical Report Prepared For

Abbvie Ireland NL B.V.
Ballytivnan,
Co. Sligo

Technical Report Prepared By

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Our Reference

CN/21/12124AR01_2

Date Of Issue

26 March 2021

Document History

Document Reference		Original Issue Date	
21/12124AR01_2		16 February 2021	
Revision Level	Revision Date	Description	Sections Affected
1	01/03/21	Revised wording	1.0, 2.8
2	26/03/21	Updated flow rate and stack height for A1-1, A1-2	2.8, 3.1, 3.2, 3.3

Record of Approval

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Date	26 March 2021	26 March 2021

EXECUTIVE SUMMARY

AWN Consulting Ltd. were commissioned to carry out an air dispersion modelling study of emissions from the Abbvie facility, Ballytivnan, Co. Sligo. Modelling was conducted at updated stack heights and volume flow rates for the boilers at the facility as installed. The site is currently licenced with the EPA under IE licence Reg No. P1087-01. Modelling for the purposes of the IE licence application was conducted using best available information at the time of the licence application. However, there was a discrepancy in the information provided and the actual boiler specifications differ somewhat to the licence specifications. Therefore an updated modelling study has been conducted to determine whether the emissions from the site at the corrected parameters will lead to ambient concentrations which are in compliance with the relevant ambient air quality standards for NO_2 and SO_2.

There is a second Abbvie facility located approximately 1km to the east which holds a valid IE licence (Licence No. P0643-03), emissions from both facilities have been included in a cumulative assessment to ensure compliance with the ambient air quality standards for NO_2 and SO_2.

The study consists of the following components:

- Review of emission data and other relevant information needed for the modelling study;
- Summary of background NO_2 and SO_2 levels;
- Dispersion modelling of released substances under a worst-case emission scenario;
- Presentation of predicted ground level concentrations of released substances;
- Evaluation of the significance of these predicted concentrations, including consideration of whether these ground level concentrations are likely to exceed the relevant ambient air quality limit values.

Assessment Summary

With regard to NO_2, emissions from the facility will result in ambient NO_2 concentrations (including background) which are in compliance with the relevant limit values, reaching at most 40% of the 1-hour limit value (measured as a 99.8^{th}%ile) and 48% of the annual limit value at the worst-case off-site location.

Emissions of SO_2 from the facility will result in ambient SO_2 concentrations (including background) which are in compliance with the relevant limit values, reaching at most 11% of the 1-hour limit value (measured as a 99.7^{th}%ile) and 15% of the 24-hour limit value (measured as a 99.2^{nd}%ile) at the worst-case off-site location.

The cumulative assessment with the neighbouring Abbvie facility also found results to be in compliance with the relevant ambient air quality limit values. Emissions from both facilities lead to an ambient NO_2 concentration (including background) which is 40% of the maximum ambient 1-hour limit value (measured as a 99.8^{th}%ile) and 48% of the annual mean limit value at the worst-case off-site receptor.

Results of the cumulative assessment are also in compliance with the ambient air quality standards for SO_2. Emissions from both facilities lead to an ambient SO_2 concentration (including background) that is 11% of the maximum ambient 1-hour limit value (measured as a 99.7^{th}%ile) and 15% of the 24-hour limit value (measured as a 99.2^{nd}%ile) at the worst-case location off-site.

In conclusion, ambient levels of nitrogen oxides (as NO_2) and sulphur dioxide (SO_2) from the Abbvie facility as well as the cumulative emissions from the neighbouring Abbvie facility are in compliance with the air quality limit values for the protection of human health and it is predicted that air emissions from the installation will not have a significant impact on the local environment.

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1.0 INTRODUCTION

AWN Consulting Ltd. were commissioned to carry out an air dispersion modelling study of emissions from the Abbvie facility, Ballytivnan, Co. Sligo. Modelling was conducted at updated stack heights and volume flow rates for the boilers at the facility as installed. The site is currently licenced with the EPA under IE licence Reg No. P1087-01. Modelling for the purposes of the IE licence application was conducted using best available information at the time of the licence application. However, there was a discrepancy in the information provided and the actual boiler specifications differ somewhat to the licence specifications. Therefore an updated modelling study has been conducted to determine whether the emissions from the site at the corrected parameters will lead to ambient concentrations which are in compliance with the relevant ambient air quality standards for NO_2 and SO_2.

There is a second Abbvie facility located approximately 1km to the east which holds a valid IE licence (Licence No. P0643-03), emissions from both facilities have been included in a cumulative assessment to ensure compliance with the ambient air quality standards for NO_2 and SO_2.

This report describes the outcome of this study. The study consists of the following components:

- Review of emission data and other relevant information needed for the modelling study;
- Summary of background NO_2 and SO_2 levels;
- Dispersion modelling of released substances under a worst-case emission scenario;
- Presentation of predicted ground level concentrations of released substances;
- Evaluation of the significance of these predicted concentrations, including consideration of whether these ground level concentrations are likely to exceed the relevant ambient air quality limit values.

Information supporting the conclusions has been detailed in the following sections. The assessment methodology and study inputs are presented in Section 2. The dispersion modelling results and assessment summaries are presented in Section 3. The model formulation is detailed in Appendix I and a review of the meteorological data used is detailed in Appendix II.

2.0 MODELLING METHODOLOGY

Emissions from the facility have been modelled using the AERMOD dispersion model (Version 19191) which has been developed by the U.S. Environmental Protection Agency (USEPA)(1) and following guidance issued by the EPA(2). The model is a steady-state Gaussian plume model used to assess pollutant concentrations associated with industrial sources and has replaced ISCST3(3) as the regulatory model by the USEPA for modelling emissions from industrial sources in both flat and rolling terrain(4-6). The model has more advanced algorithms and gives better agreement with monitoring data in extensive validation studies(7-10). An overview of the AERMOD dispersion model is outlined in Appendix I.

The air dispersion modelling input data consisted of information on the physical environment (including building dimensions and terrain features), design details from all emission points on-site and five full years of appropriate meteorological data. Using this input data the model predicted ambient ground level concentrations beyond the site boundary for each hour of the modelled meteorological year. The model postprocessed the data to identify the location and maximum of the worst-case ground level concentration. This worst-case concentration was then added to the background concentration to give the worst-case predicted environmental concentration (PEC). The PEC was then compared with the relevant ambient air quality standard to assess the significance of the releases from the site.

The modelling aims to achieve compliance with the guidance outlined within the EPA *AG4 Guidance for Air Dispersion Modelling*(2) for the maximum permissible process contribution: *"When modelling a facility, the uncertainty in the model should be considered. If the facility is operated continually at close to the maximum licenced mass emission rate (i.e. maximum concentration and maximum volume flow) the process contribution (PC) should be less than 75% of the ambient air quality standard and less than this where background levels account for a significant fraction of the ambient air quality standard based on the formula":*

$$Maximum\ Allowable\ Process\ Contribution = 0.75 * (AQS - BC)$$

This approach allows for inherent uncertainty in air dispersion modelling to be taken into account in order to avoid a risk of exceeding the air quality standards. The modelling assessment has aimed to achieve a process contribution that is less than 75% of the ambient air quality standard at licenced conditions.

Throughout this study a worst-case approach was taken. This will most likely lead to an over-estimation of the levels that will arise in practice. The worst-case assumptions are outlined below:

- Maximum predicted concentrations were reported in this study, even if no residential receptors were near the location of this maximum;
- The effects of building downwash, due to on-site buildings, have been included in the model;
- All emission points were assumed to run continuously, every hour of the day, 365 days per year.

The Ozone Limiting Method (OLM) was used to model NO_2 concentrations. The OLM is a regulatory option in AERMOD which calculates ambient NO_2 concentrations by applying a background ozone concentration and an in-stack NO_2/NOx ratio to predicted NOx concentrations. An in-stack NO_2/NOx ratio of 0.1 and a background ozone concentration of 60 µg/m^3 were used for modelling.

2.1 Ambient Air Quality Standards

In order to reduce the risk to health from poor air quality, national and European statutory bodies have set limit values in ambient air for a range of air pollutants. These limit values or "Air Quality Standards" are health- or environmental-based levels for which additional factors may be considered. Air quality significance criteria are assessed on the basis of compliance with the appropriate standards or limit values. The applicable standards in Ireland include the Air Quality Standards Regulations 2011, which incorporate EU Directive 2008/50/EC which combines the previous air quality framework and subsequent daughter directives (see Table 3). Although the EU Air Quality Limit Values are the basis of legislation, other thresholds outlined by the EU Directives are used which are triggers for particular actions.

The ambient air quality standards applicable for NO_2 and SO_2 are outlined in Directive 2008/50/EC (see Table 1). These standards have been used in the current assessment to determine the potential impact of NO_2 and SO_2 emissions from the facility on air quality.

Pollutant	Regulation Note 1	Limit Type	Value
Nitrogen Dioxide (NO_2)	2008/50/EC	Hourly limit for protection of human health - not to be exceeded more than 18 times/year	200 µg/m^3 NO_2
		Annual limit for protection of human health	40 µg/m^3 NO_2
		Critical level for the protection of vegetation	30 µg/m^3 NO + NO_2
Sulphur Dioxide (SO_2)	2008/50/EC	Hourly limit for protection of human health - not to be exceeded more than 24 times/year	350 µg/m^3
		Daily limit for protection of human health - not to be exceeded more than 3 times/year	125 µg/m^3
		Critical limit for the protection of ecosystems	20 µg/m^3

Note 1 EU 2008/50/EC – Clean Air For Europe (CAFÉ) Directive replaces the previous Air Framework Directive (1996/30/EC) and daughter directives 1999/30/EC and 2000/69/EC

Table 1 Air Quality Standards Regulations 2011 (Based on Directive 2008/50/EC and S.I. 180 of 2011)

2.2 Background Concentrations

Air quality monitoring programs have been undertaken in recent years by the EPA and Local Authorities(11,12). The most recent annual report on air quality "Air Quality in Ireland 2019"(12), details the range and scope of monitoring undertaken throughout Ireland.

As part of the implementation of the Framework Directive on Air Quality (1996/62/EC), four air quality zones have been defined in Ireland for air quality management and assessment purposes(11). Dublin is defined as Zone A and Cork as Zone B. Zone C is composed of 23 towns with a population of greater than 15,000. The remainder of the country, which represents rural Ireland but also includes all towns with a population of less than 15,000 is defined as Zone D. In terms of air monitoring, Ballytivnan is categorised as Zone C due to its proximity to Sligo town(11).

__NO_2__

NO_2 monitoring was carried out at the Zone C monitoring stations of Kilkenny, Portlaoise and Dundalk over the period 2015 - 2019(12). The NO_2 annual average in 2019 for the locations of Kilkenny, Dundalk and Portlaoise were 5, 12 and 11 µg/m^3, respectively. Annual average results for all locations are significantly lower than the annual average limit value of 40 µg/m^3, ranging from 5 – 14 µg/m^3 over the period 2015 – 2019 (see Table 2). The average results over the last five years at the range of Zone C locations suggests an upper average of no more than 13 µg/m^3 as a background concentration. Based on the above information, a conservative estimate of the current background NO_2 concentration in the region of the Abbvie facility is 13 µg/m^3.

In relation to the annual average background, the ambient background concentration was added directly to the process concentration with the short-term peaks assumed to have an ambient background concentration of twice the annual mean background concentration.

Station	Averaging Period	Year				
		2015	2016	2017	2018	2019
Kilkenny	Annual Mean NO_2 (µg/m^3)	5	7	5	6	5
	99.8th%ile 1-hr NO_2 (µg/m^3)	70	51	58	45	42
Dundalk	Annual Mean NO_2 (µg/m^3)	-	-	-	14	12
	99.8th%ile 1-hr NO_2 (µg/m^3)	-	-	-	67	69
Portlaoise	Annual Mean NO_2 (µg/m^3)	10	11	11	11	11
	99.8th%ile 1-hr NO_2 (µg/m^3)	84	86	80	68	60

Table 2 Annual Average and 1-Hour NO_2 Concentrations – Zone C(13)

SO_2

Continuous SO_2 monitoring was carried out at a number of Zone C locations over the period 2015 – 2019, Ennis, Portlaoise and Dundalk (see Table 3). Annual average concentrations ranged from 1 – 4 µg/m^3, with no exceedances of the daily limit value of 125 µg/m^3 for the protection of human health. Long term annual average results suggest an upper limit of 3 µg/m^3 as a background concentration. Based on this EPA data a conservative estimate of the annual mean background SO_2 concentration in the region of the facility is 3 µg/m^3.

A value of 35.8 µg/m^{3}and 15.7 µg/m^3 were used as the 1-hour background and 24-hour background SO_2 concentrations respectively within this assessment. This was based on the average 99.7th percentile of hourly concentrations and the average 99.2nd percentile of 24-hour concentrations from the suburban background Zone C monitoring station in Ennis over the period 2015 – 2019.

Station	Averaging Period	Year				
		2015	2016	2017	2018	2019
Ennis	Annual mean (µg/m^3)	3	4	3	3	4
Portlaoise	Annual mean (µg/m^3)	1	1	2	3	1
Dundalk	Annual mean (µg/m^3)	-	-	-	4	2

Table 3 Annual Average SO_2 Concentrations – Zone C(12)

In relation to the annual averages, the ambient background concentration was added directly to the process concentration. However, in relation to the short-term peak concentration, concentrations due to emissions from elevated sources cannot be combined in the same way. Guidance from the UK DEFRA(13) and EPA(2) advises that for SO_2 an estimate of the maximum combined pollutant concentration can be obtained as shown below:

SO_2 - The 99.7th%ile of total 1-hour mean SO_2 is equal to the maximum of either A or B below:

a) 99.7th%ile of hourly mean background SO_2 + (2 x annual mean process concentration SO_2)

b) 99.7th%ile hourly mean process contribution SO_2 + (2 x annual mean background concentration SO_2)

SO_2 - The 99.2nd%ile of total 24-hour mean SO_2 is equal to the maximum of either C or D below:

c) 99.2nd%ile of 24-hour mean background SO_2 + (2 x annual mean process concentration SO_2)

d) 99.2nd%ile 24-hour mean process contribution SO_2 + (2 x annual mean background concentration SO_2)

2.3 Air Dispersion Modelling Methodology

The United States Environmental Protection Agency (USEPA) approved AERMOD dispersion model has been used to predict the ground level concentrations (GLC) of compounds emitted from the principal emission sources on-site.

The modelling incorporated the following features:

- Two receptor grids were created at which concentrations would be modelled. Receptors were mapped with sufficient resolution to ensure all localised "hot-spots" were identified without adding unduly to processing time. The receptor grids were based on Cartesian grids with the site at the centre. An outer grid measured 8 x 8 km with concentrations calculated at 400 m intervals. A smaller grid measured 2 x 2 km with concentrations calculated at 50 m intervals. Boundary receptor locations were also placed along the boundary of the site at 50 m intervals giving a total of 2,236 calculation points for the model.

- Hourly-sequenced meteorological information has been used in the model. The 2015 - 2019 meteorological data from Shannon Airport has been used in the assessment(14). Shannon Airport meteorological station was chosen for consistency with previous assessments.

- AERMOD incorporates a meteorological pre-processor AERMET(15). The AERMET meteorological pre-processor requires the input of surface characteristics, including surface roughness (z_0), Bowen Ratio and albedo by sector and season, as well as hourly observations of wind speed, wind direction, cloud cover, and temperature. The values of albedo, Bowen Ratio and surface roughness depend on land-use type (e.g., urban, cultivated land etc) and vary with seasons and wind direction. The assessment of appropriate land-use type was carried out to a distance of 10km from the meteorological station for Bowen Ratio and albedo and to a distance of 1km for surface roughness in line with USEPA recommendations(16).

- The source and emissions data, including stack dimensions, gas volumes and emission temperatures have been incorporated into the model.

- Detailed terrain has been mapped into the model using SRTM (Shuttle Radar Topography Mission) data with 30 m resolution. The site is located in relatively flat terrain. All terrain features have been mapped in detail into the model using the terrain pre-processor AERMAP.

2.4 Terrain

The AERMOD air dispersion model has a terrain pre-processor AERMAP which was used to map the physical environment over the receptor grid. The digital terrain input data used in the AERMAP pre-processor was SRTM data. This data was run to obtain for each receptor point the terrain height and the terrain height scale. The terrain height scale is used in AERMOD to calculate the critical dividing streamline height, H_{crit}, for each receptor. The terrain height scale is derived from the Digital Elevation Model (DEM) files in AERMAP by computing the relief height of the DEM point relative to the height of the receptor and determining the slope. If the slope is less than 10%, the program goes to the next DEM point. If the slope is 10% or greater, the controlling hill height is updated if it is higher than the stored hill height.

In areas of complex terrain, AERMOD models the impact of terrain using the concept of the dividing streamline (H_c). As outlined in the AERMOD model formulation[1] a plume embedded in the flow below H_c tends to remain horizontal; it might go around the hill or impact on it. A plume above H_c will ride over the hill. Associated with this is a tendency for the plume to be depressed toward the terrain surface, for the flow to speed up, and for vertical turbulent intensities to increase.

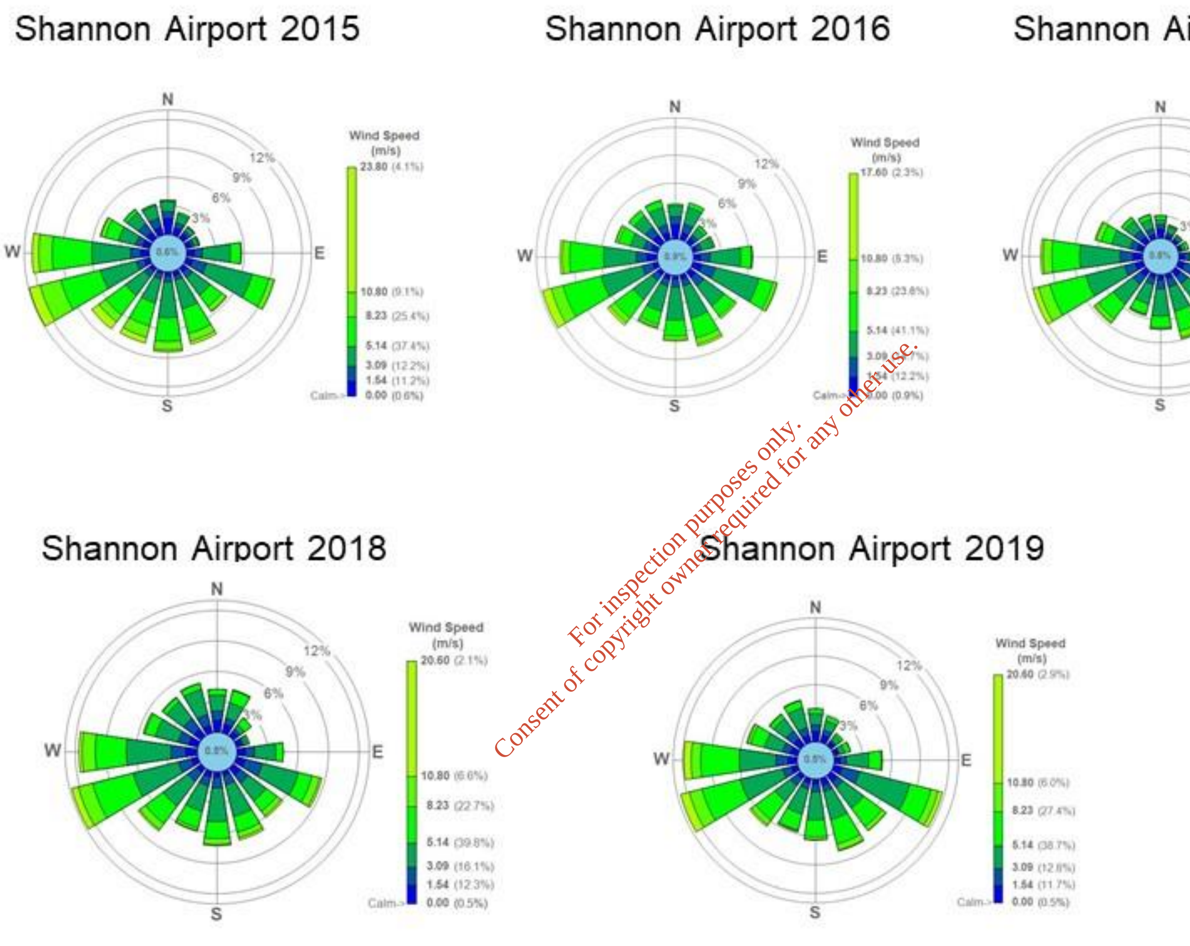
AERMOD model formulation states that the model "captures the effect of flow above and below the dividing streamline by weighting the plume concentration associated with two possible extreme states of the boundary layer (horizontal plume and terrain-following). The relative weighting of the two states depends on: 1) the degree of atmospheric stability; 2) the wind speed; and 3) the plume height relative to terrain. In stable conditions, the horizontal plume "dominates" and is given greater weight while in neutral and unstable conditions, the plume traveling over the terrain is more heavily weighted"[1].

AERMOD also has the capability of modelling both unstable (convective) conditions and stable (inversion) conditions. The stability of the atmosphere is defined by the sign of the sensible heat flux. Where the sensible heat flux is positive, the atmosphere is unstable whereas when the sensible heat flux is negative the atmosphere is defined as stable. The sensible heat flux is dependent on the net radiation and the available surface moisture (Bowen Ratio). Under stable (inversion) conditions, AERMOD has specific algorithms to account for plume rise under stable conditions, mechanical mixing heights under stable conditions and vertical and lateral dispersion in the stable boundary layer.

2.5 Meteorological Data

The selection of the appropriate meteorological data has followed the guidance issued by the USEPA[3] and EPA[2]. A primary requirement is that the data used should have a data capture of greater than 90% for all parameters. Shannon Airport meteorological station, which is located approximately 178 km south of the site, collects data in the correct format and has a data collection of greater than 90%. Shannon Airport meteorological station was chosen for consistency with previous assessments.

Hourly observations at Shannon Airport meteorological station provide an indication of the prevailing wind conditions for the region. Results indicate that the prevailing wind direction is from south-westerly to westerly in direction (see Figure 1). The mean wind speed was approximately 4.7 m/s over the period 1981 – 2010. Calm conditions account for only a small fraction of the time in any one year peaking at 0.9% of the time in 2016. There are also no missing hours over the period 2015 – 2019[14].



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AbbVie Ballytivnan Air Dispersion Modelling Assessment

Reference
21/12124AR01_2

Figure 1
Shannon Airport
Windrose
2015 – 2019

2.6 Geophysical Considerations

AERMOD simulates the dispersion process using planetary boundary layer (PBL) scaling theory[1]. PBL depth and the dispersion of pollutants within this layer are influenced by specific surface characteristics such as surface roughness, albedo and the availability of surface moisture. Surface roughness is a measure of the aerodynamic roughness of the surface and is related to the height of the roughness element. Albedo is a measure of the reflectivity of the surface whilst the Bowen ratio is a measure of the availability of surface moisture.

AERMOD incorporates a meteorological pre-processor AERMET[15] to enable the calculation of the appropriate parameters. The AERMET meteorological preprocessor requires the input of surface characteristics, including surface roughness (z_0), Bowen Ratio and albedo by sector and season, as well as hourly observations of wind speed, wind direction, cloud cover, and temperature. The values of albedo, Bowen Ratio and surface roughness depend on land-use type (e.g., urban, cultivated land etc) and vary with seasons and wind direction. The assessment of appropriate land-use type was carried out to a distance of 10km from the meteorological station for Bowen Ratio and albedo and to a distance of 1km for surface roughness in line with USEPA recommendations[15,16] as outlined in Appendix II.

In relation to AERMOD, detailed guidance for calculating the relevant surface parameters has been published[16]. The most pertinent features are:

- The surface characteristics should be those of the meteorological site (Shannon Airport) rather than the installation;
- Surface roughness should use a default 1km radius upwind of the meteorological tower and should be based on an inverse-distance weighted geometric mean. If land use varies around the site, the land use should be sub-divided by sectors with a minimum sector size of 30º;
- Bowen ratio and albedo should be based on a 10km grid. The Bowen ratio should be based on an un-weighted geometric mean. The albedo should be based on a simple un-weighted arithmetic mean.

AERMOD has an associated pre-processor, AERSURFACE[16], which has representative values for these parameters depending on land use type. The AERSURFACE pre-processor currently only accepts NLCD92 land use data which covers the USA. Thus, manual input of surface parameters is necessary when modelling in Ireland. Ordnance survey discovery maps (1:50,000) and digital maps such as those provided by the EPA, National Parks and Wildlife Service (NPWS) and Google Earth® are useful in determining the relevant land use in the region of the meteorological station. The Alaska Department of Environmental Conservation has issued a guidance note for the manual calculation of geometric mean for surface roughness and Bowen ratio for use in AERMET[17]. This approach has been applied to the current site with full details provided in Appendix II.

2.7 Building Downwash

When modelling emissions from an industrial installation, stacks which are relatively short can be subjected to additional turbulence due to the presence of nearby buildings. Buildings are considered nearby if they are within five times the lesser of the building height or maximum projected building width (but not greater than 800m).

The USEPA has defined the “Good Engineering Practice” (GEP) stack height as the building height plus 1.5 times the lesser of the building height or maximum projected building width. It is generally considered unlikely that building downwash will occur when stacks are at or greater than GEP[18].

When stacks are less than this height, building downwash will tend to occur. As the wind approaches a building it is forced upwards and around the building leading to the formation of turbulent eddies. In the lee of the building these eddies will lead to downward mixing (reduced plume centreline and reduced plume rise) and the creation of a cavity zone (near wake) where re-circulation of the air can occur. Plumes released from short stacks may be entrained in this airflow leading to higher ground level concentrations than in the absence of the building.

The Plume Rise Model Enhancements (PRIME)[8,9] plume rise and building downwash algorithms, which calculates the impact of buildings on plume rise and dispersion, have been incorporated into AERMOD. The building input processor BPIP-PRIME produces the parameters which are required in order to run PRIME. The model takes into account the position of each stack relative to each relevant building and the projected shape of each building for 36 wind directions (at 10º intervals). The model determines the change in plume centreline location with downwind distance based on the slope of the mean streamlines and coupled to a numerical plume rise model[8].

Given that the stacks on site are less than 2.5 times the lesser of the building height or maximum projected building width, building downwash has been taken into account and the PRIME algorithm run prior to modelling with AERMOD.

2.8 Process Emissions

Modelling has been undertaken at corrected stack heights and volume flow rates for the boilers at the Abbvie facility as installed. The previous modelling assessment for the IE licence application for the site was based on best available information at the time of the licence application. However, there was a discrepancy in the information provided and the actual boiler specifications differ somewhat to the licence specifications. Therefore an updated modelling study has been conducted.

The Abbvie facility has installed two boilers which are both main emission points to air, A1-1 and A1-2. Each boiler has an associated stack at a height of 12.5m above ground level. For the purposes of this modelling assessment the boilers have been modelled as operating at 100% load simultaneously, 24 hours per day, 7 days per week. In reality both boilers operate at a varying load to meet the demand for the facility. Therefore, a worst-case conservative approach has been taken in this modelling assessment which will likely over-estimate emissions.

There are also a number of existing LPHW boilers (3 no.) and new LPHW boilers (4 no.) which emit via a common flue. Separately these emission points are all less than 1 MW, however, as advised under the Medium Combustion Plant Directive, when these emission points are aggregated they are greater than 1 MW and as such have been included in the modelling assessment. These sources have been modelled as one single emission point for the existing 3 no. LPHW boilers and one single emission point for the new 4 no. LPHW boilers. For the purposes of this assessment it has been assumed that all 7 the LPHW boilers are operating continuously, whereas in reality these operate in a standby/duty mode with only 5 in operation at any one time.

The manufacturer could not provide maximum emissions values for SO_2, however the manufacturer confirmed that the SO_2 emissions would be negligible. Therefore, the SO_2 concentrations for the boilers have been modelled at the MCP Directive limit value of 35 µg/m^3 for gaseous fuels other than natural gas (all boilers will run on LPG) as this would be the worst case emissions scenario. NO_2 concentrations have been based on maximum emissions as specified by the manufacturer.

A cumulative assessment with the neighbouring Abbvie site has also been undertaken. The relevant source parameters for the neighbouring Abbvie site (emission points A1-1, A1-2 and A2-1c) are based on actual monitoring data over two previous years and licenced details. The source information for the modelled emission points can be seen in Table 4.

There are a number of other emission points on site, however as these have an output below 1MW there were not included in the air dispersion model as their emissions were deemed insignificant.

Stack Reference	Location (Irish Grid Coordinates) Note 1		Height Above Ground Level (m)	Exit Diameter (m)	Temp (K)	Max Volume Flow (Nm^3/hr) Note 2	Exit Velocity (m/sec actual)	NO_2		SO_2	
								NO_X Concentration (mg/Nm^3) Note 2	Mass Emission (g/s)	SO_X Concentration (mg/Nm^3) Note 2	Mass Emission (g/s)
A1-1	E169867	N337606	12.5	0.40	411.15	2,575	9.64	200	0.143	35	0.025
A1-2	E169868	N337605	12.5	0.40	411.15	2,575	9.64	200	0.143	35	0.025
4 no. New LPHW Boilers Combined Flue	E169861	N337604	12.0	0.30	336.15	1,461	7.95	40	0.016	35	0.014
3 no. Existing LPHW Boilers Combined Flue	E169775	N337488	12.5	0.25	336.15	1,897	14.87	40	0.021	35	0.018
Neighbouring Abbvie Site A1_1 Note 3	E170604	N337494	26.0	0.75	358.00	1,137	0.94	166	0.052	70	0.022
Neighbouring Abbvie Site A1_2 Note 3	E170604	N337494	26.0	0.75	366.00	1,518	1.28	148	0.062	70	0.030
Neighbouring Abbvie Site A2-1c Note 3	E170674	N337478	15.0	0.30	412.52	1,477	8.77	200	0.082	70	0.029

Note 1 Stack locations are accurate to nearest 5m.
Note 2 Reference conditions are 273.15K, 101.3Pa, 3% O_2 and dry gas.
Note 3 Based on monitored emission concentrations and volume flow rates where available.

Table 4 Abbvie, Ballytivnan, Co. Sligo - Process Emissions Details

3.0 RESULTS & DISCUSSION

3.1 Process Contributions

NO_2 Emissions

The nitrogen oxide (as NO_2) modelling results are detailed in Table 5. The results indicate that the ambient ground level concentrations are below the annual and 1-hour ambient air quality standards. Emissions from the facility lead to an ambient NO_2 concentration (including background) which is 40% of the maximum 1-hour limit (measured as a 99.8th percentile) and 48% of the annual limit at the worst-case off-site location for the worst-case years modelled.

The geographical variations in ground level NO_2 concentrations beyond the facility boundary for the worst-case years modelled are illustrated as concentration contours in Figures 2 and 3. The locations of the maximum concentrations for NO_2 are close to the boundary of the site with concentrations decreasing with distance from the facility.

Pollutant / Meteorological Year	Background (µg/m^3)	Averaging Period	Process Contribution NO_2 (µg/m^3)	Predicted Emission Concentration NO_2 (µg/m^3)	Standard (µg/m^3) Note 1
NO_2 / 2015	13	Annual Mean	5.26	18.26	40
	26	99.8th%ile of 1-hr means	53.27	79.27	200
NO_2 / 2016	13	Annual Mean	5.27	18.27	40
	26	99.8th%ile of 1-hr means	53.24	79.24	200
NO_2 / 2017	13	Annual Mean	5.05	18.05	40
	26	99.8th%ile of 1-hr means	52.76	78.76	200
NO_2 / 2018	13	Annual Mean	4.91	17.91	40
	26	99.8th%ile of 1-hr means	53.86	79.86	200
NO_2 / 2019	13	Annual Mean	6.17	19.17	40
	26	99.8th%ile of 1-hr means	53.43	79.43	200

Note 1 Air Quality Standards 2011 (from EU Directive 2008/50/EC and S.I. 180 of 2011)

Table 5 Dispersion Model Results for Nitrogen Oxides (as NO_2)

SO_2 Emissions

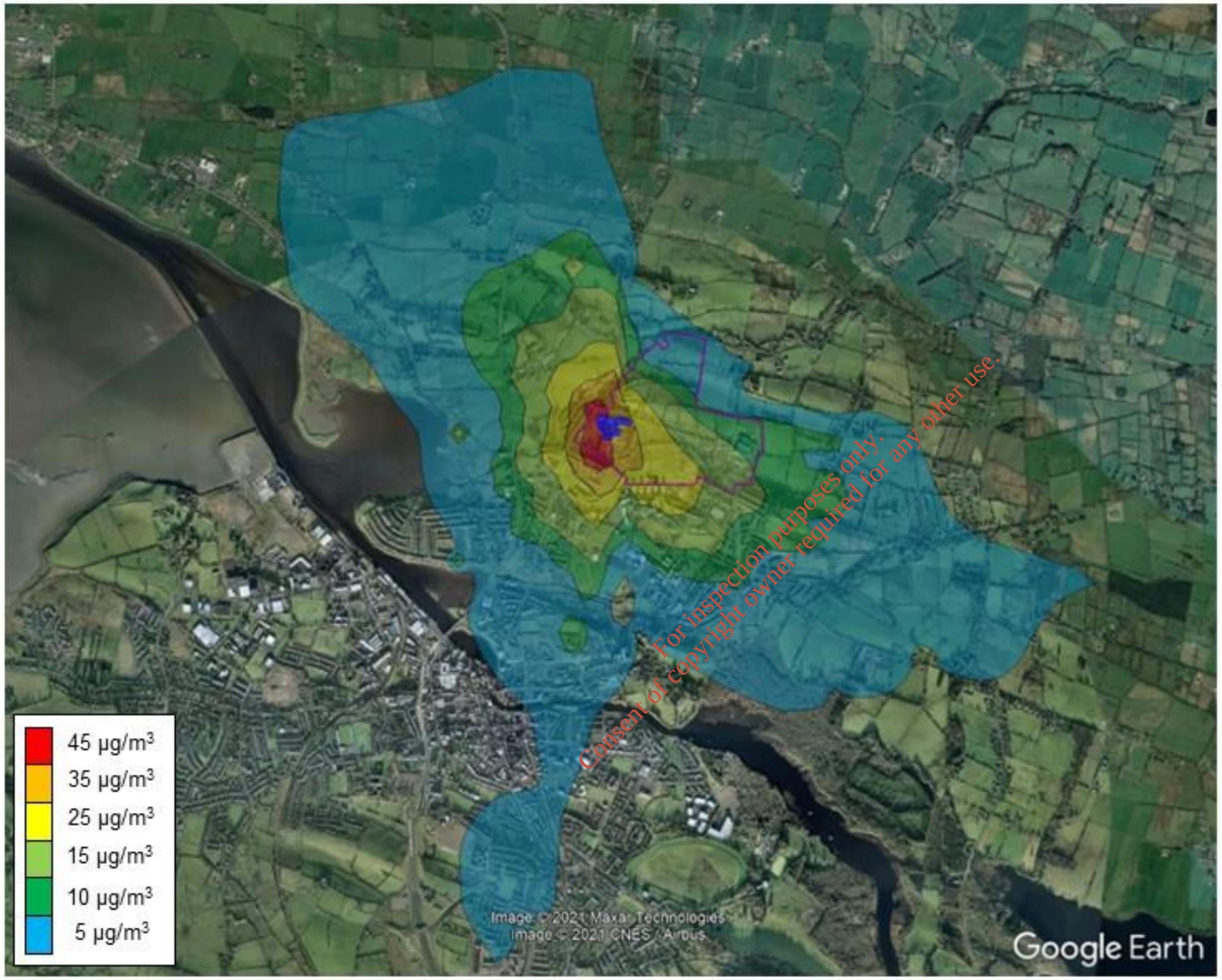
The SO_2 modelling results are detailed in Table 6. The results indicate that the ambient ground level concentrations are below the 1-hour and 24-hour ambient air quality standards. Emissions from the facility lead to an ambient SO_2 concentration (including background) that is 11% of the maximum ambient 1-hour limit value (measured as a 99.7th%ile) and 15% of the 24-hour limit value (measured as a 99.2nd%ile) at the worst-case location off-site for the worst case years modelled.

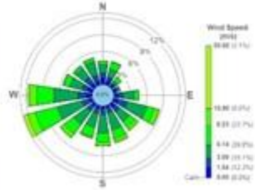
The geographical variation in the 1-hour mean (99.7th%ile) and 24-hour mean (99.2nd%ile) SO_2 ground level concentrations are illustrated as concentration contours in Figures 4 and 5.

Pollutant/ Meteorological Year	Background (µg/m³)	Averaging Period	Process Contribution SO_2 (µg/m³)	Predicted Environmental Concentration (PEC) SO_2 (µg/Nm³) Note 2	Standard (µg/Nm³) Note 1
SO_2 / 2015	15.7	99.2th%ile of 24-hr means	6.27	18.53	125
	35.8	99.7th%ile of 1-hr means	14.97	38.63	350
SO_2 / 2016	15.7	99.2th%ile of 24-hr means	6.56	18.56	125
	35.8	99.7th%ile of 1-hr means	13.37	38.66	350
SO_2 / 2017	15.7	99.2th%ile of 24-hr means	6.68	18.48	125
	35.8	99.7th%ile of 1-hr means	14.75	38.58	350
SO_2 / 2018	15.7	99.2th%ile of 24-hr means	6.11	18.40	125
	35.8	99.7th%ile of 1-hr means	14.75	38.50	350
SO_2 / 2019	15.7	99.2th%ile of 24-hr means	7.45	18.99	125
	35.8	99.7th%ile of 1-hr means	13.41	39.09	350

Note 1 Air Quality Standards 2011 (from EU Directive 2008/50/EC and S.I. 180 of 2011)
Note 2 Short-term Environmental Concentrations calculated according to EPA and UK DEFRA guidance(2)

Table 6 Dispersion Model Results for SO_2





Site boundary

Maximum concentration (excluding background): 53.86µg/m³

N

Background mapping from Google Earth

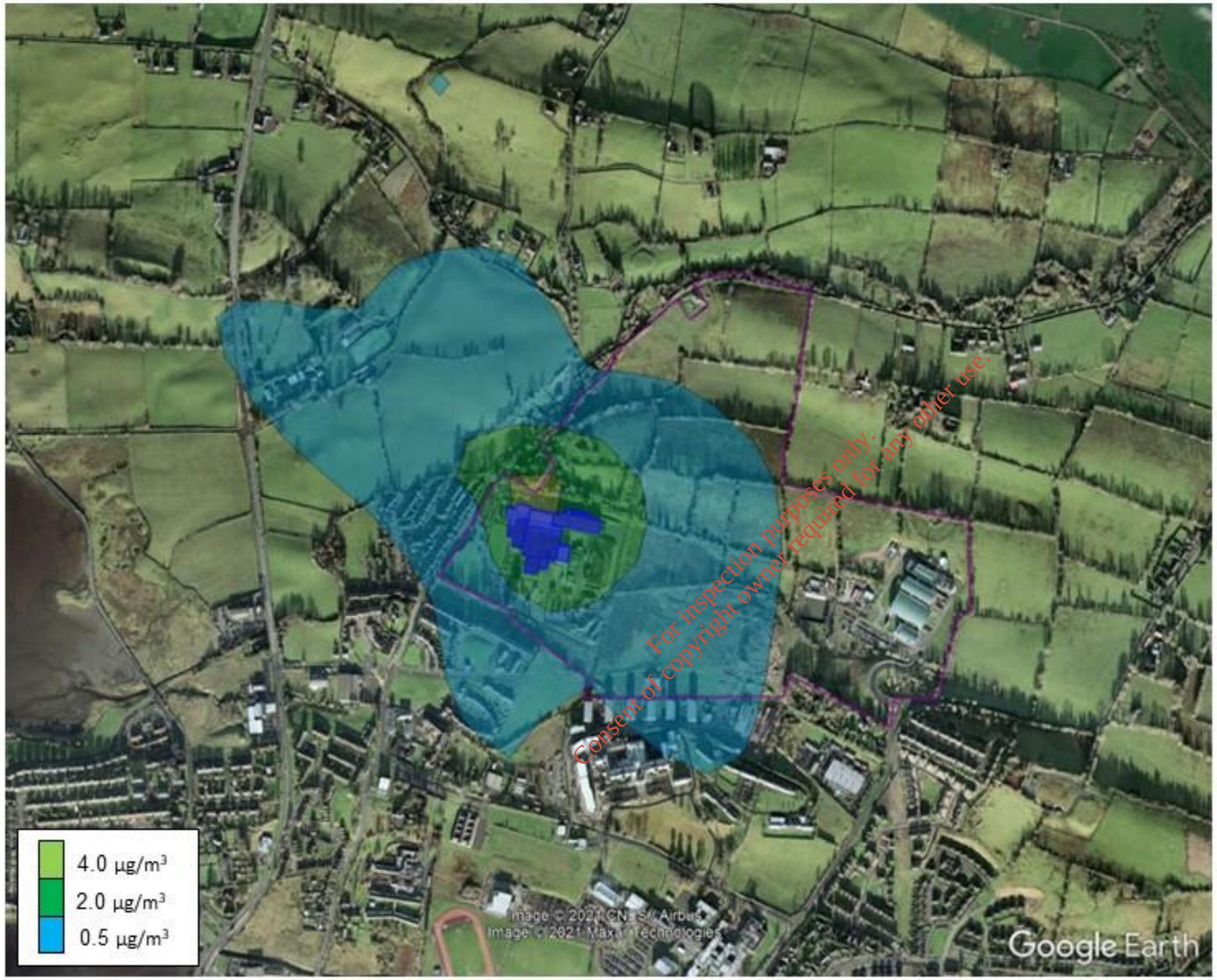
Project
AbbVie Ballytivnan Air Dispersion Modelling Assessment

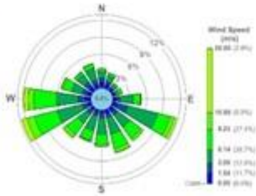
Reference
21/12124AR01_2

Figure 2
Maximum 1-Hour NO_2 Concentrations (as 99.8%ile) (µg/m³) 2018 (excluding background concentrations)

awnconsulting

The Tecpro Building, Clonshaugh Business and Technology Park, Dublin 17
T: +353 1 847 4220 F: +353 1 847 4257





Site boundary

Maximum concentration (excluding background): 6.17µg/m³

N

Background mapping from Google Earth

Project

AbbVie Ballytivnan Air Dispersion Modelling Assessment

Reference

21/12124AR01_2

Figure 3

Annual Mean NO_2 Concentrations (µg/m³) 2019 (excluding background concentrations)

awnconsulting

The Tecpro Building, Clonshaugh Business and Technology Park, Dublin 17
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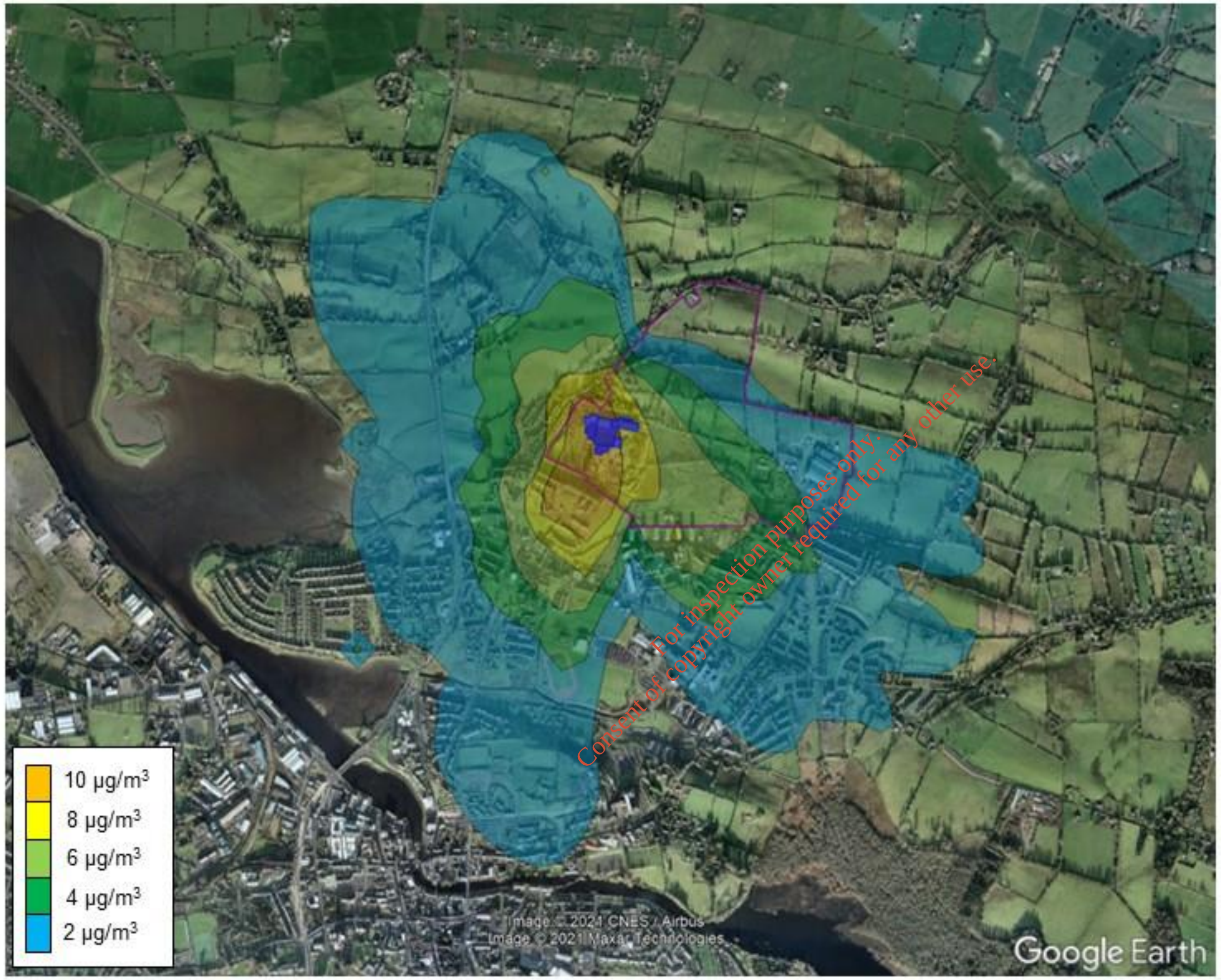

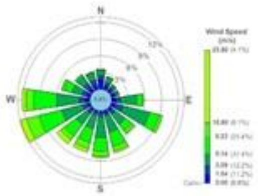

Site boundary

Maximum concentration (excluding background): 14.97µg/m^3

N

Background mapping from Google Earth

Project

AbbVie Ballytivnan Air Dispersion Modelling Assessment

Reference

21/12124AR01_2

Figure 4

Maximum 1-Hour SO_2 Concentrations (as 99.7%ile) (µg/m^3) 2015 (excluding background concentrations)

awnconsulting

The Tecpro Building, Clonshaugh Business and Technology Park, Dublin 17
T: +353 1 847 4220 F: +353 1 847 4257

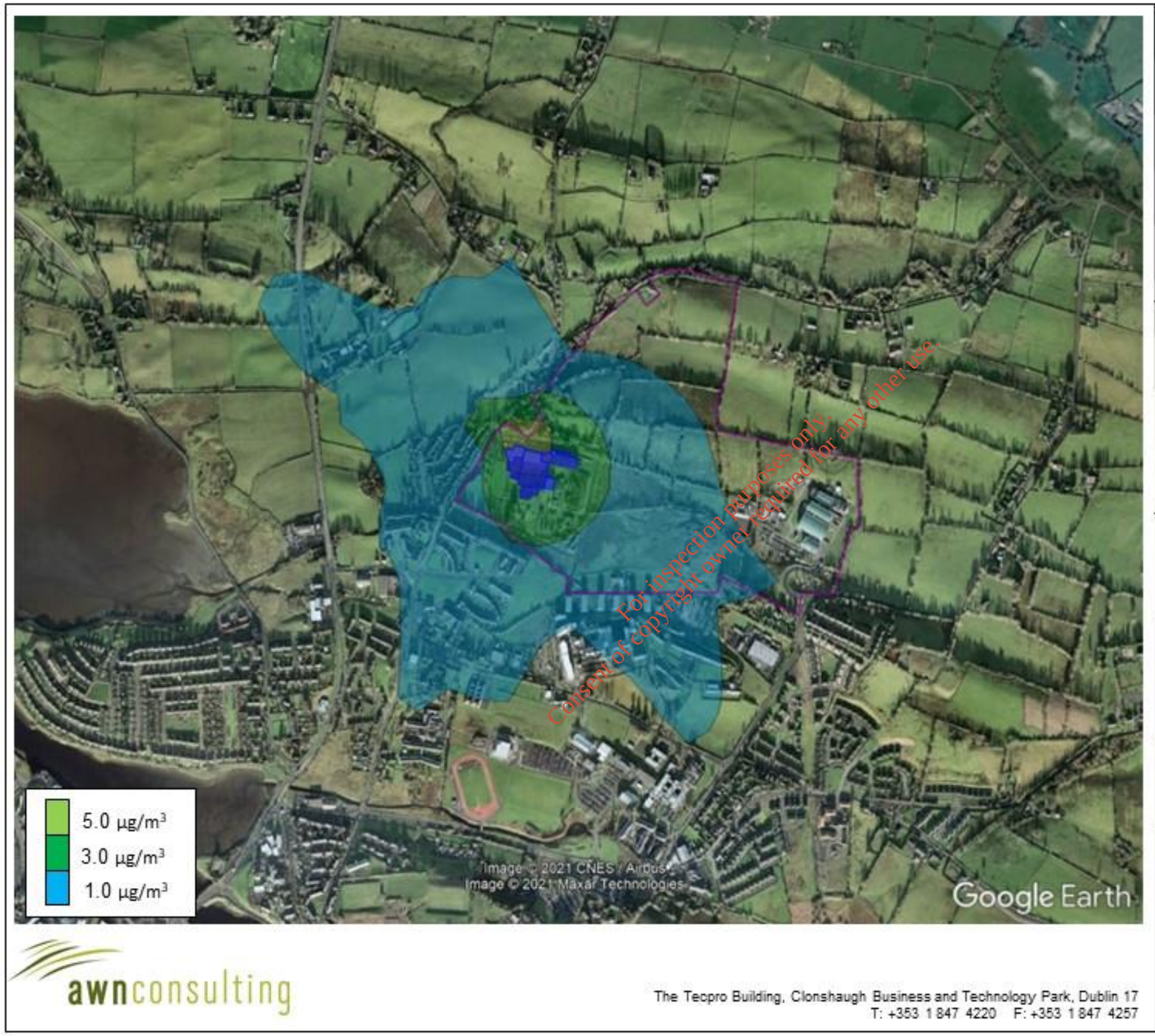

Figure 5

Maximum 24-Hour SO_2 Concentrations (as 99.2%ile) (µg/m³) 2019 (excluding background concentrations)

3.2 Cumulative Assessment

Cumulative Assessment - NO_2 Emissions

The cumulative impact of NO_2 emissions from the on site boilers and including emissions from the neighbouring Abbvie facility are detailed in Table 7 below. The results indicate that the ambient ground level concentrations are below the relevant air quality standards for NO_2. For the worst-case year, emissions from the sites lead to an ambient NO_2 concentration (including background) which is 40% of the maximum ambient 1-hour limit value (measured as a 99.8th%ile) and 48% of the annual limit value at the worst-case off-site receptor for the worst-case years modelled.

Pollutant / Meteorological Year	Background (µg/m^3)	Averaging Period	Process Contribution NO_2 (µg/m^3)	Predicted Emission Concentration NO_2 (µg/m^3)	Standard (µg/m^3) Note 1
NO_2 / 2015	13	Annual Mean	5.36	18.36	40
	26	99.8th%ile of 1-hr means	53.27	79.27	200
NO_2 / 2016	13	Annual Mean	5.36	18.36	40
	26	99.8th%ile of 1-hr means	53.24	79.24	200
NO_2 / 2017	13	Annual Mean	5.11	18.11	40
	26	99.8th%ile of 1-hr means	52.76	78.76	200
NO_2 / 2018	13	Annual Mean	4.99	17.99	40
	26	99.8th%ile of 1-hr means	53.86	79.86	200
NO_2 / 2019	13	Annual Mean	6.26	19.26	40
	26	99.8th%ile of 1-hr means	53.43	79.43	200

Note 1 Air Quality Standards 2011 (from EU Directive 2008/50/EC and S.I. 180 of 2011)

Table 7 Dispersion Model Results for Nitrogen Oxides (as NO_2) – Cumulative Assessment

Cumulative Assessment - SO_2 Emissions

The SO_2 modelling results for the cumulative assessment are detailed in Table 8. The results indicate that the ambient ground level concentrations are below the 1-hour and 24-hour ambient air quality standards. Emissions from both facilities lead to an ambient SO_2 concentration (including background) that is 11% of the maximum ambient 1-hour limit value (measured as a 99.7th%ile) and 15% of the 24-hour limit value (measured as a 99.2nd%ile) at the worst-case location off-site for the worst case years modelled.

Pollutant/ Meteorological Year	Background (µg/m³)	Averaging Period	Process Contribution SO_2 (µg/m³)	Predicted Environmental Concentration (PEC) SO_2 (µg/Nm³) Note 2	Standard (µg/Nm³) Note 1
SO_2 / 2015	15.7	99.2th%ile of 24-hr means	6.32	18.62	125
	35.8	99.7th%ile of 1-hr means	14.20	38.72	350
SO_2 / 2016	15.7	99.2th%ile of 24-hr means	6.61	18.65	125
	35.8	99.7th%ile of 1-hr means	13.37	38.75	350
SO_2 / 2017	15.7	99.2th%ile of 24-hr means	6.78	18.54	125
	35.8	99.7th%ile of 1-hr means	14.75	38.64	350
SO_2 / 2018	15.7	99.2th%ile of 24-hr means	6.17	18.47	125
	35.8	99.7th%ile of 1-hr means	14.75	38.57	350
SO_2 / 2019	15.7	99.2th%ile of 24-hr means	7.46	19.08	125
	35.8	99.7th%ile of 1-hr means	13.41	39.18	350

Note 1 Air Quality Standards 2011 (from EU Directive 2008/50/EC and S.I. 180 of 2011)

Note 2 Short-term Environmental Concentrations calculated according to EPA and UK DEFRA guidance(2)

Table 8 Dispersion Model Results for SO_2 – Cumulative Assessment

3.3 Assessment Summary

With regard to NO_2, emissions from the facility will result in ambient NO_2 concentrations (including background) which are in compliance with the relevant limit values, reaching at most 40% of the 1-hour limit value (measured as a 99.8th%ile) and 48% of the annual limit value at the worst-case off-site location.

Emissions of SO_2 from the facility will result in ambient SO_2 concentrations (including background) which are in compliance with the relevant limit values, reaching at most 11% of the 1-hour limit value (measured as a 99.7th%ile) and 15% of the 24-hour limit value (measured as a 99.2nd%ile) at the worst-case off-site location.

The cumulative assessment with the neighbouring Abbvie facility also found results to be in compliance with the relevant ambient air quality limit values. Emissions from both facilities lead to an ambient NO_2 concentration (including background) which is 40% of the maximum ambient 1-hour limit value (measured as a 99.8th%ile) and 48% of the annual mean limit value at the worst-case off-site receptor.

Results of the cumulative assessment are also in compliance with the ambient air quality standards for SO_2. Emissions from both facilities lead to an ambient SO_2 concentration (including background) that is 11% of the maximum ambient 1-hour limit value (measured as a 99.7th%ile) and 15% of the 24-hour limit value (measured as a 99.2nd%ile) at the worst-case location off-site.

In conclusion, ambient levels of nitrogen oxides (as NO_2) and sulphur dioxide (SO_2) from the Abbvie facility as well as the cumulative emissions from the neighbouring Abbvie facility are in compliance with the air quality limit values for the protection of human health and it is predicted that air emissions from the installation will not have a significant impact on the local environment.

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(7) USEPA (1999) Comparison of Regulatory Design Concentrations: AERMOD vs. ISCST3 vs. CTDM PLUS
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(16) USEPA (2008) AERSURFACE User's Guide
(17) Alaska Department of Environmental Conservation (2008) ADEC Guidance re AERMET Geometric Means (http://dec.alaska.gov/air/ap/modeling.htm)
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APPENDIX I

Description of the AERMOD Model

The AERMOD dispersion model has been recently developed in part by the U.S. Environmental Protection Agency (USEPA)[1]. The model is a steady-state Gaussian model used to assess pollutant concentrations associated with industrial sources. The model is an enhancement on the Industrial Source Complex-Short Term 3 (ISCST3) model which has been widely used for emissions from industrial sources.

Improvements over the ISCST3 model include the treatment of the vertical distribution of concentration within the plume. ISCST3 assumes a Gaussian distribution in both the horizontal and vertical direction under all weather conditions. AERMOD with PRIME, however, treats the vertical distribution as non-Gaussian under convective (unstable) conditions while maintaining a Gaussian distribution in both the horizontal and vertical direction during stable conditions. This treatment reflects the fact that the plume is skewed upwards under convective conditions due to the greater intensity of turbulence above the plume than below. The result is a more accurate portrayal of actual conditions using the AERMOD model. AERMOD also enhances the turbulence of night-time urban boundary layers thus simulating the influence of the urban heat island.

In contrast to ISCST3, AERMOD is widely applicable in all types of terrain. Differentiation of the simple versus complex terrain is unnecessary with AERMOD. In complex terrain, AERMOD employs the dividing-streamline concept in a simplified simulation of the effects of plume-terrain interactions. In the dividing-streamline concept, flow below this height remains horizontal, and flow above this height tends to rise up and over terrain. Extensive validation studies have found that AERMOD (precursor to AERMOD with PRIME) performs better than ISCST3 for many applications and as well or better than CTDMPLUS for several complex terrain data sets[7].

AERMOD has made substantial improvements in the area of plume growth rates in comparison to ISCST3[1]. ISCST3 approximates turbulence using six Pasquill-Gifford-Turner Stability Classes and bases the resulting dispersion curves upon surface release experiments. This treatment, however, cannot explicitly account for turbulence in the formulation. AERMOD is based on the more realistic modern planetary boundary layer (PBL) theory which allows turbulence to vary with height. This use of turbulence-based plume growth with height leads to a substantial advancement over the ISCST3 treatment.

Improvements have also been made in relation to mixing height[1]. The treatment of mixing height by ISCST3 is based on a single morning upper air sounding each day. AERMOD, however, calculates mixing height on an hourly basis based on the morning upper air sounding and the surface energy balance, accounting for the solar radiation, cloud cover, reflectivity of the ground and the latent heat due to evaporation from the ground cover. This more advanced formulation provides a more realistic sequence of the diurnal mixing height changes.

AERMOD also contains improved algorithms for dealing with low wind speed (near calm) conditions. As a result, AERMOD can produce model estimates for conditions when the wind speed may be less than 1 m/s, but still greater than the instrument threshold.

APPENDIX II

Meteorological Data - AERMET

AERMOD incorporates a meteorological pre-processor AERMET (version 16216)[15]. AERMET allows AERMOD to account for changes in the plume behaviour with height. AERMET calculates hourly boundary layer parameters for use by AERMOD, including friction velocity, Monin-Obukhov length, convective velocity scale, convective (CBL) and stable boundary layer (SBL) height and surface heat flux. AERMOD uses this information to calculate concentrations in a manner that accounts for changes in dispersion rate with height, allows for a non-Gaussian plume in convective conditions, and accounts for a dispersion rate that is a continuous function of meteorology.

The AERMET meteorological preprocessor requires the input of surface characteristics, including surface roughness (z_0), Bowen Ratio and albedo by sector and season, as well as hourly observations of wind speed, wind direction, cloud cover, and temperature. A morning sounding from a representative upper air station, latitude, longitude, time zone, and wind speed threshold are also required.

Two files are produced by AERMET for input to the AERMOD dispersion model. The surface file contains observed and calculated surface variables, one record per hour. The profile file contains the observations made at each level of a meteorological tower, if available, or the one-level observations taken from other representative data, one record level per hour.

From the surface characteristics (i.e. surface roughness, albedo and amount of moisture available (Bowen Ratio)) AERMET calculates several boundary layer parameters that are important in the evolution of the boundary layer, which, in turn, influences the dispersion of pollutants. These parameters include the surface friction velocity, which is a measure of the vertical transport of horizontal momentum; the sensible heat flux, which is the vertical transport of heat to/from the surface; the Monin-Obukhov length which is a stability parameter relating the surface friction velocity to the sensible heat flux; the daytime mixed layer height; the nocturnal surface layer height and the convective velocity scale which combines the daytime mixed layer height and the sensible heat flux. These parameters all depend on the underlying surface.

The values of albedo, Bowen Ratio and surface roughness depend on land-use type (e.g., urban, cultivated land etc) and vary with seasons and wind direction. The assessment of appropriate land-use types was carried out in line with USEPA recommendations[4] and using the detailed methodology outlined by the Alaska Department of Environmental Conservation[17]. AERMET has also been updated to allow for an adjustment of the surface friction velocity (u*) for low wind speed stable conditions based on the work of Qian and Venkatram (BLM, 2011). Previously, the model had a tendency to over-predict concentrations produced by near-ground sources in stable conditions.

Surface roughness

Surface roughness length is the height above the ground at which the wind speed goes to zero. Surface roughness length is defined by the individual elements on the landscape such as trees and buildings. In order to determine surface roughness length, the USEPA recommends that a representative length be defined for each sector, based on an upwind area-weighted average of the land use within the sector, by using the eight land use categories outlined by the USEPA. The inverse-distance weighted surface roughness length derived from the land use classification within a radius of 1km from Shannon Airport Meteorological Station is shown in Table A1.

Sector	Area Weighted Land Use Classification	Spring	Summer	Autumn	Winter[Note 1]
270-180	100% Grassland	0.05	0.10	0.01	0.01
180-270	100% Urban	1	1	1	1

(1) Winter defined as periods when surfaces covered permanently by snow whereas autumn is defined as periods when freezing conditions are common, deciduous trees are leafless and no snow is present (Iqbal (1983))[19]. Thus for the current location autumn more accurately defines "winter" conditions in Ireland.

Table A1 Surface Roughness based on an inverse distance weighted average of the land use within a 1km radius of Shannon Airport Meteorological Station.

Albedo

Noon-time albedo is the fraction of the incoming solar radiation that is reflected from the ground when the sun is directly overhead. Albedo is used in calculating the hourly net heat balance at the surface for calculating hourly values of Monin-Obuklov length. A 10km x 10km square area is drawn around the meteorological station to determine the albedo based on a simple average for the land use types within the area independent of both distance from the station and the near-field sector. The classification within 10km from Shannon Airport Meteorological Station is shown in Table A2.

Area Weighted Land Use Classification	Spring	Summer	Autumn	Winter[Note 1]
6% Urban, 49% Grassland, 45% Water	0.151	0.143	0.172	0.172

(1) For the current location autumn more accurately defines "winter" conditions in Ireland.

Table A2 Albedo based on a simple average of the land use within a 10km × 10km grid centred on Shannon Airport Meteorological Station.

Bowen Ratio

The Bowen ratio is a measure of the amount of moisture at the surface of the earth. The presence of moisture affects the heat balance resulting from evaporative cooling which, in turn, affects the Monin-Obukhov length which is used in the formulation of the boundary layer. A 10km x 10km square area is drawn around the meteorological station to determine the Bowen Ratio based on geometric mean of the land use types within the area independent of both distance from the station and the near-field sector. The classification within 10km from Shannon Airport Meteorological Station is shown in Table A3.

Area Weighted Land Use Classification	Spring	Summer	Autumn	Winter[Note 1]
19% Urban, 81% Grassland	0.301	0.557	0.655	0.655

(1) For the current location autumn more accurately defines "winter" conditions in Ireland.

Table A3 Bowen Ratio based on a geometric mean of the land use within a 10km × 10km grid centred on Shannon Airport Meteorological Station.