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DETERMINATION OF ODOUR EMISSIONS TO ATMOSPHERE FROM THE WATERFORD PROTEINS FACILITY, COUNTY KILKENNY

Technical Report Prepared For

Anglo Beef Processors Unlimited Company (T/A Waterford Proteins)
Christendom,
Ferrybank,
Co. Kilkenny

Technical Report Prepared By

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Our Reference

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EXECUTIVE SUMMARY

AWN Consulting Ltd were commissioned by Environet Ltd to carry out an odour dispersion modelling study of emissions from the Anglo Beef Processors Unlimited Company (T/A Waterford Proteins), Christendom, Ferrybank, Co. Kilkenny. Inputs to the model included odour emission concentrations and design details provided by Waterford Proteins including the covering of the biofilter and the installation of a biofilter stack of 10m in height. The assessment has determined, through dispersion modelling of emissions from the facility, whether the predicted ambient odour concentration at the worst-case dwelling-house was less than 1.5 OU_E/m^3 as a 98^{th} percentile of the hourly average concentrations (as per the EPA AG4 and AG9 Guidance documents and the UK Environment Agency H4 Draft Guidance document).

Odour dispersion modelling was carried out using the United States Environmental Protection Agency's regulatory model AERMOD (Version 22112). The aim of the study was to assess the contribution of all odorous emission points from the facility to off-site levels of odour and to identify the location and maximum of the worst-case ground level odour concentrations.

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

- Review of activities which are likely to generate odorous emissions based on the current operations at the facility;
- Estimate the odour emissions (in terms of OU_E/s) and other relevant information needed for the modelling study;
- Dispersion modelling of odour under the future emission scenario, where the biofilter is covered and odour emissions are released from a 10m tall stack, to determine the likely level of odour in the ambient environment;
- Presentation of predicted ground level concentrations of released odours for this scenario;
- Evaluation of the significance of these predicted concentrations, including consideration of whether these ground level concentrations are likely to exceed the relevant ambient Odour Guidelines.

Assessment Summary

An assessment of the Waterford Proteins facility has found that the biofilter (AEP-1) is the main source of odour at the facility with emission point AEP-2 (Thermal Oxidiser) contributing minor amounts.

Odour modelling, based an odour emission concentration of 1000 OU_E/m^3 from both the biofilter stack (at a height of 10m) and thermal oxidiser, and using the USEPA approved AERMOD model has found that the worst case scenario for the 98^{th}%ile of 1-hour concentrations occurs in 2017 where the maximum off-site concentrations is 83% of the guideline value at the worst case receptor based on a biofilter volume flow of 150,000 Nm^3/hr.

Based on the results, no residential receptors are predicted to experience odour nuisance issues as a result of the Waterford Proteins facility based on the modelling scenarios outlined above.

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1.0 INTRODUCTION

AWN Consulting Ltd were commissioned by Environet Ltd to carry out an odour dispersion modelling study of emissions from the Waterford Proteins facility, Christendom, Ferrybank, Co. Kilkenny. Inputs to the model included odour emission concentrations and design details provided by Waterford Proteins including the covering of the biofilter and the installation of a biofilter stack of 10m in height. The assessment has determined, through dispersion modelling of emissions from the facility, whether the predicted ambient odour concentration at the worst-case dwelling-house was less than 1.5 OU_E/m^3 as a 98th percentile of the hourly average concentrations (as per the EPA AG4[(1)] and AG9[(2)] Guidance documents and the UK Environment Agency H4[(3)] Guidance document).

The site is located at Christendom, Ferrybank, Co. Kilkenny. The site is approximately 1.5 km east of Waterford city. The facility is a rendering facility. In the immediate region of the facility, the land use is predominantly agricultural with several other industrial / logistical facilities also located nearby. There are a number of residential properties within 200 m of the site and several housing developments within 500m of the site as shown in Figure 1.

The purpose of this modelling study is to determine whether the emissions from the site, will lead to ambient concentrations which are in compliance with the criterion of 1.5 OU_E/m^3 as a 98th percentile of the hourly average concentrations and to identify the location and maximum of the worst-case ground level odour concentrations.

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

- Review of activities which are likely to generate odorous emissions based on the current operations at the facility;
- Estimate the odour emissions (in terms of OU_E/s) and other relevant information needed for the modelling study;
- Dispersion modelling of odour under the future emission scenario, where the biofilter is covered and odour emissions are released from a 10m tall stack, to determine the likely level of odour in the ambient environment;
- Presentation of predicted ground level concentrations of released odours for this scenario;
- Evaluation of the significance of these predicted concentrations, including consideration of whether these ground level concentrations are likely to exceed the relevant ambient Odour Guidelines.

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, a review of the meteorological data used is detailed in Appendix II whilst comprehensive meteorological data is presented in Appendix III.

Project
Waterford Proteins Odour Modelling Assessment

Reference
227501.0589AR01

Figure 1
Map of land use in the vicinity of Waterford Proteins, Christendom, Co. Kilkenny

2.0 ASSESSMENT METHODOLOGY

Emissions from the facility have been modelled using the AERMOD dispersion model (Version 22112) which has been developed by the U.S. Environmental Protection Agency (USEPA)[4] and following guidance issued by the EPA[1,2]. The model is a steady-state Gaussian plume model used to assess pollutant concentrations associated with industrial sources and has replaced ISCST3[5] as the regulatory model by the USEPA for modelling emissions from industrial sources in both flat and rolling terrain[6]. The model has more advanced algorithms and gives better agreement with monitoring data in extensive validation studies[7,8]. An overview of the AERMOD dispersion model is outlined in Appendix I.

The odour 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 years of appropriate hourly meteorological data. Using this input data the model predicted ambient ground level concentrations beyond the site boundary for each hour of the modelled meteorological years. The model post-processed the data to identify the location and maximum of the worst-case ground level concentration.

2.1 Characteristics of Odour

Odours are sensations resulting from the reception of a stimulus by the olfactory sensory system, which consists of two separate subsystems: the olfactory epithelium and the trigeminal nerve. The olfactory epithelium, located in the nose, is capable of detecting and discriminating between many thousands of different odours and can detect some of them in concentrations lower than those detectable by currently available analytical instruments[9]. The function of the trigeminal nerve is to trigger a reflex action that produces a painful sensation. It can initiate protective reflexes such as sneezing to interrupt inhalation. The olfactory system is extremely complex and peoples' responses to odours can be variable. This variability is the result of differences in the ability to detect odour; subjective acceptance or rejection of an odour due to past experience; circumstances under which the odour is detected and the age, health and attitudes of the human receptor.

Odour Intensity and Threshold

Odour intensity is a measure of the strength of the odour sensation and is related to the odour concentration. The odour threshold refers to the minimum concentration of an odorant that produces an olfactory response or sensation. This threshold is normally determined by an odour panel consisting of a specified number of people, and the numerical result is typically expressed as occurring when 50% of the panel correctly detect the odour. This odour threshold is given a value of one odour unit and is expressed as 1 OU_E/m^3. The odour threshold is not a precisely determined value, but depends on the sensitivity of the odour panellists and the method of presenting the odour stimulus to the panellists. An odour detection threshold relates to the minimum odorant concentration required to perceive the existence of the stimulus, whereas an odour recognition threshold relates to the minimum odorant concentration required to recognise the character of the stimulus. Typically, the recognition threshold exceeds the detection threshold by a factor of 2 to 10[9-10].

Odour Character

The character of an odour distinguishes it from another odour of equal intensity. Odours are characterised on the basis of odour descriptor terms (e.g. putrid, fishy, fruity etc.). Odour character is evaluated by comparison with other odours, either directly or through the use of descriptor words.

Hedonic Tone

The hedonic tone of an odour relates to its pleasantness or unpleasantness. When an odour is evaluated in the laboratory for its hedonic tone in the neutral context of an olfactometric presentation, the panellist is exposed to a stimulus of controlled intensity and duration. The degree of pleasantness or unpleasantness is determined by each panellist's experience and emotional associations. The responses among panellists may vary depending on odour character; an odour pleasant to many may be declared highly unpleasant by some.

Adaptation

Adaptation, or Olfactory Fatigue, is a phenomenon that occurs when people with a normal sense of smell experience a decrease in perceived intensity of an odour if the stimulus is received continually. Adaptation to a specific odorant typically does not interfere with the ability of a person to detect other odours. Another phenomenon known as habituation or occupational anosmia occurs when a worker in an industrial situation experiences a long-term exposure and develops a higher threshold tolerance to the odour.

2.2 Odour Guidelines

The exposure of the population to a particular odour consists of two factors; the concentration and the length of time that the population may perceive the odour. By definition, 1 OU_E/m^3 is the detection threshold of 50% of a qualified panel of observers working in an odour-free laboratory using odour-free air as the zero reference.

Currently there is no general statutory odour standard in Ireland relating to industrial installations. The EPA(2) has issued guidance specific to intensive agriculture which has outlined the following standards:

- Target value for new pig-production units of 1.5 OU_E/m^3 as a 98^{th}%ile of one hour averaging periods,
- Limit value for new pig-production units of 3.0 OU_E/m^3 as a 98^{th}%ile of one hour averaging periods,
- Limit value for existing pig-production units of 6.0 OU_E/m^3 as a 98^{th}%ile of one hour averaging periods.

Guidance from the UK(3), and adapted for Irish EPA use, recommends that odour standards should vary from 1.5 – 6.0 OU_E/m^3 as a 98^{th}%ile of one hour averaging periods at the worst-case sensitive receptor based on the offensiveness of the odour and with adjustments for local factors such as population density. A summary of the indicative criterion is given below in Table 1 (taken from EPA Guidance document AG9(2)):

Industrial Sectors	Relative Offensiveness of Odour	Indicative Criterion Note 1
• Processes involving decaying animal or fish remains. • Processes involving septic effluent or sludge • Waste sites including landfills, waste transfer stations and non-green waste composting facilities.	Most Offensive	1.5 OU_E/m^3 as a 98^{th}%ile of hourly averages at the worst-case sensitive receptor
• Intensive Livestock Rearing • Fat Frying / Meat Cooking (Food Processing) • Animal Feed • Sugar Beet Processing • Well aerated green waste composting Most odours from regulated processes fall into this category i.e. any industrial sector which does not obviously fall within the "most offensive" or "less offensive" categories.	Moderately Offensive	3.0 OU_E/m^3 as a 98^{th}%ile of hourly averages at the worst-case sensitive receptor
• Brewery / Grain / Oats Production • Coffee Roasting • Bakery • Confectionery	Less Offensive	6.0 OU_E/m^3 as a 98^{th}%ile of hourly averages at the worst-case sensitive receptor

Note 1 Professional judgement should be applied in the determination of where the worst-case sensitive receptor is located.

Table 1 Indicative Odour Standards Based On Offensiveness Of Odour And Adapted for Irish EPA[(2)]

Based on the guidance above, a worst-case odour threshold of 1.5 OU_E/m^3 as a 98^{th}%ile of hourly mean values has been selected for identifying the potential for odour nuisance for the facility. The selection of the "most offensive" category is conservative due to the fact that all raw materials odours are extracted under negative pressure to the biofilter or thermal oxidiser and thus no untreated odours are emitted directly from the facility.

2.3 Odour 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:

- Three 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 extended to 20 km with the site at the centre and with concentrations calculated at 500 m intervals. A middle grid extended to 5 km from the site with concentrations calculated at 250 m intervals whilst an inner grid extended to 1 km from the site with concentrations calculated at 50 m intervals. Boundary receptor locations were also placed along the boundary of the site, at 25 m intervals, giving a total of 5,086 calculation points for the model. All receptors have been modelled at 1.5 m to represent breathing height.

- All on-site buildings and significant process structures were mapped into the computer to create a three dimensional visualisation of the site and its emission points. Buildings and process structures can influence the passage of airflow over the emission stacks and draw plumes down towards the ground (termed building downwash). The stacks themselves can influence airflow in the same way as buildings by causing low pressure regions behind them (termed stack tip downwash). Both building and stack tip downwash were incorporated into the modelling.

- Detailed terrain has been mapped into the model using SRTM data with 30m resolution. The site is located in rolling terrain. This takes account of all significant features of the terrain. All terrain features have been mapped in detail into the model using the terrain pre-processor AERMAP[11] as shown in Figure 2.

- Hourly-sequenced meteorological information has been used in the model. Meteorological data over a five year period (Johnstown Castle 2016 - 2020) was used in the model (see Figure 3 and Appendix III).

- The source and emission data, including stack dimensions, volume flows and emission temperatures have been incorporated into the model.

2.4 Terrain

The AERMOD air dispersion model has a terrain pre-processor AERMAP[11] which was used to map the physical environment in detail over the receptor grid. The digital terrain input data used in the AERMAP pre-processor was obtained from SRTM. 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[4] 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"[4].

The terrain in the region of the facility is complex in the sense that the maximum terrain in the modelling domain peaks at 246 m which is above the stack top of all emission points onsite. However, as shown in Figure 2, the region of the site has sloping terrain in the immediate vicinity of the facility.

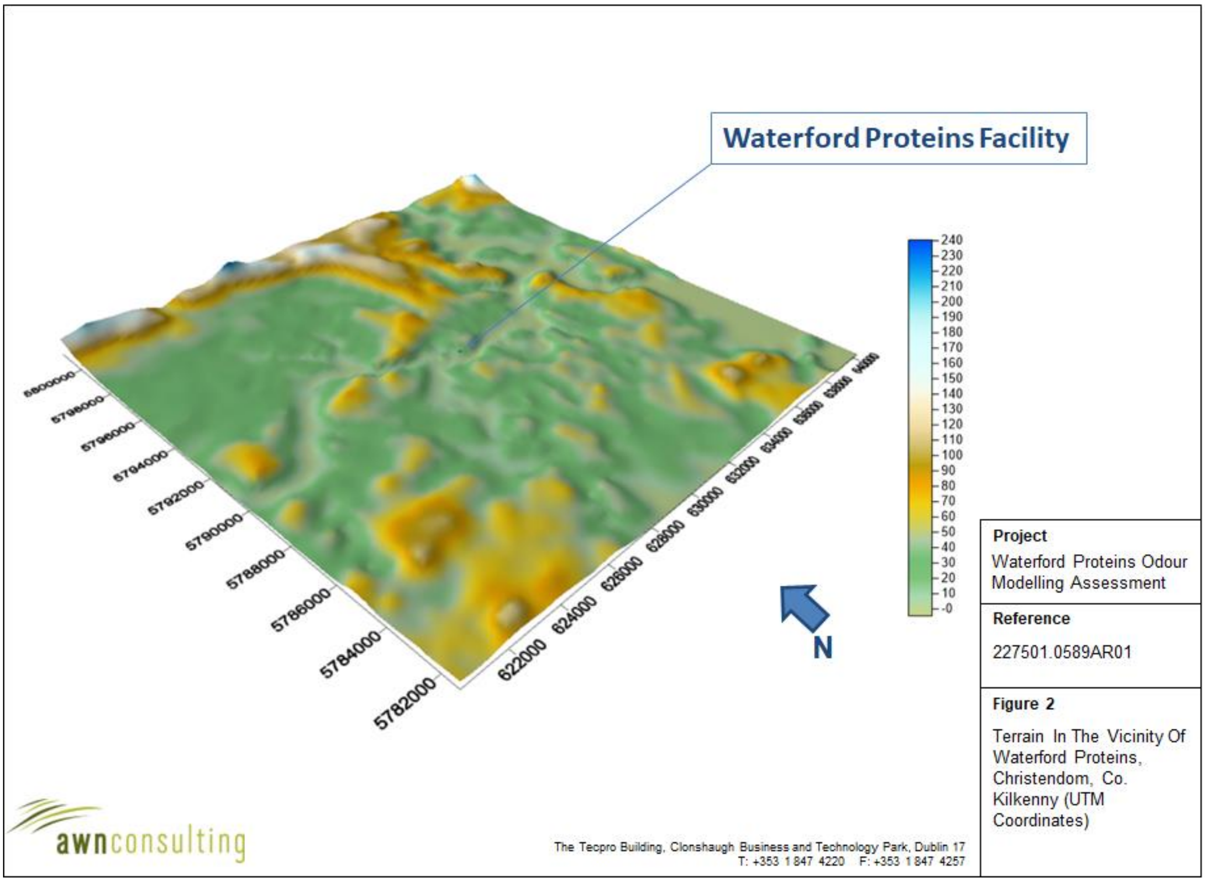
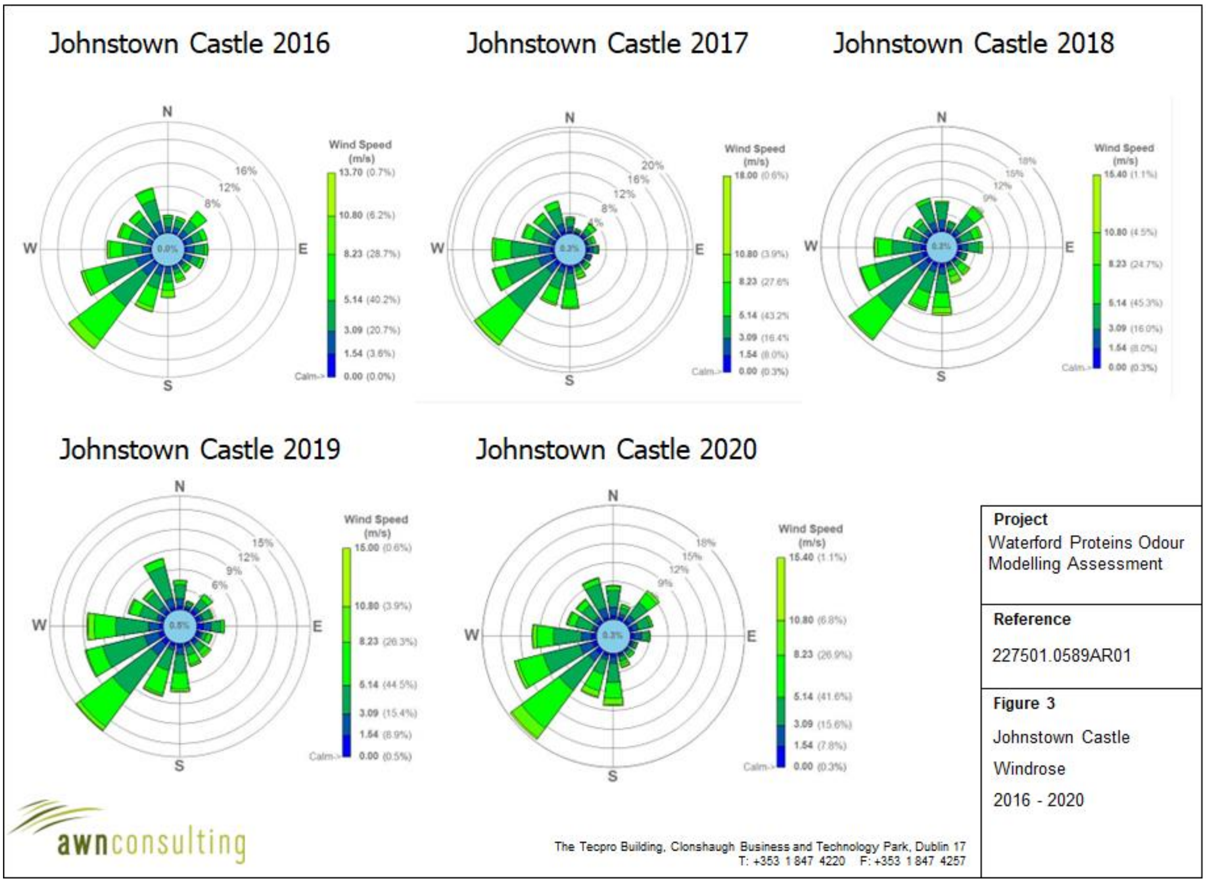


Figure 2 Terrain In The Vicinity Of Waterford Proteins, Christendom, Co. Kilkenny (UTM Coordinates)

2.5 Meteorological Data

The selection of the appropriate meteorological data has followed the guidance issued by the USEPA[6]. A primary requirement is that the data used should have a data capture of greater than 90% for all parameters. Johnstown Castle meteorological station, which is located approximately 40 km east of the site, collects data in the correct format and has a data collection of greater than 90%. Long-term hourly observations at Johnstown Castle meteorological station provide an indication of the prevailing wind conditions for the region (see Figure 3 and Appendix III). Results indicate that the prevailing wind direction is south-westerly in direction over the period 2016 - 2020. Calm conditions account for only a small fraction of the time in any one year peaking at 40 hours in 2019 (0.46% of the time). There are no missing hours over the period 2016 – 2020.



2.6 Odour Emission Rates From Waterford Proteins

The Waterford Proteins site is located at Christendom, Ferrybank, Co. Kilkenny.

In consultation with Waterford Proteins, the main odour sources at the facility were identified. Emission point AEP-1 is the biofilter for the facility and has been identified as the emission point on site with the highest potential for odour emissions. For this modelling scenario it is assumed that the biofilter is covered and the exhaust air is extracted to the biofilter stack which is at a height of 10m above local ground level. Emission point AEP-2 was also identified as potential odour emission source.

Odour modelling has been undertaken based on an odour emission concentration of 1000 OU_E/m^3 from both the TO (AEP-2) and the biofilter stack (AEP-1) as shown in Table 2. The volume flows from the TO and biofilter stack were both based on 150,000 Nm^3/hr.

Stack Reference	Exit Diameter (m)	Stack Height (m)	Temp (K)	Volume Flow Rate (Nm^3/hr)	Exist Velocity (m/sec actual)	Odour Concentration (OU_E/m^3)	Odour Emission Rate (OU/s) Note 1
AEP-1	1.5	10	293.15	150,000	25.3	1,000	41,667
AEP-2	1.5	40	573.15	150,000	22.8	1,000	41,667

Note 1 For the purposes of this assessment normalised conditions for AEP-2 are 273.15 K, 101.3 Pa, dry gas and 17% O_2

Table 2 Air Emission Details For AEP-1 (Biofilter) and AEP-2 (Thermal Oxidiser) At Waterford Proteins, Christendom, Ferrybank, County Kilkenny

3.0 RESULTS & DISCUSSION

3.1 Odour Emissions –(Biofilter Stack Height – 10m)

Details of the 98^{th}%ile of 1-hour mean odour concentrations at the worst case off site location are given in Table 3 over a five-year period based on the USEPA approved AERMOD model (version 22112) based on a biofilter volume flow of 150,000 Nm^3/hr and based on a biofilter odour emission concentration of 1000 OU_E/m^3. The worst case scenario for the 98^{th}%ile of 1-hour concentrations occurs in 2017 where the maximum off-site concentrations is 83% of the guideline value at the worst case receptor. Table 4 shows the 98^{th}%ile of one-hour guideline values at all nearby residential receptors for all five years.

Figure 4 shows the ambient odour concentration contour pattern (as a 98^{th}%ile of one-hour concentrations) in the vicinity of the facility for the worst-case year of 2017.

Based on the results detailed below, no nearby receptors are predicted to experience odour nuisance as a result of the Waterford Proteins facility.

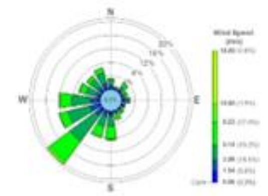
Model Scenario / Meteorological Year	Averaging Period	Predicted Overall Odour Concentration (OU_E/m^3)	Guideline (OU_E/m^3) Note 1
Ambient Odour Concentration / 2016	Maximum 1-Hour (as a 98^{th}%ile)	1.06	**1.5**
Ambient Odour Concentration / 2017	Maximum 1-Hour (as a 98^{th}%ile)	**1.25**	
Ambient Odour Concentration / 2018	Maximum 1-Hour (as a 98^{th}%ile)	1.08	
Ambient Odour Concentration / 2019	Maximum 1-Hour (as a 98^{th}%ile)	1.11	
Ambient Odour Concentration / 2020	Maximum 1-Hour (as a 98^{th}%ile)	1.04	

Note 1 Guideline limit value based on EPA Guidance AG9 (2019) based on most offensive odour.

Table 3 Predicted Odour Concentration At Worst-Case Offsite Receptor(OU_E/m^3)

Sensitive Receptor Grid Co-ordinates (UTM Zone 29N)	Maximum 1-Hour 98th%ile Predicted Odour Conc. (OU_E/m^3)				
Nearby Sensitive Receptors	**2016**	**2017**	**2018**	**2019**	**2020**
Receptor 1 – 630490, 5791240	0.38	0.32	0.24	0.33	0.32
Receptor 2 – 630808, 5791808	0.91	1.09	1.08	1.02	1.01
Receptor 3 – 629950, 5791650	0.28	0.09	0.14	0.21	0.08
Receptor 4 – 630211, 5791860	0.35	0.36	0.37	0.36	0.31
Receptor 5 – 630338, 5791079	0.67	0.40	0.86	0.66	0.91
Receptor 6 – 629865, 5790965	0.37	0.26	0.38	0.29	0.39
Receptor 7 – 630750, 5791400	1.06	**1.25**	0.99	1.11	1.04

Table 4 Predicted Odour Concentration At Closest Sensitive Receptors (OU_E/m^3)



Background Mapping from Google Earth

98th%ile of 1-Hour Mean Odour Concentrations Maximum Concentration = 1.25 OU$_E$/m^3 At Worst-Case Receptor (7)

Boundary Of Facility

Scale

1:13,000

N

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Figure 4

Scenario 1 - 98th%ile of 1-Hour Odour Concentrations (OU$_E$/m^3) (Year 2017)

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3.2 Assessment Summary

An assessment of the Waterford Proteins facility has found that the biofilter (AEP-1) is the main source of odour at the facility with emission point AEP-2 (Thermal Oxidiser) contributing minor amounts.

Odour modelling, based an odour emission concentration of 1000 OU_E/m^3 from both the biofilter stack (at a height of 10m) and thermal oxidiser, and using the USEPA approved AERMOD model has found that the worst case scenario for the 98^{th}%ile of 1-hour concentrations occurs in 2017 where the maximum off-site concentrations is 83% of the guideline value at the worst case receptor based on a biofilter volume flow of 150,000 Nm^3/hr.

Based on the results, no residential receptors are predicted to experience odour nuisance issues as a result of the Waterford Proteins facility based on the modelling scenario outlined above.

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APPENDIX I

Description of the AERMOD Model

The AERMOD dispersion model has been developed in part by the U.S. Environmental Protection Agency (USEPA)[4,6]. 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[7-8].

Due to the proximity to surrounding buildings, the PRIME (Plume Rise Model Enhancements) building downwash algorithm has been incorporated into the model to determine the influence (wake effects) of these buildings on dispersion in each direction considered. The PRIME algorithm takes into account the position of the stack relative to the building in calculating building downwash. In the absence of the building, the plume from the stack will rise due to momentum and/or buoyancy forces. Wind streamlines act on the plume leads to the bending over of the plume as it disperses. However, due to the presence of the building, wind streamlines are disrupted leading to a lowering of the plume centreline.

When there are multiple buildings, the building tier leading to the largest cavity height is used to determine building downwash. The cavity height calculation is an empirical formula based on building height, the length scale (which is a factor of building height & width) and the cavity length (which is based on building width, length and height). As the direction of the wind will lead to the identification of differing dominant tiers, calculations are carried out in intervals of 10 degrees.

In PRIME, the nature of the wind streamline disruption as it passes over the dominant building tier is a function of the exact dimensions of the building and the angle at which the wind approaches the building. Once the streamline encounters the zone of influence of the building, two forces act on the plume. Firstly, the disruption caused by the building leads to increased turbulence and enhances horizontal and vertical dispersion. Secondly, the streamline descends in the lee of the building due to the reduced pressure and drags the plume (or part of) nearer to the ground, leading to higher ground level concentrations. The model calculates the descent of the plume as a function of the building shape and, using a numerical plume rise model, calculates the change in the plume centreline location with distance downwind.

The immediate zone in the lee of the building is termed the cavity or near wake and is characterised by high intensity turbulence and an area of uniform low pressure. Plume mass captured by the cavity region is re-emitted to the far wake as a ground-level volume source. The volume source is located at the base of the lee wall of the building, but is only evaluated near the end of the near wake and beyond. In this region, the disruption caused by the building downwash gradually fades with distance to ambient values downwind of the building.

AERMOD has made substantial improvements in the area of plume growth rates in comparison to ISCST3[4,6]. 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[4,6]. 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 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.

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(16). 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 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. 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(6).

<u>Surface roughness</u>

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 Johnstown Castle Meteorological Station is shown in Table A1.

Sector	Inverse Distance Weighted Land Use Classification	Spring	Summer	Autumn	Winter[1]
0-360	100% Grassland	0.050	0.100	0.010	0.010

(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)). 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 Johnstown Castle 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 Johnstown Castle Meteorological Station is shown in Table A2.

Simple Average Land Use Classification	Spring	Summer	Autumn	Winter[1]
10% Water	0.012	0.010	0.014	0.014
5% Urban	0.007	0.008	0.009	0.009
75% Grassland	0.135	0.135	0.150	0.150
10% Cultivated Land	0.014	0.020	0.018	0.018

(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 Johnstown Castle 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 Johnstown Castle Meteorological Station is shown in Table A3.

Geometric Mean Land Use Classification	Spring	Summer	Autumn	Winter[1]
10% Water	0.1	0.1	0.1	0.1
5% Urban	1.0	2.0	2.0	2.0
75% Grassland	0.4	0.8	1.0	1.0
10% Cultivated Land	0.3	0.5	0.7	0.7

(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 Johnstown Castle Meteorological Station.

APPENDIX III

Detailed Meteorological Data – Johnstown Castle 2016 - 2020

Johnstown Castle 2016

Dir \ Spd	<= 1.54	<= 3.09	<= 5.14	<= 8.23	<= 10.80	> 10.80	Total
0.0	41	82	207	35	4	0	369
22.5	45	37	115	37	2	0	236
45.0	46	52	192	130	1	0	421
67.5	53	71	165	55	0	0	344
90.0	79	115	218	31	5	0	448
112.5	37	60	134	31	5	0	267
135.0	20	29	59	39	17	2	166
157.5	24	28	81	63	18	2	216
180.0	43	101	192	203	86	3	628
202.5	51	100	241	255	56	7	710
225.0	74	129	652	484	93	7	1439
247.5	58	187	588	208	32	6	1079
270.0	45	128	448	219	30	6	876
292.5	17	62	291	87	21	9	487
315.0	37	65	209	56	13	0	380
337.5	48	139	377	116	9	0	689
Total	718	1385	4169	2049	392	42	8755
Calms							29
Missing							0
Total							8784

Johnstown Castle 2017

Dir \ Spd	<= 1.54	<= 3.09	<= 5.14	<= 8.23	<= 10.80	> 10.80	Total
0.0	31	84	136	33	0	0	284
22.5	24	19	30	26	0	0	99
45.0	38	44	98	93	15	0	288
67.5	27	22	73	55	2	0	179
90.0	53	77	69	21	0	0	220
112.5	29	51	23	14	0	0	117
135.0	28	23	48	50	12	0	161
157.5	28	25	51	78	58	14	254
180.0	65	73	268	302	32	9	749
202.5	46	97	287	251	38	4	723
225.0	71	164	814	646	82	11	1788
247.5	58	231	591	215	20	0	1115
270.0	61	201	485	274	47	7	1075
292.5	39	86	280	148	26	5	584
315.0	41	116	251	96	9	0	513
337.5	59	127	281	118	3	0	588
Total	698	1440	3785	2420	344	50	8737
Calms							23
Missing							0
Total							8760

Johnstown Castle 2018

Dir \ Spd	<= 1.54	<= 3.09	<= 5.14	<= 8.23	<= 10.80	> 10.80	Total
0.0	42	128	255	29	0	0	454
22.5	24	37	92	20	0	0	173
45.0	44	64	260	150	22	0	540
67.5	26	36	189	100	35	0	386
90.0	55	97	176	43	0	0	371
112.5	38	36	66	18	0	0	158
135.0	29	25	72	112	35	23	296
157.5	31	28	71	92	87	25	334
180.0	62	101	284	218	87	30	782
202.5	48	103	317	236	34	7	745
225.0	65	164	730	508	30	5	1502
247.5	64	197	541	220	12	0	1034
270.0	73	130	308	216	45	7	779
292.5	31	67	172	79	6	2	357
315.0	30	69	127	67	4	0	297
337.5	40	116	306	60	1	0	523
Total	702	1398	3966	2168	398	99	8731
Calms							29
Missing							0
Total							8760

Johnstown Castle 2019

Dir \ Spd	<= 1.54	<= 3.09	<= 5.14	<= 8.23	<= 10.80	> 10.80	Total
0.0	47	100	183	51	2	0	383
22.5	31	26	48	19	2	0	126
45.0	48	52	132	74	0	0	306
67.5	46	48	110	24	0	0	228
90.0	86	100	131	45	0	0	362
112.5	47	34	65	65	5	0	216
135.0	40	34	109	66	34	2	285
157.5	23	39	110	117	27	6	322
180.0	52	93	240	213	38	2	638
202.5	41	61	270	315	29	9	725
225.0	77	172	634	534	58	9	1,484
247.5	69	191	564	223	18	1	1,066
270.0	51	139	433	281	85	16	1,005
292.5	41	56	231	129	22	5	484
315.0	37	79	210	45	15	2	388
337.5	42	121	428	106	4	1	702
Total	778	1,345	3,898	2,307	339	53	8,720
Calms							40
Missing							0
Total							8,760

Johnstown Castle 2020

Dir \ Spd	<= 1.54	<= 3.09	<= 5.14	<= 8.23	<= 10.80	> 10.80	Total
0.0	53	119	231	57	11	0	471
22.5	38	50	91	43	3	0	225
45.0	43	89	224	158	42	0	556
67.5	39	83	172	33	3	0	330
90.0	49	105	99	19	0	0	272
112.5	26	37	48	1	0	0	112
135.0	17	20	52	40	3	0	132
157.5	29	27	67	45	36	13	217
180.0	46	90	268	216	90	20	730
202.5	43	58	206	235	86	16	644
225.0	68	127	503	653	171	26	1,548
247.5	61	179	527	360	47	4	1,178
270.0	68	140	386	235	55	7	891
292.5	26	47	236	101	21	6	437
315.0	41	65	202	87	16	2	413
337.5	40	135	340	76	14	0	605
Total	687	1,371	3,652	2,359	598	94	8,761
Calms							23
Missing							0
Total							8,784