Cory Environmental Holdings Limited

CORY DECARBONISATION PROJECT

CO2 Venting Assessment

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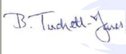
Signature				 Digitally signed by Tuckett-Jones, Bethan (TuckettjonesB) DN: cn=Tuckett-Jones, Bethan (TuckettjonesB), ou=Active, email=Bethan.Tuckett-Jones@wsp.com Reason: pp Sioni Hole Date: 2025.09.30 12:31:00 +01'00'
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1. INTRODUCTION

1.1. BACKGROUND

This CO_2 Venting Assessment has been prepared in support of Cory Environmental Holdings Limited's (hereafter referred to as Cory) application to the Environment Agency (EA) under the Environmental Permitting (England and Wales) Regulations 2016, for a new bespoke environmental permit to operate a Carbon Capture Facility (CCF) in relation to the Cory Decarbonisation Project in Belvedere, London.

This submission is part of a staged permit application as agreed with the Environment Agency (the Regulator) through enhanced pre-application advice reference EPR/JP3020LL/P001 and EPR/JP3020LL/P002, to operate a Carbon Capture Facility (CCF) at the Cory site in Belvedere, Bexley London, which will be technically connected to Cory's two Energy from Waste Facilities, Riverside 1 and Riverside 2.

Part of the carbon capture process involves the processing of gaseous CO_2 and storage in liquid form, at high pressure and low temperature. Under certain scenarios, as will be set out later within this report, it may be necessary to vent the CO_2 that is stored within the CCF system or, in some cases (i.e. where it is not possible to switch off the input feed) being generated. In cases where maintenance is foreseeable, or where the need arises for extended periods where on-site processing/storage of carbon dioxide (CO_2) becomes impossible, the option to bypass the CCF and run all emissions through the original Riverside 1 and Riverside 2 stacks is retained.

During the design of the CCF, that will be technically connected to Riverside 1 and Riverside 2 Energy from Waste Facilities, a provision has been made for several CO_2 vent points throughout the system and carbon capture train. Each of these vent points will be routed to one of two vent stacks which will be located within the Site Boundary (emission points A4 and A5). There are no expected scenarios where venting will be required from both vent stacks simultaneously and the routing of vent lines will be determined during the detailed design stage; all venting scenarios have been modelled based on one vent stack. The modelled venting scenarios presented within this assessment are representative of both the most likely and worst-case emissions from the CCF. The exit conditions of the stack are dependent on the venting point within the system that is used.

1.2. SCOPE

Preliminary dispersion modelling of the venting scenarios for the CCF has been undertaken using DNV's Phast software.

The parameters used in the assessment presented herein represent the best available information at the time of writing. The assessment is robust in that it encompasses the likely range of possible design parameters. Where required, this modelling will need to be refined at detailed design stage, taking account of all specific design elements.

This evaluation has enabled a preliminary design of stack height and location. This modelling has identified that the CO_2 release from the new CO_2 vent stack(s) may be fed from venting of the CO_2 stored within the system from multiple locations throughout the CCF. This includes areas where the gas is travelling at a high velocity, and areas where the gas is stored at high pressures which would lead to rapid expansion at the point of venting. While this has the benefit of aiding dispersion, there is a chance that it could introduce high levels of noise.

Furthermore, the gas is released from on-site storage at low temperatures or may be significantly cooled following rapid expansion from high pressure to an atmospheric release, which may cause the gas plume to “slump” (i.e. be negatively buoyant and sink towards ground level) following the release.

As part of the application for a new bespoke environment permit and proposed Site activities and processes, it is important to evaluate and optimise the design options for venting, especially if this could introduce new vent point(s) with noise and visual impacts.

This CO_2 vent study aims to characterise the parameters of the vent stack(s). The purpose of this report is to evidence the assessment and provide information to the Environment Agency to enable this determination.

This document seeks to cover the following:

- Description of the routine, planned or unplanned emergency emission scenarios in order to demonstrate understanding of the CO_2 venting process, including:
  - Venting scenarios and vent location(s) within the process;
  - Whether simultaneous releases are likely;
  - An explanation of the venting control strategies and proposed process monitoring; and
  - The release duration (h) and frequency (h/y);
- Conditions of potential releases, including process pressure (atm), temperature (DegC) and CO_2 phase, exhaust velocity (m/s);
- A review of the modelling software used, setting out the case for the adequacy of the modelling software for the venting scenarios;
- The model will be used to calculate and produce:
  - Any future limitations which should be considered for the vent height and diameter;
  - Distances from the venting stack to likely public exposure (m);
  - Estimated maximum concentration off-site and at worst-case receptors (ppm); and
  - Contour plots or concentrations footprint map.

2. VENTING SCENARIOS

2.1. OVERVIEW

The CCF will have two equally sized Carbon Capture Plants (hereinafter referred to as Trains) to process the combined exhaust gases from the Riverside 1 and Riverside 2.

The CO_2 output is compressed, combined, and liquified for onsite storage, before the liquid CO_2 is removed from the Site.

Each of the 'vent locations' i.e. the location of the vent valve within the process, will be connected to the vent stack(s) i.e. the point at which vented CO_2 will be released to atmosphere. The precise location of vent stacks has not yet been finalised, but it will sit within the installation boundary for the Site, as shown in **Figure 1**, Appendix A of the Main Technical Support Document. As all venting scenarios modelled within this assessment are expected to use one vent stack at any time and the specific vent routing has not been finalised at this stage of design, the modelling is carried out on a single vent stack basis (but not necessarily as a single train). **Figure 2** and **Figure 5** within Appendix A of the Technical Support Document, show the proposed indicative Site layout and current proposed emission points.

2.2. VENTING STRATEGY

2.2.1. CO_2 CONDITIONING FOR EXPORT

Figure 2-1 shows a schematic of the process from CO_2 capture to offsite export, alongside indicative areas within the process from which venting may occur (shown as numbers). **Table 2-1** shows the temperature and pressure at each of the numbered locations within the process. These data have been provided as indicative values to inform the dispersion modelling for the venting of the CO_2 at this stage only. The assessment will be reviewed/repeated as necessary using data available following finalisation of detailed design.

Within each single carbon capture train, following carbon capture within the Absorber Column, CO_2 is removed from the solvent within the regenerator, and the CO_2 is prepared for the compressor. This occurs at low pressure (~1 barg).

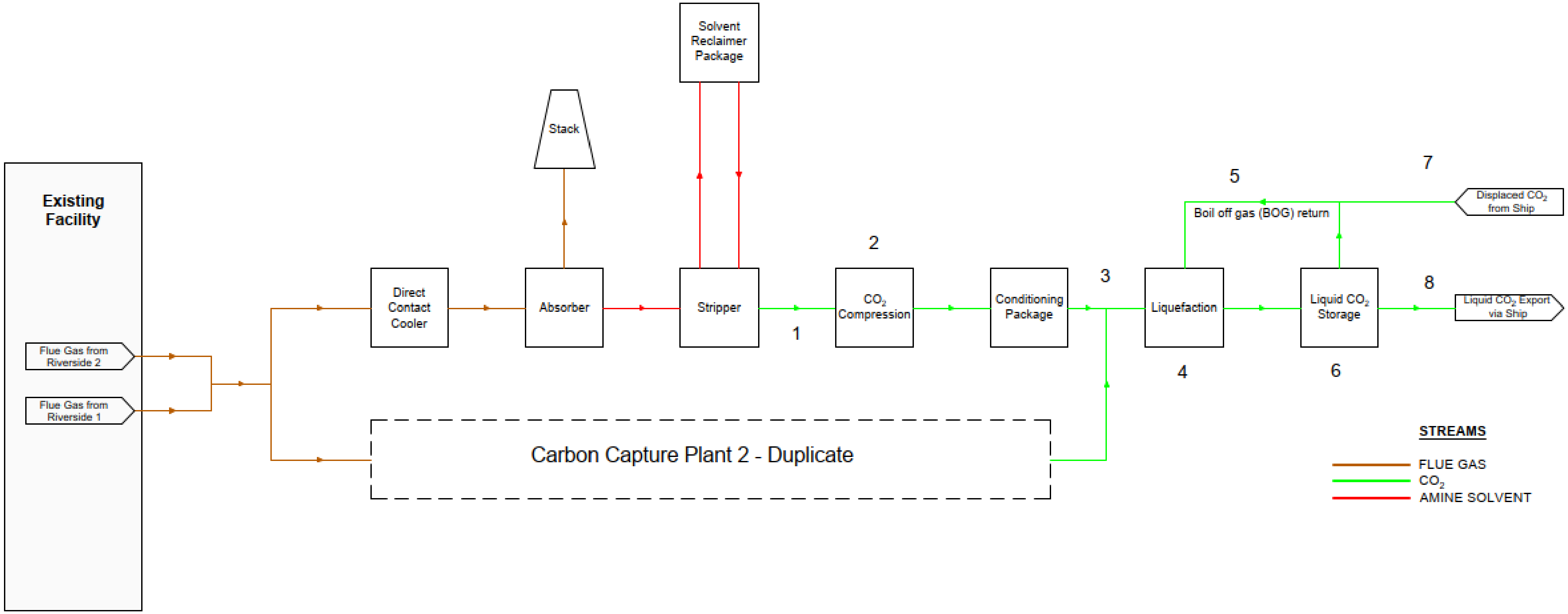
The CO_2 is in the gas phase when it leaves the regenerator at around 40ºC. The CO_2 remains in the gas phase throughout this section of the process. The mass flow rate through each of the carbon capture trains is 93.7 tonnes/hour.

After the compressor, the CO_2 is passed through a conditioning package and the output of the two carbon capture trains are combined, to reach a total mass flow of 187.4 tonnes/hour through the rest of the process. The gas is then liquefied at a temperature of -33C and a pressure of 15 barg.

Table 2-1 - CO_2 pipeline indicative conditions for dispersion modelling

Vent Number	1	2	3	4	5	6	7	8
Max Pressure (barg)	<1	16	16	16	15	15	15	15
Max Temperature (°C)	40	40	40	-26	-26	-26	-26	-26
CO2 Phase in Pipeline	Gas	Gas	Gas	Liquid	Liquid	Liquid	Liquid	Liquid
Mass Flow (tph)	93.7	93.7	187.4	187.4	Low	(24000m^3, stored)	187.4	187.4
CO2 Pipe Velocity (m/s)	20	20	20	3	3	3	3	3

Figure 2-1 - CO_2 venting flow diagram



2.3. POTENTIAL VENTING SCENARIOS

Taking account of the venting strategy described above, scenarios covering the range of risks potentially arising from either manual or emergency venting of CO_2 are set out in **Table 2-2**, below.

Table 2-2 – Scenarios under which CO_2 venting may occur.

No.	Scenario Description	Location (Figure 2-1)	Discussion
1	Over pressure compression	2	Only mass which contributes to the flow being over-pressurised, would be emitted. Very low mass flow.
2	CO_2 Boil off in storage - no liquefaction available	5	Only boil-off mass would be emitted. Very low mass flow.
3	Start-up / Shutdown	N/A	For both start-up/shutdown and outage/maintenance, relatively low mass-flow, short duration venting scenarios are expected, to ensure the equipment is safely shutdown and ready for maintenance. Start-up and shutdown procedures have not been developed at this stage, but these will be developed to avoid unnecessary venting, although some is likely unavoidable for a safe shutdown. As noted above, for periods of prolonged outage/maintenance, it would be possible to bypass the CCF altogether, with emissions being routed through the Riverside 1 and Riverside 2 stacks during these periods.
4	Outage / Maintenance		
5	Compressor Trip	1 or 2	Compressor trip may result in full flow from one train of the CCF being vented. Range of mass flow rates to be considered to account for full or partial venting of gas within system (or system not operating at full capacity).
6	Liquefaction Trip	3 or 4	Liquefaction trip may result in full flow from the CCF being vented. Range of mass flow rates to be considered to account for full or partial venting of gas (or system not operating at full capacity).

Vented CO_2 from the low-pressure section of a train (point 1 of **Figure 2-1**) will be buoyant or neutrally buoyant and will rapidly disperse (as it would under operation of the power plant(s) without carbon capture). No dispersion modelling / risk assessment is necessary for this section since it represents only a minimal change to the current CO_2 emissions with the combustion units operating without carbon capture. It is not considered further within this assessment.

2.4. MODELLED VENTING SCENARIOS

Taking account of the venting strategy and potential venting scenarios set out above, the input data set out in **Table 2-3** have been modelled within PHAST. These scenarios cover a range of potential values to cover all those scenarios set out in **Table 2-2** above. Pressure, temperature and flow are provided as indicative values for upstream conditions at the point of venting from the system. Vent stack diameter and height are at the point prior to release to the atmosphere through a vent stack. Start-Up/Shutdown and Outage/Maintenance scenarios are excluded from the assessment and will be subject to further assessment during the development of the process-specific procedures. As noted previously, the data presented below provide an envelope of potential outputs which represent the best available information at time of writing and will be reviewed following finalisation of detailed design.

Table 2-3 – Modelled venting scenarios and parameters

ID	Venting Scenario	Vent No.	PHAST Setup	Pressure (barg)	Temp. (ºC)	Flow (tph)	Vent Stack Diameter (inches)	Vent Stack Height (m)	Main Pipe Velocity (m/s)	System Phase
1	Over pressure after compression	2	Constant flow through long pipe	16	40	1, 5, 10	3, 5, 8, 10	10 – 100 (10m increments)	20	Gas
2	CO_2 Boil off in storage where no liquefaction available	5	Constant flow through long pipe	15	-33	1, 5, 10	3, 5, 8, 10	10 – 100 (10m increments)	20	Gas
5	Compressor trip resulting in full or partial flow from the CCF train being vented.	9	Constant flow through long pipe	16	40	35, 50, 100	3, 5, 8, 10	10 – 100 (10m increments)	20	Gas
6A	Liquefaction trip resulting in full or partial flow from the CCF being vented.	3 or 4	Constant flow through long pipe	15	-33	35, 50, 100, 200	3, 5, 8, 10	10 – 100 (10m increments)	3	Liquid
6B	Liquefaction trip resulting in stored volume being vented / Indicative on-site fire scenario	6	Venting from pressurized vessel	15	-33	NA (24000m^3)	3, 5, 8, 10	10 – 100 (10m increments)	3	Liquid

2.5. RELEASE DURATION AND FREQUENCY

The estimated likelihood of occurrence of the various scenarios is set out in **Table 2-4**. At this stage, the likelihood of each potential scenario is simply categorised as reasonably foreseeable / likely to occur in any given year.

Notwithstanding these durations, the modelling assumes that the duration exceeds the time of travel of the plume between the vent stacks and the nearest plume. For receptors up to 500m away, this implies a duration of the release of at least 500s (with a worst-case wind speed of 1m/s). All model simulations have run times of at least 3600s.

Table 2-4 – Modelled Venting: Scenario Likelihood

ID	Venting Scenario	Likelihood of Occurrence	Potential Duration
1	Over pressure after compression	Assume 1 per year	< 1 hour
2	CO_2 Boil off in storage where no liquefaction available	Assume 1 per year	~ 1 hour
5	Compressor trip resulting in full or partial flow from the CCF being vented.	Assume 1 in 2 years	< 1 hour
6A	Liquefaction trip resulting in full or partial flow from the CCF being vented.	Assume 1 in 2 years	< 1 hour
6B	Liquefaction trip resulting in stored volume being vented / Indicative on-site fire scenario	Assume 1 in 2 years (Significantly longer for fire scenario)	< 1 hour
N.B. These values are representative of estimates of likelihood of occurrence and potential duration for each scenario. These estimates are based on indicative events in which these scenarios may likely occur, rather than refined emergency procedures based on calculated release scenarios, these will be determined as part of the later design stages. Durations represent estimates of the period of venting to ambient air prior to outage/maintenance activation and have been selected to be representative of a combination of shorter release.			

2.6. PHYSICAL PARAMETERS

The physical parameters for the release (stack height and vent stack diameter) for each scenario are set out in **Table 2-3.** Note that the exit velocity is set by PHAST on the basis of the valve characteristics and the upstream parameters.

2.7. UPSTREAM PARAMETERS

The feed for the CCF is taken from the combined streams for Riverside 1 (which itself has 3 streams), and Riverside 2 (which has 2 streams). The full flows represent the full (and partial for the testing cases) flow rates for the system when all streams are operating. Partial mass flow cases have been included to account for reduced load operation (e.g. maintenance) or partial venting when fully operating. The upstream parameters (pressure, temperature and flow rate) for each scenario are set out in **Table 2-3**.

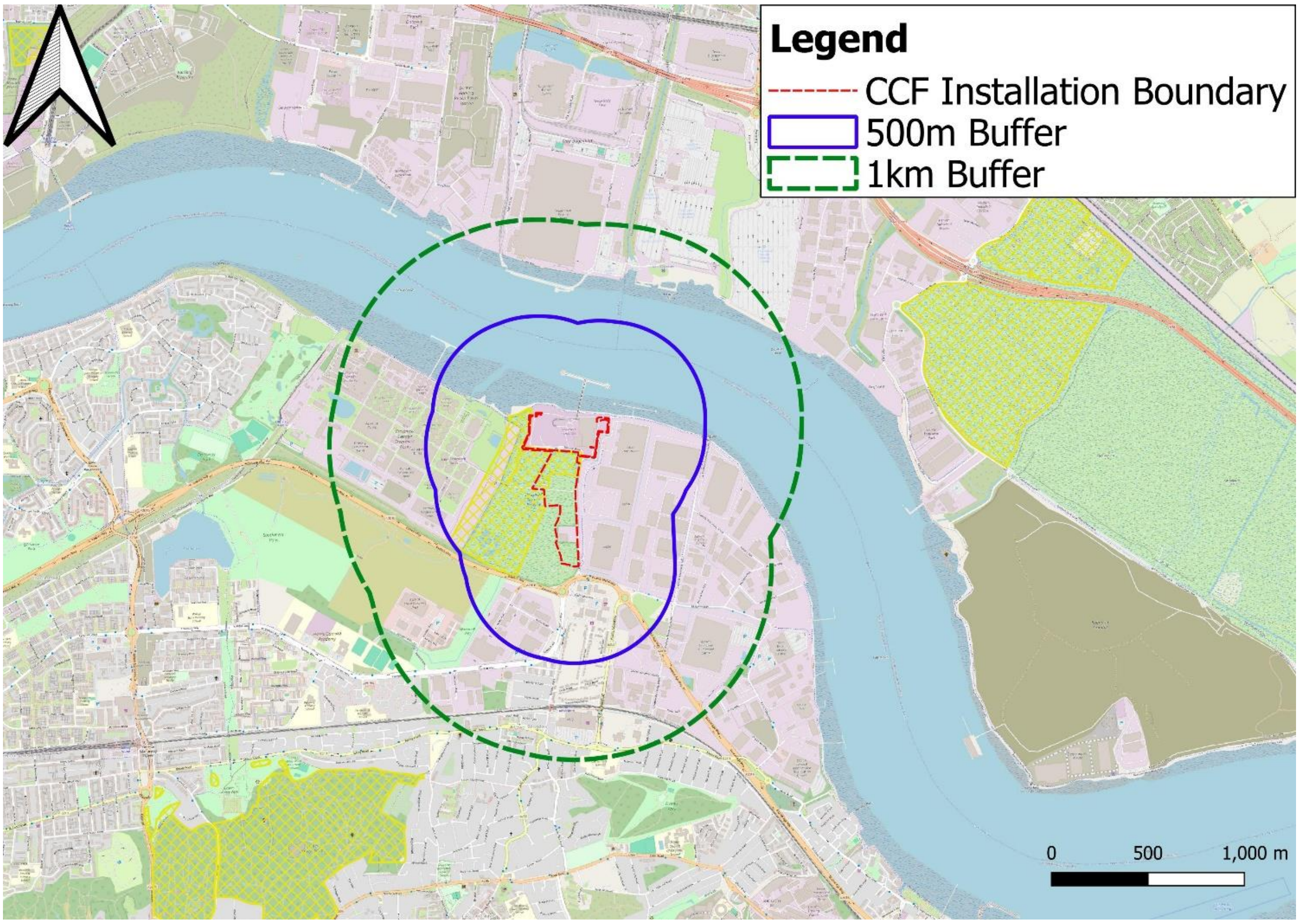
3. SITE CHARACTERISTICS

3.1. OVERVIEW OF STUDY AREA

The area surrounding the CCF is predominantly urban/industrial, with scattered receptors (**Figure 3-1**). There is limited potential for exposure over agricultural / industrial land.

There are no standards set for the protection of ecology against exposure to short term CO_2. The risks to off-site receptors apply to human exposure in the form of users of the local land, users of the local road network (primarily to the south) and residential areas.

Figure 3-1 - Setting for the Cory CCF



3.2. RECEPTORS FOR IMPACTS

The installation boundary is bordered to the north by Riverside 1 and Riverside 2 with the River Thames beyond, to the west by Crossness Local Nature Reserve, to the south by the A2016 (Eastern Way), and to the east by Norman Road. There are various public footpaths and public right of ways that are within, or adjacent, to the Site Boundary and are publicly accessible and therefore areas of potential transient public exposure.

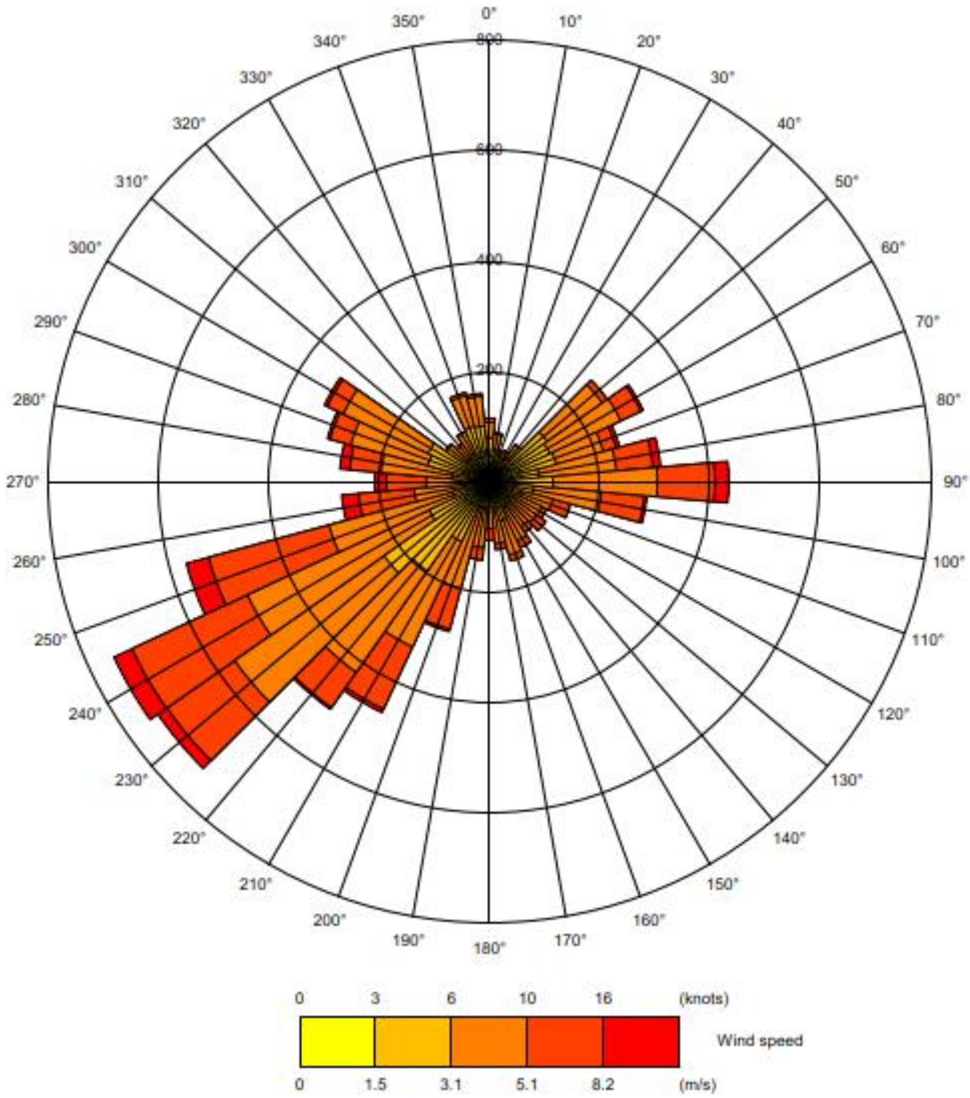
The nearest receptors where longer-term public exposure may occur include:

- Travel Lodge Belvedere, located- 110m to the south-east of the Site Boundary, approximately 500m from the likely vent stack location;
- Asda, Norman Road, located 30m to the east of the Site Boundary, approximately 100m from the likely vent stack location;
- The nearest residential receptor is located off Clydesdale Way, 120m to the south of the Site Boundary.
- Multiple residential receptors, including Norman Road, approximately 500m from the likely vent stack location;
- Residential receptors at Jenningtree Way, approximately 950m from the likely vent stack location;
- Multiple residential receptors, Aspen Green and Leatherbottle Green, approximately 1km to the south-west of the Site Boundary, approximately 1.2km from the likely vent stack location; and
- Multiple residential properties, Fairlane Road, approximately 2km to the north-east of the Site Boundary, approximately 2.5km from the likely vent stack location.

As is customary for risk assessment modelling using PHAST, an arbitrary wind direction is modelled and the distance to concentrations of concern is assumed applicable to all wind directions. Therefore, these receptors are not entered into the model itself, rather, the model has been configured to provide ground level concentrations at 100m intervals downwind of the vent stacks.

Whilst winds for any direction are possible at the CCF, the prevailing wind direction is south-westerly (**Figure 3-2**), therefore the residential properties most likely to be impacted by venting are those located along Fairlane Road, 2.5km to the north-east. Winds from the north and north-west, towards other various residential areas, are relatively infrequent.

Figure 3-2 - Windrose for London City Airport for 2022.



4. METHODOLOGY

4.1. MODELLING SOFTWARE

The dispersion modelling software PHAST v9 has been used for this study. The model has been widely used for dispersion studies involving CO_2 released from storage.

The model developers, DNV, have undertaken extensive model validation work. In particular, Witlox et al, 2012[1], described a series of tests undertaken on CO_2 releases (CO2PIPETRANS JIP) carried out at the Spadeadam site (UK) by Advantica for BP. These experiments included both high-pressure steady-state cold releases (liquid storage) and high-pressure time-varying supercritical hot releases (vapour storage). The CO_2 was stored in a vessel with attached pipework. At the end of the pipework a nozzle was attached, where the nozzle diameter was varied.

PHAST predicted the flow rate at the nozzle very accurately. The concentrations were also found to be predicted accurately (well within a factor of two) by the PHAST dispersion model (UDM). Importantly, these tests were carried out with no fitting whatsoever of the Phast discharge and dispersion models.

On this basis, it is concluded that the model is appropriate for use in this study.

4.2. MODEL INPUTS

<u>Source Data</u>

The modelling uses PHAST's internal discharge calculation model to determine the flow characteristics at the point of exit to air from the vent stack(s). This model takes account of the gas depressurisation on opening the vent valve, flow along a pipe to the vent stack(s), pipe diameter, length and number of bends, and eventual discharge to atmosphere. That is to say, the exit velocity and temperature are not input to the model, but rather, are calculated by the model itself on the basis of the upstream conditions.

The information input to PHAST for each scenario is provided in **Table 2-3**, together with the rationale for setting the input data.

A range of pipe lengths between 20m to 150m between the vent and vent stack(s) was tested, to determine the dependency of the outputs on this parameter for all scenarios involving the main vent stack(s). This actual pipe routing will be determined at detailed design, allowing this modelling to be updated, but the conclusions are not significantly impacted by this length (within reasonable bounds for the pipe length) and, given the indicative layout, up to 100m of pipework is a pragmatic assumption.

For the release to atmosphere of the liquid CO_2 stored on Site (e.g. Scenario 6B above), a fixed vessel of volume 24,000m^3 is being released through a venting pipe. This allows the full downwind

[1] Witlox,Henk W.M., Mike Harper and Adeyemi Oke, Phast Validation of Discharge and Atmospheric Dispersion model Pressurised Carbon Dioxide Releases, Symposium Series No 158, Hazards XXIII

extent of the concentration footprint to evolve since the model simulations will stop at the concentration of interest, well before the inventory is exhausted. This is a worst case, based on the parameters provided for the maximum storage of the on-site storage vessels.

For the venting of pipework within the system, a range of mass flows have been tested, up to and including the operational mass flow, reflecting a scenario wherein the Carbon Capture Systems are unable to shut down prior to venting occurring. In reality, for scenarios venting at a fixed rate, the duration of the venting and flow rate during venting will, in part, be an operational safety decision taking into account, *inter alia*, the likelihood of the ongoing trip, costs of continued operation without carbon capture, costs of restarting the carbon capture trains etc.

Meteorology

For the dispersion stage of the model, PHAST uses a set of discrete and independent meteorological conditions to determine the dispersion of the released gas in ambient air, defined by two parameters:

- Wind speed (measured in m/s); and
- Pascal-Gifford stability class (ranges from A to G).

For each model run, PHAST calculates the envelope defined by the dispersion of the gas up to the concentrations of interest, with an output provided for each meteorological condition. The envelope is defined by the height and perpendicular upwind distance from the venting stack and is therefore independent of wind direction (i.e. short-term nature of the venting, it is considered possible that the wind direction over the period of the venting could come from any direction).

For the assessment of impacts, a range of likely meteorological conditions were chosen to represent the range of likely worst case (in terms of impacts to human health) meteorological conditions. The parameters defining the range of meteorological scenarios assessed were:

- D5 – Neutral stability class, moderate wind speed. This is the most common meteorological condition in the UK
- F1.5 – Stable atmosphere, low wind speed. This stability class gives the worst-case concentrations for low to medium height dense gas releases
- G1.5 – As above, with greater stability
- G1.0 – As above with lower windspeed

In most cases, G1.0 provides the worst-case impacts.

4.3. CONCENTRATIONS OF INTEREST

CO_2 is a substance that is known to be a significant hazard, with the potential to be a major accident hazard (MAH). It is inert and poses a hazard to health through direct exposure either via

- Inhalation, or
- Handling (cryogenic burns); and
- Through indirect effects such as embrittlement of pipework and ‘grit blasting’ of neighbouring plant.

This risk assessment considers the risks through inhalation only – the other identified risks are attributable to the extremely low temperatures involved with liquid CO_2 storage which will only occur on-site. Venting should not involve the direct handling of CO_2. However, the safe handling of pipework/equipment cooled during venting will be considered within the Venting Management Strategy.

At standard temperature and pressure, CO_2 is a gas with a density around 1.5 times that of air (1.98 kg/m^3). Whilst it is an asphyxiant, inhaled concentrations would need to approach 50% before asphyxiation occurred. Toxic effects are seen at lower concentrations with the effects dependent on both the inhaled concentration and the exposure duration. For example, toxicological symptoms include headaches, increased respiratory and heart rate, dizziness, muscle twitching, confusion, unconsciousness, coma and death.

Public Health England (now UK Health Security Agency) listed the effect levels set out in **Table 4-1**, below.

Table 4-1 – Reported Effect Levels for Exposure by Inhalation.

% CO_2	Concentration (ppm)	Symptoms
2 - 5%	20,000 – 50,000	Headache, dizziness, sweating, shortness of breath
6 - 10%	60,000 – 100,000	Hyperventilation, tachycardia, worsening dizziness
11 - 17%	110,000 - 170,000	Drowsiness, muscle twitching, loss of consciousness
>17%	170,000	Convulsions, coma and death
Data taken from Public Health England, 2016, Carbon Dioxide – Incident Management[2]		

CO_2 Workplace Exposure Limits

CO_2 is classed as a 'substance hazardous to health' under the Control of Substances Hazardous to Health Regulations 2002 (COSHH). Workplace Exposure Limits (WEL) are provided in EH40/2005[3] for long (8-hour average) and short-term (15-minute average) exposure and are set out in **Table 4-2**, below. The values in bold were used in PHAST to assess exposure against the WEL.

[2] Reported effect levels from authoritative sources, accessed via: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/566568/carbon_dioxide_incident_management.pdf
[3] EH40/2005 Workplace exposure limits, accessed via: https://www.hse.gov.uk/pubns/priced/eh40.pdf

Table 4-2 – Workplace Exposure Limits for CO_2 (values in bold used in modelling)

Substance	Exposure Length	Exposure Averaging Period	Workplace Exposure Limit (ppm)
CO_2	Long Term	8 hour	5000
	Short Term	15 minute	15,000

Notwithstanding the use of the 8-hour WEL in PHAST, the risks surrounding human exposure resulting from the release of the gas are likely to be short term in nature (i.e. of the order of 15 minutes, rather than 8 hours), given the timeframes involved in the venting scenarios proposed. As such, assessment against 5000ppm is conservative.

<u>Dangerous Toxic Loads (DTLs)</u>

In addition to the WELs, which it is again emphasised are set to be protective of health, the HSE define Dangerous Toxic Loads to calculate the exposure conditions in terms of concentration and duration of exposure. In this assessment, as in HSE work on CO_2 risks, the specified level of toxicity (SLOT) and the significant likelihood of death (SLOD) measures are used. The HSE have defined the SLOT as causing:

- Severe distress to almost everyone in the area
- Substantial fraction of exposure population requiring medical attention
- Some people seriously injured
- Highly susceptible people possibly being killed, likely to cause 1 – 5% fatalities

The SLOD is defined as causing 50% lethality from a single exposure over a known amount of time. HSE reports that humans are particularly sensitive to increases in CO_2 concentrations above 7% in air.

The SLOTs and SLODs shown in are equivalent to the following equation for calculating a dangerous toxic load, A:

$$A = c^n t$$

where c is the concentration in ppm, t is the time in minutes, and n is a compound specific exponent. For CO_2, n is 8 and the SLOT shown in **Table 4-3** corresponds to a value of A equal to 1.5E+40ppm^8-min and the SLOD to 1.5E+41ppm^8-min. The values in bold were input into PHAST to calculate hazardous distances for various scenarios at the facility i.e. 20min SLOD (50% fatalities) and 60min SLOT (1-5% fatalities).

Table 4-3 - HSE derived dangerous toxic loads, defined as the concentration of CO_2 in air

Exposure Time (mins)	SLOT: 1 – 5% Fatalities		SLOD: 50% Fatalities	
	% (v/v)	Concentration (ppm)	% (v/v)	Concentration (ppm)
60	6.3%	63,000	8.4%	84,000
30	6.9%	69,000	9.2%	92,000
20	7.2%	72,000	9.6%	96,000
10	7.9%	79,000	10.5%	105,000
5	8.6%	86,000	11.5%	115,000
1	10.5%	105,000	14.0%	140,000
Dangerous Toxic Load ppm^8min	$1.5x10^{40}$		$1.5x10^{41}$	
Data taken from HSE Table of SLOT DTL and SLOD DTL Values for Various Substances[4]				

<u>CO_2 Exposure in the general public</u>

There are no standards set in the UK for exposure to CO_2 in non-occupational settings i.e. exposure of the general public. Therefore, for the purposes of this study and the assessment of impacts from fugitive emissions specifically, an assessment level has been derived that takes explicit account of potentially higher sensitivity individuals in comparison to the working population. The derived assessment levels are highly precautionary since they are derived from the WELs which are designed to be protective of human health, even with repeated exposure at that level. The potential for repeated exposure with the proposed venting scenarios, with likelihood of occurrence of 1 in 2 years at most, is very low.

The Environment Agency published a consultation document in 2012 on the derivation of new Environmental Assessment Levels (EAL) to air[5] and the approach set out in Annex 5 of the document is now recommended by the Agency for the derivation of new EALs[6]. The approach, for

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[4] Accessed via: https://www.hse.gov.uk/chemicals/haztox.htm
[5] Derivation of new Environmental Assessment Levels (EALs) to air consultation, 2012, Environment Agency. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/914697/Derivation_of_new_EALs_to_air.pdf
[6] Summary of responses to our 2012 public consultation "Hierarchy for the derivation of new Environmental Assessment Levels (EALs) to air", 2020, Environment Agency. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/914712/Summary_of_responses_-_derivation_of_new_EALs_to_air.pdf

pollutants such as carbon dioxide for which a threshold for effects has been identified, applies an uncertainty factor to the No Observed Adverse Effect Level (NOAEL) or Lowest Observed Adverse Effect Level (LOAEL).

Taking the LOAEL to be 20,000ppm CO_2 (i.e. 2% from **Table 4-1**) and applying an uncertainty factor of 10 to account for the sensitivity of individuals, leads to a tolerable concentration in air of 2,000ppm.

Table 4-4 – Proposed Assessment Level for CO_2.

Substance	Exposure Length	Proposed Assessment Level (ppm)	Percentage CO_2 by volume
CO_2	Short Term	2,000	0.2%

Phast Modelling Endpoints

Taking into account the above discussion, the concentrations shown in **Table 4-5** were set as end points in PHAST for this risk assessment

Table 4-5 – PHAST End Points for Consequence Modelling

% CO_2	Concentration (ppm)	Symptoms
9.6%	96,000	20 min SLOD (50% fatalities)
6.3%	63,000	60 min SLOT (1-5% fatalities)
1.5%	15,000	15 min ST WEL
0.5%	5,000	8-hour LT WEL
0.2%	2000	Precautionary assessment level for general public
0.1%	1,000	Indicative of 50% Precautionary level
0.05%	500	10% of 8-hour WEL

5. MODEL RESULTS

5.1. PLUME BEHAVIOUR

In this section, the overall behaviour of the vented plume in each scenario is illustrated with reference to a vertical slice through the plume.

Figure 5-1 to **Figure 5-5** show the maximum downwind extent of the plumes where concentrations exceed the specified concentrations of concern under 1G meteorological conditions for all venting scenarios. It is readily apparent that under these meteorological conditions, slumping of the plume defined as a marked decrease in the height of the plume and elevated ground level concentrations occurs only for all modelled scenarios.

Figure 5-5 to **Figure 5-9** show the maximum downwind extent of the plumes where concentrations exceed 2000ppm for all venting scenarios under each of the meteorology classes considered. The worst-case meteorology, in terms of maximum downwind extent of concentrations exceeding 2000ppm, varies between the scenarios as the balance between plume momentum, turbulent mixing and downwind advection changes. Notably, slumping behaviour occurs insofar as the concentrations of interest are reached at ground level for all meteorological conditions other than 5D.

Figure 5-1 - Maximum downwind extent of concentrations exceeding the specified concentrations of concern/interest for Venting Scenario 1, shown as a vertical slice through the plume in the down wind direction.

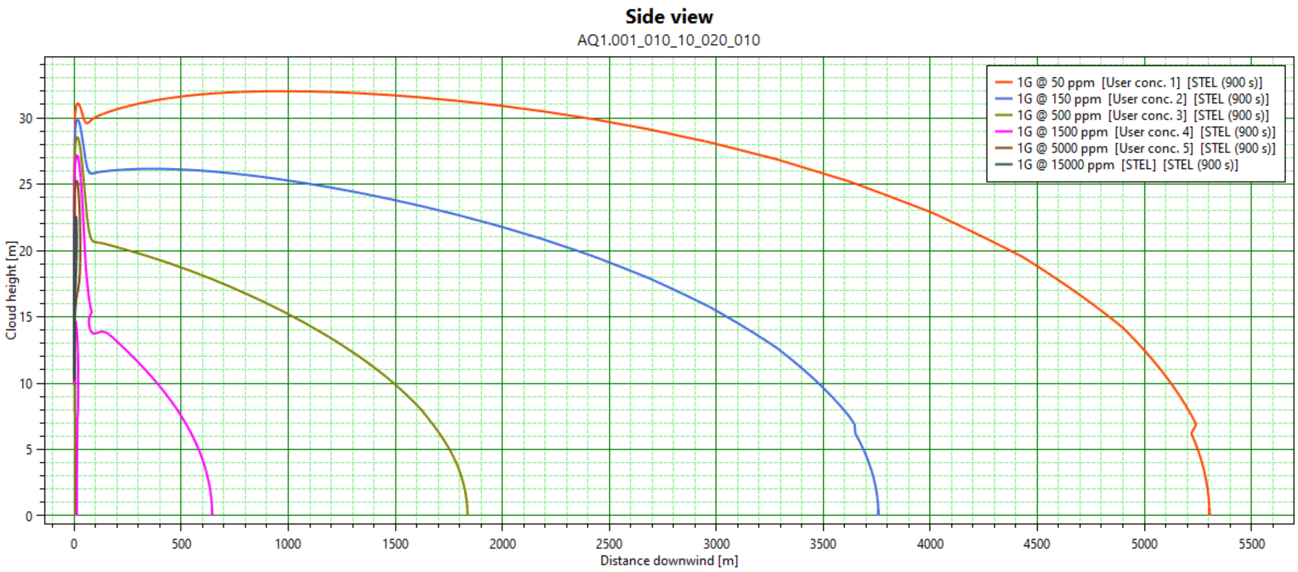


Figure 5-2 - Maximum downwind extent of concentrations exceeding the specified concentrations of concern/interest for Venting Scenario 2, shown as a vertical slice through the plume in the down wind direction.

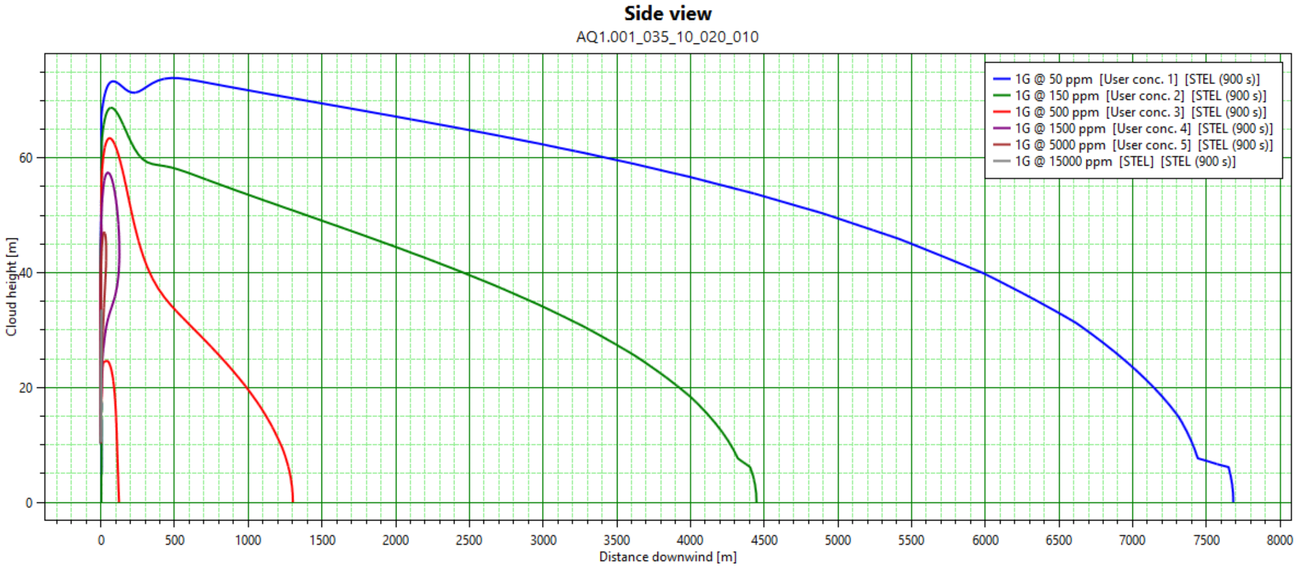


Figure 5-3 - Maximum downwind extent of concentrations exceeding the specified concentrations of concern/interest for Venting Scenario 5, shown as a vertical slice through the plume in the down wind direction.

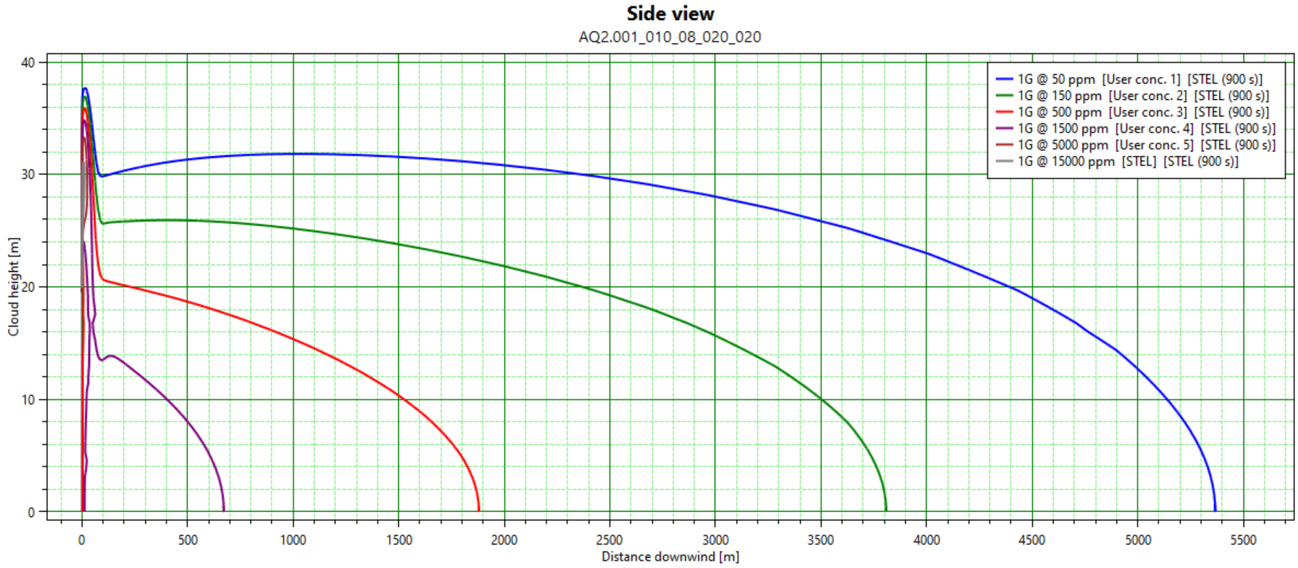


Figure 5-4 - Maximum downwind extent of concentrations exceeding the specified concentrations of concern/interest for Venting Scenario 6A, shown as a vertical slice through the plume in the down wind direction.

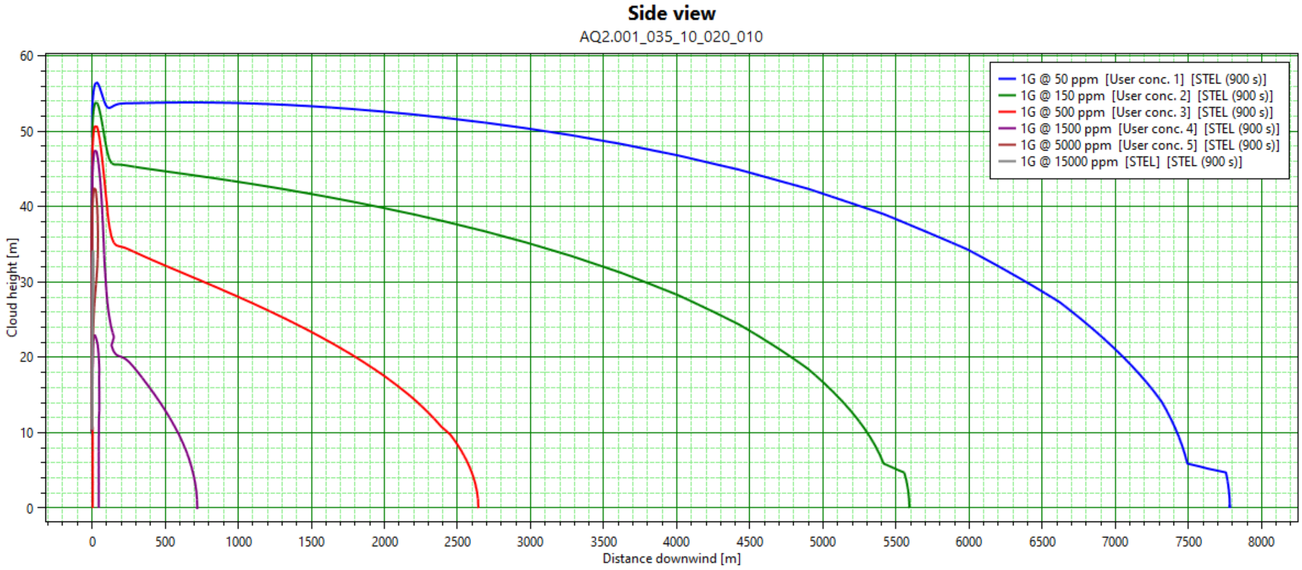


Figure 5-5 - Maximum downwind extent of concentrations exceeding the specified concentrations of concern/interest for Venting Scenario 6B, shown as a vertical slice through the plume in the down wind direction.

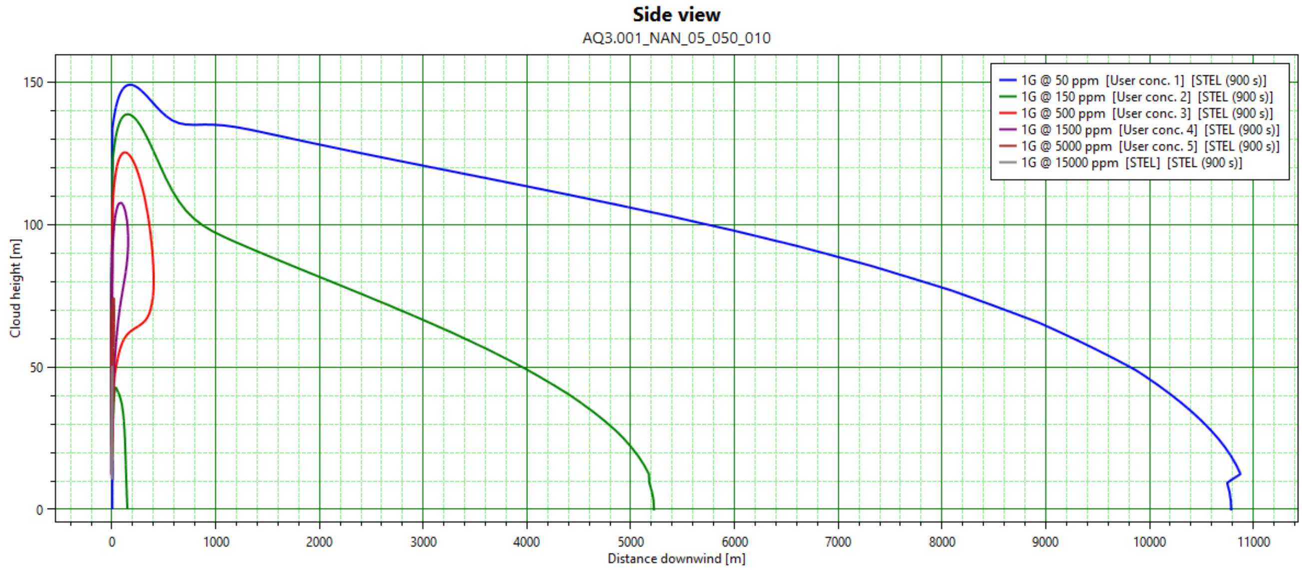


Figure 5-6 - Maximum downwind extent of concentrations exceeding the specified concentrations of concern for Venting Scenario 2, shown as a vertical slice through the plume in the down wind direction for meteorological condition 1.5F.

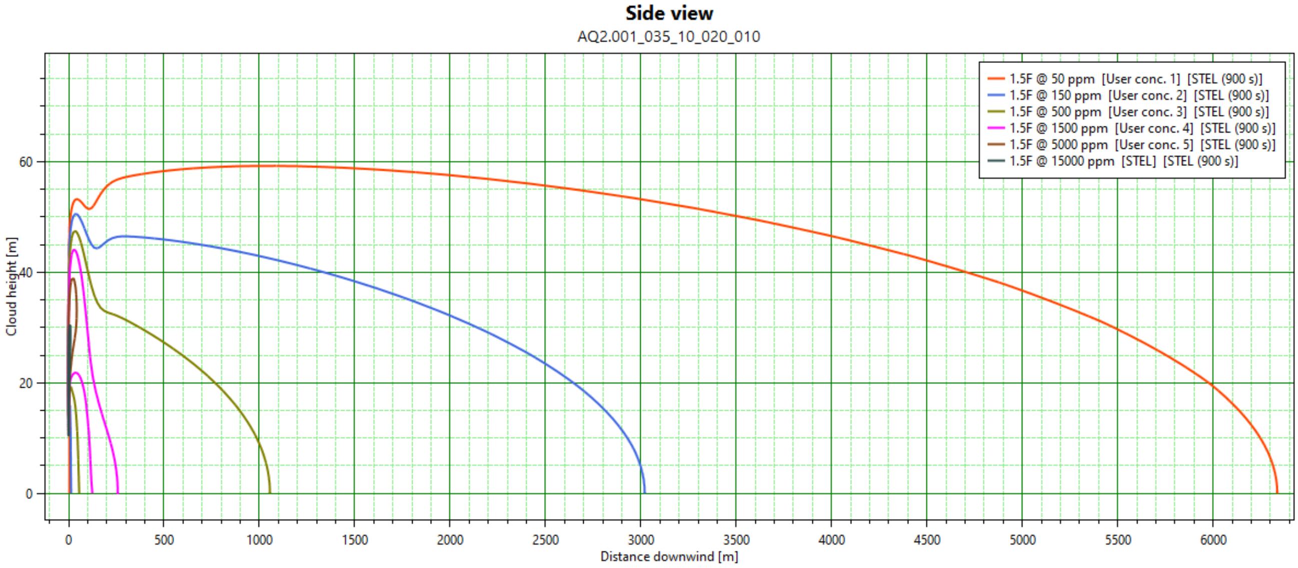


Figure 5-7 - Maximum downwind extent of concentrations exceeding the specified concentrations of concern for Venting Scenario 2, shown as a vertical slice through the plume in the down wind direction for meteorological condition 1.5G.

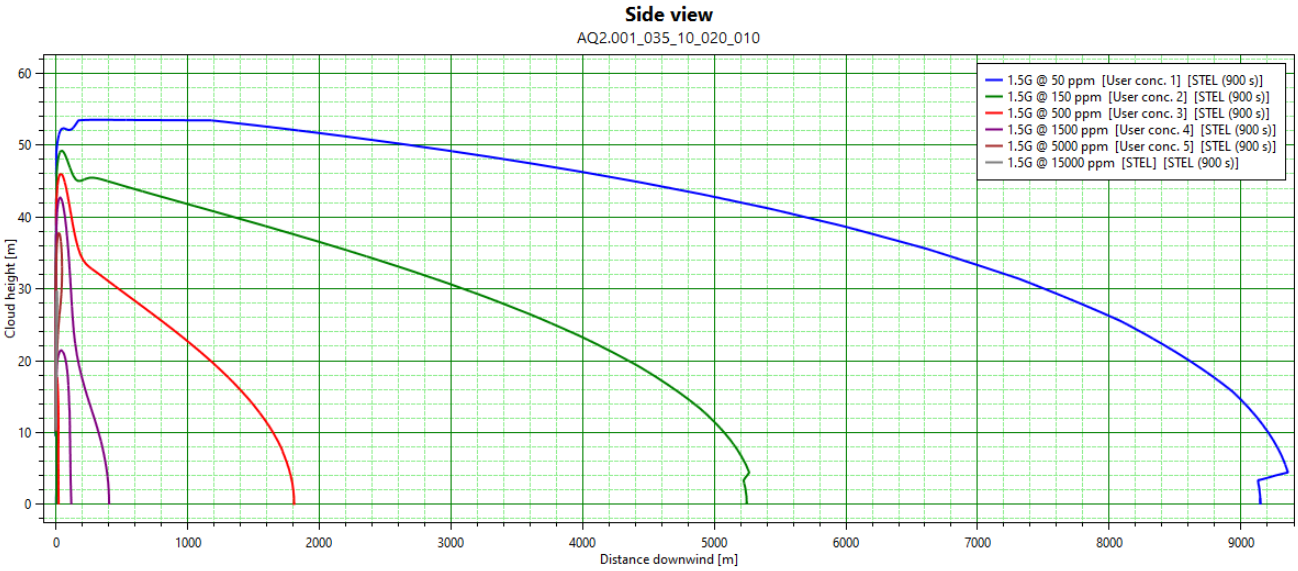


Figure 5-8 - Maximum downwind extent of concentrations exceeding the specified concentrations of concern for Venting Scenario 2, shown as a vertical slice through the plume in the down wind direction for meteorological condition 1G.

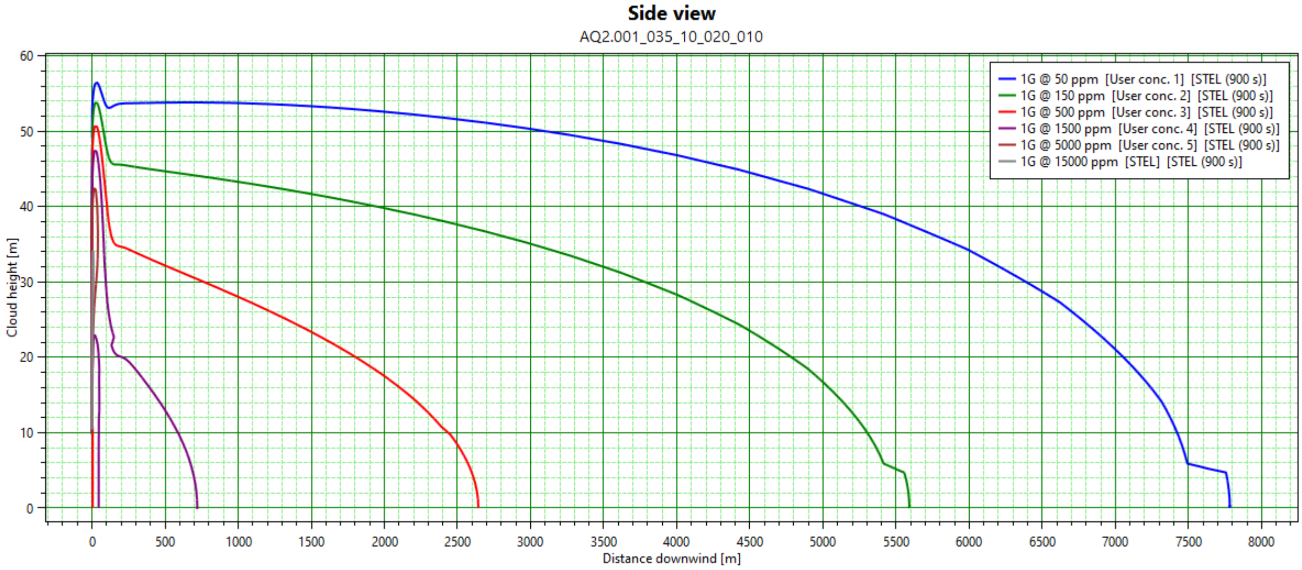
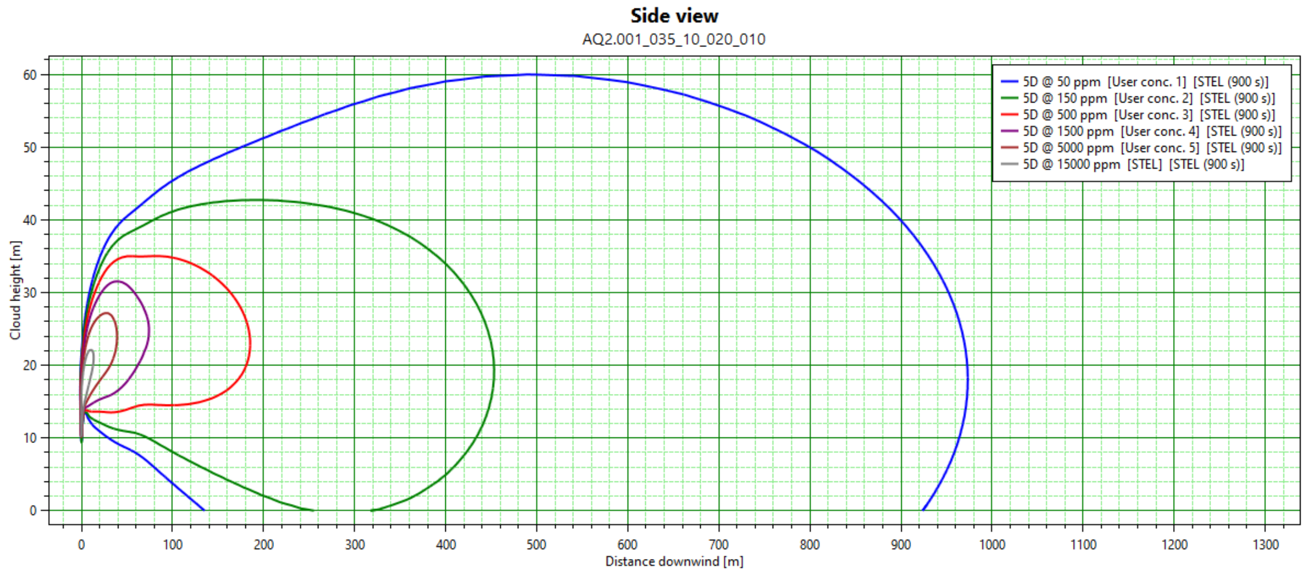


Figure 5-9 - Maximum downwind extent of concentrations exceeding the specified concentrations of concern for Venting Scenario 2, shown as a vertical slice through the plume in the down wind direction for meteorological condition 5D.



5.2. STACK HEIGHT SENSITIVITY

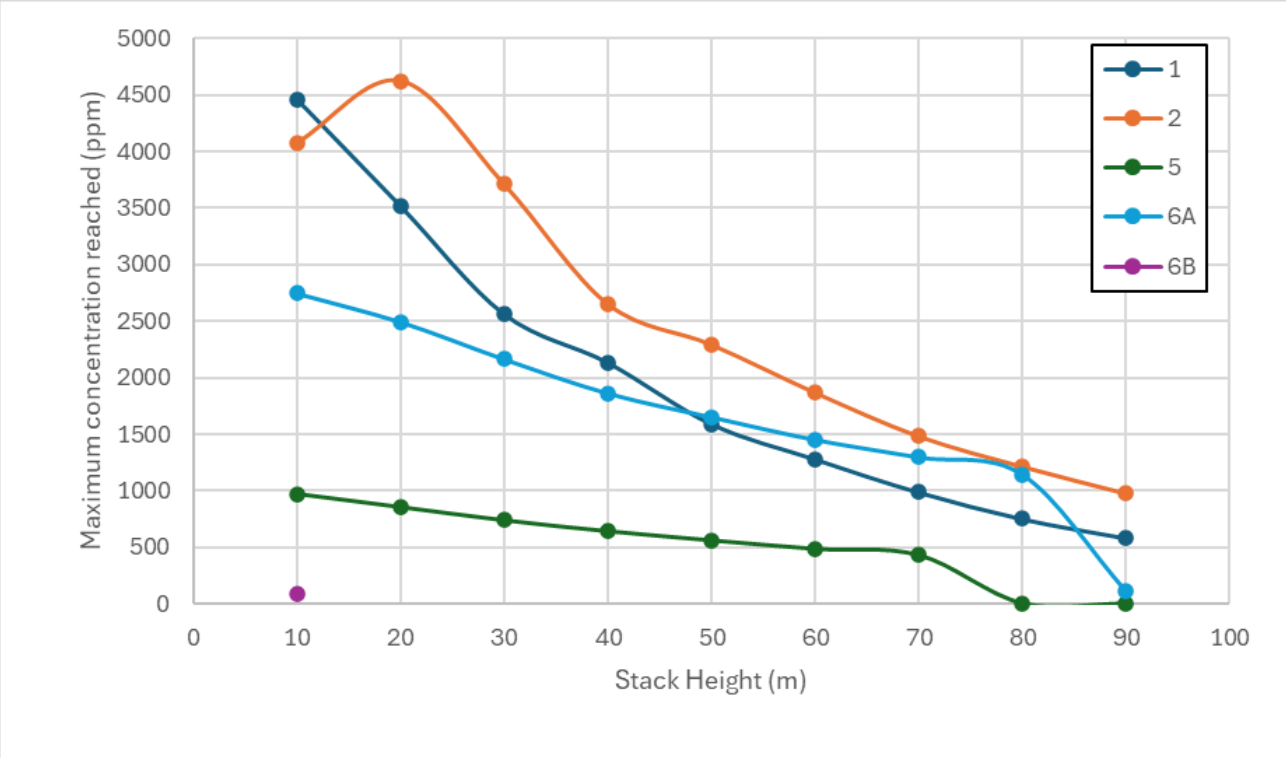
In this section, the sensitivity of the vent stack(s) height on ground level pollutant concentrations is considered. There are no modelled ground level concentrations greater than the concentration of significant concern (5000ppm). Therefore, it is concluded that the minimum modelled stack height of 10m above ground level will suffice for the venting of CO_2 for all modelled scenarios.

In order to further investigate the sensitivity of this conclusion, the maximum distance at which the concentration of interest (2,000ppm) is exceeded and the maximum ground level concentration reached for the range of modelled stack heights are presented in **Table 5-1** and **Figure 5-10**, below.

Table 5-1 – Distance at which specified concentration is exceeded downwind from vent(s) stack at any height above ground

Venting Scenario	Maximum distance downwind at which concentrations exceed 2000ppm (m) for the range of modelled stack heights								
	10m	20m	30m	40m	50m	60m	70m	80m	90m
1.Over pressure after compression.	400	300	300	200	-	-	-	-	-
2. CO_2 Boil off in storage in no liquefaction available.	300	400	300	300	200	-	-	-	-
5. Compressor trip resulting in full or partial flow from the CCF being vented.	-	-	-	-	-	-	-	-	-
6A. Liquefaction trip resulting in full or partial flow from the CCF being vented.	400	300	300	-	-	-	-	-	-
6B. Liquefaction trip resulting in stored volume being vented.	-	-	-	-	-	-	-	-	-

Figure 5-10 - Graph of the maximum concentration reached by venting stack height for all modelled scenarios.



As is expected, the data shown above indicates that there is a general reduction in both the maximum modelled concentration and the distance to which the concentration of interest is exceeded with increasing stack height. For all modelled scenarios, concentrations remain below the concentration of significant concern (5000ppm) at all modelled locations, indicating that **a minimum stack height of 10m for the venting stack(s) would be sufficient**.

Concentrations fall below 2000ppm at all locations (both on-site and off-site) where the stack(s) height exceeds 60m, although this would represent an unnecessarily conservative approach given the buffer between the final location of the vent stack(s) and potential human exposure, the likely exposure times involved, and likelihood of exposure occurring. Given the limitations set out within the Development Consent Order, the maximum height of the CO_2 venting stack(s) is 45m (48m AOD), therefore this scenario is considered unlikely.

5.3. DISTANCES TO CONCENTRATIONS OF CONCERN

In this section, the risk of off-site impacts are assessed with reference to the distance downwind from the vent stack(s) at which the concentrations of significant concern (5000ppm and above) and at lower concentrations of interest (2,000ppm and lower) are exceeded (**Table 5-2**, **Table 5-3**). As noted previously, it is assumed that any meteorological condition could occur from any wind direction and, therefore, the risk assessment simply considers the distance downwind for the vent stack(s) at which concentrations of concern are exceeded.

Neither the short term WEL (15,000ppm) nor the long term WEL (5000ppm) are exceeded at ground level for any of the modelled scenarios. The precautionary assessment level is not exceeded at ground level for scenarios 5 or 6B, where the gas compressor is tripped, and the full gas load is vented, and where the liquid CO_2 stored on-site is vented from the storage vessels. This conclusion holds for all modelled vent heights included within the assessment.

Where the precautionary assessment level of 2000ppm is exceeded in scenarios 1, 2, and 6A, the worst-case results for ground level exposure (i.e. for a stack height of 10m in the air) are presented, although, as stated above, neither the short-term nor long-term WELs are exceeded in any of these modelled scenarios. Therefore, **the risk of exposure to the public is low.**

Table 5-2 – Distance at which specified concentration is exceeded downwind from vent stack at any height above ground

Venting Scenario	Distance Downwind at which Concentration is exceeded (m)			
	500ppm	1000ppm	2000ppm	5000ppm
1.Over pressure after compression	1600	800	400	Not Reached
2. CO_2 Boil off in storage in no liquefaction available	1700	900	400	Not Reached
5. Compressor trip resulting in full or partial flow from the CCF being vented.	1100	Not Reached	Not Reached	Not Reached
6A. Liquefaction trip resulting in full or partial flow from the CCF being vented.	2500	1100	400	Not Reached
6B. Liquefaction trip resulting in stored volume being vented / Indicative on-site fire scenario	Not Reached	Not Reached	Not Reached	Not Reached

Table 5-3 – Distance at which 2000ppm is exceeded downwind from vent stack at ground level as a function of meteorological condition

Venting Scenario	Distance Downwind at which 2000ppm is exceeded (m)			
	5D	1.5F	1.5G	1G
1.Over pressure after compression.	Not Reached	100	200	400
2. CO_2 Boil off in storage in no liquefaction available.	Not Reached	100	200	400
5. Compressor trip resulting in full or partial flow from the CCF being vented.	Not Reached	Not Reached	Not Reached	Not Reached
6A. Liquefaction trip resulting in full or partial flow from the CCF being vented.	Not Reached	Not Reached	Not Reached	400

Venting Scenario	Distance Downwind at which 2000ppm is exceeded (m)				
	5D		1.5F	1.5G	1G
6B. Liquefaction trip resulting in stored volume being vented / Indicative on-site fire scenario	Not Reached	Not Reached	Not Reached	Not Reached	

5.4. MAXIMUM CONCENTRATIONS AT RECEPTORS

In this section, the risk of off-site impacts is considered with reference to the maximum ground level concentrations at key receptor locations, under any meteorological condition, as a function of the venting scenario.

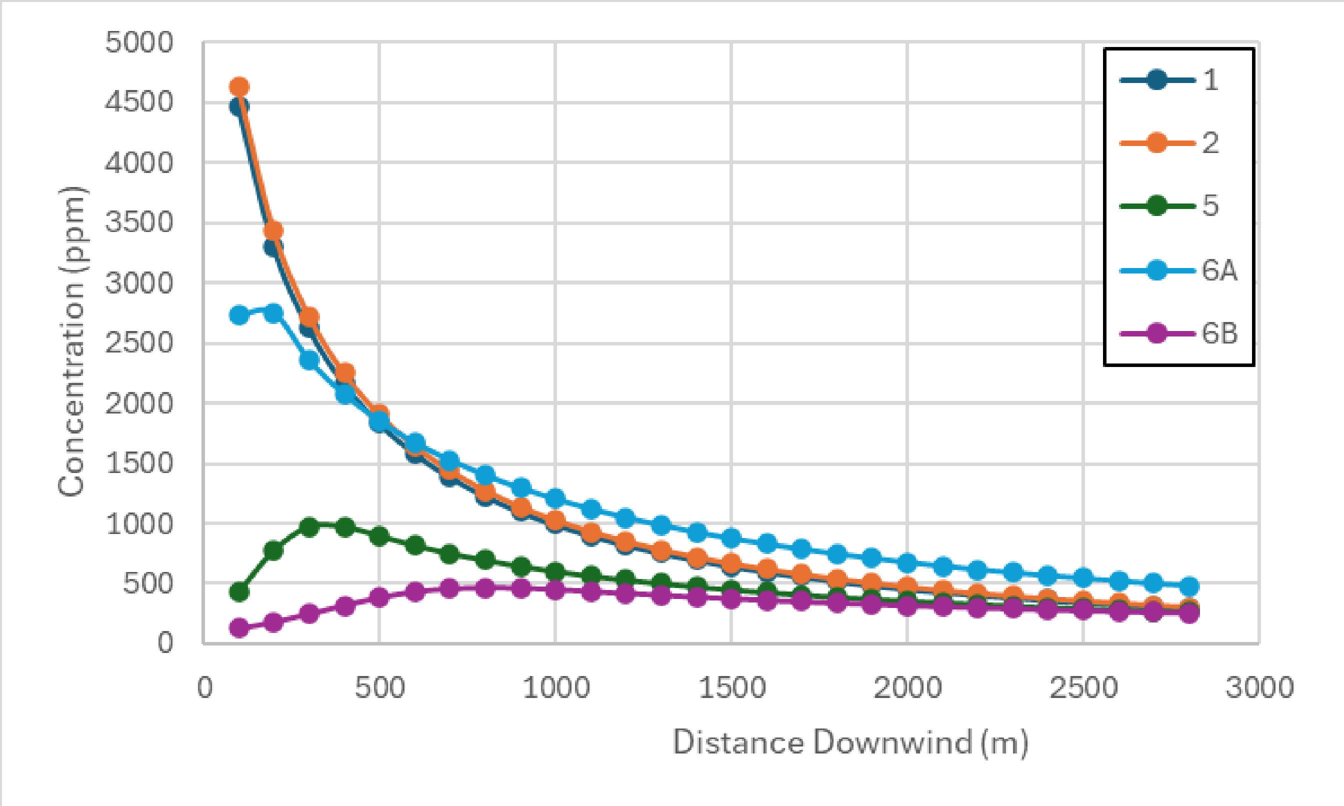
Figure 5-11 shows the maximum concentration as a function of distance downwind for all venting scenarios. At the boundary of the Site and within the Site, where transient human exposure is expected (<100m from the CCF), the maximum concentration is around 4,600ppm. This is well within the short term WEL of 15,000ppm (and therefore protective of workers' health). It is just below the long term WEL of 5,000ppm (used as a precautionary measure of acceptable off-site concentrations, since it is modelled at a 900 second averaging period rather than the regulatory 8-hour standard), but above the precautionary assessment level for members of the public (2000ppm).

The 2,000ppm assessment level is the concentration at which mild effects might be seen in sensitive members of the population, such as slightly reduced cognitive function in complex tasks. These effects would, however, be transient and a full recovery made. These effects would be similar to exposure in poorly ventilated multi-occupancy spaces such as classrooms or halls. The maximum concentration occurs for venting scenario 1 (over pressure release during compression of the gas). However, given the low potential for exposure of members of the public at the Site Boundary, **the risk of off-site health effects is negligible**.

At the nearest residential receptors, Clydesdale Way 120m from the southern Site Boundary, and approximately 500m from the likely venting location, the maximum ground level concentration is 1,905ppm. This is 38% of the long term WEL of 5000ppm, and just below the precautionary assessment level for members of the public. Therefore, **the risk of off-site health effects is negligible** at residential properties. If we were to apply a conservative uncertainty factor of ~2, as set out above, there would be an exceedance of the 2,000ppm assessment level at residential properties, although the conservatively-assessed long term WEL would still not be exceeded., given the likely release periods for each of the venting scenarios, and that simultaneous venting of the Carbon Capture Trains is unlikely to occur, this conclusion represents a robust assessment of the likely long term impacts to human health.

Furthermore, the risk of exposure at residential properties can be mitigated with advice to stay indoors and to close windows. However, the general population will experience no significant health effects during the foreseeable venting scenarios.

Figure 5-11 – Maximum ground level concentration downwind under any meteorological condition, as a function of venting scenario (see legend)

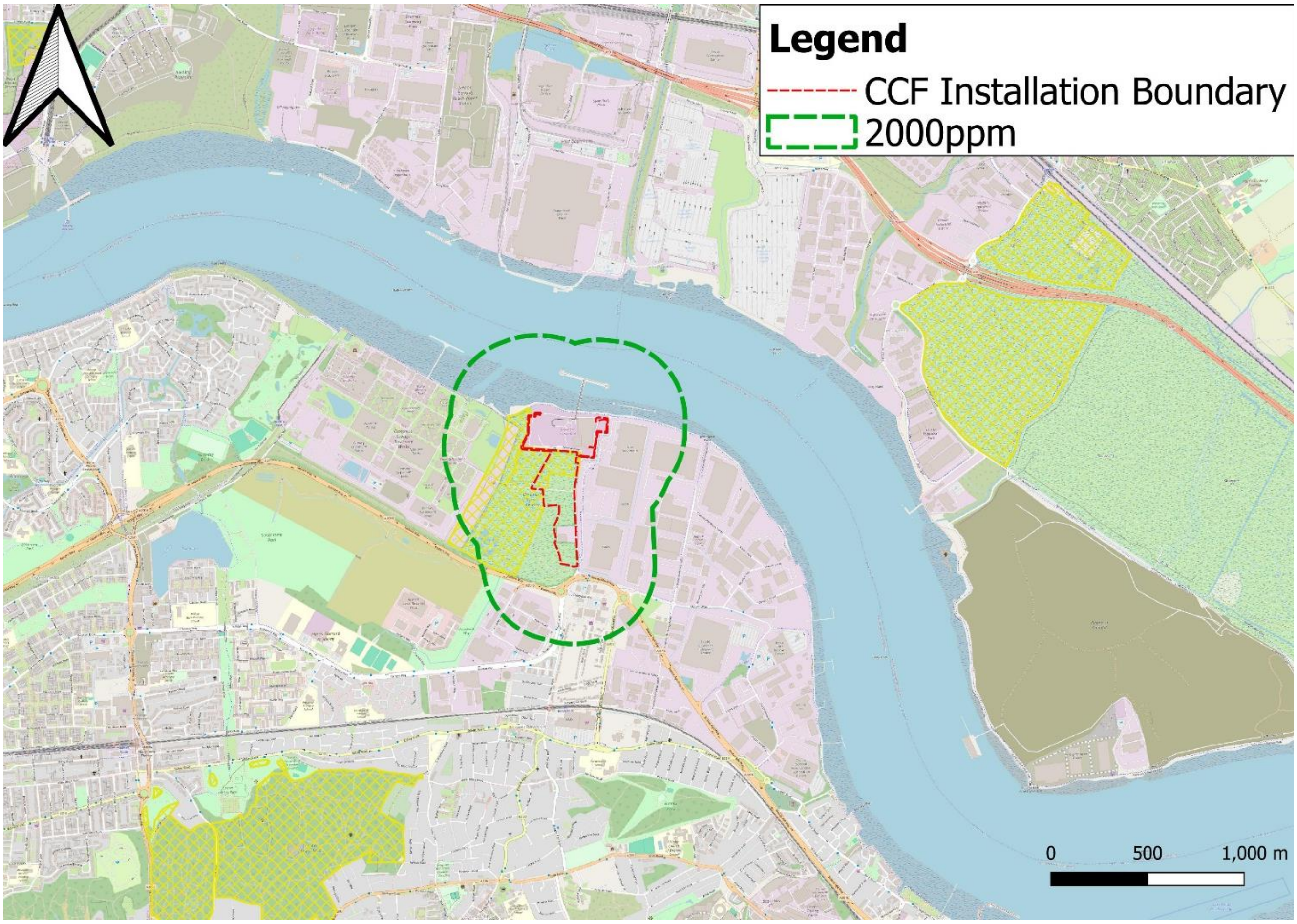


5.5. CONCENTRATION FOOTPRINT

Figure 5-12 shows the footprint within which ground level concentrations exceed 2000ppm (with 900s averaging period) for Venting Scenarios 1, 2 and 6A. (No other scenarios have ground level concentrations in excess of this 2000ppm). This buffer level has been provisionally applied to the entirety of the Site Boundary in lieu of a confirmed on-site location for the CO_2 venting stack(s). This provides a conservative estimate of the likely concentration footprint and can be revised upon finalisation of the venting stack(s) location.

There are no residential receptors or areas of likely exposure of members of the public within the 5000ppm footprint. Since 5000ppm is a concentration to which humans can be routinely exposed for long periods, **the risks of health effects off-site are negligible.**

Figure 5-12 – Footprint within which maximum concentrations exceed 2000ppm for Venting Scenarios 1, 2, and 6A (green)



5.6. ASSUMPTIONS AND UNCERTAINTY

Every effort has been made to ensure that this assessment is a robust representation of the release parameters and modelled scenarios, with conservative assumptions adopted throughout the assessment.

Dispersion modelling contains inherent uncertainties, however, in model validation studies of CO_2 venting events PHAST performed well with concentrations being predicted to within a factor of 2.

If a factor of 2 is applied as an upper bound on the uncertainty in the assessment of impacts modelled for the CO_2 Venting at Cory's CCF, then there is a risk of exceedance of the long term WEL of 5000ppm at residential properties nearby, but no predicted exceedance of the short term WEL of 15,000ppm. The former is the concentration to which workers can be exposed for long periods (the 8-hour working day, repeatedly), whilst the latter is the level to which workers can be exposed for short periods, routinely i.e. 15 minutes.

Assessing the intermittent and infrequent potential exposure to vented CO_2 against the long term WEL and even more so with consideration of the precautionary assessment level of 2000ppm, provides significant headroom to mild and transient health effects.

Multiple venting scenarios, with variable loads and process conditions have been considered in this study. The model results show that venting at relatively low load e.g. where the compressor over-pressurises gas or liquid CO_2 boils off from on-site storage, results in slumping of the CO_2 and elevated ground level concentrations. Despite this, none of the modelled scenarios resulted in an exceedance of the 5,000ppm WEL at any location either on- or off-site. The study is, therefore, robust in that it provides a demonstration of potential impacts both under venting from compressors and on-site liquid CO_2 storage. The assessment covers emissions of CO_2 from a variety of locations within the system. The upstream conditions at these locations were based on indicative data available at the time of writing. The assessment will be reviewed/repeated as necessary using data available following finalisation of detailed design to ensure that there is **negligible risk** of modelling unrepresentative conditions, and that environmental limits set out in the future Environmental Permit are met.

Furthermore, the study has considered exposure to a concentration of 5000ppm at 900s (among others) averaging period, whereas the WEL actually relates to an averaging period of 8hrs. This introduces a safety factor of around 2 into the assessment since peak concentrations at short averaging periods will be markedly higher than peak concentrations at longer averaging periods.

Overall, the risk assessment is robust and precautionary. The results indicate that there is a **low risk** that sensitive members of the public might experience mild but transient effects during some venting events (with maximum concentrations at receptors exceeding 2000ppm) but that the general population will experience **no significant health effects** during the foreseeable venting scenarios. In addition, workers on-site will not experience any significant health effects.

Further refinement of these venting scenarios and the vent specifications will be required at the detailed design phase.

The following strategy and mitigation recommendations are carried forward into detailed design:-

- The 10” vent for depressurising the system where the CO_2 is in liquid form should be a minimum of 10m tall.

Furthermore

- The venting of liquid CO_2 should be avoided where possible, and the vent system after the initial valve should be designed to promote the phase change from liquid to gas during expansion/release to atmosphere. In addition, the flow rate should be managed by appropriate sizing of the vent valves to prevent the formation of solid CO_2 upstream of the vent. This will be incorporated in the Venting Management Plan as part of the Site’s Environmental Management System as detailed in Sections 12.10 and 13.2.2 of the Technical Supporting Document submitted as part of this staged permit application.

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