# Computational Fluid Dynamics (CFD) Gas Dispersion Study for Haworth Scouring's (HS) New Anaerobic Digestion (AD) Plant

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Prepared & Approved by:

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# 1 Index of Revisions

| Rev. | Date | Remark | Originator | Reviewer | Approver |
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# 3 Confidentiality & Liability Notice

## 3.1 Confidentiality Notice

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# 4 Introduction & Background

ADH Risk Ltd (ADH Risk) is pleased to present to Haworth Scouring Company Ltd (HS) this Final Report presenting the main results obtained from the Computational Fluid Dynamics (CFD) gas dispersion simulation project for HS' new Anaerobic Digestion (AD) plant which is designed, manufactured and installed by FRE-Energy Ltd (FRE-Energy). Phil Durrant Associates Ltd (PDA Ltd) is acting as the process safety specialist to FRE-Energy, and their end client, HS, and are predominately responsible for Process Hazard Analysis (PHA) and Dangerous Substances and Explosion Atmosphere Regulation (DSEAR) Risk Assessment Study delivery for this project.

HS is located in Bradford, West Yorkshire which is the heart of the UK's textile industry and is one of the largest, modern and environmentally responsible commission wool scours in the world. However, in the wool cleaning process, a large amount of wastewater and dirt are produced. The wash water is currently processed to concentrate the organic and solid elements into a cake and the residual water is discharged to the sewer, but has a biological content with a recordable level of Chemical Oxygen Demand (COD). This discharge currently is permitted under the Environment Agency consent for which HS is charged.

HS have engaged with FRE-Energy to design, manufacture and install a new AD Plant on their Bradford site comprising of nine (9) digesters tanks and a centralised biogas holding bag. Not only will the new AD plant at HS' Bradford site create energy from biological waste, it will give a significant reduction in discharge organics (lower COD levels and reduce permitted discharge costs), and at the same time help HS move closer to net zero as well as reducing journeys to and from the factory by up to 40%. It is estimated that with the New AD Plant installed and operational, HS would see a reduction of 45 tonnes of "sludge" being removed from the site each and every day.

The AD process converts the organic elements into biogas, which is predominately methane ($CH_4$) and Carbon Dioxide ($CO_2$), with small amounts of Hydrogen Sulphide ($H_2S$), which will be used to displace electricity and gas current used to power HS' Bradford site, and provide hot water for the washing process. This process provides green electricity without the need for fossil fuels.

As the main gas components of Biogas are either flammable, toxic and/or asphyxiant in nature, depending on their concentrations, a Loss of Containment (LoC) of Biogas from the new AD plant could have a significant impact on the safety of people onsite and/or offsite, especially the railway line South-East (SE) of HS' site in Bradford. Therefore, HS has approached ADH Risk to conduct CFD Gas Dispersion Modelling on four (4) potential releases to understand their flammable, toxic and asphyxiant hazard extents under two (2) different operational & ambient temperature conditions (i.e. summer & winter), and three (3) different wind speed & atmospheric stability pairs (i.e. extremely stable, moderately stable and neutrally stable conditions).

The simulations were conducted using a validated open-source CFD software code called FDS produced and developed by NIST [1]. ADH Risk wrote the FDS model emulating the HS' new AD Plant, which has been designed by FRE-Energy, including all terrain, process equipment and a good degree of pipework (as the design was still in process when the CFD simulations where being conducted), as well as the weather and release conditions outlined later in this report. ADH Risk believes the CFD simulation tool, as well as the methodology and assumptions used and presented in this report, to be conservative in nature.

The release cases, weather and environmental conditions analysed as part of this project was discussed and agreed in July 2024 between ADH Risk, FRE-Energy and PDA Ltd, prior to the CFD gas dispersion simulations being conducted. An Interim Letter Report was provided to HS (as well as their partners FRE-Energy and PDA Ltd) in February 2025 highlighting the initial technical results and findings of the CFD Gas Dispersion Study for HS' New AD Plant at their site in Bradford, West Yorkshire. Please note that these initial technical results and findings remain the same and are reciprocated in more detail in this, the full and final report on the project. Since the Initial Interim Letter Report was published in February 2025, ADH Risk has measured and analysed a significant about of data generated as part of this project (i.e. nearly 2TB).

This full and final report has highlighted the hazards from the release scenarios investigated, not only to offsite (i.e. the adjacent railway line) as discussed in this report in more detail, but also report on onsite hazards to personnel (staff, contractors or visitors) from such releases.

Only a single release condition causes some minor concern (i.e. REL04), which is associated with the activation of the AD tank's Foam Alleviation Device (FAD) and is discussed further in this report. Only for certain flammable, toxic and asphyxiant gas cloud concentrations, in certain wind directions causes some extents to exceed HS's site boundary momentarily and enter the adjacent railway line South-East (SE) of HS' site in Bradford. This is believed to be due to the FAD release (REL04) impinging against the adjacent building wall and spreading in the boundary layer with little dispersion mixing creating larger extents. It was recommended in ADH Risk's Interim Letter Report issued to HS in February 2025, that if HS would like to reduce all CFD gas dispersion concentration (flammable, toxic as well as asphyxiant) extents simulated in this study from release case REL04 (FAD), so they do not exceed HS' railway-site boundary, HS and their partner FRE-Energy should review the function and release direction of the FAD device on the AD tank nearest the railway line.

From communications with FRE-Energy prior to finalising this report, ADH Risk understands that the FAD device on the AD tank nearest the railway line has been rotated in such a way that the discharge orientation is in the opposite direction and away from the adjacent building and towards the gantry between the AD tanks.

However, with any design change, it is highly recommended that HS or their partner, FRE-Energy, undergoes a review through their Management of Change (MOC) procedure, not only to determine whether this change provides a reduction in flammable, toxic and asphyxiant cloud concentration extents from release case REL04 (FAD) and prevents these clouds exceeding HS' railway-site boundary, but does not impose any additional risks to people on or offsite. These recommendations maybe applicable to all FAD devices on HS' new AD plant design, and may include conducting additional CFD gas dispersion simulation runs, to verify that the design change has the desired effect, and does not impose any additional risks to people on or offsite.

# 5 CFD Gas Dispersion Software, Validation & Applicability

For this study, ADH Risk used the Fire Dynamic Simulator (FDS) Computational Fluid Dynamics (CFD) software code which was developed and written by the National Institute of Standards and Technology (NIST) [1], which is an open sourced CFD model for thermal and buoyance driven flows. The software solves numerically a form of the Navier-Stokes equations, appropriate for low-speed, thermally driven flow, which has an emphasis on smoke and heat transport from fires, but handles gas dispersion extremely well, especially in natural (i.e. wind) or artificial (i.e. mechanical / forced) driven air ventilated environments.

ADH Risk has used the FDS CFD code by NIST on numerous consultancy projects in line with their own written code SRAUTAS CFD using OpenFoam, which was developed from ADH Risk's original CFD code written in COMSOL Multiphysics, with numerous validation cases to provide confidence in the results obtain. FDS CFD code is well used and validated by the international fire safety consultancy and is used more and more in the technical safety community to conduct such studies as gas dispersion analysis for safety, environmental and security applications, which the former is applicable to HS' New AD Plant gas dispersion study (i.e. this project).

FDS CFD handles refined three-dimensional (3D) cuboid mesh/cell models and has been adapted to atmospheric flow and dispersion simulation to account for the effects of complex geometries, terrain, buoyancy and turbulence. FDS CFD has a number of turbulence models, including Large-Eddy Simulation (LES) for low-speed non-compressible flows, and is applicable to the project reported as it gives a good estimation of turbulence without excessive runtimes like the higher-fidelity Direct Numerical Simulation (DNS), or alternatively Reynolds Averaged Navier-Stokes (RANS), which provides quicker runs times, but with less accuracy. A good, yet simple comparison of the how the different turbulent models simulate a turbulent jet is shown in Figure 1.

ADH Risk wrote the FDS model emulating the HS' new AD Plant, which has been designed by FRE-Energy, including all terrain, process equipment and a good degree of the process pipework (as the design was still in progress when the CFD gas dispersion simulations were being conducted), as well as the weather and release conditions outlined later in this report. The CFD gas dispersion simulations conducted for HS' new AD Plant were conducted internally on ADH Risk's small scale High Performance Workstation (HPW) cluster, with each node using high end multiple core processes and computational threads, with extensive memory management capabilities.

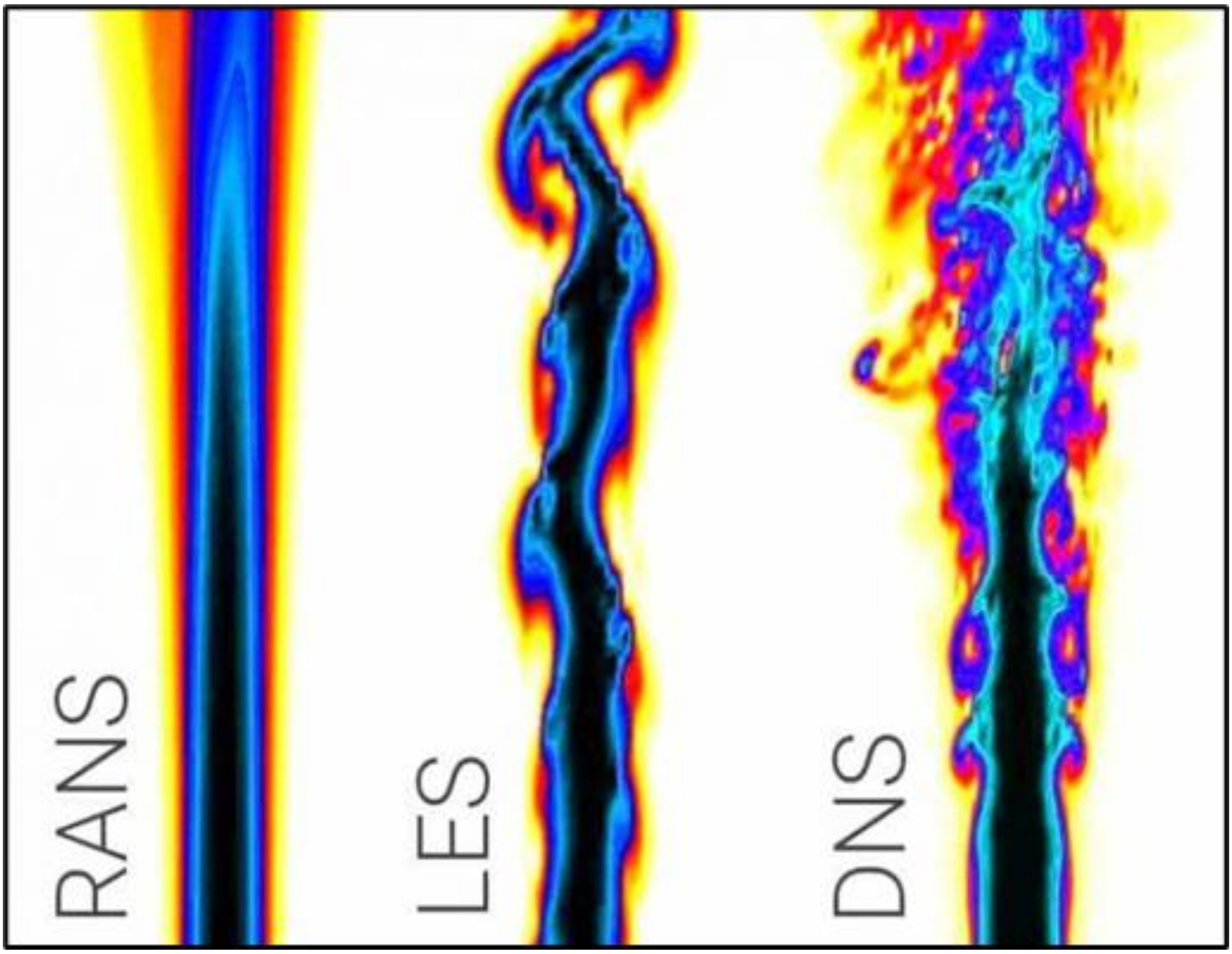


Figure 1. CFD Modelling of a Turbulent Jet using Different Turbulence Models (RANS, LES & DNS). LES was used in this CFD Gas Dispersion Simulation Study for HS' New AD Plant.

# 6 Released Gas Composition, Operational Temperatures & Release Cases Used in this Study

In this section, ADH Risk describes the (a) release gas composition, (b) release gas operational temperatures, and (c) Release Cases including Locations & Orientations, which were used in the CFD gas dispersion simulations for HS' New AD Plant.

## 6.1 Biogas - Release Gas Composition

In this study, only a single biogas composition was used, as discussed and agreed with FRE-Energy, who have designed HS' New AD Plant. The single biogas composition which has been used in the CFD gas dispersion simulation study for HS' New AD Plant can be seen in Table 1. From ADH Risk's analysis conducted, the Lower Explosive Limit (LEL) in Air (Vol%) for the Biogas Composition presented in Table 1 has been calculated to be 5.99%, based on BAMs Schroeder's Methods [2]. This calculated Upper Explosive Limit (UEL) in Air (Vol%) and the associated Molecular Weight (MW) of the Biogas Composition from Table 1 have been calculated to be 23.16% and 23.31 g/mol, respectively. The biogas composition gas group was calculated to be IIA, based on the MESG estimation using IEC / ISO 80079-20-1: 2019 [3], whereas the worst case temperature class derived from the small amount of Hydrogen Sulphide ($H_2S$) that has a Auto-Ignition Temperature of 260°C, is T3, which is believed to be conservative.

Table 1. Biogas Composition for CFD Gas Dispersion Simulations for HS' New AD Plant.

| Biogas Component: | Composition (PPM): | Composition (Vol%): |
|---|---|---|
| Methane ($CH_4$) | 740,000 | 74.00 |
| Carbon Dioxide ($CO_2$) | 259,800 | 25.98 |
| Hydrogen Sulphide ($H_2S$) | 200 | 0.02 |
| **Total:** | **1,000,000** | **100** |

## 6.2 Biogas Operational Temperatures

The operational temperature for the biogas varies depending on the ambient temperature. Therefore, a minimum and maximum operational temperature have been stipulated by FRE-Energy corresponding to the Winter and Summer Periods, which are highted in Table 2. The operational minimum (i.e. Winter) and maximum (i.e. Summer) temperatures were coupled with the ambient minimum (i.e. Winter) and maximum (i.e. Summer) temperatures as discussed later in Section 8.1.

Table 2. Biogas Operational Temperatures Used in the CFD Gas Dispersion Simulations for NS' New AD Plant.

| Seasonal Condition: | Operational Temperature (°C): |
|---|---|
| Summer | 35 |
| Winter | 10 |

## 6.3 Release Cases Used in the CFD Gas Dispersion Modelling

In this section, the release cases used in HS' New AD Plant CFD gas dispersion modelling have been presented and discussed. The following list of release cases including their release descriptions, locations, orientations, overpressure (i.e. backing pressures), and the equivalent release hole size and associated areas, if applicable, based on communications with FRE-Energy and PDA, can be seen in Table 3. A schematic plan of the HS' New AD Plant in the CFD code's computational domain, with the annotated positions of the four (4) release points used in the CFD Gas Dispersion Modelling can be seen in Figure 2.

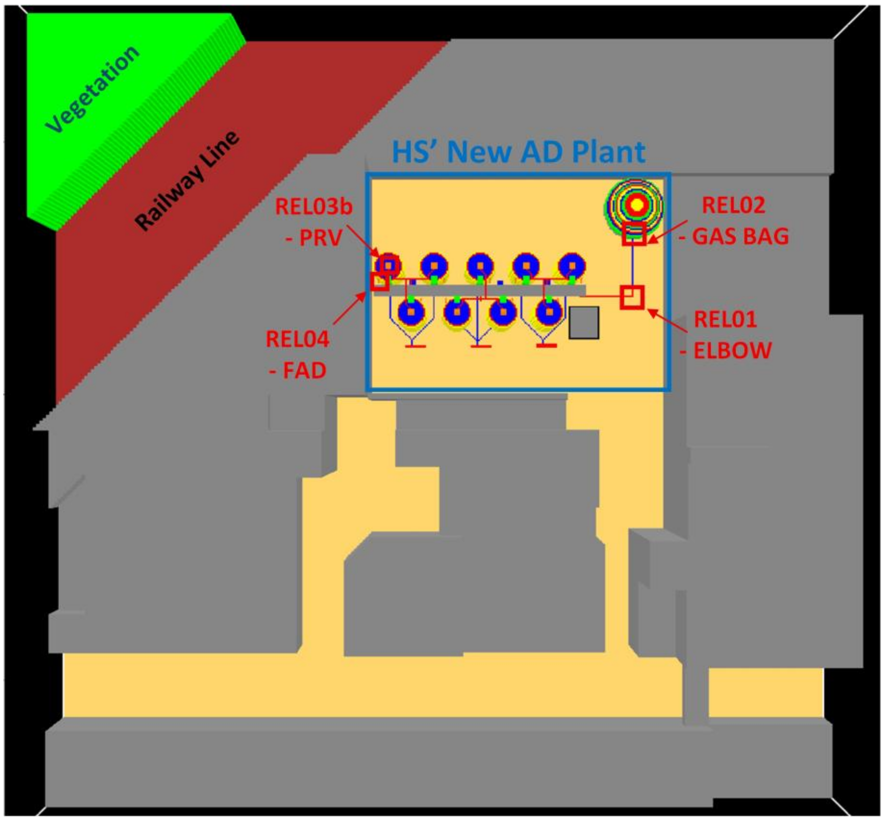


Figure 2. A Schematic Plan of HS' New AD Plant in CFD Computational Space with Annotated Release Point Locations.

Table 3. Release Cases Used in the CFD Gas Dispersion Modelling for HS' New AD Plant.

| Release Case ID: | Release Description: | Release Location & Orientation Description: | Release Over-Pressure, Equiv. Release Hole Diameter and Area. |
|---|---|---|---|
| REL01 (Gas Bag Elbow (GBE)) | (a) Flexible Hose Coupling Release emulating a guillotine failure at the corner of the interconnecting pipework feeding the gas bag.<br>(b) Release assumed to be 15mm diameter hole. | (a) Hole located at flexible hose coupling, at height of release is approximately 0.6 to 0.8m above ground / grade level.<br>(b) Release is horizontal in nature. | 6.0 mbar(g)<br>$1.50 \times 10^{-2}$ m<br>$1.77 \times 10^{-4}$ m$^2$ |
| REL02 (Gas Bag Leak (GBL)) | (a) Hole in Gas Bag due to FLT fork penetration.<br>(b) Release assumed to be equivalent to largest single FLT fork dimensions (assumed to be 150mm x 75mm) [4] | (a) Hole located at max. horizontal diameter of the Gas Bag just above the interconnecting pipework.<br>(b) Height of release is approx. 2.4 to 2.6m above ground / grade.<br>(c) Release is horizontal in nature. | 6.0 mbar(g)<br>$1.20 \times 10^{-1}$ m<br>$1.13 \times 10^{-2}$ m$^2$ |
| REL03b (Pressure Relief Valve (PRV)) | (a) Single PRV will be investigated, which is closest to the Railway Line (South East (SE) Corner of the AD Plant).<br>(b) PRV has release area of 81.08cm$^2$ from PRV spec. sheet & equiv. biogas flow rate of 180 Nm$^3$/hr (Stipulated by FRE-Energy). | (a) As the PRV is on the top and centre of the AD tank with weather cowling, the flow will be pointed directly downwards. | ~0.2 mbar(g) (Equivalent backing pressure to obtain 180 Nm$^3$/hr)<br>$1.02 \times 10^{-1}$ m<br>$8.11 \times 10^{-3}$ m$^2$ |
| REL04 (Foam Alleviation Device (FAD)) | (a) Single Tank FAD, which is closest to Railway Line (South East (SE) Corner of the AD Plant).<br>(b) Equivalent to 8" diameter hole (Stipulated by FRE- Energy). | (a) The FAD is located close to tank walkway, and has horizontal orientated discharge, which impinges the nearest building surface. | 10.0 mbar(g)<br>$2.03 \times 10^{-1}$ m<br>$3.24 \times 10^{-2}$ m$^2$ |

# 7 Gas Concentrations of Interest

In this section, the gas concentrations of interest for the flammable, toxic and asphyxiant components of the biogas modelled in the CFD Gas Dispersion Simulations for HS' New AD Plant have been presented in Table 4. Also provided in Table 4, are the main reasons behind the concentrations of interest used in the CFD Gas Dispersion Modelling of HS' New AD Plant. Please note that although flammable concentrations for typical personal gas monitoring alarms have been recorded (20% & 10% LEL), they have not been reported, presented or discussed in this report presented herein.

Table 4. Flammable, Toxic and Asphyxiant Gas Concentrations of Interest for HS' New AD Plant CFD Gas Dispersion Modelling.

| Biogas Component: | Concentration to be Investigated: | Notes / Reason: |
|---|---|---|
| Flammability - Methane, $CH_4$ & Hydrogen Sulphide, $H_2S$. | 100 % LEL (5.99% in Air). | Useful for DSEAR / ATEX Hazardous Area Classification (HAC). |
| | 50 % LEL (2.99% in Air). | |
| Toxicity - Hydrogen Sulphide, $H_2S$. | 10 ppm. | Workplace Exposure Limit (WEL), Short-Term Exposure Limit (15 minute reference period) [5]. |
| | 5 ppm. | WEL, Long Term Exposure Limit (8-hour TWA reference period) [6]. |
| Toxicity - Carbon Dioxide, $CO_2$ | 15,000 ppm. | Workplace Exposure Limit (WEL), Short-Term Exposure Limit (15 minute reference period) [6]. |
| | 5,000 ppm. | WEL, Long Term Exposure Limit (8-hour TWA reference period) [6]. |
| Asphyxiant – Reduction of Oxygen, $O_2$. | 14.0% $O_2$. | Effects: Respiration increases in rate and depth, poor judgement, faulty coordination, abnormal fatigue upon exertion, emotionally upset, blue lips. Reduced physical & intellectual performance without person's knowledge. Decision-making is compromised [7,8,9]. |
| | 8.0% $O_2$. | Effects: Onset of Fatality (< 5 mins) [10]. |

# 8 Weather & Initial Conditions Used in the CFD Simulations

In this section, ADH Risk describes the weather conditions used in the CFD Gas Dispersions Simulations for HS' New AD Plant, which includes (a) ambient temperature range, (b) wind direction, (c) wind speed and atmospheric stability, as well as (d) initial modelling conditions.

## 8.1 Ambient Temperature Range

The Met Office temperature data presented on Bradford's Wikipedia page [11] has been taken from Lister Park and goes back historically to 1908. This data provides a record high temperature of 37.9 °C (July 2022). From the same data source, in an 'average year', the warmest day should attain a temperature of 27.5 °C, with a maximum six (6) days rising to a maximum of 25.1 °C or above. This is similar to average hottest day temperature provided by the Meteoblue Website [12] for Bradford which records a value of 26 °C over the last 30 years. Therefore, ADH Risk has used a maximum summer temperature of 30.0 °C in the CFD gas dispersion simulations conducted, to encapsulate the publicly available information obtained from the Wikipedia [11] and Meteoblue [12] websites

The Met Office temperature data presented by Bradford's Wikipedia page [11] provides a record low temperature of -13.9 °C (January 1940), and a mean daily minimum temperature of 1.8 °C (shared between January and February) for the Lister Park location since 1908. However, the Meteoblue website, provides an average temperature of the coldest night of being -3 °C. Therefore, ADH Risk has used a minimum winter temperature of -5 °C in the CFD gas dispersion simulations conducted, to encapsulate the publicly available information obtained from the Wikipedia [11] and Meteoblue [12] websites.

To summarise, please find presented in Table 5, the ambient temperatures used by ADH Risk for both Summer and Winter conditions for the CFD Gas Dispersion Simulations for HS' new AD plant location.

Table 5. Ambient Temperature Used in the CFD Gas Dispersion Simulations for HS' New AD Plant.

| Seasonal Conditions: | Ambient Temperature (°C): |
|---|---|
| Summer | 30 |
| Winter | -5 |

## 8.2 Wind Directions

The most prevalent wind directions for Bradford are provided by Meteoblue [12], and can be seen in the wind rose shown in Figure 3(a). From Figure 3(a), it can be seen that the wind originating from West-South-West (WSW) is the most prevalent wind direction with over 1250 hours per year, with West (W) and South-West (SW) with > 1000 hours per year each being in second and third places, respectively.

Channelling (also known as Venturi) effect can happen when buildings are located in close proximity to one another. This effect is perpetuated by a reduction of wind pressure, resulting in wind acceleration through the tight channels created between the buildings in question. From communications with HS personnel, it is understood that a significant channelling effect occurs in the alleyway highted by the red arrows coming off the main through road on the HS site as shown in the aerial photograph (courtesy of google maps) in Figure 3(b). This identified channelling effect comes from an approx. direction of North-North-East (NNE) on the corresponding wind rose.

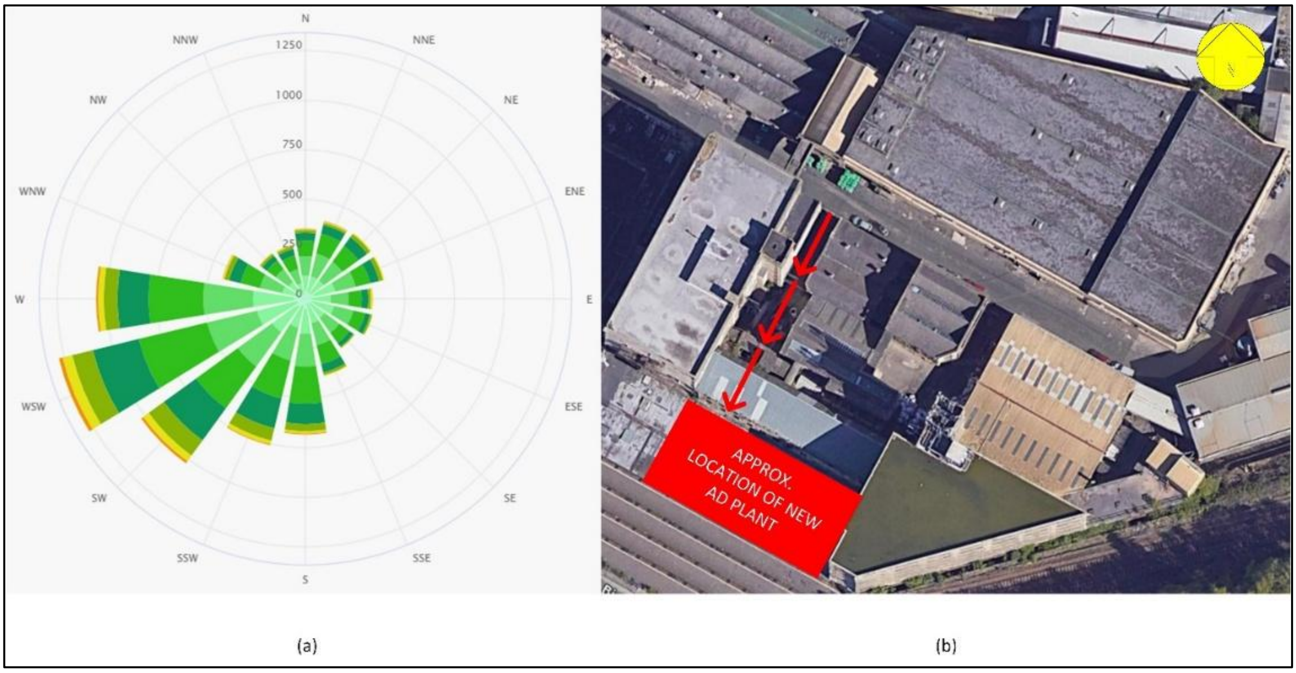


Figure 3. Wind Rose & Annotated Aerial Photo Showing Channelling for HS' New AD Plant.

Therefore, ADH Risk has used the above two (2) suggested wind directions in the CFD Gas Dispersion simulations for HS New AD Plant which are highlighted in Table 6. However, as it is unknown whether these two (2) macro wind directions are the worst case directions for the HS' new AD plant releases on site, ADH Risk has also added an additional eight (8) compass wind directions to this list as shown in Table 6. The CFD gas simulations code was written to setup up an initial steady-state gas cloud (by calculating the flammable mass and identifying the time it takes the flammable mass to plateau), and then rotate the cloud through the eight (8) identified compass wind directions, as well as the prevailing and channelling wind direction discussed and shown in Table 6 to provide a more conservative result with respect to the worst case wind direction.

Table 6. Wind Direction for CFD Gas Dispersion Simulations on HS' Site in Bradford, West Yorks.

| Wind Direction ID.: | Compass Wind Degrees (North = 0 degrees) | Compass Wind Direction: | CFD Model Wind Direction with respect to HS Model: | Notes / Reasons: |
|---|---|---|---|---|
| 1 | 247.5 | West-South-West (WSW) | 39.5 | 1. Prevalent Wind Direction for Bradford. |
| 2 | 28.0 | North-North-East (NNE) | 180.0 | 2. Local Channelling Effect Experienced on HS Site. |
| 3 | 45.0 | North-East (NE) | 197.0 | 3. Compass Direction. |
| 4 | 90.0 | East (E) | 242.0 | 3. Compass Direction. |
| 5 | 135.0 | South-East (SE) | 287.0 | 3. Compass Direction. |
| 6 | 180.0 | South (S) | 332.0 | 3. Compass Direction. |
| 7 | 225.0 | South-West (SW) | 17.0 | 3. Compass Direction. |
| 8 | 270.0 | West (W) | 62.0 | 3. Compass Direction. |
| 9 | 315.0 | North-West (NW) | 107.0 | 3. Compass Direction. |
| 10 | 360.0 | North (N) | 152.0 | 3. Compass Direction. |

## 8.3 Windspeed & Atmospheric Stability Pairs

ADH Risk has used Monin-Obukhov Similarity Theory (MOST) to predict vertical wind an temperature profiles based on surface and atmospheric conditions in the CFD Gas Dispersion Simulations for HS' New AD Plant. MOST can be interlinked with the Pasquill atmospheric stability class, which one of the most popular and used ways of defining atmospheric stability (or instability) when conducting gas dispersion projects. Atmospheric stability is defined in terms of tendency of a parcel of air to move upwards or downwards after has been displaced vertically by a small amount.

Essentially, unstable atmospheres of Stability Class A tend to develop vertical updrafts which increase boundary layer turbulence intensity. Stable atmospheres, such as those of Stability Class F, tend to suppress vertical updrafts and reduce turbulence intensity. More information concerning Pasquill atmospheric stability classes can be found in Woodward [13].

ADH Risk has incorporated two (2) typically used wind speed and Pasquill atmospheric stability class pairs, which would be expected by the UK's Competent Authority (i.e. Health and Safety Executive (HSE) and Environment Agency (EA)) for gas dispersion modelling on COMAH Regulated sites[1]. In addition, ADH Risk has used a third pair with a windspeed of 0 m/s and a Pasquill atmospheric stability class of G (Extremely stable conditions) to represent an extremely still atmosphere with no wind / movement. The suggested three (3) windspeed and Pasquill atmospheric stability pairs, their correlated Obukhov lengths, and the main reason they have been used can be found in Table 7, for the CFD Gas Dispersion Simulations for HS' New AD Plant.

Table 7. Windspeed & Atmospheric Stability Pairs for CFD Gas Dispersion Simulations of HS' New AD Plant.

| Wind Case ID:. | Wind Speed (m/s)[2] & Pasquil (Atmospheric) Stability Class: | Suggested & Conservative Obukhov Length, L (m): | Main Reasons: |
|---|---|---|---|
| 1 | 0-G | 0 | (a) Extremely stable conditions, with no wind. |
| 2 | 2-F | 350 | (a) Moderately Stable Conditions.<br>(b) CA / COMAH Modelling Condition. |
| 3 | 5-D | 1,000,000 | (a) Neutrally Stable Conditions.<br>(b) CA / COMAH Modelling Condition. |

[1] COMAH – Control of Major Accident Hazards Regulations, which are equivalent to SEVESO sites and legislation in EU. Although the new AD Plant is not classed as a COMAH site in the UK, ADH Risk believe it would be wise to follow the same expectation by the Competent Authority (CA) bodies.

[2] NOTE: Windspeed follows a logarithmic wind profile with height, where the windspeed quoted is at a reference height of 10m above ground.

## 8.4 Initial Modelling Conditions

The following initial modelling conditions with respect to atmospheric pressure, humidity, and initial gas volume within the computational domain prior to running the CFD Gas Dispersions Simulation for HS' New AD Plant, have been used:

- Atmospheric Pressure: 101,325 Pa (Default).
- Humidity: 40% (Default).
- Initial Gas Volume external to the new AD Plant: Air Only (Default at T=0 seconds).

# 9 Result & Discussions

In this section, the results have been presented and discussed for the CFD Gas Dispersion Simulations for HS' new AD plant. From this study, an extensive amount of CFD simulation data has been post-processed including its review, measurements and analysis (nearly 2TB) which has taken significantly more time than originally envisaged to conduct. However, the following results have been compiled to provide HS with an understanding of the simulations conducted and any issues associated with the gas dispersion of the flammable, toxic and asphyxiant hazard extents and their impact on the local railway line which is located adjacently and South-East (SE) of HS' site in Bradford, as shown computationally in Figure 2 and in aerial photography via google maps in Figure 3(b) earlier in this report.

In order to make the results easier to understand as well as represent them in a logical manner, ADH Risk has presented these results in two (2) subsections. The first subsection reviews the results from a concentration extent measurement perspective, to determine which releases analysed as part of the CFD gas dispersion simulation study produce flammable, toxic and asphyxiant hazard extents which Exceed Site Boundary (ESB) and impact the railway line which is located adjacently and South-East (SE) of HS' site in Bradford. The second subsection reviews the releases analysed, and reports on the measured persistence times of any clouds (plumes or puffs, or potentially a mixture of both) which ESB and impact the railway line in question.

In this context, it is important to discuss the difference between plumes and puffs with respect to gas dispersion and how the CFD simulation software models both characteristics. Ideally, plumes are associated with continuous releases and represent a stead-state situation, which is usually derived through a time-averaged approach. Puffs are typically associated with discrete releases of a single, finite volume of gas released at a specific moment, and hence tend to be more time-varying in nature. However, as the CFD gas dispersion simulations do not use a time-averaged approach, typically at the end of the gas plume regime, and given the perturbation in the wind modelling technique used in the CFD software, small pockets i.e. puffs, are formed which travel across the railway line in question in a limited number of concentration cases only.

The main bulk concentration extent analysis for the CFD gas dispersion simulation results have been taken from an aerial plan view perspective (z-direction, looking downwards) of the computational model of HS' site in order to measure the maximum horizontal extent for each gas concentration of interest. Given the way that that HS' site model has been displayed in the CFD software (i.e. FDS using SmokeView (software for postprocessing the CFD results)), does not provide a parallel orthographic view, but more like 3-point graphical perspective projection. This means that the comparative distance between a release point and the railway site boundary can vary depending at what height is referenced as shown schematically in Figure 4. In order to provide context in the next section, the maximum horizontal extent of each flammable, toxic and asphyxiant hazard concentration measurements reference distances to low (i.e. low level wall) and high level railway targets (i.e. adjacent tall building) in order to understand whether the simulated gas cloud crosses the HS' site boundary (i.e. ESB) and impacts the railway line.

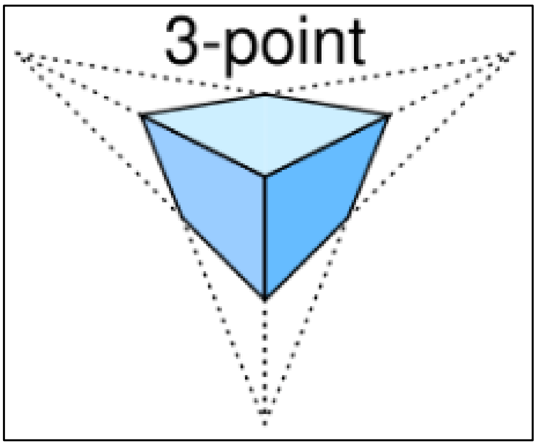


Figure 4. Three (3) Point Graphical Perspective Projection.

## 9.1 Initial Concentration Extent Measurements – REL01, 02, 03b & 04.

In this section, ADH Risk presents and reviews the results from an initial (i.e. screening) concentration extent measurement perspective, to determine which releases, as analysed as part of the CFD gas dispersion simulation study produce flammable, toxic and asphyxiant hazard extents which Exceed Site Boundary (ESB) and impact the railway line which is located adjacently South-East (SE) of HS' site in Bradford.

The maximum horizontal extents measured in any direction for summer & winter operational-ambient temperature pairs, measured from the point of discharge for release cases REL01 (Gas Bag Elbow (GBE)), REL02 (Gas Bag Leak (GBL)), REL03b (Pressure Relief Valve (PRV)) and REL04 (Foam Alleviation Device (FAD)) can be seen in Figure 5, Figure 6, Figure 7 and Figure 8, respectively for flammable, toxic and asphyxiant hazard concentrations of interest. Please note that maximum horizontal extents measured in any direction for the flammable, toxic and asphyxiant hazard concentrations of interest as shown in Figure 5, Figure 6, Figure 7 and Figure 8, incorporate and consolidate the CFD results across each of the three (3) windspeeds and atmospheric stability pairs (i.e. 0-G, 2-F & 5-D), as well as all ten (10) of the wind directions modelled.

It can also be seen in Figure 5, Figure 6, Figure 7 and Figure 8 that as well as the measured maximum horizontal extent results to a range of flammable, toxic and asphyxiant hazard concentrations, the distance to the railway line at the edge of HS' site boundary, either in the main direction of the propagating gas cloud or "as the crow flies" (i.e. the most direct path) is presented. The latter, specifically for release cases REL03b and REL04, shown respectively in Figure 7 and Figure 8, two (2) different comparative "as the crow flies" distances are presented and depends if the railway-site boundary is taken from the low level wall or the adjacent tall building given the 3-point graphical perspective project of the CFD model of HS' site when undertaking the maximum horizontal concentration extent measurements as discussed earlier.

The maximum horizontal extent results to a range of flammable, toxic and asphyxiant concentrations as shown in Figure 5, Figure 6 and Figure 7 representing the release cases REL01 (Gas Bag Elbow (GBE)), REL02 (Gas Bag Leak (GBL)), REL03b (Pressure Relief Valve (PRV)), keep inside HS' site boundary and do not touch or impact the adjacent railway line which is SE of HS site in Bradford. Due to the fact that release cases REL01 (Gas Bag Elbow (GBE)), REL02 (Gas Bag Leak (GBL)), REL03b (Pressure Relief Valve (PRV)) provide maximum horizontal extent results which do not touch or impact the adjacent railway line which is SE of HS' site in Bradford, they will not be reported further in this report and should be considered on-site hazards only.

However, the maximum horizontal extent results to a range of flammable, toxic and asphyxiant concentrations as shown in Figure 8 representing the release case REL04 (Foam Alleviation Device (FAD)), initially indicate all exceed HS' site boundary and have the potential to impact the adjacent railway line which is SE of HS' site in Bradford, except for asphyxiation by oxygen depletion (i.e. 8 & 14% $O_2$). Due to this, a more in-depth analysis of the extents associated with both flammable and toxic concentrations, including their over-boundary persistence times and gas cloud elevations associated with release case REL04 (FAD) will be discussed and presented in the next section.

It is important to note that the typical personal gas monitor alarm flammable concentrations (i.e. 10% & 20% LEL) have not been reported, presented or discussed herein (or the Interim Letter Report issued in February 2025) as they do exceed HS' site boundary and impact the adjacent railway line SE of HS' site in Bradford, but are not deemed flammable in nature, whereas 100% LEL and 50% LEL, which are used in Hazardous Area Classification (HAC) studies are reported.

Please note that the Summer and Winter operational-ambient temperature pairs are presented separately in Figure 5, Figure 6 Figure 7 and Figure 8, but also include the consolidated results from the three (3) windspeed-atmospheric pairs, and all ten (10) wind directions modelled and investigated.

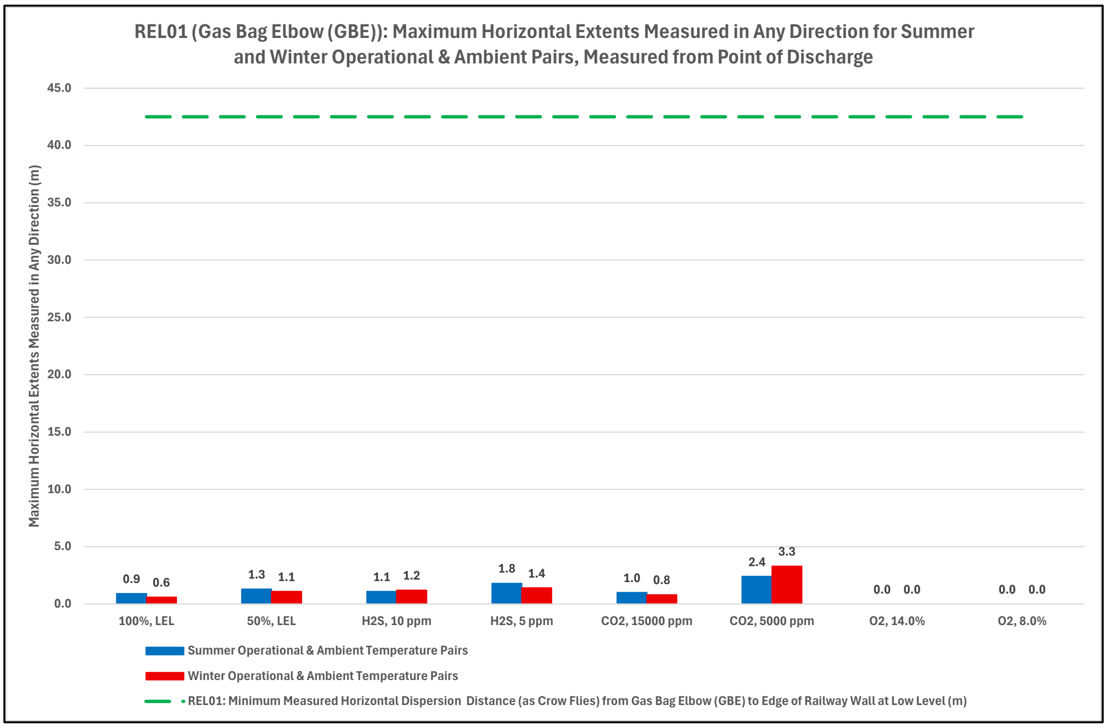


Figure 5. Max Horizontal Extents Measured in Any Direction for Summer & Winter Operational-Ambient Temperature Pairs, Measured from Point of Discharge for REL01 (Gas Bag Elbow (GBE)) Release.

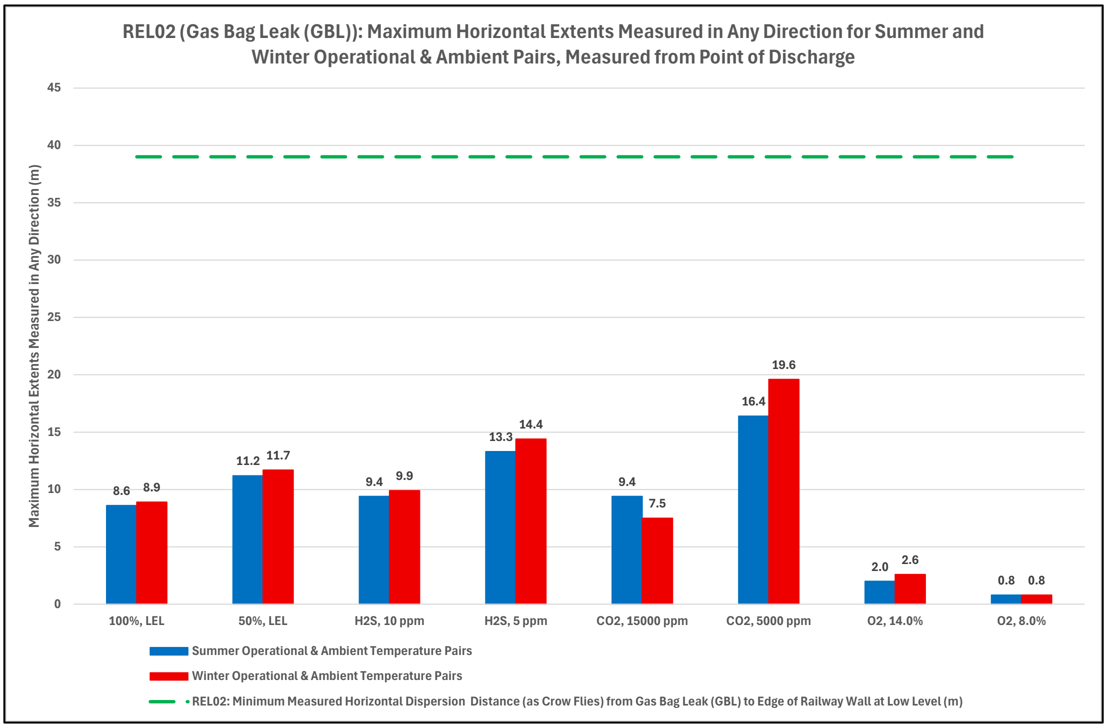


Figure 6. Max Horizontal Extents Measured in Any Direction for Summer & Winter Operational-Ambient Temperature Pairs, Measured from Point of Discharge for REL2 (Gas Bag Leak (GBL)) Release.

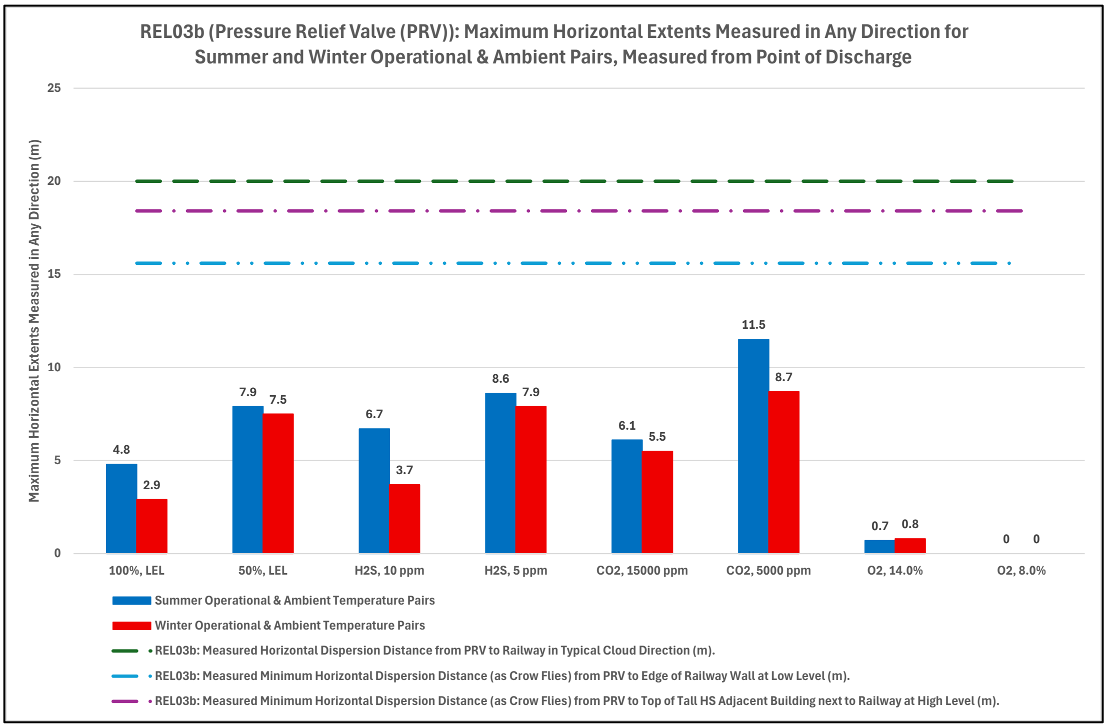


Figure 7. Max Horizontal Extents Measured in Any Direction for Summer & Winter Operational-Ambient Temperature Pairs, Measured from Point of Discharge for REL3b (Pressure Relief Valve (PRV)) Release.

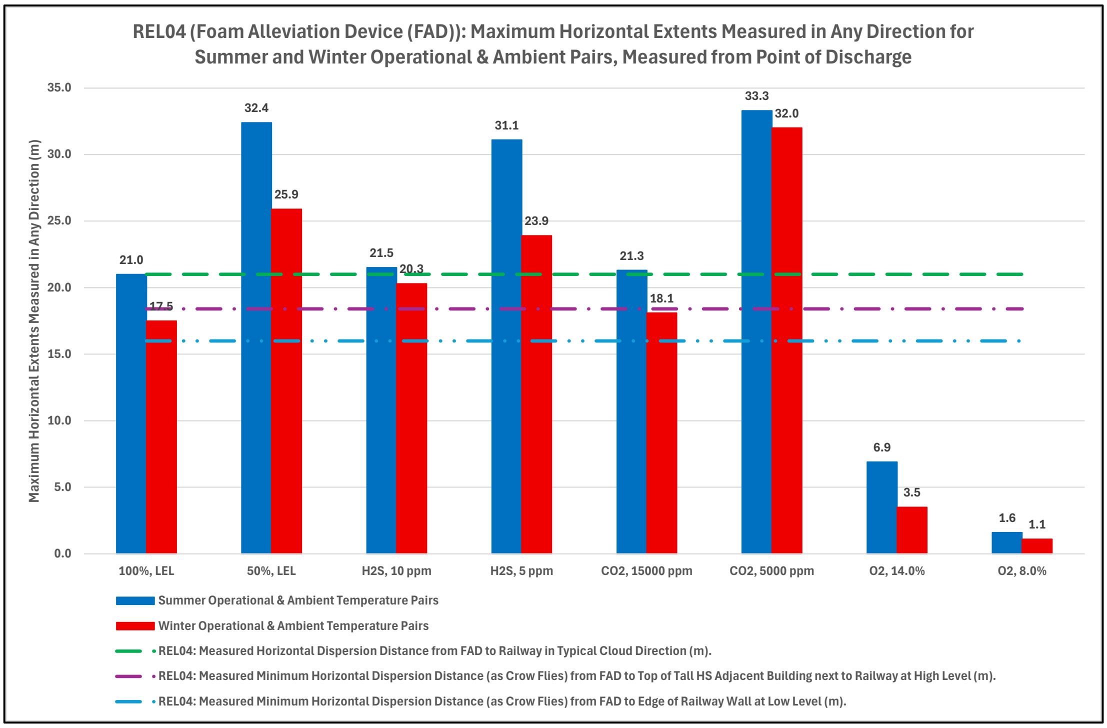


Figure 8. Max Horizontal Extents Measured in Any Direction for Summer & Winter Operational-Ambient Temperature Pairs, Measured from Point of Discharge for REL4 (Foam Alleviation Device (FAD) Release.

## 9.2 In-depth Analysis of Release Case REL04

From the initial (i.e. screening) flammable, toxic and asphyxiant maximum horizontal concentration extent measurement results, presented in the previous section for the release case REL04 (Foam Alleviation Device (FAD)) in Figure 8, it is shown that potentially all of the measured clouds for this release case exceed HS' site boundary and may impact the adjacent railway line, except for asphyxiation by oxygen depletion (i.e. 8 & 14% $O_2$) cases.

However, there maybe inaccuracies/variances in these measurements due to the 3-point graphical perspective project of the CFD model of HS' site when undertaking the maximum horizontal concentration extent measurements as discussed earlier. Due to this, ADH Risk has conducted a more in-depth analysis in order to determine which flammable, toxic and asphyxiant cloud concentrations associated with the release case REL04 (FAD) actually exceed the railway-site boundary by reviewing the side elevation cloud measurements in the plane of the railway-site boundary.

Therefore, if any of the flammable, toxic and asphyxiant cloud concentrations exceed this boundary, an estimated measurement of its maximum horizontal extent from HS' railway-site boundary in the plane in question has been conducted. Also ADH Risk conducted an estimate of the persistence time any cloud concentration exceeds HS' railway-site boundary as well as the general originating wind direction which generated the cloud was recorded. The results of this in-depth analysis for the flammable, toxic and asphyxiant cloud concentrations associated with the largest mass flow release case, REL04 (FAD) on the AD tank nearest the railway line can be seen in Table 8, where they are separated for different windspeed-atmospheric stability pairs as well as Summer or Winter operational-ambient temperature pairs.

Also presented in Table 8 is a link to the associated screenshots for the flammable, toxic and asphyxiant cloud concentration cases which exceed the railway-site boundary from release case REL04, in the plane of the HS railway-site boundary in question. These are presented further in Figure 9 to Figure 19 showing the magnitude of the maximum cloud concentration extent exceeding the railway-site boundary as well as the height of these clouds over the railway channel. For clarity, where a flammable, toxic or asphyxiant cloud concentration for release case REL04 (FAD) has not exceeded the railway-site boundary, these have not been recorded nor the in plane screenshots presented.

As it can be seen from Table 8 for situation where there is no wind speed (i.e. 0 m/s) and a very stable atmosphere (i.e. G), the flow of material forming the gas cloud moves predominately upwards (as biogas is lighter than air) and the flammable, toxic and asphyxiant cloud concentration do not exceed the railway-site boundary, except for $CO_2$ at 5,000ppm momentarily (Duration ~ 0 seconds), by up to 1m (conservative) at a high level and does not impact the railway line, as can be seen in the associated screenshot in Figure 9.

For concentrations such as flammable biogas – 100% LEL, toxic – 10ppm of $H_2S$ and 15,000ppm of $CO_2$, which are immediate danger to life (toxics are based on a 15 minute exposure time), these gas cloud concentration extents do not extend across HS' railway-site boundary – even with 2F and 5D windspeed-atmospheric stability pair cases. Therefore, they remain within the HS' site boundary and have not been reported in Table 8.

However, the larger gas cloud extents representing the lower flammable concentration of 50% LEL, toxic – 5ppm of $H_2S$ and 5,000ppm of $CO_2$, do exceed the railway-site boundary on occasion, but there persistence time has been measured from the CFD results and is typically less than 60 seconds, as shown in Table 8. It can also be seen from Table 8, that the originating wind direction for all exceedances of the railway-site boundary are from North West (NW), North (N) and North East (NE), where the predominant originating wind direction in 9 out of the 11 exceedances is North (N). From Figure 3 showing the wind rose for Bradford, the hours the wind is blowing from the originating wind direction of North West (NW), North (N) and North East (NE) is approximately 1750 hours combined, which accounts for around 20% of the yearly duration[3].

It is important to note that for the long term WEL toxic concentrations clouds that exceed the HS' site boundary for both $H_2S$ and $CO_2$ components of biogas, persistence times impacting the railway of less than 60 seconds and in majority of cases much less than this have been calculated as per the CFD gas dispersion simulation results presented in Table 8. By comparing the toxic gas cloud's calculated persistence times of less than 60 seconds to the long term WEL Time-Weighted Average (TWA) [6] over 8 hours, it is ADH Risk's professional opinion that people travelling on a train passing HS' site would not experience any toxic effects from $H_2S$ or $CO_2$ in the biogas cloud released due to these exposure timescales. Please note that a scenario of a passenger train passing HS' site at the same time as a FAD release (e.g. REL04) when the wind is blowing from an originating direction between North West (NW) and North East (NE), could be described as a rare event[4]. A more likely, but still remote scenario would be people working on the railway track conducting maintenance for

[3] Please note that the wind rose in Figure 3 shows predominately wind direction and has not been reduced to individual windspeeds (colours in each bar). Time (hours) data has been collated for North West (NW), North North West (NNW), North (N), North North East (NNE) and North East (NE) and totals approx. 1750 hours.

[4] Please note that the any frequency or likelihood discussion in this report has not been calculated and this is a qualitative estimate only. The project work presented in this report is purely associated with CFD gas dispersion consequences and is not a semi-quantitative or fully quantitative risk assessment.

example. However, this could still be described as a rare event given the frequency of workers being on the railway line at the same time as a FAD release (e.g. REL04) and optimal wind direction occurring simultaneously. At worst, it is envisaged that anyone on the railway line working or traveling by train may smell the characteristic ‘rotten-egg’ odour associated with $H_2S$, which has a concentration threshold of around 0.008 to 0.1ppm according to online public references, and is significant less than the WEL (8 hour TWA) limit of 5ppm of $H_2S$ [6] used in this CFD gas dispersion study.

As it can be seen from the screenshots in Figure 9 to Figure 19, majority of the peak maximum concentration cloud extents, typically from the lower flammable concentration of 50% LEL, toxic – 5ppm of $H_2S$ and 5,000ppm of $CO_2$, exceed the boundary slightly and momentarily as the data collected and presented in Table 8 shows. However, in the larger peak maximum concentration cloud extent cases, such as 5,000pm $CO_2$ for a 2F – Summer windspeed, atmospheric stability and operational-ambient temperature pair case, the extent can be up to half of the width of the railway line channel. However, it is important to note that not only is the persistence time as discussed previously is less than 60 seconds, but the cloud, given the density buoyancy effect of biogas, extends upwards in height missing the main volume in the railway channel that would be normally occupied by a moving train. This is shown explicitly in the screenshot presented in Figure 12.

It was recommended in ADH Risk’s Interim Letter Report issued to HS in February 2025, that if HS would like to reduce all CFD gas dispersion concentration (flammable, toxic as well as asphyxiant) extents simulated in this study from release case REL04 (FAD), so they do not exceed HS’ railway-site boundary, HS and their partner FRE-Energy, should review the function and release direction of the FAD device on the AD tank nearest the railway line. The aim of such review of the FAD function and release direction was to make sure that the release from the FAD in question, does not impinge on the wall of the adjacent (tall) building where the cloud could spread in the boundary layer with little dispersive mixing creating larger extents.

From communications with FRE-Energy prior to finalising this report, ADH Risk understands that the FAD device on the AD tank nearest the railway line has been rotated in such a way that the discharge orientation is in the opposite direction away from the adjacent building and towards the gantry between the AD tanks. It is hoped that this design change has the effect of reducing specific flammable, toxic and asphyxiant cloud concentration extents and prevents the cloud in question exceeding HS’ railway-site boundary. However, with any design change, it is highly recommended that HS or their partner, FRE-Energy, undergoes a review through their Management of Change (MOC) procedure, not only to determine whether this change provides a reduction in flammable, toxic and asphyxiant cloud concentration extents from release case REL04 (FAD) and prevents these clouds exceeding HS' railway-site boundary, but does not impose any additional risks to people on or offsite. These recommendations maybe applicable to all FAD devices on HS' new AD plant design, and may include conducting additional CFD gas dispersion simulation runs, to verify that the design change has the desired effect, and does not impose any additional risks to people on or offsite.

Finally, it is important to note that from discussions with FRE-Energy, that for any of the FAD devices to activate, all the Pressure Relief Valves (PRVs) located on each and every AD tank due to their interconnected nature, which are set at a lower activation pressure (i.e. 6 mbar(g)) would need to fail, which could be deemed as an extremely rare event. The only exception is if a AD tank is isolated, there would only be a single isolated AD tank's PRV in operation, which is in a position to protect the AD tank before the FAD activates. However, the gas production rate, which would drive the discharge, would only be approx. 20% of the release rate used in the CFD gas dispersion simulations conducted according to FRE-Energy.

Table 8. Exceeded Site Boundary (ESB) CFD Results Data for REL04 (FAD) including Measured Max Horizontal Extent, Cloud Persistence Time & Originating Wind Direction to Obtain Cloud ESB.

| Windspeed-Atmospheric Stability Pairs & Seasonal Temperature: | Concentration of Interest: | Measured (Estimated) Maximum Horizontal Extent Exceeding HS' Site Boundary into Railway Line Space (m): | Estimated Persistence Time Between Start & End of Cloud Exceeding Site Boundary at Railway (Seconds): | General Originating Wind Direction for Cloud Exceeding Site Boundary at Railway: | Representative Figure in this Report |
|---|---|---|---|---|---|
| **0G - Summer** | $CO_2$, 5000 ppm | 0m to 1m | 0 | NE | Figure 9 |
| **2F - Summer** | 50%, LEL | 8m to 10m | 13.8 | N | Figure 10 |
| | $H_2S$, 5 ppm | 5m to 6m | 20.8 | N | Figure 11 |
| | $CO_2$, 5000 ppm | 9m to 12m | 52.9 | N to NW | Figure 12 |
| **5D - Summer** | 50%, LEL | 1m to 2m | 5.1 | N | Figure 13 |
| | $H_2S$, 5 ppm | 4m to 5m | 1.9 | N | Figure 14 |
| | $CO_2$, 5000 ppm | 5m to 6m | 9.4 | N | Figure 15 |
| **0G - Winter** | Does Not Exceed Site Boundary (DNESB) for All Concentrations. | | | | |
| **2F - Winter** | $H_2S$, 5 ppm | 2m to 3m | 3.2 | N | Figure 16 |
| | $CO_2$, 5000 ppm | 6m to 8m | 7.5 | N | Figure 17 |
| **5D - Winter** | 50%, LEL | 2m to 3m | 0 | N | Figure 18 |
| | $CO_2$, 5000 ppm | 2m to 3m | 1.3 | N | Figure 19 |

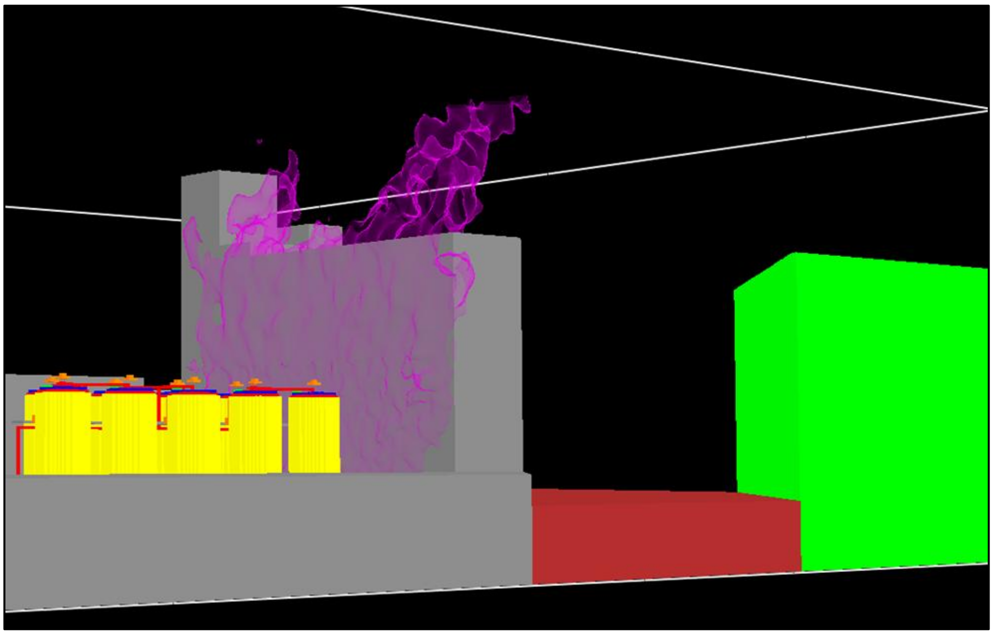

Figure 9. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for $CO_2$ at 5,000 ppm with 0-G Windspeed-Atmospheric Stability & Summer Temp Conditions (CFD Case: HS13).

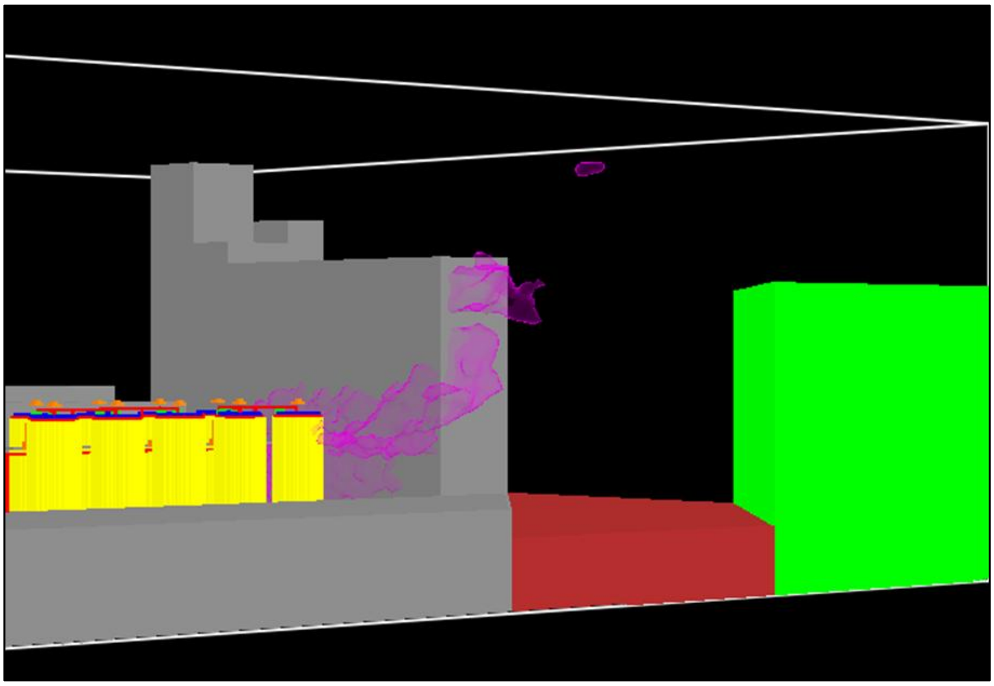

Figure 10. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for 50% LEL with 2-F Windspeed-Atmospheric Stability & Summer Temp Conditions (CFD Case: HS09).

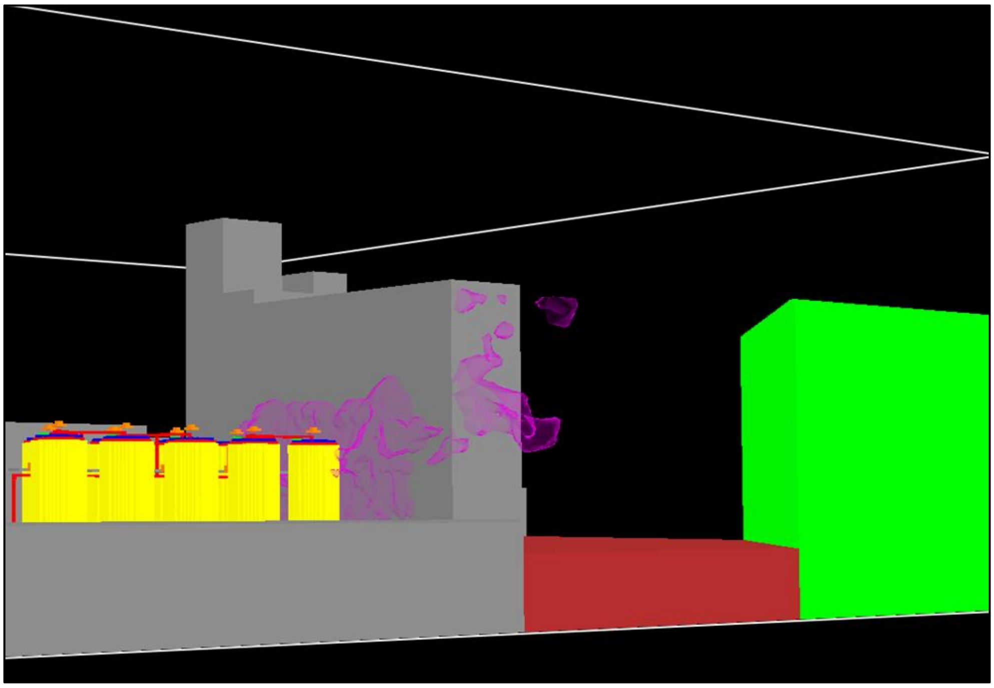

Figure 11. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for 5ppm of $H_2S$ with 2-F Windspeed-Atmospheric Stability & Summer Temp Conditions (CFD Case: HS09).

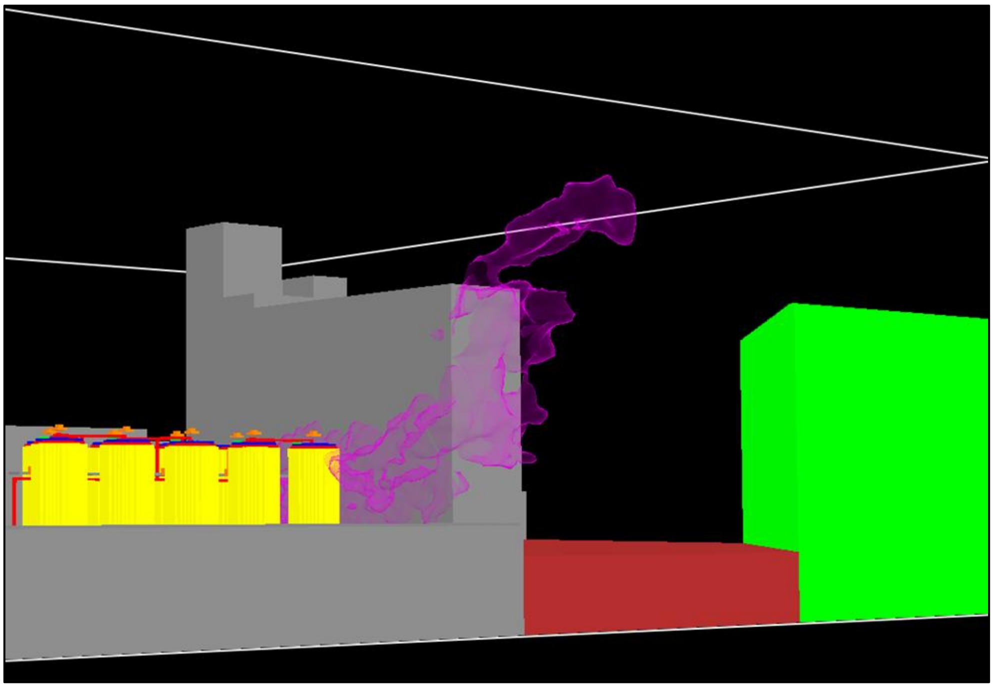

Figure 12. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for $CO_2$ at 5,000 ppm with 2-F Windspeed-Atmospheric Stability & Summer Temp Conditions (CFD Case: HS09).

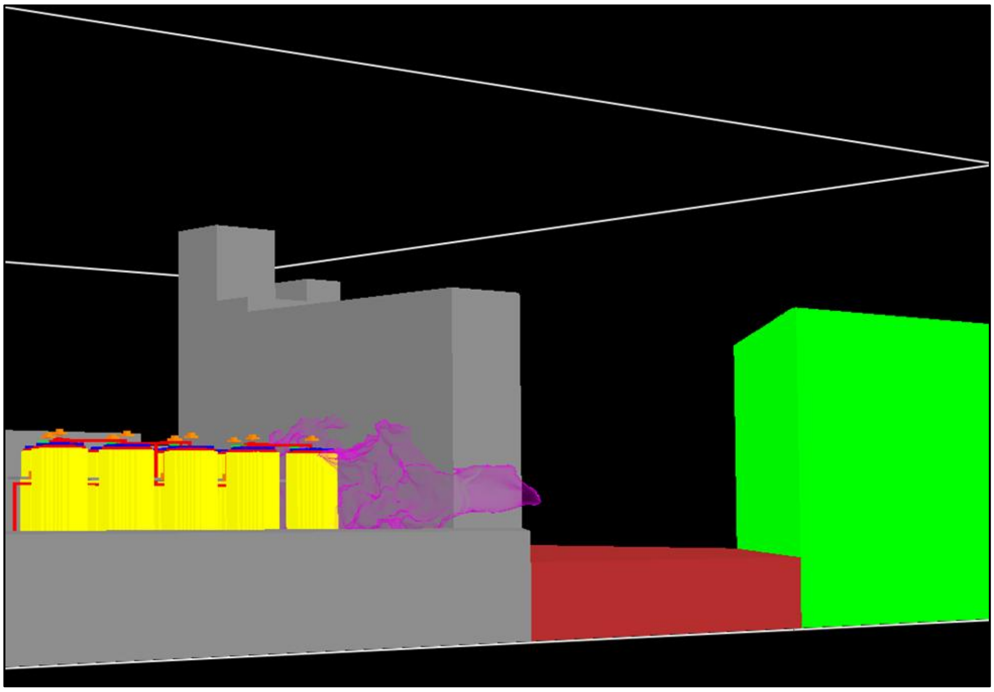

Figure 13. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for 50% LEL with 5-D Windspeed-Atmospheric Stability & Summer Temp Conditions (CFD Case: HS14).

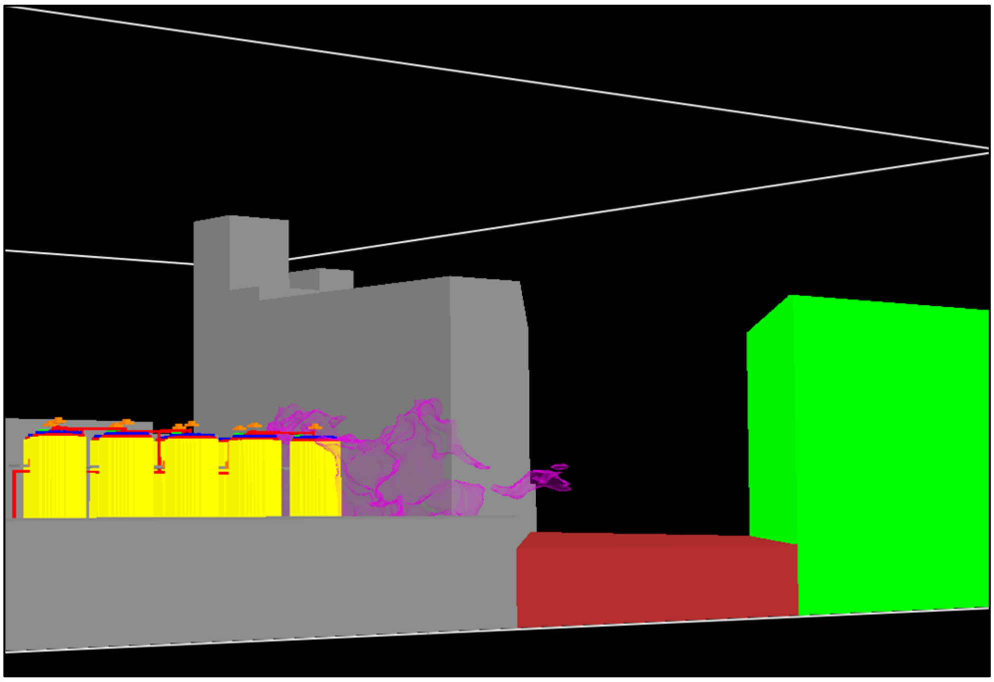

Figure 14. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for 5ppm of $H_2S$ with 5-D Windspeed-Atmospheric Stability & Summer Temp Conditions (CFD Case: HS14).

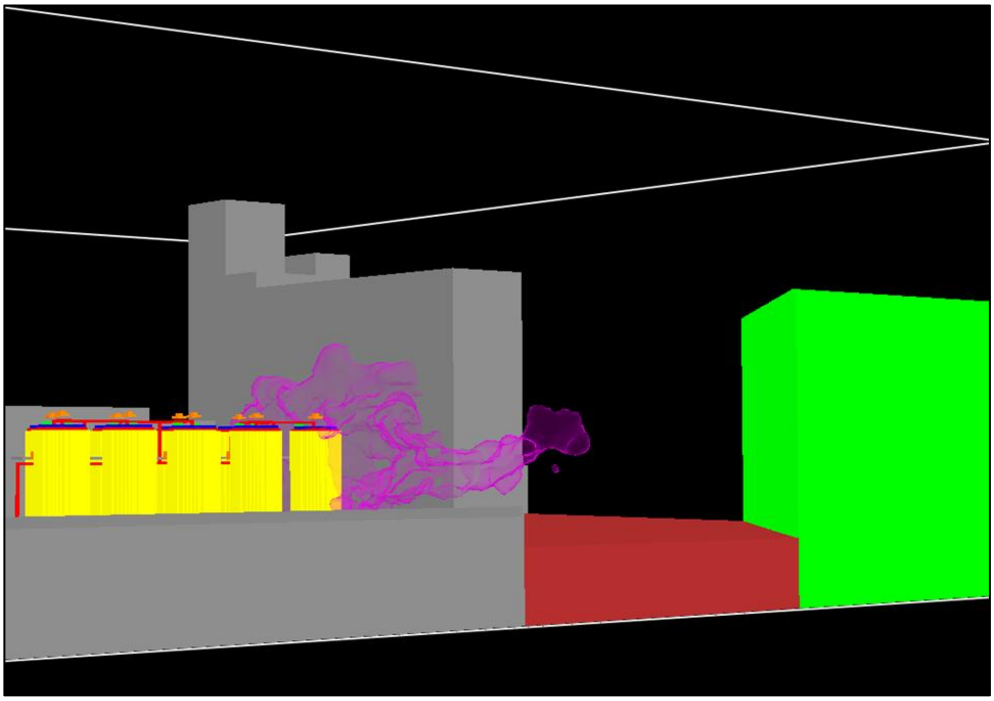

Figure 15. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for $CO_2$ at 5,000 ppm with 5-D Windspeed-Atmospheric Stability & Summer Temp Conditions (CFD Case: HS14).

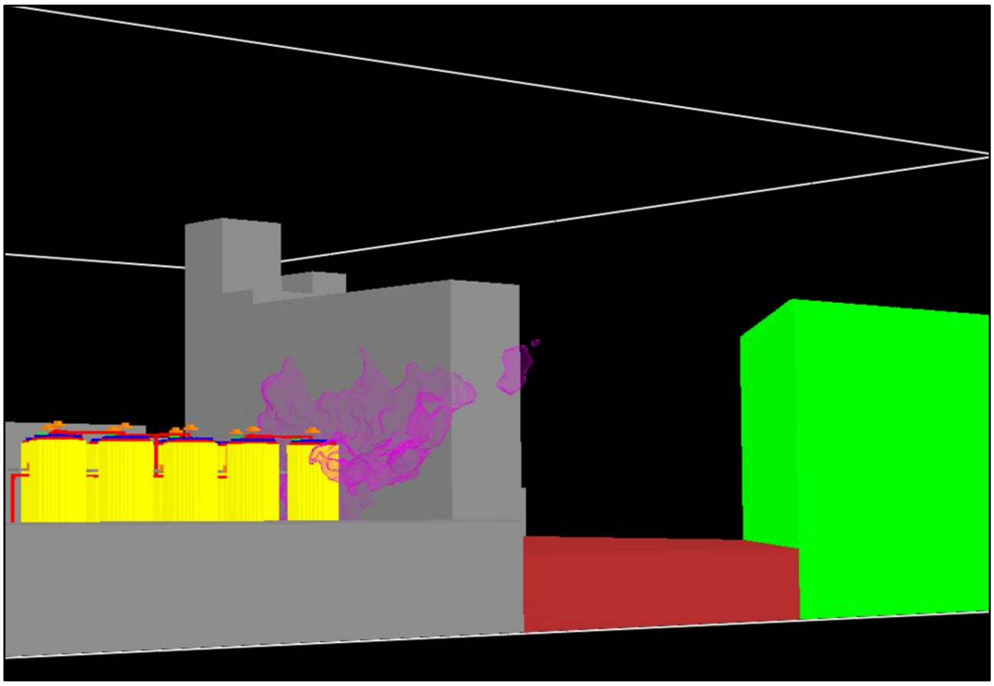

Figure 16. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for 5ppm of $H_2S$ with 2-F Windspeed-Atmospheric Stability & Winter Temp Conditions (CFD Case: HS15).

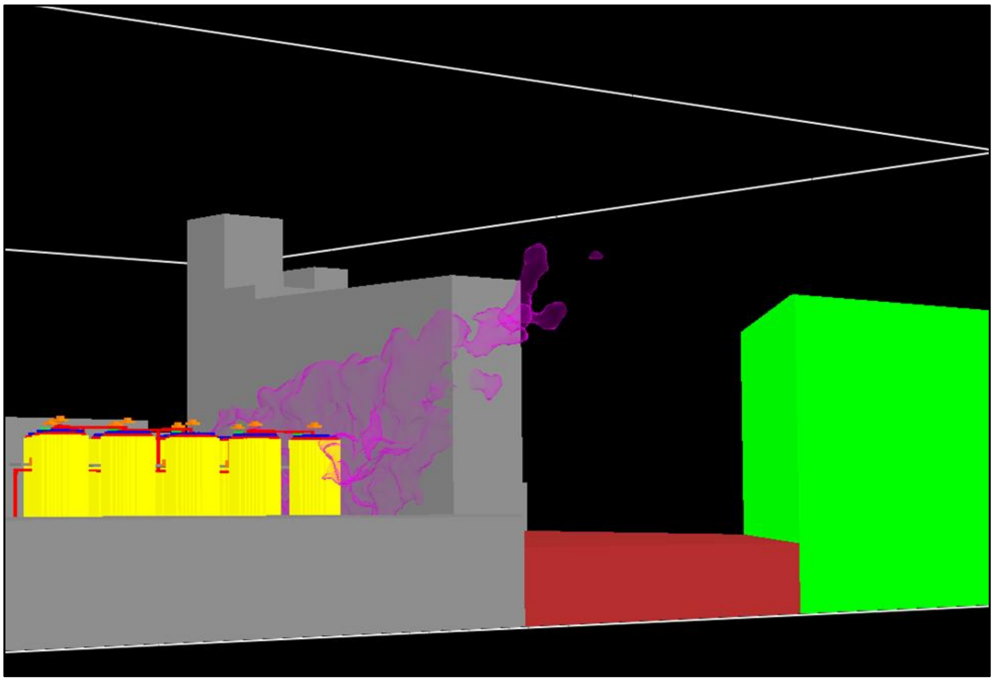

Figure 17. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for $CO_2$ at 5,000 ppm with 2-F Windspeed-Atmospheric Stability & Winter Temp Conditions (CFD Case: HS15).

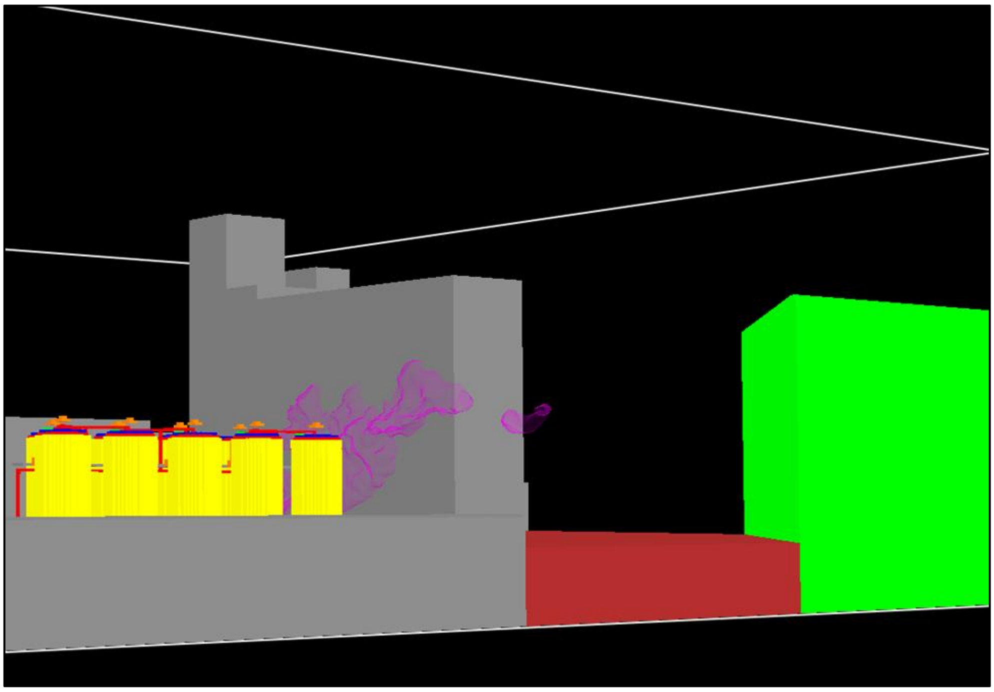

Figure 18. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for 50% LEL with 5-D Windspeed-Atmospheric Stability & Winter Temp Conditions (CFD Case: HS16).

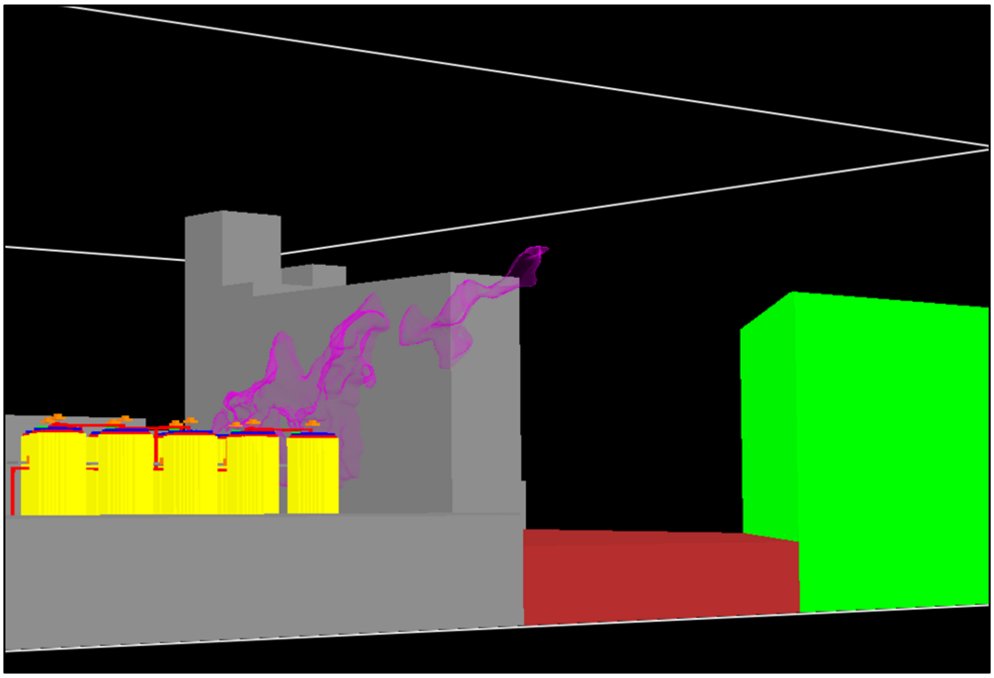

Figure 19. Release Case REL04 (FAD): Peak Maximum Horizontal Extent Across Railway-Site Boundary for $CO_2$ at 5,000 ppm with 5-D Windspeed-Atmospheric Stability & Winter Temp Conditions (CFD Case: HS16).

## 10 Conclusions & Closure

ADH Risk is pleased to present to HS this Final Report presenting the main results obtained from the CFD gas dispersion simulation project for HS' new AD plant which has been designed, manufactured and installed by FRE-Energy.

Overall, four (4) release cases were analysed as part of this study, where release cases REL01 (Gas Bag Elbow (GBE)), REL02 (Gas Bag Leak (GBL)), REL03b (Pressure Relief Valve (PRV)), keep inside HS' site boundary and do not touch or impact the adjacent railway line South-East (SE) of HS' site in Bradford. It is believed given the current and recommended safeguards highlighted in the associated PHA (i.e. HAZID and HAZOP) as well as the DSEAR risk assessment studies for HS' new AD plant, that the risks associated with such releases to people onsite are reduced to a tolerable and acceptable level in line with the UK's Competent Authority (CA) requirements. From communications with FRE-Energy, it is understood that anyone working within the boundary of HS' new AD plant will be required to wear a calibrated personal gas detector which will alarm when detecting flammable (10% & 25% LEL of Methane ($CH_4$)), toxic (5ppm & 10ppm of $H_2S$) and asphyxiant gases (19.5% of $O_2$) as a minimum.

Only a single release condition causes some minor concern (i.e. REL04), which is associated with the activation of AD tank's Foam Alleviation Device (FAD). Only for certain flammable, toxic and asphyxiant gas cloud concentrations, in certain wind directions causes some extents to exceed HS's site boundary momentarily and enter the adjacent railway line South-East (SE) of HS' site in Bradford. This is believed to be due to the FAD release (REL04) impinging against the adjacent building wall and spreading in the boundary layer with little dispersive mixing creating larger extents.

It was recommended in ADH Risk's Interim Letter Report issued to HS in February 2025, that if HS would like to reduce all CFD gas dispersion concentration (flammable, toxic as well as asphyxiant) extents simulated in this study from release case REL04 (FAD), so they do not exceed HS' railway-site boundary, HS and their partner FRE-Energy should review the function and release direction of the FAD device on the AD tank nearest the railway line. From communications with FRE-Energy prior to finalising this report, ADH Risk understands that the FAD device on the AD tank nearest the railway line has been rotated in such a way that the discharge orientation is in the opposite direction away from the adjacent building and towards the gantry between the AD tanks in question.

However, with any design change, it is highly recommended that HS or their partner, FRE-Energy, undergoes a review through their Management of Change (MOC) procedure, not only to determine whether this change provides a reduction in flammable, toxic and asphyxiant cloud concentration extents from release case REL04 (FAD) and prevents these clouds exceeding HS' railway-site boundary, but does not impose any additional risks to people on or offsite. These recommendations maybe applicable to all FAD devices on HS' new AD plant design, and may include conducting additional CFD gas dispersion simulation runs, to verify that the design change has the desired effect, and does not impose any additional risks to people on or offsite.

# 11 References

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https://opus4.kobv.de/opus4-bam/files/41830/Schroeder++Calculation+of+Flammability+Limits.pdf

[3] BS EN ISO / IEC 80079-20-1: 2019, Explosive Atmospheres - Material Characteristics for Gas and Vapour Classification. Test Methods and Data, British Standards Institute (BSI), London, Published: 30th November 2019.

[4] Largest standard single Fork Lift Truck (FLT) fork dimensions (i.e. 150mm x 75mm), https://www.north-fork.co.uk/standard-forks/

[5] Health and Safety Executive (HSE) Publication EH40/2005 – Workplace Exposure Limits, (WEL), Short Term Exposure Limit (15 minute reference period) of Hydrogen Sulphide ($H_2S$):
https://www.hse.gov.uk/pubns/priced/eh40.pdf

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