

# PREDICTION OF THE CONSEQUENCES OF A CO<sub>2</sub> PIPELINE RELEASE ON BUILDING OCCUPANTS

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## Abstract

Carbon Capture and Storage (CCS) is recognised as one of a suite of solutions required to reduce carbon dioxide (CO<sub>2</sub>) emissions into the atmosphere and prevent catastrophic global climate change. In CCS schemes, CO<sub>2</sub> is captured from large scale industrial emitters and transported to geological sites, such as depleted oil or gas fields or saline aquifers, where it is injected into the rock formation for storage. Pipelines are acknowledged as one of the safest, most efficient and cost-effective methods for transporting large volumes of fluid over long distances and therefore most of the proposed schemes for CCS involve onshore and/or offshore high pressure pipelines transporting CO<sub>2</sub>.

In order to manage the risk in the unlikely event of the failure of a CO<sub>2</sub> pipeline, it is necessary to define the separation distance between pipelines and habitable dwellings in order to ensure a consistent level of safety. For natural gas pipelines, existing and accepted QRA (Quantitative Risk Assessment) techniques can be implemented to define safety zones based on thermal hazards. However for high pressure CO<sub>2</sub> pipelines, for which the hazard is toxic, the consequences of failure need to be considered differently, which will impact on the QRA assessment and the definition of safety distances.

The requirement to develop a robust QRA methodology for high pressure CO<sub>2</sub> pipelines has been recognised by National Grid as being critical to the implementation of CCS. Consequently, as part of the COOLTRANS (CO<sub>2</sub> Liquid pipeline TRANSPORTATION) research programme, failure frequency and consequence models are being developed that are appropriate for high pressure CO<sub>2</sub> pipelines. One of the key components in the consequence modelling of a release from a CO<sub>2</sub> pipeline is an infiltration model for CO<sub>2</sub> into buildings to describe the impact on people inside buildings, and outside seeking shelter, during a release event.

This paper describes the development of an infiltration model to predict how the concentration of CO<sub>2</sub> within a building will change based on both wind driven and buoyancy driven ventilation of an external CO<sub>2</sub> cloud into the building. The model considers the effects of either a constant or changing external concentration of CO<sub>2</sub> during a release and allows the density effects of the dense cloud to be taken into account to enable the toxic effects on people within the building to be predicted. The paper then demonstrates how the ventilation model can be coupled to the results of a dispersion analysis from a pipeline release under different environmental conditions to develop the consequence data required for input into the QRA. These effects are illustrated through a case study example.

**Keywords:** CO<sub>2</sub> pipeline, building infiltration, CCS, consequence analysis, QRA



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## 1. Introduction

As a result of growing environmental concerns, interest in developing Carbon Capture and Storage (CCS) schemes has increased over recent years. These schemes involve the capture, transport and storage of carbon dioxide (CO<sub>2</sub>) from an emitting source (such as a power plant or large industrial source) to a geological sink (such as a depleted oil or gas reservoir or saline aquifer) in an effort to reduce the level of CO<sub>2</sub> emissions to the atmosphere.

The most efficient method of transporting CO<sub>2</sub> from the capture facility to the storage site is by pipeline in which the CO<sub>2</sub> is maintained in the dense phase. Unless the capture facility is located at the coast, for subsequent transportation to an offshore storage site, or the capture facility is co-located at the storage site, CCS schemes will require a portion of the pipeline transportation network to be located onshore.

An important consideration for the operation of an onshore dense phase CO<sub>2</sub> pipeline is to determine the risk that the pipeline presents to the public using quantitative risk assessment (QRA) procedures. An essential part of a QRA analysis is the assessment of the potential consequences to any surrounding population in the event of a catastrophic pipeline failure. In the unlikely event of a rupture of a pipeline carrying dense phase CO<sub>2</sub>, it could have dramatic consequences for people located in the vicinity of the release as CO<sub>2</sub> is both toxic and acts as an asphyxiant in high concentrations. In addition, due to the high density of CO<sub>2</sub> in comparison to air, a CO<sub>2</sub> cloud emitted during a pipeline rupture could remain at or return to

ground level depend on the particular circumstances, therefore increasing the probability that people could be affected by such concentrations.

It is assumed that in the event of a pipeline rupture, people in the vicinity will attempt to move away from the CO<sub>2</sub> cloud to safety. It has also been proposed that nearby buildings could offer some form of shelter against the harmful effects of CO<sub>2</sub>. As the CO<sub>2</sub> enters the building through open windows, doors or via the adventitious openings characteristic of all buildings, the concentration of CO<sub>2</sub> within a building engulfed in a CO<sub>2</sub> cloud is a matter of importance. For example, if the release was constant and continuous, eventually the concentration inside could increase to match that of the external atmosphere. However it is considered that the time required for this process to occur could provide those taking shelter in the building with additional time before a harmful concentration is reached, increasing the chance of help arriving. In the case of a decaying release, it may be that the maximum concentration experienced indoors would be limited due to the effects of the decaying nature of the release and the closing of valves.

This paper describes the development of an infiltration model, based on both wind and buoyancy driven ventilation, which can be used to predict the effect of CO<sub>2</sub> exposure on humans in buildings during a potential release from an onshore CO<sub>2</sub> pipeline.

## 2. Infiltration Model Description

The infiltration model considers the ingress of CO<sub>2</sub> into a single building and the subsequent effect this has on the building occupants. The model is based on the principles of natural building ventilation which are explained by Etheridge and Sandberg (Etheridge and Sandberg, 1996) and form the basis for the simple ventilation equations in British Standard BS 5925 (BS5925, 1991).

In the model, it is assumed that initially the concentration in the building is the low background level in the atmosphere. It is assumed that the pipeline release occurs and that, as a result, the building is subject to a cloud of CO<sub>2</sub> that drifts past the building. The concentration of CO<sub>2</sub> in the external atmosphere is transient and will change with time as the CO<sub>2</sub> cloud released from the pipeline disperses. Similarly, the concentration of CO<sub>2</sub> within the building will change as CO<sub>2</sub> is drawn in from the concentrations outside through the process of natural ventilation. The change in the internal concentration of CO<sub>2</sub> is modelled over the course of the rupture event.

For the purposes of the model, a building is represented as a three dimensional rectangular structure of specified length, width and height ( $l, w, h$  respectively), located at a fixed distance from a pipeline rupture. Openings in the building envelope between the indoor and the outdoor environment are used to represent the doors, windows and adventitious openings found in real buildings. The building is assumed to have no internal partitions, an assumption which is considered to be conservative, and the concentration within the interior is assumed to be uniform.

Air flow between the internal and external atmospheres in the building occurs due to a pressure difference across the openings in the building envelope. Air will flow from a region of higher pressure to a region of lower pressure. The pressure difference can arise as result of wind effects externally and/or buoyancy effects internally. An example of ventilation air flow incorporating both of these effects is shown in Figure 1.

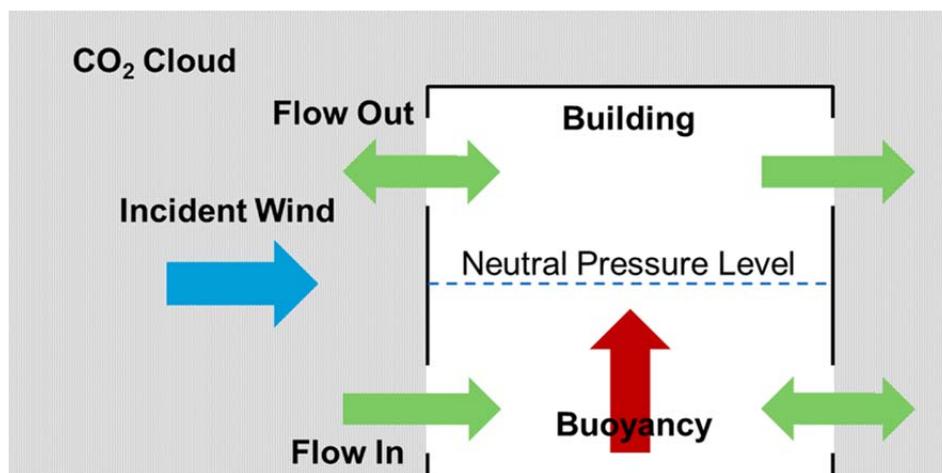


Figure 1: Air Flow Through Openings due to Pressure Difference (Side View)

### 2.1 Wind pressure

The dynamic pressure due to the (free stream) wind flow is:

$$P_{wind} = \frac{1}{2} \rho U_{wind}^2 \quad (1)$$

Where  $\rho$  is the density of the external air and  $U_{wind}$  is the wind speed (Etheridge and Sandberg, 1996, Etheridge and Sandberg, 1984)

The wind blowing on the building will stagnate and recirculate. The pressure on each surface is therefore calculated as the dynamic pressure head of the 'free stream' multiplied by a surface pressure coefficient,  $C_p$ . The value of  $C_p$  depends upon the angle at which the wind impacts the surface in question and is taken from the literature.

## 2.2 Buoyancy Pressure

Pressure differences due to buoyancy arise as a result of a difference in temperature between the internal and external environments. Due to the principle of hydrostatics, atmospheric air pressure decreases with increasing altitude (Etheridge and Sandberg, 1996, Etheridge and Sandberg, 1984). This can be represented using the following equation:

$$P = P_{reference} + \rho g z \quad (2)$$

Where  $P_{reference}$  is the atmospheric pressure at a defined height above ground level,  $\rho$  is the density of air,  $g$  is the acceleration due to gravity ( $9.81 \text{ ms}^{-2}$ ) and  $z$  is the height above ground level.

The density of air in Equation (2) can be approximated using the ideal gas equation:

$$\rho = \frac{P}{RT} \quad (3)$$

Where  $P$  is the air pressure,  $R$  is the ideal gas constant for air and  $T$  is the air temperature.

If the building is not air-tight and the internal atmosphere is at the same temperature as the external atmosphere then the internal and external pressure will be the same (assuming there is no wind) and will display an identical variation with height.

An increased internal air temperature however, results in a reduction in the internal air density, from Equation (3). Because of the principle of hydrostatics, the less dense air within the building will rise and therefore the internal air pressure is therefore increased from its initial value at the top of the building and decreased from its initial value at the bottom of the building. The resultant outcome is one of a steeper pressure gradient within the building than that outside, given by Equation (2). At some point within the building above ground level there will exist a plane in which the internal pressure equals the external pressure, this is the neutral pressure level shown in Figure 1 and its position depends on the magnitude of the temperature difference between the internal and external atmospheres. Air will flow from high pressure to low pressure, therefore any openings in the envelope of the building below the neutral pressure level will draw air in from the outside and any openings above the neutral pressure level will push air outside. This sets up a flow of air within the building from the floor to the ceiling.

## 2.3 Pressure Differences and Building Air Flow

Within the infiltration model, pressure differences across the openings in the envelope of the building are calculated by combining the effects of wind and buoyancy. Taking into account wind and hydrostatic effects, an expression for the external air pressure on a particular building face, at a height  $z$  above ground level, can be written as:

$$P_{external}(z) = P_{reference} + \frac{1}{2} \rho_{external} U_{wind}^2 C_p + \rho_{external} g z \quad (4)$$

Similarly, the corresponding expression for the internal air pressure on the same face at the same height can be written as:

$$P_{internal}(z) = P_{reference} + P' + \rho_{internal} g z \quad (5)$$

Where  $P'$  as yet undefined, that is determined by the location of the zero pressure level and volume conservation. From (4) and (5), the difference in pressure across an opening in the envelope of the building at height  $z$  is given by:

$$\Delta P(z) = \frac{1}{2} \rho_{external} U_{wind}^2 C_p - P' + g z (\rho_{external} - \rho_{internal}) \quad (6)$$

As explained previously, a pressure difference between the internal and external environments causes air to flow through openings in the building envelope. The magnitude of the air flow across an opening at height  $z$  can be calculated using (Etheridge and Sandberg, 1996, Etheridge and Sandberg, 1984):

$$Q(z) = C_d W(z) \sqrt{\frac{2|\Delta P|}{\rho}} \quad (7)$$

Where  $C_d$  is the coefficient of discharge for the particular type of opening under consideration,  $W(z)$  is the width of the opening at height  $z$  and  $\rho$  is the internal or external air density.

By imposing a boundary condition for the conservation of volume, *i.e.* all air flow into the building must equal all air flow out of the building; the unknown pressure  $P'$  in equations (5) and (6) can be calculated and the air flow for the building solved:

$$\int_0^{z_0} Q_{in} = \int_{z_0}^h Q_{out} \quad (8)$$

Where  $h$  is the height of the building and  $z_0$  is the height of the neutral pressure level from Figure 1 at which it is known that:

$$P_{internal}(z_0) = P_{external}(z_0) \quad (9)$$

## 2.4 CO<sub>2</sub> Concentration

In Equations (4) to (8) the flow rate of air into and out of a building is dependent on both the external and internal density of air. In the infiltration model, the building is surrounded by a cloud of CO<sub>2</sub> from a ruptured dense phase CO<sub>2</sub> pipeline resulting in a high external concentration of CO<sub>2</sub> in the air. The external concentration of CO<sub>2</sub> will change over time as the rupture event evolves. Furthermore the internal concentration of CO<sub>2</sub> will change with time as more CO<sub>2</sub> is drawn in from outside. An increased presence of CO<sub>2</sub> compared to normal air will affect the air density. The internal and external air densities at any one time can be calculated by assuming an air/CO<sub>2</sub> mixture which behaves as an ideal gas:

$$\rho_{external} = \frac{P_{external}}{R} \left[ \frac{c_{external} m_{CO_2}}{T_{external}} + \frac{(1-c_{external}) m_{air}}{T_{external}} \right] \quad (10)$$

$$\rho_{internal} = \frac{P_{internal}}{R} \left[ \frac{c_{internal} m_{CO_2}}{T_{internal}} + \frac{(1-c_{internal}) m_{air}}{T_{internal}} \right] \quad (11)$$

Where  $P_{external}$  and  $P_{internal}$  are the external and internal pressures respectively; R is the ideal gas constant;  $T_{external}$  and  $T_{internal}$  are the external and internal temperatures;  $c_{external}$  and  $c_{internal}$  are the internal and external volume concentrations of CO<sub>2</sub>; and  $m_{CO_2}$  and  $m_{air}$  are the molar masses of CO<sub>2</sub> and air respectively. For the purposes of the model the internal and external pressures in Equations (10) and (11) are assumed to be the same and equal to  $P_{reference}$  in equations (4) and (5). For cases of interest, associated with relatively higher external concentrations of CO, this makes only a small difference to the calculated value of the density compared to the changes resulting from concentration variations and so is ignored.

In the infiltration model, Equation (8) is solved in order to determine the rate of air flow by ventilation into and out of the building at any instant in time. The air/CO<sub>2</sub> mixture from the outside drawn into the building is assumed to mix perfectly with the internal air/CO<sub>2</sub> causing the internal concentration of CO<sub>2</sub> to change. The internal concentration of CO<sub>2</sub> is calculated using the perfect mixing method from Harris (1983).

The volume of CO<sub>2</sub> flowing in to the building in a time period  $dt$  is:

$$\Delta V_{CO_2 in} = Q_{in} c_{external} dt \quad (12)$$

And the volume of CO<sub>2</sub> flowing out of the building over  $dt$  is:

$$\Delta V_{CO_2 out} = Q_{out} c_{internal} dt \quad (13)$$

Therefore the total change in internal CO<sub>2</sub> concentration over  $dt$  is:

$$dc_{internal}(dt) = \frac{(V_{CO_2 in} - V_{CO_2 out})}{V_{building}} \quad (14)$$

Where  $V_{building}$  is the total volume of the building. The total internal concentration at a time  $t + dt$  will therefore be:

$$c_{internal}(t + dt) = c_{internal}(t) + dc_{internal}(dt) \quad (15)$$

## 2.5 Temperature Change

Section 2.2 outlined the importance of internal and external temperature difference in establishing a ventilation flow rate due to buoyancy. CO<sub>2</sub> vapour from a dense phase pipeline rupture can be released into the atmosphere at temperatures down to approximately -80 degrees Celsius due to the Joule-Thomson effect. A low vapour temperature such as this can change the temperature of the external environment surrounding the building and therefore affect the ventilation flow rate. Furthermore, as external air is drawn into the building as the event progresses the temperature of the internal environment, its density and the ventilation flow will also be affected. These considerations are taken into account in the model by considering energy conservation. The energy equation is approximated to Equation (16), which is derived assuming that heat changes from inside to outside are not significant and that any inflow caused by temperature changes in the interior can be neglected.

$$M_{internal} \frac{dT_{internal}}{dt} = \frac{dm_{in}}{dt} (T_{external} - T_{internal}) \quad (16)$$

In equation (16),  $M_{internal}$  can be calculated using:

$$M_{internal} = \rho_{internal} V_{building} \quad (17)$$

Where  $\rho_{internal}$  is calculated using equation (11) and  $V_{building}$  is the total volume of the building. Additionally:

$$\frac{dm_{in}}{dt} = \rho_{external} Q_{in} \quad (18)$$

Where  $\rho_{external}$  is calculated using equation (10) and  $Q_{in}$  is the ventilation flow rate into the building over  $dt$ . Hence the change in internal temperature over  $dt$  can be calculated using Equation (16).

## 2.6 Validation

The infiltration model has been tested using experimental data gathered as part of the COOLTRANS experimental test programme (Allason et al., 2012). Although not described in this paper, the model has been used to predict the internal concentrations and temperatures recorded in a simulated building situated downwind of the source of a release in a scaled CO<sub>2</sub> pipeline rupture experiment. The concentrations and temperature at the openings on the front face of the model building

were recorded in the experiments as well as the internal concentrations and temperature at a number of locations. The wind speed and direction of the undisturbed flow was monitored upstream of the release and it was assumed that the cloud drifted passed the building at this rate and angle. The building was sited at a location where the dispersion models predicted that any solid CO<sub>2</sub> formed in the initial release would have been vaporised. The predicted concentration and temperature in the interior showed an encouraging level of agreement with the observations.

### 3. CO<sub>2</sub> Toxic Dose

The effect that an increased atmospheric concentration of CO<sub>2</sub> has on people is quantified in terms of a toxic dose. The toxic dose is cumulative over time meaning that duration of increased CO<sub>2</sub> exposure is equally as important as the value of the concentration. A generalised equation for the toxic dose of exposure to some contaminant is:

$$D = \int c(t)^n dt \quad (19)$$

Where  $c(t)$  is the concentration of the contaminant a person is exposed to in parts per million (ppm), and  $t$  is the time of the exposure in minutes.  $n$  is the toxic index which can take different values depending on the nature of the contaminant. For CO<sub>2</sub> the Health and Safety Executive (HSE) specify that the value  $n = 8$  is used (HSE, 2015).

#### 3.1 Dangerous Toxic Loads

Dangerous toxic loads (DTL) are values of dose specified by the HSE which represent harmful levels of exposure to a contaminant (HSE, 2015):

- The Specified Level of Toxicity (SLOT). The SLOT dose for CO<sub>2</sub> is  $1.5 \times 10^{40}$  ppm<sup>8</sup>.min.
- The Significant Likelihood of Death (SLOD). For an average population exposed to the SLOD dose, 50% of people would be expected to die. The SLOD dose for CO<sub>2</sub> is  $1.5 \times 10^{41}$  ppm<sup>8</sup>.min.

#### 3.2 Lethality

The DTL values for CO<sub>2</sub> can be used as part of a probit analysis. For the purposes of determining CO<sub>2</sub> lethality in the indoor and outdoor models, a straight line probit relationship has been derived using the SLOT and SLOD values, assuming that the SLOT dose gives a lethality of 3% and the SLOD dose gives a lethality of 50%. The probit equation is:

$$probit = 0.82 \ln(dose) - 72.41 \quad (20)$$

In this way the chances of death, or lethality, for a building occupant can be plotted with exposure time using the infiltration model.

## 4. Case Study

In order to demonstrate the use of the infiltration model to calculate the change in internal CO<sub>2</sub> concentration in a building enveloped by a CO<sub>2</sub> cloud, a case study pipeline rupture is considered. The main input data required for the infiltration model is the change in external CO<sub>2</sub> concentration and ambient temperature with time and distance from the release event. This data could have been calculated using commercially available dispersion analysis software such as PHAST (Witlox et al., 2014). However, in this study, the input values were provided as part of the COOLTRANS Research Programme, using the models developed as part of that programme.

### 4.1 Input Data

The particular pipeline rupture that has been modelled to provide the CO<sub>2</sub> dispersion data for input into the infiltration model was a double-ended guillotine break at the mid-point of a 96 kilometres buried transportation pipeline. The initial internal pressure is 150 barg and the initial internal fluid temperature is 30°C. Block valves are assumed to be located 8 kilometres upstream and 8 kilometres downstream of the rupture and these are closed 15 minutes after the start of the release. The pipeline has an assumed external diameter of 610 mm and a nominal wall thickness of 19.4 mm. The atmospheric conditions at the time of the release were 5 m/s wind at 10 m in neutral atmospheric stability conditions (5D).

The data includes two values for atmospheric CO<sub>2</sub> concentration and one value for external temperature. The concentration values are termed “C-mean” and “C-equiv”. “C-mean” is a value for the mean atmospheric CO<sub>2</sub> concentration and “C-equiv” is an “equivalent” higher value adjusted so that concentration fluctuations are included when evaluating the dose. For the cases considered, the values for “C-mean” have been used in conjunction with the temperature values in order to calculate the air flow rates between the internal and external atmospheres in the indoor model. The values of “C-equiv” have been used in conjunction with the calculated air flow rates to determine the toxic dose and lethality within the building. It is assumed in the analysis that the CO<sub>2</sub> cloud completely envelopes the building over all dimensions.

The change in internal CO<sub>2</sub> concentration and temperature with time has been modelled for a building, located at 8 distances along the centreline axis in the simulated release and the wind was assumed to be blowing directly onto the face of the building closest to the rupture source (angle of 0° to the normal). In each case, following the rupture there is a period of time before the cloud reaches the building in which the internal and external conditions remain constant at their initial levels. The duration of this time period is determined by the wind speed, which controls the speed of the released CO<sub>2</sub> cloud; and the distance of the building from the rupture.

Input	Value
Starting Internal Temperature	293 K (20° C)
Initial Internal CO <sub>2</sub> Concentration	0.039%
Wind Direction	0° to the normal
Initial External CO <sub>2</sub> Concentration	0.039%
Building Height	5 m
Building Length	10 m
Building Width	10 m
C <sub>p</sub> Front Face	0.7
C <sub>p</sub> Back Face	-0.2
Window Discharge Coefficient, C <sub>d</sub>	0.61
Number of Windows on Front/Back Face	2 on each
Height of Bottom of Lowest Window	0.25 m
Vertical Separation of Windows	2 m
Window Area	0.02125 m <sup>2</sup>

**Table 1:** Indoor Model Input Conditions and Assumptions

Table 1 provides the assumptions and input conditions for the indoor model used in the investigation. The window discharge coefficient and pressure coefficients for the specified wind direction were taken from BS 5925 (BS5925, 1991). The building used in the analysis was a single cuboid structure with dimensions given in Table 1. The interior of the building does not contain different rooms or partitions. The windows in the building were square shaped and identically sized. For the investigation the window area has been chosen as 0.02125 m<sup>2</sup>. A starting internal temperature of 20° C was chosen as an example of a typical room temperature.

The choice of input conditions and assumptions produces a ventilation flow rate of approximately 0.65 AC/hr when the building is subject to a direct wind of 5 m/s with a 10° C temperature difference between the internal and external environment. As explained in Section 2 the ventilation flow rate will vary depending on the wind speed; internal and external CO<sub>2</sub> concentration; and internal and external temperature difference. The ventilation flow rate is therefore subject to continuous variation throughout the course of each simulation. Typical ventilation rates for a real dwelling with internal partitions range between 0.5 and 3 AC/hr (Harris, 1983). In practice the sensitivity to this value would be examined.

## 4.2 Case Study Results

### Internal Concentration and Temperature

Figure 2 and Figure 3 show the change in the mean and equivalent internal concentration of CO<sub>2</sub> (C-mean and C-equiv) calculated using the infiltration model for a building placed at a distance of 100 m, 150 m, 200 m, 300 m, 400 m, 500 m, 700 m and 1000 m from the release. The input data showing the change in the corresponding external concentrations with time are also indicated in Figure 2 and Figure 3. Figure 4 indicates the change in the internal temperature calculated using the infiltration model together with the input data showing the change in external temperature with time.

It should be noted in Figure 2 and Figure 3 that, in each case, following the rupture there is a period of time, before the cloud reaches the building in which the internal and external conditions remain constant at their initial levels. The duration of this time period is determined by the wind speed, which controls the speed of the released CO<sub>2</sub> cloud; and the distance of the building from the rupture.

For each case considered, the calculated internal concentrations and follow a trend of diminishing decrease and the internal temperature follows a trend of diminishing increase. The reason for this is that the internal values always act to match the time-increasing external values. As a result, the maximum mean or equivalent internal concentration of CO<sub>2</sub> is reached when it equals the corresponding external concentration, after this point it begins to fall. Conversely, the minimum internal temperature is reached when it equals the external temperature, after this point it begins to rise.

### Toxic Dose

Figure 5 shows the CO<sub>2</sub> dose that a building occupant would receive, as calculated using the equivalent internal concentration from the indoor model. Lines for the SLOT and SLOD DTLs are also shown. The toxic dose is a cumulative quantity; this is reflected in the charts, which show a continuous increase in dose for each case. When the block valves on the pipeline are assumed to close, isolating the rupture, the magnitude of the increase diminishes as the simulation progresses because the internal equivalent CO<sub>2</sub> concentration reaches its maximum value and begins to fall (Figure 3). As the external concentration of CO<sub>2</sub> returns to atmospheric levels the toxic dose value for each case will become constant.

## Lethality

Figure 6 shows the chances of lethality for a building occupant, as calculated using the toxic dose for the 8 building distances in this case study. Lines for the SLOT and SLOD percentages are also shown. It is assumed in this analysis that, for an average population exposed to the SLOT dose, 3% of people would be expected to die. Lethality is represented as a cumulative percentage and is derived from the toxic dose. Its value therefore increases as the toxic dose increases (Figure 5). It can be seen from both Figure 5 and Figure 6 that the SLOD criterion is never exceeded for the case study presented. The SLOT criterion is only exceeded after 1.2 hours under these conditions for a building located at 100m from the release. Alternatively, for these case study conditions, it can be concluded that the minimum distance for which the internal concentration of CO<sub>2</sub> in the building considered will remain below the level required for a SLOT DTL is between 100 m and 150 m. The minimum distance for which the internal concentration in the building will remain below the level required for a SLOD DTL is less than 100 m. Thus safe shelter will be provided in any building located more than 150m from the release for this case study. It is highlighted that these calculations have been conducted for a worst case direction (*i.e.* for the downwind direction on the downwind axis). The conclusions would be different (and less severe) for different directions throughout the cloud (*i.e.* the upwind and crosswind directions). In conducting a risk assessment, locations throughout the cloud would be considered and the failure frequency taken into account in order to put the results from this model into perspective by evaluating the risk at a particular location.

## 5. Conclusions

This paper has described the development of an infiltration model for the prediction of the casualty probability for persons in a building that is engulfed by a dispersing cloud of CO<sub>2</sub> vapour. The model is able to calculate the change in internal CO<sub>2</sub> concentration and temperature with time within the building, taking into account the effects of wind driven and buoyancy driven ventilation.

It has been shown that the infiltration model can be readily coupled to the output data from dispersion analysis software that provides changes in external CO<sub>2</sub> concentration and temperature as a function of time after a release event. Although the case study used the data from DNV-GL dispersion predictions, the model is also able to use data from commercially available dispersion software packages such as PHAST.

For the case study conditions considered, the minimum distance for which the internal concentration of CO<sub>2</sub> in the building considered will remain below the level required for a SLOT DTL is between 100 m and 150 m in the worst case direction of downstream of the release. The minimum distance for which the internal concentration in the building will remain below the level required for a SLOD DTL is less than 100 m in the worst case condition downwind direction. Based on this case study, it has been demonstrated that the ability of buildings located on a pipeline route to provide shelter in the event of a pipeline rupture can be determined using the infiltration model.

The case study presented has only considered one set of atmospheric conditions. The model can now be used to investigate the effects of other variables such as wind speed, ambient temperature, valve closure times and window area on the effect of shelter and to examine the effect at other locations within the cloud (*i.e.* not directly downwind of the release). This would be carried out within the context of a risk assessment, in which the failure frequency of the release would be taken into account.

## 6. Further Developments

The CO<sub>2</sub> cloud in the analysis was assumed to completely envelope the building; work is ongoing to consider clouds which only cover a fraction of the building's height. In addition, it is recognised that the building considered is a single cuboid structure and therefore a simplified representation of the majority of buildings which could be occupied. A focus of further study is to introduce partitions within the building to simulate different rooms, thereby refining the analysis.

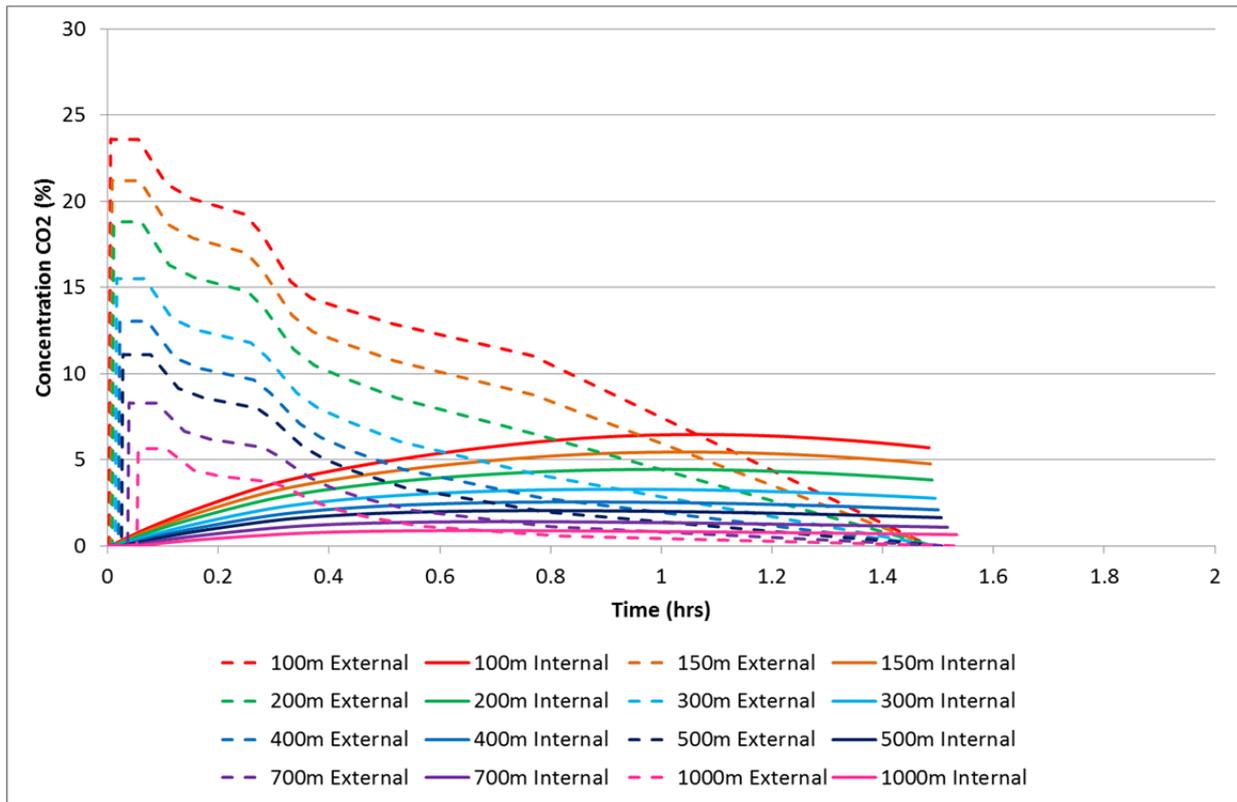
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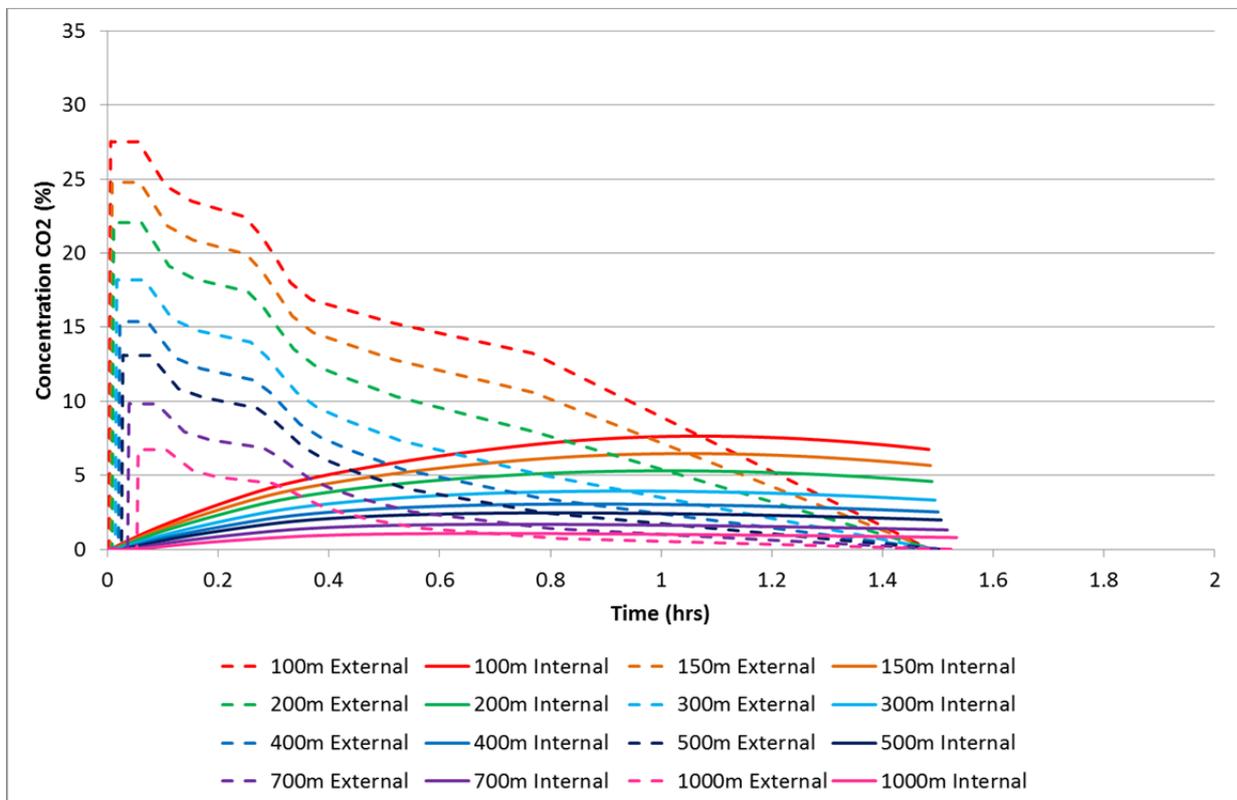
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**Figure 2:** Change in Mean Internal CO<sub>2</sub> Concentration with Time After the Release Event and Distance from the Release Point



**Figure 3:** Change in Equivalent Internal CO<sub>2</sub> Concentration with Time After the Release Event and Distance from the Release Point

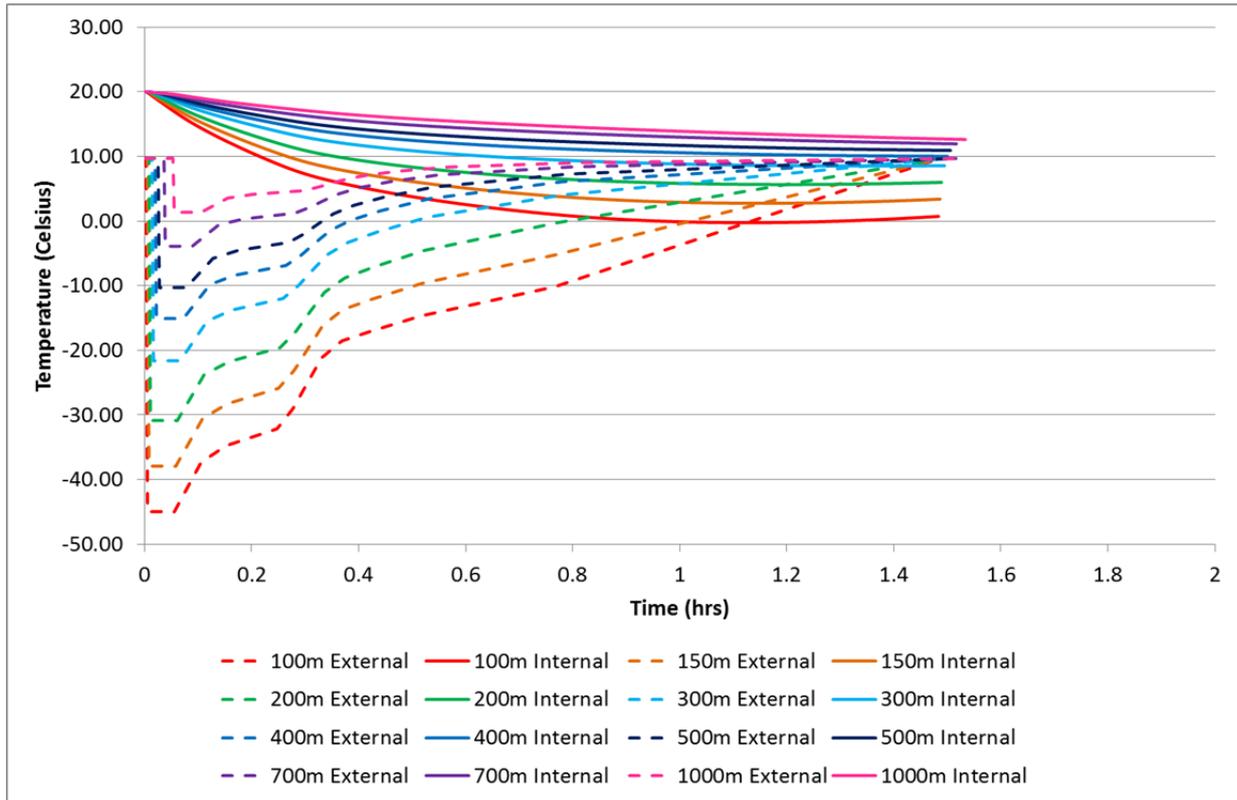


Figure 4: Change in Internal Temperature with Time After the Release Event and Distance from the Release Point

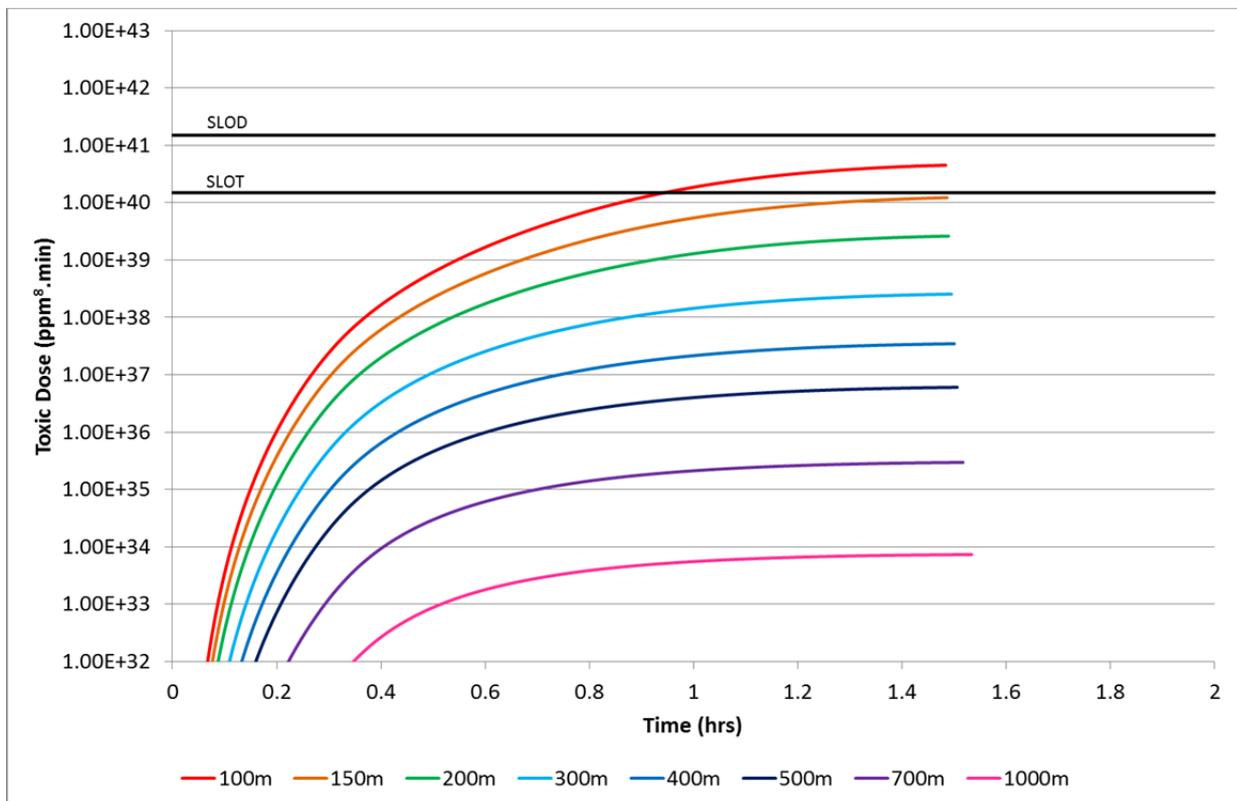
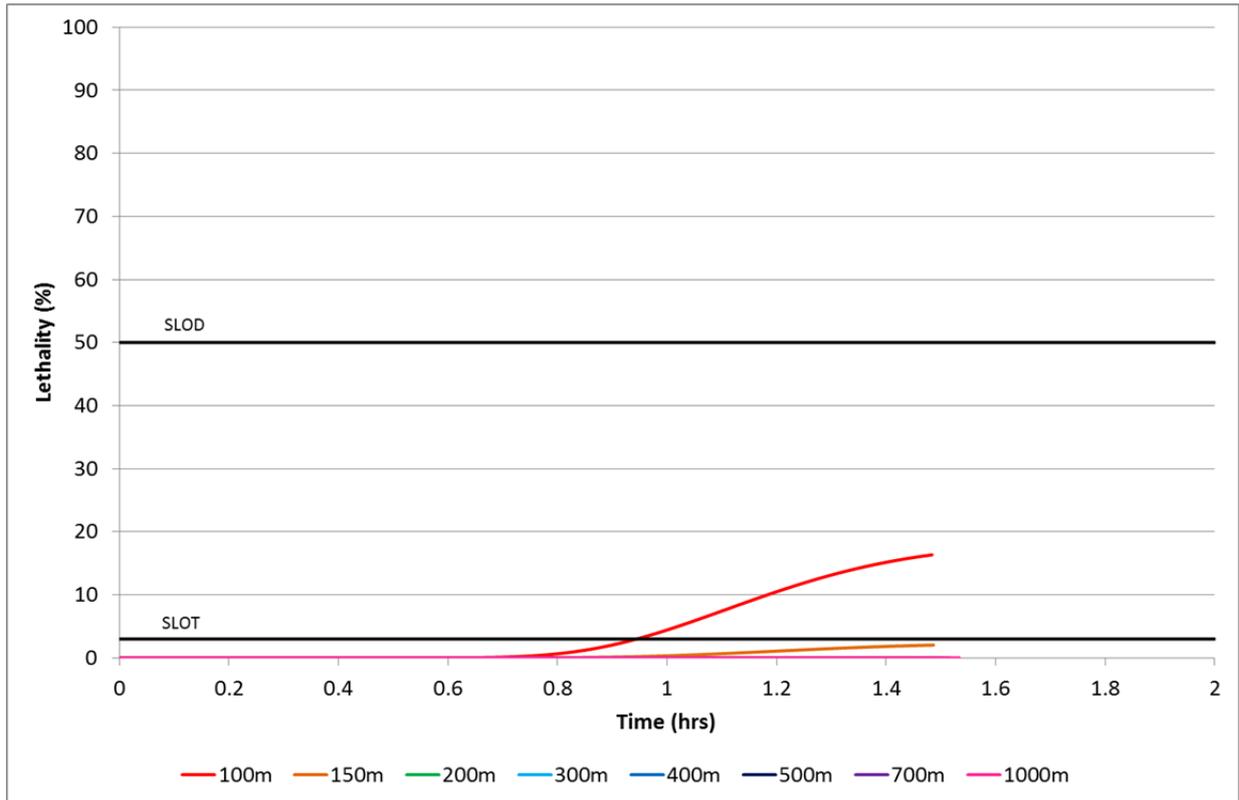


Figure 5: Dose Received by a Building Occupant with Time After the Release Event and Distance from the Release Point



**Figure 6:** Percentage Lethality for a Building Occupant with After the Release Event and Distance from the Release Point