Gas Ingress into Buildings – Experimental Studies and their Relevance to Risk Assessment

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Abstract: As part of National Grid's COOLTRANS (CO_2 Liquid pipeline TRANSportation) research programme, a methodology was developed to assess the risks arising from buried carbon dioxide (CO_2) pipelines. This methodology was used to help develop a screening method and guidance on routeing CO_2 pipelines. Just as for natural gas pipelines, the CO_2 assessment methodology distinguishes between the risks posed to people who are indoors and people who are outdoors. The purpose of this paper is to investigate the reasons for the differences between the indoor and outdoor risks and to provide support for the assumptions made in the methodology.

A number of the parameters that have an influence on the accumulation of CO_2 within a building are presented. Theoretical reasons for differences between the indoor and outdoor risk are discussed in general terms and the specific case of CO_2 pipelines is considered further. This includes examining the influence of the highly transient outflow behaviour observed initially following the rupture of a pipeline and considers the steadier, but much smaller-sized, puncture releases from a below-ground pipeline.

The theoretical method to assess CO_2 ingress developed at Newcastle University, as part of the COOLTRANS research programme, is noted. Further, previously unpublished experimental results on CO_2 ingress into enclosures are examined and analysed. The paper ends with a brief discussion of the significance of these results to the assessment of the risks from CO_2 pipelines.

Keywords: CO_2, COOLTRANS, pipelines, ingress, risk assessment.

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Introduction

National Grid's long term aspiration is to develop a pipeline network configuration that links multiple carbon dioxide (CO_2) industrial emitters in the Yorkshire and Humberside area with an offshore storage site, where the CO_2, captured by the emitters, would be safely stored. The planned developments are supported by a European Union grant, which has been used to partly fund the required technical studies. A major component of these studies has been National Grid's COOLTRANS (CO_2 Liquid pipeline TRANSportation) research programme, [Cooper, 2012].

The COOLTRANS research programme included the development of state of the art Computational Fluid Dynamic (CFD) models by University College London (UCL), the University of Leeds, Kingston University and the University of Warwick to predict the behaviour of major accidental releases of CO_2 from a buried pipeline, to cover the outflow from the pipeline itself [Brown et al., 2013], the behaviour of the release in and close to any crater that is formed [Wareing et al., 2013] and the dispersion in the atmosphere, [Wen et al., 2103]. The ability to predict the dispersion of a CO_2 release is important, as CO_2 is a weakly toxic gas that poses a risk to people above that arising as an asphyxiating gas. The results of this research were used to help develop a more pragmatic Quantified Risk Assessment (QRA) methodology for dense phase CO_2 pipelines, [Cleaver et al., 2015]. This methodology has been used in routeing and design studies to ensure that the principles of the UK standards and codes are correctly applied.

One aspect of the methodology is that it distinguishes between the risks that are posed by a release from the buried pipeline to people who are indoors and to people who are outdoors. There is a precedent for differentiating in this way. The methodology developed originally by the former British Gas makes this distinction for natural gas releases, see for example [Acton et al., 1998] and [Warhurst, 2015]. In this methodology, the response of a building is evaluated based on the time dependent radiation flux received at the front face of the building. A correlation for the spontaneous or piloted ignition of wood is used to help determine the level of shelter provided, and hence risk, to people within the building. In contrast, the risk to people who are outdoors is calculated directly from the thermal dosage people receive in attempting to escape to a safe radiation level or non-burning shelter, as appropriate.

The purpose of this paper is to explore further the reasons why there might be a difference between the indoor and outdoor risks arising from a toxic gas release in general and to provide information to support the development of an assessment methodology for CO_2 in particular.

General Considerations

Conventional wisdom has it that in the event of a toxic gas release into the atmosphere, members of the public who live nearby the release should remain inside their buildings, closing all windows and doors, whilst awaiting further guidance from emergency services called to the scene. Such advice has been given in the UK and appears in many other countries around the world (see for example, the web sites listed in the references). It is based on the assumption that it would take a drifting cloud a period of time to enter and accumulate to a dangerous level within a building and that, during this time, remedial action would be taken to halt the release or the release would decay gradually as a result of the depressurisation of the finite inventory at the source. The trend towards making buildings more airtight for environmental reasons, to prevent heat escaping from a property, for example, gives support to adopting this strategy in houses of recent construction.

Further, many toxic gases form clouds that are heavier than air when released into the atmosphere. This offers the possibility that the highest concentration in a drifting cloud will be at ground level and as a result, people would be safer in the upstairs rooms of a house rather than downstairs, offering an in-built safety feature at night time, when people may be asleep upstairs and not readily able to detect gas ingress.

Previous work has considered this issue from a modelling perspective and has produced a number of modelling approaches that can be used to investigate the rate of accumulation of gas within a building (see for example some earlier work in [Brighton, 1986] and [Linden et al., 1990]).

The factors that have been identified that have an influence on the gas accumulation for a single enclosure include the following:

External Parameters

The external cloud speed, U_{Cloud}

The density of the external cloud, ρ_c

The concentration of the contaminant

The temperature of the cloud

The variation of the cloud properties with time

Internal parameters

The volume of the enclosure

The total free area of opening available for flows into or out of the enclosure, A_{Free}

The background ventilation rate of the enclosure, Q_{bv}

The density of the air within the enclosure initially, ρ_a

The temperature of the air within the enclosure initially

In addition, details such as the height and orientation of the different openings on the enclosure and the direction of travel of the external cloud are important. For the purposes of illustration here, a simple case is considered in which it is assumed that there are distinct, equal areas of openings at a high and low level, separated by a distance H. A large cloud is incident on the front face of a single enclosure and the openings are equally split between the front and the rear face.

In this case, buoyancy driven flows through the building can be characterised by the term:

$$B = \sqrt{g(\rho_c - \rho_a)H}\,(0.5A_{Free})\,C_1 \tag{1}$$

And momentum driven flows by:

$$M = U_{Cloud}(0.5A_{Free})\,C_2 \tag{2}$$

Where C_1 and C_2 are constants and g is the acceleration due to gravity.

The ratio of buoyancy to momentum,

$$R_{Force} = B/M \tag{3}$$

gives an indication of the relative importance of these two terms.

The effective net inflow and outflow, Q_{eff}, will be determined by the pressure distribution across all of the openings in the enclosure. Assuming the velocities within the enclosure are relatively small but that the flows are sufficient to keep the gas cloud within the enclosure well-mixed, the flow can be modelled assuming that the pressure is hydrostatic and so is a function of distance from the ground. As a result of this, there is a 'zero' pressure level on the front and rear face of the enclosure. Assuming the external cloud is heavier than the air within the enclosure initially, there will be inflow below the zero pressure level and outflow from above it. This modelling approach has been used previously to consider the accumulation of lighter than air gases, such as natural gas, within a building (see [Linden et al., 1990] for example) or to model the combination of buoyancy and wind driven motions (see [Lyons et al., 2015] and [Etheridge and Sandberg, 1996], for example). The above approach has been used for drifting CO_2 clouds and can be solved numerically by iterating to find the pressure distribution such that the inflows and outflows balance (see [Lyons et al., 2015]). Alternative simple approximations that have been used include taking some weighted combination or the maximum of the buoyancy or momentum driven flows to represent the effective ‘ventilation’ rate, Q_{eff}, when the cloud is present. The ratio of this value to the pre-existing background ventilation rate, Q_{bv}, gives an indication of the importance of the release driven motions.

Assuming the accumulation takes place in a well-mixed layer of volume, V_l, the accumulation rate within the enclosure is determined by the perfect mixing equation:

$$V_l \frac{dC_{Int}}{dt} = Q_{eff}\left(C_{Ext} - C_{Int}\right) \quad (4)$$

where C_{Ext} is the external concentration, C_{Int} is the internal concentration and Q_{eff} is the ventilation rate.

If the properties of the external cloud remain constant, the timescale over which the internal concentration approaches the external concentration, t_{Accum}, is given by:

$$t_{Accum} = V_l / Q_{Eff0} \quad (5)$$

where Q_{Eff0} is the initial value of the effective ventilation rate, when the buoyancy difference between the inside and outside is greatest. (Note that the actual ventilation rate may change with time as the release progresses. Implicit in the use of Q_{Eff0} in the above is that this change is relatively slow or small.)

Assuming the properties of the release change over some timescale, $t_{Release}$, determined by the source conditions, the ratio:

$$R_{Time} = t_{Accum} / t_{Release} \quad (6)$$

will determine the importance of the transient nature of the release.

Assuming the release is decaying with time, if R_{Time} is large, the release is changing relatively rapidly or, equivalently, the concentration is accumulating internally relatively slowly. As a result, the peak concentration inside will be less than that outside. Alternatively, if R_{Time} is small, the release can be viewed as approximately constant or the enclosure is sufficiently open to allow a large through-flow, so the internal and external concentration time histories will be similar.

That is, adopting this simple approach, the value of R_{Time} gives an indication of the degree of protection afforded by being inside a building as any external cloud passes, compared with being outside.

Releases from Buried CO_2 Pipelines

The motivation for the studies reported in this paper comes from the possibility of a release occurring from a buried CO_2 transportation pipeline. Issues such as the frequency with which large diameter, thick-walled CO_2 pipelines would fail and the pipe body toughness requirements for such pipelines to prevent the possibility of a long-running fracture occurring have been addressed as part of the COOLTRANS research programme, [Cooper, 2012].

The combination of these studies [Brown et al., 2013], [Wareing et al., 2013] and [Wen et al., 2103] showed that releases from buried pipelines of above a certain size are likely to form a crater below ground. The CO_2 impinges within and on the crater sides and floor and has been observed to leave the crater in an upwards direction. The flow leaving the crater is denser than the surrounding air and eventually stalls under the influence of gravity. Depending on the ratio of the downwards buoyancy forces to the horizontal momentum, gained from the wind, the flow may gradually return to ground at some distance downwind or fall back on itself to surround the crater to form a ground-level dense gas cloud emerging from the downwind end of a ‘blanket’ around the crater. This behaviour leads to the possibility that a grounded plume or dense gas cloud could interact with buildings in such a way as to cause the CO_2 cloud to enter the buildings.

If the pipeline ruptured, there would be an initial period of rapid decompression to the saturation envelope for the CO_2 mixture within the pipeline. There would be a significant fall in the flow rate out of the pipeline once the two-phase boundary is established and propagates away from the rupture within the pipeline. Thereafter the flow rate would decay more slowly whilst the flow remained in two phases at the outlet (flow referred to as either two-phase or in two phases).

If the pipeline had been punctured, it would depend on the pre-existing flow rate in the pipeline and the size of the puncture as to whether the pressure in the pipeline and the initial outflow rate from the pipeline were maintained, the flow rate decreased slightly until a new constant equilibrium pressure was reached or the pressure and flow rate continued to decay, similar to a pipeline rupture described above.

Hence, it might be expected that the parameter R_{Time} will be larger for ruptures initially and could take a range of values for different sizes of punctures in a specific pipeline. This suggests that there is the potential for shelter indoors to provide a benefit, especially for ruptures, but that there is a need to consider further modelling of the interplay between the external cloud and the accumulation within a building to confirm this.

One approach to the modelling of the internal concentrations, given the external cloud parameters, wind speed and direction and properties of the openings, was adopted by [Lyons et al., 2015]. This extended the earlier work of [Brighton, 1986], to combine the flows generated by the cloud buoyancy and the wind, as suggested by [Etheridge and Sandberg, 1996]. The predictions using this approach were compared with data for one experiment in which a drifting gas cloud entered an enclosure which had two deliberate openings, one on its front face and one on its back face. The gas cloud was generated during an experiment simulating a rupture of a CO_2 pipeline at a reduced scale. The effective ventilation rate of this enclosure was considerably more than would be expected for a conventional domestic building, with a wind speed of 5 m/s giving a ventilation rate of approximately 20 ACPH (air changes per hour). The time dependence of the predictions and the concentration immediately outside on the upwind side and within the enclosure are illustrated in Figure 1, based on data from [Lyons et al., 2015].

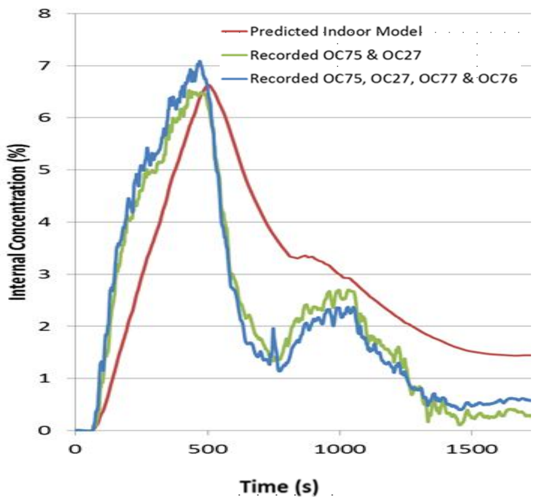


Figure 1: Observed and predicted concentrations in an enclosure with a high ventilation rate

As a result of the relatively high ventilation rates, the highest internal concentration approached, but never quite reached, the highest external values. The model of [Lyons et al., 2015] reproduces the rise and maximum value of the internal concentration for this case, involving an enclosure with deliberate openings. The absolute time of the peak concentration and the decay period after the release was terminated are less well predicted, possibly suggesting that the ventilation rate is being under-predicted in this case. However, because of the size of the deliberate openings relative to the volume of the enclosure, this case is not typical of all domestic buildings.

Further gas ingress data for enclosures with high ventilation rates was collected in an opportunistic manner during an experiment specifically designed to investigate fracture propagation in CO_2 pipelines. A temporary enclosure was placed in the likely path of the gas cloud produced during the fracture propagation experiment. Similar trends were found to the earlier scaled rupture experiment, discussed above. The openings in the enclosure used in this experiment were larger than would be expected in a typical domestic property, with a ventilation rate of around 250 ACPH predicted in a wind speed of 5 m/s and it is for that reason that a number of further experiments were carried out in November 2015, as described in the next section, to consider gas ingress from dense drifting clouds in more detail.

Overview of Experiments

A series of experiments were carried out specifically to investigate CO_2 accumulation in enclosures. In each experiment, the release was from a pipe routed horizontally from a CO_2 vessel, with the final section of pipe angled 45 degrees towards the ground. The release height was 0.5 m above ground level. This set up produced a drifting cloud of denser than air gas at ground level. This case is directly relevant to above ground releases on an Above Ground Installation (AGI), such as a block valve site or pump station, for example, and gives a drifting cloud comparable to that produced by a grounded puncture, although the flow velocities in the cloud close to the release may be higher in this case.

Two separate bulk containers, one on top of the other, were used to simulate part of the upstairs and downstairs of a building. They were located 15.3 m from the release point. The containers each had two deliberate ventilation openings, one on the largest (front) face, situated perpendicular to the release, and one on an adjacent short (side) face, as sketched in Figure 2.

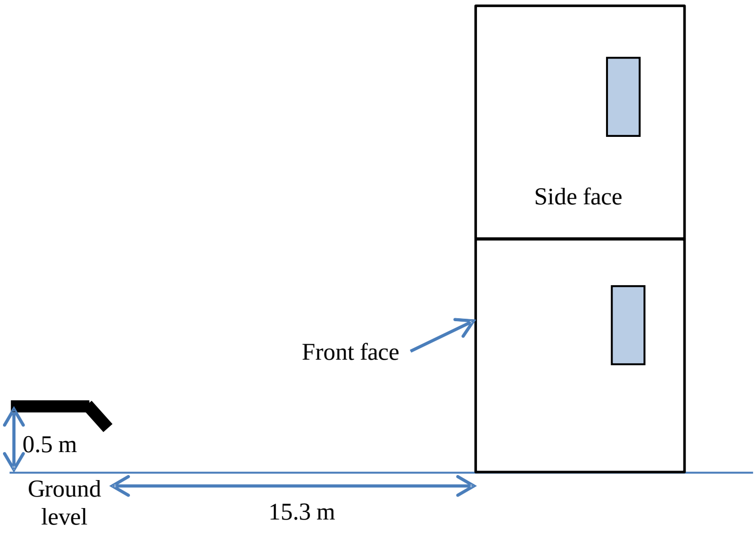


Figure 2: Configuration of the release and the containers (side view)

Each container was approximately 6.1 m x 2.3 m x 2.6 m (L x W x H). The ventilation openings on the containers were up to a maximum of 0.92 m x 0.97 m (W x H) and were located as indicated in Figure 3.

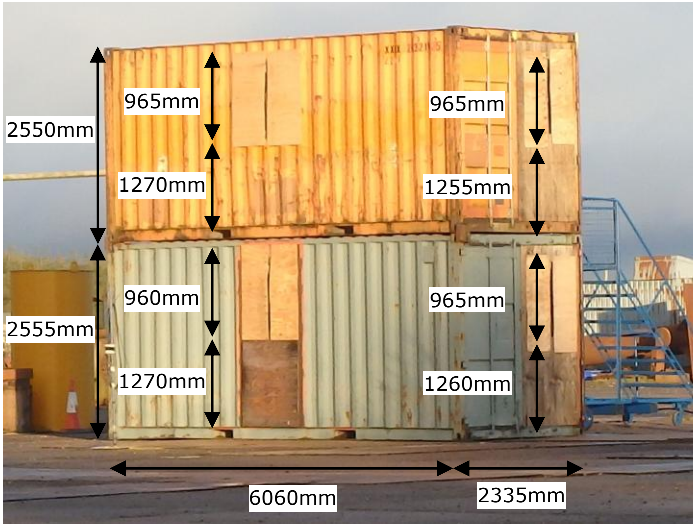


Figure 3: Layout of the containers, showing the positions of the deliberate openings

The widths of these openings were reduced in the experiments to approximately 25 mm, 50 mm and 150 mm, denoted options 1, 2 and 3 respectively, to investigate different ventilation rates. These openings are similar to those that would be present in a domestic property under typical conditions, and they would be expected to give a volume flow rate that is similar to that experienced throughout the whole of a property, ignoring high local rates in individual rooms caused by fully open doors or windows. However, because the enclosures are small, the ventilation rates expressed as air changes per unit time are larger than would be expected for a typical house.

The sizes of the releases were chosen to investigate different release durations and time dependencies. The position of the enclosures relative to the release was chosen so that the enclosures were exposed to external concentrations of between 2% and 20% of CO_2. This means that cases where the external cloud is potentially lethal or possibly capable of causing injury were studied to examine the resulting exposure inside the enclosures.

A summary of experiments carried out is given in Table 1.

Table 1: Release sizes and ventilation sizes used in the experimental programme, and measured wind parameters for each experiment

Test	Release diameter (mm)	Ventilation opening option on lower container	Ventilation opening option on upper container	Wind speed (m/s)	Wind direction (deg)
1	15	Option 2 – 50 mm	Option 2 – 50 mm	2.9	239
2	5	Option 2 – 50 mm	Option 2 – 50 mm	1.8	228
3	15	Option 1 – 25 mm	Option 3 – 150 mm	1.6	228
4	30	Option 2 – 50 mm	Option 3 – 150 mm	3.7	260
5	10	Option 2 – 50 mm	Option 3 – 150 mm	2.1	227
6	5	Option 2 – 50 mm	Option 3 – 150 mm	2.7	243
7	40	Option 1 – 25 mm	Option 3 – 150 mm	3.0	254
8	10	Option 1 – 25 mm	Option 2 – 50 mm	1.3	244
9	10	Option 3 – 150 mm	Option 2 – 50 mm	0.3	10

The measurements that were made included the following in all of the experiments:

- Pressure and temperature in the CO_2 vessel and in the release pipe.
- Wind speed and direction at two different locations/heights, with one mast upwind of the containers.
- Ambient temperature and humidity.
- CO_2 concentration and temperatures at 22 locations inside and outside the enclosures

The cloud that was produced in the experiments was approximately the same height (2.5 m) as the bottom enclosure as it approached the containers. Video records of the experiments show that the cloud 'splashed' against the front face of the enclosures, with some of the CO_2 moving around the enclosure and some up and over it. A side view from one of the experiments is shown in Figure 4, illustrating this behaviour.

Figure 4: Side view of the interaction of the dispersing plume with the containers

In this test, CO_2 concentrations of between 4% and 6% were measured on the front face of the enclosures. For the release and atmospheric conditions in this test, the cloud reduces the visibility at such concentration values, obscuring parts of the containers. The plume increases in height as it passes over the containers and reduces in height some way behind them. However, the plume downwind of the containers appears to be significantly higher than it would have been if the containers had not been present.

Analysis of the Experimental Data

The CO_2 was released from an orifice in the end of a 50 mm diameter release pipe connected to the vessel containing the CO_2. The measurements taken of the pressure and temperature in the CO_2 vessel and the release pipe were examined and it was confirmed that a saturated liquid was approaching the orifice. As an example, the measured temperature and pressure in the release pipe approaching the orifice during two of the tests are shown in Figure 5.

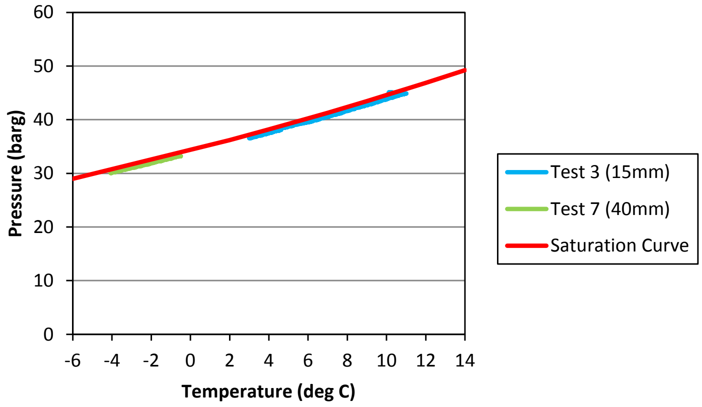


Figure 5: Measured temperature and pressure immediately upstream of the orifice compared to the predicted saturation source for CO_2

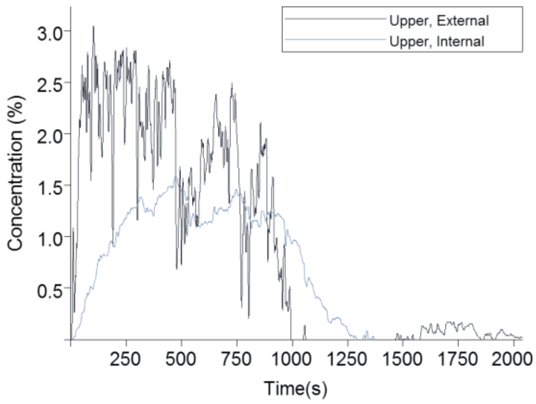
The pressure drop along the release pipe was dependent on the diameter of the release, with a negligible pressure drop recorded for the 5 mm diameter releases, and pressure drops of 1.2 barg for the 30 mm diameter release and 3.3 barg for the 40 mm diameter release. This is consistent with the larger releases giving higher flow speeds and greater frictional losses in the release pipe.

The predicted values of the average release rates over the duration of the release vary from 0.5 kg/s for the 5 mm releases to 29 kg/s for the 40 mm diameter release.

The measured values of the wind speed and direction, the properties of the release and video records of the progress of the cloud were used to estimate the relative importance of buoyancy to momentum forces, R_{Force}, in the CO_2 cloud during the release. These values suggest that the momentum driven ventilation forces should dominate over the buoyancy driven forces in the majority of the experiments. However, in several of the tests, the CO_2 cloud advection speed is significantly faster than the ambient wind speed, suggesting that the momentum of the CO_2 release may affect the rate of gas ingress into the containers.

Figure 6 illustrates the time dependent accumulation observed in two of the experiments with different estimated values of R_{Time}. The 5 second averaged concentrations are used in plotting this figure and the internal concentrations are an average over the whole height of the enclosure. During the accumulation period, the interior of the enclosure appeared to be well mixed during all of the experiments and this finding allows the analysis to be simplified significantly. However, in one third of the experiments there was evidence during the decay periods after the release had passed, that the CO_2 cloud was removed preferentially from the upper part of the enclosure, leading to some stratification. The remaining two thirds of the experiments were reasonably well mixed during the decay period. A more detailed analysis of this behaviour has not been undertaken at this time.

a) Test 5, Upper Container, $R_{Time} = 0.24$



b) Test 7, Lower Container, $R_{Time} = 2.97$

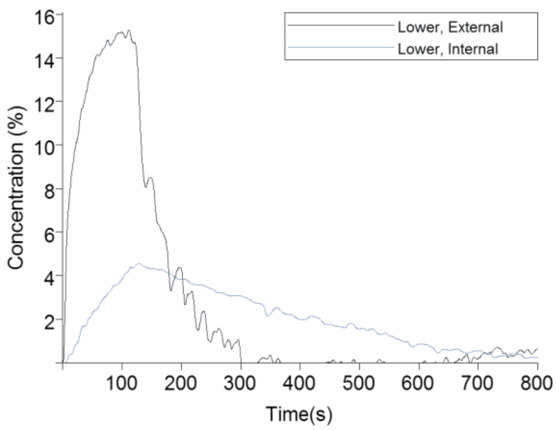


Figure 6: Comparison of the internal concentration and external concentration on the front face, for tests with different values of R_{Time}

The first experiment (Test 5) with the smaller value of R_{Time} almost reaches a steady state during the release (duration 900 seconds), with the average internal and external concentrations being almost the same towards the end of the release, whereas in Test 7, which has a larger value of R_{Time}, the internal concentrations have not yet approached the external values. The value of R_{Time} and the ratio of the maximum internal and external concentrations have been calculated for each experiment, and the results are shown in Figure 7.

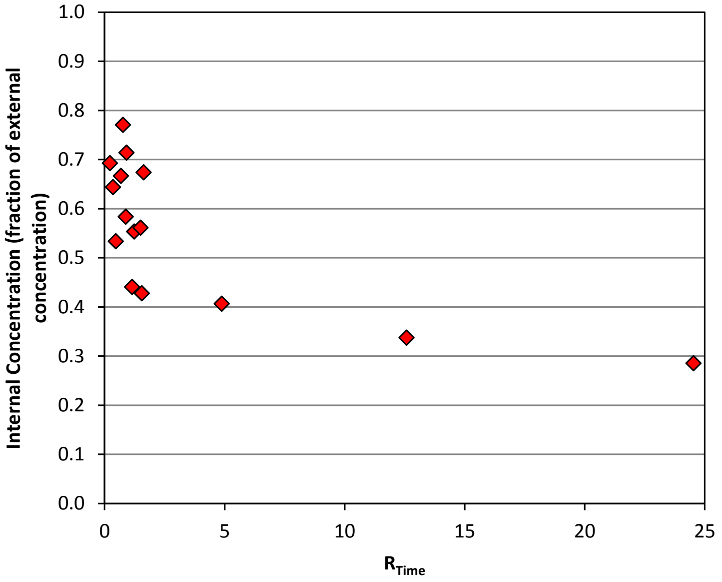


Figure 7: Comparison of the ratio of the internal and external concentrations with the dimensionless parameter R_{Time}

There is some scatter in this graph, but it shows that the internal concentration was always less than the external concentration in these experiments, and tended to be smaller compared to the external concentration for larger values of R_{Time}. This figure confirms that enclosures can offer protection during exposure to drifting clouds, with the parameter R_{Time} having an important role to play in determining the extent of the beneficial effect.

The maximum external concentration at the upper enclosure is up to about 85% of the maximum external value on the lower enclosure for all of the experiments. This suggests that there is a vertical profile of concentration that is present in the external cloud over a 5 m height range. Bearing in mind the large value of 8 in the toxic index for CO_2 used in evaluating the dose, this result suggests that, irrespective of any stratification that might arise within an enclosure, the exposure to near ground releases of up to about 50 mm in diameter is likely to be less upstairs than downstairs.

A plot of the maximum observed internal concentrations against the maximum observed external concentrations on the opening on the enclosure front face is shown in Figure 8, for both the upper and lower enclosures.

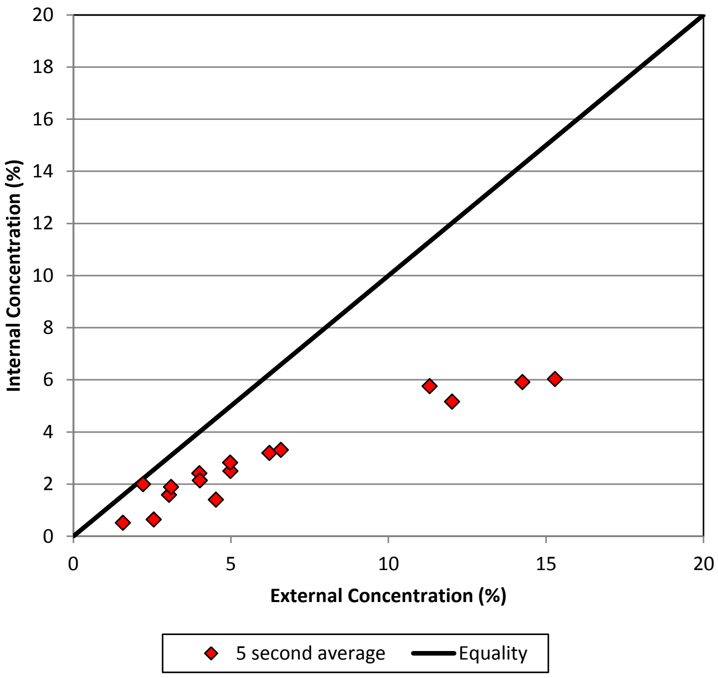


Figure 8: Comparison of the maximum internal and external concentrations (5 second average values used)

This figure shows that in all cases, the maximum internal concentration is less than the corresponding maximum external value. Further, it is apparent from the majority of the experiments that there is less fluctuation in the concentrations detected by the instrumentation internally than externally.

The dose accumulated over the time from 250 to 850 seconds, when the concentration internally and externally appear to be fluctuating about a relatively steady value, has been evaluated from the measurements for the upper container in Test 5 (see Figure 6a). The toxic dose over this period has been evaluated using the 5 second moving average value and compared with the value deduced from the overall average. The results are given in Table 2. As discussed in [Cleaver et al., 2015], there is a significant difference in the dose that is evaluated depending on the time averaging applied to the concentration records. However, the difference is significantly more for the external cloud than for the internal cloud.

Table 2: Concentrations and toxic doses for the upper container in Test 5, for a 10 minute period

Parameter	External	Internal
Mean concentration (%)	1.78	1.29
5 second Peak Concentration (%)	2.42	1.58
Dose calculated from mean (ppm^8.min)	1.2×10^{35}	7.8×10^{33}
Dose calculated from fluctuating 5 second average (ppm^8.min)	5.2×10^{35}	1.0×10^{34}
Ratio of peak to mean concentrations	1.56	1.33
Ratio of doses calculated from fluctuating and mean concentrations	4.32	1.28

This, and results from the other experiments, illustrate that over the timescale over which people breathe, there is usually much less variation recorded in the experiments in the internal concentration than the external concentration. Therefore, even if the long-time mean values were the same inside and outside, the calculated dose received by a person inside is likely to be significantly less than outside, as the dose is calculated as a time integral of the eight power of the concentration.

A partial check on the importance of the buoyancy contribution to the ventilation rate can be made by considering the period after the release has stopped when the concentration of CO_2 outside the enclosures is small. If the ventilation rate were dominated now by the wind driven motions rather than buoyancy motions, the effective ventilation during this period would be steady if the wind speed remained steady. The concentration level inside the enclosure would be expected to decay exponentially, with a plot of the logarithm of the internal concentration showing a linear decay with time. This is examined for the data from the lower container in Test 3 in Figure 9, where the 5 second averaged concentration over the whole height of the enclosure is plotted. The solid blue line in the figure shows the best exponential fit between the time that the external cloud had dispersed to the time that the internal concentration had decayed to 20% of its value at that time. The dashed line is an extrapolation of this fit to longer times, greater than 1700 seconds, showing that the linear decay continues down to quite low concentration levels.

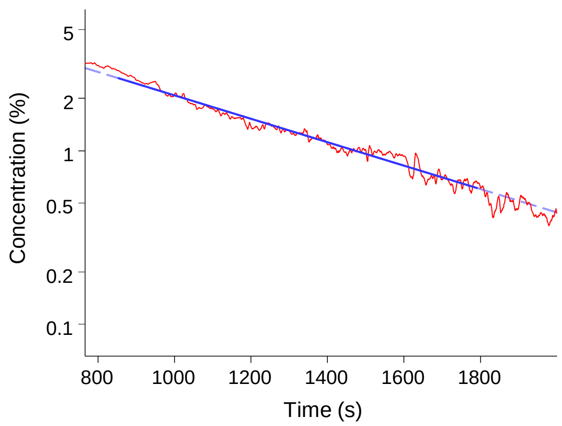


Figure 9: Concentration decay inside the lower container for Test 3, in the period when the external cloud has dispersed, and the external concentration is negligible

The slope of the best fit straight line, illustrated in Figure 9 above for one of the experiments, can be used to estimate the effective ventilation rate during the decay period for the experiments in which the enclosures had the higher concentrations present when the release ended. These cases were selected as it proved easier to fit the decay curve for the experiments involving higher concentrations.

Ignoring buoyancy effects, the equations in BS 5925 can be used to estimate the possible wind-driven ventilation rate during this time. According to this analysis, for a wind normally incident on the front face of the enclosure, the ventilation rates of the container (in the absence of a release or its effects) can be calculated as follows:

$$Q_{Front} = A_{Free}^{Front} C_D \sqrt{\frac{2(P_{Front} - P_{Int})}{\rho_a}} \text{ and } Q_{Side} = A_{Free}^{Side} C_D \sqrt{\frac{2(P_{Int} - P_{Side})}{\rho_a}} \quad (7)$$

where Q_{Front} and Q_{Side} are the ventilation flows into the front and out of the side of the enclosure, A_{Free}^{Front} and A_{Free}^{Side} are the open areas on the front and side respectively, ρ_a is the density of air, P_{Front} and P_{Side} are the pressures on the front and side of the enclosure respectively due to the wind, P_{Int} is the internal pressure and C_D is a discharge coefficient.

The equations are solved to find the value of P_{Int} which conserves volume, or $Q_{Front} = Q_{Side}$ in this case.

The pressure differences from the background atmospheric pressure on the faces of the enclosure can be calculated from the wind speed:

$$\Delta P_{Face} = \frac{1}{2} C_P^{Face} \rho_a U_{Wind}^2 \quad (8)$$

where C_P^{Face} is the pressure coefficient on the face and U_{Wind} is the wind speed.

For the aspect ratio of the enclosures used in these experiments, BS 5925 suggests pressure coefficients of +0.7 and -0.7 on the front and side faces respectively. Under these conditions, and given that the open areas on the front and side of the enclosures are always equal in this set of experiments, the equations reduce to:

$$Q_{Front} = Q_{Side} = A_{Free} C_D \sqrt{0.7} U_{Wind} \quad (9)$$

If a value of 1 is used for C_D, this reduces to $0.84 A_{Free} U_{Wind}$. This equation can be compared with the values inferred from the concentration decay, as shown in Figure 10, where the estimated ventilation rate during this period is plotted against the product of the component of the wind speed directed normally on to the front face of the enclosures and the free area available on the nominal inlet face. The inferred ventilation rates are only shown for the twelve cases where the maximum internal concentration was sufficiently large to allow the gradient of the decay to be estimated. Experiments where the CO_2 inside the enclosures was well mixed or stratified in the decay period are plotted in different colours.

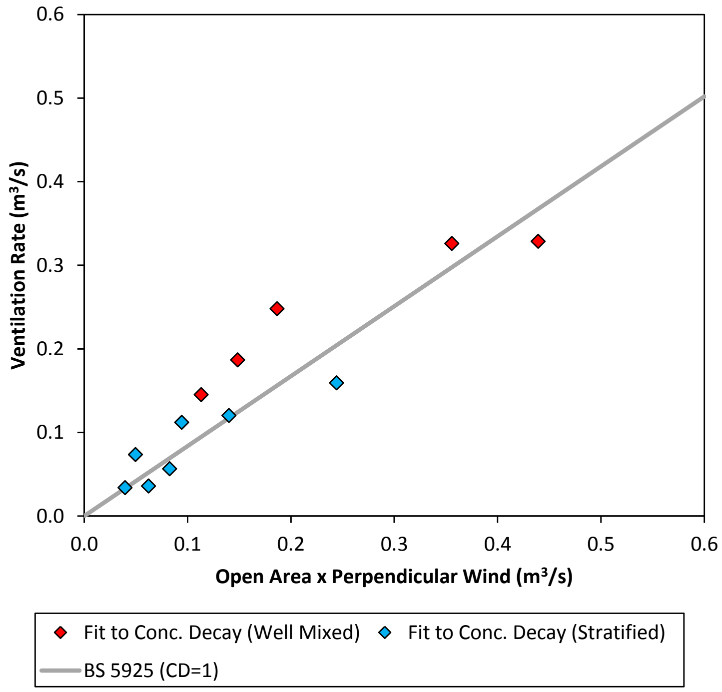


Figure 10: Comparison of the estimated ventilation rate over the decay period with the product of the open area on the front face and the perpendicular wind

The equation is seen to give an approximate fit, with little difference apparent between the experiments that stratified or remained well-mixed in the decay period. It is noted that the inferred ventilation rate tends to be higher for the experiments where the CO_2 remained well mixed throughout the container during the decay period.

Similar plots of the rise in concentration whilst the CO_2 cloud is present suggest that the effective ventilation rate was approximately constant whilst the release was occurring. However, as noted earlier, during this time the external flow is likely to be affected by the momentum of the CO_2 release and buoyancy effects may be relatively more important. The behaviour of the ventilation rate during this period is considered in the following section.

Predictive Methods

The analysis of the experiments reported above suggests that the data that has been collected is self-consistent and the trends observed in the experiments follow a logical pattern. As a result, it is valid to use the data to explore the performance of predictive models for dense gas accumulation in enclosures. Before doing this however, it is worthwhile considering the type of predictive models that are required for QRA work. When carrying out a QRA, the details of the location and size of any openings on a building are not likely to be available for a general case. Therefore, either some form of generic approach has to be adopted for indoor risk or the differences between indoor and outdoor risk have to be ignored. The experimental work reported here provides some direct evidence that the latter approach would have the advantage of being cautious. However, when considering that the results of a QRA are often used to help decide between different options, there is the potential that some very real differences in risk would be lost if the cautious approach were always applied. As a result, a generic approach is reasonable, provided that specific situations that are being modelled do not lie too far from the assumptions made in deriving the approach. It is for the exceptional situations that a more case-specific model is required. In addition, such a case-specific model would be useful when exploring or explaining the outcome of an actual release during subsequent incident investigations, if an accidental release were to take place.

As a result of the above, in the QRA methodology developed as a result of the COOLTRANS research programme, a generic model based on the perfect mixing equation (see Equation 4 above) was used to infer a representative indoor concentration from the external value at each location, as a default. The ventilation rate that was used was based on the results of a series of calculations of the wind driven ventilation of an enclosure. A range of different wind speeds and angles, open areas on the enclosure walls and enclosure size were considered. In order that the ventilation rate that was used was not unrealistically small at lower wind speeds, a cut-off was applied, corresponding to a wind speed of 4 m/s at 10 m elevation and for lower wind speeds the ventilation rate at 4 m/s was used. (A check was made on the likely size of any buoyancy driven ventilation when choosing this value). In practice, in the QRA the proportions of time that the indoor and outdoor risk are used for each location can be varied from location to location, to reflect different situations, should this be needed.

It is of interest to know how the generic approach, based on the assumed volume flow rate for a representative building, would fare when predicting the CO_2 accumulation observed during these experiments. The performance of the model in predicting the maximum observed internal concentration and the dose is illustrated in Figure 11.

a) Maximum internal concentration b) Internal dose

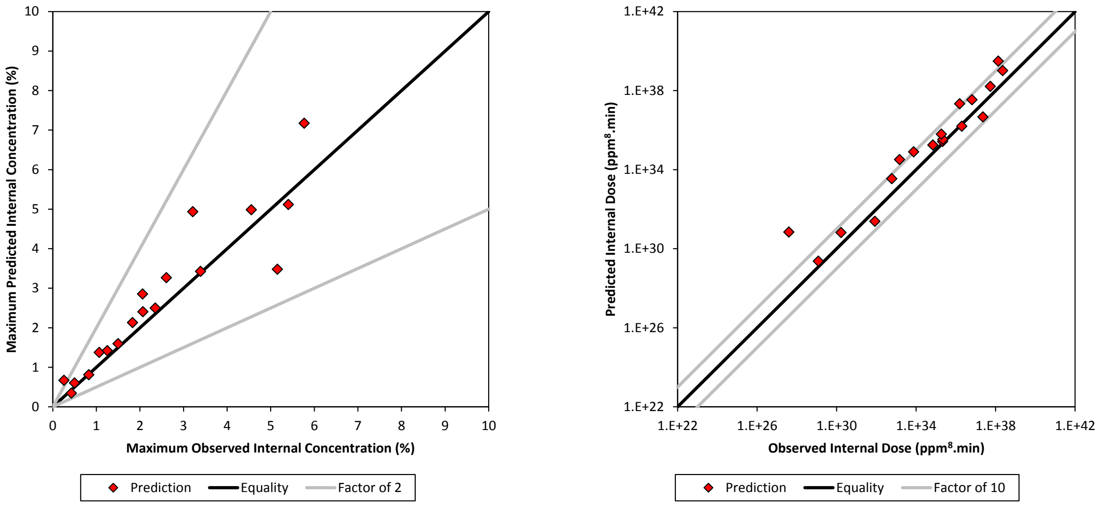


Figure 11: Comparison of the observed and predicted maximum internal concentration and internal dose with the predictions of the generic QRA model

This suggests that the generic approach would have been reasonable if applied to these specific experiments. However, as noted earlier, the openings on the containers were chosen to be similar to those that may be present on a domestic property and so this result is not too surprising.

However, there may be specific situations that require more detailed investigation or that fall outside the range in which the estimate of the generic ventilation rate is reasonable. In such situations, a case-specific approach is needed. The work of Kingston University and Warwick University in the COOLTRANS research programme showed that CFD models can be applied to specific cases in which it is important to model the precise details. The approach of [Lyons et al., 2015] represents an intermediate level of sophistication that would have the attraction of speed and ease of application. It is the intention to explore developing this latter approach in future work. For the present, however, this section ends with further consideration of how well a perfect mixing model based on some knowledge of the ventilation rate would perform. That is, the inferred ventilation rate from the decay period can be used in a perfect mixing model to predict the internal concentration from the observed external concentration. The predictions are shown in Figure 12 for those particular experiments in which the measured internal concentration was sufficiently large that the calculation of the ventilation rate from the concentration decay was likely to be robust.

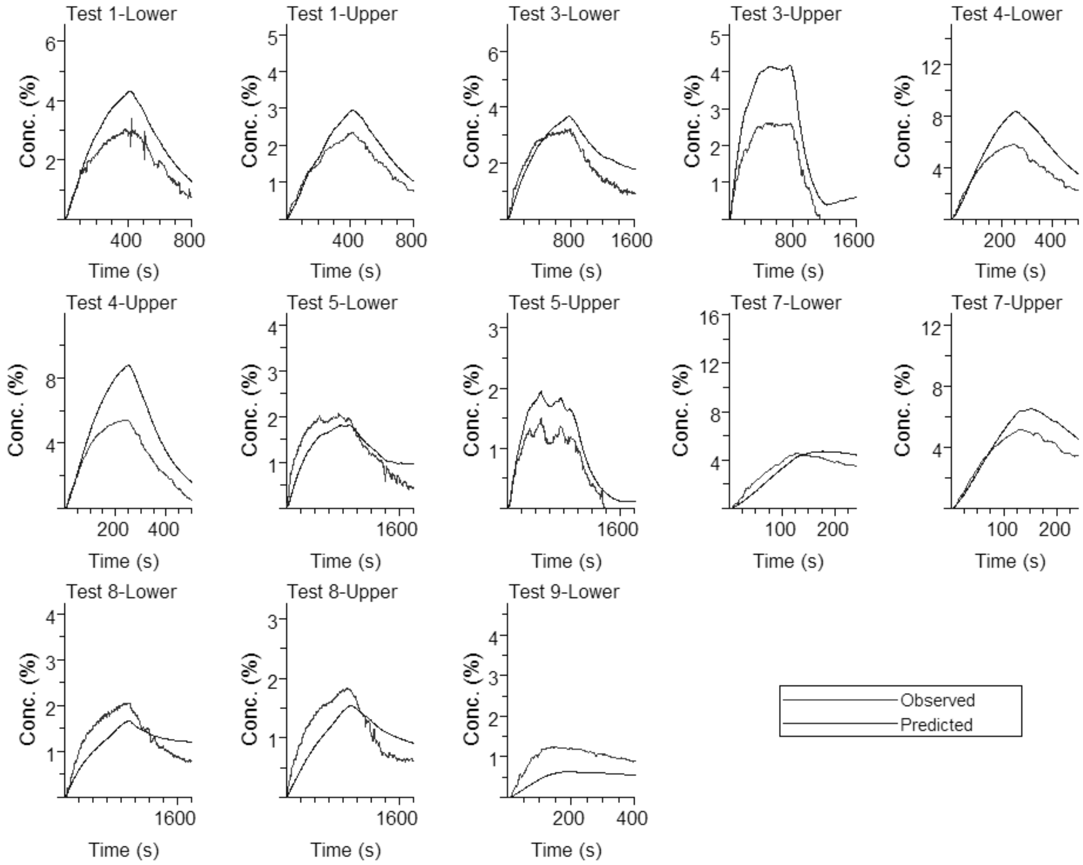


Figure 12: Observed internal concentration and internal concentration predicted from external concentration using a perfect mixing model

Overall, the predicted maximum concentrations tend to be slightly too high. This would suggest that the effective ventilation rate may have been slightly lower in the majority of the cases whilst the release was present. This may be some combination of the effect of the release momentum on the wind flow or a buoyancy difference between inside and outside acting against the inflow. Of the three cases in which the predicted concentrations are noticeably lower than the observed values, one occurred in Test 9, which had a low wind speed. Under such a case, it is likely that buoyancy-driven forces may be important. The calculated value of R_{Force} for this case is larger than in the remaining experiments, indicating that this may be the reason. This was investigated in a series of further calculations, in which a constant buoyancy difference between outside and inside was included in calculating the ventilation rate. (In practice, the difference starts at a relatively high value and decreases as the difference between the internal and external concentrations reduces.) The resulting predictions are compared with the observed values in Figure 13. Two additional predictions are shown, an upper bound, where it is assumed that the CO_2 concentration difference is 4% (its maximum value) and a ‘best estimate’, where it is assumed that the concentration difference is 2%, the estimated average difference over the decay period.

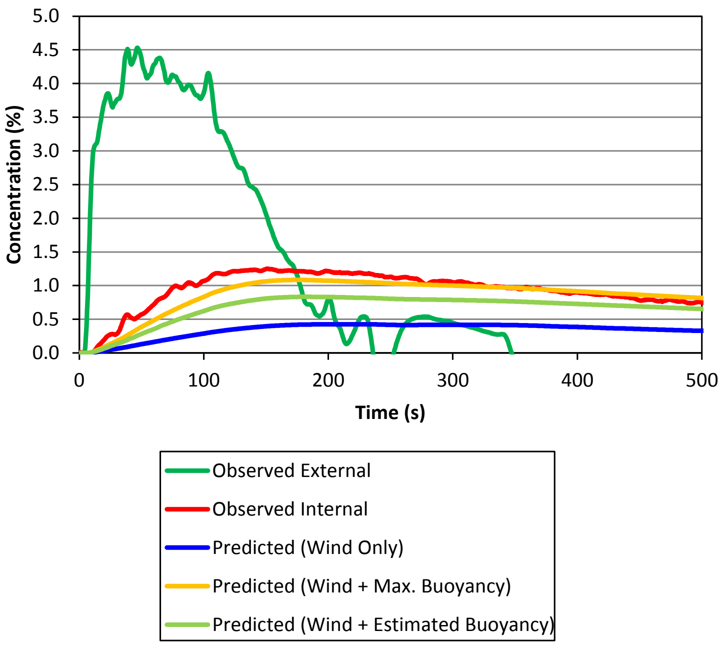


Figure 13: Observed internal concentration and internal concentration predicted from external concentration using a perfect mixing model for the lower container in Test 9

The predictions are much improved by including a buoyancy term and suggest that that buoyancy effects are important in this case, involving low wind speeds.

Overall, the predictions obtained using a case-specific approach (information on the size and distribution of the openings) shows promise and suggests that it may be possible to improve or refine the model of [Lyons et al, 2015] to provide a useful intermediate level modelling approach.

Discussion

The specific experimental data presented in this paper has been examined and shown to be self-consistent and consequently the results can be used to help investigate the effectiveness of different modelling approaches to dense gas accumulation. It has been shown in this paper that the existing generic approach adopted in the QRA methodology derived during the COOLTRANS research programme is not unreasonable. Further, it appears that a simple, zonal type of case-specific approach to modelling this situation can be developed. Such a model would be of benefit in investigating more critical or unusual cases in more detail or for establishing the effectiveness of the generic approach.

However, one of the main purposes of this paper was to investigate whether a person is likely to be safer inside than outside in the event of exposure to a drifting toxic cloud. The results from the experiments help to address this and confirm the conventional wisdom that people are generally safer indoors than outdoors in the event of a toxic release. It has been shown that the extent of the benefit seems to depend on a range of parameters, making generalisation difficult. Nevertheless, the ratio of time scales of the release to dense gas accumulation appears to be influential in determining the outcome. Further, there is evidence from these experiments that for releases of up to 50 mm in diameter close to ground level, there is a further benefit in sheltering upstairs, as opposed to downstairs, in a building if the passing cloud is denser than air.

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Emergency advice websites: See, for example, http://www.suffolkcoastal.gov.uk/yourhome/majoremergency/ for UK advice and http://www.alldeaf.com/showthread.php?t=87691 for USA advice (downloaded 11 January 2016)