EXPERIMENTAL STUDIES OF THE BEHAVIOUR OF PRESSURISED RELEASES OF CARBON DIOXIDE

Dan Allason, Keith Armstrong
GL Noble Denton, Spadeadam Test Site, UK
Julian Barnett
National Grid, Warwick, UK
Phil Cleaver, Ann Halford
GL Noble Denton, Holywell Park, Loughborough, UK

A large Research and Development programme has been initiated by National Grid to determine the feasibility of transporting carbon dioxide (CO_2) by pipeline. As part of this programme, National Grid has commissioned a series of experimental studies to investigate the behaviour of releases of CO_2 and mixtures in the gaseous and the liquid (or dense) phase. These experiments are being carried out both to understand the outflow and dispersion behaviour and to provide data that can be used in related mathematical modelling studies, in the development and validation of particular models, for example. In this paper, an overview of the experimental programme is provided. In addition, further details are provided on two of the experimental programmes that have been completed.

1. INTRODUCTION

National Grid is funding research, referred to as the COOLTRANS programme, to address gaps in knowledge on the safe design and operation of onshore pipelines for transporting anthropogenic, high pressure, dense phase carbon dioxide (CO_2) from large industrial emitters to storage. UK safety legislation requires that the risks associated with high pressure pipelines are as low as reasonably practicable (ALARP). Demonstration of this generally requires compliance with recognised pipeline codes. However, current pipeline codes do not apply to dense phase CO_2 or dense phase CO_2 with impurities. The aim of the COOLTRANS research programme is to provide data and information as technical justification for the operation of dense phase CO_2 pipelines, and the development, scrutiny and publication of code requirements, which National Grid considers essential to ensure the safe design and operation of onshore dense phase CO_2 pipelines in the UK. One of the parts of this programme is to collect experimental data during releases of CO_2 in order to assess and understand the observed behaviour. The experimental programme includes the collection of data covering deliberate releases through different vent arrangements and the simulation of accidental releases from buried pipelines.

As well as providing data that helps further the understanding of such releases, the data is being used in a parallel programme of theoretical studies in the COOLTRANS programme. The theoretical studies by University College London (UCL), the University of Leeds and Kingston University are being carried out to provide 'state of the art' models for the outflow, near field dispersion behaviour and far field dispersion behaviour associated with below ground CO_2 pipelines that are ruptured or punctured. Further, the Health and Safety Laboratory (HSL) is currently involved in developing a model evaluation protocol to use to assess the performance of predictive models using this data. Ultimately, it is the intention to apply the learning from these studies in any development work that might be required to model releases from a dense phase CO_2 pipeline and within an appropriate quantified risk assessment (QRA) methodology.

The purpose of this paper is to give an outline of the contents of the experimental programme and to provide information that summarises some of the findings to-date. To this end, Section 2 provides an overview of the different experimental studies that are being carried out as part of this research programme. Section 3 gives more details of a series of venting experiments undertaken and Section 4 provides details of the experiments conducted to study punctures in a below ground pipelines. The preliminary results from these two programmes are discussed in Section 5, where the way in which the information is being used within the programme is discussed in more detail in a final summary in Section 6.

2. OVERVIEW OF THE EXPERIMENTAL PROGRAMME

National Grid is currently funding a series of experiments that study the rapid depressurisation and behaviour immediately following the fracture of a below ground dense phase CO_2 pipeline. These studies are being carried out at GL Noble Denton's experimental test facility at Spadeadam in Cumbria. Overall, the experiments are concerned with providing information to confirm that the possibility of generating a long running fracture in the pipeline has been minimised. However, where the opportunity presents itself, further measurements are being taken in these experiments to provide data of relevance to the outflow and dispersion behaviour.

An example of this is during a series of preparatory instrumented burst tests on different pipeline sections, the opportunity was taken to measure the size and nature of the crater that was formed by the sudden release from a pressurised, buried section of pipeline. Figure 1 shows that the crater that was formed in one of the experiments had a similar character to those observed during other pipeline incidents.

A series of shock tube experiments have been conducted to understand the decompression behaviour of CO_2, see Cosham et al (2012). An experiment was carried out by suddenly opening one end of a 144 m length of 150 mm diameter pipe to initiate an instantaneous, full bore release, of a specific mixture at a pre-defined pressure and temperature. The resulting depressurisation was monitored using an array of pressure transducers mounted along the bore of the shock tube. These record the rapid pressure changes that took place. A series of thermocouples were attached to the external surface of the shock tube along its length to monitor the wall temperature. The bottom of the tube was positioned about 600 mm above the local ground level and instrumentation was deployed at suitable locations downstream of the point of release to gather data on the dispersion of this highly transient release in the atmosphere.

The earlier experiments were carried out with the dispersion taking place over relatively flat terrain, but in some of the later experiments, a specially constructed mound was placed in front of and perpendicular to the direction of the outflow in order to investigate the effects of an obstruction on the flow. In the final experiments in this programme, an area of sloping terrain was created to one side of the nominal plume centreline, to see how this influenced the release behaviour.

A specific full-scale instrumented fracture propagation experiment was carried out in late April 2012 and as part of the planning for the experiments, a number of predictions were made of how the transient cloud that is formed would disperse and, as with the earlier shock tube experiments, the opportunity was taken to record the dispersion of the cloud produced by the release. Whilst the above data is valuable in terms of illustrating the range of behaviour it is less than ideal for the purposes of model development or validation. The highly transient nature of the outflow means that steady conditions are not reached in the dispersing plume and the concentration data that has been captured is insufficient on its own for the development of meaningful statistical analysis on model performance over the range of conditions of interest. However, in the other parts of the COOLTRANS programme, specific experiments are being conducted with a purpose of gathering a data set of more use to modellers. In particular, a series of idealised venting experiments have been completed at Spadeadam. In the first series, a flow delivery system was designed to provide approximately steady release conditions from a vessel connected by a short length of pipeline to a vertical vent. The subsequent dispersion was observed and measurements were made in the region around the release and further downwind at ground level. The second series of experiments involved releases from an isolated section of pipeline through a horizontal vent arrangement. The purpose of these experiments was to make measurements within the isolated section and to record the changing conditions as the system slowly depressurised. These experiments are described more fully in Section 3.

Figure 1. View of crater formed during instrumented burst tests on a buried section of pipeline

A series of puncture experiments has been carried out from a section of buried pipeline. The situation of most practical interest in risk assessment arises when the flow from a punctured pipeline is less than the flow rate within the pipeline before the release commenced. For example, the CO_2 flow rate through a 900 mm diameter pipeline could be up to 1000 kg/s and so would be well in excess of the flow generated through a 25 mm or 50 mm puncture. This means that an approximately steady state could be generated, with little change in the conditions within the pipe. As a result, unless other action was taken, a hazard could be present for a long time. An experimental rig was set up to simulate this type of situation at full scale. This involved constructing a 'test section', consisting of 914 mm outside diameter pipeline, that was supplied with dense phase CO_2 from a connected 'charge line' in order to maintain approximately steady conditions within the test section. The test section was buried 1.2 m below ground to simulate a typical transportation pipeline. The programme included a series of 7 experiments in which the pipe was backfilled and so the release was left to form its own route to the surface. In one experiment, a pre-formed crater was constructed to take the shape and size of a crater that had been formed in an earlier experiment. The release was initiated into the pre-formed crater without backfill being added. Therefore, the release took place initially into air, in this case. A series of measurements were made immediately above the pre-formed crater, as there were no problems to contend with from soil debris created by the release. In all of the experiments, the resulting plume was videoed and measurements were made of any CO_2 present at ground level in a nominal downwind quadrant from the release and at an intermediate distance surrounding the release location. The outflow was continued in these experiments for a sufficiently long period for an approximately 'steady' plume to be formed. These experiments are described in Section 4.

A further series of experiments are proposed to study simulated scaled rupture experiments. It is envisaged that these will be carried out at a nominal scale of 1 to 6, and the purpose of the releases is to simulate specific stages of the outflow that might arise following the rupture of a full-scale pipeline. Again, it is proposed to consider a combination of experiments in which any crater is allowed to form 'naturally' and an experiment involving a release into a pre-formed crater without backfill. It is proposed that these experiments will be commenced in late 2012, with final details of the programme being established after completion of the full-scale fracture propagation experimental programme.

In addition, other experiments are being carried out to examine the cooling effect around a pipeline in the event of small leaks from the pipeline. These experiments are being carried out to address specific concerns over the integrity of the pipeline, although as with the fracture control experiments, where possible to do so, outflow and dispersion measurements will be made.

In the following sections more details are given about two particular experimental programmes that have been completed to study venting operations and punctures in a below ground pipeline, respectively.

3. VENTING OF CO_2

An outline drawing of the experimental rig used to study the venting through a vertical pipe is given in Figure 3. The rig consists of the following four main components:

- Charge line. This is a pipe of diameter 150 mm which is 132 m in length that slopes downwards from its connection with a high pressure nitrogen reservoir at the upper end towards the CO_2 storage vessel at the lower end.
- Main CO_2 storage vessel. This is a horizontal vessel of outside diameter of 610 mm that is 24 m in length. It can be filled independently from a large refrigerated CO_2 storage vessel or from the charge line.
- Supply pipe. This is a horizontal pipe of 51 mm diameter and length 12 m that is connected to the main storage vessel at one end by a flexible pipe and, having turned through 90 degrees at an elbow, to the vertical vent pipe at its other end.
- Vent pipe. This is a length of pipe that is connected to the supply pipe at one end and is open to the atmosphere at the other end. Vertical vent pipes of nominal diameters of 12 mm, 25 mm and 50 mm were used in the experimental programme.

A number of temperature and pressure measurements were made in the charge line and the vessel in order to monitor the experiments. A Coriolis flow meter was installed in the horizontal section of the supply pipe to monitor the mass flow rate. The pressure and temperature of the fluid was measured in the supply pipe at two locations 9 m apart. The pressure and temperature of the fluid near to the base and near to the exit of the vent pipe were measured for the 25 mm diameter vent test using the shorter vent pipe (release at 3 m elevation). In addition, in the experiments involving the longer vent pipe (release at 5 m elevation), an additional measurement was made at an approximately mid-point along the pipe length.

Above the vent exit, measurements of the plume temperature were made in two horizontal planes using thermocouples attached to a suspended frame, as illustrated in Figure 4. An array of oxygen cells was located at ground level in arcs at fixed distances from the vent in the nominal downwind quadrant. These were set out to capture information on the concentration and, at certain locations, temperature in the plume if it returned to ground. The layout of the instrumentation is shown in Figure 5. In addition, measurements were made of the atmospheric wind speed and direction, and the ambient temperature and humidity.

The charge line, storage vessel and supply pipe to the vent were filled with CO_2 to a pressure of 150 barg prior to an experiment taking place. After the checks had been made on the conditions in the system, a trigger was sent from the control room to open the valve in the supply pipe remotely to allow flow into the vent and to start recording the concentration and temperature data. The test proceeded for a pre-set time, during which quasi-steady conditions were set up in the flow path. The time was set so that the nitrogen used to maintain the pressure in the vessel did not enter the vessel during the data collection period. Appropriate valves in the charge line and the vent pipe were closed to terminate the flow.

The measurements collected during these experiments have been used in the COOLTRANS Project as a 'Case Study' in the theoretical work being carried out by UCL, the University of Leeds and Kingston University. Some preliminary predictions for this situation have been discussed by Russell (2011) and the data from the tests is being used in the development of a model evaluation protocol by Gant (2012).

The second phase of the venting programme involved horizontal releases from the shock tube rig described earlier (see Figure 2), consisting of an isolated section consisting of a 144 m length of pipeline, with an outside diameter of 150 mm. The pipe has a constant slope to the horizontal of approximately one half of a degree. In the venting experiments, the rig was filled with dense phase CO_2 until the required temperature and pressure was obtained. The rig was isolated and a valve was opened to allow outflow through a section of horizontal vent pipe. A photograph of the arrangement used when venting at the lower end of the rig is shown in Figure 6. No concentration measurements were made in these experiments, although thermal images were taken of the release and this shows a characteristic, momentum dominated jet like flow in the near field.

4. PUNCTURE EXPERIMENTS

The experiments in this series were carried out to study how a puncture in a below ground pipeline would behave.

a) View of the shock tube test rig, showing the release location

b) View of the instrumentation used to make the field dispersion measurements in the gaseous phase experiments

Figure 2. View of the shock-tube rig and field instrumentation deployed in the gaseous phase experiments conducted

A sketch of the experimental configuration is shown in Figure 7. A similar approach to the venting experiments was used in an attempt to maintain the pressure in the test section. For these experiments, the charge line was approximately 300 m in length and has an outside diameter of 305 mm (12 inch nominal bore) for much of its length, although it does change cross-sectional area at various points along its length (see below). The test section consists of a section of horizontal pipeline of outside diameter of 914 mm and of length approximately 16.5 m. Approximately 20 m upstream of the test section, the charge line splits into two lengths of 203 mm diameter pipeline, each one containing a Coriolis meter that could be used to measure the flow rate during the test. The test section was buried so that the crown of the pipe was at a depth of 1.2 m below the local ground level.

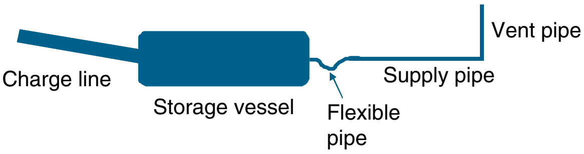


Figure 3. Schematic of experimental rig

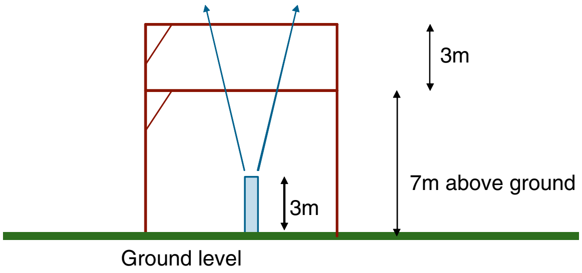


Figure 4. Location of horizontal planes in which temperature measurements were made for the releases at 3m elevation

The pipeline was fitted with a number of outlet ports around its perimeter in order to carry out the simulated puncture experiments from a below ground dense phase CO_2 pipeline at different locations. In each experiment, all of the outlets except one were fitted with blanking plates to prevent release. However, one outlet was fitted with a bursting disk that was designed to fail once a set pressure level was exceeded.

A sketch of the test section is given in Figure 8. This shows the locations of the outlets used in the test series and the positions where the wall temperature and internal fluid temperature and pressure information could be collected (note that not all of the instrumentation positions were used in each experiment). In the majority of the experiments, the release was allowed to form its own pathway that allowed the escaping CO_2 to reach the atmosphere. The size and shape of any crater that was formed was recorded as part of the experiment. In one experiment, a 'pre-formed' crater was constructed around the release location to simulate the shape of the crater formed in a previous experiment. This was not re-filled with soil and so the release in this experiment was initially into air. The lack of soil backfill meant that instrumentation could be deployed immediately above the crater in order to attempt to make velocity and temperature measurements close to the source of release.

The soil surface within about 100 m downstream of the test rig was levelled prior to carrying out the experiments. However, the reality is that the ground roughness at Spadeadam varies at greater distances than this from the release.

In the experiments involving releases from the dense phase, the measurements from the Coriolis meters were monitored during the experiment and the time at which the nitrogen-CO_2 interface passed this location could be detected. The valves separating the charge line from the test section could be closed at this point, effectively terminating the steady phase of these experiments. The pressure and temperature in the test section could be monitored after this time, in order to record the behaviour within an isolated section undergoing depressurisation. However, in most of the experiments, a valve connected to the bottom

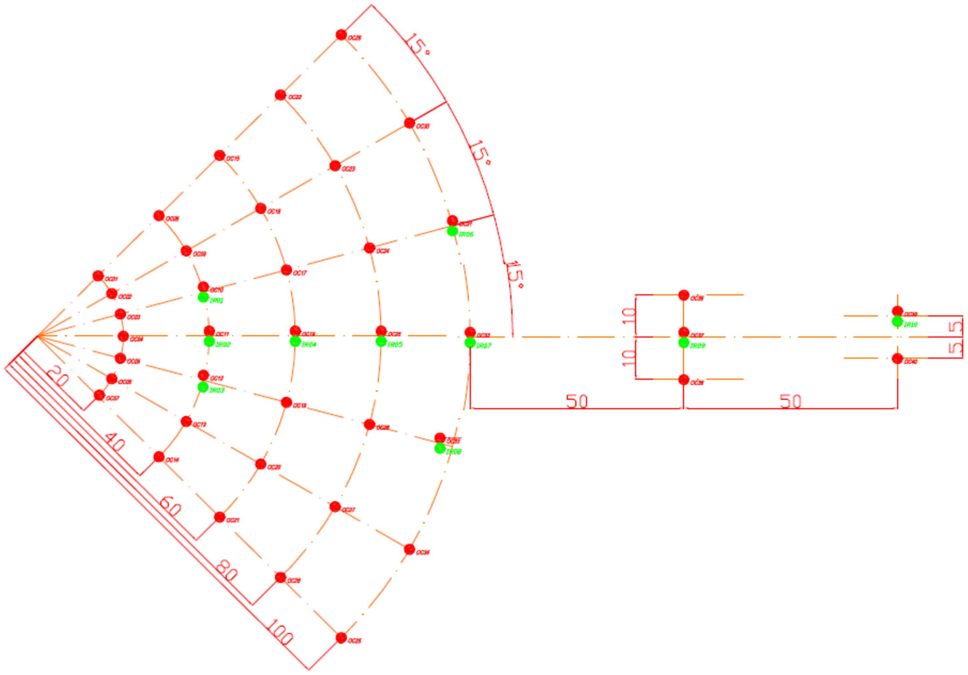


Figure 5. Location of concentration measurements at ground level (Pad North is directed from bottom to top of the page in these figures)

of the test section was opened to allow CO_2 to vent to atmosphere in order to shorten the time taken to depressurise the test section and to prevent too low temperatures being reached in the test section.

An array of oxygen cells was located close to the ground level around the crater and in arcs at fixed distances from the point of release in the nominal downwind quadrant. These were set out to capture information on the concentration of CO_2 and, at certain locations, temperatures in the dispersing plume. The locations of the sensors are shown in Figure 9. In addition, measurements were made of the wind speed and direction at a number of locations.

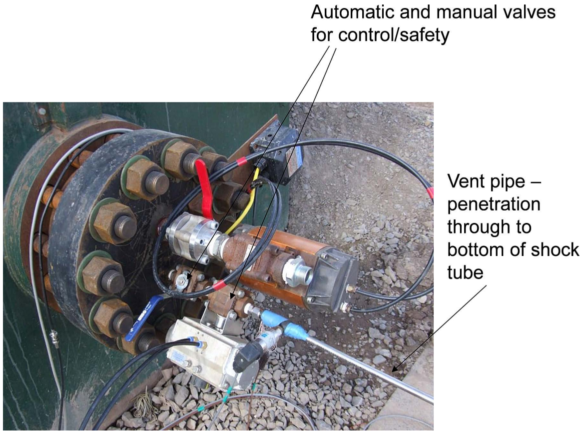


Figure 6. Arrangement used for venting from the bottom end of the shock tube

The ambient temperature and humidity were measured at a weather station within 500 m of the release location.

The configuration resulted in a quasi-steady flow through the opening on the side of the pipe into the pre-formed crater. Measurements were made of the concentration and temperature within the CO_2 cloud that was produced, as it dispersed in the atmosphere. The experiment involving the release into the pre-formed crater is being used as a further Case Study in the COOLTRANS Project by UCL, University of Leeds and Kingston University, see Gant (2012) for an outline of the planned programme of work.

5. LESSONS LEARNT FROM THE EXPERIMENTS

The venting experiments yielded useful and self-consistent information on the internal behaviour of CO_2 during a release, the outflow rate and the dispersion behaviour in the near and far field. The measured temperatures and pressures inside the test vessel (vertical venting) and the shock tube (horizontal venting) were used to estimate the phase of the contents. This indicates that the contents of the storage vessel remained in their initial phase during the experiments and that the flow from the storage vessel was approximately steady. There is some circumstantial evidence that the largest gaseous phase release may have condensed to form a two-phase mixture in the vertical vent pipe connected to the storage vessel, but this did not appear to affect the release behaviour greatly. The dense phase releases appear to produce conditions close to the saturation line inside the vent pipe towards its exit, with some suggestion that the flow was not

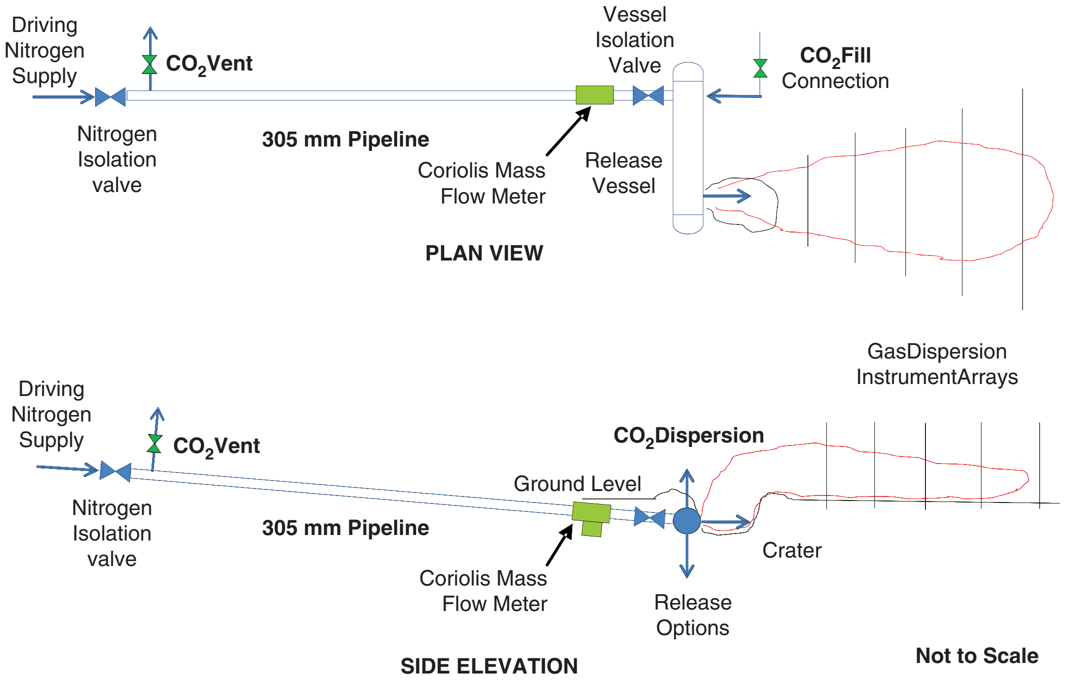


Figure 7. Sketch of experimental rig

in homogeneous equilibrium for the largest vent size used. In contrast, in the horizontal vent experiments, the pressure in the shock tube quickly fell to the saturated value when the release started and there were no significant pressure gradients along the 144 m length of the shock tube, despite the vent only having an internal diameter of 9.4 mm in some of the experiments.

The predictions of the outflow were in good agreement with the measurements for the vertical vents from a vessel containing CO_2 in the gaseous phase. For the equivalent dense phase releases, which took place at above the saturation pressure, i.e. with a subcooled liquid, Figure 10 compares the pressure and temperatures recorded along the flow path along the charge line, through the storage vessel, along the supply pipe and within the vent pipe during the quasi-steady period for one particular experiment involving the release from a vent through an 25 mm diameter vent pipe at an elevation of 3 m with a second experiment in which the release took place through a longer length of vertical vent at an elevation of 5 m.

The saturation line for pure CO_2 and a line representing an adiabatic expansion of the fluid from conditions at the exit from the storage vessel into the supply line are shown in the diagrams for reference. There is some indication that the

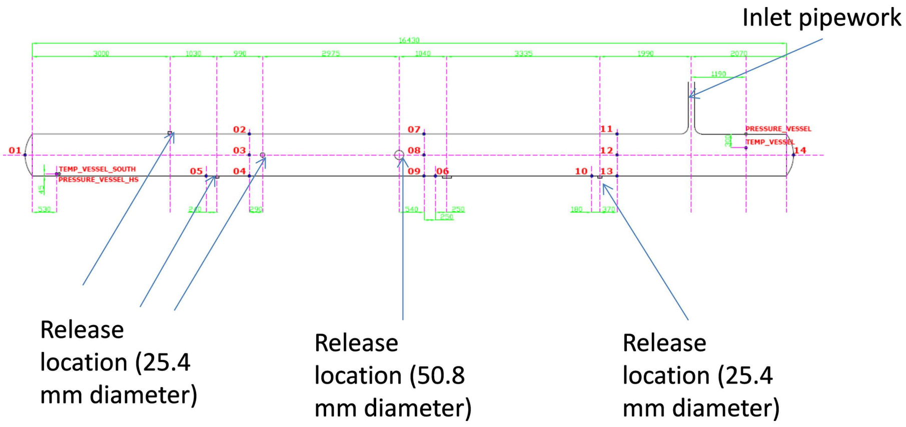


Figure 8. Location of release (horizontal), inlet pipework and externally mounted wall temperature measurements (numbers 1 to 14) and internal temperature and pressure measurements in the test section

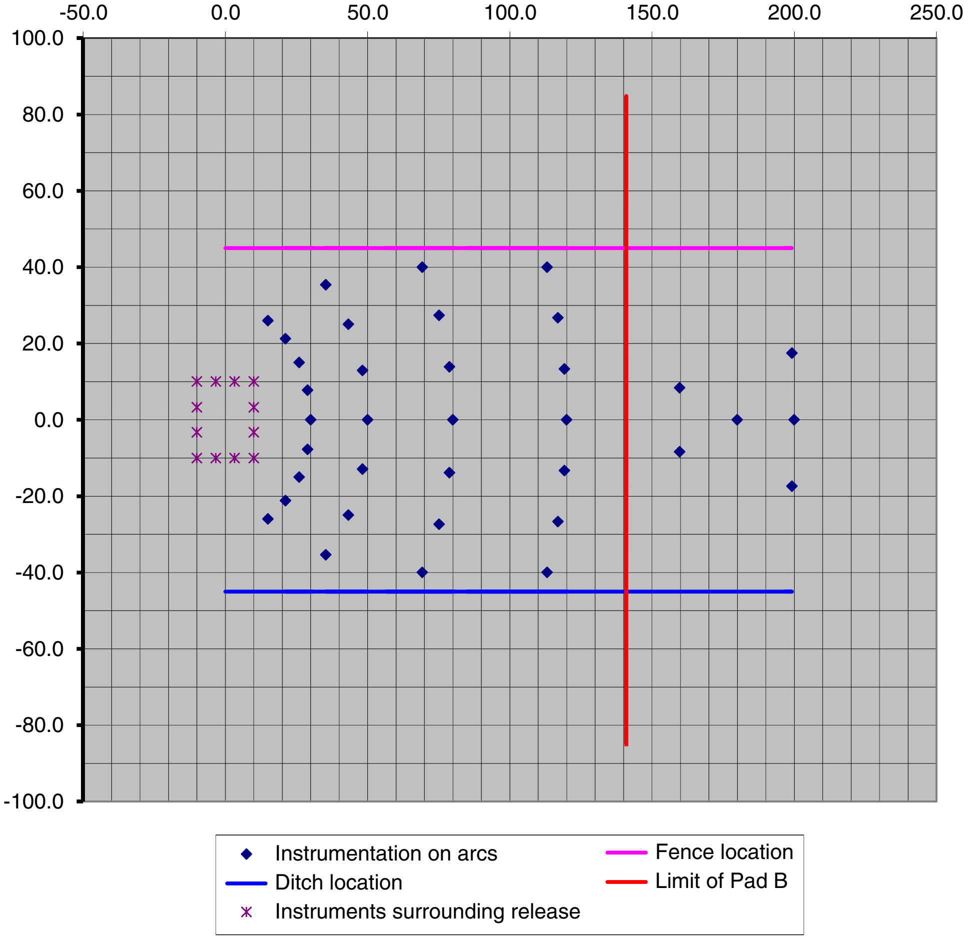


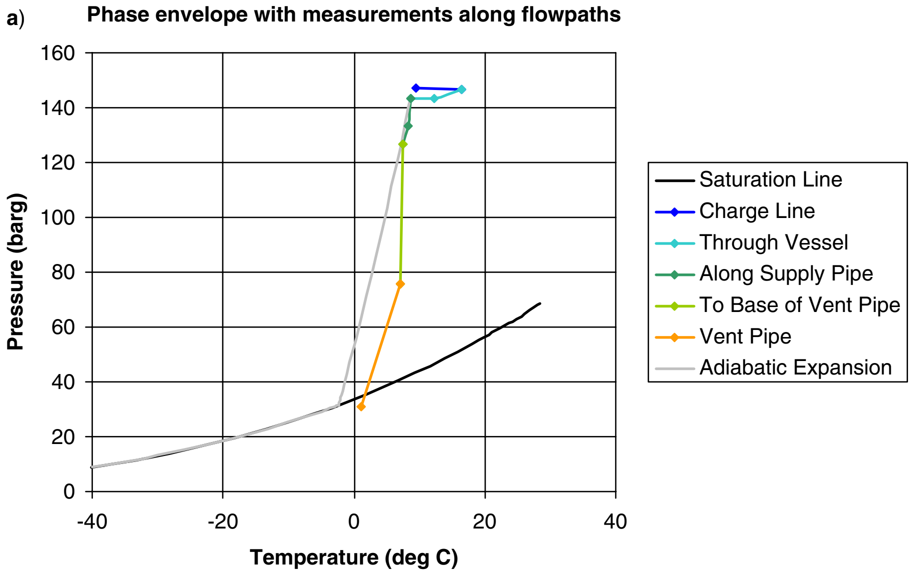
Figure 9. Locations of external temperature and concentration measurements

fluid may have overshot the saturation line on the approach to the vent, behaving as a metastable liquid, for the shorter length of vent. However, using a simple modelling approach based on the DIERS model, the predictions are not sensitive to whether it is assumed that the flow is a metastable liquid or in homogeneous equilibrium for the two smaller vent sizes (9.4 mm and 24 mm internal diameter) as little vapour is predicted to be formed along the flow path and both sets of predictions are in reasonable agreement with the observations.

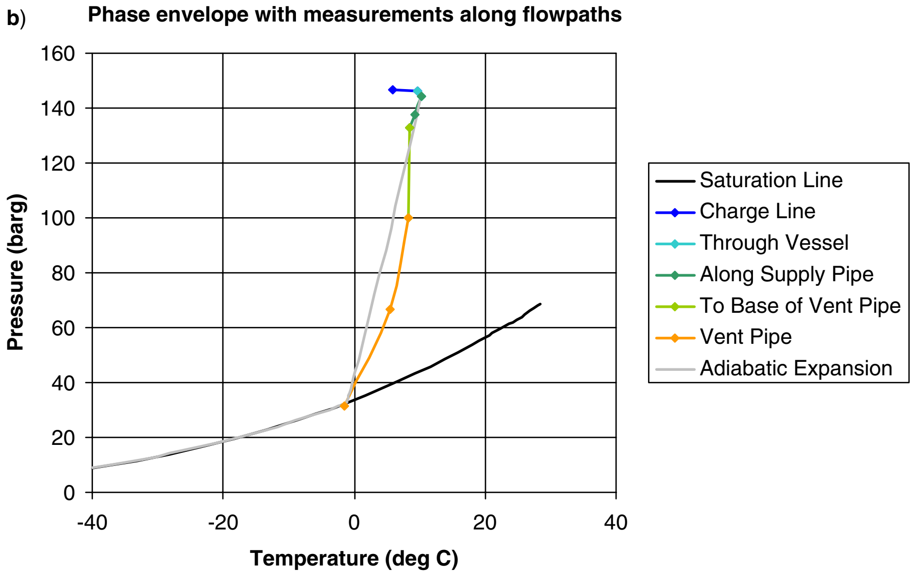
The outflow was larger than could be recorded when the largest size of vent pipe (50 mm nominal diameter) was connected and, from this, it appears that the predictions assuming homogeneous equilibrium are too small. That is, the flow did not ‘flash’ as much within the vent pipe to produce vapour as would be predicted assuming homogeneous behaviour, indicating a delay in the process of nucleation to form vapour.

For the horizontal releases from the shock tube, the pressure in the shock tube fell to saturation very quickly and there was little variation in the pressure observed along the pipeline, as seen from the graphs in Figure 11. The behaviour could be predicted assuming that the shock tube behaved as a single vessel with a pipe connected at the appropriate elevation. For releases from the bottom of the shock tube, good agreement is obtained with the observations of the duration of the release, if it is assumed that the fluid is in homogeneous equilibrium in the vent line, whilst the assumption of metastable liquid behaviour gives a flow rate that is too large and a pressure decay that is too rapid. This suggests that some flashing of liquid to vapour occurred along the flow path in the vent line in this case.

Vertical gaseous phase releases were observed to disperse upwards, and not to return to ground level in the immediate vicinity of the release. The plume trajectories are consistent with the predictions of various dispersion jet models over the range in which the plume could be observed. The vertical dense phase releases were observed to initially disperse upwards, but to return to ground level downwind of the release. The concentration at ground level was observed to fluctuate significantly, with maximum concentrations of up to about 1% being recorded for the largest diameter vent. This is well below the limit at which the CO_2 would be immediately dangerous to people.



Release through shorter vertical vent at 3 m elevation



Release through longer vertical vent at 5 m elevation

Figure 10. Recorded pressure and temperature in the internal flow path to the vent tip

The puncture experiments have shown that the nature of the surrounding soil is important in determining the precise nature of the flow into the atmosphere. For the smaller diameters of puncture in the clay soil, a distinct crater was not always produced. The release lifted and broke the soil surface but was not sufficient to blow the soil away completely. It appeared that an underground ‘cavern’ was created around the release and this was connected to the surface via a small number of distinct flow paths or ‘tracking routes’, each with a diameter of typically 100 mm. Taking into account the measured flow rate into the pipeline section, this indicates that the exit velocity from these flow paths was of the order of 40 m/s. This is similar to the type of behaviour that has been observed following a failure in a buried natural gas distribution main and it is possible that a model that has been used for risk assessment purposes could be extended to apply in this case as well. In this model, the flow path is modelled as from the pipe into an intermediate chamber that is connected to atmosphere by a tracking route. The pressure drops

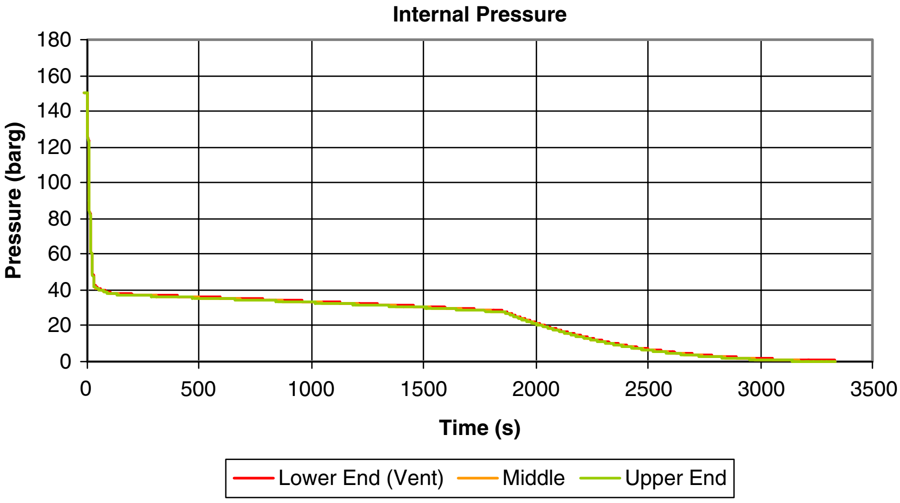


Figure 11. Recorded pressure against time at different locations in the isolated shock tube, for the case of a vent through a horizontal pipe of 9.4 mm internal diameter

through the system are balanced until a self-consistent prediction of the flow is obtained.

In the sandy soils and for some of the clay soil experiments, a distinct crater formed. The craters had steep sides and the flow emerged from them in an upward direction, with a significant component of vertical velocity. The speed of the emerging flow was estimated to be between about 40 m/s and 60 m/s. A different sized crater was formed in the different experiments, depending on the puncture size and location and the nature of the surrounding soil. Typically, the diameter in sandy soil was about 3 m for a puncture having a diameter of about 25 mm in a pipeline at a pressure of about 150 bar. It is the combination of the release characteristics and the surrounding soil that in combination determine this behaviour. It is a potential source of uncertainty to use a specific size and shape of crater in which to study different flows. The flow and the crater evolve in harmony with one another. To use a rather inexact analogy, a mattress will adapt to the shape and weight of a person who sleeps on it. Someone would not necessarily be comfortable trying to lie on the shape formed by another person. Similarly, the flow from a release from one pipeline will not necessarily fit comfortably within the crater formed by a release from another pipeline!

Some solid CO_2 was observed in the below ground 'caverns' and tracking routes in those experiments in which open craters did not form but not in significant amounts. No significant rain-out of solid CO_2 was observed from any of the dispersing clouds. In some of the experiments, the upward flow from the soil surface was observed to stall and fall back to ground around the source. In the higher wind speed conditions this happened at some distance downwind of the source and no additional upwind or crosswind spread of the plume occurred near the source. However, in the lower wind speeds, this occurred around the source itself. This meant that the subsequent upward flow no longer entrained free air, but a mixture already containing some CO_2. As suspected from the observations of previous pipeline incidents involving the release of heavier-than-air mixtures, a 'blanket' was formed around the release. (The Port Hudson pipeline failure, described in the Appendix to Lees' Loss Prevention in the Process Industries, Mannan (2009), provides an example of an incident in which this occurred). Figure 12 illustrates the important controlling parameters for the formation of a blanket. Preliminary investigations suggest that the controlling parameters in determining whether this happens are the Richardson number of the release and the wind speed to exit velocity ratio. There appears to be a critical value of the Richardson number at which the blanket forms for a given wind to exit velocity ratio. It requires a higher value of the Richardson number for the blanket to be produced for larger values of the wind to exit velocity ratio.

Given this discussion, somewhat surprisingly, the effect that the formation of a source blanket made on the downwind dispersion is less than might have been expected. However, it did make a difference to the extent of the cloud in a cross-wind and upwind direction and so may have some impact within a risk assessment.

The importance of fluctuations within the dispersing plume has been investigated. Firstly, the structure of the concentration fluctuations across the plume has been examined. This is demonstrated in Figure 13, where the frequency with which the observed concentrations, recorded every 0.1 second, at 3 locations on an arc that is 120 m downwind of the release lie within a certain band of concentration values at each location has been plotted for a 300 second period during the release. The three locations were selected to be near to the nominal plume centreline based on the mean wind direction, at its edge and at a location halfway between the edge and the centreline.

It can be seen that at the edge of the plume, zero concentration is recorded for approximately 86% of the time, but that on the plume centreline, the plume was always

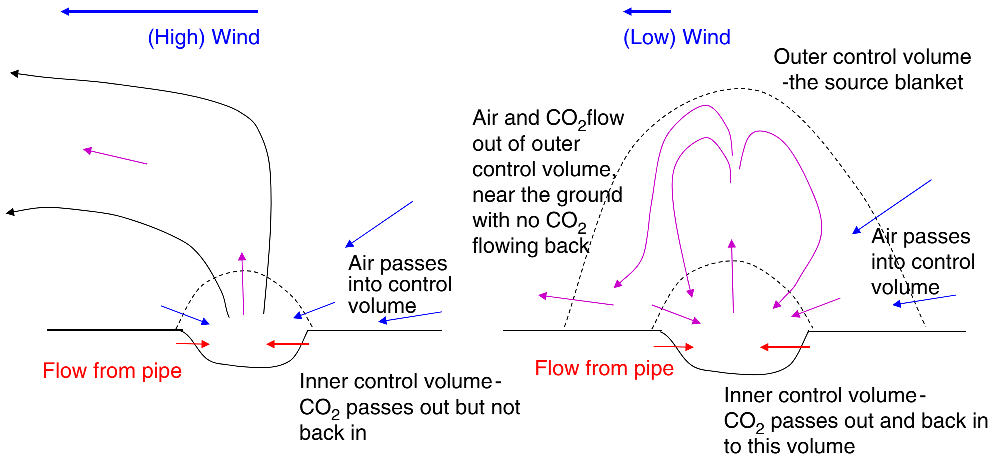


Figure 12. Illustration of releases forming a source blanket

recorded as being present and the most frequently observed values lie between 40% and 95% of the maximum value at this location. Zero values are observed for about 33% of the time half-way across the plume, but values that are between about 75% and 90% of the maximum at this location are observed for about another 30% of the time. The peak to mean ratio varies across the plume as a result of this distribution of values, with the peak being about 1.6 times the mean value on the centreline, about 2.5 times the local mean approximately half way between the centreline and the edge and about 17 times the local mean value at the edge. Results at other locations away from the immediate source region confirm that higher peak to mean ratios are observed towards the edges of the plume, as would be expected based on observations of other plumes dispersing in the atmosphere, see Mylne and Mason (2005), for example.

The difference this makes to the dosage has been assessed by comparing the dosage calculated from the 60 distinct 5 second average values with the dosage calculated from a 300 second mean value. In this case, the dosage evaluated using the sequence of 5 second, shorter-time averaged values is about 70 times larger than the value derived from

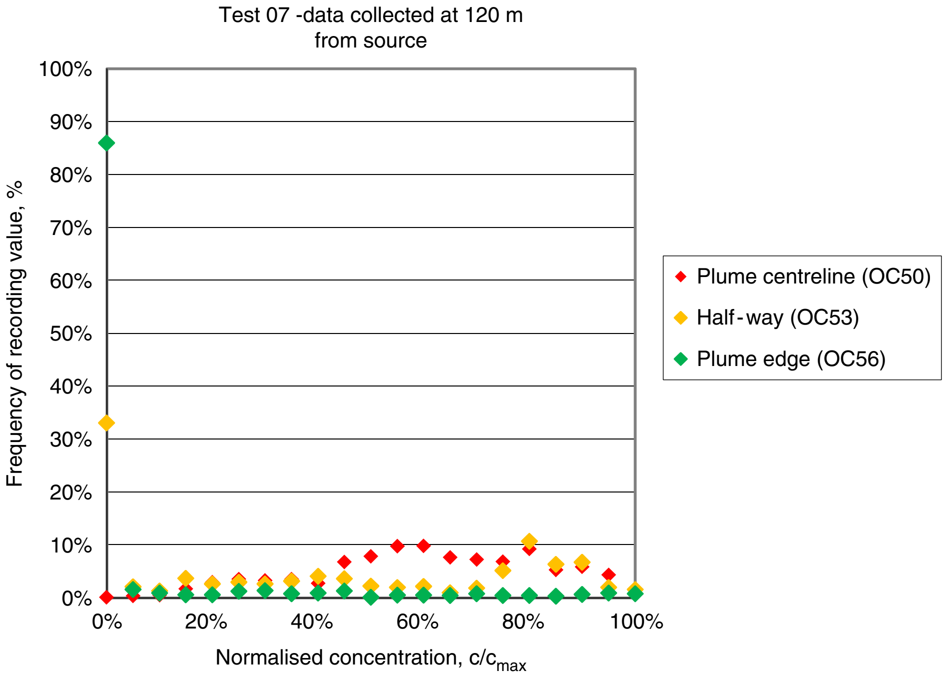


Figure 13. Distribution of recorded concentrations across the plume

the 300 second time averaged value at the centre line, 13,000 times the value at the mid-point and 200,000,000 times at the edge. This is a reflection on the large value of the index (8) in combination with variations in the wind direction that took place over that time period. The differences this would make to a risk assessment are not necessarily as dramatic as the above ratios suggest, as values at the edge of the plume tend to be lower in any case. However, it does suggest that it is important to consider the impact of variations within an assessment and the averaging time being used by a particular predictive model.

6. DISCUSSION AND CONCLUSIONS

The results obtained to date have indicated how realistic releases of CO_2 behave. A number of the experiments produce interesting observations but are not ideal for providing data for model development. However, the venting and puncture experiments conducted by National Grid were both carried out in such a manner as to make comparison with mathematical models easier. This has led HSL to propose the use of the data in preparing a model evaluation protocol to assess CO_2 dispersion models. The way in which this can be done has been presented in outline by Cooper (2012), and it is envisaged it would follow the protocol developed for dense gas dispersion models by HSL, see Ivings et al. (2007).

The venting experiments have shown that it is possible to use a vertical vent arrangement successfully during approximately steady conditions. No rain out of solid CO_2 was observed during the venting. The gaseous plume dispersed and was not detected at ground level in a downwind direction. The dense phase plume was observed to return to ground some way downstream of the release, but at concentrations that were well below those that pose an immediate danger to people. A 144 m length of 150 mm diameter pipeline was vented at one end through a short length of horizontal pipeline of either 12 mm or 25 mm diameter. The pressure along the pipeline was observed to be relatively constant and there is an indication that some solid CO_2 could form during certain of the vent operations. The results of these experiments have been compared with a number of the more pragmatic mathematical models and, in general, the results have been found to be consistent with the predictions. This gives some confidence that the dispersion of this type of above ground CO_2 release can be predicted satisfactorily, if the release conditions are known.

The puncture experiments have shown that the release and the path it creates to the surface cannot be disassociated. If a crater is formed however, significant 'rainout' of solid material was not observed to occur within the crater and in all cases, rainout from the plume in the atmosphere was not observed. The presence of solid CO_2 was only noted after the experiments in which the underground chambers were formed but it was only relatively small quantities. That is, it appears to arise for severely impacted cases, but even then, not if the velocities are high. The flow from the punctures was observed to stall in the atmosphere above the source and, in low wind speed conditions, a 'blanket' was observed to form around and over the source. This had less effect on the downwind dispersion behaviour of the cloud but did have an influence on the extent of the upwind spread, if any, and the crosswind spread. This suggests that it is particularly important to take due account of the correct 'source' conditions for the different below ground releases and this is an area that is being studied further as part of the overall COOLTRANS programme of research.

The results from the puncture tests show that the random variations in wind direction and turbulent fluctuations within the plume, combined with the high toxicity index for CO_2, lead to differences in the calculated integrated dose, depending on what time-averaged value is used for the concentration during the evaluation. If it is the time-averaged value of a few seconds that is important, to reflect the breathing rate of people, these results suggests that basing the calculated dosage on longer time-averaged values of the order of minutes may under estimate the risks, especially towards the edge of the plume.

REFERENCES

Cooper, R., 'Integrated analysis of pipeline decompression, near and far field dispersion', presented at 2nd International Forum on the Transportation of Carbon Dioxide by Pipeline, Newcastle, 22-23 June, 2011.

Cooper, R., 'Modelling studies in the COOLTRANS research programme', to be presented at 3rd International Forum on the Transportation of Carbon Dioxide by Pipeline, Newcastle, June 2012.

Cosham, A., Jones, D.G., Armstrong, K., Allason, D. and Barnett, J., 'The decompression behaviour of carbon dioxide in the dense phase', to be published at IPC2012, Calgary, Canada, 2012.

Gant, S., 'Model evaluation protocol for predicting the behaviour of releases of dense phase carbon dioxide', to be presented at 3rd International Forum on the Transportation of Carbon Dioxide by Pipeline, Newcastle, Newcastle, June 2012.

Mannan, S, 'Lees Loss Prevention in Process Industry', 3rd edition, 2005, published by Elsevier ISBN 0-7506-7555-1 (see description given in Appendix I/37).

Mylne, K.R. and Mason, P.J., 'Concentration fluctuation measurements in a dispersing plume at a range of up to 1000 m', Quarterly Journal of the Royal Meteorological Society, Volume 117 Part A, Issue 497, pages 177–206, January 1991.

Ivings, M.J., Jagger, S.F., Lea, C.J and Webber, D.M., 'Evaluating Vapor Dispersion Models for Safety Analysis of LNG Facilities Research Project', The Fire Protection Research Foundation, Massachusetts, USA, 02169, April 2007 (HSL report MSU/2007/004).