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Comparison of risks from carbon dioxide and natural gas pipelines

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Comparison of risks from carbon dioxide and natural gas pipelines

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Carbon capture and storage (CCS) is likely to form a significant part of the UK's strategy for achieving its Kyoto targets for CO2 emission reduction. CO2 is not currently regulated as a dangerous fluid under the Pipeline Safety Regulations (PSR) so further investigation is required to determine if it should be re-classified.

This project continues previous work (Moonis and Wilday, 2008) that recommended further investigation into the possibility of including CO2 as a dangerous fluid under the PSR. This previous work suggested that in terms of hazard range and hazard footprint area, CO2 should be classified as a dangerous substance but that further analysis would be required in terms of risk.

PHAST (commercial consequence modelling software) and TPRAM (HSE land-use planning software) were used to perform dispersion and risk modelling respectively for a release of CO2, so that the risk associated with the release could be determined. MISHAP (HSE land-use planning software) was also used to obtain the associated risks for methane (natural gas) with similar inputs to the CO2 modelling. Comparison between the risk values should determine if a CO2 release generates similar risks at distances that are smaller, equivalent or larger than natural gas.

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EXECUTIVE SUMMARY

Background

Carbon capture and storage (CCS) is likely to form a significant part of the UK's strategy for achieving its Kyoto targets for CO_2 emission reduction. CO_2 is not currently regulated as a dangerous fluid under the Pipeline Safety Regulations (PSR) so further investigation is required to determine if it should be re-classified.

This project continues previous work (Moonis and Wilday, 2008) that recommended further investigation into the possibility of including CO_2 as a dangerous fluid under the PSR. This previous work suggested that in terms of hazard range and hazard footprint area, CO_2 should be classified as a dangerous substance but that further analysis would be required in terms of risk.

PHAST (commercial consequence modelling software) and TPRAM (HSE land-use planning software) were used to perform dispersion and risk modelling respectively for a release of CO_2, so that the risk associated with the release could be determined. MISHAP (HSE land-use planning software) was also used to obtain the associated risks for methane (natural gas) with similar inputs to the CO_2 modelling. Comparison between the risk values should determine if a CO_2 release generates similar risks at distances that are smaller, equivalent or larger than natural gas.

Objectives

The overall purpose of this project was to determine if CO_2, when used for the purpose of CCS, should be regulated as a dangerous fluid under the Pipeline Safety Regulations. This work will also inform HSE's other ongoing work on approaches for CO_2 in terms of land use planning and the Control of Major Accident Hazards Regulations (COMAH).

Main Findings

The main findings are:

- Unlike natural gas, CO_2 does not require ignition for it to cause harm;
- Distances to a similar level of risk are roughly comparable between CO_2 and natural gas;
- Increasing the pressure increases the distance to a given risk level for both CO_2 and natural gas; and
- Modelling was carried out at lower pressures than that of likely pipeline transport because there is some uncertainty when modelling dense phase CO_2, as the formation of solids cannot be modelled accurately. The hazard ranges and therefore risks are expected to be substantially larger for releases at higher pressure (which would therefore be in the dense phase).

Recommendations

On the whole, this would imply that in terms of risk, CO_2 used for CCS has sufficient toxicity to be regulated as a dangerous fluid under the Pipeline Safety Regulations (PSR).

1 INTRODUCTION

Carbon capture and storage (CCS) is likely to form a significant part of the UK's strategy for achieving its Kyoto targets for CO_2 emission reduction. Several projects are in discussion and the Department of Energy and Climate Change (DECC) is running a competition for the funding of a demonstration project in the UK.

All CCS projects are likely to involve onshore CO_2 capture, transport by pipeline, and storage in an offshore storage facility. Given the large scale of proposed CCS projects, there may be the potential for leakage from a pipeline in close proximity to residential areas to cause a Major Accident Hazard (MAH) due to the toxicity and asphyxiant properties of CO_2 (Connolly, 2007), which incidentally, is currently not defined as a dangerous fluid under the Pipeline Safety Regulations (PSR). Calculating risks associated with the transport of CO_2 is particularly problematic at proposed pressures as CO_2 will be dense phase (liquid or supercritical) and will produce solid CO_2 on release. Over short periods of time, massive amounts of material can be released from a pipeline, resulting in a cloud of dense CO_2 followed by solid discharge and slow sublimation (Mahgerefteh *et al.*, 2008). Current risk assessment tools do not have the scope for modelling discharges of solid materials.

HSE has therefore requested the Health & Safety Laboratory (HSL) to perform risk modelling for vapour phase releases so that the risks associated with CO_2 can be compared to those of natural gas (a dangerous fluid which is currently transported throughout the UK by pipeline). PHAST and TPRAM (Toxic Pipeline Risk Assessment Method) were utilised to perform the CO_2 modelling while MISHAP was used to calculate the risks from a natural gas (methane) release. MISHAP was a suitable choice as the code has undergone extensive testing.

PHAST (DNV, 2006) is a commercial consequence modelling tool which uses an equation of state and so accounts for vapour phase non-ideality. However, the current commercial version does not handle solid CO_2. TPRAM is a HSE land-use planning tool for toxic pipelines and MISHAP is a HSE land-use planning tool for flammable pipelines. TPRAM and MISHAP, together, can be used to compare the risk (frequency of similar levels of harm) for CO_2 (toxicity/asphyxiation) and natural gas (flammable) events.

Section 2 lists the pipeline characteristics that were used in the PHAST/TPRAM and MISHAP methodologies. Section 3 outlines the PHAST/TPRAM modelling while MISHAP is discussed in section 4. The results are reviewed in section 5 and conclusions and recommendations based on the results are given in section 6.

2 PIPELINE CHARACTERISTICS

The characteristics of the pipeline required to model releases of CO_2 and natural gas are given in Table 1.

Table 1 Pipeline characteristics

Parameter	Value
Operating pressure (barg)	32 and 15
Operating temperature (K)	278
Internal diameter (mm)	736.6
Wall thickness (mm)	12.7
External pipe diameter (mm)	762
Grade of steel	X60
Depth of cover (m)	1.1
Length of pipeline (km)	18

The majority of these parameters were obtained from previous work (Moonis and Wilday, 2008) that was based on a real natural gas pipeline, except for the grade of steel and the depth of cover, which were supplied separately by HSE. Both values were obtained from analysis of existing pipelines and the most appropriate values were chosen.

The failure rates of a release can be determined based on the pipeline characteristics. The same pipeline characteristics were used for both PHAST/TPRAM and MISHAP modelling but because the substance was different, the calculated failure rates were also different. The failure rates generated by PIPIN (pipeline failure prediction code used by HSE) (HSE, 2004) for each substance are found in their corresponding chapters.

3 PHAST AND TPRAM MODELLING

To model the risk associated with a CO_2 pipeline, two steps were required. The first step utilised PHAST for consequence modelling to generate the hazard ranges associated with a catastrophic release, pipeline rupture or large hole. The second step took the hazard ranges and input them to TPRAM where the frequency was calculated and the overall risk was output.

The majority of PHAST inputs were based on previous work (Moonis and Wilday, 2008) so that comparisons could be made between the outputs; however, some amendments were required as the previous work focussed on catastrophic releases. For an indoor release in D5 weather, the building air change rate was taken as 3 air changes per hour and for F2 weather, the rate was taken as 2 air changes per hour (HSE, 1998) and are current HSE LUP assumptions. The concentration and toxic calculations were performed at a height of 1m above the ground as this was assumed to cover the population in a range of postures.

3.1 MODELLED SCENARIOS

A variety of different parameters were used to model a range of possible events including location of recipient, weather conditions and hole size.

In addition to a catastrophic release, two different hole sizes were modelled to capture large and small releases. A rupture resulting in a hole size of 150mm was used as an input as well as a smaller 50mm puncture. A pipeline can be pierced over its entire circumference so obstructed and unobstructed releases were taken into account. A release directed downwards was taken as the obstructed release, while a jet angled upwards from the horizontal was taken as the unobstructed release. The hazard range and therefore risk associated with an event can be greatly affected by weather conditions at the site. Taking this into consideration, D5 and F2 weather were both used as inputs to PHAST as they are representative of typical daytime and night-time weather respectively. Furthermore, the location of the pipeline in terms of its proximity to populated areas was also of importance in terms of risk. The dose received by individuals depends on if they are present inside or outside of buildings so location was used a parameter.

Appendix A illustrates the full range of scenarios that were modelled. The angle from the horizontal used for the unobstructed release required further investigation, and is discussed in section 3.3.

3.2 HARM CRITERIA

There are a number of criteria against which the level of harm experienced by a population in close proximity to a CO_2 failure can be measured. SLOT DTL or Specified Level of Toxicity Dangerous Toxic Load is defined (HSE, 2008a) as a level of toxicity that causes:

- Severe distress to almost everyone in the area;
- A substantial fraction of the exposed population to require medical attention;
- Serious injury that requires prolonged treatment for some people; and
- Death for highly susceptible people.

In terms of likelihood of death, SLOT DTL corresponds to 1% mortality and SLOD (Significant Likelihood of Death) DTL corresponds to 50% mortality.

The toxic properties for CO_2 can be found in Table 2. SLOT DTL and SLOD DTL values have been generated for a number of toxic substances and are available on the HSE website (HSE, 2008a).

Table 2 CO_2 toxic properties

Parameter	Value
SLOT DTL	1.5×10^{40} ppm^8.min
SLOD DTL	1.5×10^{41} ppm^8.min
Toxic n value	8

CO_2 begins to affect the respiratory system after several hours' exposure to a concentration of 3%, causing headaches and restricted breathing. Unconsciousness can result within a few minutes of exposure to 7% CO_2, while coma and death is possible within a few minutes of exposure to 17% CO_2 (DNV, 2008). As a result, CO_2 does not need to ignite, like some flammable substances do, to cause harm.

3.3 CALCULATION OF THE CRATER ANGLE

An angled jet release was not part of previous work [Moonis and Wilday, 2008] so it was calculated from another study [Kinsman and Lewis, 2002] that analysed a number of pipeline accidents using HSE's risk assessment programs MISHAP and PIPERS. Details of the pipeline and the surrounding area before and after the rupture/failure were reproduced in a number of tables.

The crater length, width and depth are examples of the data provided, as listed in Table 3 and can be manipulated using simple geometry, as illustrated in figure 1, to provide the angle of the crater. The angle can be calculated in two ways: the first involving geometry between the crater length and the crater depth and the second involving geometry between the crater width and the crater depth. For the purpose of this report, the crater length and crater depth were used to calculate the crater angle. There were two reasons for choosing this route, the first was the assumption that the crater angle was equal to the jet angle and because the momentum of the jet would cause a larger diameter in one direction, it was assumed that this was the crater length. Secondly, sensitivity studies, as given in Appendix B, confirm that the largest hazard ranges are produced by smaller angles from the horizontal.

PHAST requires angle θ as input, which is ($90^\circ - \alpha$) and equates to 19º.

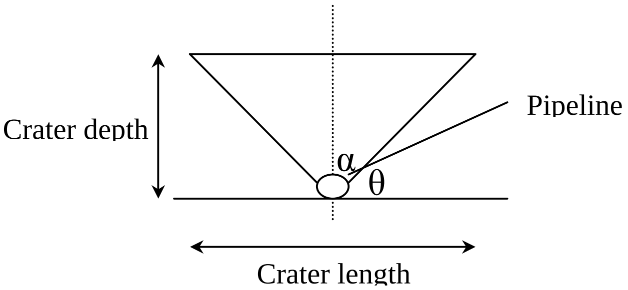

Figure 1 Calculation of crater angle

Table 3 Calculation of crater angle

Crater length (m)	Crater width (m)	Crater depth (m)	Crater Angle, θ (°)
27	20	6	24
20	10	3	17
3.3	1.7	0.5	17
17.8	9	2.7	17
49	33	5	12
4.6	1.5	1.7	36
2.1	2.1	1.8	60
17	14	5	30
36	11	2.1	7
28	12	3.7	15
14	7.6	3.1	24
43	20	4.3	11
13	5.2	3	25
20	15	2.8	16
17	17	3	19
28	7.6	3	12
152	9.1	1.8	1
36	16	3	9
30	9.1	7.6	27
23	9	4.5	21
56	14	4.5	9
51	23	5	11
		Average	19

The crater angle was used to calculate the conditional probability of jet dispersion. From Figure 1, the crater angle is given by θ so the jet itself is represented by the angle (90-θ) otherwise known as α. Because the jet is symmetrical it will occupy 2 × α out of the full 360° circle around the pipeline. The probability of the jet was calculated using:

$$P_{jet} = \frac{2 \times (90 - \theta)}{360} = \frac{2 \times (90 - 19)}{360} = 0.4 \qquad (1)$$

The crater angle study (Kinsman and Lewis, 2002) focussed solely on catastrophic ruptures so the crater angle obtained should be treated with caution as the CO_2 pipeline study included leaks as well as catastrophic releases. The crater angle was calculated using the best knowledge that was available at the time of writing.

3.4 SETTING CO_2 AS A TOXIC SUBSTANCE

Several steps were required to force PHAST to accept CO_2 as a toxic substance (CO_2 exhibits a level of toxicity which may lead it to have major accident potential when used for CCS, but which is below that which would categorise it as ‘toxic’ under CHIP regulations (HSE, 2002)). A new substance was created in the materials tab that was based on a copy of the original CO_2

data but amended to set CO_2 as toxic. This caused PHAST to require a number of extra inputs that were not necessarily known.

3.4.1 Probit numbers

PHAST required specific toxic data including: probit values, the dangerous toxic load and the n value. The SLOD DTL (1.5×10^{41} ppm^8.min), SLOT DTL (1.5×10^{40} ppm^8.min) and n (8) values were obtained from literature (HSE, 2008a).

The probit constants (A and B) were calculated using equation 2 (HSE, 2008b), where $C^n t$ is equal to the toxic load and Pr is equal to the probit value which was obtained from a probit table.

$$\Pr = A + B\ln(C^n t) \qquad (2)$$

The SLOD DTL probit value was set equal to 5.00 and the SLOT DTL probit value was set equal to 2.67 (HSE, 2008b). As the SLOD and SLOT toxic loads and the probit numbers for both were known, solving two equations simultaneously gave the A and B values that were required by PHAST. The inputs to PHAST were:

A = -90.8 and B = 1.01 and n = 8

Note that the analysis carried out and described below did not use these probit values but they were needed in order for PHAST to run and produce toxicity output, so it seemed appropriate to use the correct values as opposed to arbitrary ones.

3.4.2 Changes to default parameters

Several other parameters were changed in order for PHAST to work:

- The hydrodynamic calculations for the chosen material did not converge so the accuracy for droplet evaporation integration value was changed from a default value of 0.001 to 1×10^{-6};

- The droplet evaporation thermodynamic model was changed from ‘rainout, non-equilibrium’ to ‘rainout, equilibrium’; and

- The results grid in the toxic parameters tab was changed from 25 m in the x-direction to 1 m and from 2.5 m in the y-direction to 0.1 m. The height for calculation of effects was changed to 1 m.

3.5 PHAST – HAZARD RANGE RESULTS

Based on the method outlined above, the 20 scenarios required for the TPRAM event tree (see Appendix A) were run using:

- 32 barg pressure for SLOD DTL;

- 32 barg pressure for SLOT DTL;

- 15 barg pressure for SLOD DTL; and

- 15 barg pressure for SLOT DTL.

3.5.1 SLOD

Table 4 lists the results for SLOD DTL hazard ranges for 32 and 15 barg pressure in the pipeline. The event numbers are defined in the event tree in Appendix A.

Table 4 SLOD hazard ranges

	Contours (m) – 32 barg		Contours (m) – 15 barg	
Event	Distance	Half-width	Distance	Half-width
1	99	5.3	90	6.6
2	79	4.0	74	4.6
3	107	12	105	20
4	76	6.4	71	9.7
5	14	0.4	10	0.2
6	12	0.3	8.7	0.2
7	14	0.4	11	0.3
8	9.7	0.3	8.4	0.2
9	107	6.0	69	3.4
10	87	4.5	55	2.4
11	100	9.8	77	8.6
12	74	5.3	53	4.2
13	5.1	0.1	3.0	0.1
14	4.6	0.1	2.7	0.1
15	5.5	0.1	3.1	0.1
16	4.5	0.1	2.6	0.1
17	28	1.0	-	-
18	20	0.5	-	-
19	37	3.3	18	0.7
20	23	1.2	-	-

Table 4 shows that on the whole, most releases generate hazard ranges that are less than 100 m in length and half-widths that are considerably smaller in all cases. The hazard ranges indicate long, thin plumes for leak releases while catastrophic release clouds are similar to elongated ovals as they are also long but substantially wider.

The largest hazard range is generated by event 3, which is for the catastrophic release in F2 weather that is measured outdoors. PHAST did not produce results for three of the 15 barg cases as the dose present was lower than the SLOD dose being measured.

3.5.2 SLOT

Table 5 lists the results for SLOT DTL hazard ranges at 32 and 15 barg pressure.

Table 5 SLOT hazard ranges

	Contours (m) – 32 barg		Contours (m) – 15 barg	
Event	Distance	Half-width	Distance	Half-width
1	142	8.6	113	10
2	115	6.4	100	7.9
3	138	21	160	43
4	106	12	104	19
5	18	0.4	12	0.3
6	16	0.4	11	0.3
7	17	0.4	13	0.3
8	14	0.4	10	0.3
9	149	10	99	5.7
10	122	7.5	78	4.1
11	138	17	104	16
12	101	9.7	77	8.2
13	6.3	0.1	3.7	0.1
14	5.5	0.1	3.2	0.1
15	6.8	0.2	3.8	0.1
16	5.4	0.1	3.1	0.1
17	43	1.9	17	0.3
18	33	1.3	-	-
19	56	8.1	31	2.6
20	37	3.2	18	0.7

The hazard ranges given in Table 5 indicate that hazard ranges of up to 160 m in length are possible. Hazard ranges for events 1 to 4 and events 9 to 12 are typically over 100 m in length, particularly for the 32 barg case. The hazard ranges here are longer and wider than those generated in Table 4.

The largest contour is produced by event 3 for the 15 barg release which is for a catastrophic release in F2 weather that is measured outdoors. PHAST did not produce results for event 18 as the dose present in the cloud was lower than the SLOT dose value being measured.

3.6 TPRAM – RISK RESULTS

TPRAM (Toxic Pipeline Risk Assessment Method) is a tool that calculates the overall risk associated with events 5 to 20 as outlined in Appendix A. To incorporate catastrophic releases (events 1 to 4), the code was amended to include these calculations before modelling work was commenced. TPRAM required the hazard ranges that are listed in Tables 4 and 5 as input as well as the parameters listed in Tables 6 and 7.

3.6.1 Failure Frequencies

PIPIN was run using the characteristics for a typical natural gas pipeline (as outlined in section 2). The failure frequencies obtained are given in Table 6.

Table 6 Failure frequencies generated by PIPIN for use in TPRAM

	Failure frequency (per m/yr)			
Pressure (barg)	Pinhole	Small hole	Large hole	Rupture
32	1.87×10^{-7}	1.00×10^{-7}	4.65×10^{-8}	3.39×10^{-8}
15	1.87×10^{-7}	1.00×10^{-7}	4.65×10^{-8}	3.34×10^{-8}

The small hole and pinhole failure frequencies given in Table 6 were combined to give the puncture probability used in TPRAM. The large hole probability from PIPIN corresponded to the large hole probability in TPRAM and the rupture probability corresponded to the probability of catastrophic rupture in TPRAM. Table 7 shows how the probability values were used within TPRAM.

However, there is considerable uncertainty in the failure rates for CO_2 pipelines and caution should be applied to the use of PIPIN here as the defect growth mechanism may lead to differences in source terms such that risks may be greater than predicted.

Table 7 TPRAM Inputs

Parameter	32 barg	15 barg
Probability of catastrophic rupture (cpm/yr)	0.039	0.034
Probability of large hole (cpm/myr);	0.0465	0.0465
Probability of puncture (cpm/myr)	0.287	0.287
Conditional probability of jet dispersion	0.4[1]	0.4[1]
Conditional probability of D5 weather	0.8	0.8
Conditional probability of being indoors in D5 weather	0.9	0.9
Conditional probability of being indoors in F2 weather	0.99	0.99

Tables 4 and 5 show that for some of the smaller 15 barg releases, hazard ranges were not generated by PHAST, however, TPRAM failed to run unless numerical values were input. This problem was overcome by using, the smallest possible hazard range values as input to TPRAM for these cases.

An output of risk (cpm/myr) was given at a predefined range of distances from the pipeline for each of the 20 scenarios. The risk was then combined over the 20 scenarios which produced one value of risk at each of the designated distances. A chart of risk (cpm) versus distance (m) was generated based on these results, and from this, the distance to a risk value of interest was obtained.

Note that a BPD (building proximity distance) equivalent is required to set the inner zones when risks are insufficient.

Appendix C contains the graphs of risk versus distance that were output from TPRAM.

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[1] *Calculated in section 3.3*

3.6.2 SLOD

For the SLOD cases, the distance was measured when the risk reached 5, 0.4 and 0.1 cpm (Franks *et al*, 1996), so that they were comparable to the SLOT distances and are listed in Table 8. These values were taken from the SLOD graphs given in Appendix C. From Table 8, a risk of 5 cpm is not reached for the 32 barg case but there would be sufficient risk to implement a middle zone (0.4 cpm) and an outer zone (0.1 cpm) around the pipeline. For the 15 barg case, a small middle zone and an outer zone (0.1 cpm) would be required around the site.

Table 8 Risks based on SLOD hazard ranges

Risk (cpm)	Distance 32 barg (m)	Distance 15 barg (m)
5	-	-
0.4	19	1
0.1	65	45

3.6.3 SLOT

Using the SLOT hazard ranges as input, TPRAM calculated the distance to each of the risk values listed in Table 9, that is to say 10, 1 and 0.3 cpm.

Table 9 Risks based on SLOT hazard ranges

Risk (cpm)	Distance 32 barg (m)	Distance 15 barg (m)
10	-	-
1	20	-
0.3	70	45

As with the SLOD cases, the 32 barg release would require middle and outer zones around the pipeline as the risk would be sufficiently large for them to be implemented. A risk of 10 cpm is not reached so a risk-based inner zone is not generated, however, a zone equivalent to the natural gas building proximity distance would be required. With the 15 barg case, a consultation distance of 45 m would be necessary around the site and would be equivalent to the outer zone.

4 MISHAP MODELLING

In previous work (Moonis and Wilday, 2008), the CO_2 hazard ranges were compared against those from a MISHAP run that used similar inputs to the CO_2 method, but considered the same pipeline carrying natural gas rather than CO_2.

For this assessment, MISHAP was employed to calculate the risks associated with a natural gas release based on the outputs outlined in section 2.4. MISHAP (HSE, 2000a) is a code currently used by HSE to assess the risk from major hazard pipelines transporting flammable substances in Land Use Planning Assessments (LUP) and therefore has undergone rigorous testing.

4.1 HARM CRITERIA

Different harm criteria were required for use in MISHAP as natural gas is a flammable substance as opposed to CO_2 which is toxic. The flammable equivalent of SLOT DTL is the dangerous thermal dose (DTD) and is measured in thermal dose units (tdu).

MISHAP is capable of calculating distances to thermal doses of 1000 and 1800 tdu, which are equivalent to SLOT DTL and SLOD DTL respectively.

4.2 INPUTS

The general MISHAP inputs were based on the pipeline characteristics set out in section 2, but using methane as the modelled substance as MISHAP does not have a natural gas option. Natural gas is referred to for the rest of the report.

The failure rates were added manually after consultation with HSE and are discussed in section 4.2.1. LOSSP (gas) was used to input details of the pipeline that affect the quantity of fluid released. The FBALL option was used to model the possible fireball events and the PIPEFIRE option was used to model jet fire events. The flashfire option is not used by HSE when modelling natural gas.

4.2.1 Failure Frequencies

PIPIN was run using the characteristics for a typical natural gas pipeline (as outlined in section 2) and the following failure frequencies were obtained:

Table 10 Failure frequencies generated by PIPIN for use in MISHAP

	Failure frequency (per m/yr)			
Pressure (barg)	Pin hole	Small hole	Large hole	Rupture
32	1.33×10^{-7}	9.38×10^{-9}	9.99×10^{-10}	2.74×10^{-9}
15	1.33×10^{-7}	9.35×10^{-9}	9.93×10^{-10}	2.28×10^{-9}

4.3 RESULTS

MISHAP calculated the risk results by summing the risks from two windspeed categories[2] (one for day and one for night) for each of the following scenarios:

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[2] *There are four wind speeds available but the current version of MISHAP uses two.*

- Fireball followed by jetfire, and
- Jetfire;

4.3.1 1000 tdu (equivalent to SLOT)

The distances to a dangerous thermal dose, equivalent to 1000 tdu were obtained at 10, 1 and 0.3 cpm and are listed in Table 11.

Table 11 Risks based on 1000 tdu (equivalent to SLOT)

Risk (cpm)	Distance 32 barg (m)	Distance 15 barg (m)
10	-	-
1	-	-
0.3	100	-

According to the MISHAP results, risk-based inner and middle zones would not be required for a release at either 32 or 15 barg pressure, based on inputs discussed in previous sections. However, there would be sufficient risk to apply an outer zone (consultation distance) around the pipeline, for both pressures.

4.3.2 1800 tdu (equivalent to SLOD)

Table 12 lists the distances that were obtained to a dangerous thermal dose equivalent to 1800 tdu at a risk of 5, 0.4 and 0.1 cpm.

Table 12 Risks based on 1800 tdu (equivalent to SLOD)

Risk (cpm)	Distance 32 barg (m)	Distance 15 barg (m)
5	-	-
0.4	-	-
0.1	150	75

The results indicate that there would be sufficient risk to implement a consultation distance equivalent to the outer zone around the pipeline. Risk-based inner and middle zones would not be required for this case at both pressures.

5 DISCUSSION

5.1 PHAST DISCUSSION

Overall the largest hazard ranges tend to be produced by the catastrophic releases, while the smallest hazard ranges, for both SLOT and SLOD, tend to result from the jet releases. Figures 2 and 3 illustrate typical graphical output for the side view of a jet release at an angle of 19º and a downward impinging release cloud respectively. These figures show that only a small portion of the angled cloud makes contact with the ground before it bends into the air.

For the SLOD cases, PHAST failed to produce results for events 17, 18 and 20 and for the SLOT cases, PHAST did not produce results for event 18. This is because only levels of toxicity significantly below the levels of interest were produced in the plume so no hazard ranges were generated.

Overall, the PHAST results seem appropriate.

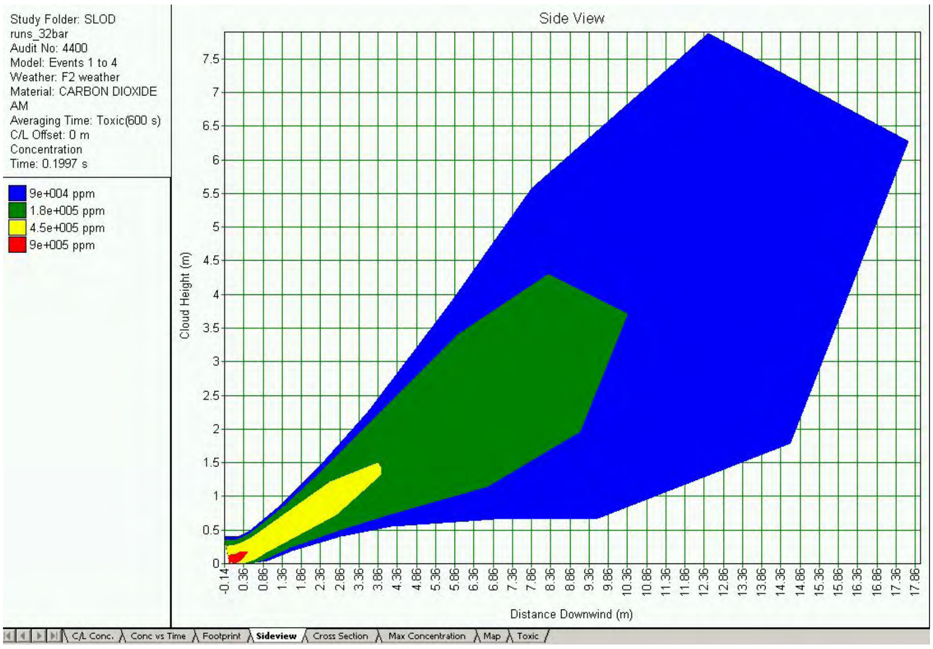
5.2 TPRAM DISCUSSION

The main problem that arose with TPRAM was running the code where PHAST did not produce hazard ranges. As a compromise, the smallest possible values were input to TPRAM where PHAST failed so the code would run. This meant that the cloud would be of the smallest possible width and length so wouldn't affect the local population and therefore the risk too much. However, the risks obtained close to the pipeline could possibly be slightly larger due to the input of these small clouds.

Tables 4 and 5 indicate that the 32 barg cases are unaffected by this as PHAST generated results for all cases. If an effect does result from this, the 15 barg SLOD results are likely to be affected the most.

5.3 MISHAP DISCUSSION

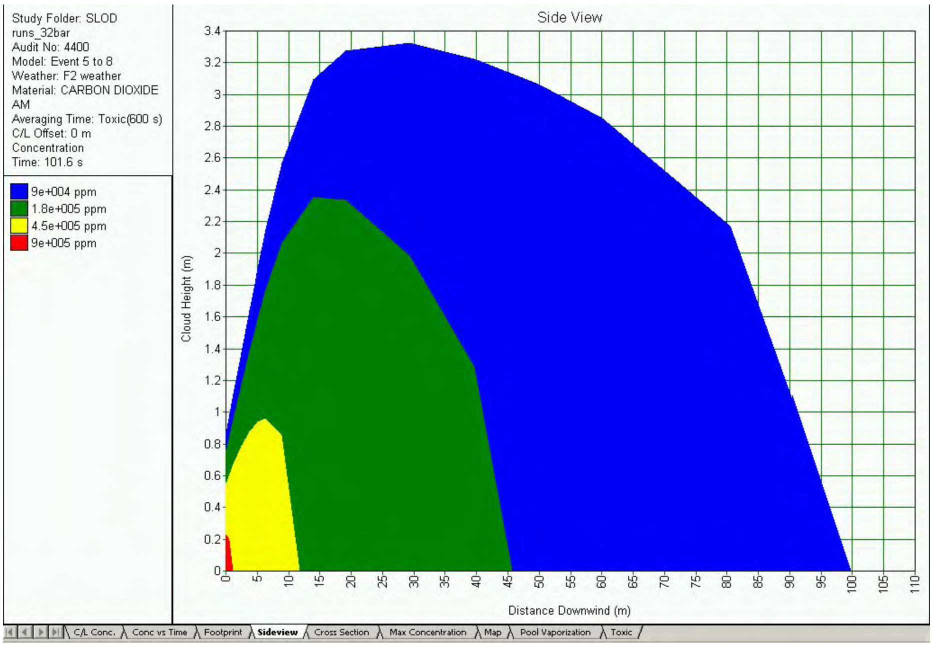
MISHAP is a risk assessment tool used to calculate the risks associated with flammable substances, so a direct comparison can only be made between these results and those of TPRAM on the basis of similar levels of harm to people in the different events. However, the results should indicate if CO_2 is more, less or equally as dangerous as natural gas because the pipeline details used in MISHAP were of the same specification as TPRAM but with a different substance of interest. The risks were obtained based on exposure to 1000 tdu, which is equivalent to the SLOT distances for CO_2 and 1800 tdu which is equivalent to the SLOD distances for CO_2.



Study Folder: SLOD
runs_32bar
Audit No: 4400
Model: Events 1 to 4
Weather: F2 weather
Material: CARBON DIOXIDE
AM
Averaging Time: Toxic(600 s)
C/L Offset: 0 m
Concentration
Time: 0.1997 s

🟦 9e+004 ppm
🟩 1.8e+005 ppm
🟨 4.5e+005 ppm
🟥 9e+005 ppm

Figure 2 Side view of an angled jet release output from PHAST



Study Folder: SLOD
runs_32bar
Audit No: 4400
Model: Event 5 to 8
Weather: F2 weather
Material: CARBON DIOXIDE
AM
Averaging Time: Toxic(600 s)
C/L Offset: 0 m
Concentration
Time: 101.6 s

🟦 9e+004 ppm
🟩 1.8e+005 ppm
🟨 4.5e+005 ppm
🟥 9e+005 ppm

Figure 3 Side view of a downward impinging release output from PHAST

5.4 OVERALL DISCUSSION

Tables 13 (32 barg pressure) and 14 (15 barg pressure) give the distances at which the risk based inner, middle and outer zones should be applied, for each of the cases modelled in PHAST/TPRAM and MISHAP.

Table 13 Distances to specified risk contours for a 32 barg release

Contours	CO_2 SLOT	CO_2 SLOD	Natural Gas 1000 tdu	Natural Gas 1800 tdu
IZ	-	-	-	-
MZ	20	19	-	-
OZ	70	65	100	150

Table 14 Distance to specified risk contours for a 15 barg release

Contours	CO_2 SLOT	CO_2 SLOD	Natural Gas 1000 tdu	Natural Gas 1800 tdu
IZ	-	-	-	-
MZ	-	1	-	-
OZ	45	45	-	75

For CO_2, the largest zones produced are for the 32 barg cases, particularly when measuring to SLOT. The outer zone in this case extends to 70 m from the pipeline with a middle zone existing at 20 m from the release source. The measurements at SLOD for this case are similar with an outer zone at 65 m and a middle zone at 19 m.

The 15 barg releases are less energetic so the distances achieved are expected to be less than the 32 barg cases. An outer zone is present up to 45 m from the pipeline for both 15 barg cases while the measurement at SLOD indicates that the implementation of a middle zone at 1 m would be appropriate.

For the natural gas cases, the largest zones are also generated by releases at 32 barg pressure. This time, however, only outer zones are generated by MISHAP and when this occurs they are referred to as the consultation distance. This time a consultation distance of up to 150 m from the pipeline would be appropriate for the 32 barg release at a measurement of 1800 tdu. Measurement at 1000 tdu generates a slightly smaller distance at 32 barg pressure.

The 15 barg cases generate results than are smaller than the 32 barg case but they are, nevertheless, still notable in length.

Comparisons between the CO_2 and natural gas zones should indicate if a CO_2 pipeline generates risks that are smaller, equivalent or larger than natural gas. Tables 13 and 14 indicate that the zones generated by CO_2 are smaller than the equivalent natural gas zones, but are still notable in size. Despite the fact the no inner zone is generated by any of the methods used, there is still sufficient risk to implement middle and outer zones around the pipeline in most cases. This is particularly applied to releases at the larger pressure of 32 barg, which indicates that if the pipeline was operating at supercritical pressure (approx 74 barg at 304K), as proposed (Mahgerefteh *et al.,* 2008), then the risk contours could be present at much wider ranges.

Where there is no risk-based inner zone, it is HSE policy for natural gas pipelines to set the inner zone equal to the Building Proximity Distance (BPD) as determined from the Institute of Gas Engineers and Managers document TD/1 (IGEM, 2008). CO2 pipelines would categorized as a Class C fluid in BS PD 8010 (BS, 2004) and the equivalent to the BPD can be calculated. However, the substance factor used in PD 8010 is likely to be for gaseous CO2. Dense phase or supercritical CO2 would require a new value to be determined to reflect the increased major hazard potential (and hence an increased separation distance).

The graphs in Appendix C indicate that close to the pipeline, the risks associated with a release of CO_2 are larger than a similar release of natural gas. For the example pipeline used in this study, CO_2 would require a middle zone whereas natural gas would not. The risks associated with natural gas become larger than CO_2 after 30 m for equivalent SLOD and 60 m for equivalent SLOT. However, the consequences for natural gas releases are likely to be realised within 15 minutes of rupture and ignition whereas for CO_2, a 30 minute post event period may need to be considered, so CO_2 hazard ranges may be greater especially if solids are subliming.

On the whole, a CO_2 release generates distances to a level of risk that are comparable to natural gas, implying that CO_2 has sufficient toxicity to be included in PSR.

6 CONCLUSIONS AND RECOMMENDATIONS

The overall purpose of this project was to determine if CO_2, when used for the purpose of CCS, should be regulated as a dangerous fluid under the Pipeline Safety Regulations. The work will also inform HSE's other ongoing work on approaches for CO_2 in terms of land use planning and the Control of Major Accident Hazards Regulations (COMAH).

A sub-critical CO_2 release was modelled and distances to SLOD and SLOT were obtained and combined with failure rates to determine the risks associated with the release. To make the results comparable, the inner, middle and outer zone distances were obtained for risk values appropriate for SLOD (5, 0.4 and 0.1 cpm) and SLOT (10, 1 and 0.3 cpm). A MISHAP run was also performed using the same inputs used to model CO_2, but as MISHAP models flammable substances, natural gas (or methane) was used as comparison substance. Distances to these risks were then obtained at 1000 tdu (equivalent to SLOT) and 1800 tdu (equivalent to SLOD) for comparison against CO_2. The purpose of this review was to determine if CO_2 produced distances to specified risks that were smaller, equivalent or greater that of natural gas. This would indicate if the inclusion of CO_2 in PSR should be re-evaluated as the risks associated with releases of natural gas/methane are well documented by HSE.

6.1 CONCLUSIONS

The conclusions are:

- Unlike natural gas, CO_2 does not require ignition for it to cause harm;

- Tables 13 and 14 in section 5 illustrate that for a CO_2 release, the distances to specified risks are roughly comparable between CO_2 and natural gas.

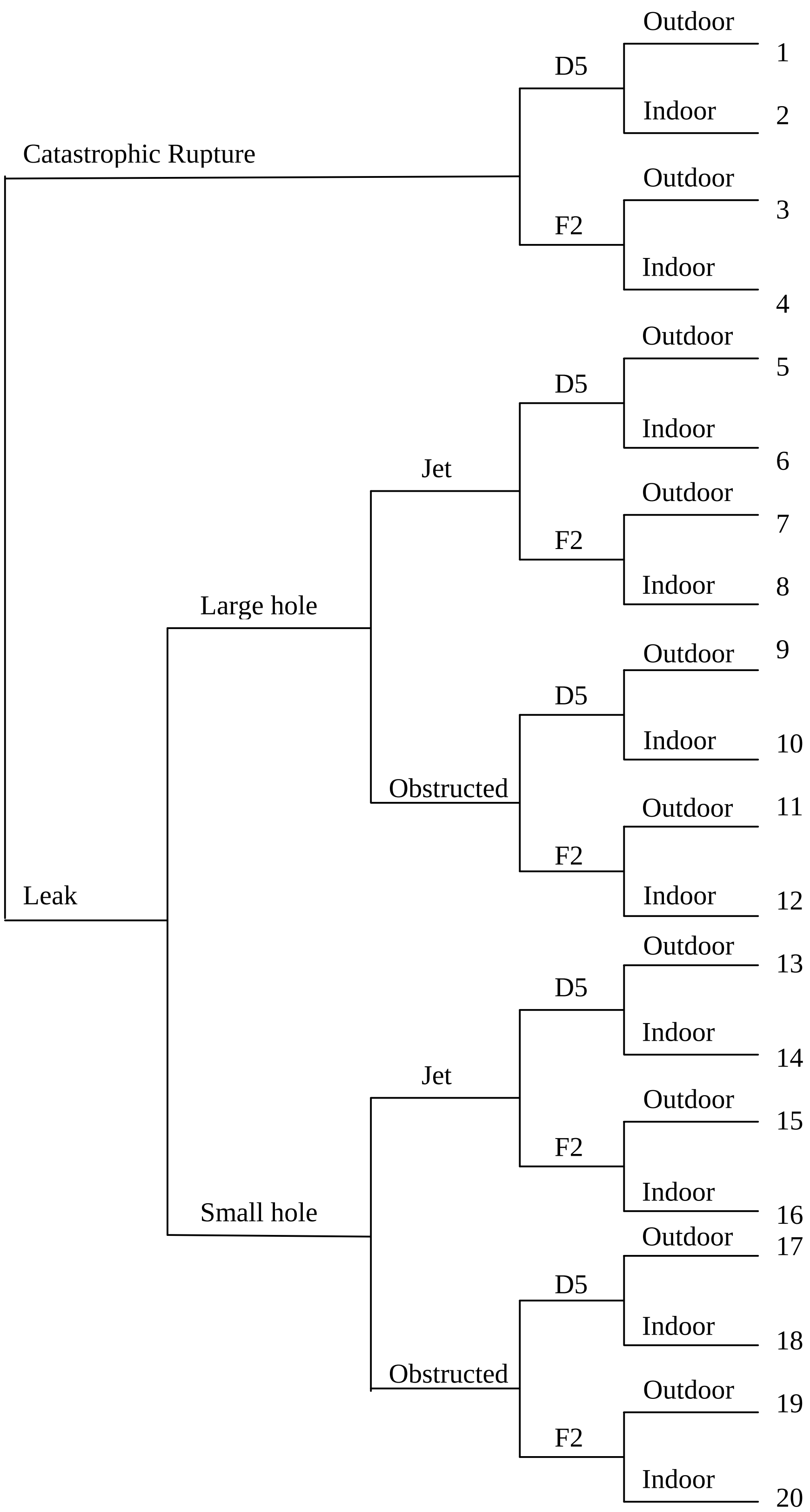
- Increasing the pressure increases the distance to a given risk level for both CO_2 and natural gas.

- Modelling was carried out at lower pressures than that of likely pipeline transport because there is some uncertainty when modelling dense phase CO_2, as the formation of solids cannot be modelled accurately. The hazard ranges and therefore risks would be expected to be substantially larger for releases at higher pressure and therefore in dense phase.

6.2 RECOMMENDATIONS

On the whole, this would imply that in terms of risk, CO_2 used for CCS has sufficient toxicity to be regulated as a dangerous fluid under the Pipeline Safety Regulations (PSR)

7 APPENDIX A – MODELLED SCENARIOS



8 APPENDIX B – CRATER ANGLE SENSITIVITY

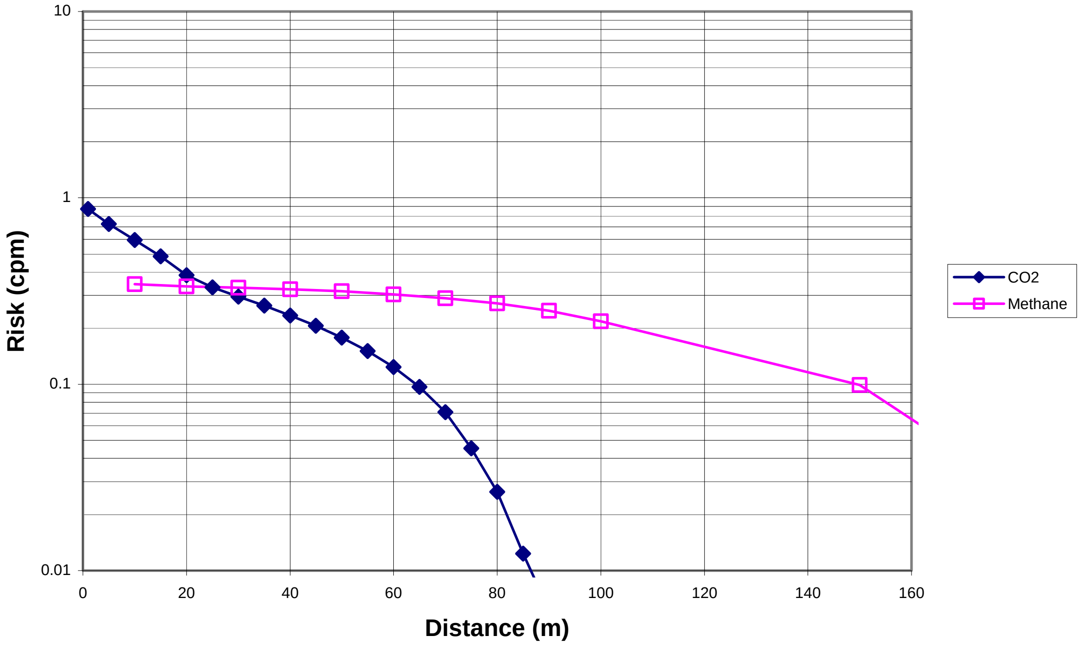
This sensitivity study confirms that a release angle 19º from the horizontal produces the largest hazard ranges, and should consequently be used in the remainder of the assessment.

Table 15 Release angle sensitivity

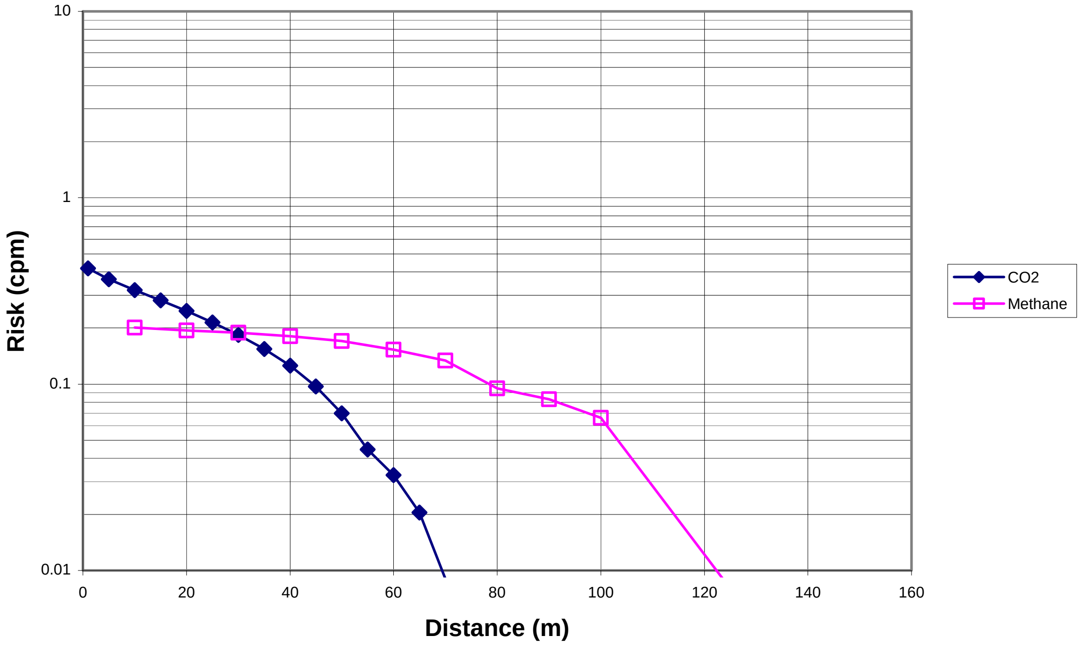
	Contours (m) - 19º		Contours (m) - 34º	
Event	Distance	Half-width	Distance	Half-width
1	15	0.39	4.4	0.33
2	13	0.36	4.1	0.33
3	15	0.39	3.8	0.33
4	12	0.36	3.6	0.33
5	97	5.3	97	5.3
6	78	3.8	78	3.8
7	97	8.8	97	8.8
8	70	4.6	70	4.5
9	5.0	0.12	4.5	0.12
10	4.5	0.10	4.0	0.11
11	5.3	0.12	4.9	0.12
12	4.4	0.10	3.9	0.11
13	-	-	-	-
14	-	-	-	-
15	-	-	-	-
16	-	-	-	-

9 APPENDIX C – RISK VS DISTANCE PLOTS

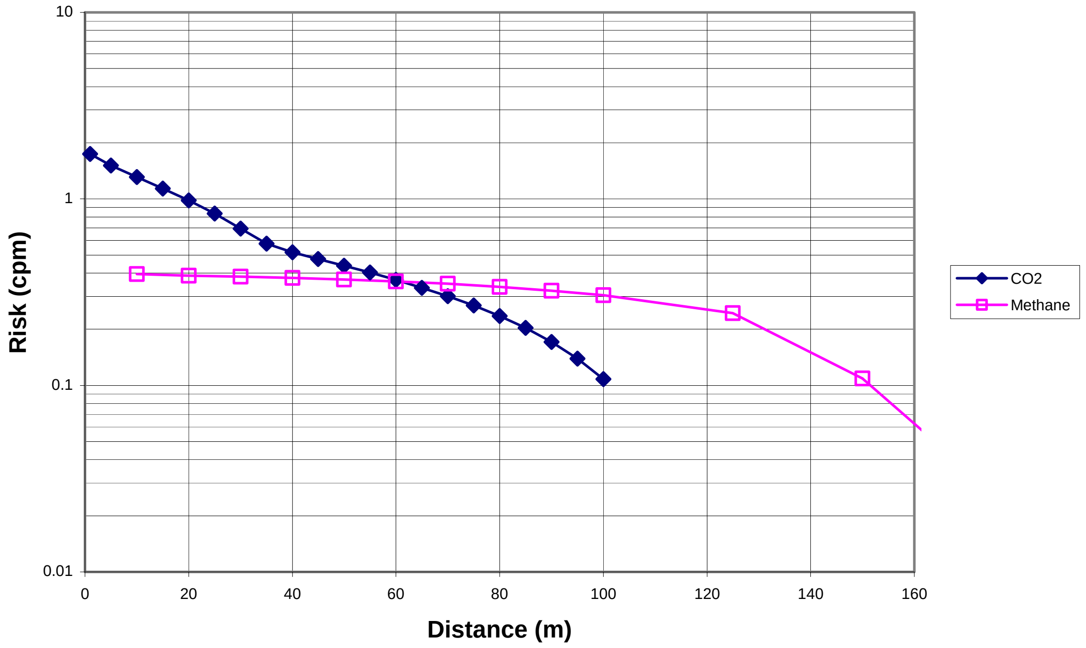
9.1 SLOD EQUIVALENTS, 32 BARG RELEASE



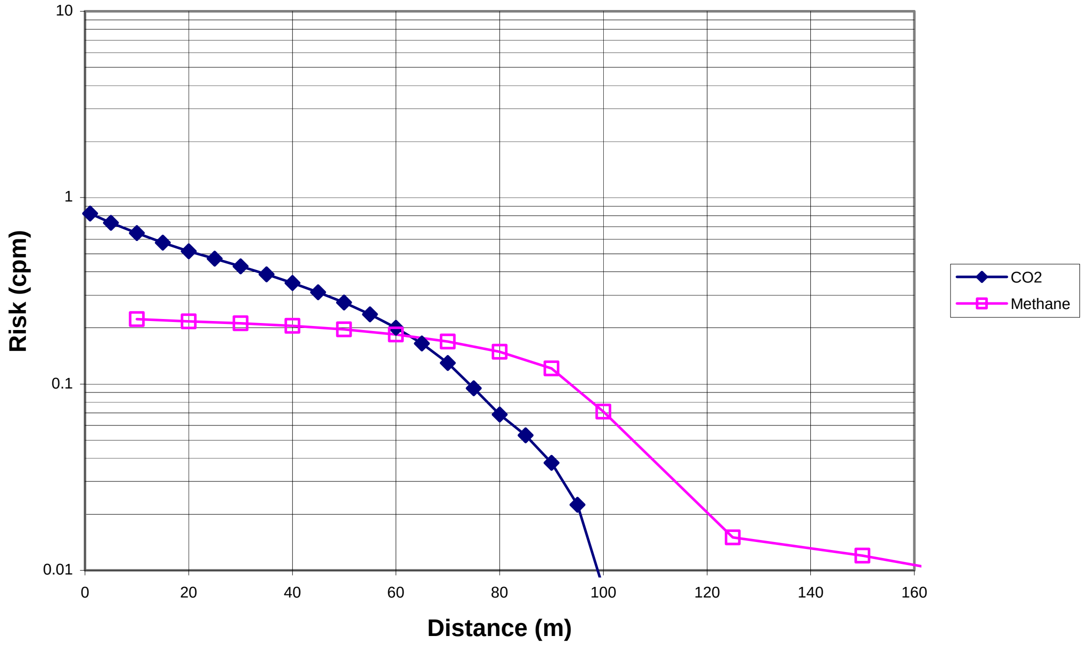
9.2 SLOD EQUIVALENTS, 15 BARG RELEASE



9.3 SLOT EQUIVALENTS, 32 BARG RELEASE



9.4 SLOT EQUIVALENTS, 15 BARG RELEASE



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HSE

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Executive

Comparison of risks from carbon dioxide and natural gas pipelines

Carbon capture and storage (CCS) is likely to form a significant part of the UK's strategy for achieving its Kyoto targets for CO2 emission reduction. CO2 is not currently regulated as a dangerous fluid under the Pipeline Safety Regulations (PSR) so further investigation is required to determine if it should be re-classified.

This project continues previous work (Moonis and Wilday, 2008) that recommended further investigation into the possibility of including CO2 as a dangerous fluid under the PSR. This previous work suggested that in terms of hazard range and hazard footprint area, CO2 should be classified as a dangerous substance but that further analysis would be required in terms of risk.

PHAST (commercial consequence modelling software) and TPRAM (HSE land-use planning software) were used to perform dispersion and risk modelling respectively for a release of CO2, so that the risk associated with the release could be determined. MISHAP (HSE land-use planning software) was also used to obtain the associated risks for methane (natural gas) with similar inputs to the CO2 modelling. Comparison between the risk values should determine if a CO2 release generates similar risks at distances that are smaller, equivalent or larger than natural gas.

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