Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 1 (2009) 1587–1594
Energy Procedia
www.elsevier.com/locate/procedia

GHGT-9

Uncertainties in risk assessment of CO_2 pipelines

J.Koornneef[a]*, M. Spruijt[b], M. Molag[b], A. Ramirez[a], A. Faaij[a] and W. Turkenburg[a]

[a]Group Science, Technology and Society, Copernicus Institute for Sustainable Development and Innovation, Utrecht University, 3584 CS Utrecht, The Netherlands
[b]TNO, section Environment, Health and Safety, 3584 CB Utrecht, The Netherlands

Abstract

The main goal of this study is to identify knowledge gaps and uncertainties in Quantitative Risk Assessments (QRA) for CO_2 pipelines and to assess to what extent those gaps and uncertainties affect the final outcome of the QRA. The impact of methodological choices and uncertain values for input parameters on the results of QRA's have been assessed through an extensive literature review and by using commercially available release, dispersion and effect models. It is made apparent that over the full life cycle of a QRA knowledge gaps and uncertainties are present that may have large scale impact on the accuracy of assessing risks of CO_2 pipelines. These encompass the invalidated release and dispersion models, the currently used failure rates, choosing the type of release to be modeled and the dose-effect relationships assumed. Also recommendations are presented for the improvement of QRA's for CO_2 pipelines.

© 2009 Elsevier Ltd. All rights reserved.

Keywords: quantitative risk assessment; CO_2 pipeline; infrastructure; CCS.

1. Introduction

Carbon capture and storage (CCS) is often considered in literature as one of the temporary technological solutions to control CO_2 emissions from large point sources. Between the capture and storage, the CO_2 has to be transported by one or a combination of several transport media (truck, train, ship or pipeline with possible intermediate storage). Transport by pipeline is preferred when transmitting large quantities of CO_2 over longer distances. In the international arena, specifically in the United States (USA), there is significant amount of experience with transporting large quantities of CO_2 by pipeline at high pressure. Currently, over 6000 km of CO_2 pipelines are being operated in the USA primarily for Enhanced Oil Recovery (EOR) projects [1]. These pipelines are mainly situated in remote areas with low population densities. When CCS will be implemented on a large scale, CO_2 transport infrastructure including a large network of CO_2 pipelines will be needed. Part of this infrastructure

* Corresponding author. Tel.: +31-30-253 3544; fax: +31-30-2537601.
E-mail address: j.m.koornneef@uu.nl.

doi:10.1016/j.egypro.2009.01.208

may be located in densely populated areas. Safety issues surrounding the operation of pipelines in these areas are expected to be more complex compared to current practice [2].

External safety is one key aspect that should be assessed prior and during the operational phase of CO_2 transport. Several risk assessments for CO_2 transport pipelines have been performed, for instance see [3-12]. The review of these risk assessments allows the identification of important knowledge gaps. At the moment, several uncertainties and knowledge gaps exist with regard to, for instance, the dispersion behavior and the modeling of (supercritical) CO_2 released into the atmosphere, CO_2 threshold values and (possible) effects of CO_2 leakages at different distances from the pipeline. Furthermore, existing literature shows significant differences in chosen outflow and dispersion models, assumptions on the distribution of population surrounding a pipeline, pipeline diameter, pressure, temperature, material, material thickness, soil coverage, risk mitigating options, assumed failure scenarios with accompanying diameters of the orifice, release rates, meteorological assumptions and frequency of pipeline failures. Other knowledge gaps may be due to the nature of the transported flow such as toxicity, corrosiveness and thermodynamic properties of CO_2.

These uncertainties and knowledge gaps may lead to opposing viewpoints and controversies. For instance, on the one hand, in literature it is suggested that CO_2 pipelines do not pose a higher risk than that already tolerated for transporting hydrocarbons or other dangerous substances [5, 7]. Heinrich et al. [13] also suggests that risks associated with CO_2 transport are well understood, while others indicate that it is a misconception that there is significant experience with designing CO_2 pipelines and that CO_2 pipelines near to population centers might pose a higher risk than pipelines transporting hydrocarbons [14].

From this preliminary review of risk assessments it can be concluded that there is no consensus on the risks of transporting CO_2 by pipeline. Furthermore, a systematic overview of the impact of methodological choices and values for uncertain input parameters on the results of QRA's for CO_2 pipelines is currently lacking. These findings form the rationale for this study.

The goal of the research is twofold. First, to identify (additional) knowledge gaps and uncertainties in QRA's for CO_2 pipelines. Second, to assess to what extent those gaps and uncertainties affect the final outcome of a QRA for CO_2 pipelines. We will present a ranking of uncertain inputs of the dispersion and effect models according to their contribution to variance in the results, which together with the identification of critical gaps helps setting R&D priorities for the improvement of QRA's.

2. Approach

In general, a QRA involves the determination of failure scenarios with a certain probability. These failure scenarios have a certain probability attributed to them based on expert judgment or heuristics; in this case experience with pipeline operation and failure. Then source region release and dispersion modeling is used to estimate the concentration of CO_2 at a certain location after elapse of time. In this way the exposure to CO_2 can be modeled (see Figure 1). With a probit function also the relationship between exposure to CO_2 and the effect on human mortality rate can be integrated into the calculations. Iso-risk contours can then be drawn that depict the probability that a person dies due to the release of CO_2 at a certain distance from the pipeline.

The whole process of performing a QRA involves that several methodological choices and assumptions for input parameters have to be made. In this study, we conduct a systematic overview of the impact of methodological choices and uncertain values for input parameters on the results of a QRA for CO_2 pipelines. Based on an in-depth literature review we have made a selection of input parameters and methodological choices that have shown, or are expected to have, large impacts on the results of the QRA. The importance of the values assumed for these parameters in QRA's is being assessed using commercially available dispersion and effect models (i.e. EFFECTS and RiskCurves software developed by TNO).

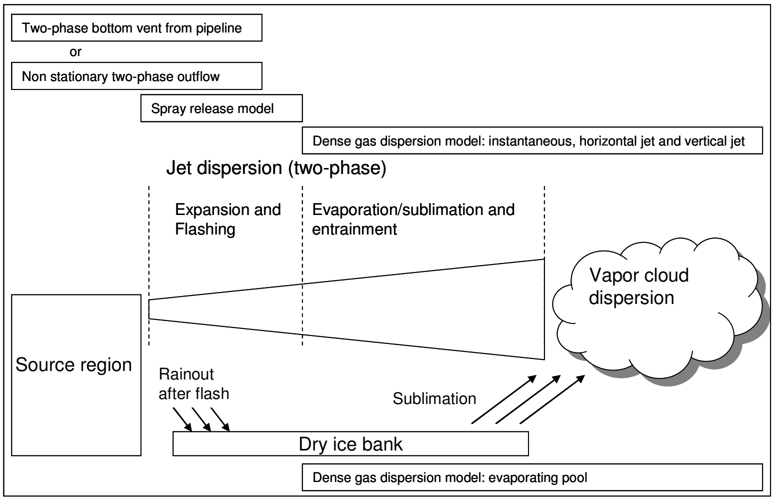

Figure 1 Overview of the methodological approach used in this study for a puncture and full rupture of a carbon dioxide pipeline.

In general, a failure is a puncture or a rupture that is primarily caused by third party interference, corrosion, construction or material defects (e.g. welds), ground movement and operator errors [5, 15]. This division into two types of failure (i.e. puncture and rupture) is followed in this research.

For the full rupture cases the source region is modeled by the Morrow model [16] for non-stationary two-phase outflow from a large pipeline. This is coupled with a spray release model, which calculates the jet properties and possible rain out of solid CO_2. Results from this model are then fed into a dense gas dispersion model (based on the SLAB model). This model makes distinction between horizontal jet (shown in Figure 1), vertical jet and instantaneous releases. Sublimation of possible precipitated CO_2 is modeled with an evaporating pool model for gases that are heavier than air.

For the puncture cases the TPDIS model developed by [17] is used to estimate the two-phase discharge from the pipeline. Further, the linkage of subsequent models (spray release and dense gas dispersion model) is equal to that of the full rupture case.

The parameters and the values for these parameters that have been selected and assessed are shown in Table 1. In total 14 scenarios (indicated in Table 1 by a 'S' followed by a number) have been developed in this research. Each scenario consists of two cases: one for a full rupture and one for a puncture. The release conditions in the puncture case are assumed to be the same for all scenarios, the only exception being the failure rate (scenario S2 and S5). In this paper only the final risk profile as depicted in Figure 2 will be discussed concisely.

In the results and discussion section the results of varying parameters in the QRA are discussed per distinctive step in the QRA, being: the probability of failure, release and dispersion, impact on health and risk mitigation.

Table 1 Parameters and values selected in the 14 failure scenarios for CO_2 pipelines

Parameter		**Values used in the scenarios**			
Pipeline diameter (in mm)		Default: 406	S8: 914		
Length of isolable section (km)		Default: 20	S14: 50		
Hole size (in mm)		full rupture: diameter pipeline	puncture: 20		
Vapor mass fraction in release		Default: 58%	S6: 100%	S7: 10 %	
Jet diameter (m)		Default: 0.8	S9: 0.5	S10: 2	
Type of release	Full rupture	Horizontal jet: S3, S6, S7, S8, S9, S10 and S14	Instantaneous: S1, S2, S4 and S5	Vertical jet: S11	Sublimating bank[a]: S12 (10% rain out), S13 (20% rain out)
	Puncture	Default: vertical			
Failure rates[b]		Default: pipeline rupture and puncture (NEN 3650 specifications)[c] ($6.1*10^{-4}$/(km*year))	S2[c]: Reserved lane pipeline puncture and rupture[d] ($0.7*10^{-4}$/(km*year))	S5: Rupture and puncture as in the QRA for the Souris pipeline[e] ($1.55*10^{-4}$/(km*year))	
Probit function[f]		Default: Probit function as derived by TNO [12] S4: Probit function as derived by Lievense [11]			

Note: the scenarios are indicated by the letter S followed by a number. For the parameters mentioned above the input value is the 'default' value unless indicated otherwise. [a]The sublimating dry ice bank is based upon an evaporating pool model including thermodynamic properties of CO_2 in the solid phase. [b]The distribution of failure between a full rupture and a leak is assumed to be 0.25:0.75 for the default and S2 scenarios. In the S5 scenarios a 50:50 distribution is assumed. [c]Standard failure rates for a pipeline that meets the requirements of the NEN 3650 pipeline code. [d]Standard failure rates for a pipeline that is situated in a reserved lane for pipelines. [e]This pipeline supplies CO_2 to the Weyburn oilfield in Canada, see [18] for more details. [f]The probit function has the form: $Pr = a + b*\ln(C^n *t)$. In this equation a, b, n are substance specific constants describing the probability of lethality related to a dose of a toxic substance, explosion or heat, C is the concentration and t is the exposure time.

3. Results & Discussion

3.1. Probability of failure

Cumulative failure rates (puncture plus rupture) assumed within studies on risks of CO_2 pipelines show a range within one order of magnitude, i.e. from 1.6 to $6.1*10^{-4}$ /(km*yr). The distribution of failure rates between a full rupture and leak also varies significantly between studies although the probability is in general estimated to be higher for a leak compared to full rupture.

Furthermore, the assumed failure rates are often based on failure rates for natural gas pipelines or pipelines in general. Expected impurities such as SO_x, NO_x, O_2 and H_2S may increase corrosion rates which may lead to higher failure frequencies in CO_2 pipelines if not addressed properly. Also, minimizing water content in the CO_2 flow is important to limit corrosion.

The effect of varying failure rates on the final result of the QRA can be seen in Figure 2 by comparing scenarios 1, 2 and 5. For the S2 (scenario with the lowest failure rates) the $1*10^{-6}$ risk contour lies at a maximum distance of 37 meter from the pipeline contrary to the 117 meters found for the S1 scenario with the highest failure rates. Reducing failure rates by a factor of ten here reduces the distance with 80 meters.

None of the puncture cases yielded a contribution to the risk shown in Figure 2. The contribution of punctures, which are expected to be more probable than full ruptures, to the risk of CO_2 pipelines is thus expected to be limited.

3.2. Release & Dispersion

A critical step in a QRA for CO_2 pipelines is defining the source term. In this part of the QRA the physical phenomena that take place during the accidental release from a pipeline are defined using models and failure scenario narratives. These phenomena are the dimensions of the source (area, height, direction), amount, velocity and duration of release, and the thermodynamic state (e.g. pressure, temperature) of the CO_2. Important factors in the further dispersion of CO_2 are the diameter of the expanded jet, the direction and impulse of the release, vapor mass fraction and the weather conditions (atmospheric stability, wind speed). These parameters in the QRA are determined with the use of release and dispersions models. A main issue of concern is that these models have not been validated yet for the release and dispersion following a high pressure release from CO_2 pipelines.

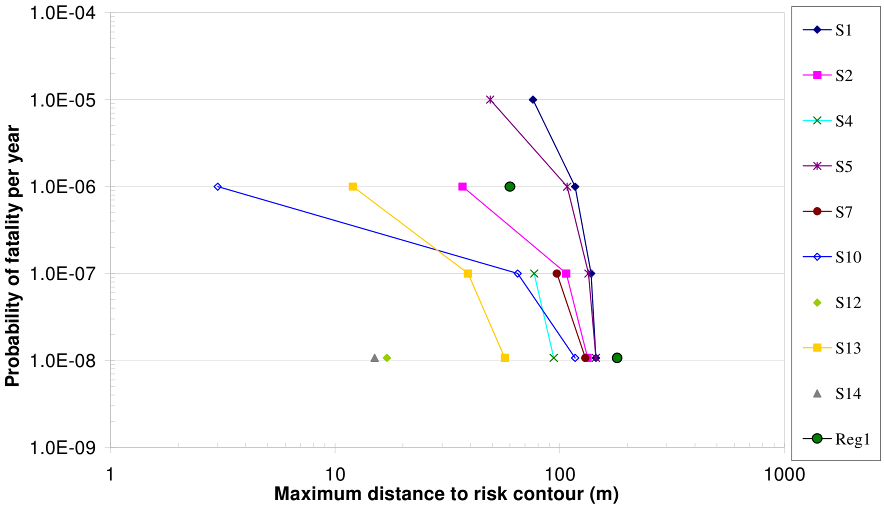

Figure 2 Overview of various failure scenarios formulated in this study showing the maximum distance from a pipeline to a probability of a fatality per year. Note that some scenarios (3, 6, 8, 9 and 11) the risks are too low to be shown in this graph. Reg1 indicates regulated distances for natural gas pipelines (80-110 bar, 1219 mm) operated in the Netherlands. Scenarios are calculated using RiskCurves software developed by TNO.

The direction and momentum of the released CO_2 has an important impact on the dispersion and consequently the calculation of risks. In literature various types of release (horizontal, instantaneous, vertical and evaporating pool) have been used to model the release and dispersion of escaping CO_2 [3-5, 7, 8, 10, 12]. The effect of varying the type of release can be seen in Figure 2 by comparing S1, S3 and S11, respectively the instantaneous, horizontal and vertical release. The $1*10^{-8}$ risk contour lies at 145 meter for the S1 scenario and is not present for the S3 and S11 scenarios, i.e. the risk is lower for the latter scenarios. The distance to the $1*10^{-6}$ risk contour for the S1 is further away than currently regulated for high pressure natural gas pipelines (indicated by Reg1 in Figure 2). The S12 and S13 scenarios are scenarios in which a part (10% and 20%) of the release of the S3 scenario is expected to rain out. The contribution of these fractions to the risk profile is assessed. The results show that a 10% rain out of the release results in a $1*10^{-8}$ risk contour at 17 meters from the pipeline. For the 20% variant this distance is 57 meters and the $1*10^{-6}$ risk contour lies then at 12 meters. When compared to the S3 it is striking that the dry ice banks, which result in a release rate significantly smaller than for the S3, result in a higher risk. An explanation is that for the sublimating dry ice banks, as well as for the instantaneous type of release, maximum concentrations are reached near the source, as both types of release are assumed to be without momentum. The opposite is seen for the releases with momentum (the vertical and horizontal release) where maximum concentrations are anticipated relatively further away from the source. Altogether this indicates that varying the type of release has significant impact on the risk profile of the CO_2 pipeline.

When increasing the diameter of the ruptured pipeline the higher exit flow rates are sustained for longer time periods. However, the smaller the diameter the longer the duration of a release. Comparing the S3 and S8 scenario may provide insight in the effect of the pipeline diameter on the risk profile. Both scenarios result however in too low risks to be shown in Figure 2.

Increasing the diameter of the expanded jet clearly has an effect on the risk profile. Such increase will result in higher CO_2 concentrations nearer to the source and a wider CO_2 cloud. The S3 scenario with a diameter of 0.8 meters yields no $1*10^{-8}$ risk contour versus a distance of 117 meters found for the S10 scenario with a diameter of 2 meters. The risk of the S9 scenario (diameter of 0.5 meters) is also too low to be shown in Figure 2.

Phase transition is an important phenomenon during release. It occurs when a pressurized liquefied gas, as CO_2 is likely to be transported through pipelines, suddenly encounters a pressure drop. If the pressure in the pipeline drops, the CO_2 will expand adiabatically which results in cooling of the pipeline content. When the pressure reaches the saturation pressure a two-phase flow of gas and liquid CO_2 is found. This occurs when part of the CO_2 evaporates by extracting heat from the liquid CO_2, which is called flashing. Under atmospheric pressure the boiling point is the sublimation point where gas and solid but no liquid phase occurs i.e. flashing ultimately results in the formation of solid CO_2 or dry ice and CO_2 in gaseous state (vapor fraction). The vapor fraction in the released CO_2 depends on the initial operating conditions (temperature, pressure). Vapor fraction is influenced by the pipeline temperature and to a lesser extent by varying pipeline pressure. The effect of this fraction on the dispersion and final risk profile is large, as can be seen by comparing the scenarios S3, S6 and S7. The highest distance, 130 meter, to the $1*10^{-8}$ risk contour is found for the scenario with the lowest vapor fraction (i.e. 10%) in the release. The risks of S3 and S6 with vapor fractions of respectively 56% and 100% are calculated to be too low to be shown. Furthermore, the vapor mass fraction is expected to influence the shape of the released CO_2 cloud. In general, in the case of a horizontal release, the lower the vapor fraction the wider the CO_2 cloud and the further it develops in downwind direction (at a height of 1 meter). The shape of the cloud in vertical direction is also significantly affected by the vapor fraction in the release.

According to literature, meteorological conditions have an important influence on the risk of a release of CO_2. Vendrig et al. [8] mention the F2 (Pasquill stability class[2]: F, wind speed: 2 m/s) conditions as the most problematic as these stable atmospheric conditions hinder dispersion and result in increased concentrations further downwind. Another study suggests that for vertical release the D stability class is worst than F stability class due to "the complex interaction of stability class and elevated plumes" [10]. The effect of meteorological conditions has not been studied yet in detail in this study but preliminary results show that when these conditions are varied that concentration profiles surrounding the pipeline after release also vary considerably. Under F2 conditions higher concentrations can be expected at great distances downwind. However, concentrations near the source show to be the highest under B5 conditions. It depends on the assumed probit function what is worst in terms of final risk, short duration high concentration or long duration low concentration.

3.3. Impact on health

Assuming different dose-effect relationships has a clear impact on the outcomes of the QRA. The probit function is used and is necessary in QRA's as it describes the relationship between exposure to a substance and the probability of dying from that exposure. In the absence of this function, pipeline risk assessments show a divergence in threshold values of several orders of magnitude for the exposure to CO_2 assumed to cause an effect (for instance see [4, 5, 7, 8]). At the moment there is no international standard for the application of an exposure threshold for CO_2 (see also [7]).

The S1 scenario with a probit function suggested by TNO [12] and the S4 scenario with a probit function suggested by Lievense [11] show a difference in the risk profile. The S4 has no $1*10^{-6}$ risk contour, indicating lower risk. Furthermore, the $1*10^{-8}$ risk contour lies approximately 50 meters (145 vs. 94 meters) further away for the S1 scenario. The effect of assuming no probit function but other thresholds can also be significant. In literature

[2] Pasquill stability classes: A = Very unstable; B = Unstable; C = Lightly unstable; D = Neutral; E = Stable; F = Very stable.

currently a wide range (2000 to 100000 ppm) of thresholds, including non-lethal, is used to construct the risk profiles. Using the lower end of these thresholds can result in the most extreme case in a $1*10^{-6}$ risk contour at 3400 meter (see ref [8]). For performing or comparing QRA's a uniform dose-effect relationship or standardized threshold clearly is required. The publication of a probit function for CO_2 for the use in QRA's in the Netherlands is expected end 2008. A probit function then should be adopted internationally to allow for methodological consistency.

3.4. Risk mitigation

Mitigation of risks should be focused on reducing the probability of large releases (see section 3.1). Several mitigation options are available to reduce the failure rate originating from third party interference. The first is physical protection of the pipeline by increasing soil coverage or covering the pipeline with concrete sheets. Both measures may reduce the probability of failure with a factor 10. Adjusting pipeline wall thickness, material selection and cathodic protection may help to reduce failure rate caused by corrosion. A higher level management option may be the registration of pipelines in a database to limit damage by third party operations and/or obligate third parties to notify on digging activities.

Risks can also be mitigated by reducing the consequences of failure. Decreasing the distance between block valves thus should have a positive effect on the risk profile as it decreases the duration of the release and total amount of released CO_2, and consequently exposure. According to the results of the models used in this study other characteristics of the release (e.g. maximum flow rate, pressure and temperature) are not affected by installing block valves. The results show that S14 (50 km between valves) has a distance to the $1*10^{-8}$ risk contour of 15 meters and thus a higher risk than S3 (20 km between valves) of which the risk contours are too small to be shown. A block valve may however be a potential failing component and will add cost when installed at shorter distances. Also, higher quality pipeline materials may be required near the block valves. An optimum thus has to be found between risk (increasing failure rate, shorter duration and less mass released) and economics (see also [15]).

4. Conclusion and recommendations

In this study knowledge gaps and uncertainties in QRA's for CO_2 pipelines have been identified and briefly discussed. A systematic assessment of the impact of these gaps and uncertainties on the results of QRA for CO_2 pipelines has been presented. A preliminary conclusion that can be drawn is that over the full life cycle of a QRA- i.e. probability of a failure, release and dispersion of CO_2 and the impact on health- knowledge gaps and uncertainties are present that may have large scale impact on the accuracy of assessing risks of CO_2 pipelines. The most important issues are:

- It is not certain whether failure rates for natural gas pipelines can be used for CO_2 pipelines. Failure rates may be different for CO_2 pipelines. The divergence of rates that have been used is within one order of magnitude and certainly has a clear impact on the risk profile of CO_2 pipelines.
- Results also indicate that the risk of CO_2 pipeline punctures is significantly lower than that of ruptures. Mitigation of risks should be focused on reducing the probability of large releases and less on that on reducing the probability of small scale leaks.
- Options for mitigating the risk are available but will add cost to the pipeline infrastructure and thus an optimum between risk and economics should be found.
- Preliminary results show that the type of release is one of the most important factors affecting the risk of a CO_2 pipeline. Currently, there is no consensus on the type of release that should be used when modeling CO_2 release and dispersion. The results indicate that when varying the type of release, risks values may be higher than currently regulated for high pressure natural gas pipelines. Clearly, methodological standards are required here.
- Also knowledge gaps are present surrounding the vapor mass fraction in the release. This parameter has a large influence on the dispersion and consequently on the risk profile of CO_2 releases. Release and dispersion field tests are required to measure the vapor fraction and the impact of dry ice formation on the dispersion of the release.
- Both a dose-effect relationship as well as internationally standardized exposure thresholds for CO_2 for use in QRA's is currently lacking. This results in a divergence of results in QRA's for CO_2 pipelines.

Based on these knowledge gaps and uncertainties, priorities for future R&D and methodological efforts are:

- Validation of high pressure CO_2 release and dispersion models by performing field tests.
- Definition and adoption of a universal dose-effect relationship (probit function) for CO_2. During the absence it is necessary to define uniform concentration and exposure thresholds for CO_2 to be used in QRA's.
- In cases where there is significant uncertainty when defining a methodological choice or value for an input parameter then the worst case outcome of that specific choice or input should be reported in the QRA, following the precautionary principle.

A more in-depth analysis of the knowledge gaps and uncertainties briefly discussed here as well as additional considerations for improving QRA's for CO_2 pipelines will be disclosed in a follow-up paper.

Acknowledgments

This research is part of the CATO programme. CATO is the Dutch national research programme on CO_2 Capture and Storage. CATO is financially supported by the Dutch Ministry of Economic Affairs under the BSIK programme. More information can be found on www.CO_2-cato.nl.

References

[1] Kadnar, J.O., Experience in CO2 transportation via pipeline, in CCS Web Conference on CO2 Transport, Health and Safety Issues. 2008, Internation Energy Agency: Paris.
[2] IPCC, IPCC Special Report on Carbon Dioxide Capture and Storage, in Prepared by Working Group III of the Intergovernmental Panel on Climate Change, B. Metz, et al., Editors. 2005: Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. p. 442.
[3] Golomb, D., Transport systems for ocean disposal of CO2 and their environmental effects. Energy Conversion and Management, 1997. 38(Supplement 1): p. S279.
[4] TetraTech, Final Risk Assessment Report for the FutureGen Project Environmental Impact Statement. 2007: Lafayette, CA, USA.
[5] Hooper, B., Murray, L., and Gibson-Poole, C., eds. Latrobe Valley CO2 Storage Assessment. 2005, CO2CRC.: Melbourne, Australia.
[6] Kruse, H. and Tekiela, M., Calculating the consequences of a CO2-pipeline rupture. Energy Conversion and Management, 1996. 37(6-8): p. 1013.
[7] Turner, R., Hardy, N., and Hooper, B. Quantifying The Risks To The Public Associated With A CO2 Sequestration Pipeline: A Methodology & Case Study. abstract. in Greenhouse Gas Control Technologies 8. 2006. Trondheim.
[8] Vendrig, M., Spouge, J., Bird, A., Daycock, J., and Johnsen, O., Risk analysis of the geological sequestration of carbon dioxide, DNV consulting, Editor. 2003, Department of Trade and Industry, London, UK.
[9] National Energy Board, Reasons for Decision Souris Valley Pipeline Limited. 1998.
[10] Cameron-Cole, Air dispersion modelling of well blowout and pipeline rupture scenarios Salt Creek field, in Environmental Assessment Howell Petroleum Phase III/IV CO2 Enhanced Oil Recovery Project: Salt Creek Oil Field, RETEC, et al., Editors. 2005, U.S. Department of the Interior; Bureau of Land Management Casper Field Office.
[11] Lievense, OCAP CO2 v.o.f. CO2 GREENGAS PROJECT Risico analyse NPM-leiding document 042282 rev. 3. 2005, Raadgevend Ingenieursbureau Lievense B.V: Breda.
[12] Molag, M. and Raben, I.M.E., Externe veiligheid onderzoek CO2 buisleiding bij Zoetermeer. 2006, TNO: Apeldoorn. p. 46.
[13] Heinrich, J.J., Herzog, H.J., and Reiner, D.M., Environmental Assessment of Geologic Storage of CO2. 2004, MIT LFEE Report.
[14] Barrie, J., Brown, K., Hatcher, P.R., and Schellhase, H.U. Carbon dioxide pipelines: a preliminary review of design and risk. in Greenhouse Gas Control Technologies 7. 2004. Vancouver, Canada.
[15] Gale, J. and Davison, J., Transmission of CO2--safety and economic considerations. Energy, 2004. 29(9-10): p. 1319.
[16] Morrow, T.B., Bass, R.L., and Lock, J.A., A LPG Pipeline Break Flow Model. Journal of Energy Resources Technology, 1983. 105.
[17] Kukkonen, J. Modelling source terms for the atmospheric dispersion of hazardous substances. in Commentationes Physico-Mathematicae 115/1990. 1990: Finnish Society of Sciences and Letters, Helsinki.
[18] NEB, Reasons for Decision in the matter of Souris Valley Pipeline Limited. 1998, National Energy Board: Calgary, Canada.