Open Access Journal
Journal of Power Technologies 94 (4) (2014) 323–328
journal homepage:papers.itc.pw.edu.pl

Assessment of risk related to transport of carbon dioxide

Andrzej Rusin*, Katarzyna Stolecka

Silesian University of Technology, Institute of Power Engineering and Turbomachinery ul. Konarskiego 18, 44-100 Gliwice, Poland

Abstract

Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide anticipates the need for carbon capture, transport and storage for power units that are planned or already under construction. Therefore, new power technologies based on firing hard coal or lignite have to take this requirement into account. This has legal and environmental impact ramifications, and pipeline infrastructure will have to be created to transport the captured CO_2. This paper presents an analysis of the risk related to transport of CO_2 from power plants to storage sites. Potentially hazardous effects of an uncontrolled release of CO_2 caused by pipeline failure are shown and the risk level in areas surrounding the pipeline is determined.

Keywords: carbon dioxide, pipeline, risk

1. Introduction

One of the factors commonly perceived to be driving climate change is the emission of greenhouse gases, carbon dioxide in particular. In 2009 the European Union adopted Directive 2009/31 EC of the European Parliament and of the Council on the geological storage of CO_2. The Directive requires that Poland, as an EU member state whose power sector is based on firing hard coal and lignite, should initiate works on the development and implementation of carbon dioxide capture and storage (CCS) technologies. Putting these technologies into practice will be a complex process, involving changes to law, major financial commitments and intense technical engagement to ensure the safety of each stage of CCS. Research is now being done to develop technologies that will allow commercially effective CO_2 capture. The following CO_2 capture technologies are known: technologies based on chemical absorption using a solution of monoethanolamine (MEA), separation from process gas in systems with coal gasification (pre-combustion) or oxy-combustion with CO_2 recirculation [1]. Individual CO_2 separation technologies may employ different methods of CCS. Research is also being carried out to identify possible CO_2 storage sites. Determining the conditions of safe gas transport is an issue that still needs to be addressed more specifically. Although carbon dioxide is considered to be a non-noxious gas, in large concentrations it can pose a serious threat to life. The risk related to CO_2 transport is presented below. There are various individual hazards involved: leakage of CO_2 from pipelines; release from facilities or intermediate storage points creating a hazard of human contact with a stream of very low temperature gas; leakage from CO_2 storage tanks in sea/river ports; and leakage from equipment during CO_2 injection into geological formations.

---

[*] Corresponding author

2. Risk of carbon dioxide storage

Hazards related to CO_2 storage are posed by leakage of the gas from storage sites, its migration into inner layers and release into the atmosphere. The factors affecting storage safety are: the thickness, porosity and permeability of geological formations, as well as their chemical composition. The following are typical potential storage sites: saline aquifers located at a depth of 800m, structures formed from entirely or partially depleted oil or gas deposits and unmined deep coal beds containing methane. Poland is estimated to have approximately 100 potential storage locations. At each such location, storing carbon dioxide poses a potential health, environmental and economic hazard [2, 3].

The main environmental hazard arises from possible carbon dioxide migration resulting in contamination of clean water reservoirs. It may also have a negative effect on nearby marine and freshwater flora and fauna. The health hazard comes from the physiological effects of carbon dioxide on humans and animals, particularly at higher concentrations. At a concentration of 1%, carbon dioxide causes drowsiness. Concentrations exceeding 2% have a slightly narcotic effect and result in elevated blood pressure and a faster heart rate. They also affect hearing acuity. In concentrations ranging from 3 to 5%, carbon dioxide impedes breathing, raises blood pressure significantly, causes dizziness and headaches and accelerates the heart beat. At concentrations higher than 10%, loss of consciousness may occur and longer exposure results in death from suffocation [4, 5]. In atmospheric concentrations carbon dioxide is not harmful to plants. However, increased concentrations may disturb growth, causing yellowing and drying out. High CO_2 concentrations may also disturb the soil pH level and restrict root development. It is hypothesized that vegetation could disappear completely in an area where carbon dioxide concentrations exceed 20% for longer periods. The economic hazard involves costs of any failures of CCS installations, including CO_2 transport facilities. Higher taxes on extra emissions of carbon dioxide into the atmosphere might contribute to additional losses if leakage from storage sites occurs. Attention should also be drawn to the destructive impact of carbon dioxide on concrete and reinforced concrete structures and on plastics.

3. Risk of carbon dioxide transport

The process of transporting carbon dioxide to storage sites seems to be the most serious health and environmental risk. Carbon dioxide is now transported via pipelines in the USA for example and it appears to be one of the most effective methods of gas transport to storage sites [6–8]. However, a pipeline failure may release a cloud with a high concentration of CO_2 in a relatively short period of time, thereby posing a health hazard. The size of the cloud will depend on factors such as the pipeline geometry or gas parameters. The diameters of pipelines transporting CO_2 range from 0.3 to 0.7 m, and the pressure of the transported gas—from 10 to 20 MPa. Data on causes of damage to CO_2 pipelines include items such as: leaking valves, poor quality of weld seams, corrosion and human errors resulting from excavation works carried out in close proximity to transporting facilities. Another important problem is the formation of ‘hydrate plugs’, caused by CO_2’s strong propensity to produce hydrates and the high content of water in the flow stream. Measures to eliminate pipeline failures include: CO_2 drying to prevent corrosion, avoidance of elastomeric seals in the CO_2 installation because the gas can dissolve such materials, and—at the design stage—taking account of the possibility of brittle cracking and crack propagation in the pipeline [7–9]. Another crucial element of pipeline safety is the correct placement of safety valves together with automatic gas leak detection systems. This makes it possible to close the two valves either side of the leak, thus limiting the gas leak to the gas contained in that stretch of the pipeline. The optimum arrangement and number of shut-off valves are especially important in densely populated areas. These factors determine the size of the hazard zone around the pipeline. Thus, when analyzing the CCS installation risk, the key factor is determining hazard zones around the pipeline. These zones depend on the potential concentration of CO_2.

An example range of zones with a 5, 10 and 20% CO_2 concentration is presented in Fig. 1. The figure was obtained based on analyses conducted using

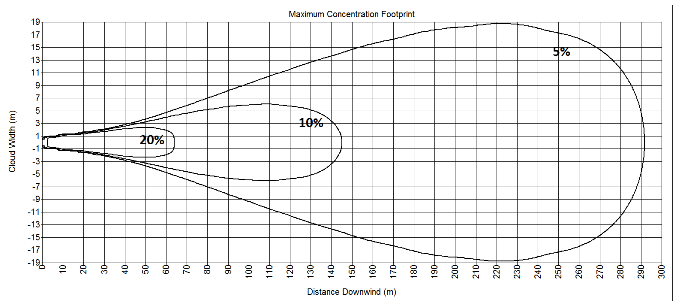

Figure 1: Example CO_2 concentration areas for a pipeline (d = 0.3 m)

the PHAST v6.7 software package [10]. The program makes use of the Unified Dispersion Model (UDM) which enables the calculation of quantities describing the movement and development of the gas cloud in the atmosphere, taking account all cloud stages such as release, touchdown, pool formation and evaporation for example. A more detailed description of the models applied is given in [5, 11, 12].

The diagram concerns a steady outflow from a 10 km long damaged pipeline with 0.3 m diameter. It can thus represent a situation in which safety valves are present. The parameters of transported carbon dioxide are as follows: pressure 152.6 bar and temperature 20°C [5]. As indicated in Fig. 1, the 20% concentration zone occupies an area of about 209 m^2, the 10% concentration zone about 1126 m^2, and the 5% concentration zone about 6,657 m^2. The analyses presented above concern issues related to the safety of carbon dioxide pipeline transport. If due to a failure CO2 is released into the atmosphere, in certain concentrations it may pose a hazard to humans, as described in Section 2 above. Another hazard involved with transport using rail tankers or with CO_2 storage in tanks, in liquid form, is the BLEVE phenomenon. Such a disaster hit Repcelok (Hungary) in 1969. BLEVE, i.e., a boiling liquid expanding vapor explosion, is a phenomenon which takes place if a vessel containing a pressurized liquid above its boiling point is ruptured. The vessel may be damaged by factors such as collision with another object or internal pressure on vessel walls weakened by corrosion or material faults. After it is ruptured, the BLEVE results in the tank fragments being thrown large distances, the creation of a shock wave and, if the liquid is flammable, formation of an intensely radiating fireball. The PHAST v.6.7 software was used to analyze the BLEVE phenomenon and to calculate the ranges of zones where the pressure wave generated was higher than 13.8 kPa, 50 kPa and 120 kPa. It was assumed that carbon dioxide was in spherical tanks with a capacity of 60 m^3 and 1 m^3. The CO_2 parameters were as follows: pressure 15 bar and temperature—30°C.

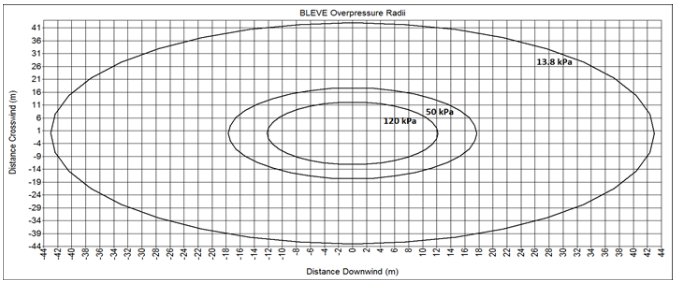

Figure 2: Pressure wave caused by the BLEVE phenomenon (V = 60 m^3)

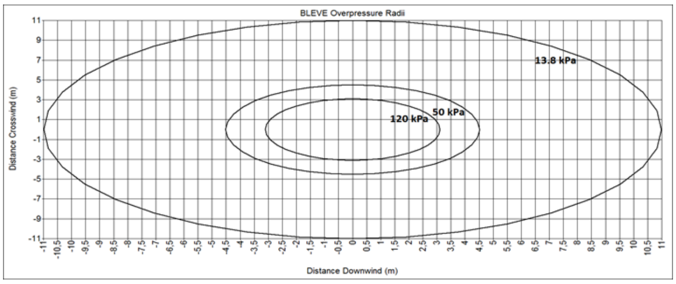

Figure 3: Pressure wave caused by the BLEVE phenomenon (V = 1 m^3)

Fig. 2 and Fig. 3 present the ranges of zones for spherical tanks of 60 m^3 and 1 m^3 respectively. Fig. 2 and Fig. 3 illustrate the BLEVE and the resulting pressure wave that may occur if a tank filled with carbon dioxide is ruptured. The range of the pressure wave will depending on the tank capacity and CO_2 parameters, among other things. For example, in the case of a 13.8 kPa pressure wave, which is equivalent to the boundary value at which the eardrum is damaged, the range is about 43 meters for a tank with a capacity of 60 m^3 and 11 meters for a tank capacity of 1 m^3.

4. Death risk assessment in zones around a damaged pipeline

The risk is understood here as the product of the consequence of a hazardous event and the probability of its occurrence. Regarding carbon dioxide transport, it can be expressed by the following relation:

$$R = P \cdot C_e \tag{1}$$

where: P is the probability of occurrence of a hazardous carbon dioxide leak event and C_e is the consequence of the event.

The risk related to a given industrial facility can be presented as the risk of the occurrence of undesirable events, e.g. death or serious injury to an individual in the risk occurrence zone. This is referred to as individual risk. Social risk is the measure of risk posed to a community. In both cases, in order to calculate the risk, the probability or frequency of the occurrence of hazardous events and their consequences have to be estimated. Moreover, for social risk it is necessary to estimate the size of the population exposed to a given risk. The social risk assessment is especially important for facilities where large amounts of dangerous substances are stored and for installations and transport means intended for such substances. In the next part of the article the individual risk related to carbon dioxide transportation will be analyzed. The consequence of a CO_2 leak depends on the distance from the damaged pipeline, the gas concentration or—with BLEVE—on the resulting pressure wave. A measure of the consequence of carbon dioxide release or of the pressure wave effect on people (death) is the probit function.

The function describes the impact of the failure on humans and surroundings. It thus relates the quantity of the harmful factor and the response to it. For the carbon dioxide release from a damaged pipeline, the probit function was calculated from the expression using the gas concentration [9]:

$$P_r = 4.45 + \ln(C^{5.2} \cdot t) \tag{2}$$

where: C—carbon dioxide concentration at a specific distance from the failure location, t—time.

Since with BLEVE it is the pressure wave that creates the hazard, the probit function can be defined using the following expression:

$$P_r = -77.1 + 6.91 \ln(\Delta p) \tag{3}$$

where: Δp—pressure wave, Pa.

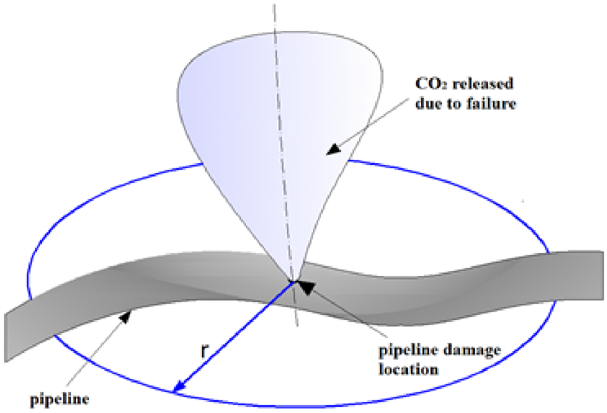

Figure 4: Outflow of gas from a damaged pipeline

The diagram in Fig. 4 shows the hazard zone around a damaged pipeline. The size of the zone depends both on the amount of gas released and the atmospheric conditions [5, 9].

Based on statistical data the probability of pipeline rupture equal to $2 \cdot 10^{-5}$ per year and per kilometer was assumed [13].

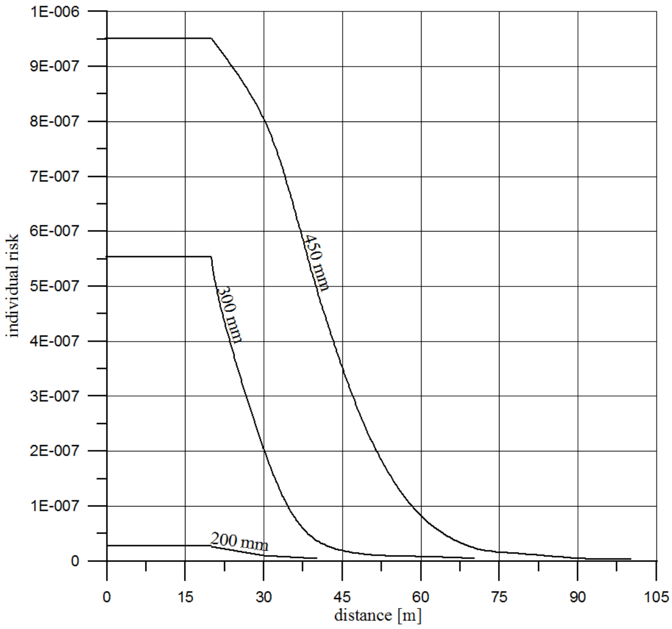

Figure 5: Individual risk as a function of distance from the location of the pipeline rupture (0.5 km)

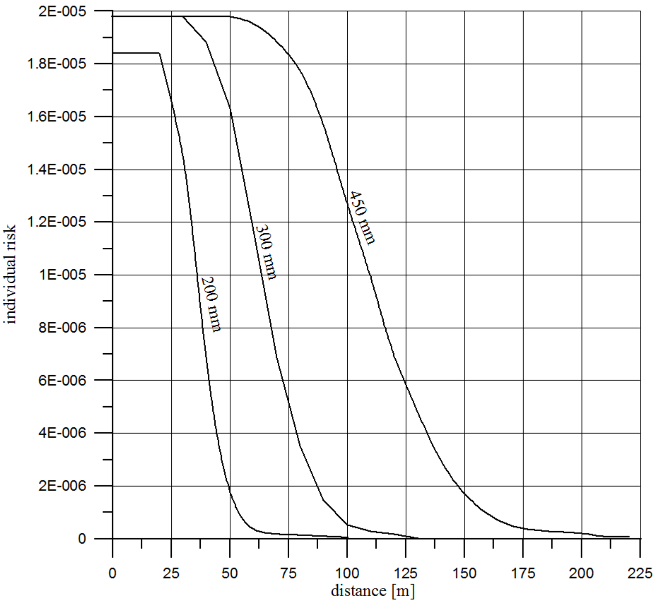

Figure 6: Individual risk as a function of distance from location of the pipeline rupture (10 km)

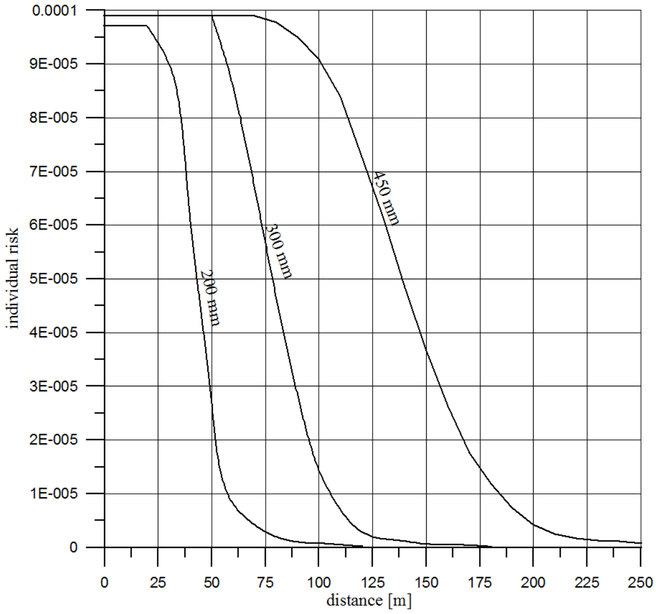

Figure 7: Individual risk as a function of distance from location of pipeline rupture (50 km)

Example results of individual risk assessment in the area surrounding a damaged pipeline are shown in Fig. 5, 6, 7. They present the level of risk created by a carbon dioxide release from a pipeline with a length of 0.5, 10 and 50 km as a function of distances from the location of the pipeline rupture. Individual curves were plotted for different diameters of pipelines.

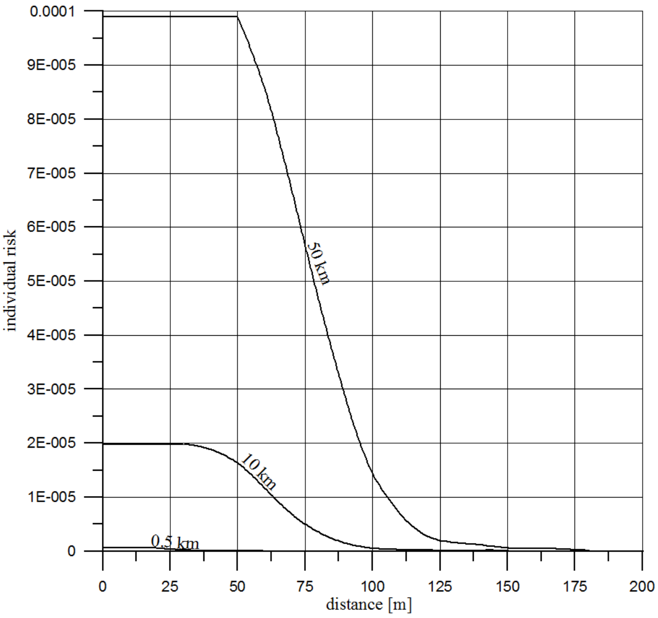

Figure 8: Individual risk as a function of distance from the pipeline failure location (d = 0.3 m)

Fig. 8 presents the individual risk value depending on the distance from the location of the pipeline failure. Individual curves were plotted for different pipeline lengths of 0.5, 10 and 50 km. In each case the assumed diameter of pipeline is 300 mm.

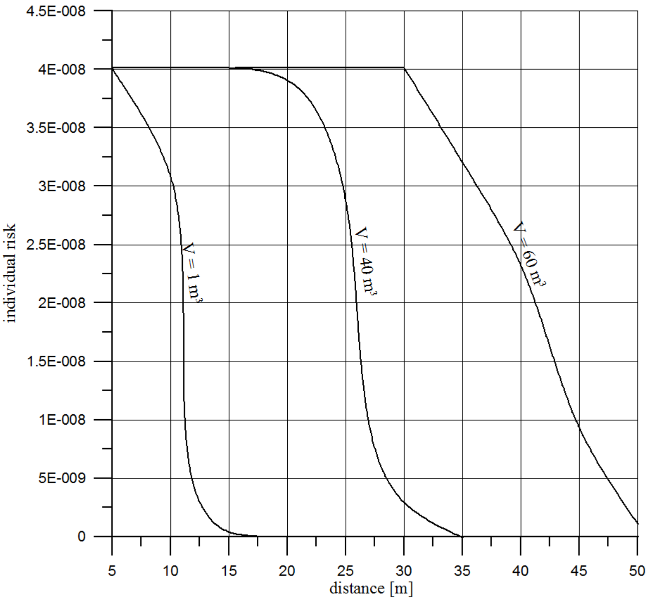

Figure 9: Risk value as a function of distance from BLEVE (spherical tank)

Fig. 9 presents the death risk as a function of the distance from the failure location for BLEVE from a spherical tank. Individual curves were plotted for different capacity values of 1, and 60 m^3, respectively. The probability of tank rupture equal to $4.01 \cdot 10^{-8}$ [13].

5. Conclusions

This paper presents an analysis of the consequences of a potential failure of a pipeline transporting carbon dioxide. It is a reliable tool for assessing the safety of the CO_2 transport infrastructure and should be an indispensable element of any new power plant design that anticipates the construction of a CCS installation. It could also form part of an information campaign aimed at local communities in areas potentially affected by carbon dioxide capture, transport and storage facilities.

Acknowledgments

The results presented in this paper were obtained from research work co-financed by the National Center Research and Development in the framework of Contract SP/E/1/67484/10—Strategic Research Programme—Advanced technologies for energy generation: Development of a technology for highly efficient zero-emission coal-fired power units integrated with CO_2 capture.

References

[1] C. Alie, P. L. Douglas, J. Davison, On the operability of power plants with co2 capture and storage, Energy Procedia 1 (2009) 1521–1526.

[2] J. Condor, D. Unatrakarn, M. Wilson, K. Asghari, A comparative analysis of risk assessment methodologies for the geologic storage of carbon dioxide, Energy Procedia 4 (2011) 4036—4043.

[3] Y. Zhang, C. Oldenburg, F. S., P. Jordan, Probability estimation of co2 leakage through faults at geologic carbon sequestration sites, Energy Procedia 1 (2009) 41–46.

[4] Design and operation of co2 pipelines. recommended practice. dnv-rp-j202, Tech. rep., Det Norske Veritas (2010).

[5] A. Witkowski, A. Rusin, R. S. Majkut, M., S. K., Comprehensive analysis of the pipeline transportation systems for co2 sequestration. thermodynamics and safety problems,, Energy Conversion and Management 76 (2013) 665–673.

[6] M. Molag, C. Dam, Modelling of accidental releases from high pressure co2 pipelines, Energy Procedia 4 (2011) 2301–2307.

[7] F. Eldevik, B. Graver, L. Torbergsen, S. O.T, Development of a guideline for safe, reliable and cost efficient transmission of co2 in pipelines, Energy Procedia 1 (2009) 1579–1585.

[8] C. Rybicki, M. Łaciak, Transport rurociągowy co2 [pipeline transport of carbon dioxide], Rurociągi – Polish Pipeline Journal 4 (2008) 2–5.

[9] J. Koornneef, M. Spruijt, A. Ramirez, W. Turkenburg, A. Faaij, Quantitative risk assessment of co2 transport by pipelines – a review of uncertainties and their impacts, Journal of Hazardous Materials 177 (2010) 12–27.

[10] PHAST v.6.7 DNV Software 2010.

[11] UDM Theory Document, DNV Software, 2009.

[12] H. Witlox, M. Harper, A. Oke, Modelling of discharge and atmospheric dispersion for carbon dioxide releases, Journal of Loss Prevention in the Process Industries 22 (2009) 795–802.

[13] R. Gerboni, E. Salvador, Hydrogen transportation systems: Elements of risk analysis, Energy 34 (2009) 2223–2229.