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Assessment of risk from transport of carbon dioxide

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Abstract
Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide anticipates the need for the gas capture, transport and storage in the case of new power units the construction of which is either under way or planned. Therefore, new power technologies based on firing hard coal or lignite have to take this requirement into account. Their application will involve adopting a certain legal framework and their environmental impact will have to be determined. A pipeline infrastructure will have to be created for the transport of captured CO_2. This paper presents an analysis of the hazards and risk related to CO_2 transport from power plants to potential storage sites. Potential hazardous effects of an uncontrollable release of CO_2 caused by a pipeline failure are shown and the risk level in areas surrounding the pipeline is determined.

Keywords: carbon dioxide, pipeline, risk

1. Introduction

An unequivocal explanation of climatic changes observed in the contemporary world is a problem that requires further studies. A common belief is that one of the factors leading to these changes is 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 a 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. Applying these technologies will involve taking many steps, both legal and financial, as well as solving problems related to the safety of each stage of CO_2 capture, transport and storage. Painstaking research is now being done to develop technologies that will allow CO_2 capture that is economically effective. 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 the gas capture, transport and storage. Research is also being carried out to determine the directions and possible sites of CO_2 storage. Determining the conditions of the gas safe transport is an issue that still needs to be addressed more specifically. Although carbon dioxide is considered to be an indifferent gas, in big concentrations it can pose a serious health or even life hazard to both humans and animals.

The problem of the risk related to CO_2 transport is presented hereinbelow. Hazards involved with it might arise from a potential leakage of CO_2 from transport pipelines. Moreover, CO_2 may be released from facilities or intermediate storage points and create a hazard of coming into contact with a stream of gas with a very low temperature. During sea transport, leakage from CO_2 storage tanks in ports may pose another potential danger. During CO_2 injection into geological formations, leakage from the gas injection installations and equipment may also occur.

2. Risk of carbon dioxide storage

Potential hazards related to the storage of CO_2 are posed by leakage of the gas from storage sites, its migration in inner layers and release into the atmosphere. Hence, the factors that will decide about carbon dioxide storage safety are the following: the thickness, porosity and permeability of geological formations, as well as their chemical composition. The potential storage sites are usually as follows: saline aquifers located at the depth of 800 m, structures formed from entirely or partially depleted oil or gas deposits and unmined deep coal beds containing methane. It is estimated that in Poland there should be about 100 potential carbon dioxide storage locations. At each such location, storing carbon dioxide involves a potential hazard to the environment, health and economy [2,11].

The environmental hazard is related to carbon dioxide migration resulting in contamination of clean water reservoirs. It may also have a negative effect on the marine flora and fauna (if CO_2 is stored in immediate vicinity of seas and oceans). The health hazard is related to the impact of carbon dioxide on humans and animals. In higher concentrations, carbon dioxide has an adverse impact on human behaviour and health. In a concentration at the level of 1%, carbon dioxide causes drowsiness. Concentrations exceeding 2% have a slightly narcotic effect and result in a higher blood pressure and pulse. 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. Additionally, at concentrations higher than 10%, loss of consciousness may occur and longer exposure results in death from suffocation. [3,9]. In atmospheric concentrations carbon dioxide is not harmful to plants. However, increased concentrations may disturb the plants growth, their yellowing and drying out. High CO_2 concentrations may also disturb the soil pH level and restrict root development. It is supposed that vegetation could totally disappear if carbon dioxide concentrations in a given area exceed 20% for longer periods. The economic hazard involves costs of potential 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 CO_2 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 gas sequestration stage that potentially creates the most serious hazard to humans and to the environment. Carbon dioxide is now transported via pipelines in the USA for example and this seems to be one of the most effective methods of the gas transport to storage sites [4,6,7]. However, a failure of such a pipeline may cause a release of a cloud with a high concentration of CO_2 in a relatively short period of time, which will pose a potential hazard to human health and life. The size of the cloud will depend on factors such as the pipeline geometry or the 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. The 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 so-called hydrate plugs, which is the effect of the CO_2 strong tendency to produce hydrates and of the high content of water in the flowing stream. The measures taken 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 designing stage – taking account of the possibility of brittle cracking and crack propagation in the pipeline [4,5,7]. Another crucial element of safety of the pipelines transporting CO_2 is the correct placement of safety valves together with automatic gas leak detection systems. This makes it possible to close the two valves neighbouring the leakage location, thus limiting the amount of gas that gets into the surroundings to the amount contained in between the valves. Consequently, the CO_2 cloud released into the atmosphere is smaller. The optimum arrangement and the number of such valves are especially important in densely populated areas. These factors determine the size of the hazard zone around the pipeline. Thus, analyzing the CCS installation risk, the key element to prevent the adverse effects of an uncontrollable CO_2 leakage is to determine 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 the PHAST v6.7 software package [12]. The program makes use of the Unified Dispersion Model (UDM) which allows the calculation of quantities describing the transport of the gas cloud in the atmosphere, taking account of all cloud stages such as release, touchdown, pool formation and evaporation for example. A more detailed description of applied models is given in [8÷10].

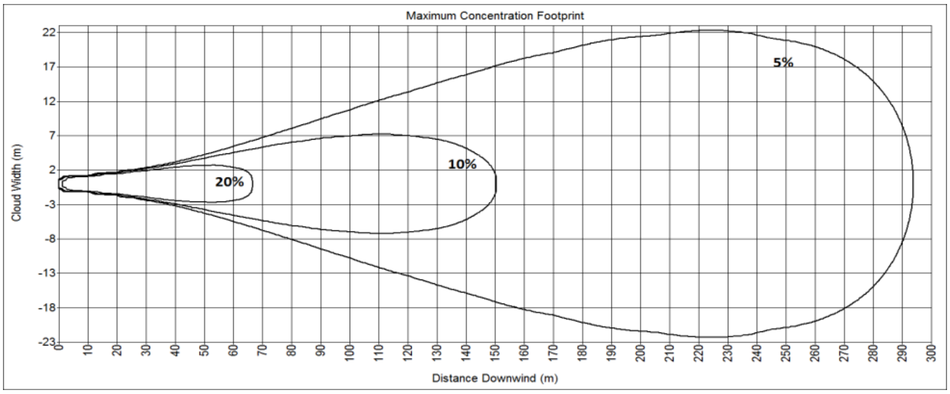

Fig. 1. Example CO_2 concentration areas for a pipeline (d = 0.35 m)

The diagram concerns a steady outflow from a 10 km long damaged pipeline with 0.35 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^oC [9]. As indicated in Fig. 1, the zone with a 20% concentration occupies an area of about 250 m^2, with a 10% concentration – about 1380 m^2, and with a 5% concentration – about 8000 m^2.

The analyses presented above concern issues related to the safety of carbon dioxide pipeline transport. If due to a failure CO_2 is released into the atmosphere, in certain concentrations it may create 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 a liquid form, is the BLEVE phenomenon. Such a disaster hit Repcelok (Hungary) in 1969. BLEVE, i.e. the boiling liquid expanding vapour explosion, is a phenomenon which takes place if vessel containing a pressurized liquid above its boiling point is ruptured . The vessel may be damaged by external factors, such as a collision with another object, or due to the effect of internal pressure on the vessel walls weakened by corrosion or material faults. After it is ruptured, the BLEVE phenomenon results in the tank fragments being thrown at large distances, creation of a shock wave and, if the liquid is flammable, formation of an intensely radiating fireball.

Also in order to analyze the BLEVE phenomenon, the PHAST v.6.7 software was used, and the ranges of zones in which the value of the pressure wave generated due to the explosion was higher than 13.8 kPa, 50 kPa and 120 kPa were calculated. 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^oC.

Fig. 2 and Fig. 3 present the ranges of zones in the case of a spherical tank with the bigger and smaller capacity, respectively.

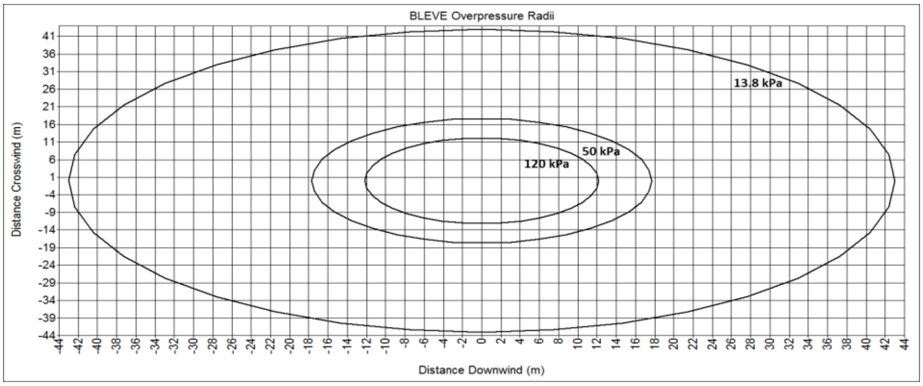

Fig. 2. Pressure wave caused by the BLEVE phenomenon (V = 60m^3)

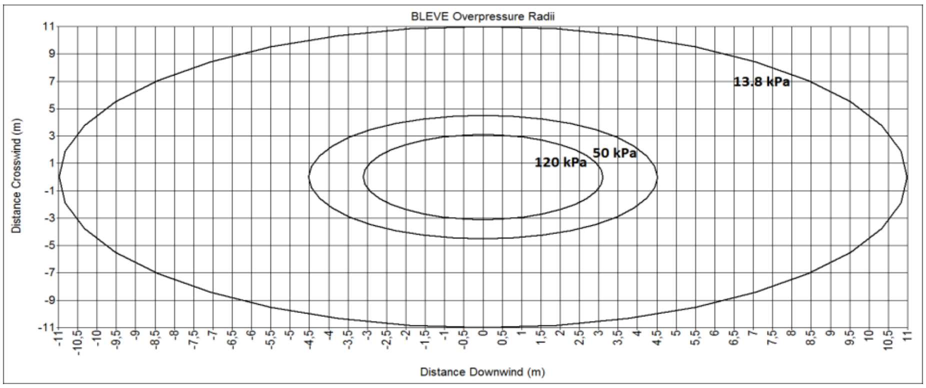

Fig. 3. Pressure wave caused by the BLEVE phenomenon (V = 1m^3)

The diagrams presented above indicate that the BLEVE phenomenon and the resulting pressure wave can pose a hazard to humans and structures if a tank filled with carbon dioxide is ruptured. Depending on the tank capacity, and on CO_2 parameters, the pressure wave will have a different range. For example, in the case of a 13.8 kPa pressure wave, which is equivalent to the boundary value at which the eardrum gets damaged, the range is about 43 metres for a tank with a capacity of 60 m^3 and 11 metres for a tank capacity of $1 m^3$.

4. Death risk assessment in zones surrounding a damaged pipeline

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

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

where: P is the probability of occurrence of a hazardous event of carbon dioxide leakage from a damaged pipeline and C is the consequence of the event.

The consequence of a CO_2 leakage depends on the distance from the damaged pipeline, the population density and the gas concentration or – in the case of the BLEVE phenomenon – on the resulting pressure wave. It can therefore be expressed as:

$$C = D \cdot A \cdot P_r \tag{2}$$

where: A is the pipeline surrounding area with a certain population density D. P_r is the probit function which is a measure of the consequence of carbon dioxide release or of the pressure wave effect on people (death).

The function describes the impact of the failure consequences on humans and surroundings. It thus relates the quantity of the harmful factor and the response to it.

For the release of carbon dioxide from a damaged pipeline, the probit function was calculated from the expression using the gas concentration [5]:

$$P_r = 4.45 + \ln(C^{5.2} t) \tag{3}$$

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

Because in the case of the BLEVE phenomenon it is the pressure wave that creates the hazard, the probit function can be defined using the following expression:

$$P_r = -77.1 + 6.91 \ln(\Delta p) \tag{4}$$

where: Δp – pressure wave [Pa]

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

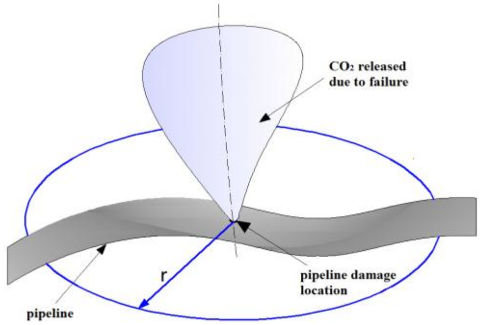

Fig. 4. Outflow of gas from a damaged pipeline

Example results of risk assessment in the area surrounding a damaged pipeline are shown in Fig. 5÷7. They present the level of risk created by a carbon dioxide release from a pipeline with a diameter of 0.35 m as a function of the pipeline length for different population density values of 150, 750 and 1500 persons/km^2. The individual curves were plotted for different distances from the location of the pipeline rupture diagram in Fig. 4 shows the hazard zone around.

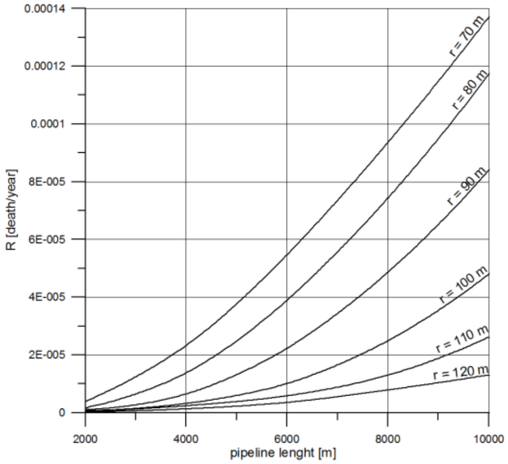

Fig. 5. Death risk as a function of the pipeline length (D = 150 persons/km^2)

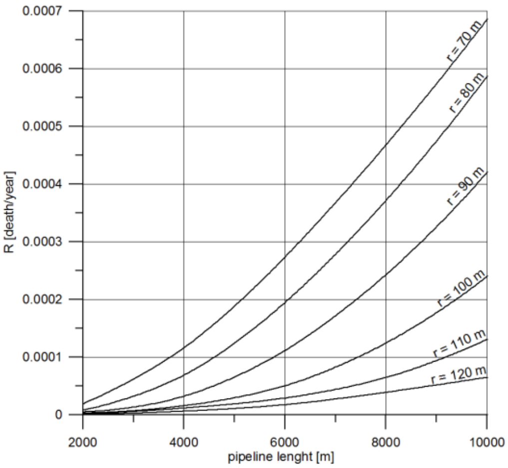

Fig. 6. Death risk as a function of the pipeline length (D = 750 persons/km^2)

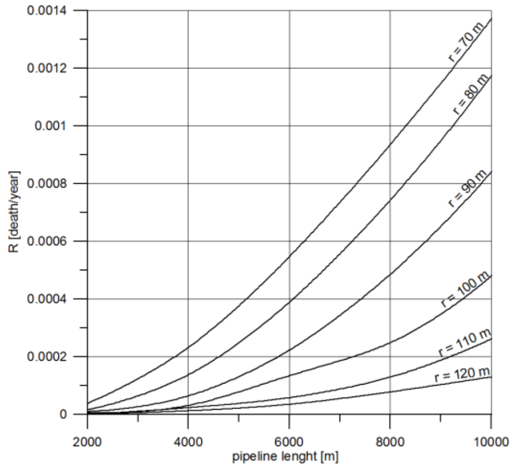

Fig. 7. Death risk as a function of the pipeline length (D = 1500 persons/km^2)

Fig. 8 presents the risk value depending on the distance from the location of the pipeline failure. The individual curves were plotted for different pipeline lengths of 2, 6 and 10 km. In each case the assumed population density is 150 persons/km^2.

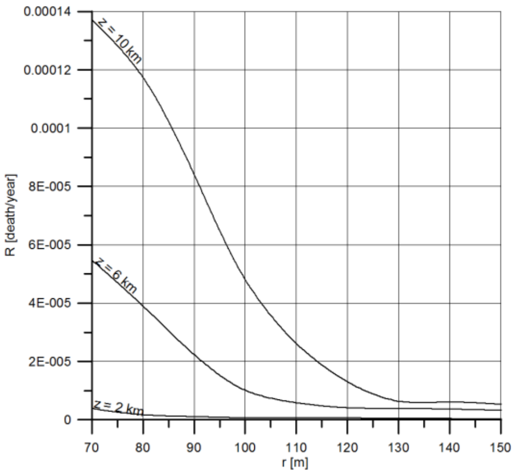

Fig. 8. Death risk as a function of distance from the pipeline failure location (d = 0.35 m)

Fig. 9 presents the death risk as a function of the distance from the pipeline failure location for a spherical tank BLEVE phenomenon. The individual curves were plotted for different population density values of 500, 1000 and 1500 persons/km^2, respectively.

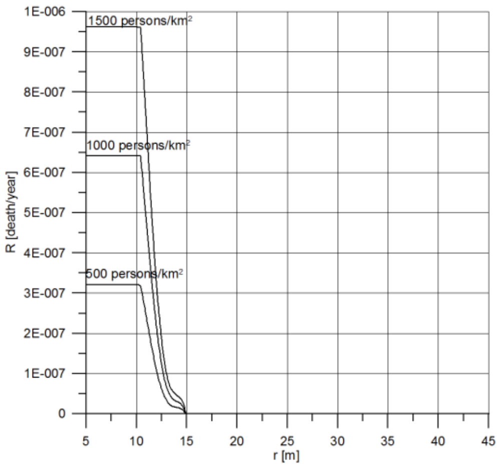

Fig. 9. Risk value as a function of distance from the BLEVE phenomenon (spherical tank)

5. Conclusions

The presented analysis of the consequences of a potential failure of a pipeline transporting carbon dioxide is a reliable tool for the assessment of safety of the infrastructure serving the needs of CO_2 transport. It should be an indispensable element of any new power plant design anticipating a construction of the CCS installation. It could also be an essential element of information campaigns addressed to local communities in regions where a deployment of carbon dioxide capture, transport and storage facilities is planned.

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