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Safety and effectiveness of carbon dioxide storage in water-bearing horizons of the Upper Silesian Coal Basin region

Introduction

In Poland and worldwide intensive operations are conducted concerning the possibility of carbon dioxide storage in water-bearing horizons. They are concentrated on the indication of optimum sites for underground carbon dioxide injection (among others Torp 2004; Uliasz--Misiak 2007; Chadwick et al. 2008; Tarkowski 2008; Nagy, Siemek 2009; Solik-Heliasz 2009; Stopa et al. 2009). The subject of analyses are mainly reservoir parameters of storage site formations, tightness of the overburden and tightness of faults. They allow to determine the ranges of future storage sites. However, the results of investigations have shown that the impact of underground CO_2 injection will not be limited only to the storage site area; it will appear also beyond its boundaries (Solik-Heliasz 2010b). According to the opinion of the authoress, an underground carbon dioxide storage site should not enter into interaction with other undertakings of utilitarian character, located in the neighbourhood (underground water intakes, exploitation of fossil fuel deposits etc.). Therefore appears the need to determine the minimum distance between them (protective zone or pillar), ensuring a safe course of individual economic initiatives. Moreover, initial economic analyses of the CCS (*carbon capture and storage*) process have shown that this process will be capital-intensive (Dreszer et al. 2007). In connection with the above significant will be all initiatives and proposals aiming at the increase of CO_2 injection effectiveness and thus limitation of storage costs. The results of investigations realised hitherto have suggested some solutions.

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Below has been presented an analysis of problems, which were the subject of investigations performed at the Central Mining Institute in the years 2007–2010 in the framework of the project Technological Initiative I entitled: "Study of safe carbon dioxide storage by example of the Silesian agglomeration", statutory works of the institute and projects realised for economic subjects.

1. Problems connected with the selection of sites for underground carbon dioxide storage

The results of investigations realised hitherto show that the areas of future storage must fulfil several conditions, namely:

— the storage sites must be safe and the CO_2 injection process must be effective and should not influence other undertakings in the neighbourhood,

— the determined CO_2 storage capacities must be sufficient for the needs of CO_2 emitters,

— the storage sites cannot be located in the areas of urban agglomerations and big industrial objects.

The fundamental condition for the selection of rock structures and formations for underground storage is their good recognition by means of *in situ* and laboratory tests (Bachu et al. 1994; Kumar et al. 2005; Chadwick et al. 2008). Generally most attention is devoted to the determination of parameters of the reservoir series – chiefly hydrogeological parameters, thickness, physico-chemical composition of waters and gases comprised in them and the mineralogical composition of rocks. A narrower scope of investigations concerns generally isolating formations occurring in the roof and floor of the storage site. Their fundamental parameters are determined mainly on the basis of geophysical investigations and geological charts. Meanwhile the results of carbon dioxide injection can be also undesirable reactions and phenomena occurring within the range of the storage site and beyond it. It has been ascertained during the performed investigations that this may concern among others rock fracturing and changes in the hydro-dynamic system of the water-bearing horizon. Rock fracturing is connected with CO_2 injection pressure. The analysis of possibility and usefulness of formation fracturing is a complex task, which will be developed in the further part of the work. The basis of inference within this scope are the results of denotation of physical features and strength parameters of rocks.

2. Safety of underground CO_2 storage

The assurance of safe underground carbon dioxide storage is one of the principal rules connected with the CCS process. Taking into consideration the factors presented above, from storage the area of the central part of the Silesian agglomeration was eliminated – on account of dense population and accumulation of industrial plants, and the area of its north-eastern border – on account of the lack of sufficient recognition of supply conditions of the potentially convenient for management water-bearing horizon of the Lower Jurassic system (Solik-Heliasz 2010a). Advantageous conditions for CO_2 injection have been stated, however, in the water-bearing horizon of the Dębowiec layers on the southern border of the Upper Silesian Coal Basin (Fig. 1). The formations of the storage site are connected with Miocene sandstones of the Dębowiec layers of thickness 70–250 m. In their roof occurs

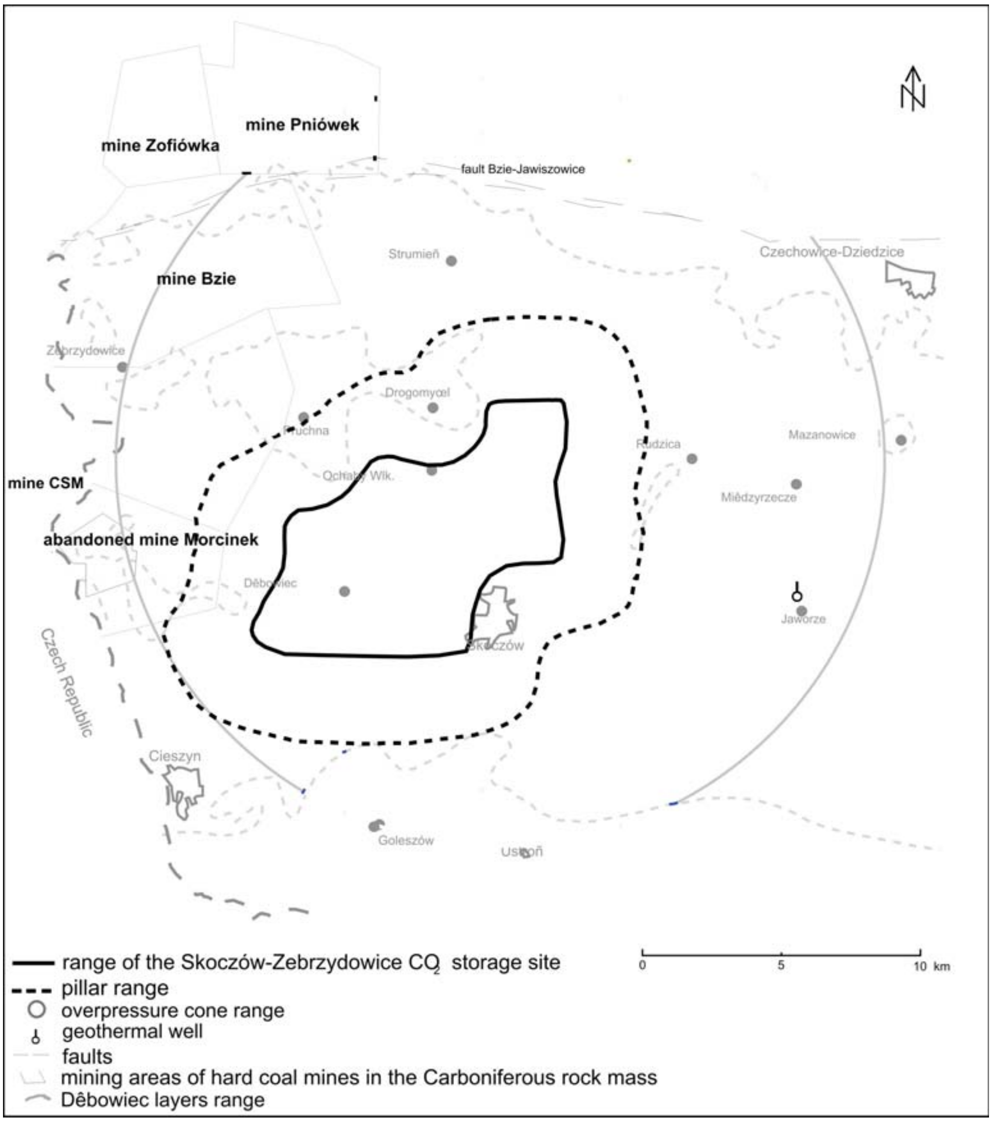

Fig. 1. Location of the Skoczów-Zebrzydowice underground coal dioxide storage site

Rys. 1. Lokalizacja podziemnego składowiska dwutlenku węgla Skoczów-Zebrzydowice a complex of silty Miocene formations and locally clay shales and mudstones from the flysch series of total thickness 400–950 m. The complex has an isolating character, what is essential, because the rock mass in the area of the underground storage site must be tight even in the case of local increasing of its permeability as a result of carbon dioxide injection. And here appears the problem of rock mass fracturing, which in unfavourable conditions can be the source of water hazard. Unsealing and/or permeability increase of rock series can occur in the case of carbon dioxide injection under a higher pressure than the rock fracturing pressure. Generally rock fracturing is assessed as a phenomenon being undesirable during CO_2 injection. According to the opinion of the authoress, controlled fracturing, limited to the reservoir series or its fragment, can lead to the increase of CO_2 injection effectiveness. In the case of suitably selected injection pressure, fracturing should not constitute a hazard with respect to the terrain surface, especially therefore that in the case of the Skoczów-Zebrzydowice storage site it has been determined at great depth, 825–1020 m below the terrain surface level. Planned rock fracturing can concern only the storage site area. However, there exists an exception; one cannot allow reservoir formation fracturing in the area of big discontinuity zones, particularly faults. Even non-flooded faults can be made permeable as a result of cracks in rocks occurring in their environment. This can lead to the rise of new hydraulic connections, not necessarily safe for the storage process. A phenomenon of this type was observed in mine workings of the Morcinek mine, where outflows of underground waters frequently have not originated from the main fault fissure, but from small cracks surrounding the dislocation zone (on the basis of own observations of the authoress).

The effect of CO_2 injection into the water-bearing horizon will be also the rise of the cone of depression. The radius of the cone will increase with the passage of time, and the overpressure front will outstrip the CO_2 injection front. With reference to the Skoczów--Zebrzydowice storage site, the radius of the cone after 5 years of injection was determined at 11.8 km (Solik-Heliasz 2010a). Currently the physical effects of the overpressure front in the water-bearing layer are not known. In the case of high overpressure rock cracking can follow. According to the opinion of the authoress, rock fracturing as a result of CO_2 injection (e.g. in the injection borehole area) and fracturing as a result of overpressure front displacement (beyond the injection site) concern two different phenomena, though connected to each other. Fracturing occurring in the injection borehole area results from the pressure of injected CO_2. This medium is present in the underground water environment and during injection fills the additional space in the system of pores and rocks. In turn, fracturing occurring beyond the injection area may result from the "accumulation" of water particles as a result of their expulsion and displacement by pores, successively filled through carbon dioxide. The scale of the phenomenon will depend on CO_2 injection pressure, porosity and strength parameters of rocks. A physical effect of overpressure can be among others the increase of flow velocity of underground waters. This may result in the increase of intensity of water inflows into boreholes and mine workings in the neighbourhood of the storage site.

With reference to the Skoczów-Zebrzydowice storage site, its location was approved after the ascertained lack of influence on other undertakings existing and planned in the neighbourhood. On the basis of this issue appears the problem of determination of protective zones (pillars) for underground carbon dioxide storage.

3. Determination of protective zones for underground CO_2 storage

The problem of determination of protective zones or pillars for underground CO_2 storage hitherto has not found reflection in the literature. The storage sites determined in Poland and in Europe are located in water-bearing layers that are not used from the economic point of view. Thus there did not appear the problem of their neighbourhood with other undertakings located in the near vicinity. The authoress has ascertained the need to determine such zones in the course of research work concerning the delimitation of the range of the Skoczów--Zebrzydowice storage site. The storage site is located on the border of the Upper Silesian Coal Basin, in a poorly populated region, however, at some distance from it occurs a big fault zone with thrust 400–600 m, an intake of geothermal waters, and in the Carboniferous rock mass – mine fields of coal mines (Fig. 1). The designed storage site must be located at a safe distance from them, therefore appeared the need to determine an optimum distance (pillar) between them.

The notion "safety pillar" was adopted from spheres connected with underground mining. By help of this term the rock solid left in the rock medium between the water hazard source and the mine working is defined (Rogoż 1987). In the case of underground CO_2 storage sites the aim of the pillar will be protection against the gas hazard connected with CO_2, and the water hazard. Hazards can create among others: water-bearing horizons, faults, underground water reservoirs. Their source can be also the phenomena of rock mass fracturing as a result of carbon dioxide injection and propagation of the overpressure front. An underground carbon dioxide storage site should be both an object protected against other environmental elements (e.g. flooded faults), as well as creating a hazard (e.g. for other undertakings in the vicinity).

The methodology of determination of pillars of underground CO_2 storage sites must be the subject of further work. It is not possible to use directly the existing calculation methods relating to underground water filtration. For the estimation of the minimum width of the pillar between the storage site and mine workings and underground water intake the Slesariev's formula was used (Frolik 1998):

$$D_{kr} = g \cdot \sqrt{60 \cdot p} \tag{1}$$

where:

D_{kr} – minimum pillar width [m],

g – average thickness of the reservoir series [m],

p – destination pressure in the reservoir [MPa].

For calculations the following data were adopted:
— g = 115 m,
— p = 10.75 MPa.

It has been assumed that the pressure of the water-gas medium on the border of the CO_2 storage site will adopt the value equal to the maximum injection pressure, i.e. 10.75 MPa. The minimum width of the storage site pillar was determined at 2921 m (Fig. 1). In the case of the Bzie-Jawiszowice fault zone, comprising a bundle of parallel faults, the distance from the storage site to the main discontinuity line was adopted at min. 7 km.

The safety pillars should be determined towards all surfaces of the storage sites, what schematically was presented in Figure 2: lateral – what is especially responsible, because it concerns the formations of water-bearing layers and other economic undertakings, which can be designed in it; roof surface – still important, because it concerns the possible CO_2 impact on the terrain surface; and floor surface – also essential on account of the possibility of economic management of water-bearing horizons and rock series occurring below the pillar. The pillars will constitute a safety buffer for other utilitarian undertakings planned in the environment of underground carbon dioxide storage sites.

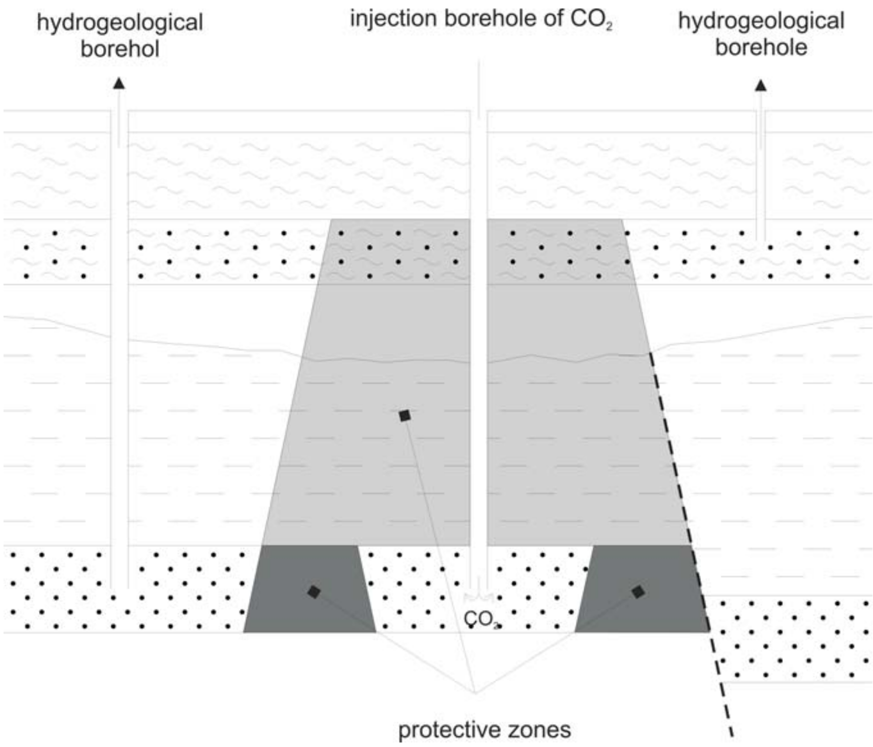

Fig. 2. Conception of location of protective zones for underground CO_2 storage

Rys. 2. Koncepcja lokalizacji stref ochronnych dla podziemnego składowania CO_2

3. Effectiveness of CO_2 storage

The effectiveness of underground carbon dioxide storage depends on a number of factors, which will lead to the limitation of CO_2 injection costs. Some of them can be mentioned here:

- — determination of the optimum storage site location,
- — determination of the suitable number and location of injection boreholes,
- — use of some phenomena improving the effectiveness of CO_2 injection,
- — advanced determination of phenomena hindering CO_2 injection.

The optimum location of the storage site on account of its favourable reservoir parameters, tightness of the storage site and distance from the emitter, are the basic factors conditioning the successful course of the investment connected with CCS. Worthy of notice is also the environment of the future storage site, on account of its "collision susceptibility" relating to other economic undertakings. It should be taken into consideration that in the area of carbon dioxide storage sites and surrounding them pillars it will not be possible in the future to conduct any other economic undertakings. Thus when locating by way of example CO_2 storage sites in usable water horizons (thermal, drinking or curative waters) one should be conscious of the loss of possibility to drill to them boreholes for economic, curative or recreation needs. Similarly as in the case of deposits of minerals as well as rock and chemical raw materials, they could be exploited only from a safe distance, both beyond the range of mutual influence, and interference with the storage site.

About the effectiveness of CO_2 injection will also decide the number, location and construction of injection boreholes. The investigation results have pointed out that more safe for the injection course will be the exploitation of the storage site by means of more than one injection borehole (in the case of the considered storage site the number of injection boreholes should amount to 2–3). A greater number of boreholes will allow current correction of injection parameters, such as: intensity and time of injection, possible injection breaks etc. If necessary, it will be possible to increase the injection effectiveness through the fracturing of reservoir formations. We can consider here two variants: fracturing outstripping the CO_2 injection process and fracturing taking place during CO_2 injection. Fracturing can be especially advantageous in water-bearing layers with average reservoir parameters.

The CO_2 injection process can considerably slow down phenomena of chemical compounds precipitation, being the effect of reaction at the contact water-rock-CO_2. These phenomena should be determined in advance. Also in this case the presence of more than one injection borehole can ensure the continuity of storage site exploitation.

Summary

The indication of sites for underground carbon dioxide storage should not be limited to the analysis of geological conditions within the storage site range. It has been ascertained in the course of investigations that the CO_2 injection process can also influence the area extending beyond the storage site boundaries. Also other utilitarian undertakings existing in the neighbourhood of storage sites can influence the storage process. Therefore the determination of protective zones for underground carbon dioxide storage and other important environmental elements, e.g. big fault zones, was proposed. They will be a safety guarantor for the storage process and for other undertakings conducted in the neighbourhood.

The CO_2 injection process must be also efficient. The injection effectiveness can be increased through controlled fracturing of reservoir rocks. In turn, the necessary injection continuity can ensure the exploitation of the storage site by means of more than one injection borehole.

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BEZPIECZEŃSTWO I EFEKTYWNOŚĆ SKŁADOWANIA DWUTLENKU WĘGLA W POZIOMACH WODONOŚNYCH REJONU GÓRNOŚLĄSKIEGO ZAGŁĘBIA WĘGLOWEGO

Słowa kluczowe

Składowiska CO_2, strefy ochronne składowisk, efektywność zatłaczania CO_2, szczelinowanie utworów zbiornikowych, składowiska w GZW

Streszczenie

Przedstawiono wyniki badań w zakresie składowania CO_2 w poziomach wodonośnych na obszarze GZW. Stwierdzono, że proces iniekcji CO_2 zaznaczy się w obszarze składowiska oraz poza jego granicami. Zaproponowano wyznaczanie stref ochronnych dla podziemnego składowania CO_2 i innych elementów strukturalnych, np. dużych stref tektonicznych. Strefy te będą stanowiły bufor bezpieczeństwa między podziemnym składowiskiem i przedsięwzięciami utylitarnymi prowadzonymi w jego sąsiedztwie. W pracy przedstawiono propozycję intensyfikacji zatłaczania CO_2 poprzez kontrolowane szczelinowanie utworów przyszłego składowiska. Zabieg powinien zwiększyć efektywność zatłaczania CO_2 zwłaszcza w seriach skalnych cechujących się przeciętnymi wartościami parametrów zbiornikowych.

SAFETY AND EFFECTIVENESS OF CARBON DIOXIDE STORAGE IN WATER-BEARING HORIZONS OF THE UPPER SILESIAN COAL BASIN REGION

Key words

CO_2 storage sites, protective zones of storage sites, CO_2 injection effectiveness, fracturing of reservoir formations, storage sites in the Upper Silesian Coal Basin

Abstract

The results of investigations in the field of CO_2 storage in water-bearing horizons in the area of the Upper Silesian Coal Basin were presented. It has been stated that the CO_2 injection process will appear in the area of the storage site and beyond its boundaries. The determination of protective zones for underground CO_2 storage and other structural elements, e.g. big tectonic zones, was proposed. These zones will constitute a safety buffer between the underground storage site and utilitarian undertakings conducted in its neighbourhood. In the work the proposal of CO_2 injection intensification through controlled fracturing of formations of the future storage site was presented. This action should increase the CO_2 injection effectiveness, especially in rock series characterised by average values of reservoir parameters.