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A FEASIBILITY STUDY OF SYNTHETIC SUBSTANCES USED FOR THE SEALING OF OLD WORKINGS TRANSFORMED INTO UNDERGROUND GAS STORAGES**

1. INTRODUCTION

While constructing underground gas storages (UGS) in abandoned hard coal mines attention should be paid to the following elements:

- physical phenomena accompanying gas storing, and their dynamics in time;
- designing equipment and surface infrastructure of UGS, in that: configuration of collective and connecting gas pipelines, individual wellbore equipment, group equipment, injection systems worked out for methanol (or other drying agents), gas compression systems, systems for gas pressure measurement and regulation, gas streams and also plans of the wells, wellheads, as well as the systems for mine brine utilization and management;
- current control of UGS in view of acquiring planned pump ability and reception of gas; verification of the amount of gas in the storage;
- design and managing of underground gas storage, implementing, monitoring and iterative correction of the geological-reservoir model of the storage is a system of interconnected issues. None of the presented stages of the process is independent. Only together they constitute about the successful operation of the UGS. The basic factor conditioning the success in the build and exploitation of the storage is optimization. The process of deposit planning and management should be carefully worked out and cyclically updated depending on the dynamics of the changes of reservoir parameters or when additional important pieces of information are obtained. This report addresses the issue of the control of tightness of the rock mass around the gas storage place. The control can be efficient when the nature of the rock mass around the old working is known. All is needed is a good knowledge of geology, properties of rocks and reservoir fluids, dynamics of flow in porous and fractured media, knowledge about the wellbore design and wellbore production characteristic.

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Prior to UGS design works, some of the most important issues have to be solved within the feasibility studies, e.g. preliminary studies and analyses determining the aims, possibilities and possible size of underground gas storage. The studies usually cover temperature-climate changes in the region, evaluation of gas demand, i.e. magnitude of gas market, possible strategic reserves, localization of the storage, its capacity and global productivity.

It seems purposeful to precede the design stage with a geological evaluation of the area, assess water conditions in the potential storing structure, collect data about the threshold pressures or boundary pressures over the capillary pressure in the roof part, yield of the wellbores. The predominant part of the feasibility study is connected with the deposits and reservoir engineering, generally with determining the hydrodynamic field in the storage layer.

2. PLANNING AND CONVERSION OF A COAL MINE INTO AN UNDERGROUND GAS STORAGE

Before making a decision about the conversion of a given mine into an underground gas storage it is important to make a detailed analysis of the influence of adsorption and volume of the existing voids on the quantity of the stored and recovered gas. The way in which the mine is prepared and sealed to play its new function depends on the geological-technical conditions in a given mine. The following elements have to be sealed in the future underground gas storages:

– mining shafts,
– rock mass around the old working.

Sealing of mining shafts

An exemplary sealing of a mining shaft is presented in Figure 1. A cement plug of diameter bigger than the wellbore diameter and about 6 m high is performed in the existing shafts. Then it is filled with slag with concrete reinforcements to the groundwater level. At the groundwater level another cement plug is made (ten or so meters long). The successive part of the shaft is filled with blocks of magmatic rock of 8 to 15 cm in diameter and 15 m high. Then the shaft is filled with a layer of assorted crushed rock 60 cm in diameter, followed by assorted slag 120 cm high, assorted sand 120 cm high and compact silt 6 m high. The remaining part of the shaft is filled with slag and sand and silt. All voids in the rock are filled with thick mud injected through the mud pipes 6 5/8″ and 7″. Drainage pipes 2" are disposed between the filler layers. Thus, filled shaft (210 m deep) provides gas storage at a maximum hydrostatic pressure of 18 bar.

Sealing of rock mass around old workings

Two sealing methods are known to provide appropriate tightness of an area to be used as a gas storage. The first lies in lowering the permeability of the rock mass around the working, and the other one is based on the use of impermeable barriers.

In this way the tightness of the old working can be provided by:

– hydrodynamic barriers (water curtains),
– steel lining and protections on walls of the working,
– freezing of surrounding rocks,
– injection of cement or sealing slurries into a system of cracks and fractures around the working,
– using synthetic materials.

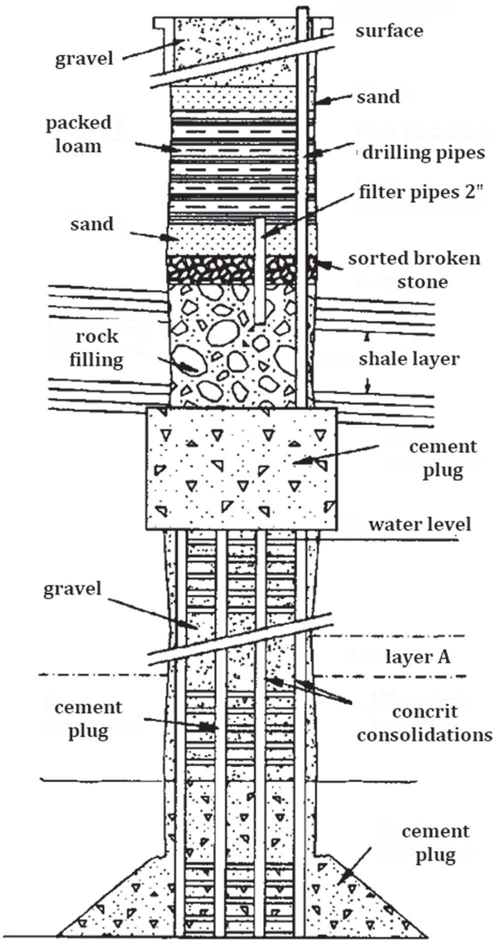

Fig. 1. Example of sealing of a mining shaft [1]

HYDRODYNAMIC BARRIERS

In industrial practice the rock mass is most frequently sealed with water curtains. In this case the gas is stored in an old working, around which the rock mass is naturally saturated with water and the storage gas pressure does not exceed the threshold pressure which is assumed on the level of 65 to 70% of hydrostatic pressure at a given depth. The threshold pressures for reservoir waters in the rock mass and for various gas pressure values in the working are presented in Figure 2. If the gas pressure is lower than the threshold pressure the storage can be considered to be tight. Otherwise the storage is untight. For obtaining a tight gas storage of higher working pressure (at most equal to the hydrostatic pressure) water has to be pumped through a system of wellbores to the rock mass, increasing its pressure above hydrostatic pressure value and forming a water curtain.

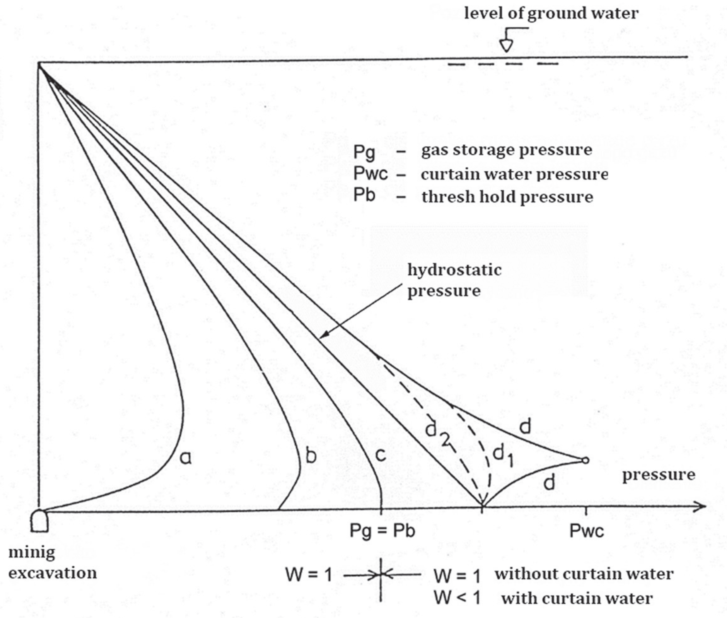

Fig. 2. Distributions of gradients of pressure in the rock mass around an old working or rock cavern with and without a water curtain [2]

The analysis of the curves in Figure 2 reveals that the network of pumping wellbores should be sufficiently dense to form a field of increased water pressure, and so appropriate saturation of zones around the entire working.

In this way the gas permeability in this zone was considerably lowered. As a result the working became much more gas tight. Among the disadvantages of this method is the infiltration of part of the water to the working, reducing its geometrical volume and wetting the gas.

LINING AND PROTECTIONS ON THE WALLS OF THE WORKING

If the pressure in the underground gas storage localized in an abandoned working is to be ten or so MPa the tightness can be provided by steel lining.

In this way the storing space is perfectly tight and the dryness level of the injected and recovered gas is the same. For reinforcing the steel mantle in the working, water is injected between the rock mass wall and the mantle, paying attention to the pressure. In this way the workings are well sealed, but this method is very expensive.

FREEZING OF SURROUNDING ROCKS

Another way of providing tightness to the rock mass lies in performing freezing wellbores. A number of wells are drilled around the working and then freezing mixtures are injected to them, providing a sufficient drop of temperature in the rock mass (−20°C to −30°C).

INJECTION OF SEALING SLURRIES

The third method of sealing rock mass around the working lies in drilling boreholes to which sealing slurries are injected. The injected fluids start swelling and increasing their volume. In this way they seal the existing voids.

USE OF SYNTHETIC SUBSTANCES

Authors propose a sealing method based on the use of synthetic materials. This technique has not been used for the sealing of commissioned workings yet.

Presently, we have numerous synthetic materials having various properties. Further in this paper, the authors characterized synthetic substances used for the production of composites, which may be used as gas-tight materials.

TYPES OF SYNTHETIC SUBSTANCES

The notion of "composite material" stands for a substance made of two or more materials, one of which plays the role of a binder whereas the remaining ones in the granular, fibrous or laminated form are used as reinforcement. The composites are frequently based on epoxy and polyester resins, whereas the glass and carbon fibers are used as reinforcement. Polymer-based composites make up the most numerous group of composite materials. Thermoplastics take the second position in the ranking as they reveal relatively low mechanical properties. The properties of the gas-tight composites depend on the properties of fibers from which the reinforcing materials were produced. The planned usage of the final products should determine the selection of the warp/reinforcement system.

For instance, in the case of synthetic substances for the production of high-pressure gas pipelines, the circumferential stresses, which are usually twice as high as the longitudinal stresses, usually dominate at the pipeline walls. Therefore, when designing the structure of a composite for gas pipes the circumferential parameters should be maximally strengthened. The properties of most popular resins which are applicable to composites production are presented in Table 1.

Table 1

List of selected properties of some resins used for the production of composite, gas-tight items [5]

Property	Type of resin	
	polyester	epoxy
Density [kg/m^3]	1100–1460	1100–1400
Damaging stress [MPa] – cutting – compressive – bending	 23.5–68.5 79.3–250 10–127	 27.4–96 85–274 58–157
Young modulus [GPa]	1.5–4.5	1.9–4.9
Temperature of work [K]	393	473
Temperature of damage [K]	473	533

APPLICABILITY OF SYNTHETIC MATERIALS
FOR THE SEALING OF ROCK MASS

According to the authors synthetic materials can be used for the sealing of workings only after the drift or shaft have been properly prepared.

Then the synthetic material, e.g. carbon fiber, glass fiber, kevlar or some of them can be disposed simultaneously. The properties of such composites allow for obtaining very high strength to tensile strains.

Prior to producing the protection, its localization should be selected in the mine. For doing so, the existing drifts and shafts should be evaluated. In the most suitable places no irregularities were observed during extraction (e.g. goafs, explosions *etc.*), water and gas inflow was low or none, and the surface was poorly urbanized.

Another stage was to prepare a base for the composites. Such a base will fill the unevennesses in the working before the main sealing layer is applied. Additionally the base will level out to some extent the small movements of the rock mass. The polyurethane foam, silicon or other specialist substance should be used.

Once applied to the working, the base should be smoothed out and shaped much to the cylinder form as it gives the highest strength of the composite protection and also makes it easy to apply the synthetic layers. This concept of sealing is presented in Figure 3.

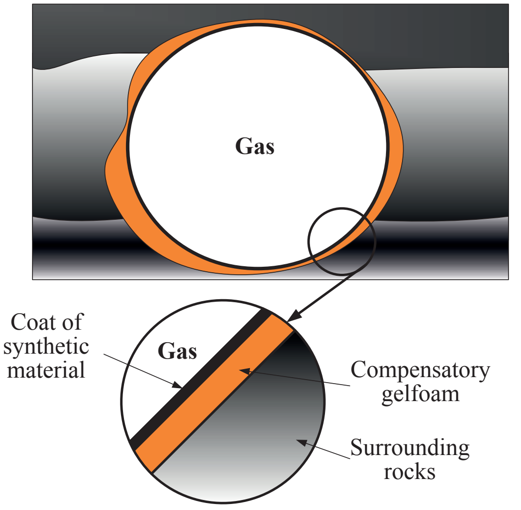

Fig. 3. Concept of sealing of a working with synthetic substances

Another stage lies in covering the base with synthetic materials. The number of layers and material to be used will depend on the parameters of the future storage for natural gas. The higher the pressure the more layers should be applied.

Finally the gas-tight barrier can be installed. It is equipped with suitable measuring devices thanks to which the storage can properly operate and possible break-downs can be avoided.

A schematic of above described sealing operation is presented in Figure 4.

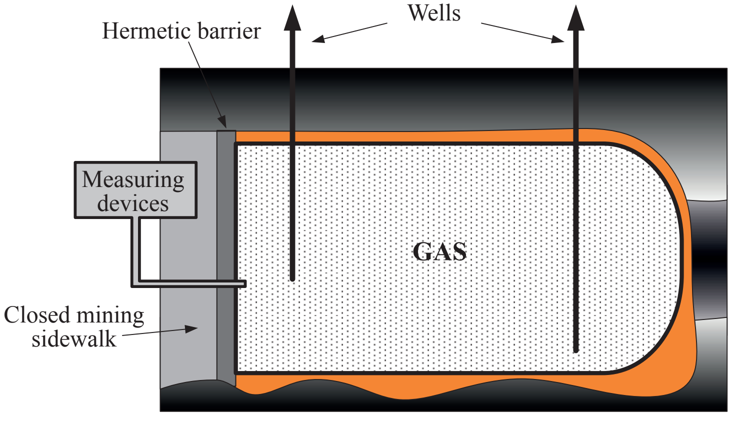

Fig. 4. Schematic of complex sealing of a working

For obtaining better tightness and strength, more layers and a denser weave are recommended. The authors suggest a minimum of three layers. One of the possible combination may take the following form: a layer of glass fiber followed by a layer of carbonate fiber and again a layer of glass fiber.

The authors propose two methods of sealing workings with synthetic materials. The first is the manual method. It is cheap but time consuming and performed directly by trained workers. The other one is mechanical, where most of operations are performed by machines which shortens the time of performing the protection, improves the accuracy of work but is more expensive because of the specialist machines which have to be involved.

In the manual method all works are performed by people in small steps (e.g. ring-by--ring ca. 1 m wide).

The following activities are performed in this method:

– spray polyurethane foam,
– form the required shape of the base with common-use tools,
– spray resin on so prepared base,
– dispose sheets of fabric.

Then, the fabric is pressed so that the resin soaks through it and the excess is removed from under the material.

If needed, the pressed and still wet surface is once again covered with resin and then with fabric. This operation is repeated again and again till the required number of layers is applied.

Then, the procedure is repeated on the successive fragments. Attention should be paid to the fact that the neighboring sections should overlap.

This method is time-consuming and noxious for the workers who are exposed to the resin vapors while performing sealing operations. For this reason some mechanization was introduced in the second method.

Here the composite protection will be performed by specially designed machines (the authors are at designing them), thus minimizing the presence of people in the working area. The rate of the work will also significantly increase.

All works connected with the application of the base, resin and fabric as well as the smoothing operations will be performed by machines operated by one trained worker.

The gas-tight bulkhead will be performed in a similar way in both methods, i.e. a specialist wall will be mounted in the working and sealed with composite materials.

3. CONCLUSIONS

Synthetic materials technology gives the following possibilities as far as the sealing of the rock mass is concerned:

1. Managing inactive drifts: The method proposed by authors can be applied for the sealing of inactive drifts and mine shafts. This will have a very positive effect on the longevity and viability of mines and also on people who will be offered more places of work. After performing the sealing, then the maintenance will have to be provided.
2. Storage of hydrogen as energy agent: A number of new application concepts of hydrogen as an energy agent have been worked out recently. The authors suggest using sealing technologies based on synthetic materials for small hydrogen storages. Hydrogen has a very high storing density, two orders higher than that of pumped-storage hydroelectricity plants. Besides hydrogen obtained through water hydrolysis is exceptionally clean and can be injected directly to the storage performed in mining voids with the use of the proposed technology. Hydrogen can be produced from an excess of electrical energy (during the night hours the energy demand is lower). The technologies aimed at hydrogen use for storing energy purposes have been developed both in Poland and in other countries. Presently, the efficiency of such a process is 45 to 60%.
3. Lower scale of mining damage: Mining damage can be reduced by managing inactive workings and creating underground gas storages. The storage pressure will counteract the relaxation of the rock mass. Properly assumed minimum pressure in the storage may considerably limit or even eliminate mining losses. Unlike other methods, in this case they will be constant and unchangeable in time. Besides the comfort of life of people living in the mining impact areas will be improved, which will also have a positive effect on the economy of the mines.
4. Peak season/emergency storages: In authors' opinion the proposed technology can be used for making peak season/emergency gas storages. The geometrical capacity of the storage is small as compared to regular storages made in depleted gas fields or caverns. High efficiency, and the shortness of time in which such storages are filled and emptied ideally fits in the short-term delivery system.
5. Utilization of toxic waste: Owing to their high tightness and zero reaction with the environment, storages performed in the proposed technology can be used for storing toxic substances which cannot be utilized otherwise. The sealing will efficiently stop any migration of toxic substances to the rock mass.
6. Storing of various fluids: This type of sealing can be also used for other gases and fluids. Apart from natural gas and hydrogen which can be stored in UGS, storages can be used for CO_2 sequestration or storing of substances needed by industry in the mining basin area.

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