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TIGHTNESS OF HYDROGEN STORAGE CAVERNS IN SALT DEPOSITS***

1. INTRODUCTION

One of the most important problems concerning designing of gas storage caverns is to determine the range of storage pressures. Considering hydrogen storage, one may assume that the minimum storage pressure is the same as in the case of natural gas storage. In the case of the maximum storage pressure, due to small size of hydrogen molecules, fracturing of a cavern may occur under a lower pressure compared to natural gas storage. The aim of carried out tightness tests was to verify the possibility of such a phenomenon.

In designing of natural gas storage caverns in unidentified deposits, a conservative assumption is that the maximum operation pressure should correspond to $15.8 \cdot 10^{-3}$ MPa/m of depth. In practice, when appropriate tightness testing of a rock mass, casing and cementation are carried out with positive results, the maximum pressure can be increased from $16.95 \cdot 10^{-3}$ MPa/m to $18.08 \cdot 10^{-3}$ MPa/m. The technical designs of cavern storages of CUGS Mogilno and CUGS Kosakowo assumed the maximum storage pressure gradient of up to $18.08 \cdot 10^{-3}$ MPa/m. Some authors assume that this value can be used in hydrogen storage [3, 4].

This paper presents results of laboratory permeability tests and *in-situ* tightness tests carried out in boreholes drilled in a drift in the Polkowice-Sieroszowice Mine. In all the tests described below, due to safety reasons, analogue gases were applied, i.e. nitrogen as the analogue of natural gas and helium as the analogue of hydrogen.

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2. PRELIMINARY LABORATORY TESTS OF PERMEABILITY OF ROCK SALT ON A PULSE DECAY PERMEAMETER PDP-200 APPARATUS

Permeability analyses of sealing rock core samples were performed on an apparatus, the scheme of which is presented in Figure 1. The apparatus was designed on the basis of the pressure pulse decay principle and consists of the following major elements: reference upstream gas storage of volume V_1, high-pressure coreholder type Hassler with a rock sample of porous volume V_p, reference downstream gas storage of volume V_2, transmitter which continuously measures the difference of pressures between storages V_1 and V_2 and an another transmitter measuring pressure p_2 in the downstream storage.

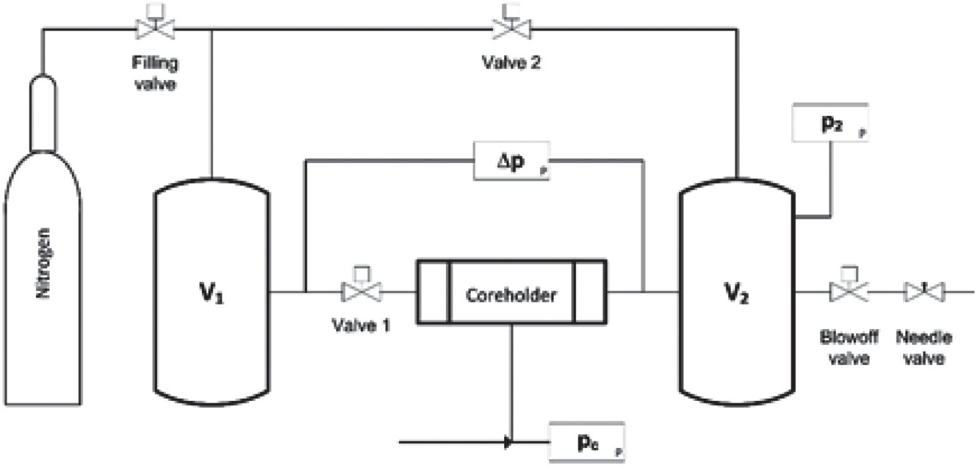

Fig. 1. Scheme of the low-permeability measuring apparatus – Pulse Decay Permeameter PDP-200

A laboratory stand does not require any instrument for measuring flow rate. When the gas is flowing from the V_1 storage its pressure will lower with time and increase in the V_2 storage. Thus, the flow intensity is calculated on the basis of known values, i.e. the volume of a reference storage, gas compressibility and the magnitude of the gas changes.

The ratio of a temporary volumetric flow rate to the magnitude of pressure changes in time equals to the product of volume of the reference storage and effective compressibility of the gas and of the storage. This product is also referred to as the "compressive storage". The analyses of low permeability rock samples (lower than 0.1 mD) are performed with the use of storages of appropriately low volume, typically one to five times bigger than the pore volume of the sample. Opening the entry valve and valves

1 and 2, the reference storages and rock sample are filled with clean and dry gas (e.g. nitrogen or helium) to a pressure of 1000 to 2000 psi (7–14 MPa). This high pressure of gas in the experiment reduces the „gas slip” effect on measurement results.

After closing the entry valve the pressure will equalize in the entire measuring system to a value of $p_2(0)$. This process may take a few minutes or hours, depending on the permeability of the sample. Then valves 1 and 2 are closed and the pressure in the supply storage is increased by 1% to 3% of pressure $p_1(0)$. After reaching thermal equilibrium in the measuring system, valve No. 1 is opened, which gives a pressure pulse to the sample. Changes of pressure differences in the reference storages and pressure in the storage on the downstream side are recorded over the time of the measurement.

The rock salt samples of cylindrical shape with a length of 30.5 mm and a diameter of 38.4 mm were cut from larger cores taken from a borehole. Two types of gas, i.e. nitrogen and helium were used in the permeability measurements. Tests were carried out under confining pressure (pc) equal to 1,200 psi (8.27 MPa) and an average pore pressure 1,000 psi (6.89 MPa). The results of the tests indicate that rock salt permeability is 60.4 nD for helium and 5.2 nD for nitrogen. Laboratory tests under conditions of higher confining pressure have shown no permeability both for nitrogen and helium, which could be caused by the high deformation of rock salt. This will be tested by additional measurements.

3. TIGHTNESS TESTS OF ROCK SALT MASSIF

Because of the difficulty in precise determination of the rock salt permeability coefficients values in laboratory tests, an idea appeared to determine these values in natural conditions (*in situ*). Due to the cost and availability, the best way was to perform *in-situ* tightness tests in boreholes drilled in a drift in an underground salt mine. The only Zechstein rock-salt mine in Poland currently operating in stratiform deposits is the Polkowice-Sieroszowice mine located in the Fore-Sudetic Homocline.

3.1. Location of the test studies

Over the area of Poland, stratiform Zechstein (Upper Permian) rock salt deposits occur in marginal parts of the original Zechstein Basin, at a depth ranging from several hundred meters to several kilometers. Hence, according to earlier studies [7], they are suitable for location of gas storage caverns. However, the recognition of their relevant parameters is poor, limited so far to the area of Mechelinki deposits, where underground gas storage caverns have been constructed (near Kosakowo) [6].

The studies on rock salt tightness were carried out in ~115 m thick Oldest Halite (Na1) rock salt bed of the first Zechstein cycle (PZ1), in boreholes drilled in an underground mining drift situated at a depth of ~900 m below the ground surface. The bed was underlain and overlain by anhydrite beds. The distances to the top and base of the rock salt bed were ~47 m and ~68 m, respectively, therefore the tests were performed in the middle section of the salt bed. Thus, it can be assumed that the surrounding strata did not influence the state of the initial stress in the rock salt and that only lithostatic pressure was imposed on the rocks. The rock temperature measured during the test was 38°C.

The zone of the salt bed in which boreholes were drilled was built of relatively pure, white rock salt containing vague layering marked by rare grayish smears of anhydrite. The rock salt displayed medium- to coarse-grained porphyric structure over the whole analyzed bed section. Halite grains were predominantly irregular in shape, and locally elongated concordantly with layering. These features imply that halite has strongly altered primary structure due to dynamic recrystallization [1]. Investigations under a microscope showed that anhydrite occurs as individual grains, in assemblages or as flakes dispersed between halite grains. Location of the testing site in the mine is shown in Figure 2 [8].

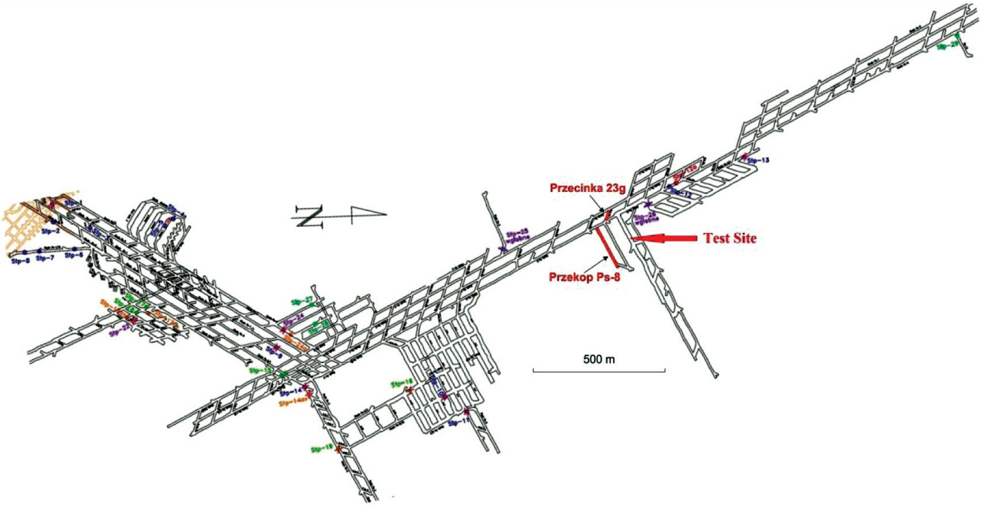

Fig. 2. Location of the rest pressure test site in the Polkowice-Sieroszowice mine [8]

3.2. Methodology and scope of the study

The tests were performed by GEOD Company, which has also prepared an appropriate set of instruments for fracturing pressure measuring and recording the pressure drop in time to get the rest value. The measuring set is shown in Figure 3.

Fig. 3. The measuring set

The tests were carried out in two horizontal and one vertical boreholes. The vertical borehole was drilled in the base of a mine drift and was initially 10 m deep. The set of two packers, each 1.5 m long, were installed in the bottom part of the borehole with a distance of 0.5 m fracturing zone. Thus, the fracturing zone was located at a depth of 8.0–8.5 m below the drift. After the interpretation of the results of the tests, it was found that the obtained results are not fully reliable, so the test was repeated in the same borehole, deepened to 20 m and thereby the fracturing zone was located 18.0–18.5 m below the drift in the second test.

Horizontal boreholes were 10 m long and inclined at an angle of 60° to the drift wall. Thus, the real distance between the drift wall and the fracturing zone was 7 m. After installation of packers the fracturing medium (helium or nitrogen) was injected. The rate of injection was 0.05–0.1 MPa/min. After fracturing, manifested by rapid drop in pressure, the valves were sealed to register a pressure drop in the borehole to the resting value. At each testing site, the fracturing measurements were performed using both helium and nitrogen. In Section 3.3, in figures presenting the results of the tests, nitrogen is marked in blue and helium in red. The medium used for fracturing in the first place is indicated by a solid line, and the medium used in the second place, at a given depth interval, by a dotted line [2].

3.3. Analysis of test results

First two tests (Fig. 4) were carried out in the vertical borehole at a depth of 10 m. The medium used for fracturing were first helium and subsequently nitrogen.

The value of the fracturing pressure obtained in the first test in the case of helium was 8.6 MPa and was significantly lower than the value obtained in the case of nitrogen which equaled to14 MPa. Also the rest pressure was lower, although not significantly. Taking into account subsequent tests carried out in other boreholes, it seems that the obtained value of fracturing pressure was the result of leaking packers.

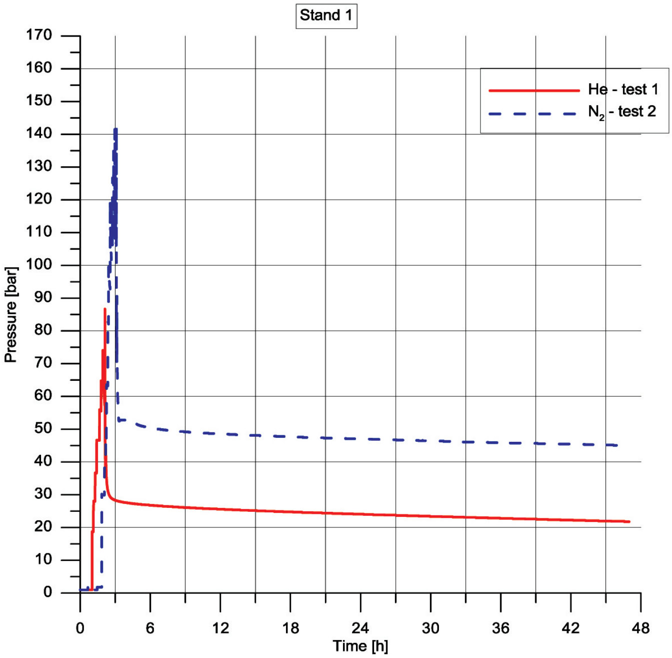

Fig. 4. The test in a vertical borehole (Stand 1) drilled in the mine gallery; fracturing medium: first helium, then nitrogen

The following tests were carried out in horizontal boreholes. In the borehole at Stand 2, first test (No. 3) with helium and second test (No. 4) with nitrogen were performed. The results of these tests are presented in Figure 5. A slightly higher fracturing pressure was recorded for helium compared to the nitrogen but in the case of the rest pressure higher values were recorded for nitrogen compared to the helium.

In the test at Stand 3, the first test (No. 5) was performed with nitrogen and the second test (No. 6) was carried out using helium. Both the value of fracturing pressure and of rest pressure were significantly higher for nitrogen compared to the helium, which is presented in Figure 6.

Considering the uncertainty of the results obtained in the Stand 1, tests were repeated in a deepened borehole. The results of repeated tests are presented in Figure 7.

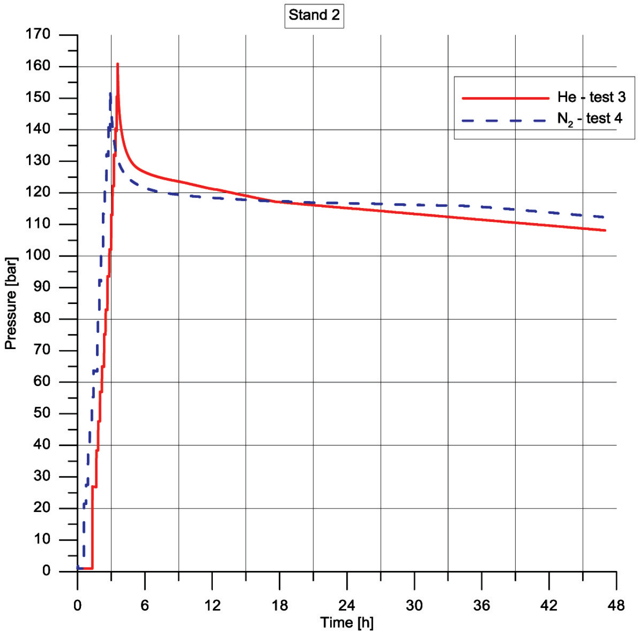

Fig. 5. The test in a horizontal borehole (Stand 2) drilled in the drift wall; fracturing medium: first helium, then nitrogen

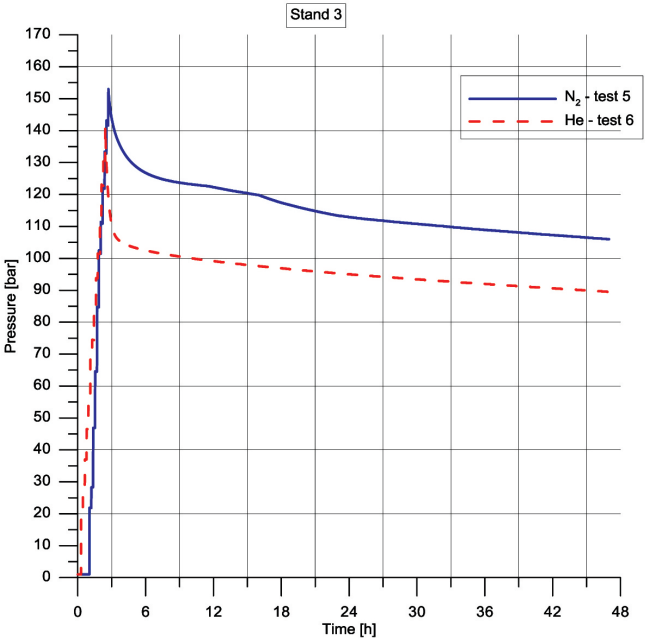

Fig. 6. The test in a horizontal borehole (Stand 3) drilled in the drift wall; fracturing medium: first nitrogen, then helium

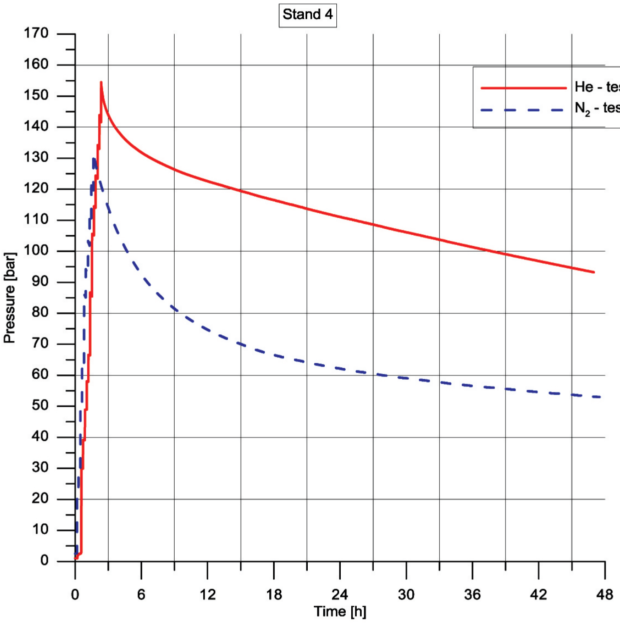

Fig. 7. The additional test in a deepened vertical borehole (Stand 4); fracturing medium: first helium, then nitrogen

The fracturing pressure value does not differ from the values obtained in horizontal boreholes, however, the values of the pressure in the final testing phase were much lower than in the vertical borehole. Interpretation of these phenomena requires numerical calculations. Duration of individual tests and the values of the obtained pressures are shown in Table 1.

Table 1

The values of duration of individual tests, obtained fracturing pressure and rest pressure

Stand	Test	Date	Starting time	Duration [min]	Fracturing pressure [bar]	Rest pressure [bar]
1 vertical	1 He	07.04	08:20	2 840	86	22
	2 N_2	11.04	08:20	5 764	142	46
2 horizontal	3 He	13.04	09:40	2 869	161	110
	4 N_2	15.04	08:40	4 307	152	113
3 horizontal	5 N_2	18.04	09:20	2 845	153	106
	6 He	20.04	08:03	2 898	141	90
4 vertical	7 He	22.04	08:40	4 318	155	90
	8 N_2	25.04	08:15	2 867	131	53

In general, the values of fracturing pressure recorded in the first test at a given test site (except for test No. 1) range from 15 MPa to 16 MPa and in the second test from 13 MPa to 14 MPa. Considering further pressure drop, in particular obtained in horizontal boreholes, it can be stated that research has shown that helium shows a greater ability to penetrate the rock salt massif than nitrogen. This is probably due to smaller particle sizes of helium and lower helium viscosity.

4. STRESS DISTRIBUTION IN THE VICINITY OF A HYDROGEN STORAGE CAVERN

4.1. Considered models

Numerical calculations were performed for the steady strain-stress conditions. The aims of these calculations were to determine the stress and strain distributions around the storage cavern, the displacements of the cavern contour and its convergence at different but constant storage pressures. Such simulations are routine and precede simulations of stress distribution in real conditions of storage cavern operation.

Calculations concerned caverns located at a depth interval of 1020 m (the top of the cavern's neck at 1000 m) to 1250 m below the ground surface, i.e. the cavern's height was 230 m in all cases. Five different shapes of storage caverns were considered (Fig. 8).

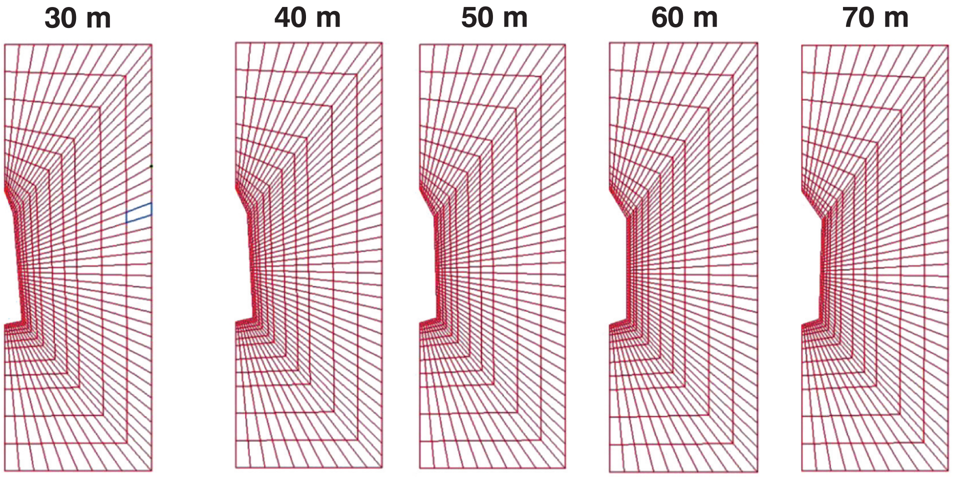

Fig. 8. Grids assumed in calculations in Geosolk code

In all considered variants, the diameter of the cavern in its lower part is 60 m and in its upper part is equal to 30 m, 40 m, 50 m, 60 m, 70 m in the following models. Also the loading scenario which assumed 9 two-year stages in which the pressure varied from 18 MPa to 2 MPa in steps of 2 MPa, was the same in all considered models. In all cases, it was also assumed that the temperature of the rock salt massif is constant over time and depends only on the depth.

4.2. Fracturing range

The primary aim of calculations was to determine the distribution of the middle principal stress and to check what is the range of the zone in which the middle principal stress drops below the storage pressure. Under such stress conditions, the stored gas migrates from the cavern into the rock salt massif. Figures 9 and 10 show the distribution of the middle principal stress (vertical stress) along the cavern radius at a depth of the cavern center under the storage pressure of 14 MPa and 18 MPa [5].

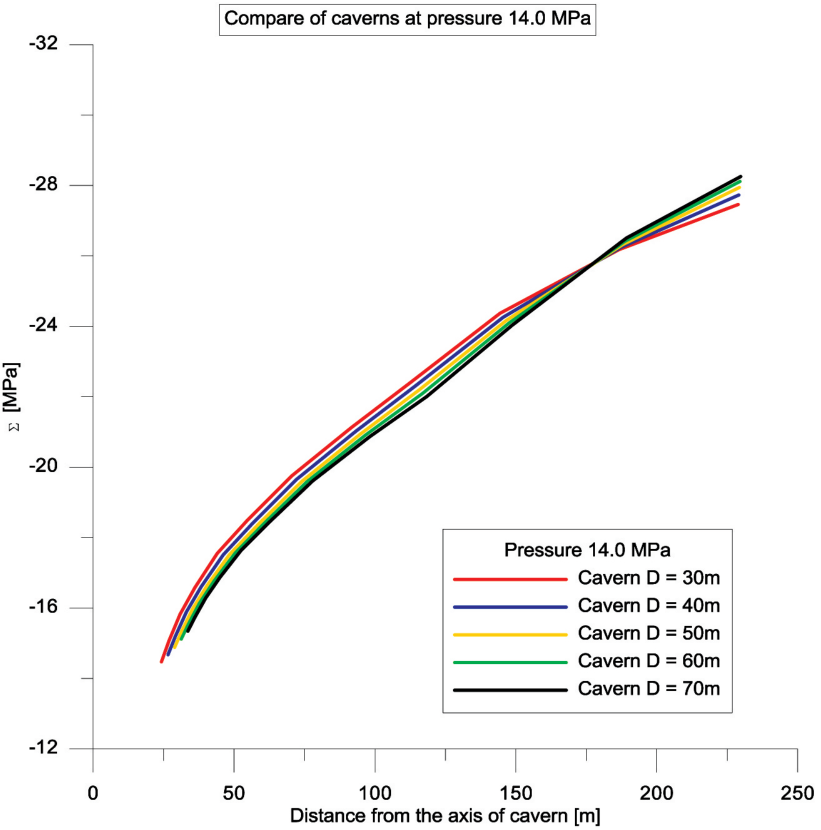

Fig. 9. Middle principal stress distribution along the cavern radius (i.e. away from the cavern's wall) under storage pressure of 14 MPa

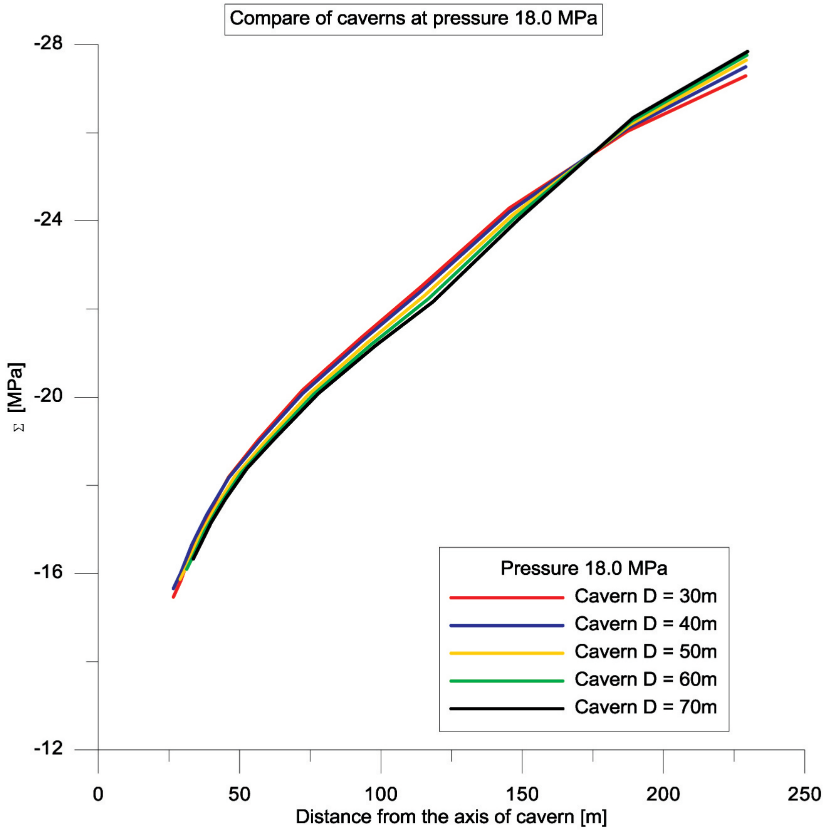

Fig. 10. Middle principal stress distribution along the cavern radius (i.e. away from the cavern's wall) under storage pressure of 18 MPa

In the first case (Fig. 9), at any point of the rock salt massif in the vicinity of a storage cavern, the middle principal stress does not drop below the storage pressure. However, if the storage pressure reaches 18 MPa (Fig. 10), the middle principal stress will drop below the storage pressure in the rock salt massif within the zone of up to 20 m wide around the cavern. This may cause migration of the stored gas into the surrounding rock salt massif.

5. CONCLUSIONS

The study of *in-situ* fracturing indicated a small but visible difference in fracturing pressures and in rest pressures for nitrogen and helium. In all tests, there was an evident influence of the excavation, which is indicated by the lower value of fracturing pressure than the value of the rock massif stress. This particularly applies to the vertical boreholes. Such a phenomenon will occur in the case of hydrogen storage. As numerical calculations show, the zone of middle principal stress drop below the storage pressure gas ranges up to a few tens of meters within the rock salt massif. The shape of the cavern does not significantly affect the range of this zone.

The obtained results indicate that the design of a hydrogen storage cavern cannot assume the same fracturing pressure gradient value of $18.08 \cdot 10^{-3}$ MPa/m as is accepted for natural gas in CUGS Mogilno and CUGS Kosakowo. It is expected that this value will need to be reduced to the range of $15\text{–}16 \cdot 10^{-3}$ MPa/m, which should be further verified by microfracturing tests in a borehole.

Aknowlegement

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