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ANALYSIS OF GEOLOGICAL AND TECHNICAL CONDITIONS FOR CREATION OF UNDERGROUND GAS STORAGE IN A DEPLETED GAS RESERVOIR OF YUZHNO-LUGOVSKOYE FIELD IN RUSSIA

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Abstract

Around the world, gas produced in excess of demand during the warmer seasons is most often stored in depleted oil and gas reservoirs, water-bearing structures and in salt dome formations from which it is extracted in the cold season when industrial and household demand for natural gas is higher. This paper, in addition to presenting an overview of the geological and technical conditions for creating underground gas storage (UGS) in depleted reservoirs, carries out an analysis of Yuzhno-Lugovskoye field and calculates key parameters to determine the suitability of its depleted reservoirs for the purpose of underground gas storage.
The calculated parameters of the depleted reservoir in horizon III of the field are as follows: Total gas storage capacity, $Q_{max} = 803.96 \times 10^{6} m^3$, Maximum allowable pressure in the storage, (MPa) Pper = 9.5 MPa, and the vertical rock pressure, (MPa), Prock = 15.5 MPa. The pressure values satisfy the necessary condition, $P_{per} \leq (0.6 - 0.7)*P_{rock}$, and therefore, guarantees that the integrity of the cap of the formation is not compromised and leakage of stored gas into the overlying strata or to the surface is prevented.
Based on the field's location and calculated reservoir properties the depleted reservoir of horizon III in Yuzhno-Lugovskoye field is an economically suitable site for underground gas storage.

***Keywords**: Underground storage; depleted field; natural gas; pressure; deliverability; maximum allowable pressure.*

1. Introduction

Home heating is one of the major uses of natural gas in some regions of the world. Varying temperatures and hence varying heating demands during the different seasons, lead to a fluctuation in gas demands. For instance, the demand for natural gas is more in winter than in mid summer. Therefore, storing the excess volume produced during the summer to compensate additional demands in the winter to ensure a regular and reliable supply of gas to the household and industrial facilities is a major task of the gas industry. To balance this fluctuation various forms of gas storage facilities including but not limited to underground gas storage (UGS) in depleted reservoirs are employed, which forms the subject of this paper.

Storage fields act as an underground warehouse that allow consumers to have a steady supply of natural gas year-round without interruption [1]. Underground storage of gas in depleted reservoirs entails injecting produced gas back into depleted reservoirs during low gas demand season, typically April to October and extracting the stored gas from these storages during high demand periods (November to March) to meet home and industrial needs. After solid removal, the produced gas is pumped to a gas metering station, after which it is compressed in a compressor shop, and then supplied to gas distribution stations. At this point, the general gas flow is divided in process lines which are connected to well loop. This permits the measurement of temperature and pressure of gas during an injection into each of the storage wells. The technological process of recovering stored gas from these underground storage sites is principally the same as the process of extraction from gas fields, differing only in the necessity to extract the entire commercial volume of gas stored in an underground storage facility in the period of increased demand.

The first UGS became operational as early as 1915. Since then hundreds of facilities have been developed with some 150 in Europe and Central Asia, over 400 across the United States and 59 in Canada. Underground storage of natural gas has become a large and essential part of the natural gas delivery system and continues to grow as a result of continually increasing demand for natural gas. This calls for an enhancement of underground storage capacity and deliverability both by creating new facilities and by upgrading existing ones [2].

UGS (underground gas storage) facilities largely contribute to the reliability of gas supplies to consumers. They level off daily gas consumption fluctuations and meet the peak demand in winter. UGS facilities are of particular importance in Russia with its cold climate and huge distances between resources and end users [3], in addition to difference in climatic conditions between the southern and northern regions of the country.

This paper presents an overview of the various types of underground gas storage facilities, examines the factors that determine the suitability of a depleted reservoir for the construction of underground gas storage and carries out an analysis of Yuzhno-Lugovskoye field and calculates key parameters to determine the suitability of its reservoirs for underground gas storage.

2. Type of underground gas storage facilities

Most gas storage fields were, originally, gas fields, oil fields or aquifers that were converted to gas storage after depletion of native gas or oil reserves [4]. Depending on a number of factors, and to suit the different gas supply needs, various types of UGSs are distinguished as follows:

- Gas storage in depleted fields.
- Gas storages in a water-bearing structure.
- Gas storages in salt dome formations [5].

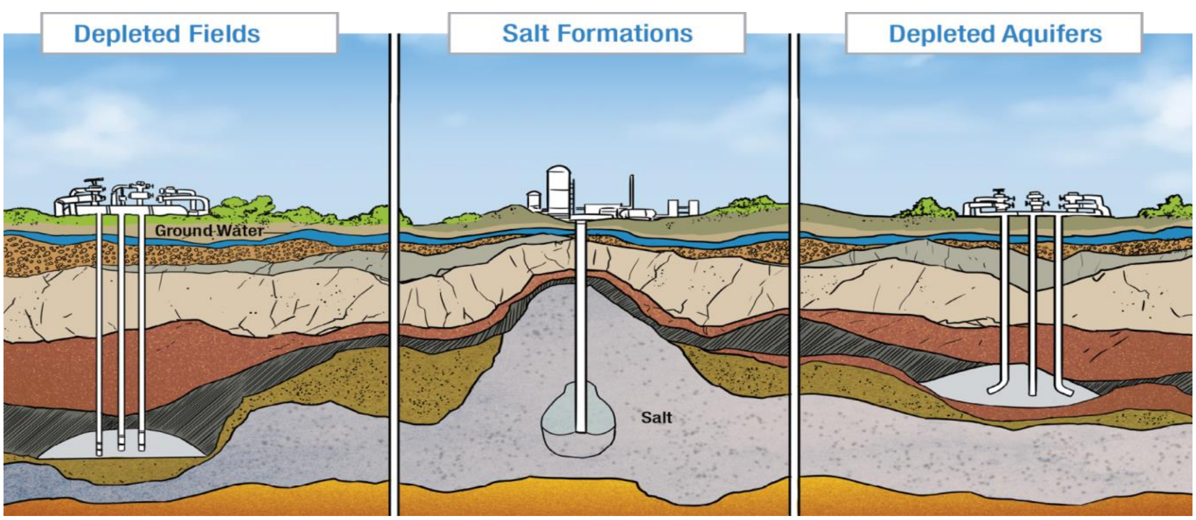

Figure 1. Various types of underground gas storages [6].

Each storage type has its own physical characteristics (porosity, permeability, retention capability) and economics (site preparation and maintenance costs, deliverability rates, and cycling capability), which govern its suitability for particular applications [7].

Several volumetric measures are used to quantify the fundamental characteristics of an underground storage facility and the gas contained within it. For some of these measures, it is important to distinguish between the characteristic of a facility, such as its capacity, and the characteristic of the natural gas within the facility such as the actual *inventory level*. These measures are as follows:

Total natural gas storage capacity is the maximum volume of natural gas that can be stored in an underground storage facility in accordance with its design, which comprises the physical characteristics of the reservoir, installed equipment, and operating procedures particular to the site. Total gas in storage is the volume of natural gas in the underground facility at a particular time.

Base gas (or cushion gas) is the volume of natural gas intended as permanent inventory in a storage reservoir to maintain adequate pressure and deliverability rates throughout the withdrawal season.

Working gas capacity refers to the total gas storage capacity minus base gas. Working gas or active gas is the volume of gas in the reservoir above the level of base gas. Working gas is available to the marketplace.

Deliverability is most often expressed as a measure of the amount of gas that can be delivered (withdrawn) from a storage facility on a daily basis. Also referred to as the deliverability rate, withdrawal rate, or withdrawal capacity, deliverability is usually expressed in terms of million cubic feet per day (MMcf/d)

Injection capacity (or rate) is the complement of the deliverability or withdrawal rate – it is the amount of natural gas that can be injected into a storage facility on a daily basis. As with deliverability, injection capacity is usually expressed in MMcf/d [7].

The measurements above are not fixed for a given storage facility. For example, deliverability depends on several factors, including the amount of gas in the reservoir and the pressure [8].

Conversion of an oil or natural gas field from production to storage takes advantage of existing wells, gathering systems and pipeline connections. Depleted oil and natural gas reservoirs are the most commonly used underground storage sites because of their wide availability [6].

3. Underground storage in depleted deposits

3.1. Factors that determine the suitability of gas reservoirs for construction of gas storage facility

Factors that affect whether or not gas reservoirs will make good storage reservoirs are both geographical and geological [9].

Storage location is a very important consideration. For example, if the reservoir is not close to existing transmission lines or market areas, the developer may incur greater expenses to establish connection with pipelines [10]. Basic Storage Requirements: High porosity, high permeability, hold adequate volumes of gas, extract gas at high rates, contain and trap gas, and cushion gas [11]. The greater the porosity of the rock, the faster the rate of injection and withdrawal. The size of the reservoir, the thickness of the gas-bearing rock stratum and the extent to which the stratum is covered by cap rock are also important [10].

3.2. Construction of underground storage facilities in a depleted deposit

Depleted oil and natural gas reservoirs are considered to be the most economical, since:

- gas or oil reservoir is well studied: detailed information is available on the area, gas or oil content, capacity, reservoir parameters (geometric shapes and sizes, porosity, formation permeability), the degree of tightness of the cover, the volumes of gas and liquids recovered, the initial reservoir pressure and temperature, characteristics of wells and their operation mode;
- on the field, there is a certain number of drilled and equipped production wells, field equipment (compressor stations, separator, process pipelines), housing and cultural facilities that can be used for the underground storage of gases and liquids, and which generally reduce the capital investment on construction and operation costs;
- the time-frame for the creation of the storage and achievement of its design capacity are significantly reduced;

- when using oil deposits, it becomes possible to extract residual oil by increasing reservoir pressure.

The construction of underground storage facilities in a depleted deposit is usually performed in two stages. At the first stage, the inspection of landfilling facilities, repair and replacement of obsolete, worn out parts is carried out. The problems of automation, raising labor productivity, environmental protection and sources of drinking water are being addressed. At this stage, the industrial filling of the gas storage is also carried out. At the second stage, the testing and cyclic operation of the storage facility is carried out.

At the beginning of the extraction period, the gas is supplied by pressure in the gas storage facility, and then, when the pressure falls, the compressor switches on. Consequently, the compressor in underground gas storage facilities is used both for pumping gas into the formation and for feeding it to consumers during the selection process. Since gas returning from the reservoir is often moistened and contains mechanical impurities (mainly sand), facilities for purification and drying of gas are necessarily built at the underground storage facilities. A set of measures is also envisaged to prevent the formation of hydrate plugs in the wells and in the system of their connection.

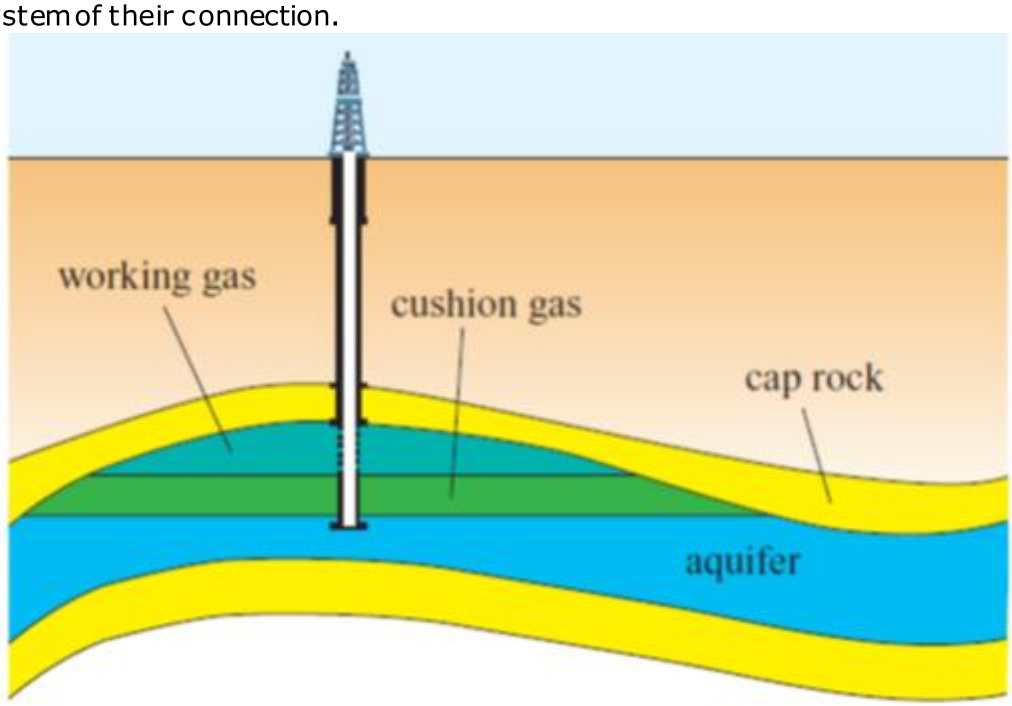

Figure 2. Storage facilities in depleted gas reservoirs [12]

When designing the construction of an underground storage facility in a depleted gas field, the following parameters are determined:

- maximum allowable pressure;
- minimum required pressure at the end of the sampling period;
- volumes of active and cushion gas;
- number of injection wells;
- diameter and wall thickness of reservoir and connecting gas pipelines;
- type of compressor unit;
- total power of the compressor;
- type and size of the underground storage facility for gas purification from solid suspensions when injecting it into the formation and drying it during selection;
- the volume of additional capital investments, the cost of gas storage, the payback period of additional capital investments.

After that, technological condition of the wells, wellhead equipment, production gas pipelines, separators, compressors are inspected. The types of repairs, replacements, and the need to build new structures are also determined.

Particular attention is paid to determining the tightness of wells, the speed and intensity of the corrosion processes of metallic field equipment and the development of measures to combat it, the integrated automation of the operation of all elements of the underground storage facility, increment of labor productivity, environmental protection, and drinking water sources in the upper horizons.

4. Geological and technical conditions for the construction of an underground storage facility

The prospects for the further development of underground storage of gases depend, first of all, on the geological, hydrogeological and mining technical conditions of occurrence of rocks. When assessing areas for the construction of underground gas storage facilities, it is necessary to take into account the features of the geological structure of the territory [13]. The rocks of the reservoir should have sufficient thickness, permeability, porosity and be characterized by relative lithological uniformity.

The creation of storage facilities in well-permeable and porous reservoirs with a small heterogeneity allows to apply increased depressions when filling gas storage facilities, to reduce the number of operational and observation wells, and to simplify control over the movement of reservoir waters during the extraction of gas from the storage.

The numerical values of the physical parameters of the reservoir bed intended for use as a storage facility can vary considerably. Tectonic disturbances always raise concerns about the tightness of the cap rock over the storage. The presence of faults, thrusts and other disturbances complicates the interpretation of geological and hydrodynamic data, makes difficult the choice of the gas injection scheme, complicates the technological calculations, etc.

The extent of formation water mobility and the magnitude of the reservoir bed elevation (the difference in the marks of the highest point of the reservoir bed and the deepest depth contours closed within the area under consideration) have some influences on the terms of creation of the storage and the mode of its operation.

When creating underground gas storage facilities, both in depleted fields and in water-saturated reservoirs, it is important to correctly establish the maximum permissible pressure in them.

Increasing the pressure in the storage to the maximum allowable contributes to reducing the time of construction of underground storage and positively affects the conditions of its operation as a whole. The greater the pressure in the storage, the greater the amount of gas stored and the less wells required to provide the required gas removal. Increasing the pressure in the storage during storage increases the compressor-free period of gas supply to the consumer from the storage process, reduces the capacity of the compressor station and improves the technical and economic performance of the gas supply system as a whole.

However, an excessive increase in pressure in the underground storage can lead to a breach of the tightness of the reservoir and gas losses, the breakthrough of gas on the daylight surface with the occurrence of explosions and fires, the formation of crystalline hydrates of hydrocarbon gases in the wells, and an increase in the cost of gas compression.

The maximum allowable pressure in the storage facility is due to many geological and technical factors and, first of all, depends on the depth of the formation; density, strength and ductility of the roof of the formation; the method of creating the storage and the rate of gas injection, the maximum compressor discharge pressure chosen for pumping gas into the storage and for taking gas out of it.

The maximum pressure is significantly affected by the structural and tectonic features of the formation, upper boundaries, bedrocks, and also the section of rocks above the reservoir.

When creating and operating underground storage facilities, one should also take into account the rate of increase in pressure during gas injection. The smaller the rate of increase in pressure, the greater the pressure in the storage can be increased.

Another important parameter for the operation of underground storage facilities is the minimum permissible depth of underground reservoirs, which is determined, first of all, by the vapor pressure of the stored product. This value is set taking into account that one atmosphere of the maximum working pressure of the product in the storage should be balanced by the pressure of the strata above the reservoir of at least six meters.

Approximate calculation of the storage depth of the storage (H) is carried out under the condition that the excess pressure in the storage ($P_{ex.pre}$) is lower than the overburden rock pressure (P_{rock}). It allows for the protection of the walls of the storage from destruction under the influence of internal pressure.

$$\boldsymbol{P}_{ex.p} < \boldsymbol{P}_{rock} = \rho_{rock}.g.\boldsymbol{H} \qquad (1)$$

where ρ_{rock} - average density of overlying rocks [13].

When selecting a site and deciding on the suitability of the reservoir for the construction of a storage facility, the overall geological condition of the deposit is assessed in order to establish disturbed zones. The tightness of the storage can be disturbed by unfavorable tectonic conditions: faults, shifts, etc. Only a comprehensive analysis of the results of exploration makes it possible to conclude on the degree of tightness of underground storage, increasing its operational reliability [13].

5. Geology and reservoir of the Yuzhno-Lugovskoye field

5.1. Characteristics of the Yuzhno-Lugovskoye field

The Yuzhno-Lugovskoye field is multi-layered and contains gas deposits in sediments of the lower Mazhuisk subhorizon at a depth of 700-1400 m. Type of collector - porous. The Yuzhno-Lugovskoye field is divided into three blocks: Zolataribni, Central and Northern. The northern block, starting from the ninth horizon up the section, is an arch of the South Lugovskaya structure, within which there are unlimited reservoirs of layers: III, IV, V, VI, VII, VIII. The gas storage operations are carried out on reservoir III. Gas water contact of III horizon of the Yuzhno-Lugovskoye field is determined in accordance with the interpretation of well log survey data at -669 m.

The main part of the studied rocks is characterized by low filtration properties (permeability from 1.68 to 36.4 × 10-3 μm2).

5.2. Analysis of the parameters of the geological structure of the Yuzhno-Lugovskoye field from the point of view of the construction of an underground gas storage facility

During the selection of the reservoir for the creation of an underground storage, a number of the most appropriate horizons were studied. The choice of the facility was made in accordance with the conditions imposed by the UGS construction; on the interpretation of Geologic Information System GIS data, on structural constructions, on seismic studies, etc. In addition, the depth of the deposit is taken into account when choosing a horizon. This is due to the fact that a sufficiently high pressure must be created in the reservoir to ensure the storage of significant volumes of gas. The reservoir of horizon III was selected for underground gas storage. This reservoir being a depleted gas reservoir satisfies the conditions for the creation of an underground gas storage and saves the costs of additional research to verify reservoir integrity, an important factor that determines the ability of a reservoir to hold the stored gas.

6. Calculation of the main parameters of the underground gas storage

When calculating the parameters of the underground gas storage: the size and shape of the gas-saturated formation, the volume of the pore space of the deposit, the coefficients of porosity and permeability coefficients, the formation pressure and temperature, the composition of the gas, the placement of injection wells on the gas-bearing area, the coefficients of the filter resistances, the change in the rate of gas pumped into the storage facility in time are known.

The purpose of this calculation is to determine:

- The maximum volume of gas pumped into the UGS (active),
- The total volume of gas in the storage,
- Cushion gas volume,
- Time of gas injection into the storage,
- The pressure at the bottom of the well at the end of the gas injection period,
- Pressure at the wellhead of the injection well at the end of the injection period,
- Vertical rock pressure,
- Bursting Pressure of the reservoir,
- Number of compressors.

In the design and operation of underground gas storage facilities, active, cushion and total gas volumes are distinguished.

Active volume is the volume of gas that is taken and pumped. This volume is determined by the formula below. For several years, its quantity in the storage can be considered permanent.

$$Q_{act} = \Omega\frac{P_{max}-P_{min}}{z} \qquad (2)$$

where Ω is the volume of the pore space; P_{max} and P_{min} are the maximum and minimum pressure in the storage.

Cushion gas volume is the volume of gas that is not extracted from the underground gas storage, but necessary to maintain a certain minimum pressure for supplying gas to the surface, counteracting the introduction of formation water into the storage facility, etc.:

$$Q_{cushion}=\frac{\Omega P_{min}}{z} \qquad (3)$$

Cushion gas - the volume of gas that is constantly in the UGS during its operation. The volume of cushion gas in the underground storage depends on the depth of the trap, the physico-geological parameters of the reservoir, the thickness of the formation and the slope of the structure, and the mode of operation of the storage facility.

The costs of cushion gas and its injection into underground gas storage facilities are equivalent to capital investments in the construction of underground gas storage facilities. The volume of the cushion gas, the number of production wells and the power of the compressor are interrelated.

*Total gas volume is the maximum amount of gas that can be placed in the storage:

$$Q_{total}=\frac{\Omega P_{max}}{z} \qquad (4)$$

When creating and operating underground gas storage facilities, the maximum permissible, maximum, minimum and average pressures are also distinguished.

Maximum permissible pressure is the greatest pressure in the storage, which can be assumed, based on the condition of reservoir (roof) preservation. The higher the pressure in the formation in which the storage is created, the more gas can be stored in it. However, if the pressure is increased excessively, the integrity of the roof of the formation may be compromised, and conditions for gas leakage into the overlying strata or to the surface are created.

To prevent this, the maximum permissible pressure in the formation is assumed to be somewhat less than the pressure of the overlying rocks (rock pressure):

$$P_{per} \le (0.6-0.7)P_{rock} \qquad (5)$$

The maximum is the pressure established on the basis of technical and economic calculations and corresponding to the active gas volume.

The minimum is the pressure established on the basis of technical and economic calculations and corresponding to the buffer volume of the stored gas.

$$\frac{Q_{cushion}}{Q_{act}} = \frac{P_{min}}{P_{max-P_{min}}} \qquad (6)$$

The average pressure in the storage tank is determined from the expression below:

$$P_{av} = \frac{1}{T}\int_0^T P(t)dt \tag{7}$$

where T is the time equal to a year or a value that is a multiple of one year.

The injection time of the gas is determined from the ratio:

$$t = \frac{Q_{act}}{N(t)} \tag{8}$$

For an approximate determination of the pressures at the bottom of injection wells when pumping gas at a constant rate, we use formula [14].

$$P_{bhp}^2 - P_k^2 = AQ + BQ^2 \tag{9}$$

$$A = \frac{116\mu_0 z_0 T_0}{\pi k h p_a T_c}\left(\ln\frac{R_k}{R_c} + \xi_1 + \xi_2\right) \tag{10}$$

$$R = R_C + 1.5\sqrt{xt} \tag{11}$$

$$x = \frac{KP_k}{m\mu_0} \tag{12}$$

$$B = \frac{63.10^6 \rho_a T_0^2 [1+\xi_1+\xi_2]}{(k/m)^{3/2} 2\pi^2 h^2 T_c^2 R_c \rho_a .0.746.10^4} \tag{13}$$

when R is reached, the R_k value for uniform well placement on the gas area

$$R_k = \sqrt{\frac{\Omega}{\pi h m n}} \tag{14}$$

But in the case of battery placement of wells

$$R_k = L_k = \sqrt{\frac{\Omega}{\pi h m n}} \tag{15}$$

The pressure at the mouth of the injection well is determined by the formula GA Adamova:

$$P_{whp} = \sqrt{P_{bhp}^2 e^{-2s} - \frac{1.377\times10^{-2} z^2 T^2 \lambda Q^2}{d^5}\left(e^{-2s} - 1\right)} \tag{16}$$

$$2s = 0.06833 \times \Delta L / zT$$

Bursting pressure

$$P_{bp} = P_{vp} - P_{res} + \sigma_p \tag{17}$$

$$P_{vp} = \frac{H\rho_r}{10} \tag{18}$$

where Pvp - vertical overburden pressure; σp is the rock stratification pressure (it can be assumed that σp = 1.5 MPa)

The number of compressors necessary for pumping gas into the storage is found assuming that the compressor is located near the injection wells and the loss of gas pressure along the compressor path is small:

$$n_k = \frac{N(t)}{q_k} \tag{19}$$

where q_k is the flow rate of gas injected into the formation by a single compressor of a known type.

Table 1. Basic data of the underground gas storage

№ п /п	Initial data	Values
1.	Initial pressure in the storage, (MPa) $P_{initial}$	7
2.	Volume of the deposit, (m3)	2,158,000
3.	Permeability, (μm2) k	0.5 × 10-3
4.	Porosity, m	0.3
5.	Viscosity, (MPa * s) μ	0.012
6.	Thickness of the formation, (m) h	12
7.	The radius of the well, (m) Rc	0.1
8.	Number of injection wells, n	5

№ п /п	Initial data	Values
9.	Constant flow of gas pumped into the storage facility by one well, (m^3/day) N 1 (t)	240000
10.	Maximum allowable pressure in the storage, (MPa) Pper	9.5
11.	Depth of borehole, (m) L	640
12.	Inside diameter of the production string, (m) d	0.132
13.	Coefficient of hydraulic resistance of pipes, λ	0.02
14.	The relative density of the injected gas through the air, Δ	0.6
15.	Gas supercompressibility factor, z	0.85
16.	Coefficient of filtration resistance, B	0
17.	Stratification pressure of rocks, (MPa) σ	1.5
18.	Density of overlying rocks, ρ_r	2.5
19.	The compressor capacity is 10 GHz/55-125, (m^3/day).	842400

7. Calculation, result and analysis

From equation (4), Total gas storage capacity Q_{max} = 803.96 × 10^6 m^3; from (2), active gas volume Q_{act} = 211.56×10^6 m^3, from (3), cushion gas volume $Q_{cushion}$ = 592.39 × 10^6 m^3, Q_{act} +$Q_{cushion}$ = Q_{max}

Therefore, the sum of the active gas and the cushion gas gives the total gas storage capacity. From (8), time of gas injection into the storage, (d) T =2.11,56×10^6/1200000 = 176.3 days.

From (19), number of compressors:

$n_K = N(t)/q_K$ = 1200000/842400 = 1.424.

Maximum allowable pressure in the storage, (MPa) P_{per} = 9.5 MPa, which is less than than the vertical rock pressure, (MPa), P_{rock} = 15.5 MPa.

This satisfied the condition in (5) that: $P_{per} \leq (0.6-0.7)P_{rock}$

Therefore, the integrity of the roof of the formation will not be compromised, and conditions for gas leakage into the overlying strata or to the surface will also be prevented.

Table 2. Results of the calculation of the main parameters of the underground gas storage

№ п/п	The values obtained	Values	
1.	The maximum volume of gas pumped into the UGS, (m^3) Qact.	211568627.5	211,56×10^6
2.	Time of gas injection into the storage, (d.) T	176,3071895	
3.	Total gas storage capacity, (m^3) Q_{tot}	803960784.3	803,96×10^6
4.	The pressure at the bottom of the well at the end of the gas injection period, (MPa) P_{bh}	10.12	
5.	Pressure at the wellhead of the injection well at the end of the injection period, (MPa) P_{whp}	9.79	
6.	Storage radius, (m) R_K	356.7500283	
7.	Determine the number of compressors, n	1,424,501,425	thus 2 compressors
8.	Vertical rock pressure, (MPa) P_{rock}	15.5	
9.	Bursting pressure, (MPa) P_b	10.5	
10.	Cushion gas, (m^3) $Q_{cushion}$	592392156.9	592.39 × 10^6
11.	Volume of pore space in the storage, (m^3) Ω	71933333,333	719 × 10^5
12.	The constant flow of gas pumped into the storage, (m^3/day) N (t)	1200000	1.2× 10^6

8. Conclusions

1. Construction of underground storage facilities around the world has largely helped to contribute to the reliability of gas supplies to consumers.
2. The construction of underground gas storage comes with a lot of challenges. The prospects for the further development of storage of gases depend on geographical, geological and technical conditions of the reservoir.
3. At the end of this study, it has been shown that, for construction of underground storage in a depleted reservoir, some main parameters are considered and determined. These main parameters include: maximum allowable pressure; minimum required pressure at the end of the sampling period; volumes of active and cushion gases; diameter and wall thickness of reservoir and connecting gas pipelines; type of compressor unit; number of injection wells; type and size of the underground storage facility for gas purification from solid suspensions when injecting it into the formation and drying it during the selection.
4. As a result of the technological calculation, the investigated horizon can act as UGS, since the maximum and minimum pressures in the storage, the total volume of gas in the storage, the required number of new wells, and the compressor capacity have been determined.
5. From the analysis of geological and technological parameters, it is concluded that it is possible and also profitable to construct an underground storage on the chosen reservoir on the field.

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Nomenclature

B	*Coefficient of filtration resistance*	P_{rock}	*Overburden rock pressure, MPa*
d	*Inside diameter of the production string, m*	P_{vp}	*Vertical overburden pressure, MPa*
g	*Acceleration due to gravity, m²/s*	P_{whp}	*Pressure at the wellhead, MPa*
H	*Depth of the storage, m*	Q_{act}	*Active volume, m^3*
h	*Thickness of the formation, m*	$Q_{cushion}$	*Cushion gas volume, m^3*
k	*Permeability, μm2*	Q_{total}	*Total gas volume, m^3*
L	*Depth of borehole, m*	qk	*flow rate of gas injected, m^3 / day*
m	*Porosity*	R_c	*Radius of the well, m*
MMcf/d	*million cubic feet per day*	R_K	*Storage radius, m*
n	*Number of injection wells*	T	*Time of gas injection into the storage, d*
n_k	*Number of compressors*	UGS	*Underground Gas Storage*
$N (t)$	*Constant flow of gas pumped into the storage, m^3/day*	Z	*Gas supercompressibility factor*
P_{av}	*Average pressure in the storage tank, MPa*	λ	*Coefficient of hydraulic resistance of pipes*
P_{bh}	*Pressure at the bottom of the well at the end of the gas injection period, MPa*	μ	*Viscosity, MPa * s*
P_{bp}	*Bursting Pressure, MPa*	ρ_{rock}	*Average density of overlying rocks, kg/m^3*
$P_{ex.p}$	*Excess pressure in the storage, MPa*	σ_p	*Rock stratification pressure, MPa*
$P_{initial}$	*Initial pressure in the storage, MPa*	Δ	*Relative density of the injected gas through the air*
P_{max}	*Maximum pressure in the storage, MPa*	Ω	*Volume of the pore space, m^3*
P_{min}	*minimum pressure in the storage, MPa*	P_{per}	*Maximum allowable pressure, MPa*
P_{res}	*Reservoir pressure, MPa*		

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