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Analysis of the functional dependability of underground gas storage compressor stations in cases when actual performance indicators deviate from the design values

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Abstract. Aim. *The paper examined the matter of assessment of the functional dependability of compressor stations (CS) of underground gas storage (UGS) facilities. A definition of CS functional dependability and guidelines for its assessment were proposed.* **Methods.** *Design calculation of compressor stations, scenario analysis.* **Results.** *The paper presents: a) a definition, indicators of CS functional dependability and guidelines for its assessment; b) an example of the guidelines application for UGS CS; c) a comparative analysis of UGS CS functional dependability in a number of various versions: use of single-unit and two-unit centrifugal compressors as part of gas turbine gas pumping units for two-stage compression with intercooling.* **Conclusion.** *The paper shows the requirement to analyse the functional dependability of various versions of UGS CS for the purpose of identifying the most rational option that ensures unconditional performance of the key UGS CS function under uncertain initial design data.*

Keywords: *compressor station, UGS compressor station, primary target process functions, gas compressor unit, centrifugal compressor, two-unit centrifugal compressor, functional dependability.*

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1. Introduction

In order to ensure peak consumption volumes, as well as flexibility and dependability of gas supply, UGS are created for the purpose of collection and storage of natural gas and its subsequent prompt delivery to consumers as required [1]. There is experience in creating UGS facilities based on depleted hydrocarbon deposits, water-bearing formations or salt caverns. Regardless of the type of underground reservoir, each UGS facility uses compressor stations required for ensuring the temperature and pressure conditions for gas withdrawal and injection into the formation.

CS is a critical element of the UGS process system, which defines the high requirements for its dependability and efficiency. That is largely due to the fact that a CS is an "active" process facility, as it ensures increased gas pressure, whereas the other UGS facilities are primarily "clients" of the target value of pressure. For example, the operation of gas purification systems and injection process require the design value of pressure, while gas collection systems cause losses of pressure that need to be amended, etc. Therefore, the CS UGS is the only facility, modifying the operating modes of which the changes in the operating conditions can be compensated for the purpose of enabling the planned performance indicators.

In general, as regards ensuring the dependability of technical systems, two classes of tasks are to be distinguished. The first class includes problems of structural dependability. Those are solved using the methods of the traditional dependability theory that studies the processes of item failure and restoration (of an entire technical system and its elements). The second class includes problems related to the analysis of functional dependability (FD) of technical systems that characterizes the reliability of a system's target functions when actual operating conditions deviate from the design values [2]. The analysis of structural dependability is based on classical methods of statistical analysis, which significantly limits its applicability to complex systems, while the FD is analysed using modern methods of computer simulation, queuing theory, machine learning, etc.

The methods of FD analysis of complex technical systems are used (and are being actively developed) for identifying the most efficient technical and process-specific solutions in the power industry, including nuclear [3], development of information management and operating systems [4], security system [5], etc. Problems, whose solution involves evaluating the FD of gas industry process systems, are examined in a number of papers, including those by Gazprom VNIIGAZ [6, 7].

This paper examines the solution of the problem of ensuring reliable performance of primary UGS CS target functions subject to uncertain operational indicators (OI) its design is based upon (temperature and pressure, consumption parameters, etc.). This problem belongs to the second class of problems of technical system dependability. To solve it, a methodological approach has been developed that consists in identifying the UGS CS FD and indicators for its quantification. The paper presents the methodological approach and an example of its application for comparing the FD of equipment options of UGS CS with a gas turbine-driven gas compressor unit (GCU) and various types of centrifugal compressors (CS), single-section single-unit and single-unit two-section.

2. Key provisions of the methodological approach, concepts and terms

UGS CS FD research includes the following main activities:

– definition of the list of functional failures;

– identification of UGS CS FD factors (threats) (evaluation of the probability of their future occurrence);

– development of a system of UGS CS FD indicators;

– development of methods for FD indicator calculation;

– definition of UGS CS FD requirements.

A functional failure (FF) should be identified as nonperformance (entirely or in part) of a system's primary functions, while FD factors should be defined as the causes and events that entail an FF, i.e. FD threats. Therefore, identifying an FF and UGS CS FD threats (factors) requires defining the meaning and formalizing the concept of UGS CS FD.

3. Functional dependability and primary process-specific functions of compressor stations of underground gas storage facilities

In the academic community, there is still no generally accepted definition of the term "functional reliability/dependability", and, consequently, there is still no single understanding of the subject and goals of FD analysis of technical systems.

In this paper, by analogy with [2, 8 – 11], it is assumed that UGS CS FD is the ability of CS to ensures the performance of its primary target process functions (PTPF) when the primary OI (pressure at the output and input of the compressor station, volume and/or composition of the compressed natural gas, its temperature at the input of the compressor station, etc.) deviate from the design values.

The PTPF of UGS CS is ensuring that the pressure of a given amount of gas increases to the values required for: a) injection of the required amount of gas into UGS; b) withdrawal of the required amount of gas in autumn and winter for delivery to the main gas line (MG).

4. Functional failures and factors of functional dependability of compressor stations of underground gas storage facilities

As it was mentioned above, FF is the impossibility of performing a system's primary process functions. Taking into account the above definition of PTPF, the FF of UGS CS are:

– impossibility to increase the pressure for the required amounts of gas for withdrawal or injection to the design values;

– maintaining PTPF in the course of long CS operation in suboptimal operating modes, e.g., in case of the low polytropic efficiency of the compression process, deviation from the nominal value by more than 20 % (rel.) or if backup GPUs need to be put in operation with violation of regulatory requirements for redundancy.

It is important to note that, in terms of FD evaluation, only those cases are of interest when the above FFs occur with fully operable equipment, i.e., not due to accidents or GPU failures, etc., but due to changes in the operating conditions. Accordingly, for UGS CS, those are deviations of consumption and temperature and pressure indicators from the design values that may be due to the following causes:

– decreased pressure in the UGS due to a reduced amount of stored gas, e.g., when the amount of withdrawn gas is higher than planned;

– increased pressure in the UGS due to an increased amount of stored gas, e.g., when the amount of injected gas is higher than planned;

– decreased or increased pressure in the UGS due to changes or better definition of the structure and properties of the UGS reservoir;

– changed temperature of gas at the input to the UGS CS;

– changing MG operating mode;

– increased rate of gas withdrawal, etc.

The above events are among UGS CS FD factors, i.e., threats that may cause FFs, and their elimination may require additional costs, e.g., associated with the reconstruction of the CS (deployment of additional GPUs, re-wheeling, etc.) Therefore, when choosing the UGS CS equipment option, the results of the FD analysis should be taken into consideration, since that allows determining the facility alternatives that ensure the PTPF performance within a wide range of consumption and pressure parameters with no additional material costs. Quantitative FD analysis requires a system of UGS CS FD indicators.

5. UGS CS functional dependability indicators

As primary UGS CS FD indicators, parameters are adopted that allow quantifying the consequences of changes in the CS operating mode as an FF occurs:

– required deployment of backup GCUs (with no violation of redundancy requirements);

– required installation and commissioning of additional GCUs;

– CS performance margins when operating with the predefined number of GCUs and in compliance with the GCU redundancy requirements;

– variation of required fuel gas.

The requirement to deploy backup GCU with no violation of redundancy requirements characterizes the CS's ability to maintain the PTPF subject to consumption, temperature and pressure indicators deviating from the design values without additional costs for the installation and commissioning of equipment. The required installation and commissioning of additional GCUs indicates the requirement to overhaul the CS, which means additional capital investment.

The CS performance margin characterizes the difference between the design performance and the maximum possible performance if pressure deviates from the design values (characterizes the existence of a performance margin). In other words, it indicates the feasibility of intensifying the scope of useful UGS performance.

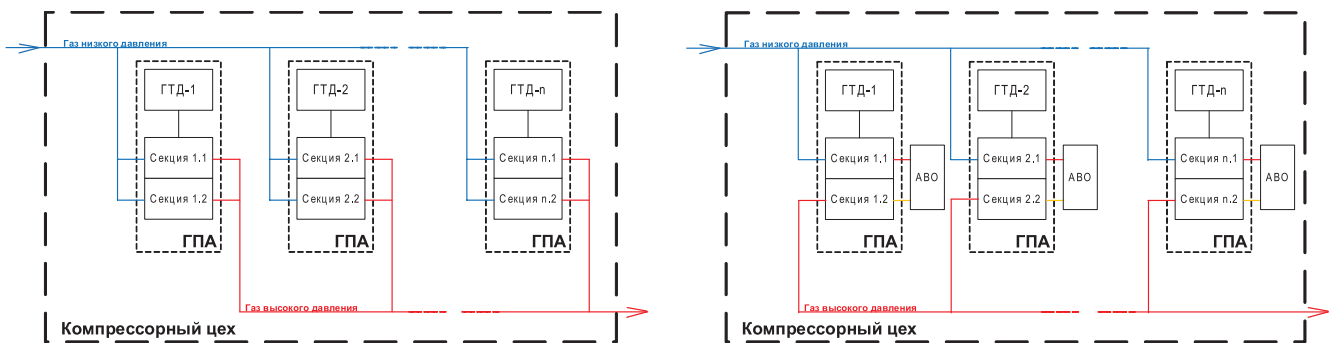
The variation in the fuel gas demand allows comparing the UGS CS equipment options based on the variation of the energy efficiency indicators of the gas compression process in changing operating conditions. That means that it characterizes the increase in operating costs.

The presented system of indicators is the foundation of the developed methodological approach to assessing the UGS CS FD. Each of the system's indicators characterizes both the process-specific, and economic aspects of UGS CS operation.

6. Methodological approach and an example of its implementation

Quantifying the FD of various design and engineering solutions in terms of UGS CS equipment requires performing the following calculations and analytical studies for various station equipment options:

1. Quantitative assessment of possible deviation of the consumption and temperature and pressure parameters of



a) b)

Fig. 1. UGS CS option with a GCU with a two-unit CC: a, single-stage compression (parallel operation of units); b, two-stage compression (sequential operation of units); where ACU is air cooler unit

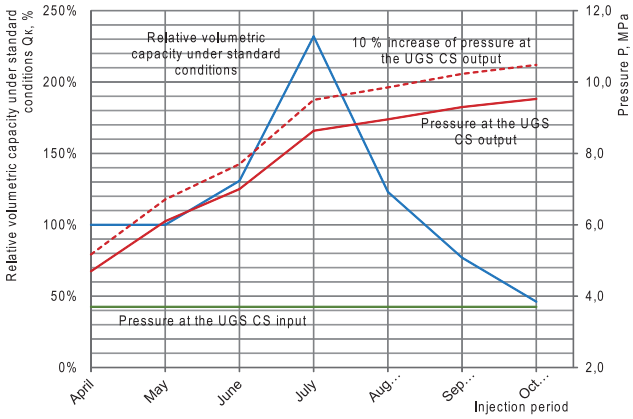


Fig. 2. Graph of performance dynamics (relative values) and gas pressure at the CS inlet and outlet during UGS injection

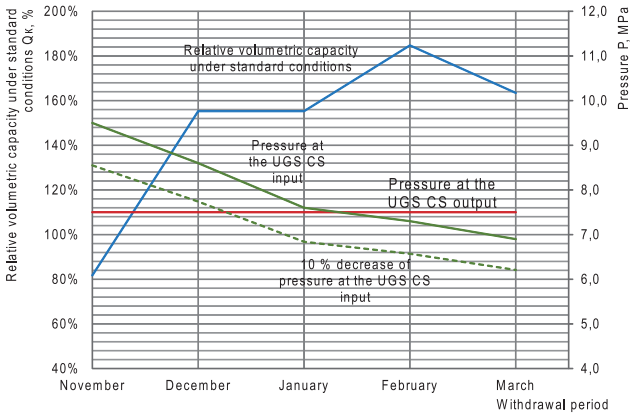


Fig. 3. Graph of productivity dynamics (relative values) and gas pressure at the CS inlet and outlet during UGS withdrawal

the actual operating modes from the design values. This stage is to be carried out in cooperation with geology experts involved with the examined UGS, gas transport experts, etc.

2. Calculations of UGS CS operation modes for various equipment options:

– calculation of design operation modes;

– calculation of operating modes in cases of OI deviation from the design values;

– calculation of quantitative FD indicators through comparative analysis of the UGS CS operating mode calculations for cases when design OI values are and are not fulfilled.

3. Comparative analysis of UGS CS FD indicators for various equipment options for the purpose of developing guidelines for primary station design solutions.

Below is an example of implementation of the examined methodological approach for UGS CS with gas-turbine GCUs with single-unit and two-unit CCs.

In case single-unit CCs are used, the UGS CS includes one compressor shop, whose GCUs operate in parallel.

In case two-unit CCs are used, the UGS CS includes one compressor shop. Additionally, special process piping of the CC units is foreseen for the purpose of ensuring their sequential or parallel operation (see Fig. 1).

The initial data used in the calculations are shown in Fig. 2 and 3 and in Tables 1 to 4. It is accepted that in the course of the injection period, gas comes from the main gas line with a constant pressure of 3.7 MPa, while in case of gas withdrawal from UGS it is required to supply gas to a pipeline with the working pressure of 7.5 MPa.

Scenarios of UGS CS operation under the design operating conditions and FD factors (threats) caused by geological risks were considered. It is accepted that operation in off-design conditions causes the requirement for a 10% increase of the UGS CS output pressure when injecting gas and a 10% reduction of the UGS CS input pressure when withdrawing gas.

The calculation data are shown in Fig. 4 to 6 and Table 5.

Table 1. Temperature and pressure parameters of the gas injected into UGS

Month	Gas pressure at the station input P_1, MPa	Gas temperature at the station input T_1, K	Gas pressure at the station output P_2, MPa (per design / deviates from design)
April	3.70.	283.15	4.70 / 5.17
May			6.10 / 6.71
June			7.00 / 7.70
July			8.64 / 9.50
August			8.95 / 9.85
September			9.30 / 10.23
October			9.53 / 10.48

Table 2. Temperature and pressure parameters of the gas withdrawn from UGS

Month	Gas pressure at the station input P_1, MPa (per design / deviates from design)	Gas temperature at the station input T_1, K	Gas pressure at the station output P_2, MPa
November	9.50 / 8.55	283.15	7.50
December	8.60 / 7.74		
January	7.60 / 6.84		
February	7.30 / 6.57		
March	6.90 / 6.21		

Table 3. Compressible gas composition

No.	Name	Composition	Molar concentration, %
1	Methane	CH_4	98.511
2	Ethane	C_2H_6	0.360
3	Propane	C_3H_8	0.066
4	n-Butane	n-C_4H_{12}	0.013
5	n-Pentane	n-C_5H_{12}	0.028
6	Nitrogen	N_2	0.782
7	Carbon dioxide	CO_2	0.280

Table 4. Primary technical characteristics of GCU with single and two-unit CCU

Primary characteristics	GCU with single-unit CC	GCU with two-unit CC	
Unit power GCU N_{e0}, MW	8.0	8.0	10.0
Mechanical efficiency η_{MEX}, %	98	96	96
Pressure loss between compression stages $\Delta\rho_{cm}$, MPa	–*	0.50	0.50
Nominal pressure ratio of one unit	3.0	1.7	1.7

*Note: * – operation involves one compression stage*

Table 5. Calculated indicators of UGS CS FD

Quantitative indicators of FD	Gas injection into UGS (P_{out} increased by 10%)			Withdrawal from UGS (P_{in} reduced by 10%)		
	Single-unit	Two-unit		Single-unit	Two-unit	
Unit power of GCU, MW	8	8	10	8	8	10
Required backup GCUs, pcs	1	–	–	–	–	–
Required installation and commissioning of additional GCUs, pcs	–	–	–	–	–	–
Margin of cubic capacity under standard conditions q_{Δ}, mln m^3/day	-0.39*...27.42	0.11...34.51	6.94...57.96	21.27...23.56	70.65...72.95	91.83...94.13
Increased fuel gas consumption as compared to the reference case Δq_{fg}, mln m^3	4.07 (13.9%)	2.75 (10.7%)	2.87 (10.9%)	3.37 (32.4%)	1.50 (32.5%)	1.64 (32.6%)

*Note: * The minus symbol indicates that the station will not be able to provide the specified gas flow rate with the designed number of operating GCUs. Implementing this mode will require increasing the number of operating units compared to the design values.*

The analysis of the calculation data per the UGS CS FD assessment system shows that:

1. Deployment of backup GCUs with violation of redundancy requirements is only necessary if the pressure at the CS outlet increases by 10 % if the CS is equipped with a UGS GCU with a single-unit CC (see Fig. 4a, Table 5).

2. Installation and commissioning of additional GCUs is not required in the above situations.

3. The minimal margin of CS volume efficiency when operating with the predefined number of GCUs is:

– minus 2.2%[1] when UGS CS is equipped with a GCU with a single-unit CC with the unit capacity of 8.0 MW (see Fig. 6a, Table 5);

– 0.6% when UGS CS is equipped with a GCU with a two-unit CC with the unit capacity of 8.0 MW (see Fig. 6a, Table 5);

– 38.4% when UGS CS is equipped with a GCU with a two-unit CC with the unit capacity of 10.0 MW (see Fig. 6a, Table 5);

4. If pressure deviates 10 % from the design values, fuel gas consumption grows:

– by 13.9% in the course of injection and by 32.4% in the course of withdrawal if a GCU with a single-unit CC with a unit capacity of 8.0 MW is used (see Fig. 4b and Table 5);

– by 10.7% in the course of injection and by 32.5% in the course of withdrawal if a GCU with a two-unit CC with a unit capacity of 8.0 MW is used (see Fig. 4d and Table 5);

[1] * The minus symbol indicates that the station will not be able to provide the specified gas flow rate with the designed number of operating GCUs and required redundancy. Implementing this mode will require a larger number of operating units.

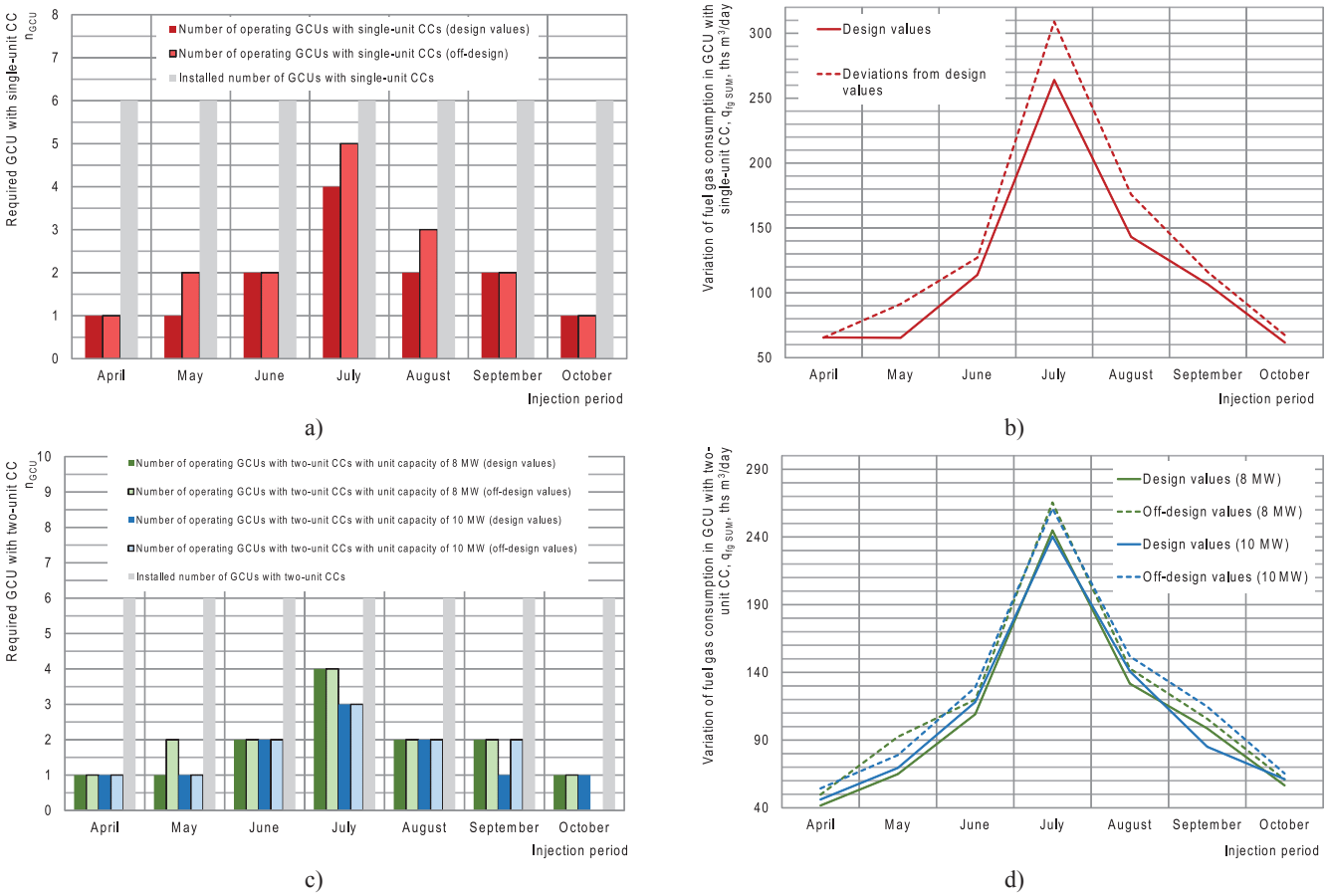


Fig. 4. Calculation data for the UGS operation in the course of gas injection in the reference conditions and when affected by FD factors (threats): a, required GCU with single-unit CC; b, variation of fuel gas consumption in GCUs with single-unit CCs; c, requirement for GCUs with two-unit CCs of different unit capacity; d, variation of fuel gas consumption in GCUs with two-unit CCs of various unit capacities

– by 10.9% in the course of injection and by 32.6% in the course of withdrawal if a GCU with a two-unit CC with a unit capacity of 10.0 MW is used (see Fig. 4d and Table 5).

The analysis of the FD assessment results showed that UGS CSs using GCUs with two-unit CCs have higher FD indicators as compared with GCUs with single-unit CCs as part of the UGS CS.

Thus, the analysis of the UGS CS FD allowed:

– identifying the optimal UGS CS options enabling MTF performance when the OI deviate from the design values, while ensuring the GCU redundancy standards with insignificantly decreased energy efficiency of the compression process;

– reducing the number of considered options for a detailed trade-off study.

7. Conclusion

A methodological approach to assessing the UGS CS FD was developed that consists in quantifying the negative consequences that may be caused by deviations of the actual operational parameters from the design values.

The methodological approach to FD assessment includes the following primary stages:

– quantification of FD factors (threats);

– computation of UGS CS operation modes for various versions operating per design and under FD factors (threats);

– comparative analysis of FD indicators for various UGS CS versions.

It was proposed quantifying FD with a number of indicators that affect the capital and operating costs:

– required backup GCUs;

– required installation and commissioning of additional GCUs;

– CS performance margins with a predefined number of GCUs and in compliance with the GCU redundancy requirements;

– changing requirements for fuel gas and installed GCUs.

The practical use of the methodological approach is shown by comparing the UGS CS GCU variants with single-unit and two-unit CCs. Based on the results of FD assessment, it was determined that UGS CSs equipped with a GCUs with two-unit CCs have higher functional dependability indicators as compared with single-unit CCs as part of the GCU.

The developed methodological approach to FD assessment has the potential for further improvement for the purpose of establishing a common approach for CS of various technical designation.

FD assessment allows comparing various CS versions in terms of the feasibility of ensuring the target design indica-

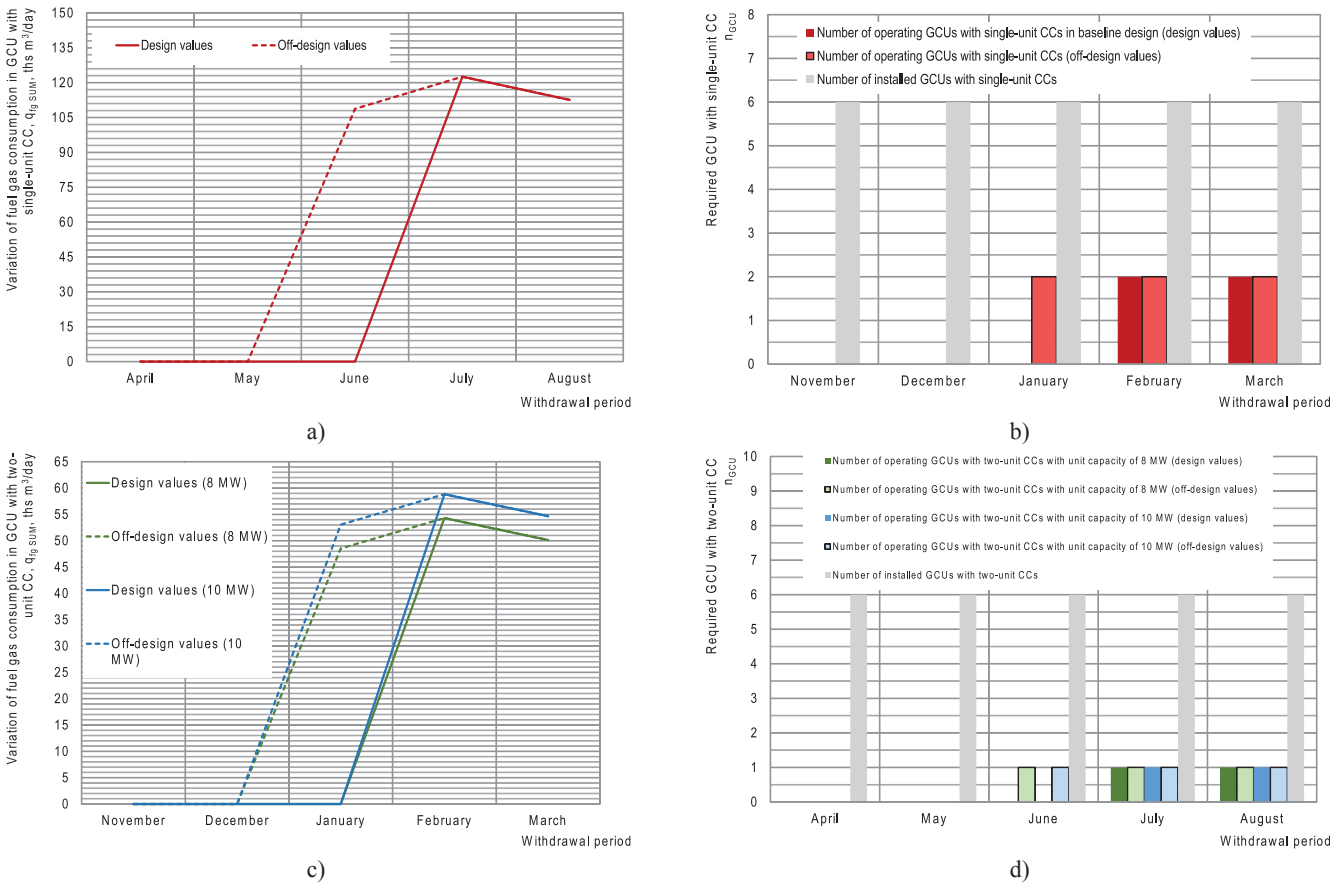


Fig. 5. Calculation data for the UGS operation in the course of gas withdrawal in the reference conditions and when affected by FD factors (threats): a, required GCU with single-unit CC; b, variation of fuel gas consumption in GCUs with single-unit CCs; c, requirement for GCUs with two-unit CCs of different unit capacity; d, variation of fuel gas consumption in GCUs with two-unit CCs of various unit capacities

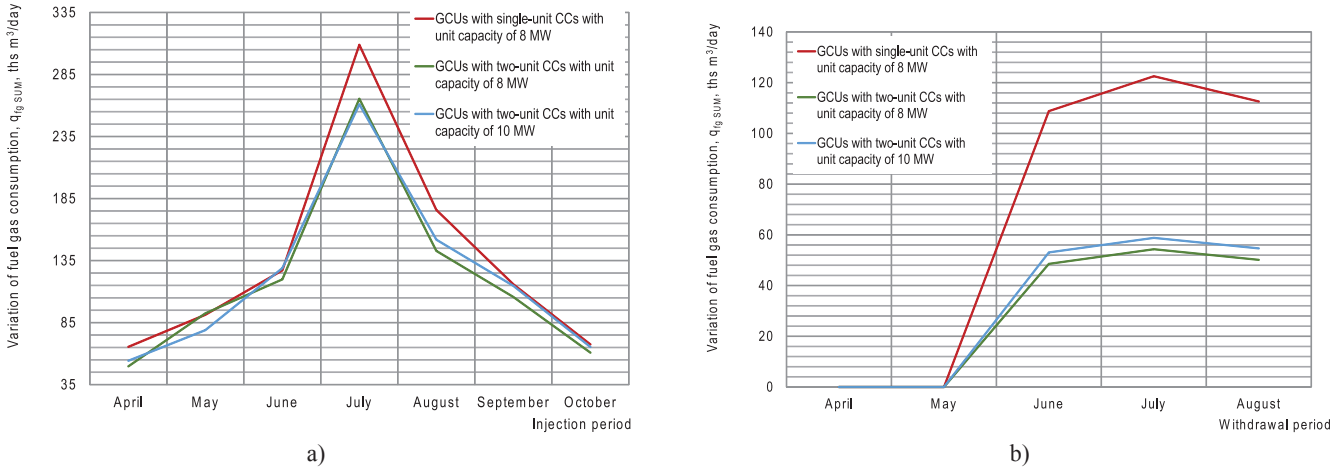


Fig. 6. Variation of fuel gas consumption for GCUs with single-unit and two-unit CCs (of various unit capacities) when affected by FD factors (threats): a, when injecting into UGS; b, when withdrawing from UGS

tors and CS performance variation when the actual operating conditions deviate from the design. It is recommended defining requirements for the UGS CS process system in terms of meeting the designed volume of gas extraction and injection, including in cases when the consumption, as well as the temperature and pressure performance, deviate from the design values, and assessing FD as early as at the CS design stage in order to substantiate the primary engineering solutions.

The findings can be used for creating risk-oriented approaches to the design of compression systems, i.e., those based on the risk and uncertainty assessment and management [7], as well as for assessing risks as part of investment decision support.

References

1. Lyugay D.V, Dolgov S.I., Rakitina G.S. A role of underground gas storages in provision of stable functioning of the Unified System of Gas Supply of Russia. *Povyshenie nadezhnosti i bezopasnosti obektov gazovoy promyshlennosti* 2018;2(34):101-108. (in Russ.)

2. Shubinsky I.B., Schäbe H. On the definition of functional dependability. *Reliability: Theory & Applications* 2012:7;4(27):8-18.

3. Wakankar A., Kabra A., Bhattacharjee A.K., Karmakar G. Architectural model driven dependability analysis of computer based safety system in nuclear power plant. *Nuclear Engineering and Technology* 2019;51(2):463-478.

4. Kleiman L., Freyman V. Improving the functioning dependability of the information management system elements, using built-in diagnostic tools. *Radio Electronics, Computer Science, Control* 2021;1:158-171.

5. RD 25.03.001-2002. Guard and security systems of objects. Terms and definitions. Moscow: Izdatelstvo standartov; 2002. (in Russ.)

6. Vorontsov M.A., Grachiov A.S., Kirkin M.A., Bogatyriova E.V., Nuriev M.F., Drozdov A.V., Novikov A.I., Snezhko D.N. [Technological risks of the operation of underwater compressor units]. In: *[Proceedings of the 2018 International contest of research, engineering and innovative solutions aimed at the development of the Arctic and the continental shelf]* 2018. [accessed 11.02.2022]. Available at: https://in.minenergo.gov.ru/upload/tek/analitika/Arctica-2018-web.pdf . (in Russ.)

7. Vasiliev Yu.N., Gimadeyeva R.N., Ilnitskaya V.G. Uncertainties and risks of gas field development design and management. *Vesti gazovoy nauki: Problems of development of gas, gas condensate and oil/gas/condensate fields* 2014;4:16-22. (in Russ.)

8. GOST R 56205-2014 IEC/TS 62443-1-1:2009 Industrial communication networks. Network and system security. Part 1-1. Terminology, concepts and models. Moscow: Standartinform; 2014. (in Russ.)

9. GOST R 57329-2016/EN 13306:2010 Automation systems and integration. Maintenance and repair systems. Terms and definitions. Moscow: Standartinform; 2020. (in Russ.)

10. GOST R ISO/IEC 15026-1-2016 Systems and software engineering. Systems and software assurance. Part 1. Concepts and vocabulary. Moscow: Standartinform; 2016 (in Russ.)

11. Burgazzi L. Reliability Evaluation of Passive Systems Through Functional Reliability Assessment. *Nuclear Technology* 2003;144:145-151.

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The authors' contribution

Vorontsov M.A. Developed the method for assessing functional dependability, organized the research to test the method.

Grachiov A.S. Developed the method for assessing functional dependability, collected the input data for the calculation study.

Grachiova A.O. Conducted the calculation study, made the search and analysed sources, prepared an overview of research findings regarding the subject matter.

Kirkin M.A. Developed the method for assessing functional dependability, organized the research to test the method, prepared an overview of research findings regarding the subject matter.

Melnikova A.V. Participated in the discussion of the research methods and analysis of the findings.

Conflict of interests

The authors declare the absence of a conflict of interests.