SOCAR Proceedings

Reservoir and petroleum engineering

journal home page: http://proceedings.socar.az

AUTOMATED PROCESSING OF WELL LOGGING DATA TO MONITOR THE POSITION OF THE GAS–WATER CONTACT IN UNDERGROUND GAS STORAGE FACILITIES

G. R. Vakhitova*[1], R. A. Valiullin[1], V. Y. Fedotov[1], V. K. Mukhutdinov[1], F. I. Ibadov[2]

[1]*Ufa University of Science and Technology, Ufa, Russia*

[2]*SOCAR, Baku, Azerbaijan*

ABSTRACT

Natural oil and gas deposits in most fields include some fluid contacts, such as oil–water, gas–water, or gas–oil. Monitoring the position of the gas–water contact in underground gas storage (UGS) facilities is crucial for monitoring the safety of the subsurface environment. As UGS facilities are geological features of long-term operation, the condition of these features must be regularly monitored for possible gas leaks due to various reasons, whether geological or technical. Periodic surveys of production wells using geophysical methods make it possible to timely detect the reasons for abnormal technical conditions and higher-than-normal water cuts of reservoirs, and to assess shifts in gas–water contact. The suite of production logging methods for surveying and monitoring underground gas storage facilities includes nuclear logging with the use of steady radiation sources (i.e., gamma ray logging and neutron logging). Analysis and interpretation of these methods make it possible to track the shift over time of the gas–water contact in gas-saturated sandstones with an interparticle porosity of >15%. Data from nuclear logging, temperature logs, and composition-based and flow-based surveying are processed and interpreted with the use of known methods and diagnostic indicators to achieve the following goals: to determine the intervals of inter-reservoir and behind-the-casing fluid movement on the base of the well log, to assess the technical condition of the wellbore, to monitor the position of the gas–water contact in the reservoir, to assess the gas saturation of the reservoir, and to monitor the thickness and integrity of the clay caprocks of UGS facilities [1]. This paper discusses the results of automated processing and interpretation of well data recorded during the survey of an UGS facility to determine the current position of the gas–water contact in the reservoir and the gas–water interface in the well. Quantitative interpretation of the neutron logging data with the use of steady radiation sources was performed, and the current gas saturation factor was estimated.

Keywords: gas–water contact (GWC); gas saturation; underground gas storage; processing algorithm; gas–water interface (GWI).

Introduction

Underground gas storage (UGS) facilities are seasonal containers for «blue fuel» for its further use as necessary. Geological features are often used as gas reservoirs. In Russia, depleted productive reservoirs, water-bearing horizons, and salt mines are currently used as UGS facilities.

In UGS, a large volume of gas is pumped into depleted reservoirs or other types of underground storage facilities, distributed throughout the pore space of the facility and stored there for a long time. Of course, such facilities require regular condition monitoring. In practice, there may be cases when gas from the storage facility breaks into the overlying layers through a clay caprock, or, if the well cementing quality is low, through behind-the-casing space. This is a consequence of gas release into the overlying layers or on the surface of the UGS facility, which poses a danger to the environment [2]. Depending on the origin of UGS facilities and the technical condition of the well stock, certain problems arise during the operation of storage facilities, which can be diagnosed during comprehensive geophysical surveys.

The traditional suite of field surveying methods of UGS facilities, along with thermometry, flow metering, and composition-based methods, includes nuclear logging with the use of steady radiation sources (i.e., gamma ray logging and neutron logging). In gas-saturated sandstones with an intergranular porosity of >15%, analysis and interpretation of the data/results of these surveys make it possible to track the shift in gas-water contact (GWC) over time and to evaluate the current gas saturation factor. Neutron logging can be performed with the use of a single probe or a dual-probe, referred to as neutron gamma ray logging (NGL) and neutron–neutron logging (NNL), respectively. This paper considers a UGS facility in Russia where gas in stored in a high-porosity sand aquifer.

UGS operation control implies permanent monitoring accompanied with typical field and geophysical survey and processing procedures. Automated interpretation makes it possible to accelerate the resolution of relevant tasks when monitoring UGS, and to immediately obtain the output of arrays of calculated data throughout the facility.

E-mail: guzel.geotec@mail.ru

http://dx.doi.org/10.5510/OGP20240100948

Theory

Data from nuclear logging, as well as temperature log data and data from composition-based and flow-based surveying, are processed and interpreted with the use of known methods and diagnostic indicators to achieve the following goals: detection of fluid movement (e.g., annular, behind-the-casing, and inter-reservoir), diagnostics of the technical condition of wells, control of the GWC position, assessment of the gas saturation and operational characteristics of the reservoir, and control of the integrity of the clay caprocks of the UGS.

Gas-saturated reservoirs are distinguished by the following qualitative characteristics in log charts: the readings of gamma-gamma density logging are reduced, and the hydrogen content decreases compared to fluid-saturated reservoirs, with all other factors being equal. The recorded neutron logging data are characterized by an increase in readings against gas-saturated reservoirs relative to the values of oil-saturated and water-saturated reservoirs [3].

When processing neutron logging data, the gamma ray index q_g is calculated, which is determined using the following equation [3]:

$$q_g = \frac{J - J_w}{J_g - J_w} \qquad (1)$$

where J is the NGL readings against the surveyed gas-saturated reservoir, and J_w and J_g are the readings in water-saturated and gas-saturated (with maximum K_g=95%) reservoirs, respectively. The gamma ray index q_g in Eq. (1) is a dimensionless quantity, and the responses of the neutron gamma log (NGL) chart are recorded in conventional units.

In cases where reservoirs are characterized by a sufficiently high porosity of the interparticle space (i.e., >15%), the gamma ray index of NGL qg, determined in a cased well with a deactivated flushed zone, is related to the gas saturation factor K_g as follows [4]:

$$q_g = -0.77 \cdot \lg(1 - K_g) \qquad (2)$$

Reservoirs can also be distinguished by the nature of their saturation based on the chlorine content in the reservoir fluid [5, 6, 7, 8]. It is well known that chlorine is contained only in the reservoir waters. Consequently, the chlorine content in reservoirs determines the water-saturated porosity. As the chlorine content increases, the density and mineralization of the reservoir water also increase.

Nuclear logging with the use of steady radiation sources as part of a suite of survey methods makes it possible to distinguish gas- and water-saturated reservoirs. For reservoirs saturated with mineralized reservoir water, due to the chlorine contained within, NGL readings increase, and NNL readings decrease.

The NGL method was included in the survey suite of wells at the UGS under consideration. The determination of the current and residual gas saturation of reservoirs is based on the well-known technique (described in open sources) of two reference reservoirs with equal porosity: a gas-saturated reservoir with the known gas saturation and a water-saturated reservoir. Otherwise, undiluted clays and dense sandstone rocks are taken as reference reservoirs.

Processing results

A sand layer lying directly above the weathering crust of the Archean crystalline basement is used as a UGS facility. The porosity of the formation is 20–22%, which is quite high. Two deposits have been identified in the sandstone sediments. The gas spreads through microcracks from one deposit to the other.

Geophysical monitoring of changes in gas saturation and the position of the GWC in the wells of the UGS has been carried out with the use of steady-state NGL since the start of its injection in 1973. The average thickness of the sandstone into which the gas is injected is 10.8 m. The reservoir temperature is 29.2 °C, and the reservoir pressure is 11.65 MPa. All wells under consideration are vertical.

The suite of field geophysical survey methods is almost the same in all wells, which made it possible to automate data processing. To increase the speed of interpretation, an algorithm was created to automatically monitor the position of the current GWC in the reservoir, calculate the current gas saturation factor, and simultaneously determine the position of the gas–water interface (GWI) in all UGS wells.

The positions of the GWC and GWI were determined based on the algorithm proposed by the authors and the implemented software module. The GWI depth was determined as that corresponding to the maximum value of the second derivative of the pressure curve. The corresponding GWI primitive was used to visualize the depth. When determining the position of the GWC in the reservoir, the following algorithm was used: (1) the first derivative is determined from the NGL curve, and its maximum value is sought within the interval of the surveyed reservoir; (2) the depth that corresponds to the maximum value of the derivative is taken as the depth of the GWC.

Figure 1 shows the initial data recorded in well X1 and the interpretation results. The following suite of surveys was performed here: NGL of natural radioactivity (GR) (historical GR1=purple curve; current GR2=red curve), NGL (black curve), thermometry (T=green curve), barometry (MAN=blue curve), moisture measurement (VLG=red curve), and coupling location (LM)=thin blue curve.

The UGS operation mode was gas withdrawal. The first derivative of the NGL (D1 curve in fig. 1) and the second derivative of the pressure (D2 curve in fig. 1) were calculated.

As a result of the automatic interpretation, the following values were determined: reservoir water cut, the current position of the GWC in the reservoir, and the GWI in the borehole. The current value of K_g was not determined, as the reservoir was flooded.

Figure 2 shows the initial data and the results of their interpretation for well X2. The UGS operation mode was gas withdrawal. The suite of field surveys includes GR (historical=purple curve; current=red curve), NGL (historical=blue curve; current=black curve), thermometry (T), barometry (MAN), and gamma–gamma density logging (Density).

Similar to well X1, the first derivative of the NGL (D1) and the second derivative of the pressure (D2) were calculated.

As a result of automatic interpretation, the nature of the current reservoir saturation (gas- saturated) was assessed, and the current K_g was calculated as 33%. The position of the GWC was not determined as the reservoir was gas-saturated, without any signs of watering. GWI was not observed in the surveyed depth interval.

The resulting reliability of GWC level monitoring by production log methods using the proposed algorithm is quite high, which is determined by the error in the approximation

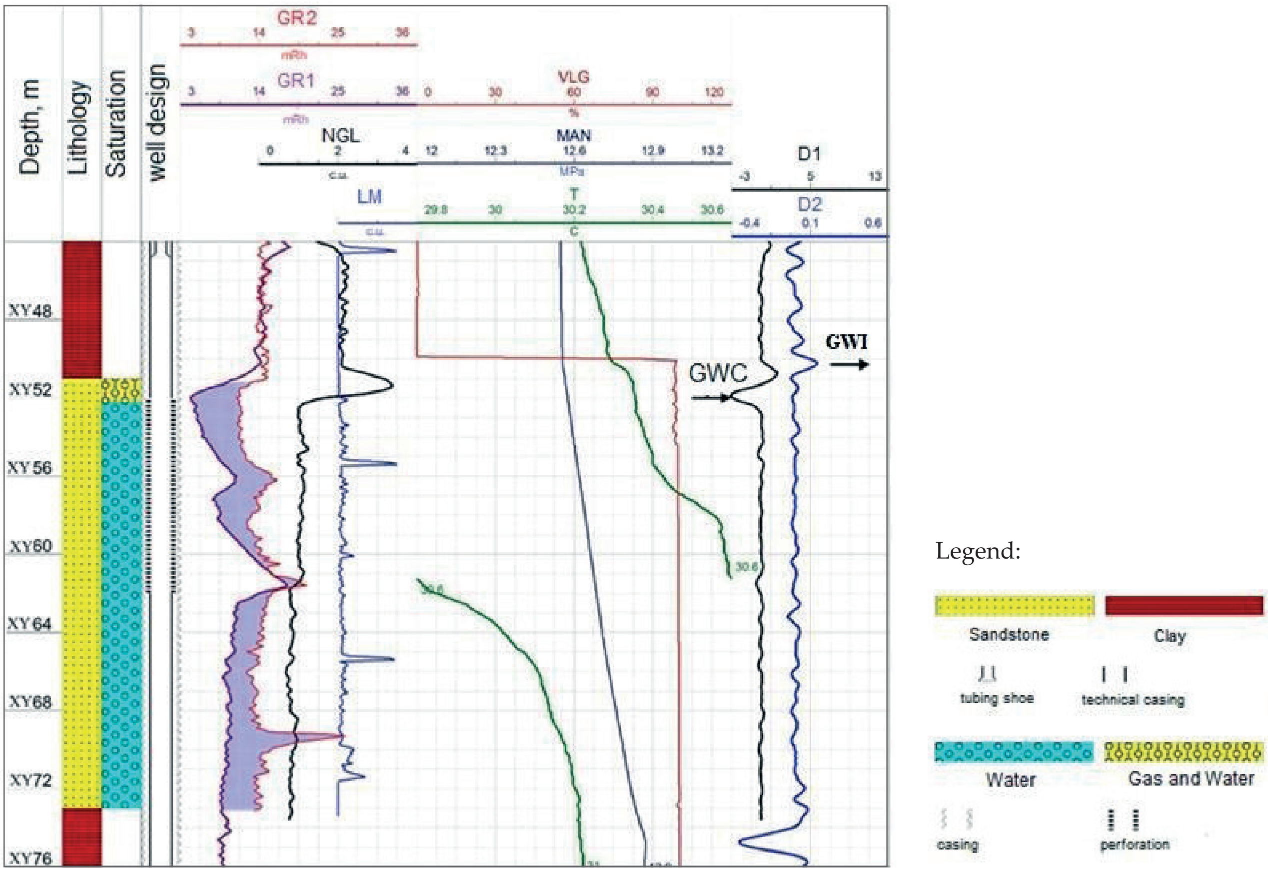

Fig. 1. Production logging data processing results for well X1

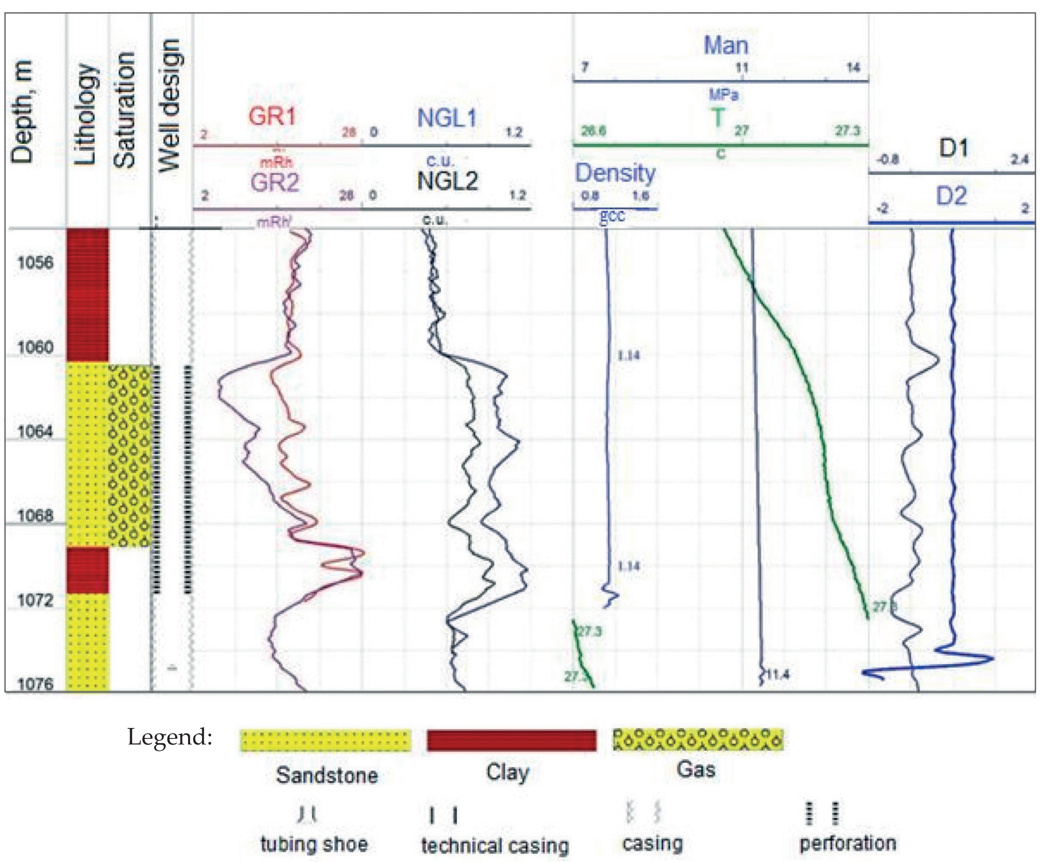

Fig. 2. Production logging data processing results for well X2

of the derivative when differentiating the corresponding curves of neutron logging and pressure logging, which represents the remainder of the Taylor series $O(h^2)$ (1-3) [9]:

$$f(x+\Delta x)=f(x)+\frac{\Delta x}{1!}f'(x)+\frac{\Delta x^2}{2!}+f''(x)+\frac{\Delta x^3}{3!}f'''(x)+\ldots \quad (3)$$

$$y_i'=\frac{y_{i+1}-y_{i-1}}{2h}+\frac{2h^3}{2h3!}y_i''+\ldots=\frac{y_{i+1}-y_{i-1}}{2h}+O\left(h^2\right) \quad (4)$$

$$y_i''=\frac{y_{i-1}-2y_i+y_{i+1}}{h^2}+O\left(h^2\right) \quad (5)$$

where $O(h^2)$ is the remainder term of the Taylor series, and $O(h)$ is the approximation error of the first order of accuracy.

According to Eqs. (4) and (5), the error is proportional to the square of the spacing, so the point of GWC depth, considering the sampling spacing of the curves themselves (0.1 m in depth), can shift by 0.01 m. The algorithm is resistant to the scope and completeness of the well logging data, as the main initial input data are neutron logging arrays and pressure distributions along the wellbore, which are always present. Additionally, research on resistance to the completeness of the well log data is currently taking place, and we plan to discuss the results in the public domain in a future publication.

Conclusions

Based on the results of this work and the process of analyzing and interpreting the UGS data, the following conclusions are noted:

1. An algorithm has been developed for the automatic determination of the GWI in the well and the automatic determination of the current GWC in the reservoir in batch (multi) mode.
2. Based on the algorithm, the data of six UGS wells were processed.
3. The data processing time using this algorithm was reduced by 2–2.5 times compared to the manual interpretation.

As further plans for the development of automated processing and control of the position of the current GWC in UGS wells, the following can be noted: it is necessary to check the operation of the algorithm on a larger number of wells by increasing the statistics of UGS data, and to check the stability of the algorithm for the scope of the initial field survey data.

The work was carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation on the topic: «Invention of an intelligent integrated technology for the study and interpretation of field survey data of wells, including fiber optic measurements to control the development of oil and gas fields and environmental monitoring of the state of the subsoil, based on the use of mathematical simulation, machine learning, processing algorithms and robotic induction equipment», Agreement No. 075-11-2021-061 dated June 25, 2021.

References

1. Fibbi, G., Del Soldato, M., Fanti, R. (2023). Review of the monitoring applications involved in the underground storage of natural gas and CO_2. *Energies*, 16(1), 12.

2. Al Rizeiqi, N., M., Al Rizeiqi, N., Nabavi, A. (2022). Potential of underground hydrogen storage in Oman. *Journal of Advanced Research in Applied Sciences & Engineering Technology*, 27(1), 9.

3. Molíková, A., Vítězová, M., Vítěz, T., et al. (2022). Underground gas storage as a promising natural methane bioreactor and reservoir? *Journal of Energy Storage*, 47(3), 103631.

4. Muonagor, C. M., Anyadiegwu? C. I. C. (2014). Development and conversion of aquifer for underground natural gas storage in Nigeria. *Petroleum & Coal*, 56(1), 1.

5. Zhang, Y. (2021). Construction progress of deep underground salt cavern gas storage and challenges of its drilling and completion technology. *E3S Web of Conferences*, 329, 01043.

6. Lungu, I., Dinu, F., Stoicescu, M., et al. (2021). Pro and con features regarding underground gas storage in depleted reservoirs versus saline deposits. *MATEC Web of Conferences*, 343, 09007.

7. Vo Thanh, H., Safaei-Farouji, M., Wei, N., et al. (2022). Knowledge-based rigorous machine learning techniques to predict the deliverability of underground natural gas storage sites for contributing to sustainable development goals. *Energy Reports*, 8, 7643.

8. Lai, J., Su, Y., Xiao, L., et al. (2024). Application of geophysical well logs in solving geologic issues: Past, present and future prospect. *Geoscience Frontiers*, 15(3), 101779.

9. Groza, G., Razzaghi, M. (2013). A Taylor series method for the solution of the linear initial–boundary-value problems for partial differential equations. *Computers & Mathematics with Applications*, 66(7), 1329.