Lessons learned from the optimization of the Suchohrad -Gajary storage object

Stanislav Bilík, Jozef Levoča, Ján Wallner, Lubomir Olšovský, Dušan Hudeček, Ján Beňo
NAFTA a.s.
Keywords: Debottlenecking, Analysis, Evaluation

1. Background

The gas storage in the middle of Europe has a long lasting tradition and the impetus for its development was construction of the gas pipelines connecting the Russian fields with Europe in the second half of the last century. The main original role of storage was to balance the difference in winter and summer consumption. This role as well as the diversified gas routes, expanding customer portfolio, different regulatory and commercial framework has been modified and changed during the years of operation.

NAFTA a. s., the major Slovak gas storage operator, has 40 years of experience in gas storage design, construction and operation. Throughout all these years the company has been able to understand the changing needs of its customers, has matched the geological and reservoir characteristics with technical design, with the customers demand and thus has proved the reliability of its UGS facilities.

Figure 1: Location of the UGS Suchohrad -Gajary in the middle of Europe

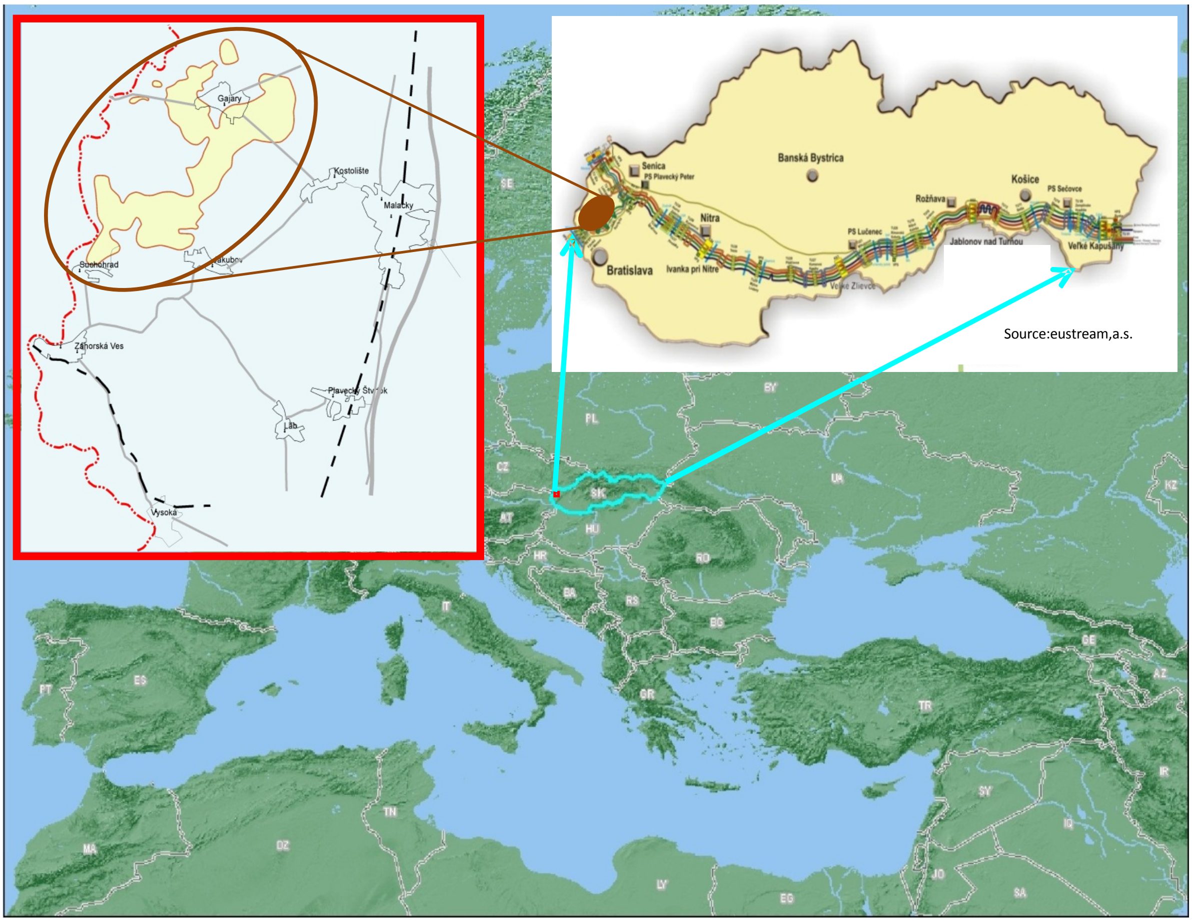
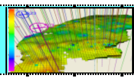
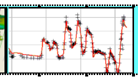


Table 1: Milestones in history of the Suchohrad -Gajary UGS

year	Milestone	Additional information
1955	Discovery of the reservoir (well Su -1)	On the base of the structure exploration
1955-1959	Geological Exploration Discovery of the Suchohrad field (1955) Discovery of the Gaj ary field (1957)	Totally drilled 28 wells The Suchohrad 1 well The Gajary 5 wells.
1960	October 1960: The start of primary production.	7 wells in the Suchohrad field
1964-1966	Production analyses showed an evident discrepancy between produced gas and calculated reserves.	New exploration campaign, new discoveries in the NW Gajary field .
1972-1973	A new sedimentological concept of the Gajary field	exploration campaign in the NE Gajary field - new gas discoveries
1973-1976	Intensive exploration, drilling of 17 wells	Discovered gas reserves 850.10^6 m^3
1976-1978	Intensive additional exploration – 42 wells	Pre-conversion geological works .
1974-1983	Construction and Build-up period	
1984	Commissioning of the new technology. Start-up cycling in projected parameters	
1998-2000	UGS Láb 3 storage improvement was initiated	
2001	Interpretation of the 3D seismic Suchohrad	Focused on the 8th Pannonian horizon
2001	First 3-D mathematical model (dynamic)	Identified UGS Development potentials
2004	Start of UGS Láb 3 storage operation after reconstruction	
04/2006	Second mathematical model (Geological and dy namic models)	 
2006-2008	Increase of the storage capacity by 21.5%	
2010	Recent storage capacity increase d by 0.5%	Based on the model analyses

The main aim of this work is to show how the new techniques in geology helped to c hange our view of gas storage from our experience and the lessons learned which we have arrived at during the last 10 years. Further we go on describing pieces of kn owledge gained during the optimization and operation processes of the UGS Suchohrad -Gajary. Some new knowledge was also used in the new UGS Gajary -badenian that is now in development.

In this document, which we build on our previous presentation at the 22 nd WGC, we would like to share our experience with you.

2. Aims

Every day our existing experience keeps convincing us of the fact, that optimization of the operation is not just a continuous process, but it's especially a never-ending process. Our previous experience is being constantly tested by new states of objects; we are dealing with and new requirements of external environment.

The technologies that have been recently put into processes are tested just after a short time under the pressure of the opportunities presented by the new technologies.

Mentioned storage experience is an advantage from the know-how point of view and a solid basis for continuous optimization of storage operation. Within the optimization effort of our activities we have also naturally focused on the key elements of the storage, i.e. the geological structure and internal reservoir processes between reservoir fluids.

Seeing further demand on the market and having in-house knowledge and modern technology we have employed the project for optimization of the storage capacity of our major storage object Suchohrad-Gajary with the aim:

- to exceed its original working gas volume by more than 20%,
- to verify and proof its deliverability within the injection and withdrawal seasons and
- to prepare conditions for higher flexibility.

3. Methods

Among the geological methods there were four new dominant approaches: (i) the way of sampling the drilling cores and their interpretation, (ii) the way of log interpretation, (iii) the way of using the 3D seismic data by the advanced processing and interpretation methods, (iv) the facial analysis and application of sequence stratigraphy in the geological modelling.
A crucial moment of the new approach was the most objective and reliable forming of the geological structure of the solid spatial geological modelling.

Among the dynamic methods there are two basic moments (i) Inputs from the Geological Model and (ii) Outputs from the Dynamic model to the next modelling.
A crucial moment of the approach within this working sequence is reliably matched by the dynamic model comprising all main life periods of the field and its main reservoir parts; among the Predictions, it is to set a long term trustworthy stability of the storage operation and/or its meaningful and feasible development.

Based on the workflow of a mathematical modelling we are displaying those milestones which we consider as the first portion of Lessons Learned from the storage optimization process. Those lessons, which directly helped us to move due to their positive impact are depicted by "the blue book mark - 📖" and those which resulted in negative, are depicted by "the red book mark - 📖". Irrespective of whether the resulting findings are positive or negative, they are indispensable and important.

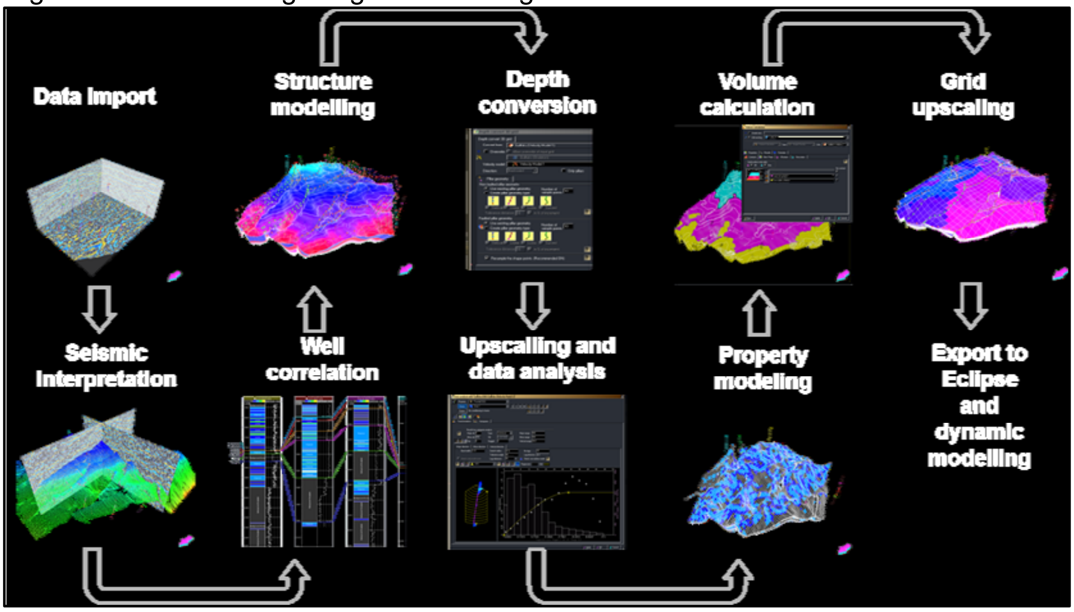
a. GEOLOGICAL MODEL LING

Geological structure and parameters of the horizon 8th Pannonian was implemented to the recent model. The main inputs for geological model were coming from:

- 3D seismic (measured in 2000)
- Reinterpretation of all logs
- New well correlation (logs, available cores and 3D seismic)
- Using new approach of parameter setting distribution – stochastic analysis as a part of geological modelling.

Scheme of geological model workflow used in NAFTA a.s. is shown in Figure 2.

Figure 2: Workflow of geological modelling



During the process of gathering data, its interpretation and preparation of inputs to the model as well as from processing the geological model, we have gained experience which we describe in the following chapters.

i. <u>Methods employed for preservation data from cores</u>

Experience with the old cores has led to some knowledge about the way for preserving core data. We have learned that the correct preservation is not such a simple process. That's why we have changed the way of cores preservation in case of newly drilled wells, for example Ga131 (2009, the 8th Pannonian and also deeper horizon Middle Badenian).

Correct core preservation:
Correct core preservation is the crucial factor for the cap rock gas threshold pressures analyses on core samples. Coring was carried out by NAFTA using a conventional coring system. Two approaches of the core preservation were used, i.e. the foam stabilisation and the core packing into airtight plastic coated aluminium bags. We used this way not only for Ga131, but also for the

wells drilled later and we were able to use the cores for repeated analyses without any problems 2 years after that.

Approach 1:

The foam stabilisation (well Gajary 131) - the 9 metre core liner was laid down on the core cradle, holes were then drilled in the core liner every 0.50 metres and foam injected into the liner, this stabilised the core and helped to remove the drilling mud. Then aluminium liner was cut into 1 metre sections and closed with the rubber stopper. The sections were then wrapped in the bubble wrap and housed in the aluminium core boxes (Figure 4).

Figure 3: The foam stabilisation

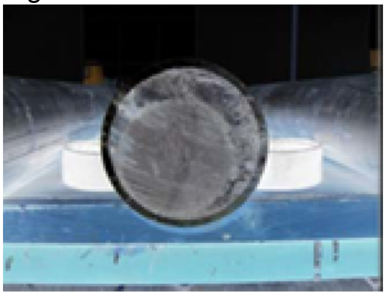
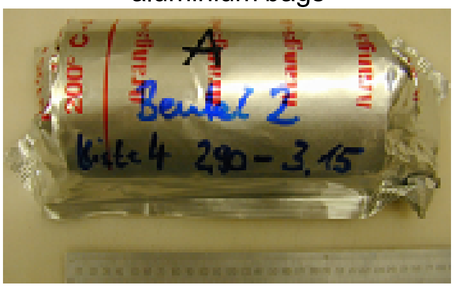


Figure 4: Aluminium core boxes

Approach 2:

Core is packed into airtight plastic coated aluminium bags. The air is completely sucked out and the bags are hermetically sealed.

Figure 5: Packing in airtight plastic coated aluminium bags



Long-term storage of clay samples at constant temperature and free of oxygen in Nitrogen pressurised liners

Figure 6: Long-term storage of clay samples

ii. Log Analysis and reinterpretation

Very important data for geologic modelling gives log interpretation. Total number of interpreted log curves for Suchohrad part 714 logs and for Gajary part it is 1607 logs.

The challenge was to interpret correct value of next quantities from the old log measurements:

- Clay volume
- Water and gas saturation
- Porosity
- Permeability as a function of porosity

Log reinterpretation methodology:
Using original petrophysical properties as an input to the geological model brought non -realistic reservoir parameters, for example the initial volume. Therefore another equation (Clavier equation) for clay volume calculation was used. Results were more realistic, that means lower clay volume, higher porosity and higher gas saturation.

Reinterpretations of old logs :
Reinterpretations of the old logs had to be done in order to obtain the correct values for clay volume, initial water saturation, porosity and permeability. The calculations are given on the basis of the common parametric equations. Parameters of the common equations must be tuned according to the results of the core analyses. The reinterpretations of all logs were done in order to obtain the correct data for the geological model. Clay volume calculation is shown as an example.

<u>Example: Clay volume (Vclay):</u>
The clay volume calculation is predominately based on the Gama ray log (GR). The GR is preferred to the Spontaneous potential (SP), as this log is not affected by the salinity contrast of the fluids Resistivity of mud filtrate (Rmf) and Water resistivity (Rw), not affected by the gas content and generally presents a more detailed character of the measured curve.

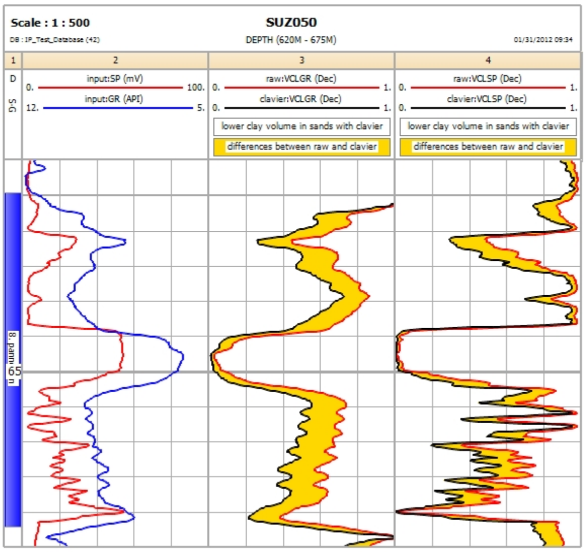
$$\text{Vclay raw GR} = (\text{GR Log} - \text{GR min}) / (\text{GR max} - \text{GR min})$$
$$\text{Vclay raw SP} = (\text{SP Log} - \text{SP max}) / (\text{SP min} - \text{SP max})$$

Correction of the calculated raw clay volume for young formations using the CLAVIER formula is:

$$\text{Vclay (Clavier)} = 1{,}7 - (3{,}38 - (\text{Vclay raw} + 0{,}7)^{2})^{0{,}5}$$

<u>Results and additions:</u>
The result by using the clavier correction was lower clay volume in sands as without correction. The Clavier clay volume was used as an input to the porosity and water saturation analysis (PSA). The PSA computed higher porosity and higher gas saturation.
The clay volume for the 8^{th} Pannonian horizon is shown in the Figure 7. Black curves show lower clay volume from the clavier formula. Red curves show higher clay volume from the raw data. Gold shading shows a difference between the raw and clavier clay volume for both curve types: SP (3^{th} column) and GR (4^{th} column). The 1^{st} column shows the 8^{th} Pannonian horizon position.

Figure 7: The clay volume for the 8th Pannonian horizon



iii. Facial Analyses

Facial analyses:
The results from the facial analysis application did not come up to expectations. Possible reasons behind this were in all probability a small number of cores and their quality.
A verification of received results requests a study of larger reservoir material from cores that were not available. In case of the development of a new UGS it is necessary to plan a sufficient amount of cores and their analyses.

iv. 3D seismic

Measurement parameters have been tailored to the storage at the 8th Pannonian and the following methods have been used :

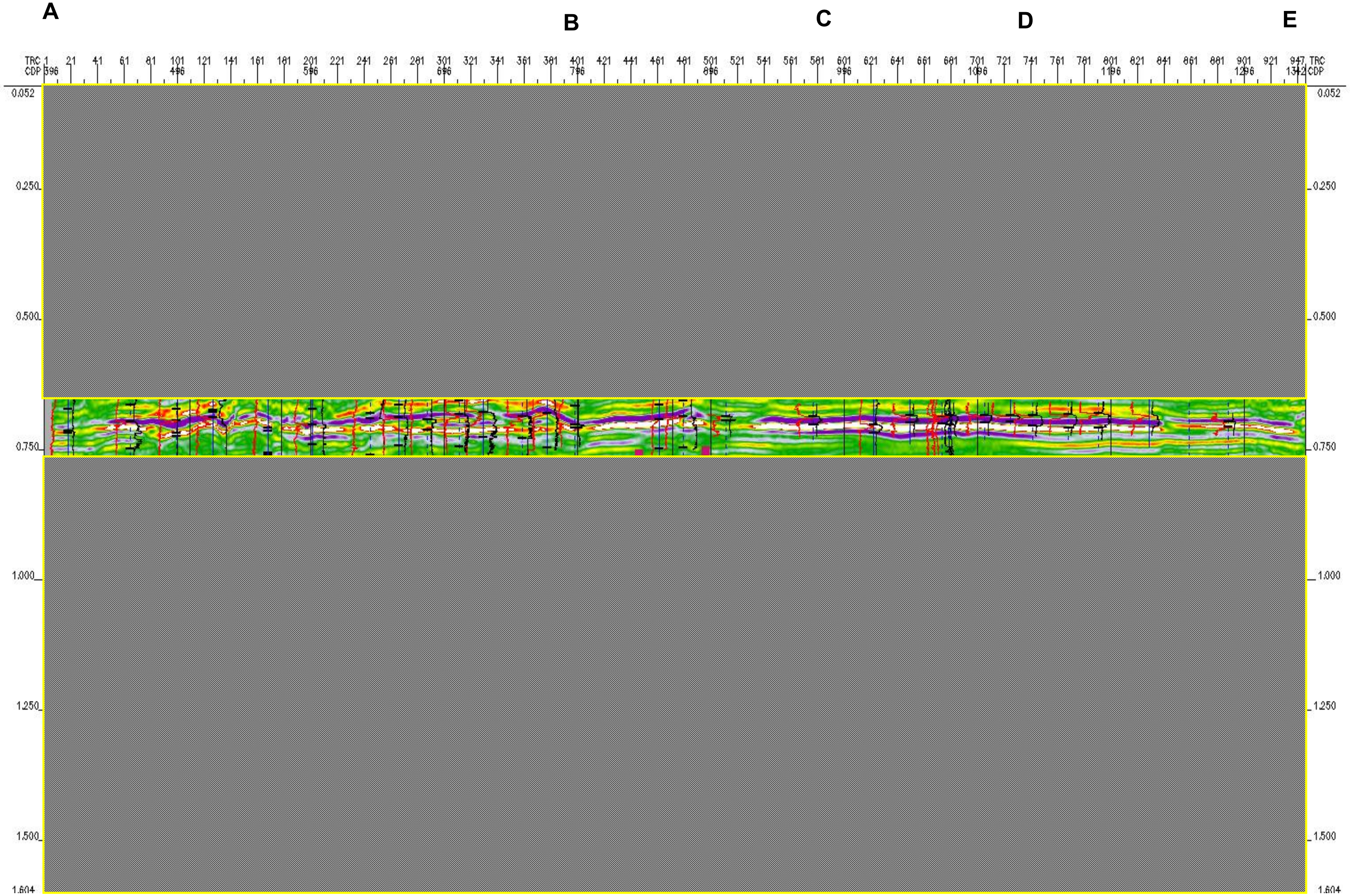
a. RAP (Real Amplitude Preservation) for the use of signal amplitude attributes and under certain circumstances also for more reliable porosity determination .
b. CRS (Common Surface Reflex) - to increase the vertical distinctiveness and detection of fractures incl. course of their lines

Parameters of 3D seismic measurement were adapted to the 8 th Pannonian horizon, bin size 12.5x25.0 m inside of the UGS object and 25.0x25.0m outside. The fold applied inside the UGS object was 64 and 36 outside of it.

The 3D seismic brought new data about volume of the object, knowledge about its shape with deformations, information about the detailed structure of individual parts of the 8 th Pannonian horizon. This data was essential for the creation of the geological model.

The vertical seismic section ABCDE is shown in the Figure 8. A set of log measurements show correlation between the 3D seismic and the log measurements. The horizon of the 8th Pannonian is highlighted for better orientation and a position of vertical profile ABCDE is shown in a UGS Suchohrad-Gajary scheme.

Figure 8: Vertical time section in the **A**BCD**E** profile



b. DYNAMIC MODEL LING AND PREDICTIONS :

Dynamic model based on the new 3D geological model confirmed the possibility of developing the UGS storage. Predictions were prepared for upper pressure limit 73 bar, i.e. for the maximum pre ssure reached in the history of storage operation and also accordin g to the uncertainty in thres hold pressure determination. Lower pressure limit was tested up to 38 bar.

i. **<u>History matching</u>**

The history match (HM) process continued after the initialization procedure by the usual way. First the pressure history match was a djusted. One example of well pressure History match is illustrated from the well Suchohrad – 20 located in the central part of the reservoir, where also observed pressures from the primary gas production are present. Next examples of HM are shown in Figures 10 -13.

Figure 9: History match - well Suchohrad 20 (central part of the reservoir)

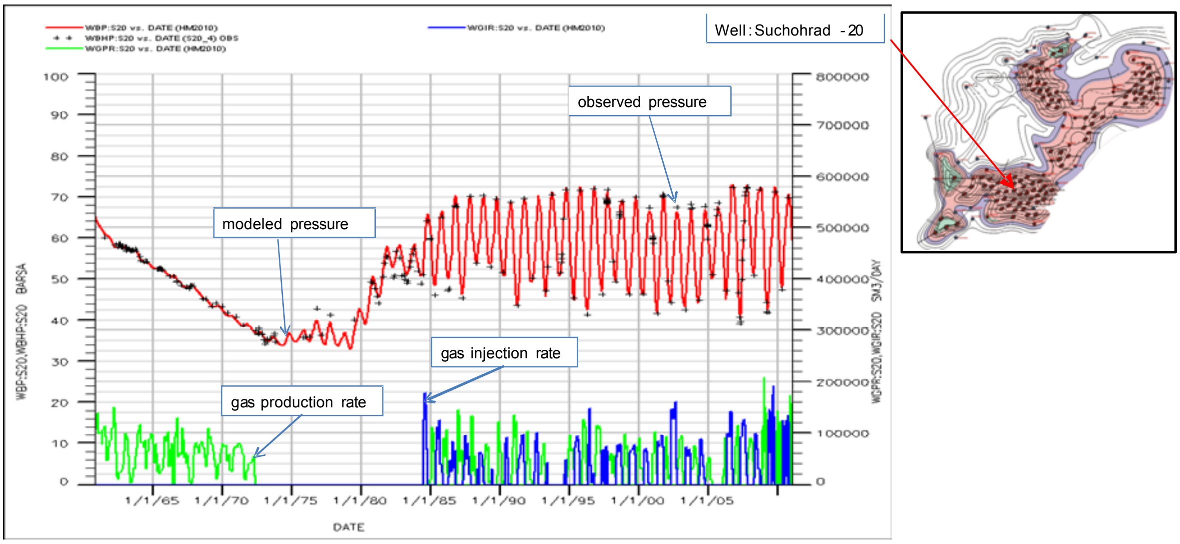


Figure 10: History match - well Suchohrad 1 (western part of the Suchohrad part)

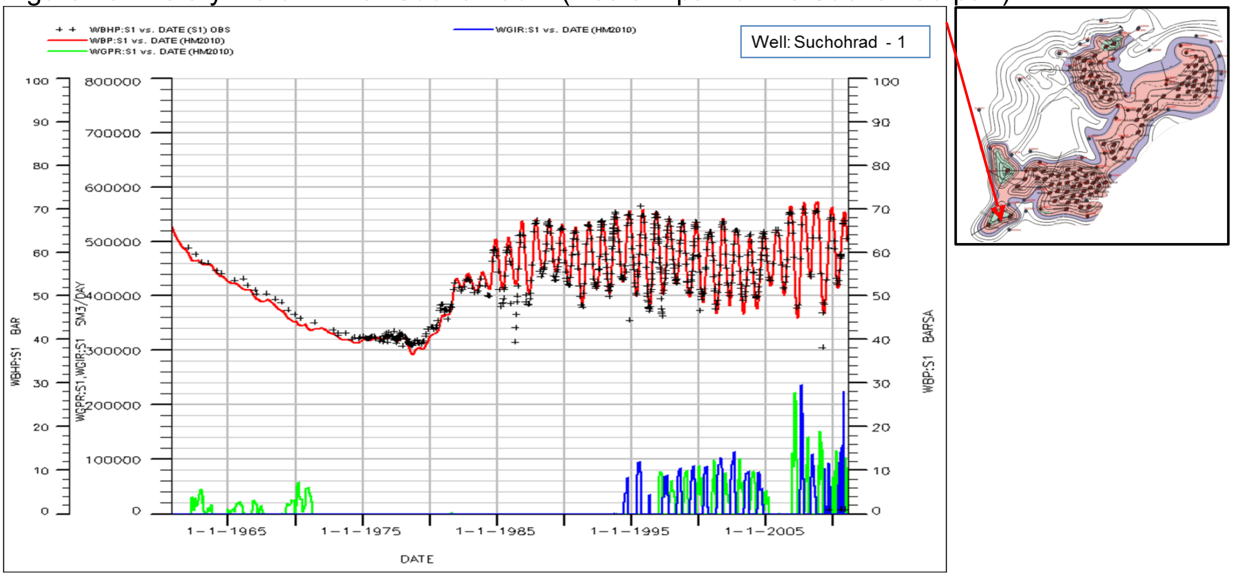


Figure 11: History match - well Suchohrad 24 (eas tern part of the Suchohrad part)

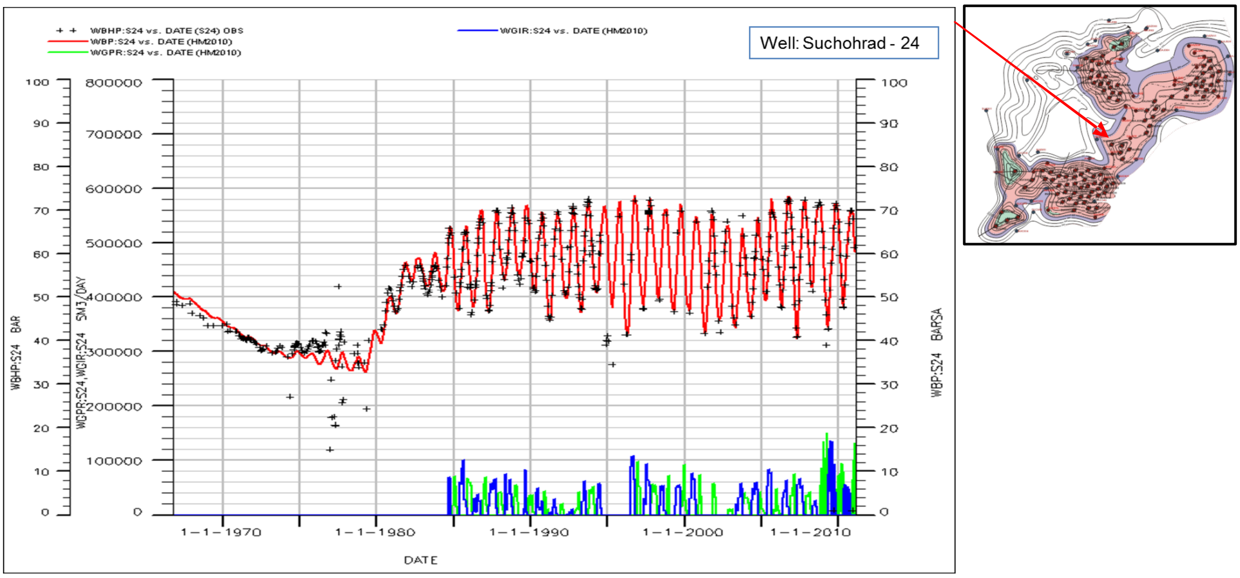


Figure 12: History match - well Gajary 15 (eastern part of the Gajary part)

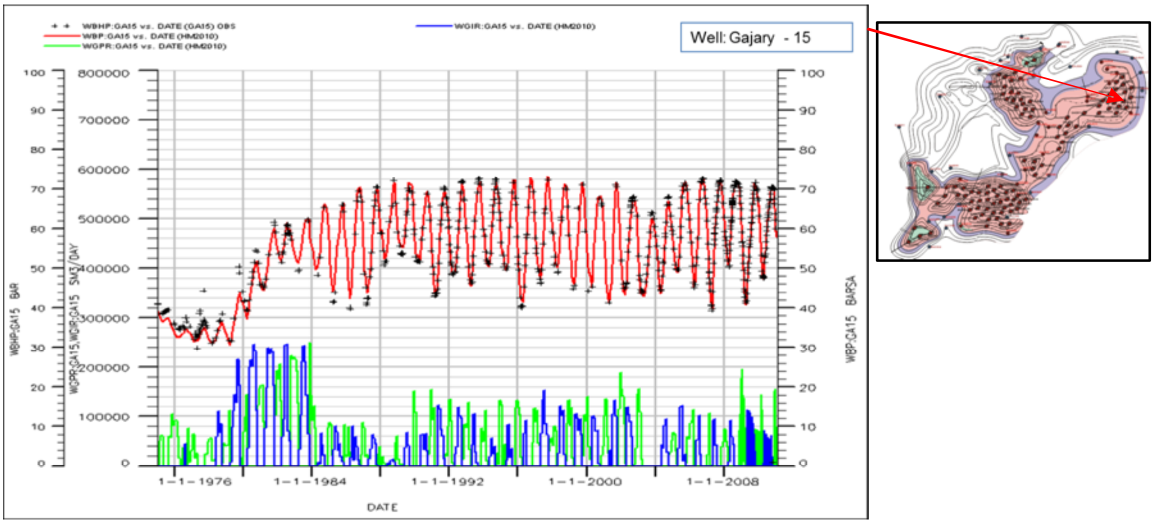
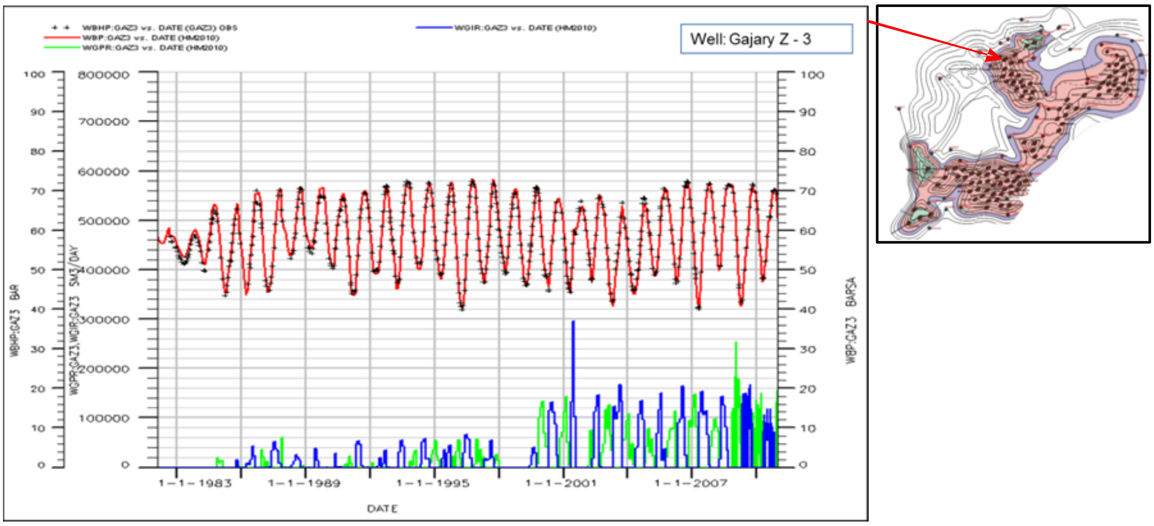


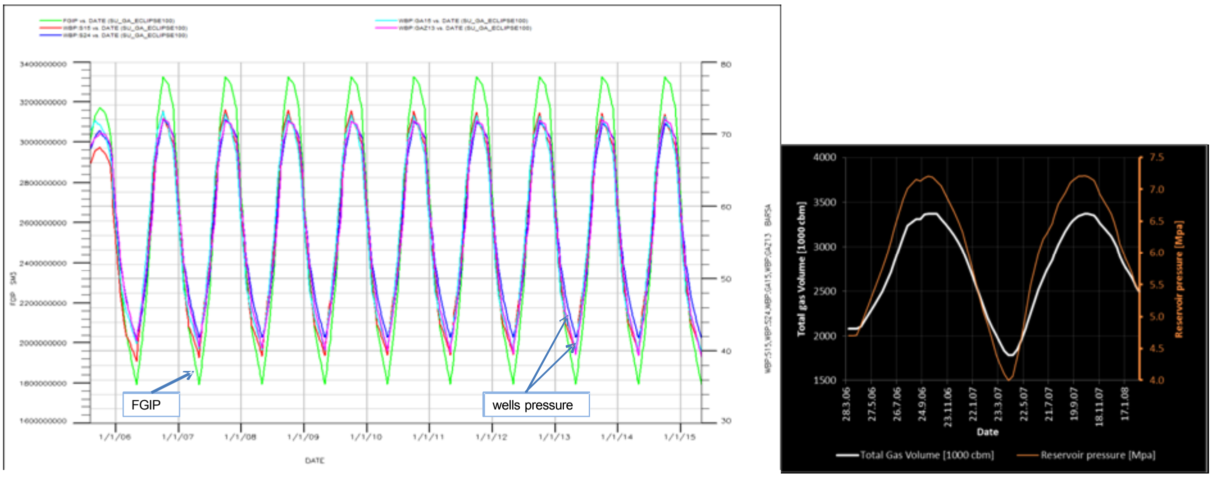
Figure 13: History match - well Gajary Z-3 (western part of the Gajary part)



ii. <u>Predictions</u>

In prediction runs we have tested condition s for stabile UGS operation finding adequate working gas and cushion gas in the proper pressure range. The cycling with constant gas volume was applied. Behaviour ad ditional parameters were observed. One example of prediction run with cycling constant gas volume is illustrated in the Figure 14. This Figure shows also reservoir pressure in the individual wells. The conclusion from the dynamic model prediction was the possibility to increase the gas storage capacity by 280 $10^6 m^3$.

Figure 14: Prediction run - gas cycling with constant gas volume and the real development in 2006-2008



Deliverability test during crisis in 2009 (Figure 15):
The results from the dynamic model indicated also a possibility for higher daily rate from the reservoir. An interesting test of the reservoir deliverability was performed during the period of raised gas demand in Jan 2009 (the gas shipment crisis). The daily rate reached 20-25 10^6 m^3 of gas during the crisis.

Managing the drilling operations (Figure 16):
One approach to an application for outcome from the dynamic model in the practical use was for example preparing proper pressure conditions for drilling new wells in UGS Gajary-badenian. The reservoir Gajary-badenian is situated structurally in a deeper part under the UGS Suchohrad - Gajary. Safe drilling requested cooperation amongst the drilling group, the reservoir engineering group and the operation group. Their common work results were available for drilling when the 8th Pannonian horizon was drilled.

Figure 15: Deliverability test during crisis in 2009

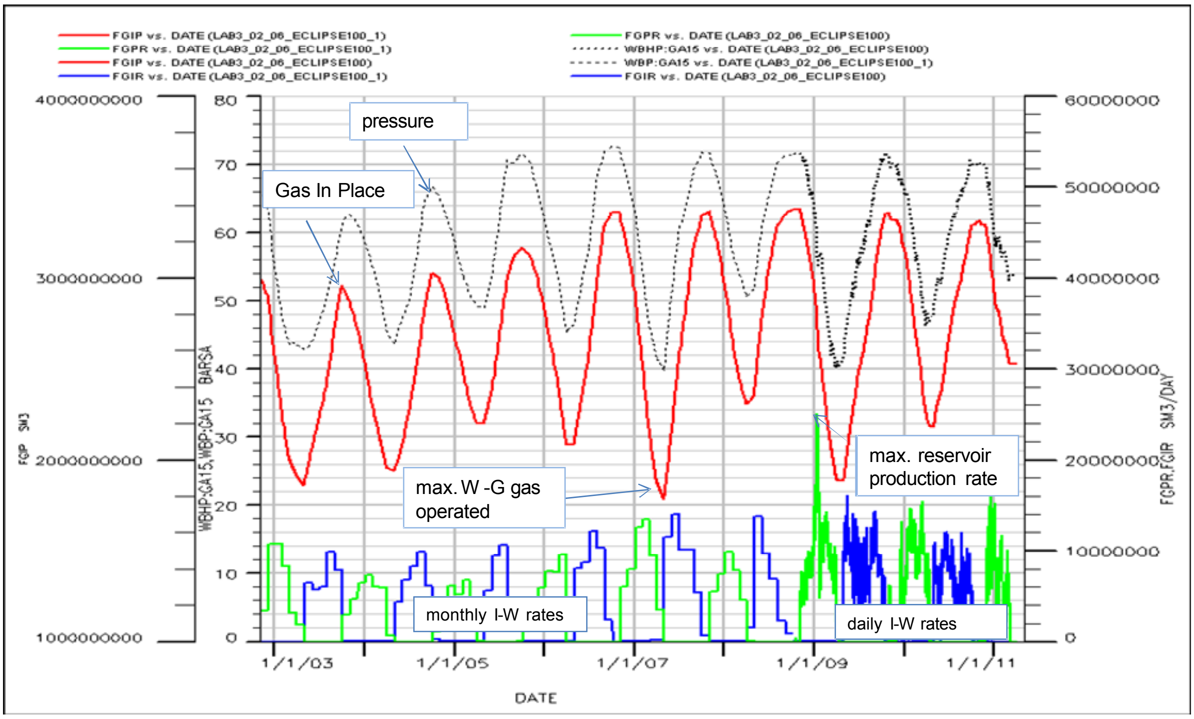
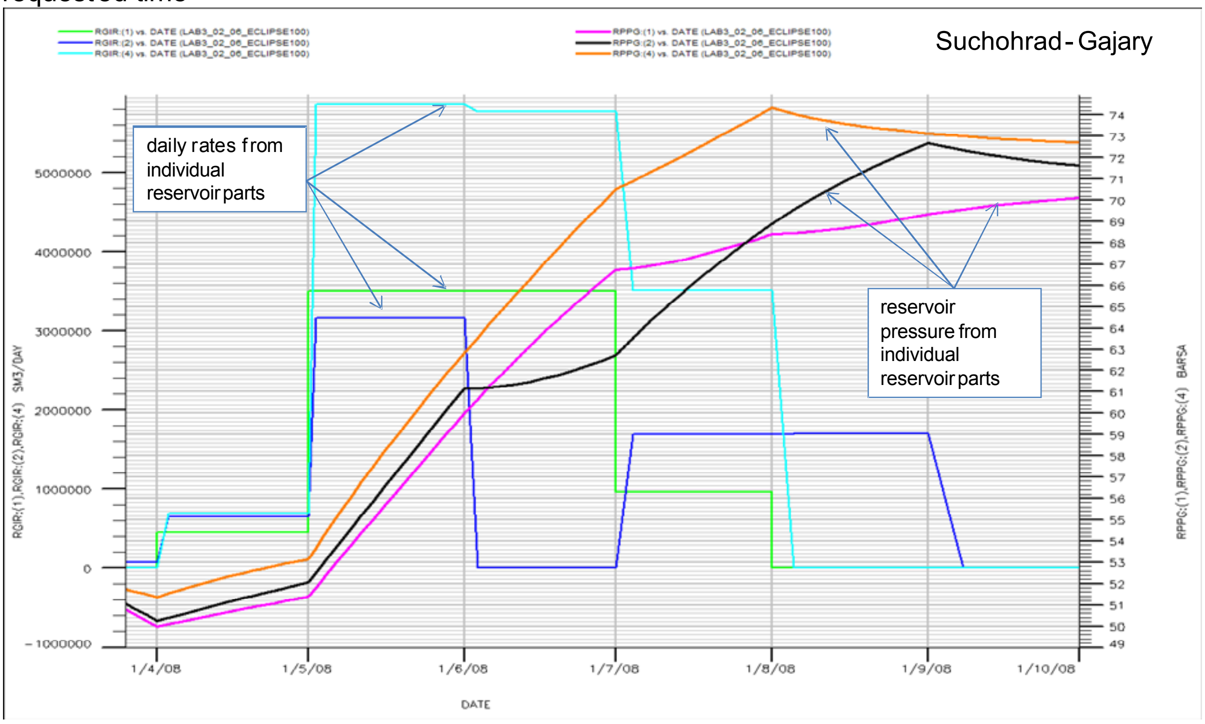
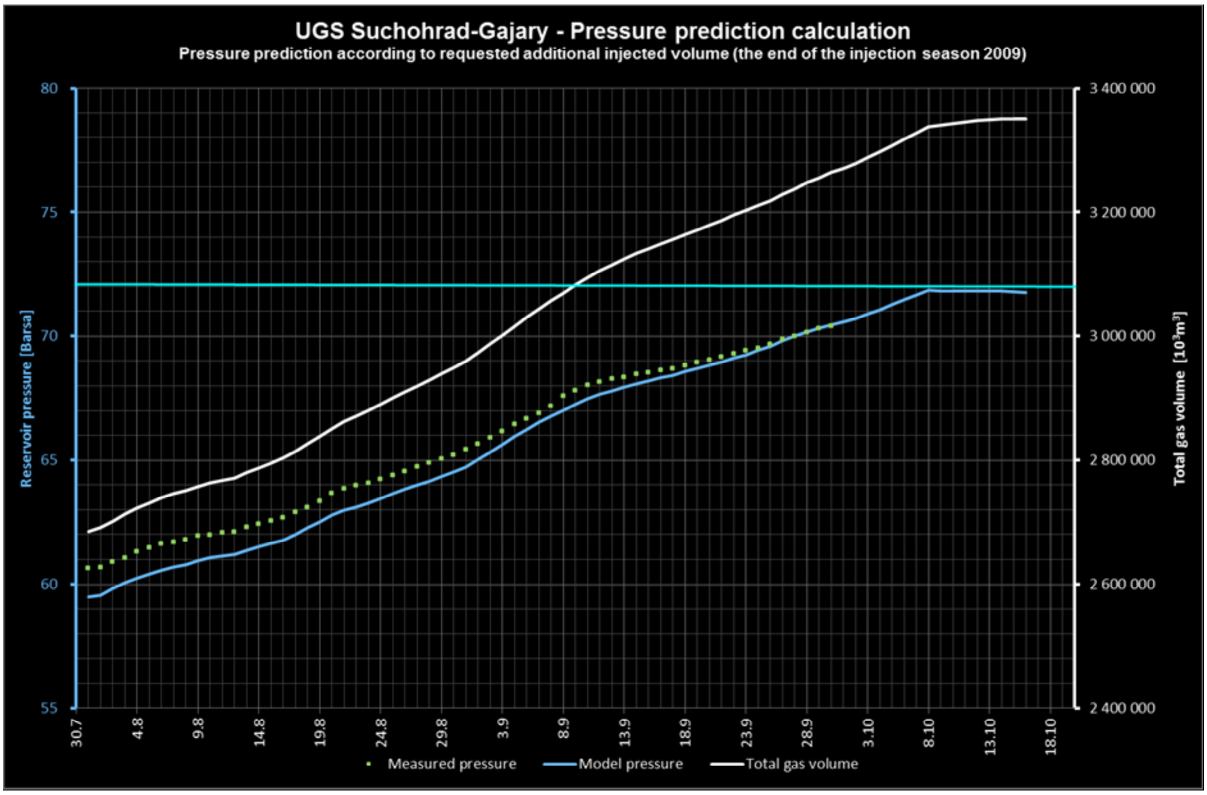


Figure 16: Model scenarios for different injection schedules to reach request pressure in requested time



📖The short-time prediction (Figure 17):
An example of short-time model prediction is presented in the Figure 17. The prediction was used in the end of the injection season 2009 for making a decision for a possibility to inject requested additional gas volume in the end of injection season. The model prediction showed two months ago that upper pressure limit would not be exceeded.

Figure 17: An example of model short time prediction

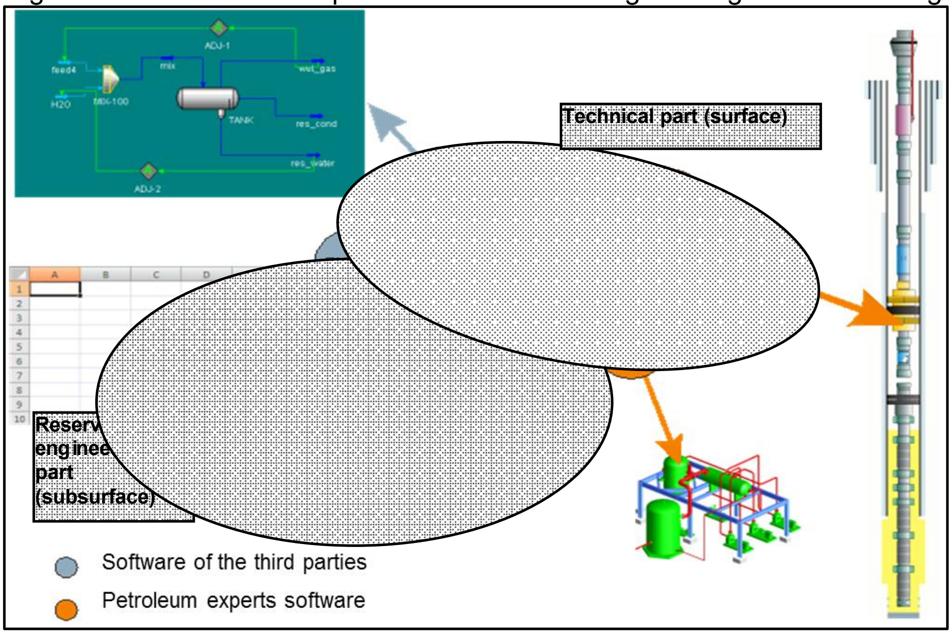


iii. Surface model ling

The subsurf ace model ling fluently continued with the surface mode lling with the aim to debottl eneck and optimize the technology of the storage facility.

The close connection between the technical and reservoir engineering groups can be seen from the Figure. There a re activities of those two groups in the Figure and it is obvious they cooperate together.

Figure 18: Scheme of cooperation of reservoir engineering and technical groups



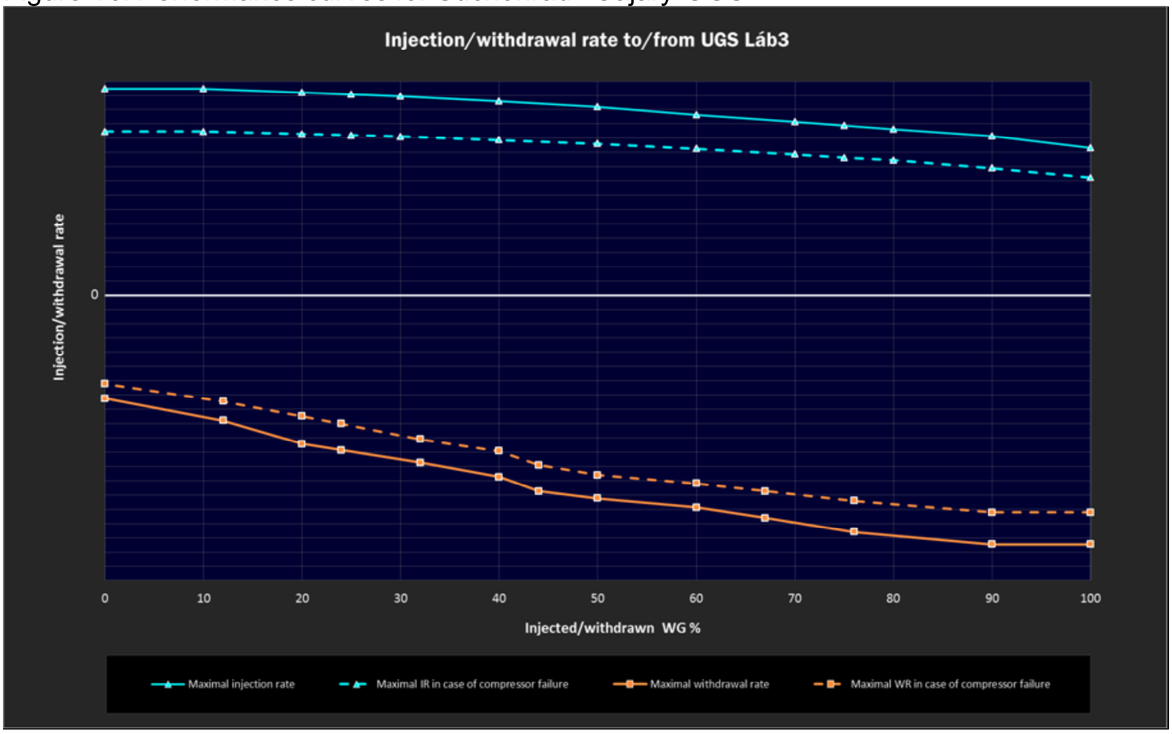
The connection gives possibilities for cooperation o f both groups, technical (as a surface part) and reservoir engineering (as a subsurface part) groups. ECLIPSE outputs prepared for the technical group are used for:

- calculation of injection and withdrawal rate for whole range of storage depletion
- calcula tion of design point for surface equipments (pressure, flowrate)
- analysis of different scenarios (constraints regarding the flow rate: compressor failure, repair of pipelines, workover ...) and their impact on W/I rate
- calculation of input data for optimiz ation tool (plan for future - optimization tool is under development)

Performance curve calculations

An example of result of the performance curves for the UGS Suchohrad -Gajary is shown in the Figure 1 9, where performance curves for UGS Suchohrad -Gajary are calculated. The performance curves are calculated on the base of model results (reservoir engineering group) in the beginning of any season or when are necessary (for example new commercial demand).

Figure 19: Performance curves for Suchohrad -Gajary UGS



📖 Cooperation and close activity coordination among individual groups

Close cooperation of technical and reservoir engineering group was mentioned above. But there is necessity for the cooperation of three groups:

- Reservoir engineering group
- Technical group
- Commercial group

All three groups have to coordinate their activities and give a feedback to both other groups

4. Implementation and Results

The development potential was the most important result from the dynamic mod el prediction. The prediction analyses showed possibility to increase the storage capacity. Full working gas volume was physically operated first in seasons 2006 -2007. Increased volume of gas was cycled also in seasons 2008 -2009.

The implementation of the development scenario required close coordination not only between the technical and reservoir engineering group, but in this case high importance was given to cooperation with the commercial group. The cooperation with the commercial group guaranteed sufficient gas volume during the injection season and requested marketing during the withdrawal season. Due to the cooperation of all three groups was possible to fulfil the development scenario.

The implemented results of the mode lling led to improvement of capacities and performan ces of Suchohrad-Gajary UGS, namely to an increase of the storage capacity by 280 10^6 m^3 or 21.5% between 2006 and 2008 (Figure 22).

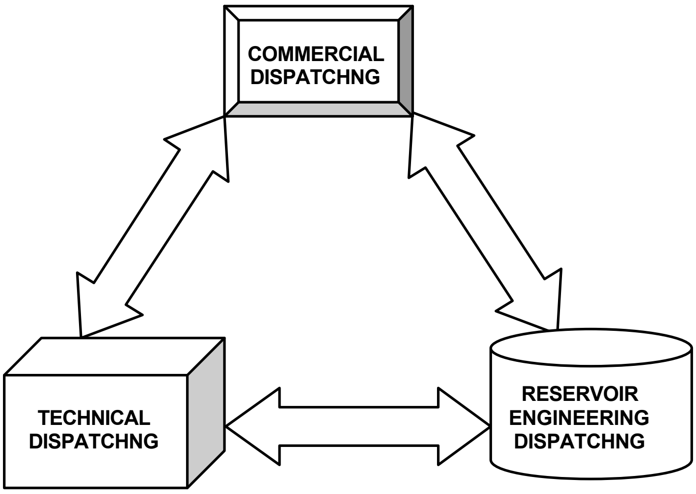
The optimization results are put into practise by commercial, technology and reservoir enginee ring groups together . The scheme in the Figure 20 shows implementation process in NAFTA a.s.

Figure 20 : Implementation of the optimization results

Results Of Optimization **Actual UGS status**	- Model results - Resu lts of all other exploration (reservoir -engineering knowledge, results of tightness monitoring)
(Year) Development Plan	- Commercial: Year, seasonal or short -time plans - Technology: Technology provision of requests - Reservoir/engineering : Subsurface development management
Implementation Of the Development Plan	- Seasonal priorities: Defining main goals for a season (injection, withdrawal or both seasons) in priorities form - Monthly meetings : Transfer ing the seasonal priorities into month activities Coordination of individual groups activities - Daily regimes: Operative manag ement of the UGS on daily basis

Operative control of a UGS in NA FTA is managed by dispatchings (commercial, technology and reservoir engineering). Their activity and flow of infor mation is shown in the Figure 21 . Each dispatching is connected with both other ones and each dispatching can send information to any other one.

Figure 21 : Scheme of dispatchings in NAFTA a.s.



The development was physically tested within the maximum range of operation and the data implemented into the model updates, which has led to the additional optimization and capacity increase. The overall capacity increase within this project was almost 22%.

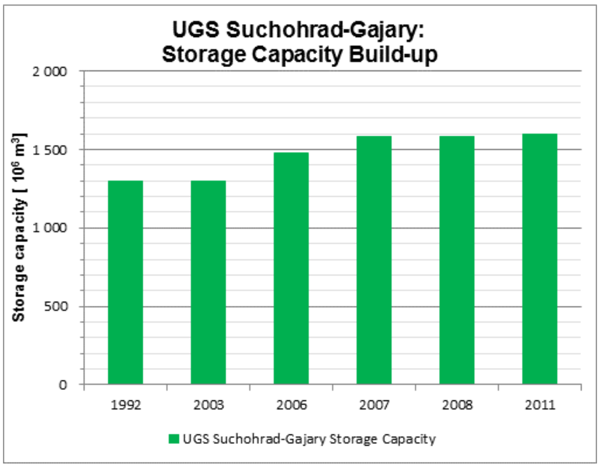
From the cost point of view, since the optimization was related mostly to better utilization of the reservoir parts and improved reservoir management, the impact on changes in technology was limited and the necessity of additional investment cost minimal.

The substantial expenses were connected with:

- the 3D seismic acquisition,
- creation of the geological model
- preparation and matching of mathematical models.

Nevertheless such costs are only a fraction of the commercialized value of the increased storage capacity recast into modern flexible product.

Figure 22: UGS Suchohrad-Gajary storage capacity build-up



5. Conclusions

The described optimisation project was presented at the World Gas Conference in 2003 after the second phase of modelling as a future project. Nowadays, we can summarise the project after implementation. The Suchohrad-Gajary storage object has been optimised based on the modern modelling, its results were physically verified during injection and withdrawal seasons and successfully commercialised. The model is now regularly developed and used for making decisions. The impact of the project was not only on the storage capacity but also on the change of internal organisation and processes.

The management of the UGS is now based on the cooperation of three groups - commercial, technological and reservoir engineering groups. All three groups need to cooperate and give necessary feedback after any activity to the other groups. Each group has its own field of responsibility, but the most important is a common responsibility for the complex process of UGS management. Monthly coordination meetings of representatives of all groups implemented in UGS management have become one of the most important parts of UGS control.

Within the project we implemented reservoir engineering workflow matching available geological data, new data gathering principles. The UGS monitoring and data gathering is based on the long-term schedules that include not only the model support, but they are focused also on the safety monitoring, for example tightness monitoring or well integrity management.

The most important was identification of the key knowhow needed to develop internally within the company. The creation of the competence group which is able to analyse subsurface and surface parts of the storage was one of the natural outcomes of the project. The Competence centre group is being utilised for operational tasks, optimisation projects, storage construction project Gajary Baden where it proved its expertise and abilities.

The competence group has been created to improve quality level of all activities including in the UGS management.

The setting of priorities from the reservoir engineering, from the technical and commercial point of view inevitable during the mentioned project has been implemented as a standard procedure. The priorities are set in the beginning of each season and follow possibilities given by the commercial requests and the technical and reservoir actual possibilities. The priorities and their actual status are discussed monthly in coordinative meetings, where all responsible representatives take part.

Such procedure, as operating several storage objects, helped us in the capacity development of also other objects and enabled a fluent development of our brand new storage object Gajary Baden.

Subtle and predictable knowledge of the structures, knowledge of the technical possibilities and understanding the customer needs are decisive elements for proper offer of the seasonal or flexible products as well as for ability to react to immediate commercial possibilities. We believe this is the only way how to stay competitive not only within the storage business but also to keep the storage business competitive within the energy sector.