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CO_2 Gas Flooding in Sandstone and Limestone Reservoirs in Hungary

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الغمر بغاز ثاني أكسيد الكربون في مكامن الحجر الرملي والحجر الجيري بالمجر

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أحرزت طريقة الغمر بغاز ثاني أكسيد الكربون بالمجر تطبيقات حقلية واسعة معتمدة على موارد ثاني أكسيد الكربون الطبيعية، وكان أقدم تطبيق على مستوى الحقل بالجزء الغربي من المجر بمكامن الحجر الرملي في حقول بودافا ولوفاسزي، وكذلك بمكامن أحجار الدولوميت والأحجار الجيرية المتشققة والمتكهفة بحقل ناجي لينجيل.

بدأ أقدم تطبيق على مستوى الحقل بعد إجراء بعض التجارب المعملية بالتكاوين الرملية من حقل بودافا عام 1972. وكان الخام المنتج من النوع البارافيني المتوسط وبمتوسط كثافة قدرها 820 كلغ/م3 (API=41⁰).

تم استعمال طريقة الغمر بغاز ثاني أكسيد الكربون في الاسترداد الثلاثي بعد طريقة الغمر بغاز الميثان أو الماء. وأحدثت هذه الطريقة زيادة 1.450.000 م3 (9.120.000bbl) اليوم نجم عنها استخراج إضافي يصل ما بين 6 – 10% من النفط الخام بالمكمن.

تم استعمال غاز ثاني أكسيد الكربون في التكاوين المتكهفة بحقل ناجي لينجيل المحتوي على نفط ثقيل وغير مشبع، كما تم إنتاج نفط مخلوط بكميات كبيرة من الماء في السبعينيات. وفي عام 1980 بدأت التجارب المعملية بحقن غاز يحتوي على نسبة عالية من غاز ثاني أكسيد الكربون بالمكمن محدثة غطاء صناعي من الغاز. ثم أدخلت التطبيقات على مستوى الحقل عام 1988 ووصل حجم الإضافة اليوم إلى 2.260.000 م3 (14.215.000bbl). وأثناء مشروع تطبيق الغمر بغاز ثاني أكسيد الكربون تم تطوير عدة ابتكارات في مجال كل من تقنية البئر والتجهيزات السطحية، ويقدم المؤلفون نبذة عن النتائج وتطور تقنيات جديدة في مشروع الغمر بغاز ثاني أكسيد الكربون.

Abstract: *CO_2 gas flooding in Hungary has achieved a wide range of field application based on natural carbon dioxide resources. The oldest field scale application has been applied in the western part of Hungary in sandstone reservoirs of Budafa and Lovászi fields, as well as in the fractured, karstic limestone and dolomite reservoirs of Nagylengyel field.*

After some pilot tests, the first field-scale application started in the sandstone formations of Budafa field in 1972. The produced crude is of an intermediate-paraffin character, its average density is 820 kg/m³ (41 degrees API). CO_2 gas flooding has been used as a tertiary recovery following the CH-gas or water flooding. 1,450,000 m³ (9,120,000 bbl) incremental oil has been produced to date, resulting in 6-10 % of original oil in place (OOIP) additional recovery.

Carbon dioxide was also applied in the karstic formations of Nagylengyel field containing under-saturated heavy oil. Crude oil was produced with high water cut in the 70's. In 1980, a pilot test was started injecting high CO_2 content gas into the reservoir, creating an artificial gas cap. The field-scale application was introduced in 1988. Incremental oil volume to date is 2,260,000 m³ (14,215,000 bbl).

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During the implementation of the carbon dioxide flooding project, several innovations had been developed both in well-technology and in surface facilities. The authors give summary of the results and development of new technologies at the carbon dioxide flooding project.

INTRODUCTION

Hungary, located in the central part of the Carpathian Basin, has got two petroleum super systems:

- the older one is discovered and exploited oil and gas from pre-Tertiary reservoir rocks (predominantly fractured limestone, dolomite and metamorphites)
- the younger one is found in Tertiary clastic reservoir rocks.

The country was able to meet the oil demand in the late thirties and early forties with a modest surplus for export to Western Europe.

The strong industrialization in the fifties and sixties and the growing demand for the petroleum as energy source, in general, and growing appetite of the industry, in particular, changed the situation and Hungary became an oil importer. In this context, it was a necessity to be able to enhance the oil output of the domestic fields.

As a consequence, the simplest secondary methods to maintain the reservoir pressure (re-injection of the associated gas produced or water injection) have been intensively applied since the early forties.

Laboratory and pilot tests allowed full scale field application of different in-situ combustion methods which were applied to a low API gravity oil in an Oligocene sandstone reservoir in the northern part of the country. The experience accumulated during the design and implementation phase of this method allowed exporting this knowledge in the form of a joint pilot project to countries such as Canada, India and the Soviet Union.

With the commissioning and continuing depletion of the multi-layer Algyõ field with a number of oil pools both with saturated and under-saturated oil deposits, laboratory and pilot projects applying tertiary recovery methods (such as polymer injection and micellar solutions) were started and successfully implemented

The most successful method, however, was CO_2 injection in both sandstone and limestone reservoirs. The application of the principles of the subsurface displacement processes were introduced first in the sandstone reservoirs of Bázakerettye, Lovászi fields in Western Hungary. This method in young (Miocene and Pliocene) strongly stratified reservoirs after a reasonably long period of successful water flooding is the first item of this presentation. The second half of this paper outlines the history, results and lessons learned from the application of the CO_2 injection method in a karstic limestone reservoir.

The CO_2 source was available from high-pressure/high-rate wells producing from natural reservoirs. High-pressure pipelines were built to transport the gas to the fields where it was injected, so pressure boost was required only for re-injection. An extensive workover program was required to re-complete the existing old wells. New wells were also drilled as infill wells and as replacement of old wells having critical conditions. Material selection of downhole equipment was of critical importance. Corrosion monitoring and mitigation have been a critical issue throughout the project.

Location of above-mentioned fields is shown in Figure 1.

CO_2 GAS SOURCE

In the region of Budafa field a carbon dioxide natural gas reservoir had been developed in 1968 which had more than 10 billions m^3 of original gas in place (OGIP). The gas exists in the Miocene coarse clastic rock at 3200 m depth. Initial reservoir pressure was 33 400 kPa, and the reservoir temperature is 165 °C. Characteristic composition of the produced gas is as follows: 80 to 81 mole % CO_2, 16-17 mole % HC, 2 mole % N_2 and 0.3 to 0.4 mole % H_2S.

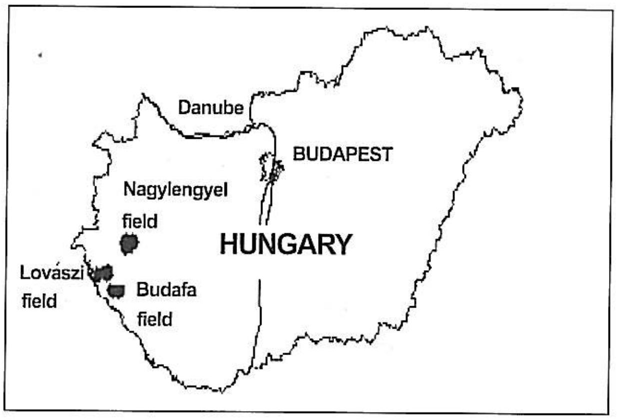

Fig. 1. Location of Budafa, Lovaszi and Nagylengyel fields.

The reservoir has very strong water drive and good hydraulic characteristics. The reservoir was exploited by three wells, with maximum production capacity of one million m^3/d at 16000 kPa well-head pressure. Thus, the gas can be injected into the crude oil reservoirs without using any compressors.

CO_2 Gas Flooding in Sandstone Reservoirs

In Budafa and Lovászi fields the oil is found in layers between 1000 and 1500 m below the surface. The reservoir rock is sandstone. Average porosity of the formations varies between 17 – 22 % and the average permeability varies between 30 – 100 mD.

The reservoir oil is of intermediate-paraffin character, its density is 820 – 830 kg/m^3 (40-38°API) at standard conditions. In the initial phase of recovery, the oil was saturated with hydrocarbon gas. Most of the reservoirs possessed initial gas cap. The initial pressures ranged from 10,000 to 15,000 kPa, and the reservoir temperature is between 60-80 °C.

Hydrocarbon production began in Budafa field in 1937 and in Lovászi in 1940. By the 1st of January 2003, cumulative oil production from Budafa field was 6.8 million m^3 and the recovery factor was 33.5 %, whereas from Lovászi field the total oil produced was 8.1 million m^3 and the recovery factor was 30.9 %. The natural edge water inflow was very weak and the reservoir pressure decreased significantly during production. Hydrocarbon gas re-injection was started in 1939 and 1944 in Budafa and Lovászi, respectively. This method resulted in 2.4 million m^3 incremental oil which implied a recovery increase of 5.27 % with respect to the area recovered by that method. In an advanced stage of production, water injection was initiated in 1953 and 1954 in Lovászi and Budafa, respectively. The water flooding was not successful as the incremental recovery factor was only 1.46 % of the OOIP.

After running the necessary laboratory tests, a pilot test was started in the Upper Lispe formation in 1969 using natural CO_2 gas. Before starting the experiment, CH gas and water–injection were performed. The oil recovery factor was 35.2 % OOIP. The pilot experiment was completed in 1980. The produced incremental oil was 67,600 m^3, and the incremental oil recovery factor was 10.13 %.

Field-scale application was started in the Budafa-West formation of the Budafa field in 1972 and in the Kiscsehi layers in 1974. Figure 2 shows a typical cross-section and Figure 3 the annual oil production rate of Budafa-West. Following the favorable

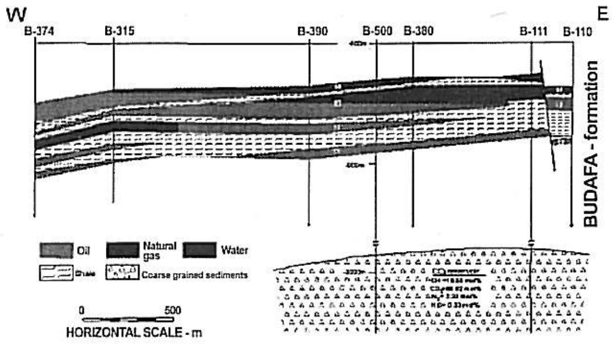

Fig. 2. Cross-section in Budafa west unit.

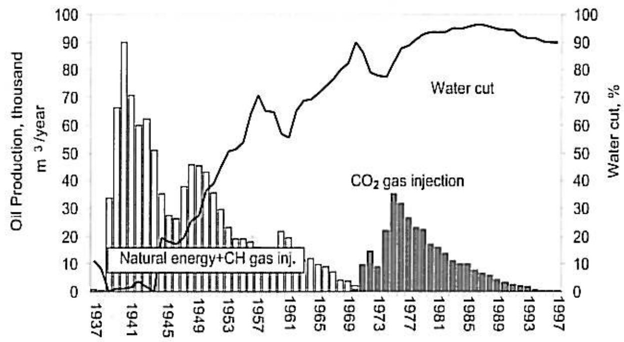

Fig. 3. Production history of Budafa-west unit.

experiences, the CO_2 natural gas was transported in pipeline to Lovászi field, where the EOR applications were begun in 1975-77. Thereafter the exploitation was continued in the Zala and Kerettye formations of Budafa field in 1981. The basic data is summarized in Table 1.

Due to the high reservoir temperature, miscible displacement could not be reached but a partial miscibility could be achieved. The carbon dioxide exerts its favorable effect, first of all, through the swelling of the oil. In the first phase of recovery, the natural CO_2 gas was injected into the reservoir through injection wells in order to increase the reservoir pressure which has declined in the primary recovery stage to its initial value. During this process, a controlled production was being performed to ensure the high (60-70 mole %) carbon dioxide concentration of the solution gas of oil. It was a fundamental condition for the success. After that, water was injected into the reservoir through the same injection wells. At those reservoirs where the produced fluid became poorer in CO_2 or in order to achieve favorable volumetric sweep efficiency, a cyclic gas-water (WAG) injection was performed.

The results of CO_2 gas flooding in Budafa and Lovászi fields have been presented in the literature. [1] Nowadays, these fields are entering a more mature phase of development. Up to date, 1,457,000 m^3 incremental oil has been produced,

Table 1. CO_2 gas flooding in sandstone reservoirs of Budafa and Lovászi fields.

Field	Budafa	Budafa	Budafa	Budafa	Budafa	Lovászi	Lovászi
Discovered	1937	1937	1937	1937	1937	1940	1940
Pay zone	Upper-Lispe	Budafa-West	Kiscsehi	Zala	Kerettye	Lovászi-East	Lovászi-West
Productive area, km²	0,7	3,5	0,9	4,1		1,4	2,3
Average depth, m (subsea level)	980	848	842	870	970	1285	1285
Mean porosity, %	21,5	21,0	20,0	21,0	20,0	17,2	17,2
Mean permeability, D	0,022	0,100	0,050	0,132	0,096	0,030	0,030
Initial pressure, kPa	10 100	9 800	9 400	10 000	11 080	15 250	15 250
Pressure at the end of primary production, kPa	3 600	2 900	5 660	3 580	6 430	9 200	5 920
Reservoir temperature, °C	68	64	64	63	69	83	83
Oil density at 20°C, g/cm³	0,834	0,817	0,817	0,819	0,835	0,823	0,823
Oil viscosity at reservoir temperature, mPa.s	1,16	1,15	1,15	0,80	1,04	0,40	0,40
Formation volume factor	1,224	1,225	1,225	1,192	1,257	1,245	1,245
Primary recovery efficiency, %(OOIP)	35,20	22,57	29,14	31,87	34,30	31,02	38,78
Start date of CO_2 inj.	1969	1972	1974	1981		1975	1977
Producing wells	19	71	17	77		27	40
Injection wells	5	42	14	60		34	44
Oil saturation at start, %	40	50	45	42	41	44	40
Inj. CO_2gas up to 1st January 2002, million m³	92	719	158	1168		372	784
Incremental oil recovery up to 1st January 2002 10³m³	67,582	310,906	60,244	540,480		163,176	304,730
Tertiary recovery, %(OOIP) 1st January 2002	10,1	7,0	13,3	6,54		6,7	10,1

resulting in an incremental recovery of 6-10 % of original oil in place.

CO_2 Gas Cap Applications in Limestone Reservoirs

Another type of reservoir can be found in the Nagylengyel field discovered in 1951. The crude is a heavy oil with high density (950-980 kg/m³ i.e. 17-12° API) and high viscosity. The fluid contains practically no dissolved gas. The fractured, cavernous formations were created by karstic corrosion. There is practically no oil in the matrix of the rock. Most of the oil accumulated in the Upper Cretaceous limestone and Triassic dolomite formations, which contain hydro-dynamically separated blocks as a result of the structural movements. Most reservoirs have very strong water inflow, so natural water drive served as the primary source of energy during primary recovery.

Until the 1st of January 2003, some 21.5 million m³ oil was produced and the average recovery factor was 47.9 % OOIP. During the primary recovery period, the water influx became more and more extensive and the water cut stabilized at about 95-98 % by the end of 1970s. In the 1960s, some pilot tests for enhanced oil recovery (EOR) had already began. Tests using surface active agents and ammonium hydroxide were not successful for field scale applications.

Analysis of the reservoir structure and performance indicated that creating an artificial gas cap would be the most effective recovery method. Figure 4 shows the basic forms of the driving mechanism.

Complicated physical, chemical and hydrodynamic conditions are taking place during this special recovery so the process could not be modeled in the laboratory. That was the reason why it was absolutely necessary to carry out pilot test before the field scale applications. The gas cap can be established theoretically by any gas, however, economic considerations supported the utilization of impure carbon dioxide natural gas discovered in the Budafa field.

The pilot test of forming a CO_2 gas cap started in 1980 in the Southern Triassic block of the field which

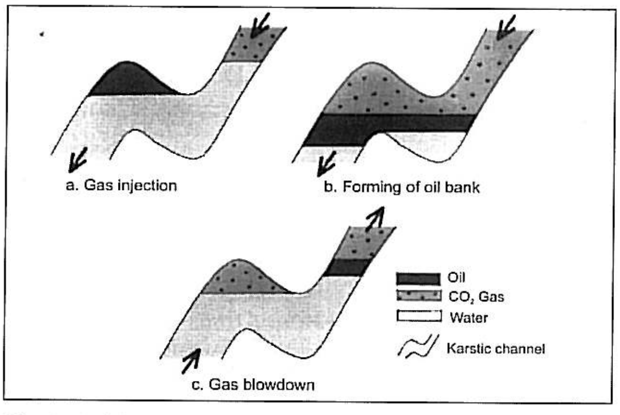

Fig. 4. Driving mechanism of CO_2 gas cap flooding.

has minor oil reserves and ended in late 1996. The characteristics of the reservoir are summarized in Table 2. Approximately 100.2 million m^3 gas were injected and 122,000 m^3 incremental oil was produced up to September 1996, which equals 10.4 % incremental recovery factor. More details of the pilot test are described in reference 2.

Based on the initial results of the pilot test it was decided to extend this technique to the whole Nagylengyel field in three stages. The annual oil production rate of the field is illustrated in Figure 5. The first stage was realized in the Block I-IV.

Table 2. CO_2 gas cap recovery of Nagylengyel field.

Reservoir properties	Pilot	Phase I.		Phase II.		
	South-Triassic block	I-IV rudistic block	VII. rudistic block	VIII rudistic block	X. North rudistic block	X. South rudistic block
Block area, km^2	0,8	11,7	3,1	5,5	2,3	2,7
Height of oil column, m	163	340	135	212	159	152
Depth at original water-oil contact, m (subsea level)	2290	2040	2010	2200	2200	2200
Initial pressure at OWOC, kPa	23 100	20 700	20 600	22 400	22 360	22 300
Reservoir temperature, °C	124	114	124	84	94	94
Mean porosity, %	2,5	1,2	3,4	1,8	0,8	1,9
Mean permeability, D	3,6	3,8	5,0	5,0	1,0	5,0
OOIP, million m^3	1,171	16,258	5,589	8,320	1,280	2,963
Stock-tank-oil gravity, g/cm^3	0,960	0,947	0,974	0,972	0,983	0,980
Oil viscosity at reservoir condition, mPa.s	92	18	49	137	125	137
Primary recovery, million m^3	0,493	6,880	2,804	4,194	0,447	1,699
% (OOIP)	42,1	42,3	50,2	50,4	34,9	57,3
Start of CO_2 gas cap recovery	Sept., 1980	Oct., 1988	Jan., 1993	Aug., 1994	Nov.,1996	Apr., 1995
Producing wells	7	105	35	44	9	22
Injection wells	1	11	2	4	-	2
CO_2 gas injection, million m^3	100,0	1851,8	470,6	1094,9		560,2
Start of blown down gas	Marc., 1985	Aug., 1994	Oct., 1997	Oct., 2000		Febr., 1999
End of project	Sept., 1996	Sept., 2000	Cont.	Cont.		Cont.
CO_2 gas production through to 1 Jan. 2003, million m^3	55,5	1214,3	320,6	426,2		291,6
Incremental oil recovery through to 1 Jan. 2003 million m^3	0,122	1,732	0,145	0,133	0,032	0,169
%(OOIP)	10,42	10,65	2,58	1,59	2,50	5,70

Block I-IV has the greatest reserves in the field. The OOIP was 16.3 million m^3. The Upper Cretaceous reservoir rock is biogenic limestone of shoreline origin. Reservoir space was formed on the impact of the authigenic (uncovered) karstification during a subaerial period before Miocene. The 0.5 % original porosity of the rock increased to 4 to 6 % in the erosion zone as a result of karstic corrosion. The crude oil is of paraffin-intermediate base, its density at 20°C is 947 kg/m^3 (17°API), and the viscosity at reservoir conditions is 18 mPas. Oil-water contact was originally at 2040 m below surface. The initial reservoir pressure and temperature were 20,700 kPa and 114°C, respectively.

Production from Block I-IV started in 1951. The peak production was reached in 1955 with 1.1 million m^3/year. By the end of 1967, most wells were producing at >90 % water. Oil produced during the primary recovery stage was 6,880,000 m^3, corresponding to 42.3 % of the original oil in place.

The EOR application was carried out using 11 gas injectors and 105 producers. The gas injection was started in October 1988 and terminated in August 1994. The cumulative gas injected was 1.852 billion m^3. Thereafter, the blow-down of the gas started and it was placed into the blocks of the second stage without compressors. The project was terminated in September 2000. By that time, 1,732,000 m^3 incremental oil was recovered corresponding to an additional recovery factor of 10.65 % of the original oil in place.

Blocks # VII, VIII, and X were used for stage II of the CO_2 gas cap flooding. Reservoir rock is Upper

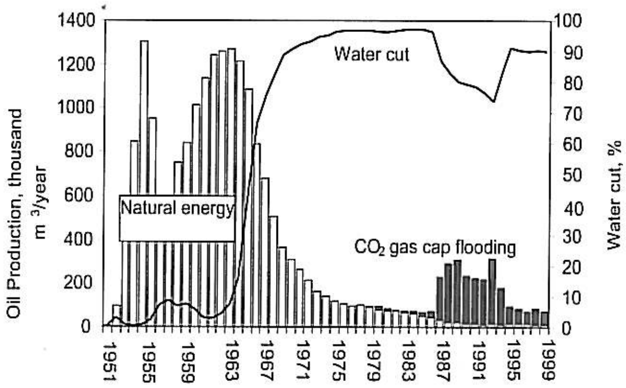

Fig. 5. Production history of Nagylengyel field.

Cretaceous biogenic limestone similar to Block I-IV. But the karstification can be characterized mainly by allogenic (covered, so called "B" type) processes. Principal geologic and reservoir engineering data are given in Table 2.

CO_2 gas injection into the blocks started at different dates between January 1993 and April 1995 and was terminated between October 1997 and October 2000. Approximately 2.126 billion m^3 of cumulative gas was injected into the reservoirs. The gas blow-down is still continuing now. The incremental oil was 477,800 m^3. Stage III is under discussion and preliminary design.

To date, 2,381,000 m^3 incremental oil has been produced from the blocks of Nagylengyel field. More information about this project is written in the literature [3].

WELL COMPLETIONS

The CO_2 producers are completed with 4 ½" gas-tight tubing. A typical HP/HT completion was selected because of the high bottom-hole temperature and the corrosive environment. Permanent drillable packers are used with Seal Bore Extension. Storm Choke is installed to prevent gas leak to the air in case of a wellhead failure. It was noted that corrosion is a problem in the upper section only (where water condensates). To reduce completion cost, it was decided to use carbon steel tubing. To mitigate corrosion, batch type inhibition treatment was applied. To eliminate elastomer problems, metal-to-metal seals were used on the wellhead installation.

The wells used for CO_2 recovery were typically 20-40 years old at the time when the CO_2 gas injection was initiated. An extensive recompletion program was required to modify the original completion and to keep the wells in proper condition to minimize operational problems.
Typical operations carried out were as follows:

- drilling deeper (where it was required)
- logging to evaluate cement bond and base log for evaluating gas migration during the CO_2 recovery
- squeeze cementing to repair cement sheath
- squeeze cementing to shut-off perforations
- re-perforate
- acid stimulation
- casing integrity test
- repair damaged casing (inside or outside casing patch)
- remove old wellhead and install new wellhead and Xmas tree to fit to the special requirements
- run completion equipment
- test the integrity of the final completion with gas (air or nitrogen).

It was of critical importance to check and repair every well (even the plugged wells) which were found within the area of CO_2 recovery, because a seal above the reservoir was necessary to prevent gas migration from the reservoir.

In some cases new wells were drilled. In sandstone reservoirs the new wells were drilled as infill wells to improve sweep efficiency. In Nagylengyel field, new wells were used generally for injection purposes because of safety reason, to replace old wells with poor casing condition.

The CO_2 injectors were completed with permanent drillable packers and gas-tight tubing. In the case of sandstone reservoirs, 2 7/8" J-55 EU tubing with Teflon ring was installed, while in Nagylengyel field metal/metal seal gas-tight connections were used to improve well safety.

Downhole Injection Safety wells and Storm Chokes were used in Nagylengyel field to avoid leakage to the air in case of a wellhead failure. Elastomers were selected carefully to meet the requirements. Viton and Teflon were used successfully in the field.

Sucker Rod Pumping is the general means of mechanical production. 13 Cr alloyed steel with controlled hardness is used widely to reduce corrosion/erosion of pump parts. Pumping wells were converted to flowing well with packer type completion when gas production was high enough to keep the well flowing.

NACE MR01-75 was taken into consideration in all completion and live well operations. Law-alloy carbon steel with controlled hardness was selected where appropriate, but in critical areas 9Cr1Mo materials were selected (*e.g.* wet parts of the packer and completion equipment below packer).

To design reliable and economical completions, a detailed analysis of the conditions and requirements was essential. A typical example illustrating the logic of completion design of the CO_2 injection well in Nagylengyel field is shown in Figure 6. A typical completion used in Nagylengyel field is shown in Figure 7. The Single String Two Zone Alternate Completion is suitable to isolate the zone which is producing with high GOR. The upper zone can be produced through a choke to lift the fluid produced from below.

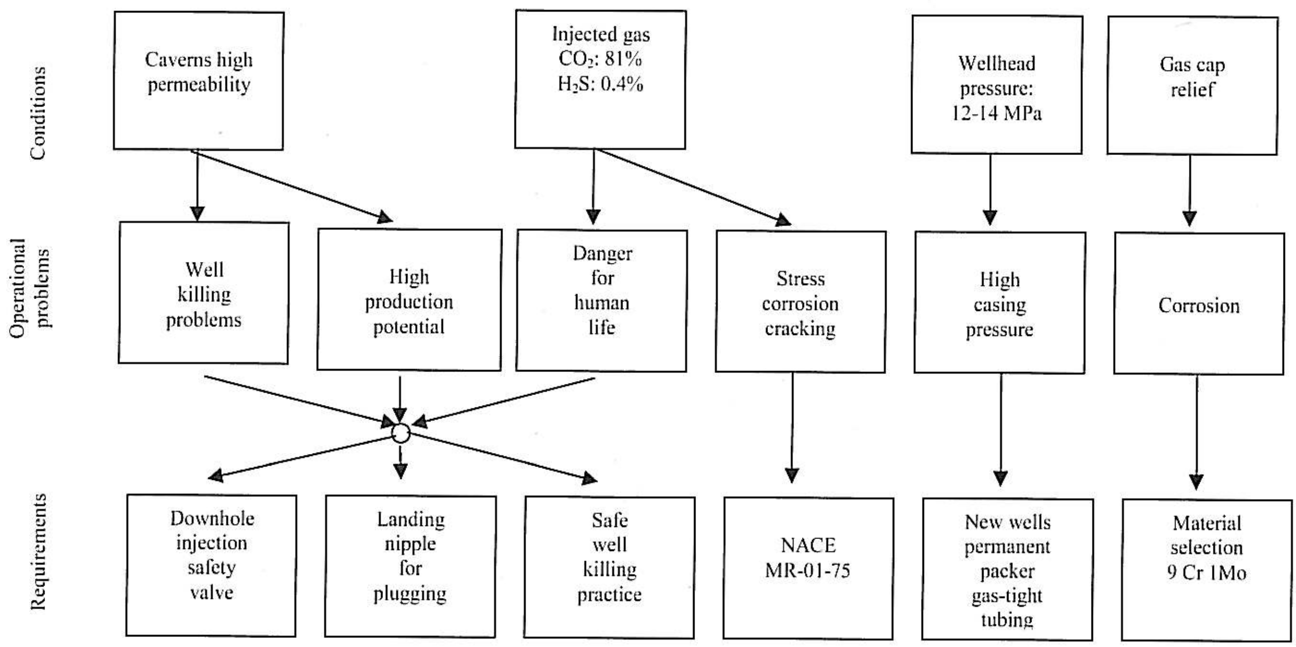

Fig. 6. Completion requirements of CO_2 injection wells in Nagylengyel field.

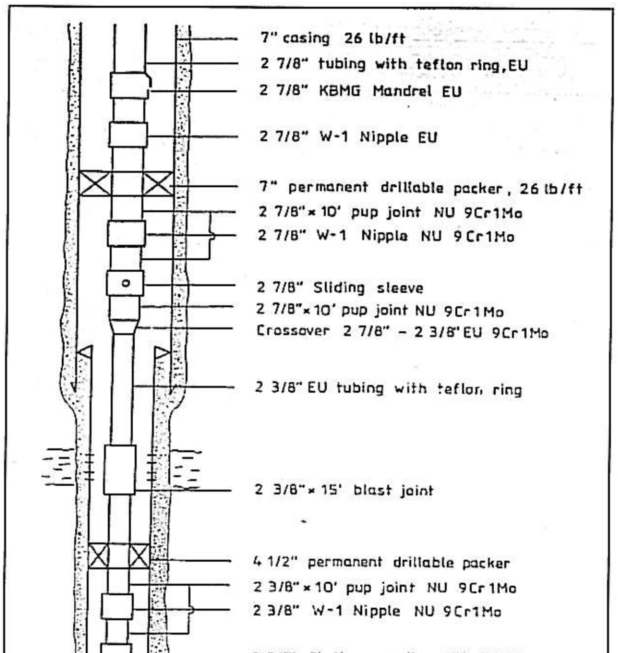

Fig. 7. Completion of selective production well in Nagylengyel field.

SURFACE FACILITIES

Two levels of technical advancement were accomplished in the design of surface facilities. At the beginning, all the facilities were simple and traditional. However, with more and more field experience and study of international literature, more sophisticated processes, methods, equipment and accessories were designed and applied.

Production, Transportation and Injection of CO_2 Gas

CO_2 gas was produced in Budafa Field from deep wells. Initially 3 production wells were used, then increased to 5 in the final stage. At the early stage the well site facilities of the CO_2 production wells were equipped with stainless steel, but for the piping system carbon steel was used. Concerning the gas treatment, it was decided not to remove the H_2S contamination, because of economical reasons. Figure 8 shows a schematic of the surface system at the early stage.

Initially the aim of gas treatment was to achieve a dehydration level necessary to avoid hydrate forming in the transportation and injection systems. The temperature of the produced gas at the wellhead was about 100°C. The gas was cooled to 45-75°C in a gas-gas and a water-gas heat exchanger. Free water was knocked out then the gas was reheated to 60-75°C by gas-gas heat exchanger. This simple treatment was good enough for short distance transportation (the distance between Budafa and Lovászi fields is about 11.3 km). Because of the very low soil temperature, methanol injection was used to

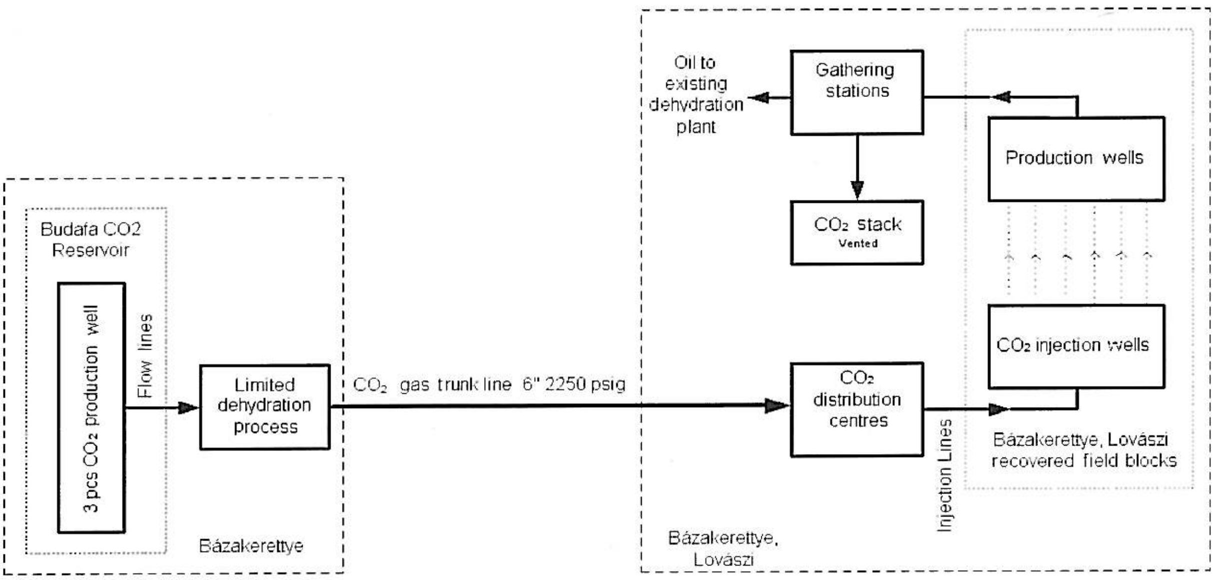

Fig. 8. Schematic of early surface system of CO_2 recovery.

prevent hydrate formation. There was no substantial pressure drop during the process so no compression was required to inject the CO_2 gas.

A higher technical level was accomplished in Nagylengyel field. The schematic of surface facilities at this stage is shown in Figure 9. The well site of CO_2 production was redesigned. Surface section of piping and all the accessories were replaced by stainless steel ones with 316 L material. The distance between Budafa and Nagylengyel field is about 34 km. The previous simple gas treatment was not acceptable for this range of transportation. A high-pressure, glycerol gas treatment plant was built, so the natural energy of the CO_2 source reservoir can be utilized to eliminate the need of compression to inject the gas in Nagylengyel field. The usual glycol as an absorbent for dehydration was not acceptable because it dissolves in the high pressure CO_2 gas stream causing a significant glycol loss. For high-pressure CO_2 stream, the glycerol proved optimal absorbent medium for dehydration. All the materials of the dehydration process on the wet gas side, piping and vessels were made of 316 L stainless steel. There were no transportation problems as the result of -5°C dew point of the treated gas. Individual injection lines were built to each injection well. The CO_2 gas was injected into the wells through distribution stations in the field.

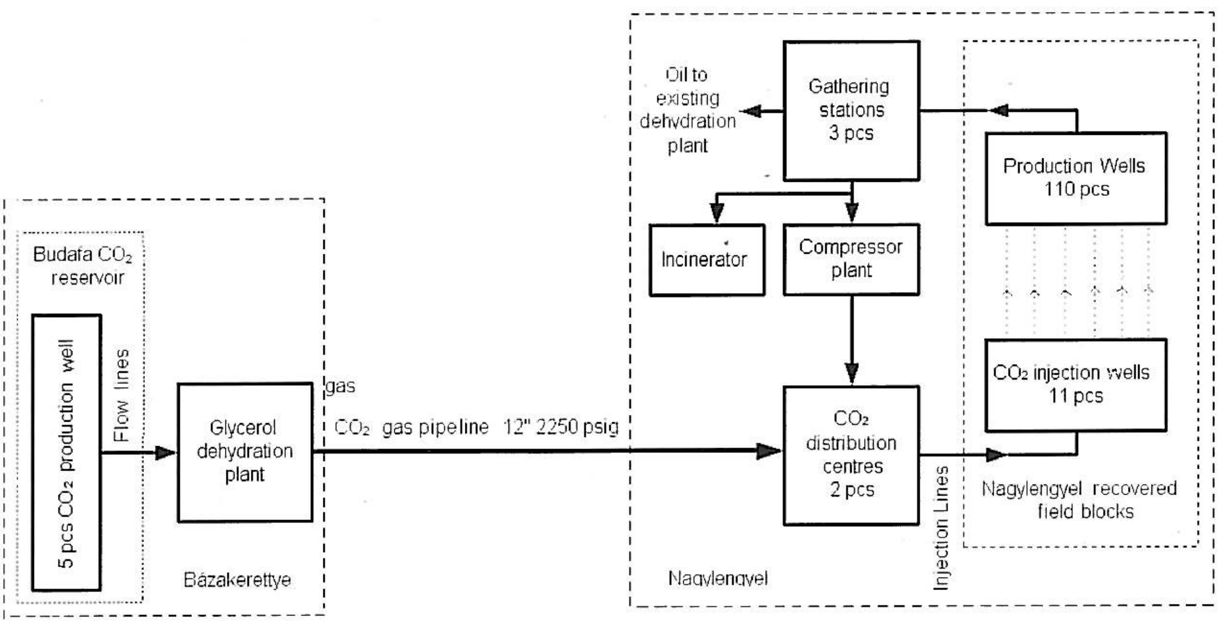

Fig. 9. Schematic of surface system of CO_2 recovery in Nagylengyel field.

Water Injection

In Budafa and Lovászi fields, the CO_2 injection was followed by water injection. Water was injected continuously or alternately (WAG). Formation water was mixed with fresh water. Following sedimentation, filtration and chemical treatment the water was injected with reciprocating pumps. The same injection lines used for CO_2 injection were used for water injection.

Surface Production Facilities

In Budafa and Lovászi fields, sucker rod pumping was used for mechanical production. Separation of the gas from the oil and water occurred in conventional metering stations. Oil was separated and treated in the central tank farm. Because of economic reasons the associated gas was vented into the atmosphere.

In Nagylengyel field initially radial gathering system with tank stations was built, but in the 2nd phase, due to economic reasons, a gathering header system was developed. Oil is treated in the central gathering station. The associated gas is reinjected and circulated to other blocks. On the gathering side also, significant advancement occurred. The associated gas with high CO_2 content was gathered, compressed and reinjected into a subsequent block of the reservoir. In case of compressor failure the low pressure associated gas was incinerated to convert the toxic H_2S content into less dangerous SO_2. During the blow-down phase in Nagylengyel reservoir an interesting method was used.

Between the block designated to blow-down and the subsequent block designated to gas injection, a gravitational stream (without any artificial pressure increase) is usable due to the special behavior of CO_2.

Certainly this gravitational stream can only take place in such a strongly fractured reservoir like Nagylengyel, in which there is, practically, no bottom-hole pressure drop/increase either in the blowing down or in the injection wells. In the Nagylengyel field, the dynamic flowing well head pressure can be higher than the static one in case of high CO_2 content gas mixture. If the surface system, especially the buried pipe system assures some temperature loss between the gas production and the gas injection well, the well head pressure on the injection well head is sufficient to inject the desired gas stream.

As for the emergency blow-down system, a further special phenomena was observed: the emergency blow-down system which consists of pressure vessels and pressure piping containing natural gas with high CO_2 content in the different sections of the system, CO_2 water hydrate, CO_2 liquid ice water and solid CO_2 can be formed due to the very low temperature during blow-down.

To prevent the consequences of this very dangerous situation, in case of a quick emergency, blow-down the initial method was to design a multi-step heating-expansion system. If it is desired to blow-down significant gas stream quickly, then huge heat exchangers and huge sources of heat were required for a short working time.

Based on our experience, if the route of the gas to be blown down is designed without sacks or sharp corners, all the multi-phased stream can be blow-down and solid particles can be swept without plugging the system. No separator, slug catcher *etc.* are built in. In case of sophisticated elaboration of the blow-down system, the high capacity of heat exchangers and heat supply system can be spared. Special steels are used to work in the low temperature environment.

CORROSION

Corrosion mitigation was a key issue throughout the recovery. The following measures were taken to reduce and solve the problem of corrosion:

- corrosion monitoring (coupons, wall thickness measurements, water analysis)
- failure analysis
- inhibition
- proper gas treatment (eliminate free water)
- reduce flow stream velocity (pipe diameter)
- select corrosion resistant materials in critical technologies (*e.g.* glycerol gas treatment)
- select proper materials for downhole equipment
- planned replacement of components of the technology, based on expected life and measurements, or visual checking
- plastic inner coating (e.g.: tanks).

Continuous corrosion monitoring is very important from the point of view of safety and smooth operations.

ENVIRONMENT PROTECTION

At the beginning of the seventies, the environment policy was not as strict as it is nowadays. Since then, the protection of the environment has become a very sensitive subject. Both the associated and the cap gas have to be gathered and reinjected. Emergency blow-down into the air can be radically reduced by dividing the system into smaller volume sections by ESD devices which simultaneously and automatically close the gas source.

The development of process engineering, instrumentation and automation gives a lot of possibilities into the hand of the engineers to reduce or eliminate the emission of hazardous gases into the environment. The cost of these investments has to be taken into consideration during the economic evaluation of future projects.

CONCLUSION

CO_2 gas flooding is an effective process to increase oil recovery in sandstone and karst type limestone reservoirs. Analysis of downhole and surface conditions and requirements are essential to design downhole completions and surface facilities suitable for CO_2 injection and production. Continuous improvement is required based on operational experiences.

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