Getica CCS project-feasibility of local logging technologies

Introduction

Monitoring operations will be conducted at designated storage sites (zone 1 and zone 5) to oversee the performance of injection operations and mitigate inherent storage risks, in compliance with the requirements outlined in Annex II of EU Directive 2009/31/EC and its implementation guidelines. For Zone 5, to monitor "CO_2 displacement and fate", we find time-lapse well logging will acquire very accurate measurement at the well, and is applicable in this case as well: sonic logging, cased-hole neutron porosity, cased-Hole resistivity logging, pulsed neutron logging. Finally, point measurements, consisting in pressure and temperature measurements work in any geological environment, and are applicable as well. Zone 5 and Zone 1 present two main strategies to fulfill the dual monitoring objectives of monitoring "CO2 displacement and fate" and "detection of leaks/migration". The first approach involves conducting regular 3D seismic surveys. The second strategy involves installing multiple monitoring wells equipped with pressure and temperature gauges. This method allows for the incorporation of additional well log measurements to precisely assess CO2 saturation distributions at the monitoring locations. This paper aims at reviewing key logging monitoring techniques and evaluates their applicability in the framework of the CO2 injection into the Sarmatian Reservoir in Zone 5.

Methods

Cased-Hole Neutron Porosity Logging

Among the existing wells within Zone 5, 3 were identified to reach the target reservoir, the Sarmatian Sequence, contain information about formation resistivity and porosity in order to estimate the feasibility of logging technologies for monitoring and are well distributed throughout the sites. These wells are: Zegujani 15, Ciovarnisani 4229 and Ciovarnisani 3001. The below table (Table 1) shows the main properties collected from the well log information. Logging monitoring techniques could be used in the deep monitoring wells which will be part of the overall monitoring infrastructure. The depth intervals in Table 1 were taken from the static model and checked against available well log data.

Well	Interval (mMD)	Average porosity (%)	Average formation resistivity (ohm-m)	Water resistivity (Rw) (ohm-m)	Formation Temperature (degC)
Zone 5: Reservoir from Top of Sa5 to Base of Sa3a					
Zegujani 15	2858.44-1992	5.3	5-30	0.014-0.084	85
Ciovarnisani 4229	2141.48-955.26	6	400	1.44	N/A
Ciovarnisani 3001	2099.6-1595.7	11.3	~ 3	0.038	64.8

Table 1: Petrophysical parameters considered during the logging technology feasibility study

Average porosities across the 3 wells within the reservoirs of interest vary between 5 and 11% and formation resistivities between 3 and 400 ohm-m.

In order to simulate tool responses in the Sarmatian reservoir, the SNUPAR* modeling tool has been applied. It takes the formation density and porosity, fluid/gas saturations, temperatures and pressures into account and computes the expected tool response (APS neutron porosity). ECLIPSE simulations showed that since many injectors are used per zone, 9 in Zone 5, several of the injectors show a very small CO2 plume movement. As a result pressure and gas saturation properties were taken from an area 500m away from the injectors. Larger distances would have caused that no CO2 would have been seen till 2135 or even later. As can be seen in Table 2, even with a spacing of 500 m between the injector and monitoring well, the CO2 plume cannot be detected right after injection, but between 2019 and 2035 depending on the injector. Based on the available information, the (limestone) neutron porosity for injector 1 would be 2.2. p.u. before CO_2 injection started and will decrease to about 0.4 p.u. at the end of injection giving a change of -1.8 p.u. over the time of 17 years (2018-2035).

Scenario	Situation	Time (Year)	Volume Fraction Water	CO2 Fraction	CO2 Density	Pressure (bar)	Temp (degC)	Water Salinity (kppm)	Neutron Porosity (p.u.)	Volume Fraction Water	CO2 Fraction	CO2 Density	Pressure (bar)	Temp (degC)	Water Salinity (kppm)	Neutron Porosity (p.u.)
Zone 5																
			Injector 1							Injector 2						
			Petrophysical Parameters from the Zegujani 15 well (porosity = 5.3%, water salinity = 300 kppm)							Petrophysical Parameters from the Ciovarnisani 3001 well (porosity = 11.3%, water salinity = 100 kppm)						
1	Start of Injection	2015	1	0		244.66	73	265	**2.2**	1	0		180.4	58	100	**8.1**
2		2016	1	0		278.46	73	265	2.2	1	0		205	58	100	8.1
3		2017	1	0		268.9	73	265	2.2	1	0		196.8	58	100	8.1
4		2018	1	0		265.6	73	265	2.2	1	0		194	58	100	8.1
5		2019	0.9469	0.0531	0.7387	264	73	265	2	1	0		192.7	58	100	8.1
6		2020	0.7418	0.2582	0.7377	263	73	265	1.3	1	0		192	58	100	8.1
7		2025	0.5048	0.4952	0.736	262.6	73	265	0.6	1	0		190.6	58	100	8.1
8	End of Injection	2035	0.4137	0.5863	0.6968	261.6	73	265	**0.4**	0.5075	0.4925	0.7222	191.3	58	100	**3.2**
9		2135	0.4453	0.5547	0.7371	232	73	265	0.5	0.5534	0.4466	0.6872	173	58	100	3.6
10		2235	0.5151	0.4849	0.6966	231.9	73	265	0.7	0.6777	0.3223	0.6872	173	58	100	4.9
11		2335	0.6074	0.3926	0.6965	231.8	73	265	0.9	0.7401	0.2599	0.6872	173	58	100	5.5

Table **2**: Summary of neutron porosity results, 500m away from the injector locations

Within a higher porosity environment close to injector 2, this change would be about -4.9 p.u. within 10 years, as can be seen in Table 7. Both cases would allow CO_2 plume monitoring over time.

Cased-Hole Resistivity Logging

Resistivity logs would also be expected to detect CO_2 breakthrough (within a saline aquifer), because less conductive CO_2 is replacing more conductive formation water in porous rocks. Cased hole resistivity measurements are more favorable in low to medium porosity and formation water salinity environments than pulsed neutron sigma. The workflow was demonstrated on the Zegujani 15 well. Using an average porosity of 5.3%, a water salinity of > 300 kppm and a reservoir temp of 85 degC (R_w = 0.014 Ωm), the tool reading in 100% water would be around 5 Ωm. In order to deploy cased-hole resistivity tools, a few criteria (good cement bond between casing and formation, cement resistivity and casing) have to be met from an operational point of view and should be checked as soon as monitoring wells are planned to be drilled. Casedhole resistivity measurements are sensitive to water saturation change. Water resistivity depends on temperature and salinity, which need to be better constrained with the addition of new measurements. Since the tool has an upper operational limit of 100 Ωm, a lower limit for S_w (and therefore S_{CO2}) can be computed. Considering average porosities between 5 and 11%, this limit would be between 17 and 23%, below which the tool is not operational. Baseline resistivity read by the tool would be around 3-5 Ωm and the CO_2 saturation would have to reach 78 to 83%.

Pulsed Neutron Logging

From the operational point of view, pulsed neutron tools can be run through casing (min. casing size = 1 13/16") and tubing (min. tubing size = 2 3/8"). They work best in medium to high porosity and high formation salinity environments (~100 kppm) and have a sigma accuracy of about +/- 0.25 cu.
In order to decide on the possibility of using Pulsed Neutron Logging for CO_2 monitoring, a simple comparison between the Frio brine and the Sarmatian reservoir in terms of formation properties is made first.

Scenario	Situation	Time (Year)	Volume Fraction Water	CO2 Fraction	CO2 Density	Pressure (bar)	Temp (degC)	Water Salinity (kppm)	Sigma (c.u.)	Volume Fraction Water	CO2 Fraction	CO2 Density	Pressure (bar)	Temp (degC)	Water Salinity (kppm)	Sigma (c.u.)
Zone 5																
			Injector 1							Injector 2						
			Petrophysical Parameters from the Zegujani 15 well (porosity = 5.3%, water salinity = 300 kppm)							Petrophysical Parameters from the Ciovarnisani 3001 well (porosity = 11.3%, water salinity = 100 kppm)						
1	Start of Injection	2015	1	0		244.66	73	265	**11.1**	1	0		180.4	58	100	**10.6**
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3		2017	1	0		268.9	73	265	11.1	1	0		196.8	58	100	10.6
4		2018	1	0		265.6	73	265	11.1	1	0		194	58	100	10.6
5		2019	0.9469	0.0531	0.7387	264	73	265	10.75	1	0		192.7	58	100	10.6
6		2020	0.7418	0.2582	0.7377	263	73	265	9.36	1	0		192	58	100	10.6
7		2025	0.5048	0.4952	0.736	262.6	73	265	7.747	1	0		190.6	58	100	10.6
8	End of Injection	2035	0.4137	0.5863	0.6968	261.6	73	265	**7.124**	0.5075	0.4925	0.7222	191.3	58	100	**7.36**
9		2135	0.4453	0.5547	0.7371	232	73	265	7.342	0.5534	0.4466	0.6872	173	58	100	7.662
10		2235	0.5151	0.4849	0.6966	231.9	73	265	7.813	0.6777	0.3223	0.6872	173	58	100	8476
11		2335	0.6074	0.3926	0.6965	231.8	73	265	8.44	0.7401	0.2599	0.6872	173	58	100	8.884

Table 3: Sigma modeling results, 500m away from the injector; the water salinity limit within the software is 265 kppm, which were used instead of 300 kppm.

Pulsed neutron monitoring was done in the Frio Brine project in Texas (figure 1) on the basis of a large contrast between the capture cross section of CO2 (Σ = 0.03 cu) and the formation water (Σw = 55 cu) due to high water salinity (95kppm) and high porosity (32-35%). Figure 1 shows the overall change in Sigma over a period of 4 months.

As for the neutron porosity monitoring also Sigma changes cannot be monitored in the first few years (around 4 years) of injection due to the small CO2 plume movement around each of the injectors. For the below computations an injector-monitoring well spacing of 500m was applied in order to monitor the plume before the end of injection.

As can be seen in Table 3, a pressure increase occurs within the first year of injection and decreases slowly afterwards as a result of CO2 plume stabilization. The Sigma change from the start to the end of injection is about -3.976 cu for 5.3% porosity (water salinity = 300 kppm) around injector 1 and -3.24 cu for 11.3% porosity (water salinity = 100 kppm) around injector 2.

Although the overall sigma change from start to end of injection varies, -3.976 cu for 5.3% porosity (water salinity = 300 kppm) around injector 1 and -3.24 cu for 11.3% porosity (water salinity = 100 kppm) around injector 2, it is still 16 to 21 times the accuracy of the tool (± 0.25 c.u.) and can therefore be used to monitor the CO2 plume over time. However the high uncertainty on petrophysical properties like porosity and water salinity should be eliminated and reservoir simulations updated accordingly.

For the moment the amount of injectors used within Zone 5 (5 injectors) and the applied petrophysical properties cause the CO2 plume movement to be restricted around each of the injectors. As a result, monitoring wells would have to be drilled very close to them (less than 500m) in order to monitor the CO2 migration.

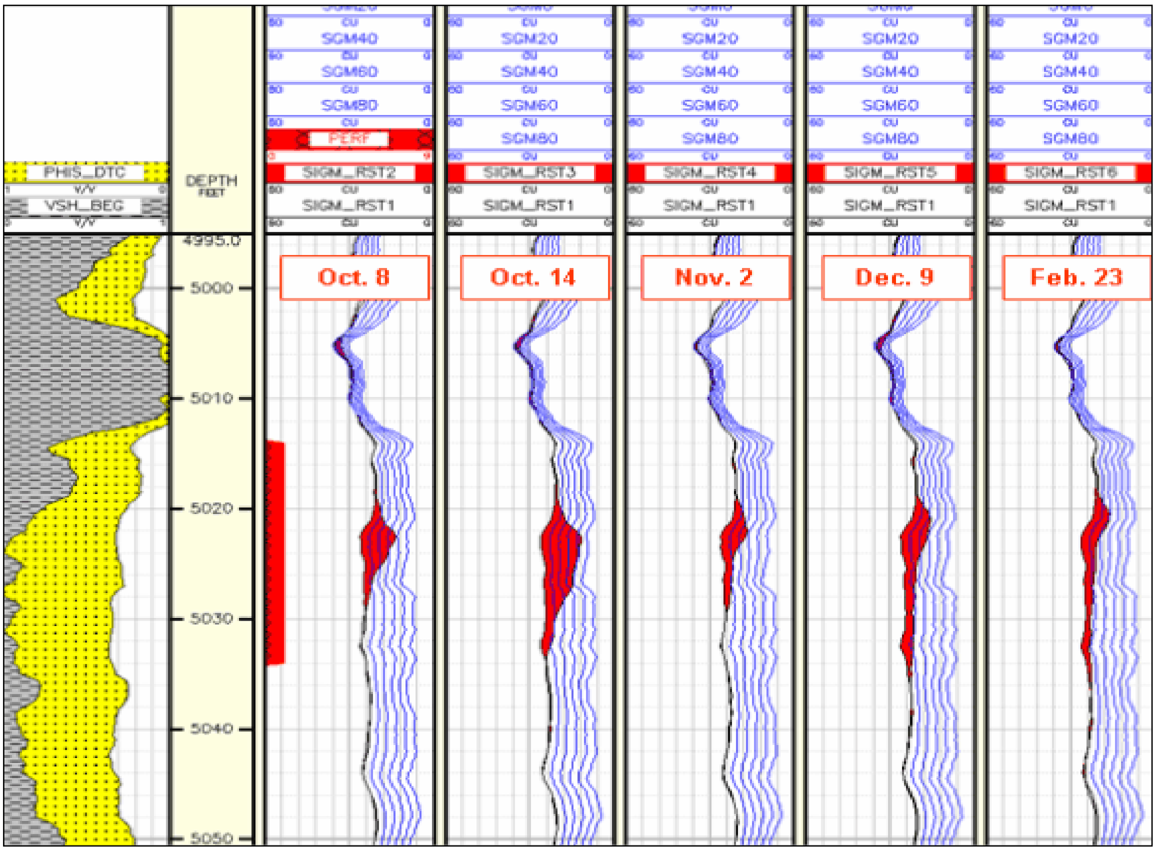

Figure 1: Time-lapse pulsed neutron log for monitoring CO_2 breakthrough in the Frio project

In the current study, the average porosity of the Sarmatian reservoir lies between 5 and 11% and the water salinity computed from available resistivity logs and reported porosities range between 100 and 300 kppm.

Conclusions

In general, neutron porosity can be used as a monitoring technique under the described situations since the accuracy of the tool is about 0.5 p.u. However the high uncertainty on petrophysical properties like porosity should be improved and reservoir simulations updated accordingly.
At the moment the amount of injectors used within Zone 5 (9) and the applied petrophysical properties cause the CO2 plume movement to be restricted around each of the injectors. As a result, monitoring wells would have to be drilled very close to them (less than 500m) in order to monitor the CO2 migration.
Although, the tool would be able to detect CO2 breakthrough and monitor the plume, it can only be operated in casings larger than 4 5/8" without any tubing present in the well.
Time-lapse neutron: large uncertainty exists for porosity. They should be acquired during the characterization phase of the study and forward modeling repeated.
However, if all the assumptions are correct, these technologies would be worth to consider for CO2 plume tracking.
Also due to the small plume movement around the injectors, as of to date, monitoring wells would have to be drilled very close the injectors, less than 500m in order to monitor the CO2 plume movement.
Based on the performed computations the CO2 plume could not be detected for the first 4-5 years after the start of injection. Due to the small CO2 plume movement around the injectors, a change in properties (Neutron porosity, sigma, resistivity) will not be detected during the first few years of injection in case the monitoring well is spaced 500m away and all our assumptions on the petrophysical properties are correct. However, due to the relative high resolution of the tools, leakage close to the wellbore could be detected after the CO2 plume has reached the monitoring well.Relating to pressure and temperature monitoring, this type of monitoring will be sensitive to CO2 leakage.
A sensitivity study, based on the ECLIPSE model should be lead so as to determine how much CO2 needs to leak in order to become detectable, depending on the location of selected monitoring wells.

Well logging methods				
Sonic log			High vertical resolution, small level of noise	Information at the well only, higher frequency than for seismic
Cased-Hole Neutron porosity			Neutron porosity decrease with increasing CO_2 saturation	Tool limitation (4 5/8" casing); Change in Sw needs to be present
Cased-Hole resistivity logging			Medium resolution CO_2 plume detection and tracking	Tool limitations (e.g. casing, cement bond and resistivity) need to be considered first; 100 ohm-m resistivity limit.
Pulsed Neutron Logging			High resolution quantitative plume saturation measurement	Has limitations in low salinity and low porosity environments

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References

Schlumberger. (2014). Well Logging Principles and Applications. Schlumberger.
Rider, M. (Ed.). (2004). The Geological Interpretation of Well Logs. Whittles Publishing.
Ellis, D. V., & Singer, J. M. (2007). Well Logging for Earth Scientists. Springer.
Asquith, G. B., & Krygowski, D. (2004). Basic Well Log Analysis. AAPG.
Whittaker, A., & Redshaw, T. (2007). Borehole Logging in Hydrogeology. John Wiley & Sons.
Warren, J. E., & Root, P. J. (1963). The behavior of naturally fractured reservoirs. Society of Petroleum Engineers Journal.